SUMMARY REPORT

OF THE

DEFENSE SCIENCES RESEARCH COUNCIL

SUMMER CONFERENCE

La Jolla, California

July 1992

Sponsored by
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DARPA Order No. 6029

The University of Michigan
Department of Chemical Engineering

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INTRODUCTION

This report is a summary of the 1992 DARPA-Materials Research Council Summer Conference which was held in La Jolla, California, during the period from July 6, 1992 through July 31, 1992. The report is being submitted to DARPA early in the contract period to enable them to utilize the results of the various workshops in a timely fashion. Later reports will be issued to include the materials generated at workshops held at periods other than those of the Summer Conference.

The principal task of the ONR-DARPA Grant is to bring together a group of the Country's leading scientists and engineers for an extended period, usually the month of July, to permit them to apply their combined talents to the planning and scoping of future materials research areas for the Department of Defense.

During the year workshops, and in some cases program reviews, are attended by smaller groups of Council members and their reports are made directly to DARPA. This is a growing activity of the Council and these reports in the future will be included in the report submitted at the end of the contract year.

The technical direction of the Council is by a Steering Committee made up of seven representative members of the Council who work with DARPA management. The Committee for 1992 is given in the following table. The Steering Committee selects the relevant topics for the annual Summer Conference and works with the other council members in developing new areas in defense research. The membership on the Steering Committee and of the Council varies from year to year depending on the research areas that are of major interest to the Department of Defense. The Council membership for 1992 is given in the following table.

The Council also serves as a resource other DARPA offices. The DARPA participants in the 1992 Summer Conference are given in the following listing.

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B. L. Yoon	MTO

The agenda for the Summer Conference is prepared initially during the prior year's conference with input from DARPA and the Council. This is refined at subsequent Steering Committee meetings and the workshops are organized. The calendar for the 1992 Summer Conference is shown in the attached figure.

JULY 1992 SUMMER CONFERENCE

(Conference dates are July 6th through July 31st)

DOYLE ELEMENTARY SCHOOL
3950 BERINO COURT
SAN DIEGO, CA 92122
619-459-3207

S	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	S
	6 MICROLAMINATES & COMPOSITES Evans & Hutchinson	7 PROCESS SENSORS Williams	8 COMPLEX OXIDE FILMS Beasley & Ehrenreich	9 RAPID PROTOTYPING Gilbert	10 COMPUTATION & MATERIALS Ehrenreich	
	13 PROCESS CONTROL MICROELECTRONIC MANUFACTURING Kailath & Larrabee	14 MULTISPECTRAL IR SYSTEMS McGill	15 DARPA DAY	16 CMOS Ferry & Osgood	17 OPTICAL ARRAYS/ OPTICAL PACKAGING Miller & Yariv	
	20 MASS STORAGE Gilbert & Ferry	21 THREE DIMENSIONAL PATTERNING & PROCESSING Economy	22 PHOTONIC INTERCONNECTS McGill	23 HEAD MOUNTED DISPLAYS Whitesides	24 TUTORIAL ON COGNITION Whitesides	
	27 ← REPORT PREPARATION	28	29	30 →	31 WRAP-UP	

July 13-16 - Amphibious Marine Operation

July 16 - There will be the option for DSRC members of a one day excursion to Camp Pendelton to observe a training exercise.

July 19 to 21 - There will be War Game Exercise for DSO personnel and DSRC members.

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TITLE PAGE

LAYERED MATERIALS

W. Barker, A. Evans, J. Hutchinson, B. Budiansky

EXECUTIVE SUMMARY

Large scale equipment for high rate magnetron sputtering and evaporation has been installed at several locations within the U.S. This equipment has been used to generate multilayer sheets and coatings that consist of metal layers alternating with either ceramics, other metals, or intermetallics. The layer thickness ranges between 10 nm and 10 μm with total thickness up to 250 μm. Based on selective testing, combined with the mechanics of dislocations and cracks in thin, contained layers, the novel opportunities afforded by layered materials can be specified with some rigor, In particular, the requirements on layer thickness, as well as constituent and interface characteristics, needed to impart unprecedented thermomechanical property combinations can be broadly outlined. The key conclusion is that layered systems offer unique flexibility for achieving the wide range of property profiles needed to satisfy the thermomechanical demands imposed on critical components used in aerospace, transportation and energy systems. This uniqueness, combined with opportunities for net shape manufacturing, provides the motivation for further assessment of the technology.

A dominant issue in the exploitation of layered materials concerns the rate of deposition and the consequent manufacturing costs. This issue has been addressed by equipment designs that facilitate high rate deposition and enhanced target utilization. Good examples include the rotating cylindrical magnetron sputtering facility at Martin Marietta, as well as the jet evaporation technique. Some cost estimations have been made for these processes which indicate that large multilayer sheets, up to 250 μm in thickness, can be produced in the range of $100-$200 per pound. Thicker layers are less viable. Machining costs might also be reduced if the net shape capabilities provided by patterning are used.

Lower manufacturing costs may be possible by jet evaporation. If validated, this range is economically attractive for many aerospace components and selected components in transportation and energy.

Explicit end-user demand for multilayer systems has been identified in the jet engine, bearing and cutting tool industries, with associated cost/benefit analysis. In each case, the multilayer would be used as a coating up to 250 μm in thickness. Coatings are already widely used in these industries. Multilayer concepts would greatly expend the potential for coatings and improve the performance of those coatings in common usage. Coatings are used for multiple purposes: wear/erosion resistance, thermal barriers, oxidation resistance, abradability. Multilayers that provide a range of properties, combined with spatial tailoring, appear to be ideally compatible with these requirements. Furthermore, presently used coatings have deficient crack growth properties. Consequently, coatings often provide nucleation sites for fatigue cracks in the substrate and limit component life. Improved resistance to crack growth in multilayer coatings would suppress this source of substrate cracks and enhance life/reliability.

It is recommended that an activity on multilayer coatings be established, wherein the potential for improved thermomechanical performance be demonstrated, along with the manufacturing ability. The coatings would be assessed on the basis of their effectiveness as thermal barriers, for oxidation protection and wear resistance, as well as their ability to resist cracking and thus, suppress fatigue crack nucleation. The activity might begin with a study of end-user requirements in a broad spectrum of industries, including trade studies. Priorities might then be set for technological exploitation. Such a study might also identify applications for sheet material; e.g., in diffusion bonded honeycomb structures.

LAYERED MATERIALS

W. Barker, A. Evans, J. Hutchinson, B. Budiansky, B. Freund

MOTIVATION

Take advantage of unprecedented ability to tailor thermomechanical properties by using the multi-layer approach.

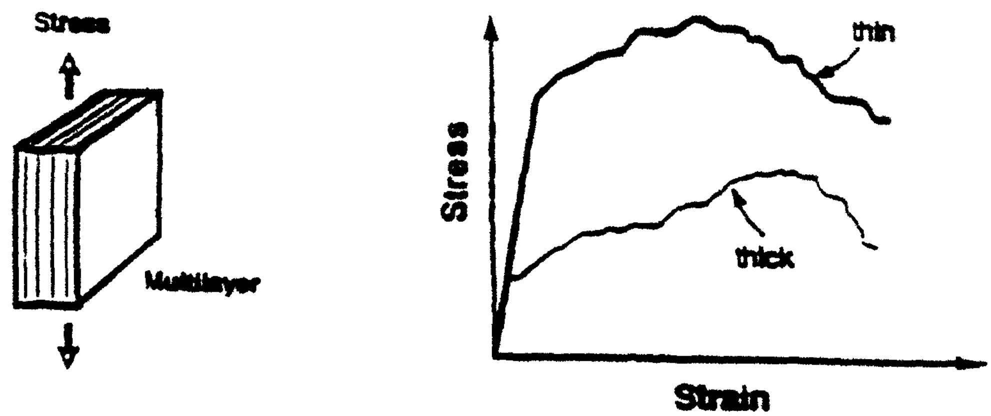
Structural Opportunities

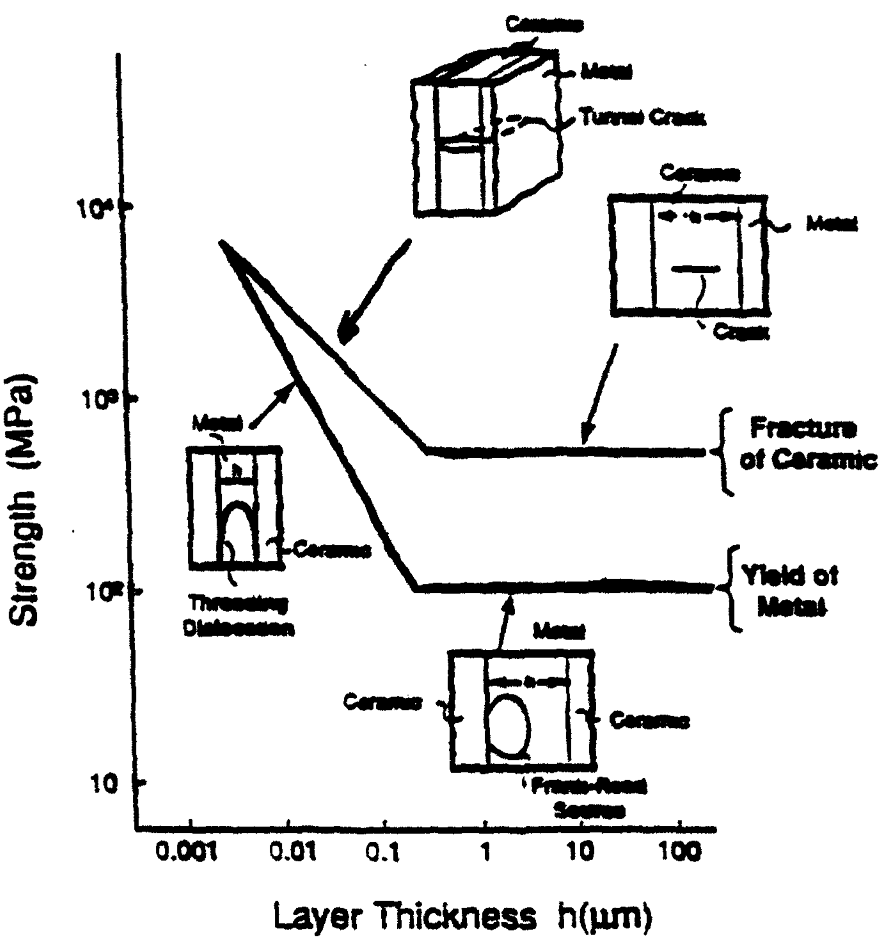
- **Wear/Erosion Resistance**
- **Strength/Hardness**
- **Elasticity**
- **Thermal/Oxidation Resistance**
- **Fracture/Fatigue Resistance**

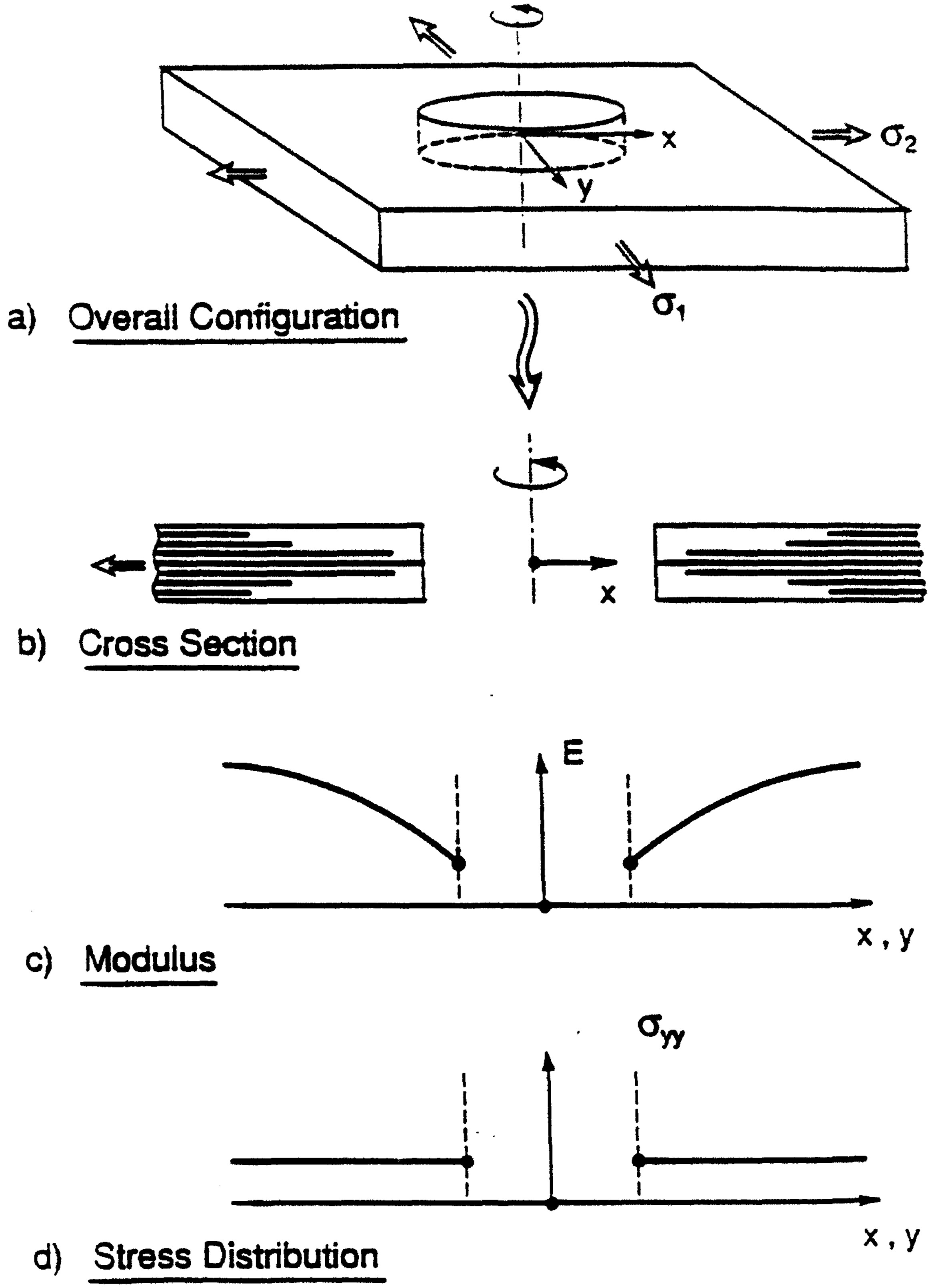
Functional Applications

- **High Energy Density Capacitors**
- **Multilayer Dielectrics for IR Sensors**
- **Solid Lubricants**

UNIQUE MECHANISMS IN MULTILAYER BEHAVIOR






x
y
σ2
σ1
a) Overall Configuration
x
b) Cross Section
E
x , y
c) Modulus
σyy
x , y
d) Stress Distribution

OBJECTIVE

Identify Applications For Multilayers And Assess Manufacturing Feasibility

MATERIALS

Metal {
- Ceramic
- Metal
- Intermetallic

MANUFACTURING

Near Term

- Magnetron Sputtering
- Jet Evaporation

Longer Term

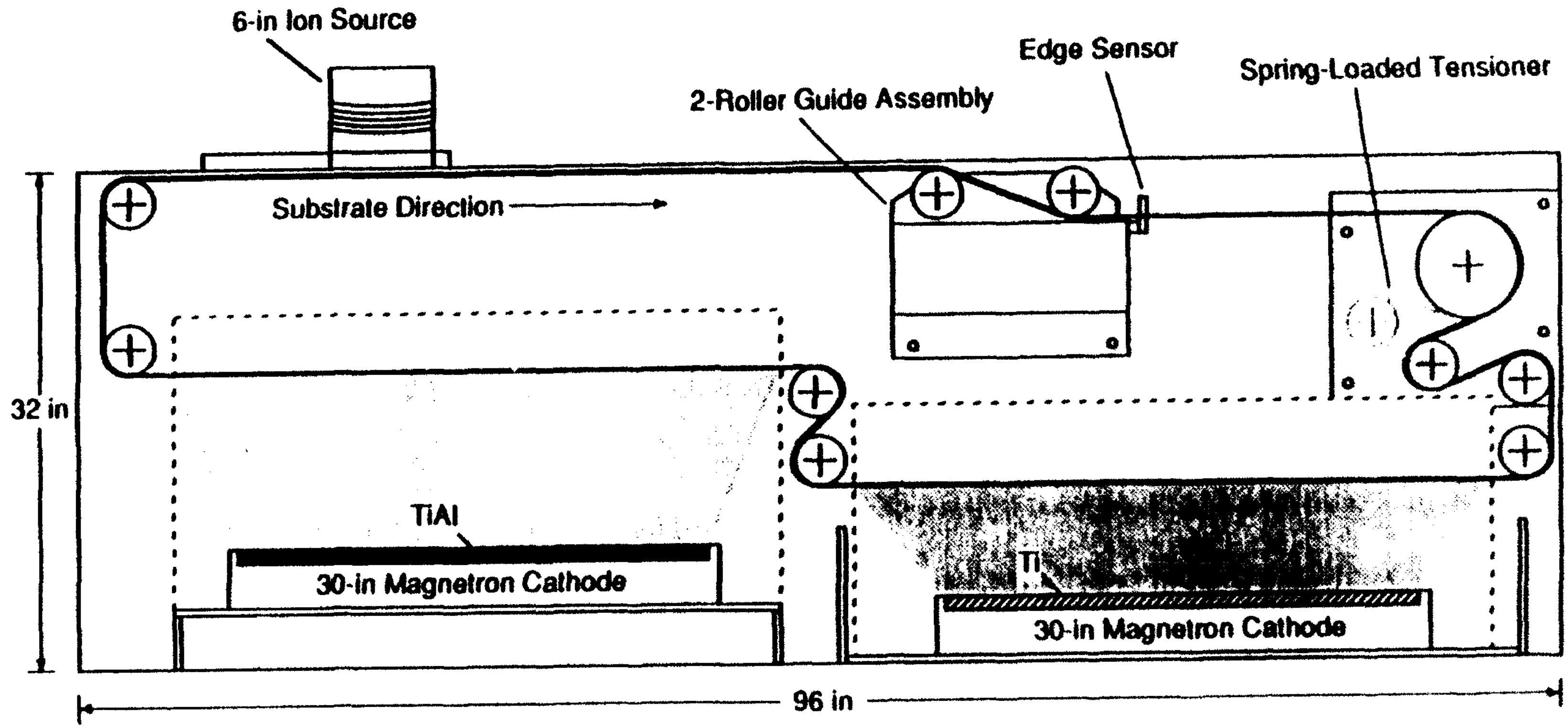
- CVD

COATINGS

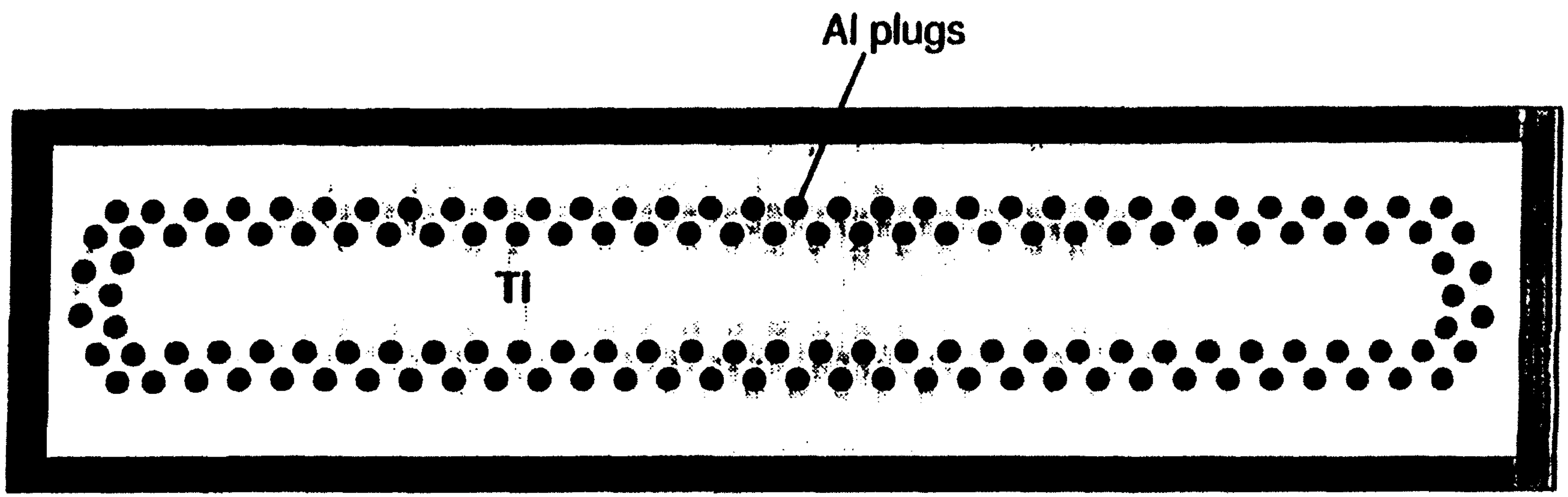
SHEET

3D OBJECTS

Continuous Multilayer Deposition System



Composite TiAl Sputtering Cathode



ESTIMATE OF COSTS TO PRODUCE THIN-GAUGE INTERMETALLIC COMPOSITE LAMINATES (Dollars Per Pound of Foil)

SCENARIO

	No. 1	No. 2	No. 3	No. 4
Sputter Power	$11.14	$22.27	$22.75	$11.14
Cooling	11.14	22.27	22.75	11.14
Alloy Casting	37.50	75.00	120.00	37.50
Target Machining	20.00	20.00	20.00	20.00
Target Reclamation	(-0.70)	(-2.81)	(-4.50)	(-0.71)
Substrate Cost	5.00	5.00	5.00	1.00
Substrate Removal	5.00	5.00	5.00	0.00
Hazardous Waste Disposal	5.00	5.00	5.00	0.00
Pumping	0.50	0.97	0.97	0.50
Labor Cost	4.44	8.88	5.56	4.44
Amortization of Equip. (20yrs)	4.75	4.75	2.97	2.97
Miscellaneous	5.00	5.00	5.00	5.00
TOTALS	**~$109.**	**~$171.**	**~210.**	**~$93.**

APPLICATIONS

I Multilayer Coatings

Near Term Transition

II High Energy Density Capacitors

Mid Term

III Multilayer Structures

Longer Term

MULTILAYER COATINGS

- Bearings
- Engine Components
- Precision Machining

- Coatings Are Already Widely Used But Have Inadequate Thermomechanical Properties And Unsatisfactory Cohesion

- Multilayer Coatings Give Several New Levels Of Flexibility

  - Property Profiles
  - Spatial Tailoring
  - Multifunctional

INSERTION PROGRAM

COATING FUNCTION / PROPERTY PROFILE

Thermal Barrier	• Low Thermal Conductivity Porous ZrO_2
Oxidation Barrier	• Low O_2 Diffusivity Crack Free/Adherent Al_2O_2 /SiO_2
Wear/Erosion	• High Hardness/Toughness Oxide, Carbide, Nitride
Abradable	• Controlled Microcracks

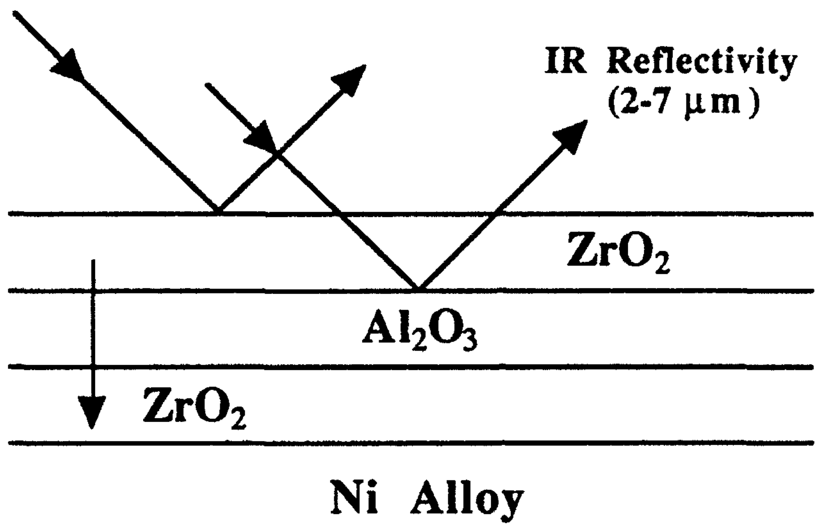
PLUS

- Fracture/Fatique Resistance
- Thermal Expansion Matching
- Elastic Modulus Matching

} Metal Interlayers

THERMAL BARRIERS

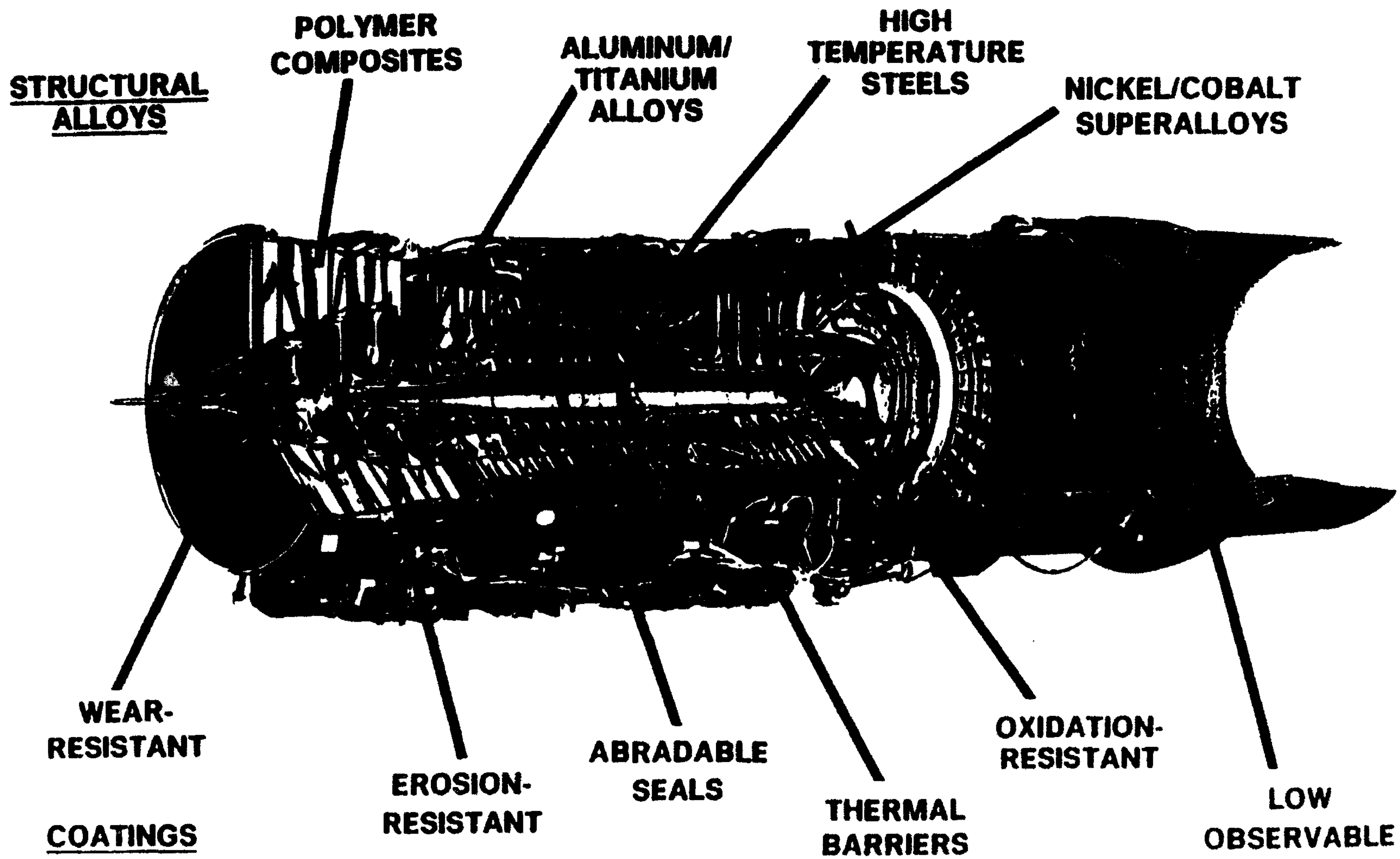
- **Replace ZrO_2 With Multilayer ZrO_2/Al_2O_3**



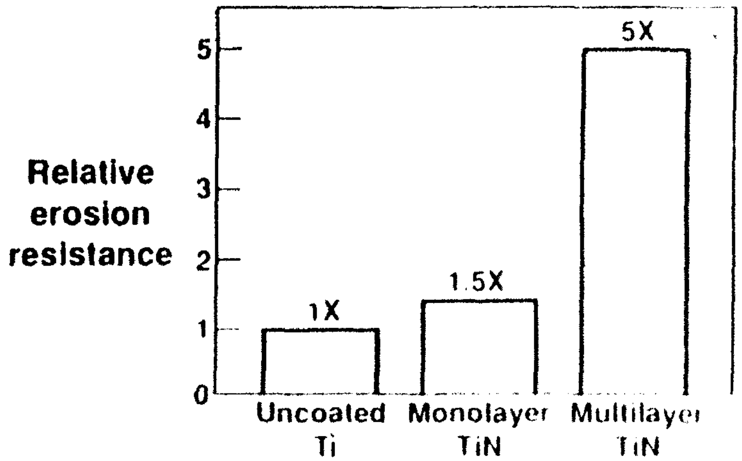
PLUS

Improved Oxidation/Hot Corrosion Protection

GAS TURBINE ENGINE MATERIALS

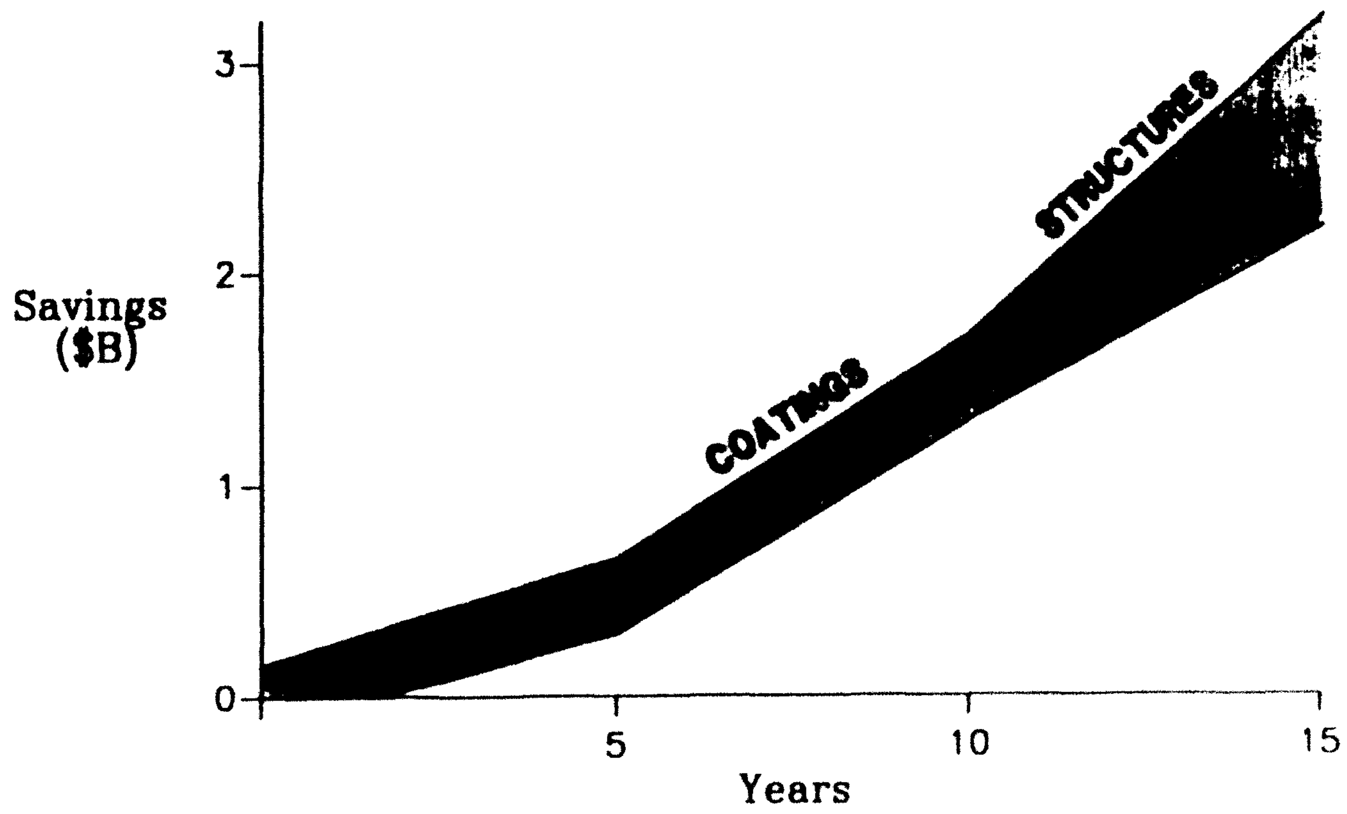


ADVANCES IN EROSION-RESISTANT COATINGS



NANOSTRUCTURED MATERIALS

Gas Turbine Engine Benefits

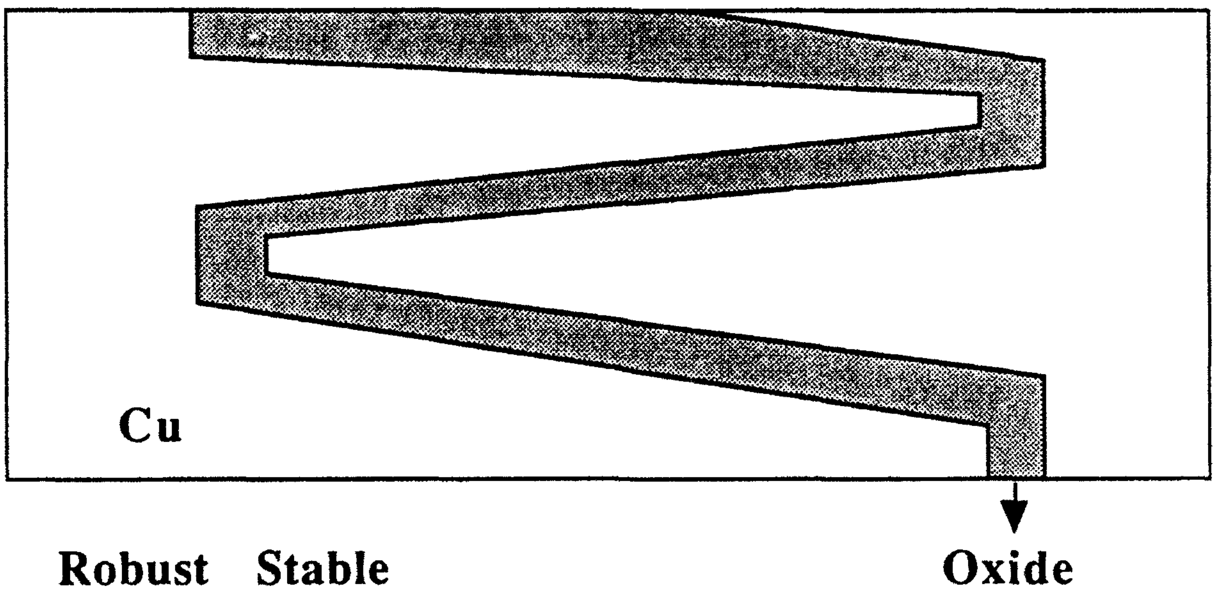


VERY HIGH ENERGY DENSITY CAPACITORS

- Capacitors Limit Applications of Electromagnetically Launched Systems
- Current Capacitor Technology Mature No Major Breakthroughs

Solid State Multilayer Capacitors

- Energy Density 6MJ/m^3 (15 MH/m^3
- Long Life >10^3 Times

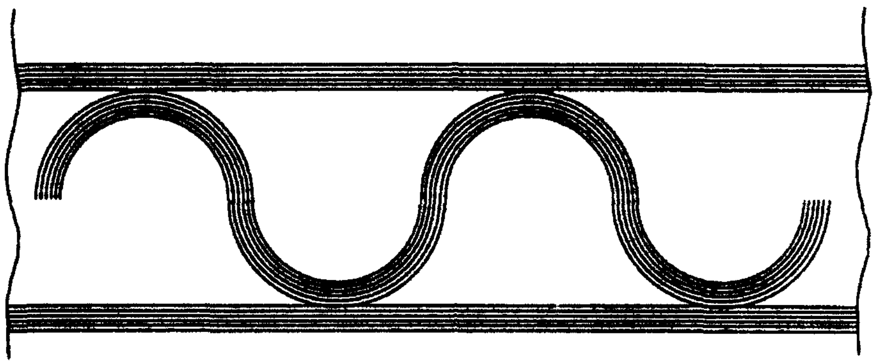


Robust Stable

Energy Storage Technology

III MULTILAYER STRUCTURES

- Honeycomb Light-Weight Structures



- Heat Exchangers
- ıurbine Vanes
- Thermal Protection

RECOMMENDATION

- Multilayer coatings produced by sputtering/evaporation have potential for major impact on component performance

  Capacitors: Bearings: Vanes: Blades: Honeycomb

  Others?

- Developments in high rate deposition indicate cost effective manufacturing feasibility

- Exploit and further develop basic understanding of unique property profiles with spatial tailorability

- DARPA led study of opportunities in aerospace, transportation, energy

- Multilayer coatings produced by sputtering/evaporation have potential for major impact on component performance

WORKSHOP ON
LAYERED MATERIALS
July 6, 1992

Monday, July 6

Introductory Remarks, W. Barker (DARPA)

Layered Materials Opportunities, A. Evans (DSRC)

New Concepts in Layered Systems, I. Aksay (U. WA)

Multilayers by Rotating Cylindrical Magnetic Sputtering,
M. Misra (Martin Marietta)

Layered Materials by Physical Vapor Deposition, T. Barbee (LLNL)

Layered Intermetallics, G. Rowe (GE)

Continuous Deposition of Multilayers, E. Courtright (Battelle)

Characterization of Layered Materials, H. Wadley (U. VA)

Growth and Characteristics of High Strength Multilayers, S. Yalisove (U. MI)

Interface Effects in Layered Materials, F. Spaepen (Harvard)

Dislocations and Flow in Thin Layers, B. Freund (DSRC)

Micromechanics Phenomena, J. Hutchinson (DSRC)

Manufacturing Concepts for Layered Systems, F. Prinz (CMU)

Discussion (Evans, Hutchinson, Barker)
Technological Role of Layered Materials

ATTENDANCE

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July 6, 1992

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ADVANCED INTELLIGENT PROCESSING OF MATERIALS

E. L. Hu, G. Larrabee, J. Williams, W. Barker and J. Crowley

OBJECTIVES

The impetus for this workshop was twofold: (1) to examine the progress and possible roadblocks in the application of advanced intelligent processing techniques to the production of high performance materials and (2) given the application of current IPM techniques, to determine how to better facilitate the transition from R&D of these processes to efficient, cost-effective commercial production.

RELEVANCE TO DOD

The DoD spends millions of dollars per year on R&D of strategic, high performance materials and processes. Billions of dollars are spent in the transition of these materials to commercial production. Facilitating the transition at lower cost is of enormous benefit to the DoD.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY

The workshop revealed that the IPM methodology has been successful in early identification of process roadblocks and critical parameters for control, with ultimate benefits to the production of high quality materials. However, these sophisticated, highly sensitive processes may mandate economic cost models that differ from those used more traditionally. In addition, it may be increasingly necessary to look to wider, more diverse markets as efficient economic drivers for the development of these high performance materials and devices. For these reasons, there is strong advocacy for the early inclusion of process cost models into the engineering and control models developed for these processes.

SUCCESSFUL APPLICATION OF IPM IN OPTIMIZATION OF MATERIAL QUALITY

The benefits of the IPM approach were clearly demonstrated in several presentations made at the workshop. 3M, working with ISI, was able to improve the consistency of a-alumina fiber production through the early identification of critical process parameters, and parameter variability. GE also demonstrated improvement in control of processed fibers, utilizing IR and optical imaging sensors. Norton Diamond Film, also working with ISI, was able to better control thermal gradients in their plasma arc jet deposition process, resulting in films with higher thermal conductivity. Progress was also made in equipment redesign for more stable control of the plasma arc.

The heart of the IPM approach, for quality optimization, has been a fully integrated, continuous interplay between in situ sensors for process monitoring, actuators to control process parameters, mediated by an overriding control program in which suitable process models are embedded. Sensors, and perhaps to a lesser extent, actuators appropriate to the particular tasks must certainly be further developed. In some cases, sensors must be able to operate within demanding environments of high temperature or high electrical background noise. The sensitivity or speed of the sensor may not be adequate. The sensor signal may be hard to interpret, or to deconvolve from background noise. These are all issues that must be addressed; however, at the present, there is still much leverage to be gained from the more widespread incorporation of existing sensors and signal processing/reduction techniques to IPM schemes.

The issue of process model development would seem to be the most formidable task for these multi-component processes whose complexities preclude simple, *ab initio*, physical or chemical models. However, one of the most encouraging messages from this workshop was that multiple process models can be developed, having different levels of complexity, but which can adequately serve as the basis of effective process control. For example, ISI's model for control of alumina fiber processing comprised a hybrid of models for the process thermodynamics, chemical kinetics, heat flux and a black box heat transfer model. That is, for process control purposes, full-blown understanding of all physics and chemistry is not needed: one needs only to capture the dominant effects and identify those parameters that can be controlled to provide the desired output. As a workshop member pointed out, these methods of parameter estimation and system identification have been successfully used in the control world for decades, and can be immediately applied to IPM. Finally neural network models can be used to shorten the development times of poorly understood process models, if they are provided with/trained on a suitably large date base.

Another encouraging outcome was the early identification of critical process parameters using the models, which allowed rapid tie-in to equipment re-design for robust processing. This coupling of process modeling to equipment design, facilitated by sensor-based process monitoring should be strongly encouraged.

INCLUSION OF COST MODELS INTO IPM METHODOLOGY

IPM, as discussed above, can ensure consistent quality and higher product yield. Implicit in the concept of IPM is the ability to carry out process prove-in more rapidly, rejecting non-viable process options, and more rapidly ascending the learning curve for high yield, high quality production. Although these techniques will allow more rapid achievement of desired material and device qualities, there has been no algorithm for explicit definition or redefinition of those qualities, within a larger economic context and coupled to the IPM methodology. The GE presentation illustrated the explicit inclusion of cost issues into process development. A particular desired output, such as a target fiber diameter, may be achieved using a variety of pull rates. The pull rate is proportional to the throughput of fiber production, and thus will ultimately affect the process cost. However, higher pull rates can also result in various fiber defects: kinking, hour-glassing and faceted growth. Plotting the various options as penalty cost contours allows the suitable optimization to be made of fiber quality and fiber cost. Incremental improvements obtained at higher product cost must be assessed within the market under consideration; each target market will have differing cost-performance trade-offs, shown by J. Busch of IBIS Associates, Inc.

The establishment of an appropriate cost model is itself an issue that needs to be addressed. As pointed out by S. Shah of RelMan, Inc. the "classical", volume-based model of manufacturing may have poor applicability here. In the classical scenario, economy of scale is obtained through amortization of overhead in direct labor, material and machine hours. In the highly sophisticated processes under consideration here, those issues may be subsidiary to the costs of new and necessary technology, process improvement and sustenance and more rapid need for product improvement. GE upgraded a traditional formulation by using Monte Carlo simulation of "uncertain" parameters to obtain a "probabilistic" cost analysis to provide bounded estimates of costs.

CONCLUSIONS

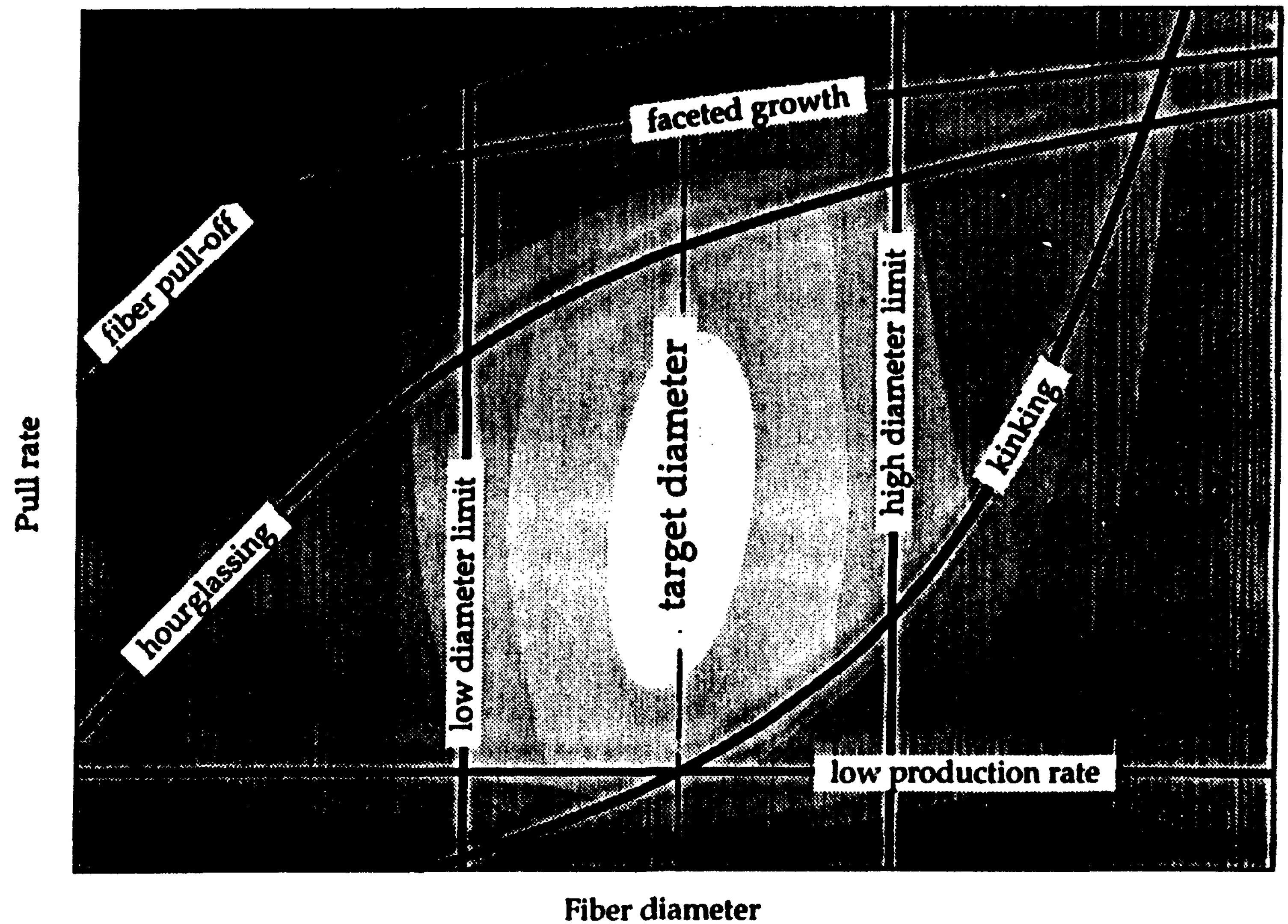
The IPM methodology has proven to be effective in the more rapid development of complex materials processing, as well as in the ongoing control of those processes. Sensitive process parameters can be identified early in the development, and equipment and process redesign be effected. Sensors and process models which comprise the core of this methodology can be made more effective; this can in turn be stimulated by the greater deployment of this methodology. Although many improvements can be made, there is enormous leverage in more diligent insertion of existing sensors into processes, and in the use of techniques which are well-established in other applications of process control. Finally, the unique constraints and demands of these processes mandate a re-examination of the attendant economics and economies. Pertinent cost models must be developed and integrated early within the IPM scheme.

SUGGESTIONS FOR ACTION BY DARPA

- Continue and extend IPM methodology
  - encourage sensor development and utilization
  - pursue process model development
    build up modular process control libraries
    leverage existing techniques: e.g. parameter estimation for control
    couple process models to process equipment design
- Foster integration of cost models early in the application of process design and development

Aerospace Materials IPM -- EFG Sapphire

Penalty cost contours defined by EFG processability constraints



WORKSHOP ON

ADVANCED INTELLIGENT PROCESSING OF MATERIALS

July 7, 1992

Tuesday, July 7

Introduction - Bill Barker, DARPA/DSO

Metal Matrix Composites IPM - Leonard Schakel, 3M Industrial and Electronic, Chris Shelton (3M), Mark Ekldad (ISI)

CVD Diamond Manufacture - Richard Woodin, Norton Co., Ted Schulman (ISI)

IPM and Cost Modeling for AeroEngine Structural Materials - Dan Backman, GE Aircraft Engineering

MultiChip Module Manufacture - Luc Bauer, nChip

Neural Network Process Control Model - Gregg Wilensky, RDA; Nardik Manuklan (R)

Modeling and Simulation for Control and Sensors in Industrial Processes - Lou Auslander, CUNY

Competing Processes Cost Models - John Busch, IBIS Associates, Inc.

Economics of Process Improvement - Sunil Shah, Relman, Inc.

Discussion

ATTENDANCE

ADVANCED INTELLIGENT PROCESSING OF MATERIALS

July 7, 1992

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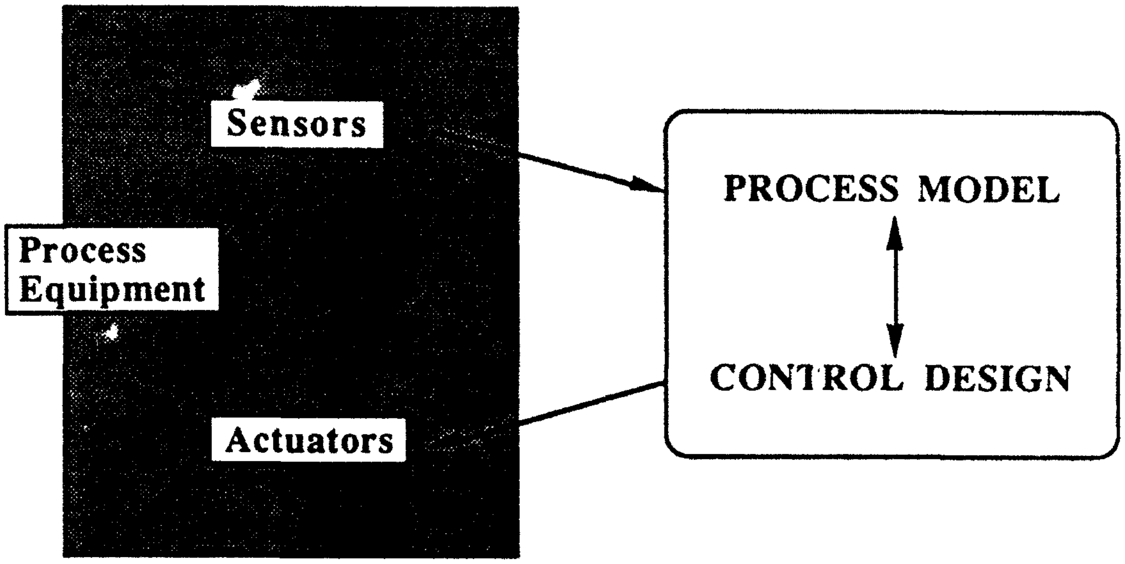
ADVANCED INTELLIGENT PROCESSING OF MATERIALS

B. Barker, J. Crowley, J. Williams, E. L. Hu

Goal: Rapid development of well-controlled, reproducible, efficient processing of high performance materials with rapid transition to the market place.

Relevance to DoD: DoD spends $Millions/year on R&D of strategic, high performance materials and processes; $Billions in transition of these materials to commercial production.

Intelligent Processing of Materials (IPM)



- Successfully applied for rapid process prove-in, improved quality
  - 3M Model Factory: fiber growth
  - GE: fiber growth
  - Norton: CVD diamond deposition

- Model-based process control achievable!

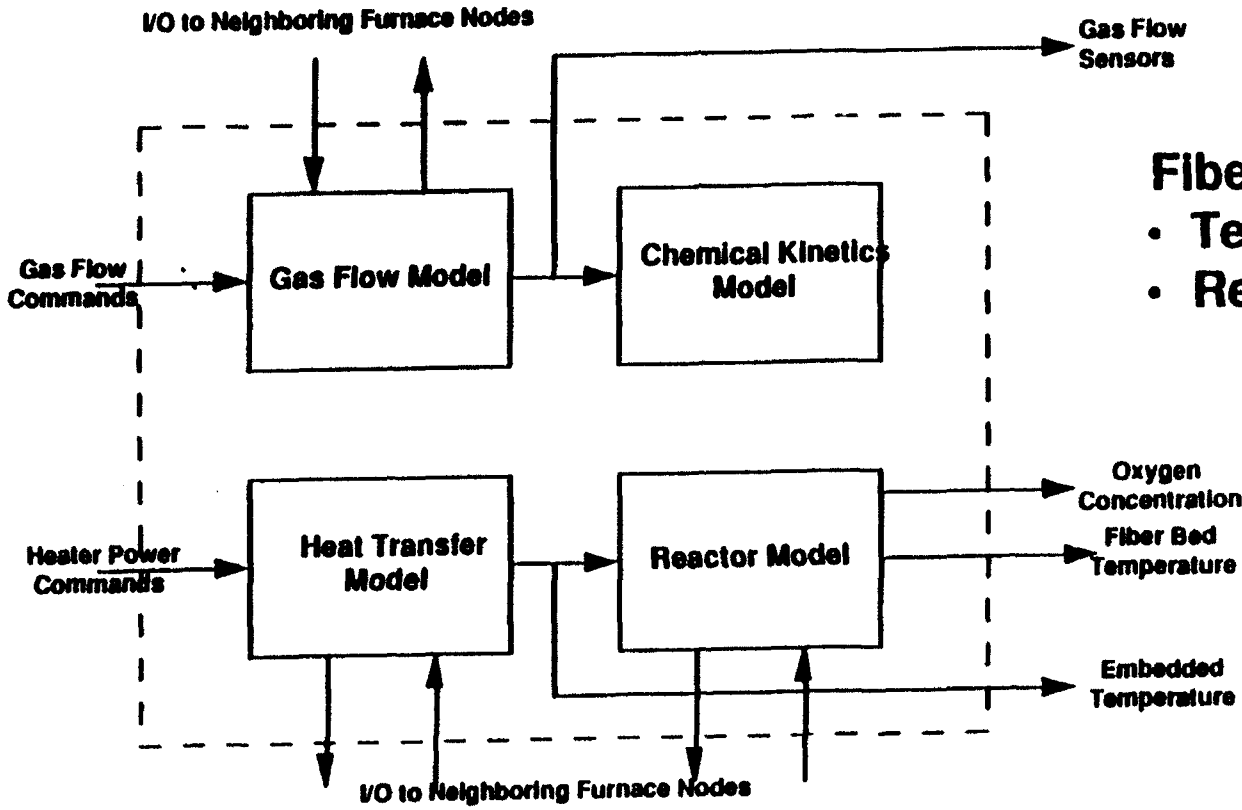
    - Hybrid, Multiple process models of differing levels of sophistication, including "black box"

    - Well-defined mathematical approaches for model reduction

    - Related to *parameter estimation* that has been used by "control community" for decades

- Early application of process models → influence equipment design

CONTROL MODEL STRUCTURE



Fiber Predictions

- Temperature
- Residual Mass

Integration of Cost Modeling with IPM

- Inadequacy of "traditional" cost models

  → shorter product life-cycles, greater process complexity

OVERHEAD

DIRECT LABOR

MATERIALS

MACHINE HOURS

New Technologies

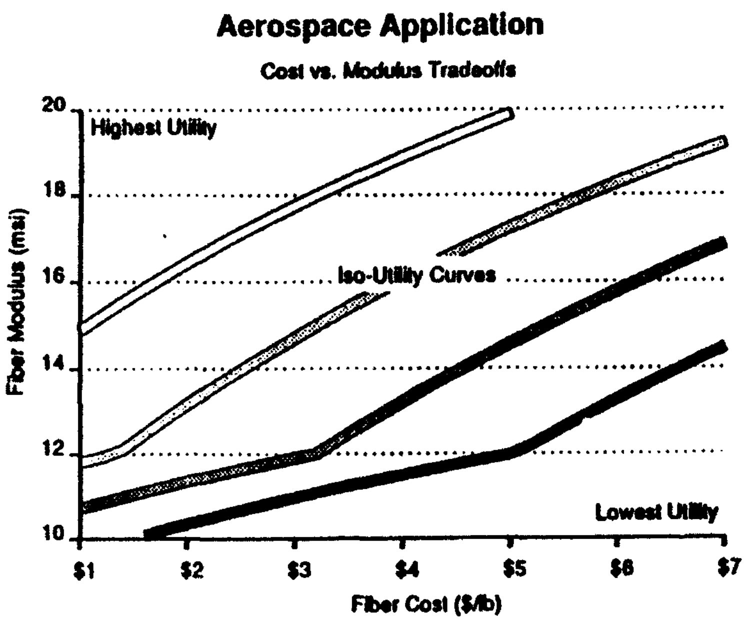
Process Improvement

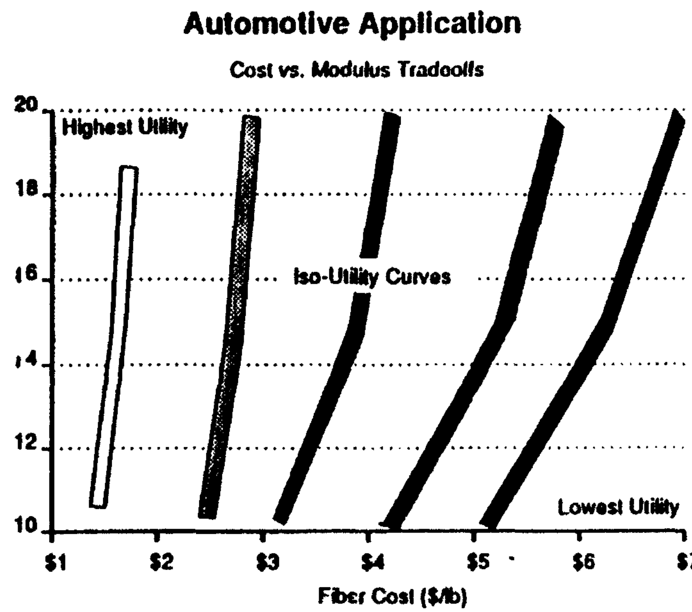
Process Sustenance

- Market-specific "cost-performance" trade-offs, "Penalty-cost contours

  → couple process design with economic feasibility

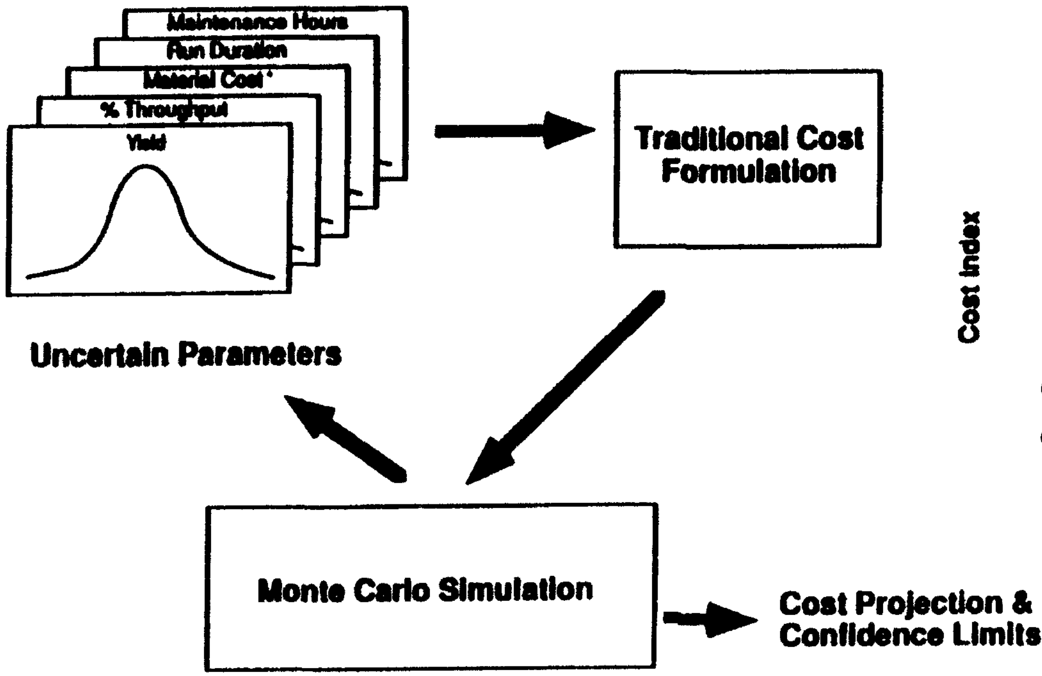
Cost-Performance tradeoffs

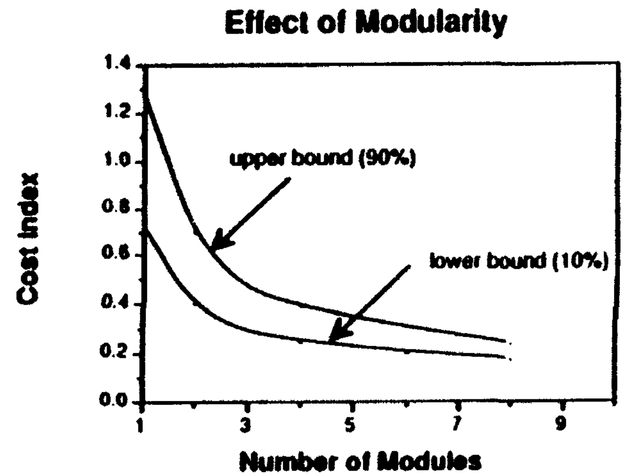




Cost Analysis - Fiber Growth Module

Approach





Summary

- IPM has been successfully applied to achieve more rapid process development and enhanced process control

- A number of paths exist to implement effective, model-based process control

  - hybrid, multi-level models

  - mathematical model reduction, parameter estimation

  - neural nets (adequate training base)

- Advocate integration of cost modeling with IPM control systems

Suggested DARPA actions:

- Continue and extend IPM methodology

  - encourage sensor development ***and*** utilization

  - pursue process model development

    build up modular process control libraries

    leverage existing techniques: parameter estimation for control

    couple process models to process equipment design

- Foster integration of cost models early in the application of process design and development

COMMENTS ON WORKSHOP ON ADVANCED INTELLIGENT PROCESSING OF MATERIALS

Shmuel Winograd

Let me start with a disclaimer: my background is not in materials, and therefore the comments will be limited to issues of modelling and simulation. I believe that by now it is generally accepted that modelling and simulation is a very promising , if not mandatory approach, for reducing design and manufacturing cost and time. The issue which faces us is to develop the technology so as to make it more widely deployed.

It was heartening to see that much of what we heard, specifically the programs at 3M, Norton, and Stanford/TI, dealt with specific and concrete modelling and simulation. This approach increases the chances that the work will have direct and short-term impact. Even more importantly, anchoring the work in specific applications ensures that the important issues will surface and be tackled, and the benefits of simulation be more easily assessed. Our current state of knowledge is such that concentrating on specific cases is a good avenue to increase our general understanding of the modelling and simulation process and its possible uses.

Another aspect of these projects which was apparent in the talk, and which, I believe, is an important contributor to their success, is that the teams were interdisciplinary. Material scientists, mathematical scientists, computer scientists, and manufacturing engineers cooperated on these projects. A successful modelling and simulation project requires people with understanding of the physical process to be simulated, the mathematical equations which describe the physics, the implementation of the system, and its deployment and use.

Having said that, the rest of the comments will deal with issues which were not discussed, or were touched upon only peripherally, either in the talks or in the discussion. I believe that these issues must be faced, in one form or another, in many modelling and simulation situations, and that learning from the experience of current specific projects will ease the task of future ones as well as help formulate generic questions which will have to be tackled.

1. Modelling

The process of setting up the equations which describe the physical (or chemical) interactions fully is often not a simple one. The physics may not be fully understood. The geometry may not be completely known, the boundary conditions may not be precisely determined. Even when all that is known, the resulting equations may be so complicated as to raise questions regarding the existence and uniqueness of the solution. Then there is the question of numerical integration and computation time. All of these force us to simplify the equations so as to make them manageable, both mathematically and computationally, while at the same time retaining enough of the physics to make the results of the simulation meaningful.

2. Parameter estimation

Equations which describe the behavior of a specific physical process must inevitably incorporate parameters which depend on the specific properties of the materials to be simulated. These values have to be measured to a degree of accuracy which depends on the sensitivity of the results on them. It is often the case that these values cannot be measured directly or observed directly (when the simulation is used for control), and have to be estimated from quantities which can be observed and measured. It is possible that this estimation will always be ad hoc and unique for each case. It is hoped that this is not the case and that a set of methods can be developed which are applicable for a relatively large class of applications.

3. Model validation

As was mentioned earlier, the model which is being used may be derived from not-completely-understood physics, was further simplified a great deal for mathematical and computational reasons, and incorporates parameters whose values are only estimated. To be of value, the results of the simulation have, nonetheless, to be a good approximation of the important physical quantities. What aggravates this problem is that a 200 - 300% error may go undetected because our intuition as to what the result ought to be may not be good enough (or else the whole simulation may not be needed). Thus the ability of the model to predict the value of the important physical quantities have to be validated before it can be deployed and relied upon. Model validation methodology have to be evolved and accepted. Based on our experience in testing other complex systems, this may be a difficult issue to resolve satisfactorily.

4. Tool-kit

If modelling and simulation is to be widely deployed we will have to develop a tool-kit to help in the implementation of simulation systems. These tools will have to be general enough to be useful in a large class of cases and also be of sufficiently "high level" to relieve the implementer of worrying about details. At the present we do not know what is needed and therefore there is little technical activity aimed at the creation of such tools (with the exception of mesh generation tools and some finite element integration tools). The only way to reach an understanding of what is needed is by learning from the experience of people who have implemented simulation systems. This is a process which is a bit unfamiliar to the technical community, and therefore a discussion of it in a workshop such as the one we had would have been welcomed.

COMPLEX OXIDE THIN FILMS

M. R. Beasley, E. Cross, H. Ehrenreich, E. Hu and B. Gilbert

Relevance to DoD

The high performance and functional diversity of the complex oxides in electronic, photonic and micromechanical systems of DoD interest makes them an important class of materials for development by DARPA.

Objectives of the Workshop:

- To survey potential new applications of complex oxide thin films in light of recent advances in the thin film deposition of these materials.
- To identify common underlying materials problems limiting their use.
- To identify possible synergistic connections between these potential new applications and current DARPA programs.

Scientific summary:

The complex oxides have a remarkable range of useful physical properties. These include high dielectric constants, ferroelectricity, piezoelectricity, pyroelectricity, large nonlinear optical, electrooptical and photorefractive coefficients, ferromagnetism and high-temperature superconductivity. Applications of some of these properties are presently being pursued by DARPA. These current programs were not explicitly reviewed as part of this Workshop. Rather, the focus was on potential new applications and on surveying the current state of the science and technology of thin film deposition of these materials.

A clear conclusion from the Workshop is that the potential for DARPA of complex oxides in thin film form continues to be outstanding. The growing ability to optimize composition by reactive codeposition, to tailor structure and hence function by multilayering and in some cases to create new materials by atomic layer epitaxy and adds to this potential. Similarly there have been significant advances in the ability to deposit these materials epitaxially on silicon and gallium arsenide through the use of appropriate buffer layers, although differential thermal contraction and potential degredation of the underlying semiconductor remain an important issue. Also, the thin film approach will lead ultimately to cheaper, more generic manufacturing approaches. So far, the applications of complex oxide thin films are limited largely to those materials whose properties are familiar in bulk form. This is a natural evolution. The full power of the thin film approach to produce superior materials is only just beginning.

A summary of the findings of the Workshop regarding the various applications of these materials is given below, organized by physical property. Specific conclusions and recommendations are included with each topic. Overall conclusions and recommendations are presented at the end of the report.

Dielectric Properties and Ferroelectricity

Oxide materials such as lead zirconate titanate (PZT) and other even more complex oxide compounds show considerable promise in electronic applications due to their high dielectric constants and ferroelectric properties. Electrical permittivities in the range from 600 - 3000 are available. Hysteretic electric fields and associated surface charge densities can be achieved using ferroelectricity. The potential of high dielectric constants to permit the further microminiaturization of semiconductor DRAMS is well recognized and surely important. Since very thin dielectric layers are needed for this application (and hence differential thermal contraction is not so important), the recent advances in epitaxial film growth of the complex oxides on silicon should be exploited for this application.

Key questions to be addressed early in any such program are whether the desired high dielectric constants can be achieved in thin films of these materials in the desired range of film thickness and lateral extent, and whether the electrical functionality of the silicon can be retained through use of appropriate buffer layers. The convoluted geometry (trenches, etc.) of current DRAM cells also may present a problem for proper film growth.

The use of ferroelectricity to create nonvolatile memories is currently being pursued by DARPA. While materials problems exist, they appear to be under control for now.

More important, given the rapid advances in the thin film deposition technology for these materials and in the understanding of their electrical properties, we expect continuing improvement in the ferroelectric properties for nonvolatile memories as part of the overall advance of this field. The prognosis for this application should not be judged in isolation of these broader advances.

The dielectric properties of the complex oxides may also provide a solution to a major problem in the emergent technology of deposited multichip modules for electronic packaging. The need to store large amounts of charge on the capacitor formed between the power and ground planes of these structures has become paramount as the chip packing density and speed of these modules has increased. The power supplies themselves are too far away from the modules to respond to rapid changes in the need for current flow as the chips undergo state changes at high clock rates. Physically small, high dielectric constant capacitors could go a long way toward ameliorating this problem. Recent data by one of the authors of this report (BG) indicate very fast charging and discharging rates appear available in PZT thin films. Further exploration of this application seems in order

Pyroelectricity

DARPA currently has a program to develop bolometric infrared imaging arrays using bulk BST (barium strontium titanate). At the same time, very impressive images obtained using an array of resistive metallic bolometric detectors integrated on a single silicon chip along with associated transistor switches were shown in the Workshop on Multispectral Infrared Imaging. Thermal isolation for each bolometric element was achieved by locally thinning the silicon. The array operated at room temperature. Even more effective performance was claimed for superconducting resistive-transition-edge bolometer made using films of the high-Tc superconductor 123 YBaCuO and the same thinned silicon technology. Of course this superconductivity version requires cryogenic cooling. As is well known, the pyroelectric properties of some complex oxides can also be used for bolometric detection. Given the advances in the deposition of complex oxides on silicon evident at this Workshop, exploration of the use of thin film pyroelectric detectors on the thinned silicon technology would be highly desirable and could be achieved with only a modest extension of current programs. The system likely would work at room temperature.

Piezoelectricity

Micromechanical systems using silicon micromachining draw upon the immensely successful methodology of semiconductor technology to provide a route for the economical fabrication of a wide range of useful microminiature mechanical parts and devices. Currently, however, development is hampered by the absence of strong electrical-to-mechanical power converters that can be simply integrated with silicon. Motors using simple electrostatic forces, while a tour de force in fabrication skill as was evident in the Workshop Three Dimensional Patterning, appear to be intrinsically limited to minuscule torques by the very low energy density
($\varepsilon_0 E^2$) in the air dielectric.

On the other hand, lead zirconate titanate (PZT) films fabricated on silicon have been shown to retain high dielectric permittivity ($\varepsilon \approx 1300$) and strong piezoelectric coupling ($K_{33} > 0.5$). They also have greatly enhanced dielectric breakdown strength (EB $\approx$ 4 MV/cm). Energy densities more that 3 orders larger than the air dielectric are immediately achieved, with piezo-electromechanical conversion of more that 25% of this energy. For newer materials such as lead lanthanum stannate zirconate titanate (PLSnZT), switching to a polarized state offers an increase of one order further in energy density and further enhanced conversion efficiency. Many of the needed films and film deposition procedures to exploit these properties have been developed on other DARPA programs. The utility of such films in MEMS applications should be assessed.

Ferromagnetism

The importance of ferrites in achieving nonreciprocal power flow (e.g. circulators and isolators) in conventional microwave technology is well known and very important. Such functions are only achieved in current MMIC circuits through a hybrid approach utilizing ferrites in bulk form. This is cumbersome and electrically inferior to an all thin film approach. The development of a successful thin film technology for MMIC based systems would have large military and commercial impact. The proposed program toward this end should be encouraged. An essential first step will be to demonstrate that the needed magnetic properties can be achieved in thin (or even thick) film form on substrates compatible with MMIC applications. Of particular importance will be to demonstrate that the needed anisotropies (eliminating the need for external magnetic fields) can be achieved. A goal to demonstrate such properties will provide an excellent vehicle to exercise and evaluate alternative thin film deposition approaches. In the longer run suitable engineering design (CAD) tools will need to be developed.

High Temperature Superconductivity

The applications of high-temperature superconductivity were not assessed at this Workshop. We simply note that the use of ferrites for nonreciprocal microwave circuit elements is equally attractive for superconducting passive rf applications, as for the more conventional MMIC systems. This possibility should be pursued. Again, as for the MMIC applications, the key issue is whether the needed magnetic properties can be obtained in thin film form and whether materials compatibility in mulitialyered film growth with the oxide superconducters (lattice matching, epitaxy, etc.) can be achieved.

WORKSHOP ON COMPLEX OXIDE THIN FILMS

July 8, 1992

Wednesday, July 8

Introduction/Goals at Workshop, M. Beasley

Applications in Electronics and Microactuators, E. Cross

Applications in MMIC, D. Webb

Applications in Photonics, M. Fejer

MBE and Laser Ablation of Complex Oxides, A. Kingon

Deposition of Complex Oxides on Si and GaAs, D. Fork

Magnetic Properties of Ferrites mde by Spin-Spray Process, C. Williams

Atomic Layer Epitaxy of High-Temperature Superconductors, J. Eckstein

Discussion

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COMPLEX OXIDE THIN FILMS
July 8, 1992

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COMPLEX OXIDE THIN FILMS

Goals of the Workshop:

- Γo survey potential new applications of complex oxide thin films in light of recent advances in the thin film deposition of these materials.

- To identify common underlying materials problems limiting progress.

- To identify possible synergistic connections between these potential new applications and current DARPA programs.

APPLICATIONS OF COMPLEX OXIDES

Property	Application
Dielectric ($\varepsilon >> 1$)	Ultradense DRAM's MCM Power Bus Capacitors
Ferroelectric	Non-volatile memories
Piezoelectric	Micro Sensors, Actuators and Motors
Pyroelectric	Imaging Bolometric IR Arrays
Optical	Waveguides, Modulators, etc., SHG of Coherent Blue Light
Magnetic	Magnetic memory, Non-reciprocal MMIC Devices
High-Tc Superconductivity	Passive RF Devices MCM's JJ Sensors & Logic Bolometers

MATERIALS ISSUES

Recent Advances

- Ability to control and optimize composition through thin film codeposition.
- Ability to tailor structure (and hence function) through multilayer deposition.
- Ability to create new artificially structured materials through "atomic layer epitaxy" (in some cases).
- Ability to grow epitaxial and textured films as well as polycrystalline films on semi-conductor substrates.

Common Problems

- Need for microstructural characterization and associated structure/property relations.
- Better understanding of transport and dielectric response across grain boundaries and in polycrystalline films.
- Better understanding of heteroepitaxial, multilayer film growth and the efficacy of buffer layers on substrates.

And the Fundamental Questions

- Why is oxygen so special?
- Can we understand it?
- Can we use the understanding?

ASSESSMENT OF THE APPLICATIONS

Ultra small DRAM's through large ε

- Importance well recognized.
- Need to demonstrate that required dielectric properties can be achieved in thin, small area films.
- Need to demonstrate the ability of buffer layers to protect underlying silicon.

High-ε MCM Power Bus Capacitors

- Oxides may be the answer to an emerging problem.

Pyro-electric Oxide Bolometers

- Candidate for thinned silicon bolometric imaging IR array technology.

Piezoelectricity

- Thin film approach basically superior
- SHG of blue light using thin film QPM waveguides is an important goal-- insurance against possible impracticality of blue diode lasers.

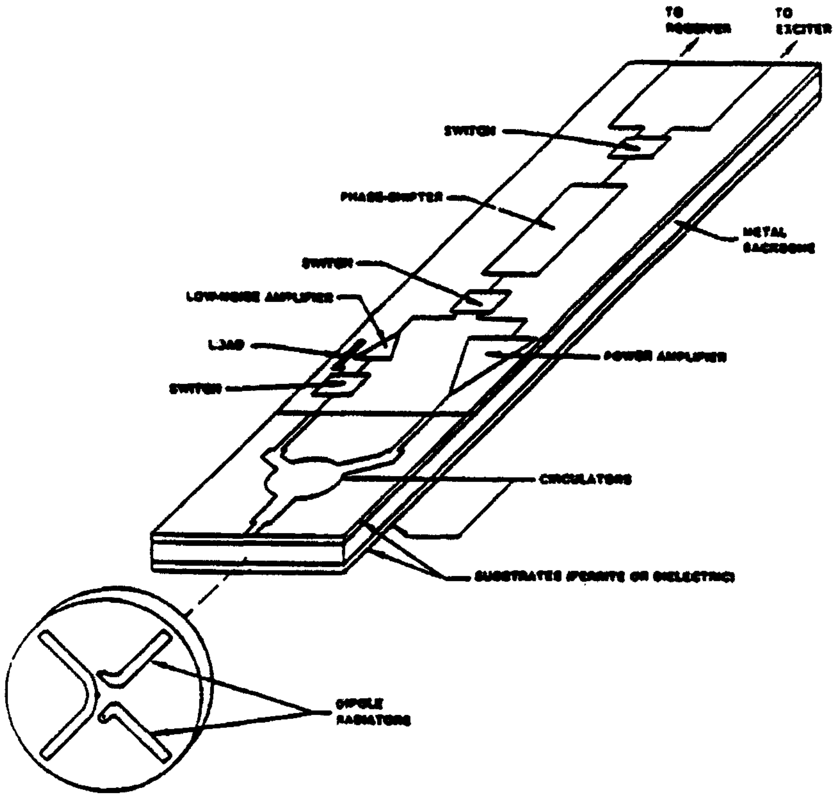
Non-reciprocal MMIC Devices

- **Natural and needed application of**
- **Need to demonstrate required and magnetic properties can be obtained in thin films.**

THIN FILM FERRITES

Integrated Non-Reciprocal Microwave Power Flow Devices (Isolaters & Circulators) for MMIC Applications

- Dual-Channel Phased Array Module



Both Military & Commercial Markets

Military	Commercial
Active Phased Arrays	Automobile Radar
Expendable Decoys	Local Area Networks
Secure Communications	Cellular Radio
Navigation	Navigation

CONCLUSIONS AND RECOMMENDATIONS

- The potential for important military and commercial applications of oxide thin films is increasing.

- DARPA should continue to nurture these applications and the underlying materials technology.

- A variety of opportunities exist to continue this nurturing through incremental efforts in and between current DARPA programs.

WORKSHOP ON
RAPID PROTOTYPING (SOLID FREEFORM FABRICATION)

W. S. Coblenz, B. K. Gilbert, and A. H. Heuer

OBJECTIVES OF THIS WORKSHOP:

A DSRC Summer Workshop on the topic of Rapid Prototyping (Solid Freeform Fabrication) was held on July 19, 1992. The purpose of this workshop was an evaluation of the current state-of-the-art in solid freeform fabrication of polymeric, metallic and ceramic parts and a definition of the role that this technology should play in an overall defense manufacturing strategy.

SCIENTIFIC AND TECHNOLOGY SUMMARY:

Solid freeform fabrication (SFF) is the production of a solid object of arbitrary shape directly from a computer model, without part-specific tooling or the need for a skilled operator. This technology is approximately six years old, and originated with three dimensional stereolithography of plastic parts, in which solid shapes are built up, layer by layer, by laser activation of a photosensitive polymer. This particular form of SFF has already been commercialized, as have alternative competitive approaches to SFF for rapid prototyping of polymeric or wax objects.

Plastic parts produced by SFF can be used to produce shell molds for investment casting of metallic parts ("lost wax" process), but metallic parts can also be produced directly by the selective laser sintering (SLS) layer by layer deposition process developed at the University of Texas/DTM Corporation. SLS can also be used for laser sintering of polymers and waxes. Variants of this technique for non-polymeric structural materials (metals and ceramics) include Selective Laser Reaction Sintering (SLRS) and Selective Area Laser Deposition (SALD). SFF of metallic and ceramic components can also be accomplished using the layer by layer 3D Printing process developed at MIT, and the layer by layer melt-deposition (flame spray) technique developed at Carnegie Mellon University. In all these versatile SFF technologies, near net shape fabrication of complex components is possible. To date, essentially no effort has yet been devoted to assessing the properties of components fabricated by SFF. However, the technology lends itself well to using information generated in a CAD format from "virtual" objects.

The Workshop attempted to cover all these facets of SFF; a set of notes summarizing the comments of the individual speakers at the workshop, and the discussion at the end of the day, is included in the Appendix.

DOD PERSPECTIVE:

SFF has certain distinct DoD advantages, particularly recognizing possible declining DoD budgets and the need to extend the life of weapons systems. Many applications can be envisaged that require rapid fabrication response and small numbers of parts. However, it is necessary to incorporate this technology into the broader context of defense manufacturing, i.e., to take it from its present status as a "boutique" technology into applications where its utility is obvious and compelling.

SFF has already achieved this status in the design cycle. Its ready compatibility with CAD/CAM technology makes early acquisition of "hands- on" plastic models of critical components achievable, to such an extent that numerous anecdotal examples of its utility in such applications were presented by several of the speakers.

In many real world situations, e.g., when replacement parts are required but engineering drawings of the original parts are unavailable, it may be necessary to "reverse engineer" certain components. SFF can be combined with 3D laser digitization of the original parts to capture complex surface geometry in a non-contact manner. Commercial systems now exist to produce a digitized CAD output file entirely compatible with available CAD/CAM systems; as already noted, this output is also suitable for SFF.

For applications in which SFF is taken past the design stage into viable small volume manufacturing, parts must be identical and of high quality for the original parts to be successfully replaced. This is a severe requirement, but one that may be compatible with some structural steels, for which post-fabrication heat treatment can dramatically alter the microstructures and thus improve properties. In many such cases, it may also be necessary to expose new parts produced by SFF to a post treatment of Hot Isostatic Pressing ("HIPing") to remove residual porosity and other potential sources of weakness, e.g., to remove possible lamination-type cracks arising from the layer by layer deposition processing.

It has been well demonstrated that a suite of specific SFF technologies exists that can produce specific solid shapes with narrow shape tolerances in plastics, metals, or ceramics, or to employ the reverse operation of digitizing solid objects, thus creating CAD files of "virtual" objects suitable for SFF. However, there have been virtually no property measurements of non-polymeric structural parts made by SFF, and certainly no structure-property investigations of the type traditionally employed in materials development programs. These studies will certainly be necessary if "Parts on Command" are to become a reality.

The technical issues to be solved include the following questions: Can advanced structural parts be produced with the same quality as those fabricated by traditional routes?; What are reasonable limits for surface finish and dimensional tolerance?; How flexible is SFF with respect to material type, particularly for advanced ceramics?; Is current technology adequate to produce "Level Three" drawings from actual components?; and, finally, What are the overall limits of SFF technology?

To summarize, the following DoD opportunities exist for SFF:

i) Improved design through ready access to prototypes.

ii) A possible new computer-based manufacturing paradigm, particularly for small volume production. In the near term, the ability to produce certain superalloy components by investment casting without the need for hard tooling may provide significant economic benefits.

iii) Upgrading of existing systems by incorporation of new materials, e.g., substitution of micro-laminated composites for monolithic materials in certain critical components.

iv) Facilitation of DoD employing the concept of an Electronic Warehouse for spare parts.

Of these, the establishment of an Electronic Warehouse for spare parts, by combining SFF with an image analysis system to generate CAD layer by layer images of critical components (and possibly a "HIPing" step for post-processing heat treatment) appears to be the most promising, and could be the basis of a significant DARPA program to bring this promise into reality.

APPENDIX 1:
SUMMARY OF REMARKS BY INDIVIDUAL WORKSHOP SPEAKERS

INTRODUCTION: Bill Coblenz DARPA/DSO:

In comparison to metals and plastics, ceramics are often unfriendly materials for designers. Plastic parts can be made from electronic blueprints in a few days if necessary, and metals can be produced nearly as quickly..

How can a potential user acquire complete manufacturing drawings from prototype structures? What will the quality of the drawings be? Will it be feasible to produce advanced structural materials which will never be mass produced, but are important for special cases? Prototypes are as necessary in mechanical design as in electronics.

"Parts on command" may be translated as the execution of the following steps: computer model, to freeform fabrication of parts, through bench-top manufacturing, to finishing operations and partial assembly, to functional prototype and test, back to modification of the computer model.

Rapid printing of ceramics, using a "dot matrix printer", is evolving, as are wax and plastic printing. The wax parts can be used for investment casting. Processes to produce plastic parts are presently the most mature. Ceramics have been demonstrated for molds and cores for investment casting; there has been some work on metal matrix composites as well.

Technical Issues: can ceramic, metallic, and polymer components be produced with the same quality as mass produced parts. What about surface finish? Can the structures be reverse engineered to achieve Level Three drawings? Can machines be fabricated directly?

INDUSTRIAL PERSPECTIVE: Dick Aubin, Pratt and Whitney:

The aerospace industry began using stereolithography (SLA) in 1987, but found the capabilities of the first generation systems fairly limited. A commercial SLA machine was Beta tested in 1990. A rapid prototyping consortium within United Technologies was formed in that year to spread the rapid prototyping technology; a significant amount of education was needed to "de-mystify" the process. P&W is currently fabricating about 1600 prototypes per year, using the same engineering files that are intended for full production tooling. This is actually a small number of prototype parts for a corporation as large as United Technologies; many more should be done. Benefits from this technology include finding design errors very quickly, the fact that suppliers generate quotations more rapidly because they can see the actual part configuration, improved design quality, and all of the associated savings of time and money. Turnaround is much faster, the designers can "think out loud", and communications between designers is improved; finally, evolution of the product is speeded considerably.

A number of different resins can be used, each with different properties. Examples were shown including impellers, bearing spacers, rocket engine nozzles, a CO_2 removal system for the space shuttle long duration facility (a 25 part structure), a six bladed propeller, parts for elevators and escalators (Otis Elevators is a part of United Technologies), an entire five foot model of a UH60 helicopter, control grips for helicopter pilots, etc. The complexity of the part is no longer an issue, as long as the part is oriented and supported correctly. In some cases, e.g., for a steering wheel, first design to prototype was achieved in a few days. All these example prototypes were fabricated with first generation SLA machines.

Second generation rapid prototyping hardware uses laser sintering techniques with wax or polycarbonate. This capability is just emerging from development. United Technologies is starting to employ high temperature laser sintering, using ceramic and metal powders.

SOLID FREEFORM FABRICATION: Joe Beaman and Harris Marcus, Univ. of Texas at Austin:

New techniques: Selective Laser Sintering (SLS), Selective Laser Reaction (SLRS) Sintering, and Selective Area Laser Deposition (SALD). All of these techniques result in the saving of time during fabrication of components.

Selective laser sintering creates parts by sintering the structure in a three dimensional powder bed.

It can be considered that this is the golden age of the process, with much research yet to be done, and many improvements yet to be made, in areas of materials properties, process control, understanding of the thermodynamics of the processes, process development machines, and better understanding of parts to be fabricated and applications of these parts.

Information processing issues still need to be worked on and refined, such as "slicing algorithms", systems architecture, artificial intelligence, interprocess interfaces, and optimization of geometric representations.

Process control needs much improvement. So far, only the grossest portions of the process are under control; for every doubling of process control, part quality quadruples.

Process development: higher temperatures, power, materials handling, beam delivery, scale up/down, hardware, secondary processing.

Parts and Applications: mechanical properties, physical properties, etc.

The process has passed through the "touchy feely" level, to dimensional accuracy, and finally to optimization of the desired internal microstructure. Much of the research needs to be done at the microstructural level.

High temperature sintered materials are amenable to this process without much laser power, because the heating is only very local; thus, interesting "games" can be played with the fine structure of the parts being fabricated. A large variety of powered materials can be used, including tungsten carbide, bronze, stainless steel, aluminum and silicon carbide, silicon, copper, copper-titanium, etc. Marcus states that in future, all metals will be viewed for their ability to work in these rapid prototyping systems.

Not only can lasers be used, but at least in theory, electron beams could be used to deposit the required energy, and the fine structure of the final prototypes structure would be different. However, because there is so much work to do with the lasers, Marcus feels that the electron beam developments are a decade away.

There is no reason why reactive gasses could not be introduced into the chamber, to be reacted with the powders (the reactions catalyzed by the laser) thus creating materials and structures with unique properties such as titanium nitride: work in this area has begun.

Selective area laser deposition is yet another technique. Using various source gases and a laser beam, pyrolytic deposition of materials can be carried out.

DIGITIZING SOLID OBJECTS: Michael McEvoy, Baxter Health Care:

Baxter Health Care is the largest supplier of intraveneous (IV) solution products in the world, and manufactures a large amount of hospital oriented disposable materials. Baxter employs large amounts of CAD and CAE, and produces many structures by rapid prototyping.

One major problem for Baxter is that they make large numbers of flexible bags and soft plastic containers. The question is, how much volume will the containers hold when they have been filled with liquid, and what shape will they assume. Baxter is developing approaches to digitization of flat fabricated structures, with the intent of then estimating the enclosed volumes. Baxter can then create pseudo three dimensional structures from these scans, and actually model the fluid flow of liquids within these structures. Baxter is using a Cubitol machine, which works to create a structure layer by layer: it operates very much like a Xerox machine, to lay down a prototype similar to the scanning laser approach.

MELT SPRAY DEPOSITION: Fritz Prinz, Carnegie Mellon:

Techniques are being developed to spray metals through masks to make parts, using a variety of spray techniques, such as plasma arcs. The details of the metal deposition at the microscale level are being studied and simulated, to understand the interaction between deposition parameters and the final microstructure of the built up part.

THREE-D PRINTING: Mike Cima and Ellie Sachs, MIT:

Ellie Sachs:

This group is working to convert the casting process from lost wax casting to three dimensional "CAD Casting" through a printing process of the refractory mold material, to produce the actual mold directly. A video was shown of the deposition of the casting material. Steps are eliminated, allowing more cycles of iteration; no tooling is necessary. The thickness of the shell can be controlled very well, so that heat transfer during cooling is more uniform. Silica-bonded alumina is used to produce the mold.

The printing machine concept can also be used to make direct metal parts, and there are calculations which seem to indicate that for part runs up to 100,000, it may be cost effective to print the parts rather to cast them.

Mike Cima:

Microstructural Control in 3D Printing: The objectives are the ability to predict component properties from the starting materials, and improvement of the surface finish in the as-fabricated parts.

Mechanical properties of the refractory material are important; the material cannot be too strong (since the mold must be removed from the cooled part), and cannot shrink too much. Some of the refractory materials can be made sufficiently small as particulates that the material can be deposited through ink jet printer ports. Shape of the minimum size aggregates, called primitives, is very important; much development is still required to be able to control the shape of the particles, which in turn will influence the density of the final casting mold structure. The details of the physics and physical chemistry of the ink jet deposition process have major effects on the surface roughness of the mold, and are beginning to be understood.

Macro-toughened composites: substructures can be fabricated with internal structure or structural braces as in a bridge cross section; this approach has been employed on a small scale, and will be extended in the near future.

There appear to be ways to develop better techniques for fabricating ceramic fine powders, and then using these fine powders to fabricate structural ceramics with greater strength and better net shape surface finish.

POLYMER PHOTOCHEMISTRY IN THREE DIMENSIONS; APPLICATIONS IN MEDICAL IMAGING: Doug Neckers, Bowling Green State University:

Work is being done to improve the chemistry of the photopolymerization; there are now materials which polymerize at longer wavelengths and very rapidly, on the order of one or two seconds. A large number of options exist for organic molecules with different photochemical properties, which will change the fine structure, and even the gross structure, of the stereolithographically fabricated part.

Since the laser polymerizes a macroscopic thickness of material, it is also important to understand the polymerization process in the thick film of liquid polymer as the process proceeds, since the microscale polymerization can affect the fine structure of the finished part, and also the macroscopic properties of the part. This chemistry can be understood by examining the flourescence emission spectra as the polymerization process proceeds very quickly. The polymers appear to cure, based on the fluorescence curves, for up to 60-80 seconds after the original flash exposure.

QUESTION AND ANSWER SESSION:

Dr. Lee Buchanan (DARPA/DSO) asked the following pivotal question: Why should DOD sponsor the development of rapid prototyping?

Answers:

To enhance support of old fielded military systems which need repair parts but are out of production; to enhance the capability for small fabrication runs for new systems; to assure the capability to conduct small fabrication runs for system upgrades. Further, it was pointed out that rapid prototyping is becoming part of the standard commercial design process, thereby to decrease costs and allow small parts runs; as a result, the DOD will need to "get on board" with this technology, incorporating it into the DOD conceptualization process; the alternative is that the DOD will be left behind in this design evolution.

This hour-long discussion seemed to reveal that the DOD does not view rapid prototyping of mechanical structures as positively as the rapid prototyping of electronic systems; in reality, the design stages for mechanical and electronic systems are becoming strongly linked by the Computer Aided Design and Prototyping process. It is becoming simply unthinkable to separate the use of M-CAD or E-CAD tools from the design process itself, because virtually no designs are conducted any longer without CAD (including electrical and/or structural simulation) as the heart of the design process. Similarly, rapid prototyping is becoming part of the design methodology; it will shortly become unthinkable for the design process/CAD process to be carried out separately from the prototyping of these elements, whether electronic or mechanical. The DOD can either help lead this revolution, to its own and the U.S's benefit, or it can resist this trend and slide gradually into obsolescence.

WORKSHOP ON

RAPID PROTOTYPING

July 9, 1992

Workshop Objectives:

1. Evaluate current machine capability and opportunity to expend and apply to defense needs. What are the current and potential figures of merit for dimensional tolerances, surface finish, engineering properties, cost, speed, size, etc.? How do we quantify the benefits?

2. How can this activity be focused to build on both ongoing commercial activity and the developing software infrastructure for design, manufacturing, and simulation?

3. What role should this technology play in an overall defense manufacturing strategy?

Thursday, July 9

Introduction (W. Coblenz, B. Gilbert)

Industrial Perspective, D. Aubin (P&W)

Solid Freeform Fabrication, H. Marcus/J. Beaman (Univ. Texas at Austin)

Digitizing Solid Objects, M. McEvoy (Baxter Health Care)

Melt Spray Deposition, F. Prinz (Carnegie Mellon Univ.)

Three-D Printing, M. Cima/E. Sachs (MIT)

Polymer Photochemistry in 3-Dimensions: Applications in Medical Imaging, D. Neckers (Bowling Green State Univ.)

Discussion: (All) Needs and Opportunities

ATTENDANCE

RAPID PROTOTYPING

July 9, 1992

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SOLID FREEFORM FABRICATION (SFF)

A COMPUTER-BASED MANUFACTURING PARADIGM

Present Capabilities

- Production of arbitrary and complex shapes of polymeric, metallic, and ceramic materials in a layer by layer computer-based process. Convert CAD files to solid objects without specific tooling or skilled operator

- Suitable for prototypes and small volume production

Major Technical Issues

- Can engineering components be produced in this near net shape process with desired properties?

Major DoD Applications

- Enormous benefits for the design process

- Facilitates DoD acquiring Electronic Warehouse capabilities

Computer-aided Component Manufacturing Methods

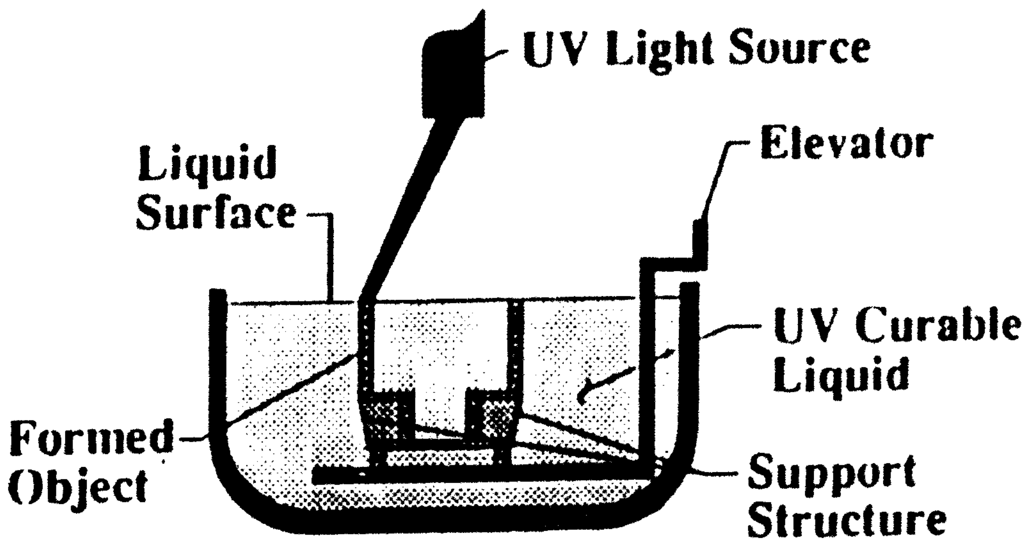
Method	Elemental Process	Materials	Pattern Definition
SLA	Selective photopolymerization	Photopolymers; acrylics	Laser tracking
SLS	Selective melting of powder material	Fusible material; wax thermoplastics, solid-binder composites	Laser tracking
Inter. Solidification	Selective photopolymerization	Photopolymers; acrylics	Laser tracking
PCM	Photopolymerization of thin sheets defined by a mask	Photopolymers; acrylics	Mask for each layer
LOM	Laser cutting of laminated sheets	Adhesive sheets; paper, composite sheets	Laser tracking
FDM	Fusion of extruded filaments	Fusible material; wax, nylon, thermoplastics	Spatially resolved extrusion
3DP	Selective binding powder material	All powder-binder combinations; ceramic and metal powders, organic and inorganic binders	Printing
BPM	Selective deposition of material	Fusible material; wax, thermoplastics, metal	Printing
MD	Selective deposition of material via thermal spray	Metals, ceramics, polymers	Mask for each layer

ACRONYMS

SLA	--	Stereolithography
SLS	--	Selected Laser Sintering
PCM	--	Photochemical Machining
LOM	--	Laminated Object Manufacturing
FDM	--	Fused Deposition Modelling
3DP	--	Three Dimensional Printing
BPM	--	Ballistic Particle Manufacturing

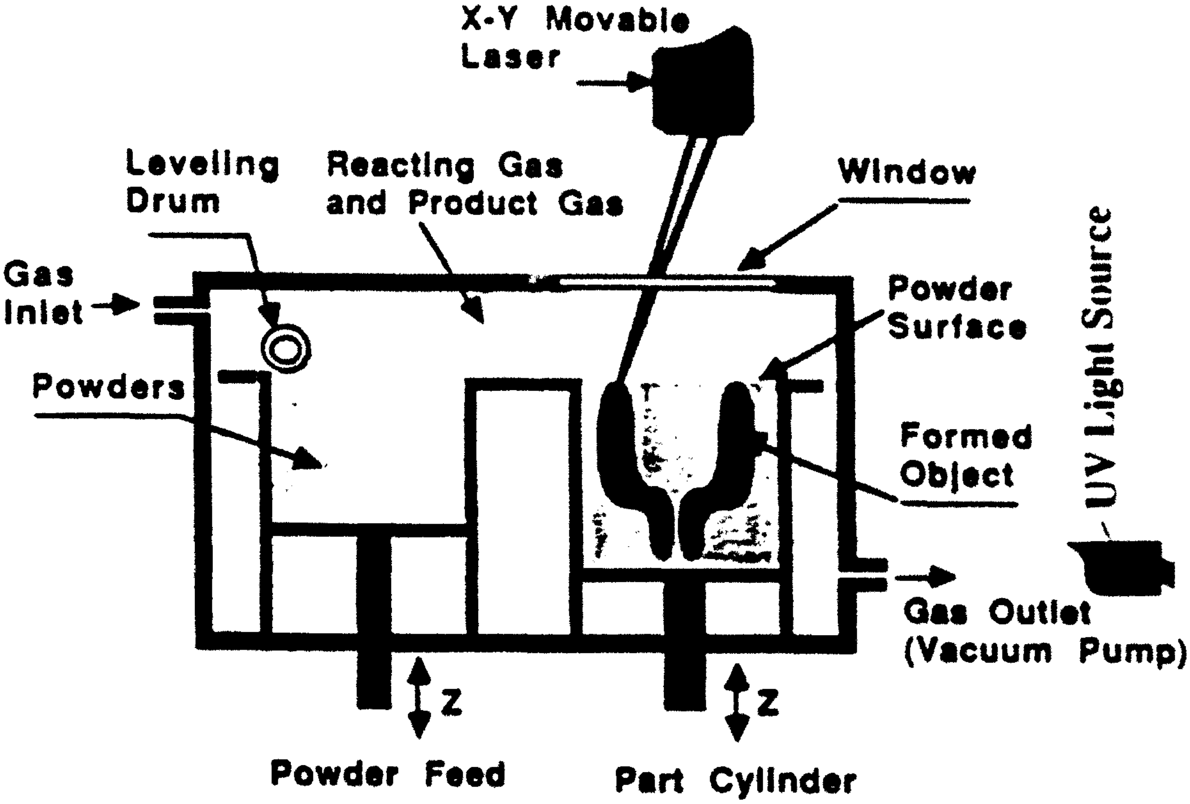
SOLID FREEFORM FABRICATION TECHNIQUES

Precursor			Approach
Liquid	(Polymer)		Stereolithography
			Photochemical Machining
			Solid Ground Curing
			Photosolidification
Solid	(Powder)	•	Selective Laser Sintering
		•	Ink-Jet
			Ballistic Particle Manufacturing
			Thermal Spraying
	(Filament)		Fused Deposition Modeling
	(Thin Strip)		Laminated Object Manufacturing
Gas		•	Selective Area Laser Deposition
Gas+Solid		•	Selective Laser Deposition

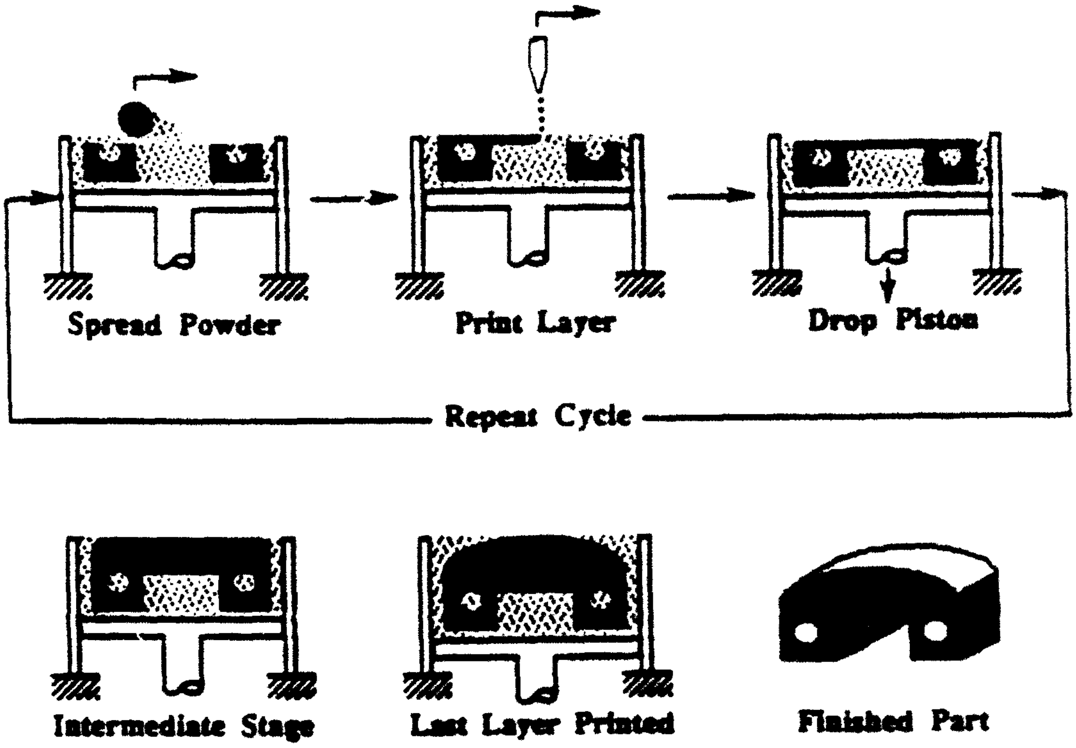


Stereolithography Apparatus (SLA)

SELECTIVE LASER REACTION SINTERING

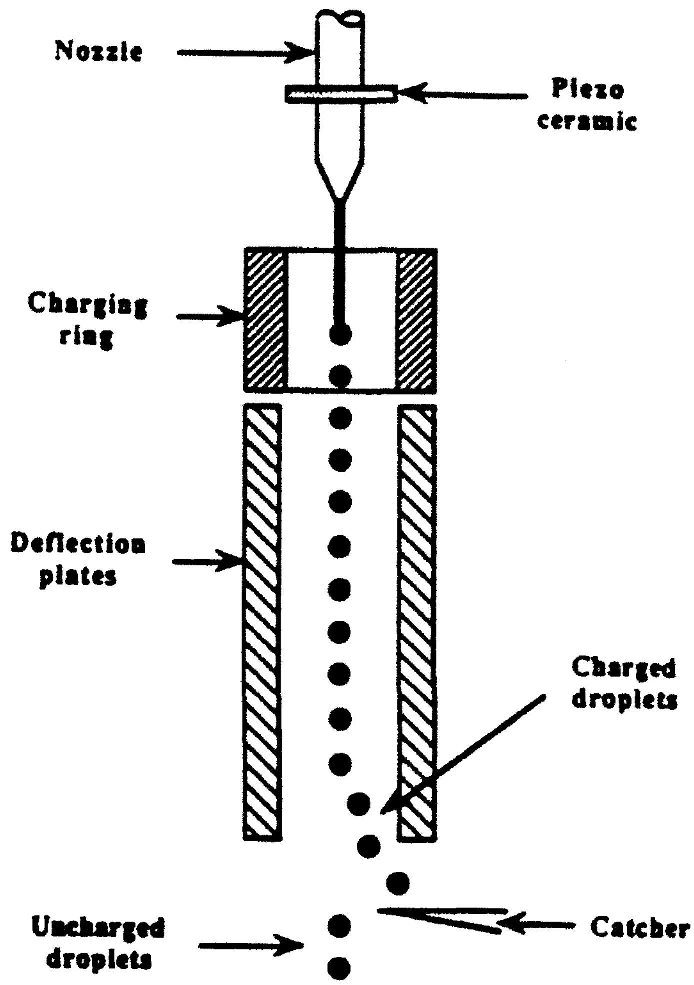


THREE DIMENSIONAL PRINTING



Information ⇒

- Any 3-D geometry
- Any surface texture
- Any material
- Local material composition
- Local microstructure

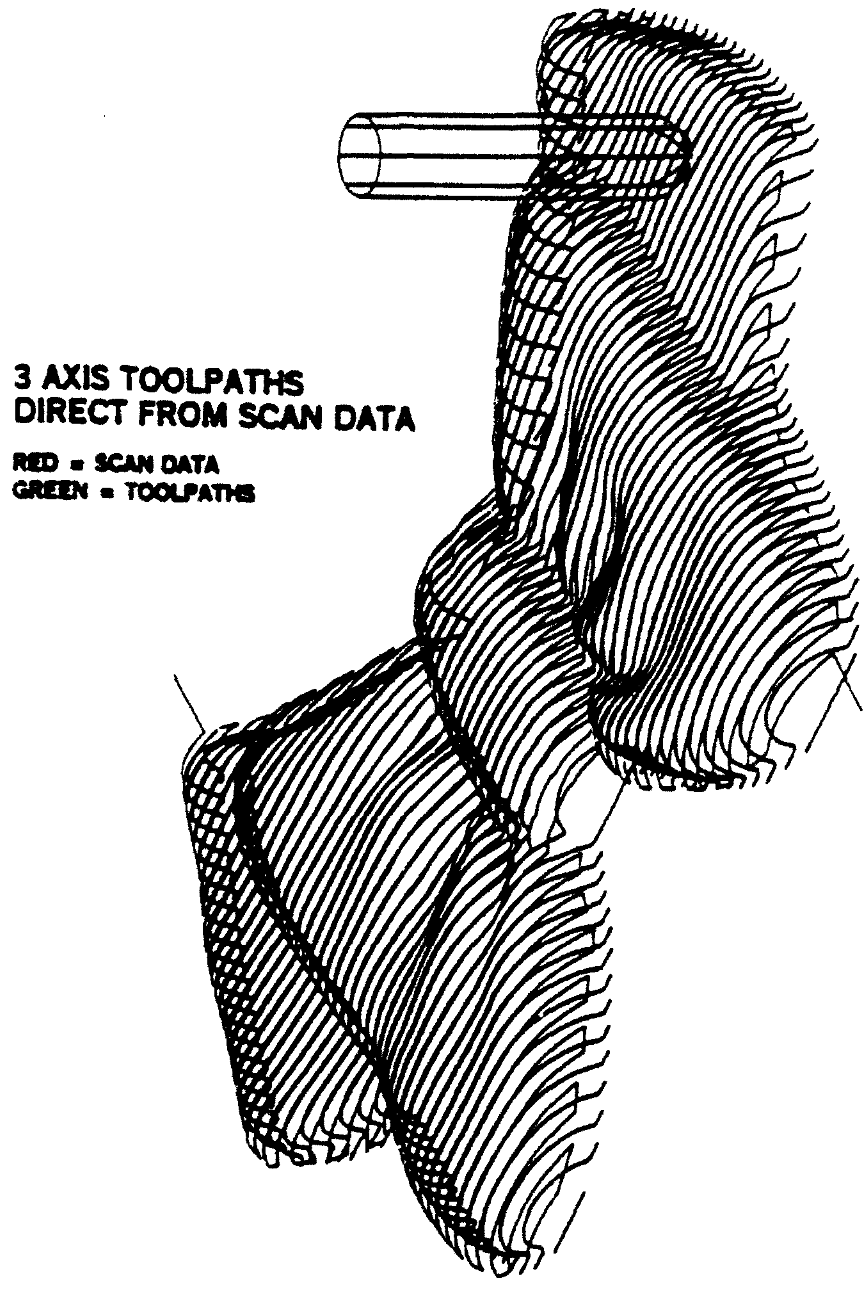


Print Modulation Schematic

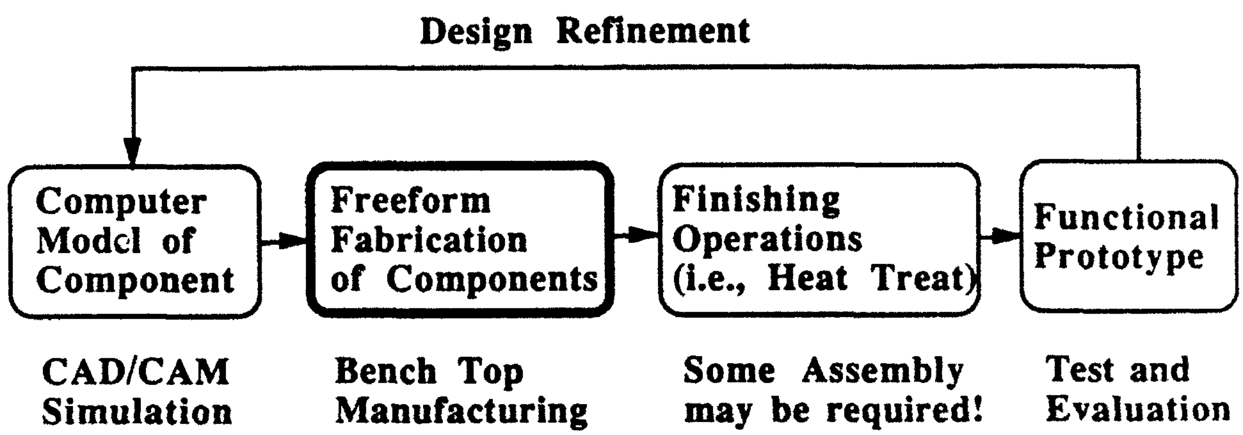
MATERIALS USED TO DATE WITH 3D PRINTING

Powders	Alumina
	Silica
	Silicon carbide
	Stainless steel
	Tungsten
	Tungsten carbide
Binders	Colloidal silica
	Tetraethylorthosilicate
	Acrylic latex
	Aqueous dispersions of submicron alumina
Infiltrants	Copper
	Aluminum
	Aqueous dispersions of submicron alumina
	Colloidal silica

3 AXIS TOOLPATHS DIRECT FROM SCAN DATA



PARTS ON COMMAND



Material Choices: Ceramics, Metals, Polymers, and <u>Combinations of Materials</u>

Component Demonstrations: Mechanical Test Specimens, Ceramic Turbine Rotor, Metal Matrix Electronic Packaging,....

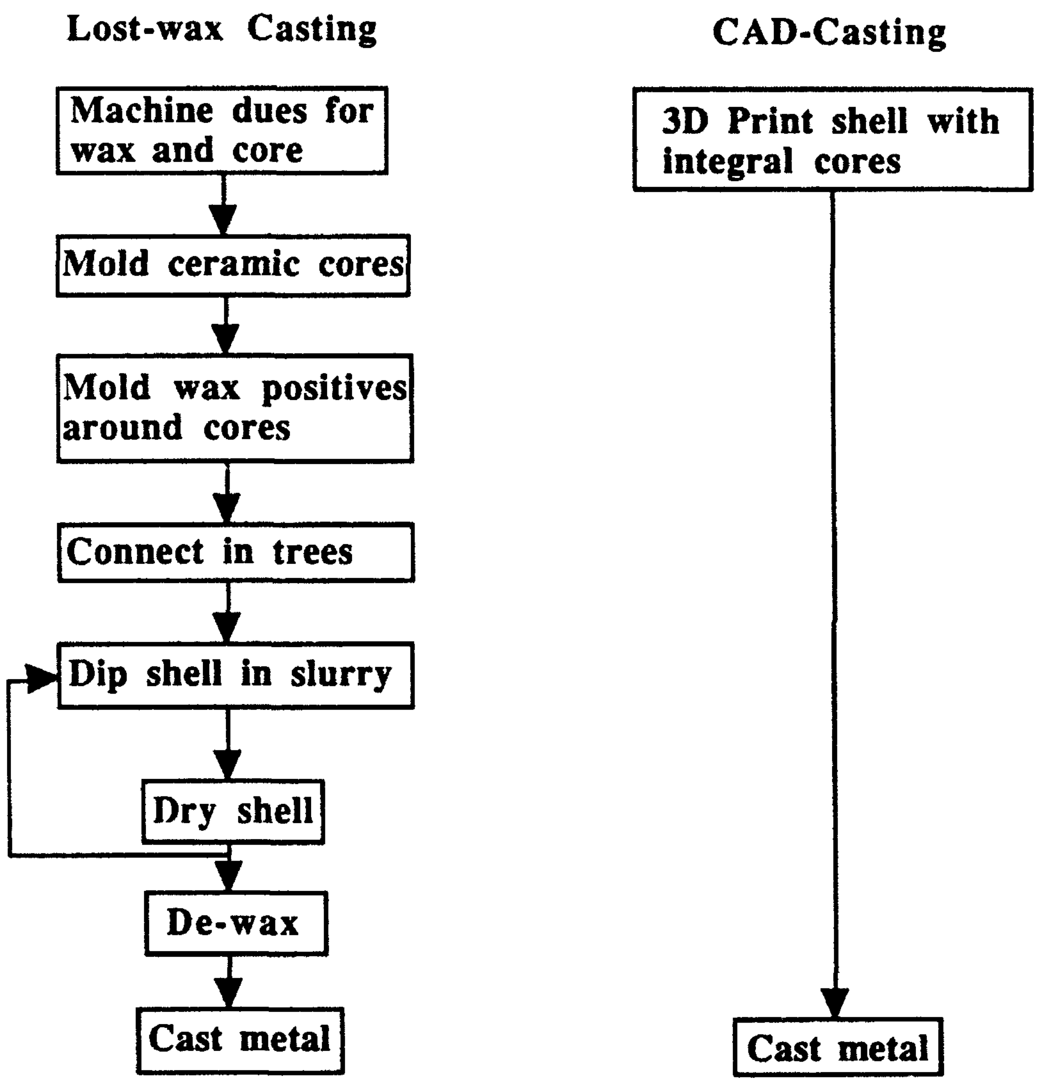
CURRENT OPERATIONS
East Hartford Connecticut Facility

- Four stereolithography machines
  - SLA-250 (3)
  - SLA-500 (1)
- Service rapid prototyping for entire corporation
  - Over 1,600 prototypes processed in 1990

CURRENT OPERATIONS
Activities and Applications

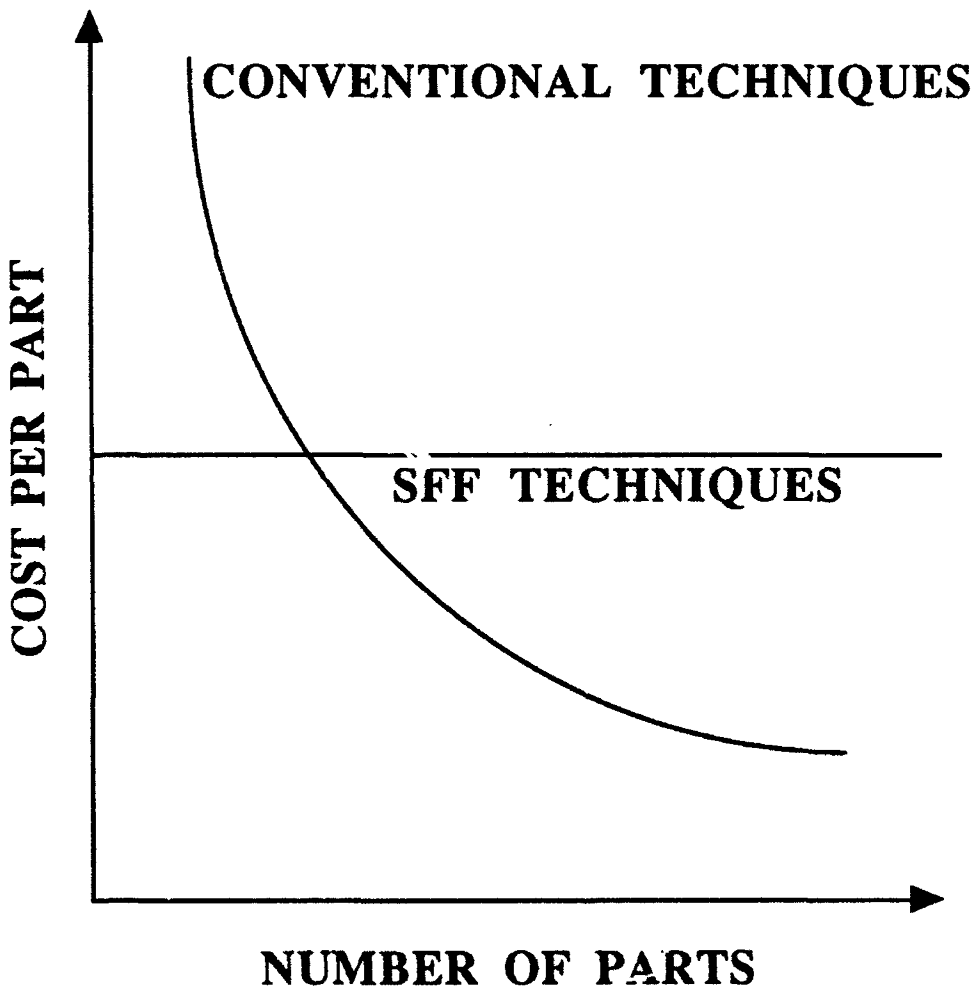
- Design verification
  - Iterate in plastic vs. hard tooling
- Manufacturing producibility studies
  - Key facilitator for
    - Integrated product development
    - Concurrent engineering
  - Earlier start-up for process development
- Prototype parts for test and conversion to other materials
  - Plastic parts used directly
  - Other plastics with better physical properties
    - Injection molding
  - Investment castings via temporary tooling
- Research and development
  - Address process steps to improve
    - Accuracy and surface finish
  - Total process must be considered

Lost-Wax Casting vs. CAD-Casting



CAD-*Casting:* A casting process where the mold is produced directly from a computer model with no intervening steps

ECONOMICS OF SFF TECHNIQUES VS. CONVENTIONAL TECHNIQUES IN MANUFACTURING



TECHNICAL ISSUES

1. Functional Prototypes: Can Ceramics, Metal, and Polymer components be produced with the same quality as produced by mass manufacturing methods?
2. What are limits in respect to surface finish and dimensional tolerances?
3. How flexible is the freeform process with respect to material type?
4. What is needed by way of reverse engineering capability to produce a level 3 drawing from a solid object?
5. Can the technology be extended to components with functional composition gradients? ...to devices? ...to machines?

DoD OPPORTUNITIES

- **Improved design through ready access to prototypes**
- **A new computer-based manufacturing paradigm for small volume production**
- **Fabrication of advanced materials such as microlaminates**
- **Electronic Warehouse**

COMPUTATION AND MATERIALS

H. Ehrenreich, M. R. Beasley, A. G. Evans, D. K. Ferry, B. K. Gilbert
J. P. Hirth, J. W. Hutchinson, T. C. McGill, A. T. Patera, S. Winograd

OBJECTIVES

The workshop was designed to examine the impact of recent advances in computation on goal oriented materials science and technology and on design, process and device simulation. It was also directed at identifying problem areas in Advanced Materials and Processing (AMPP), after the new Federal initiative by that name) which are in DARPA's direct interest and merit DARPA support.

DoD RELEVANCE

The understanding of advanced materials and how to control them is an intrinsically important part of DoD activities. The materials of interest range from highly sophisticated semiconductor nanostructures, important in computing and communications applications, to various types of structural composites important for aerospace applications. Scientific computing to further understanding, and process and device simulation to provide insight concerning process control will have a significant impact on both cost and quality control. This influence will become increasingly important with time as computation, in both its hardware and software aspects, becomes ever more powerful.

Under the High Performance and Computing Initiative (HPCC) DARPA's role is to be the coordinator of R&D efforts directed at the development of tera-op systems. DARPA's participation in AMPP will further both materials technology and aid in the development of computational algorithms that will ultimately be needed to address "Grand Challenge" problems such as semiconductor and superconductor modeling.

SCIENTIFIC AND TECHNICAL SUMMARY

W. J. Camp, the Chief Scientist of the Center for Computational Science, Computer Science and Mathematics at Sandia opened the workshop with a discussion of the prospects for computational design of materials and molecules using massively parallel computing. The three areas requiring the development and application of massively parallel algorithms and programs, which he views to have great importance, are catalysis, microelectronics and structural materials. The theoretical techniques include local density approximation and configuration on the microscopic level, molecular dynamics and Monte Carlo on the atomic level and both continuum and effective field phenomenological modeling on the macroscopic level. He stressed the importance of close interactions between experimental and computer/computational scientists for improving the effectiveness of computational approaches. The development of algorithms is still in its beginning stages, although "proof of principle" scientific results are expected during the course of the next two years. The program has a strong interdisciplinary focus and interacts with a number of DoE Basic Energy Science Activities. These include strained layer superlattices, atomic level studies of adhesion, ceramics, surface and interface science and polymer modeling. Some of these programs benefit (or hope to benefit) from industrial involvement such as Biosym (catalysis); AT&T and IBM (microelectronics), B. F. Goodrich (polymeric materials) and Amoco and Exxon (petrochemical materials).

The presentation was both knowledgeable and optimistic. Nevertheless, it is difficult to gauge the time scale required for the solution of these problems by parallel computing and for deciding for which of these problems this approach is optimal.

M. Pinto described the extensive efforts at AT&T Bell Labs to close the loop from design of a chip, to processing, to modeling using a method that provides means of ensuring that the manufactured chip is the one designed. Paradigms for device modeling and process modeling, working through hierarchies of physically based models and leading to computationally efficient models, are required.

In the device area, there is a well-developed hierarchy of good modeling methods for semi-classical device performance. These range from fundamental ensemble Monte Carlo techniques, to hydrodynamic device models, to drift-diffusion models. Once a processed profile is determined, the performance can be estimated from these models. Some factors still require work. For example, it is still necessary to resort to the most fundamental approaches, the ensemble Monte Carlo method, to accurately model impact ionization and hot carrier injection into the oxide. The results shown were impressive.

In processing, however, this well-developed hierarchy is not so well developed. Processing is only partially understood. Furthermore, the modeling from design to fabricated profiles is not particularly accurate. This area needs extensive new efforts, for smart processing of the material, for modeling the performance of fabricated structures and for the comparison of these with the design goals.

In both device and process modeling, it is necessary to incorporate adaptive, multi-grid approaches to solving the coupled differential equations. These equations are all non-linear and can be non-local. These factors complicate the transition to massively-parallel computers. Most successful work is still done on serial vector processors. Industrial modeling groups generally do not have the needed time in which to explore the potentialities of parallel computing.

J. R. Rice (Harvard) in a talk entitled *Strength and Fracture* described a programmatic approach to calculating complicated macroscopic mechanical phenomena on the basis of at least partially atomistic models. As an example, starting from atoms, it will become possible to pass, level by level, to a macroscopic description of plasticity. Calculation on the quantum electronic level yields properties such as free energies, charge distributions and atomic positions. In addition it provides descriptions of mechanical properties such as models, shear energies and solute segregation energies. It also yields simplified potentials for use on the classical atomic level. The latter includes lattice statics and molecular dynamics involving a few thousand atoms and many lattice vibration modes. The force laws include embedded atom type interactions, cluster potentials and functionals. The statics and dynamics of surfaces can be obtained in a similar way.

Problems, both fundamental and computational, are connected with the determination of optimal potentials, extending the molecular dynamics over sufficiently many time steps in order to study thermal activation processes, the wavelike reflections from boundaries of small systems, and the simulation of real three dimensional behavior as opposed to that of a few layers. Furthermore, the boundary conditions connecting microscopic and continuum regions require specification. The boundary region may well include a mesoscopic domain which has both some microscopic and continuum attributes.

This area, which includes microstructural properties such as dislocations, cracks decohesion/slip zones, interfaces, cavities was thought to be sufficiently developed that appreciable progress in understanding of these properties by extensive computation would be possible in the short term. We therefore propose an exploratory workshop, to be discussed below, for laying out a particularly basic problem involving dislocation motion for firming up problems that are most likely to yield results important for the understanding of complex structural materials.

A. T. Patera described a systematic development of a theoretical framework for model reduction and validation of possibly great importance. One begins with a reference model M_0 which provides an essentially exact mathematical description of a physical system closely related to that of interest and the associated quantities of interest. The numerical solution of M_0 involves sophisticated computer technology but yet is relatively inexpensive to calculate. The next step involves system identification and modeling leading to a simpler, less research-intensive model M_1 for predicting the quantities of interest. The model M_1 may then be used for prediction, design, optimization and control. A number of examples, e.g., the effective conductivity of a composite based on a microscale thermal conduction analysis and the problem of crystal growth, were discussed. Patera notes a phenomenon he terms as "problem migration" observed during the past decade in which "impossible" problems migrate to "complex" problems and "complex" problems migrate to "simple" problems. The first category includes some three dimensional Navier-Stokes two-scale problems; the second, conducuon and most linear elasticity problems. The reduction in difficulty is due to improvements in physical models, technology, architecture, numerical solution methods and design, optimization and control procedures. Patera also spoke at length on model construction and validation.

His views concerning the future of parallel computation (positive) and "Grand Challenge Problems" (some questions) are given in a piece accompanying this report. Because of a large number of interacting length scales and the presence of "killer" parameters such as the Reynolds number with magnitude greatly exceeding unity Grand Challenge problems such as climate modeling and turbulence are still impossible On the other hand, "Grand Opportunities" have the possibility of migration as defined above, and/or non-overlapping length scales. The mechanical structure problems defined by Rice appear to fall into this category.

The last two presentations were devoted to scientific computation of electronic properties and structural properties obtained from electronic calculations. B. Larson (Thinking Machines) presented the results of an ab initio study of the Si(111)-7 x 7 surface reconstruction which was performed in collaboration with Joannopoulos' group at MIT using parallel processing. Using this problem as an example, he delineated the ingredients of massive parallelism for algorithmic design, performance and scalability. He observes that the solution of larger problems requires more memory which must be accessible if it is to be useful. High memory bandwidth is provided most economically by distributing the memory among parallel processors. He notes that even applications without obvious real-space decomposition (e.g., Car-Parrinello) can benefit from parallelism. Communication cost among processors are important for current machines. Thus, the data geometry must be carefully organized.

S. G. Louie (Berkeley) discussed ab initio calculations of electronic and structural properties which represent the current state of the art. The ground state properties are obtained using the local density functional approach (LDA) and the Car-Parrinello method. Illustrations that were presented included the amorphization of quartz that occurs for pressures of 20-30 GPa. The theory predicts a mechanical instability as the driving force. The theoretically obtained Fermi surface of YBCO was also discussed. Finite temperature simulations for C_{60} yield excellent agreement with photoemission, EXAFS and NMR experiments. Quasiparticle excitations computed using the GW approximation yield band gaps of many semiconductors with superb accuracy, much better than that resulting from the LDA approach. This is also true of Si surface reconstructions. Applications to transition metals and related systems, the development of better algorithms for dielectric response are planned. The Quantum Monte Carlo approach was applied with superb success to the calculation of the cohesive energy of diamond, silicon and graphite and also the study of electrons in a strong magnetic field. However, problems such as overcoming the short simulation time of the Car-Parrinello method clearly point to the need for extended computing capability. It is probably fair to say that parallel computation so far has had very little impact on present state-of-the-art electronic calculations and practically none in dealing with complex materials.

CONCLUSIONS

Over one-third of the membership of the DSRC participated in this workshop and subsequent discussions. A wide spectrum of comments concerning parallel computing was evident extending from a (humorous) characterization of this approach as "a footnote to history" to a more serious other as "the wave of the future". Everyone certainly agreed that the exploration of this new tool was of great importance. The predominant opinion held that parallel computing will become increasingly important but probably slowly. In the materials field it may represent a unique way to address materials complexity and as an enabling technology for permitting adequate design, device and process simulation. Moderately parallel and distributed computing may well be adequate, at least for the short term. For less than about 30 processors operating in parallel, the familiar architectures and algorithms will probably be adequate. The development of new chips such as DEC's α-chip and Intel's Micro 2000 promise giga-op rates. Parallel processing in the tera-op range will be possible by 1997.

The Grand Challenge problems will undoubtedly be drivers leading to the ultimate adoption of parallel processing provided interdisciplinary teams of specialists are assembled for the specific purpose of addressing broad problem areas such as climate modeling. The algorithms spawned by such efforts will be adopted by other areas such as materials computation provided that the materials community perceives sufficiently clear-cut advantages to invest the time necessary to adapt these algorithms. Thus, the DARPA program should include an element of outreach, focussing funds on promising research areas which may serve as nucleation sites for parallel processing within the community.

In this new era of computers, computation must be placed on the same footing as experimental materials property measurements. Sufficient advances have been made in modeling of materials and their properties, that the time is ripe to launch an effort that will put these computational tools into the work stations of experimentalists. The experience thus gained will not only provide increased understanding, but also will provide insight in how the modeling and simulation process can be used. As Winograd points out, "We have seen several times in the past that by providing users with new capabilities, we not only better understand these capabilities, but learn of new and not foreseen uses." The development of a usable code will require some extensive effort, but the pay-off is likely to be large enough that DARPA should be urged to undertake such an effort.

The short term (3-5 years) will see substantial improvements in semiconductor process and device simulation provided that industry and DARPA supply the requisite support. This matter deserves attention because simulation will appreciably cut costs. It is far cheaper to simulate accurately than to fabricate. Quoting Winograd again:

> "We have had a long experience in modelling semiconductor devices using the drift-diffusion model. This experience clearly showed as we move to more accurate models such as the hydrodynamic model and the Monte-Carlo simulation. In this application area we have learned over what ranges of devices the models are valid, how to estimate the values of the parameters which are used in the equations, the interplay between the complexity of the model and the amount of computations needed for its solution, and how to use a hierarchy of models. I got the clear impression that modelling and simulation in this application is moving to the 'success' column."

In addition there will be qualitatively new insights obtained from mechanical properties calculations using improved computing capabilities. They, together with electronic free energy and phase diagram calculations will ultimately be directly applicable to the design of new complex alloys and composites and their simulation of actual performance.

We emphasize again that the understanding of materials and how to control them must continue to be an important part of DARPA activities. Scientific computing and process and device simulation using modern computers and computation will be enabling and furthermore be helpful in the development of DARPA's general efforts leading to the development of the computing power required for the solution of Grand Challenge Problems.

RECOMMENDATIONS

The workshop described here was planned as the first of a series. Since its scope was circumscribed, strident recommendations are not appropriate here. We have pointed to several areas requiring support: the development of work-station capability for material modeling for experimentalists; the encouragement of the further development of device and process simulation; and the establishment of nucleation efforts designed to encourage the adoption of parallel computing.

The group recommends furthermore, that, in view of the substantial progress to be expected in the mechanical properties area of materials, an exploratory workshop be organized on the subject of Dislocation Dynamics. This two-day workshop, which would not be a regular part of the DSRC's Summer Program, would include a DSRC sub-group and a few additional outside experts. Its aim is to explore a paradigm concerning "Grand Opportunities" which have non-overlapping length scales that involve microscopic, mesoscopic and macroscopic scales respectively. In this case the microscopic scale would be associated with the atomistics of the dislocation core, and the mesoscopic scale with dislocation motion and interactions, and the macroscopic scale with phenomena such as plasticity and fracture. We believe that by analyzing the approach to solving a "simple" and important materials science problem, which is basic to the understanding of mechanical properties, a procedural model will emerge that will be useful in solving other similar problems. For example, dopant diffusion in semiconductors, and important ingredient of processing, is not yet adequately understood.

The proposed program has the following outline:

1. Definition of the physical and theoretical problem;
2. The choice of interatomic potentials and the partitioning into microscopic and continuum macroscopic domains;
3. Choice of computational approaches;
4. Consideration of the available experimental information;

5. The micro-meso-macro paradigm: Consideration of disloc.ation micromechanisms as mesoscopic ingredients for more complicated macroscopic phenomenon;

6. Applicability of parallel computing approaches.

Finally we recommend that the next workshop in this series be devoted to a critical account of the present achievements in parallel computation to areas of direct interest to DARPA, particularly as they pertain to materials science.

VIEWS ON COMPUTATION AND MATERIALS

Anthony T. Patera

First and foremost, I believe that the great reduction in cost and turnaround time afforded by commodity-chip distributed-memory parallel computing will ensure the ultimate adoption of parallel processing as the premier architecture for large-scale scientific computing. Whether networked workstations or more closely integrated multiprocessors dominate, whether shared-memory or distributed-memory program models prevail, fundamental common issues of concurrency, load-balancing, locality, communication and granularity will underlie much future algorithmic work.

The issue as to when these methods and architectures will be adopted is a strong function of the research agendas of the scientists involved. Most researchers have a "list" of priorities, and they engage in new activities or learn new diagnostic techniques only to the extent that these new technologies enable them to better address the questions that interest them. Algorithm developers will embrace parallel technology only when the projected gains balance the "energy barrier" of entry; physical scientists will embrace simulation software only when not doing so would render their research program non-competitive. Although inevitable, parallel technology will become pervasive only slowly (assuming, as is likely, that no cure-all compilers suddenly appear), in response to demonstrated success in each particular field of inquiry. I believe a DARPA program in Computation and Materials should include an element of outreach, focussing funds on promising research areas which can then serve as nucleation sites for parallel processing within the community.

As to the class of problems that might be addressed, I believe it would be more instructive to focus on problems that have recently migrated from "impossible" to "do-able", rather than exclusively considering the so-called (largely "impossible") grand challenge problems. By focussing on difficult but do-able problems, there is a greater chance for fresh computational approaches, for near- and mid-term impact on technology, and for more rapid dissemination of parallel methods. Grand-challenge problems are, for the most part, marked by a very large number of interacting length scales, that is, an algebraically decaying (Fourier) energy spectrum with a high-wave number cut-off that scales with some "killer" parameter that is typically very large compared to unity (e.g., the Reynolds number of fluid flow). On the other hand, more do-able problems (grand opportunities?) are characterized by a finite number of scales which, though perhaps disparate, can often be decoupled by asymptotic or averaging techniques.

Materials science enjoys a number of grand opportunity problems: the conference presented numerous micro-meso-macro-examples concerning both the electronic and mechanical structure of materials. These problems appear to be very relevant to the development and application of new materials; they involve fundamental physical, mathematical, algorithmic, and architectural issues; and they couple physics and hierarchical modelling very closely, providing a much-needed testbed for more rigorous approaches to complex model validation and error estimation.

Fertile problems in the area of manufacturing and fabrication processing are less readily identified; however, these problems should not be abandoned in favor of the often more appealing and fundamental materials-properties calculations. A profitable approach to processing problems might address both the basic physics required for accurate modelling (e.g., surface phenomena) and the more mathematical issues of how to incorporate, solve, exploit (e.g., control) and validate existing models. The fabrication area would greatly benefit from the development of numerical methods appropriate for complex physics; for example, linear systems resulting from unstructured grids, non-self-adjoint problems, or problems with disparate time-scales continue to be a major bottleneck in many simulation attempts.

In summary, although grand challenge problems may be an appropriate vehicle by which to raise venture capital, the future of parallel processing will be decided in the applications trenches, by academic, government and, most importantly, industrial research and development sites. A research program focussing on parallel processing within this context can go a long way towards furthering ultimate acceptance of this technology. Such a research program must address not only parallel processing per se, but also the many upstream (physics) and downstream (validation and application) issues that arise due to the availability of a heretofore unprecedented abundance of processing cycles.

WORKSHOP ON

COMPUTATION AND MATERIALS

July 10, 1992

Organizer: H. Ehrenreich

Overview: This workshop will explore the relevance of rapid advances in computer modeling and simulation to the solution of important problems in materials science, engineering and fabrication

Friday, July 10

Introductory Remarks, H. Ehrenreich (DSRC/Harvard and B. Wilcox (DARPA)

Prospects for Computational Design in Materials Science, W. J. Camp (SANDIA)

The Role of Modeling in Silicon Processing, M. R. Pinto (AT&T Bell Labs)

Atomic and Continuum Aspects of Strength and Fracture, J. M. Rice (Harvard)

Statistical Synthesis Methods for the Analysis of Complex Many-Parameter Physical Systems, A. T. Patera (MIT)

A Vignette of Computational Approaches, B. E. Larson (Thinking Machines Corp.

Ab Initio Calculations of Electronic and Structural Properties: Recent Advances and Prospects, S. G. Louie (UC Berkeley)

Discussion

ATTENDANCE

COMPUTATION AND MATERIALS

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Winograd, Samuel	IBM	(914)945-2443
Yoder, George	ONR/Materials Division	(703)696-0282

COMPUTATION AND MATERIALS

H. Ehrenreich, M. R. Beasley, A. G. Evans, D. K. Ferry, B. K. Gilbert, J. P. Hirth, J. W. Hutchinson, T. C. McGill, A. T. Patera, S. Winograd

Interdisciplinary: Electronic, Materials, Computer Scientists

OBJECTIVE

- **Influence of computation on goal oriented Materials Science/Technology**

  and

- **Design, process, device simulation**
- **How to optimize applicability**

BACKGROUND

PRESIDENTIAL INITIATIVES

- **High Performance Computing and Communications** (HPCC, 1991)
  - Conventional → Scalable → Massively Parallel Architectures
  - "Grand Challenge" Problems
  - DARPA Role: To lead R&D efforts for tera-op systems
  - "Moderately" Parallel/Distributed options not considered

- **Advanced Materials and Processing** (AMPP, 1992)
  - Inventory of 10 Federal Agencies reporting Materials R&D
  - Theory, Modeling and Simulation Program Component
  - Agency Efforts include

    DoD HPC Modernization Plan

    DoE Massively Parallel Computing Lab (SANDIA)

    Have appreciable Materials Components

SCIENTIFIC COMPUTING

- **Grand Challenge: e.g., Climate Modeling, Turbulence**
  - Large Number of interacting length scales
  - "Killer" parameters, e.g., Reynolds Number >> 1

- **"Grand Opportunity": e.g., Materials Modeling**

  Electronic and Atomic Structure

  Kinetic Processes

  - Finite number of non-overlapping length scales

- **Microscopic → Mesoscopic → Macroscopic**

Microscopic	Mesoscopic	Macroscopic
Mechanical		
Atomistics: Dislocation core	Dislocation Motion; Interactions	Plasticity
Electronic		
Superconductor Electronic Structure	Magnetic Flux/Impurity Interactions	High Magnetic Field Behavior

TECHNOLOGY SIMULATION

- Accurate Prediction of Technology Performance before Fabrication
- Accessible to Device R&D and Manufacturing Communities

PROCESS SIMULATION

Silicon

- Implantation
- Impurity Diffusion

•
•
•

- Lithography
- Etching

DEVICE SIMULATION

MOSFET

- Electron, Energy Transport
- 1D/2D/3D
- Fully non-planar device geometry
- Heterostructure Effects

CIRCUIT SIMULATION

OBSERVATIONS AND CONCLUSIONS

- **Computation and Properties Measurements must be placed on same footing.**

- **Accessible work station software packages for empirical materials modeling must be designed.**

- **Conventional Supercomputing will continue.**

- **Parallel computing will become increasingly significant but slowly:**

  - As unique way to address materials complexity
  - To enable adequate design, device, process simulation.

- **Grand Challenge Problems will be drivers**

  - Require interdisciplinary teams of specialists.

- **Moderately Parallel/Distributed computing may be adequate, at least for short term.**

  - Can map problems onto familiar architectures for $\lesssim 30$ processors
  - DEC α-chip may achieve ~ 0.25 tera-ops

UNDERSTANDING MATERIALS

Scientific Computing

. . . AND HOW TO CONTROL THEM

Process and Device Simulation

IS INTRINSICALLY IMPORTANT PART OF DARPA ACTIVITIES.

- **Short term goals (3-5 years)**
  - Improved semiconductor process and device simulation
  - Qualitatively new insights obtained

    from mechanical properties calculations

    using improved computing capabilities
  - Electronic Free Energy and Phase Diagram

    calculations to predict new alloys

EXPLORATORY WORKSHOP

Materials and Computation: Dislocation Dynamics

- Will explore Micro-Meso-Macro Paradign,

- By analyzing approach to solving "simple" and important materials science problem,

- Which is basic to understanding mechanical properties,

- And will serve as model for approaching other problems: e.g., Dopant diffusion in semiconductors.

- Will involve small augmented DSRC sub-group.

PROGRAM OUTLINE

1. Definition of physical and theoretical problem

2. Interatomic Potentials; Boundary Forces

3. Computational Approaches

4. Available experimental information

5. Dislocation micromechanisms as mesoscopic ingregient for more complicated phenomena

    - Strain energy release rate in crack propagation

6. Applicability of Parallel Computing Approaches

DSRC WORKSHOP

Next year's meeting

- Achievements in Parallel Computation in areas of direct DARPA interest.

PROCESS CONTROL AND SIGNAL PROCESSING IN MICROELECTRONICS MANUFACTURING

Tom Kailath and Graydon Larrabee

OBJECTIVES OF THE WORKSHOP

The workshop was intended to examine process control in the microelectronics industry and to determine the role of other technologies in future developments. The successful roles of modern control and signal processing technologies in the aerospace and chemical industries were to be examined for applicability to microelectronics manufacturing.

DOD RELEVANCE

The DoD must have access to state-of-the-art high performance logic devices with rapid turnaround. Current industry economy-of-scale wafer fabs do not support this DoD need. A flexible intelligent microelectronics fab, scaled to the needs of the DoD, is required. A "1990's process control technology" is a key enabler for this manufacturing scenario.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY

Microelectronic manufacturing in the United States continues to lag Japan and the Pacific Rim countries. The major cause for this is inferior manufacturing management and manufacturing execution. A Flexible Intelligent Microelectronics Manufacturing (FIMM) technology can overcome these deficiencies and provide the U.S. with world-class manufacturing. An integral component of FIMM is a "1990's process control technology".

The microelectronics industry has limited itself to statistical process control (SPC) - a 1950's technology! Some forward and feedback process control for microelectronics manufacturing is emerging in the early 1990's. The chemical industry did this same kind of process control in the 1960's! The chemical and aerospace industries are 20 years ahead of the microelectronics industry in process control. There is a large base of process control technology that the microelectronics industry can adopt/adapt.

Other factors that are driving this industry to develop FIMM with a new process control technology include:

1) $1,000,000,000 Wafer fabs with only 35% equipment utilization and cluster processing equipment that cannot manufacture without real time process control.

2) The emergence of logic as a technology driver and the concomitant change in manufacturing style for logic fabs.

3) Shrinking geometries, increasing die/chip sizes, increasing wafer diameters...all demand tighter process and equipment control.

Dr. Ted Cochran (Honeywell Sensor and System Development Center) discussed chemical process control and advanced user interface technology. The importance of "transparent" control was emphasized. Data visualization was essential to facilitate control decisions. A low-cost sensor/actuator bus connected to "control enablers" using sequential control, model-based control, fuzzy control...was described. A sensor-based reactive ion etch (RIE) example with real time, feedback control was discussed. This latter activity is a new SEMATECH program.

Dr. Tom Kailath discussed the roles of modern control theory and signal processing in process control. These two technologies have been critical in aerospace, chemical engineering and in smart-sensing weapons systems. The successful development and transfer of a multizone lamp heating (Rapid Thermal Processing, RTP) methodology from Stanford to the Texas Instruments (TI) Microelectronics Manufacturing Science and Technology (MMST) program was reviewed. New methods for on-line line-width measurements, wafer defect inspection and multipoint temperature measurement were described.

Modern control theory and signal processing can impact process control and FIMM by:

1) Reducing design time through modeling, simulation and optimization

2) Sharply reducing the learning cycle using control/sensing algorithms

3) Assuming reliability and reproducibility with smart sensing algorithms and feedback control.

In a series of invited short talks, speakers from SEMATECH, SRC, University and industry made the following points:

1) SEMATECH is just starting to evolve a sensor/process control strategy. Reliability, cost of implementation and cost of ownership were felt to be overriding considerations for success

2) American microelectronic equipment manufacturers are not embedding sensors and process control. They do not perceive a "technology pull" from microelectronics manufacturers

3) There is a wide array of high quality projects underway in universities but no road map for transition to U.S. equipment manufactures

4) Microelectronic manufacture is qualitatively no different than other processes in other industries. Existing "classical" and statistical control approaches are directly applicable to semiconductor fab control problems

5) Incremental development of feedback control using active sensing will achieve robustness, broader operating regions and increased flexibility.

CONCLUSIONS

A "1990's process control technology" using modern control, signal processing and process control techniques adopted/adapted from the aerospace, chemical, nuclear weapons and other industries is essential. This new technology will be a key enabler for FIMM and a scaled microelectronics fab that will provide the DoD with quick turnaround state-of-the-art logic devices in the 1990's.

SUGGESTIONS FOR ACTION BY DARPA

It is clear that DARPA can strongly influence the course of FIMM and process control through SEMATECH. In turn, SEMATECH must embrace FIMM and develop a road map to embed a "1990's process control technology" in American equipment manufacturers mode of operation; i.e., equipment/process design and construction. U.S. companies must be aggressively encouraged to manufacture processing equipment predesigned for flexible insertion of sensing and control. This can be done by developing a DARPA sponsored smart-sensor technology starting with simple models and cost effective sensors that are available today. Both models and sensors should be capable of being regularly upgraded with higher performance models and sensors.

DARPA/SEMATECH should enhance the U.S. equipment manufacturers and equipment users acceptance and use of a FIMM compatible process control technology. This can be done through a DARPA/SEMATECH program to develop modules of process control software and software/hardware packages that integrate signal processing and modern control. These packages must be user friendly, easily integrated into emerging process equipment and make process control virtually transparent to the user.

DARPA needs to tie together all intelligent manufacturing activities in order to leverage process control and smart sensing currently on-going in DARPA'S materials and microelectronics programs. It is essential that DARPA build on DoD investments and successes in modern control, computation and signal processing to generate a process control technology for a world-class flexible intelligent microelectronics manufacturing technolog; .

AGENDA

PROCESS CONTROL AND SIGNAL PROCESSING IN MICROELECTRONICS MANUFACTURING

July 13, 1992

Organizers: G. Larrabee, T. Kailath (DSRC)

The growth of the microelectronics industry has been a remarkable success story. Now it is running up against some difficult boundaries. This workshop hopes to expose to the microelectronics manufacturing people two other disciplines (modern control and signal processing) that have proved their worth in fields such as aerospace and chemical engineering. Their application might make the microelectronics industry even more successful.

Monday, July 13

Introduction

Process Control in Microelectronics Manufacturing - G. Larrabee

Tutorial on Multivariable Control and Applications in Manufacturing - Semyon Meerkov (UM)

Advanced User Interface Technology, Chemical Process Control, the Semiconductor Industry - Ed Cochran (Honeywell)

Tutorial on Modern Signal Processing Techniques for Lithography, Metrology, Defect Inspection, and System Identification - T. Kailath (Stanford)

Panel Discussion: Quo Vadis?

Ralph Cavin (NCSU/SRC)
Tom Seidel (Sematech)
Nick Tovell (TI-MMST)
M. Moslehi/C. Schaper (TI-MMST/Stanford)
S. Spain (Integrated Systems)

The above will make 5 minute presentations. Other invited attendees and the invited speakers will participate in the discussion.

ATTENDANCE

PROCESS CONTROL AND SIGNAL PROCESSING IN MICROELECTRONICS MANUFACTURING

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PROCESS CONTROL & SIGNAL PROCESSING IN MICROELECTRONICS MANUFACTURING

Problem

- Flexible intelligent microelectronics manufacturing must have a "1990's process control technology" to be successful.
- Escalating wafer fab and equipment costs and emerging cluster tool equipment, will be positively impacted by a new process control technology.
- Shift to logic manufacturing will require new process control strategies.
- Accelerating demands on processes and equipment along with increasing device complexity will dictate intelligent manufacturing.

DoD Relevance

The DoD must have access to high performance state-of-the-art logic devices with rapid turnaround. Current industry economy-of-scale wafer fabs do not support this need. A flexible intelligent microelectronics fab that is scaled to the needs of the DoD is required. Process control is a key enabler for this manufacturing scenario.

WHAT IS DONE IN OTHER INDUSTRIES?

- The microelectronics industry has limited itself to statistical process control (SPC) - a 1950's technology!
- The chemical industry did analog control in the 1950's
  and "digital computer feed forward control" in the1960's
  and multivariant control in the 1970's
  and model-predictive control in the 1980's
- The aerospace industry did multivariant control adaptive (robust) control in the 1970's
- Other - nuclear weapons ....

There is a large base of process control technology that the microelectronics industry can adopt/adapt.

THE ROLE OF MODERN CONTROL AND SIGNAL PROCESSING TECHNOLOGIES

- Have been critical in aerospace, chemical engineering and in smart-sensing weapons systems.

- Recent DSO/MTO work has made a prima facie case that they can make a critical difference in microelectronics/intelligent materials processing, e.g.,

  1) Transfer multizone lamp control methodology from Stanford to TI/MMST.

  2) Joint work of Integrated Systems with MMM on Metal Matrix Composites and Norton/Sandia/Kopin on CVD Diamond.

  3) New methods for on-line line width measurements, automated defect inspection of regular structures and multipoint temperature measurement.

- (Such cross-disciplinary efforts) Can dramatically reduce costs by:

  1) Reducing design time using modeling, simulation and optimization.

  2) Sharply reducing learning cycle using control/sensing algorithms.

  3) Assuring reliability and reproducibility by automated multivariable feedback control and smart sensing algorithms.

  4) Increasing flexibility by allowing incremental and modular development and experimentation.

WORKSHOP ISSUES AND CONCERNS

1. Modeling for Design and Control

- At the analysis and design stage, comprehensive physical/chemical models for process, device and circuit design are very important.

- Simpler models are necessary for real-time control design, obtained by (a combination of) model reduction and black-box identification techniques.

- Neural network methodologies can usefully supplement the traditional linear black-box methods.

2. Sensors and Sensing

- Good measurements are essential for successful control. (Simple inexpensive sensors can be used to implement reasonable process control today.)

- Model-based signal processing could dramatically augment the capabilities of simple sensors by:

  i) Estimating quantities that are not directly or easily observable

  ii) Using the model to predict parameters (e.g., temperature, thickness, etc.) across a whole wafer from measurements at a few (or even one) part.

3. Equipment Design

- Needs to be coordinated with the requirements for measurement and control. Extensive simulation studies should be carried out before hardware is built.

4. Strategies

- Must leverage other industries; e.g., chemical, aerospace

- Software and algorithms are key to success.

  -- DoD developed base in signal processing and modern control.
  -- Cross disciplinary efforts to blend technologies.

5. Implementation in Manufacturing

- Microelectronic equipment manufacturers must embed sensors and process control -- but are not doing it!

- Microelectronics manufacturers are not doing "technology pull."

- How does university research get transitioned to manufacturing equipment?

- SEMATECH is just starting to evolve a sensor/process control strategy.

SUGGESTIONS FOR DARPA/SEMATECH ACTIONS

- **Aggressively encourage equipment companies to manufacture processing equipment predesigned for flexible insertion of sensing and control.**
- **Develop a smart-sensor strategy starting with simple models and cost effective sensors available today but regularly upgradable with higher performance models and sensors.**
- **Start a program to develop modules of process control software and software/hardware that are easily integrated into emerging process equipment by equipment manufacturers.**
- **Build on DoD investments and successes in modern control, computation and signal processing to generate a dramatically competitive world-class micro-electronics manufacturing technology. This should be done via multidisciplinary university-industry partnerships in various areas of manufacturing.**
- **Tie together all DARPA Intelligent Manufacturing work to leverage process control and smart sensing in materials processing.**

MULTI-SPECTRAL IR SYSTEMS

T. C. McGill, H. Ehrenreich, D. K. Ferry, R. M. Osgood, and C. A. Mead

OBJECTIVE

The objective of this workshop was to examine the possibilities for multi-spectral infrared imaging systems. The range of study included: the systems considerations for infrared systems, the possible range of applications, and the various technological options.

DOD RELEVANCE

The role of infrared imaging systems in the modern military hardly needs to be stated after the successes so graphically illustrated during the recent Desert Storm campaign. However, the fact that the US dominated night fighting in this campaign has alerted all potential adversaries to the importance of this capability, and made it one of the top priorities for future inventories of technologies. Hence, we are likely to have to increase greatly our infrared capability in order to maintain some edge in this critical technological arena. Further, with the rapidly changing role of the military, where fixed battle scenarios involving the Soviets have been replaced by a diverse worldwide global mission, flexibility of imaging systems will be extremely important. The need for detection of chemical agents, highly specific target identification (scud missile launchers versus school buses), and the development of very specific friend or foe identification procedures all argue for increased capability of military infrared imaging systems. Much advanced processing materials will require precise process control. Infrared systems could play a major role as a non-invasive process sensor.

Since the cost of infrared sensor systems is a major concern in their deployment, the military could profit by enhancements in volume that would come with wider application of these technologies in environmental sensing, process control, security systems and other commercial applications.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY

The meeting included three presentations on military systems (General Dynamics, Texas Instruments and Hughes), followed by presentations on a number of different detector technologies including the HgCdTe based detectors, quantum-well detectors, III-V superlattice-based detectors, and uncooled thermal imagers.

Generally, the systems groups indicated that there is a very large interest in producing multi-band imagers. There are very distinct advantages in producing imaging systems that have detectors operating in both the 3-5 μm and the 8-10 μm range. Both of these spectral bands offer unique information and act in complementary ways in detecting targets under differing battle situations. Experiments are now in progress to gather information using experimental dual-band systems, including one operating in the 3-5 μm and 8-10 μm range, and a second system with a visible and 3-5 μm capability. Preliminary indications are that these primitive experimental systems are providing exciting new capabilities in imaging. The current primitive systems have no true narrow-band spectral capability and have been produced using off-the-shelf arrays, either with two separate arrays for the two bands or with a color wheel that makes possible the superposition of the visible and near IR image from a single detector array.

Each of the device technologies seems to offer uniquely different possibilities for fabricating integrated multiband detector arrays. In the case of the HgCdTe detectors, single multiband detector structures that are switchable have been demonstrated. The quantum well detectors could be built into stacked structures, with different groups of wells detecting different wavelength ranges. Because of the requirement of having a grating to couple the normal incident radiation into the current generation of detectors, a more likely structure is one with side-by-side detectors, operating at different wave-lengths, with the appropriately spaced gratings for each wavelength range. The III-V IR superlattice could use all of the same structures found in the HgCdTe multi-band arrays. Because of increased process sophistication in the III-V's, detectors could be fabricated with different wavelength response side-by-side on the same chip. Historically, thermal imagers have been less sensitive than the quantum sensors discussed above, but they promise very low cost easy to use imagers.

Multi-spectral systems could be produced using filters to determine the band of radiation incident on a given pixel.

CONCLUSIONS

Multi-spectral infrared imaging shows great promise for providing the military with enhanced target detection, threat detection, and friend or foe identification systems. The full extent has not been delineated. Hence, it is essential to carry out some accurate experimental studies. Pursuit of this technology could act as an incentive to commercializing infrared systems for pollution monitoring, process control, and other commercial applications. The increased range of interest could lead to a net decrease in cost, an important driver for military as well as commercial systems.

In this context, the uncooled Si bolometer sensor technologies have potential advantages for ease of use and reduced cost.

SUGGESTIONS FOR ACTION BY DARPA

Based on this workshop, we feel that multi-spectral imaging should be pursued vigorously by DARPA. It could give the US a substantial new capability to insure security in a very different world environment. Items to be considered are:

- Experimental imaging with multi-spectral imaging and accurate simulations to asses the ways it can be employed.

- Fabrication of infrared imagers based on the various competing technologies. Our assessment of the order of priority for multi-spectral imaging is HgCdTe, InAs/GaInSb superlattices, quantum well infrared detectors (QWIR's), and thermal imagers.

- A program to assess the role for very low cost uncooled sensors in comparison with the other technologies that may require cooling.

AGENDA

MULTI-SPECTRAL IR SYSTEMS WORKSHOP

July 14, 1992

Tuesday, July 14

DARPA Introduction, R. Balcerak - DARPA/MTO

Multi-Spectral Imaging in the Infrared for Missile Seekers - Gus Goldshine, General Dynamics

Systems Applications using Multi-Spectral Imaging - Bob Sendal/Colin Whitney, Hughes

Applications of Multi-Spectral Imaging in Process Control - Jerry Schaefer, TI and Paul Norton Virginia Tech

Bias-Switchable Dual Band HgCdTe Detectors - Ed Blazejewski, Rockwell/ V. Swami Swaminathan, AT&T Bell Labs.

Multi-Spectral GaAs/AlGaAs Quantum Well Detectors - D. Chow, Hughes Research Lab.

Multi-Spectral Imaging with InAs/GaInSB Detectors - D. Chow, Hughes Research Labs.

Multi-Spectral Imaging with Thermal Imagers - Paul W. Kruse, Honeywell SSDC

Discussion

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WORKSHOP OBJECTIVE

- To examine the possibilities for multi-spectral infrared imaging systems
- Study included:
  - Systems considerations for infrared imaging
  - The possible range of applications
  - The various technological options.

DOD RELEVANCE INFRARED IMAGING

- Surveillance
- Night Time Operations
- Target Identification
- Friend or Foe

DOD RELEVANCE MULTI-SPECTRAL

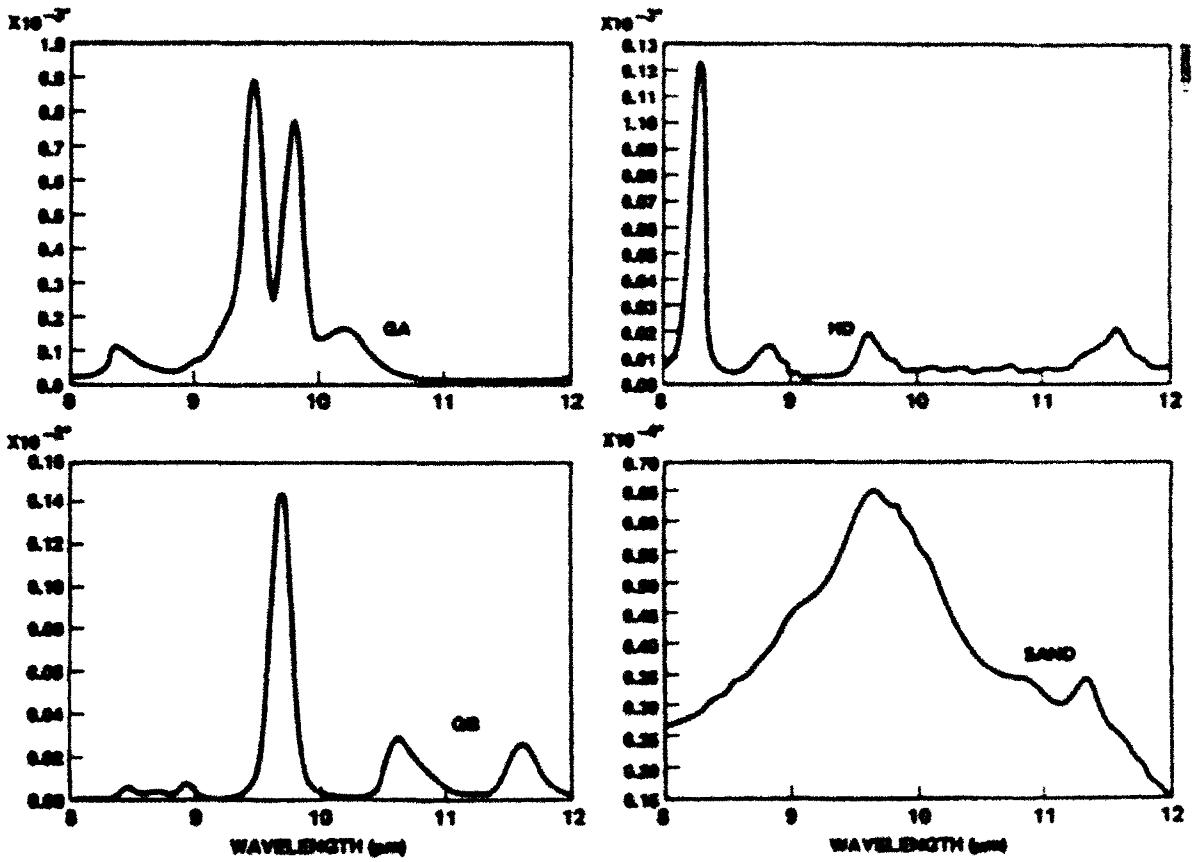
- Complimentary nature of 3-5 μm and 8-10 μm
- Diverse worldwide global mission requires flexibility of imaging systems
- Detection of chemical agents
- Highly target identification
- Very specific friend or foe identification
- Valid laser counter-measure

DOD RELEVANCE MULTI-SPECTRAL DUAL USE

- *In Situ* Process Sensors for Advanced Process Control
- Environmental Monitoring Systems
- Earth Observation Systems
- Expanded Use Could Lead to Cost Reduction

CHEMICAL AGENT CLASSIFICATION

- Nerve Gas Agents and Mustard Gas Are All Selective Absorbers
- Water and Clouds Are Grey Body Sources
- Hughes Modified Three Systems With Filter Wheels (Bradley -- M1 -- DTV)
- Tested In the Field With Simulated Chemical Agents
- Went to Desert Storm -- Never a False Alarm
- Algorithm: See A Cloud Use Filter Wheel Logic
- FPA Systems Offer More Sensitivity and Flexibility



The absorption spectra of nerve agents GA and GB and mustard gas, Hd, are shown. Identification is based on the spectral absorption differences.
Absorptivity is given in units of m^2/mg.
The absorptivity of sand is much less than the chemical agents.

*Note changes in scale

TECHNOLOGIES

A. HgCdTe Based

B. InAs/GaInSb Superlattice Based

C. Quantum Well IR Detector Structures

D. Thermal Imagers

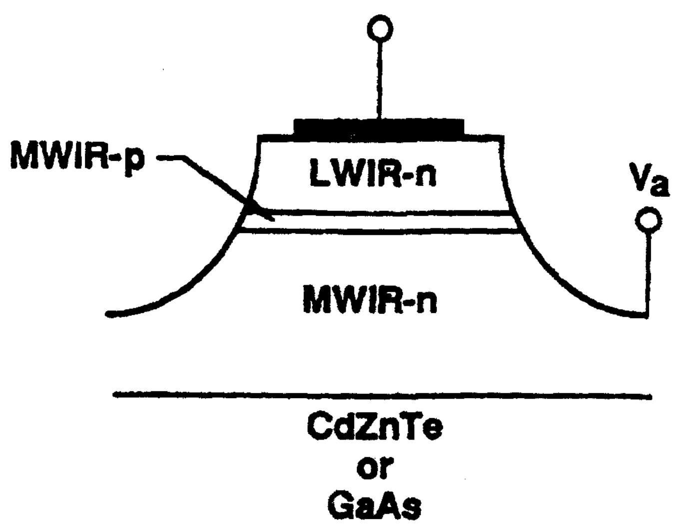
All MBE In-Situ 3 Layer HgCdTe Dual Band Detector

- Three layer MBE HgCdTe structure
  - Type: N/P/N
  - Composition: LW/MW/MW substrate
  - Continuous growth sequence
  - Post Growth anneals

- Indium doped n-type layers
  - Growth temperature 200°C

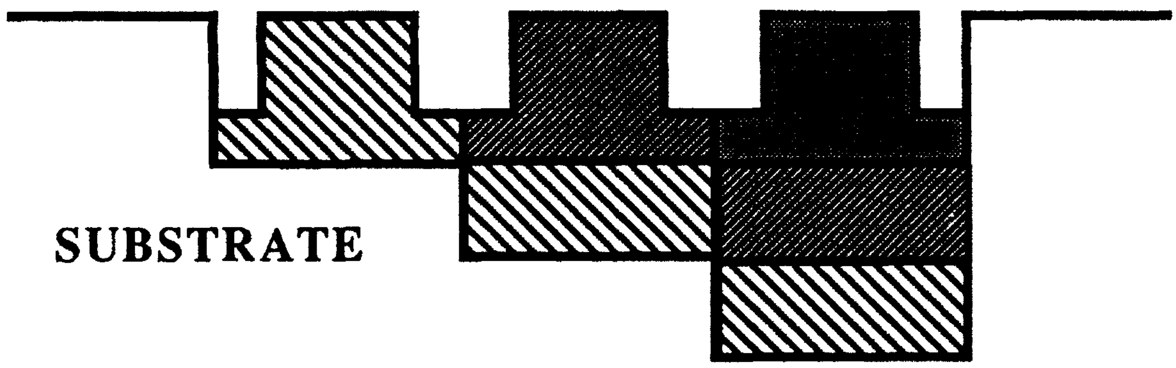
- Arsenic doped p-type layer
  - Growth temperature 165°C
  - Interdiffused superlattice
  - As introduced during CdTe cycle

- CdZnTe or GaAs substrates

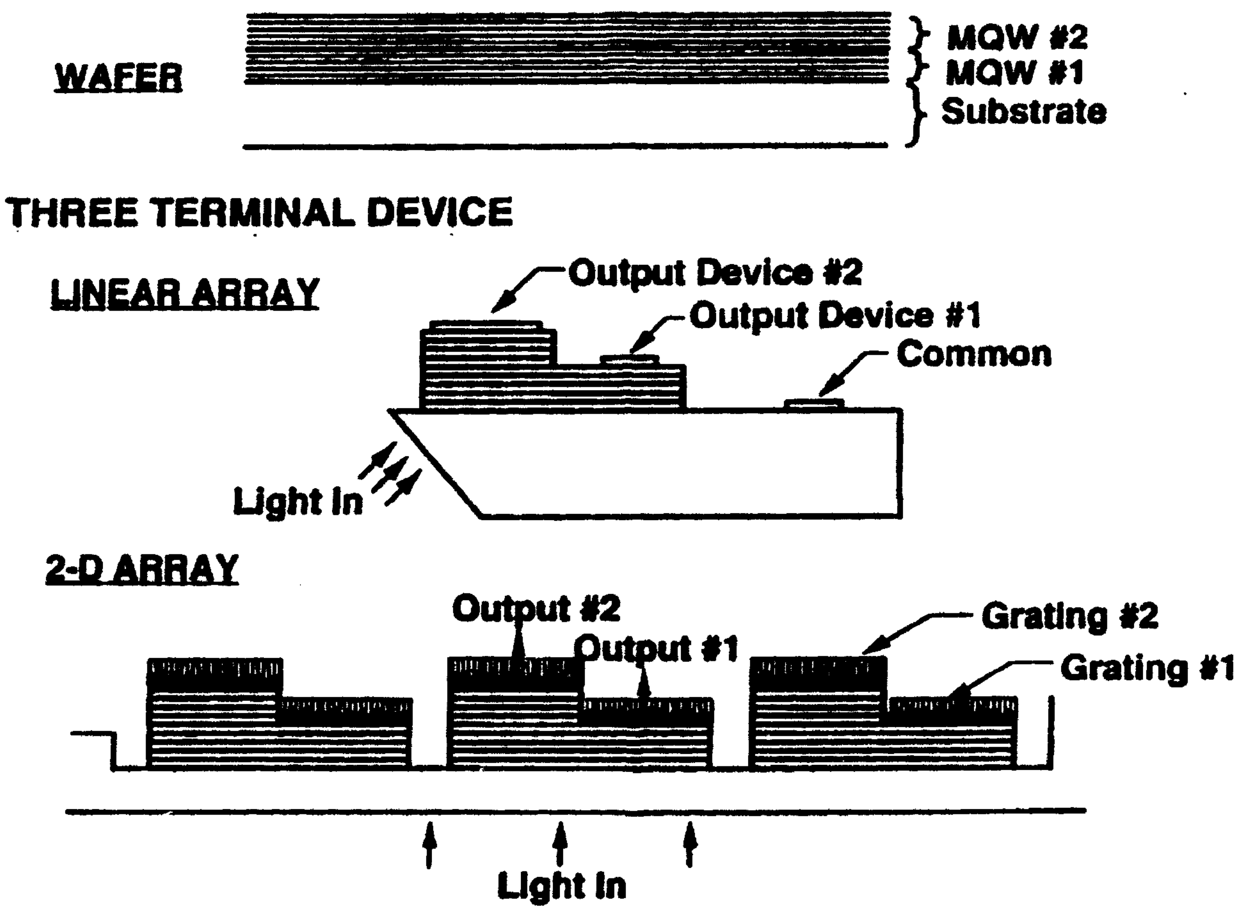


3-COLOR SIDE-BY-SIDE DETECTOR

1. Prepattern Substrate
2. Deposit MWIR Diode Structure
3. Deposit LWIR Diode Structure
4. Deposit VLWIR Diode Structure
5. Process Diodes (Pattern and Etch)



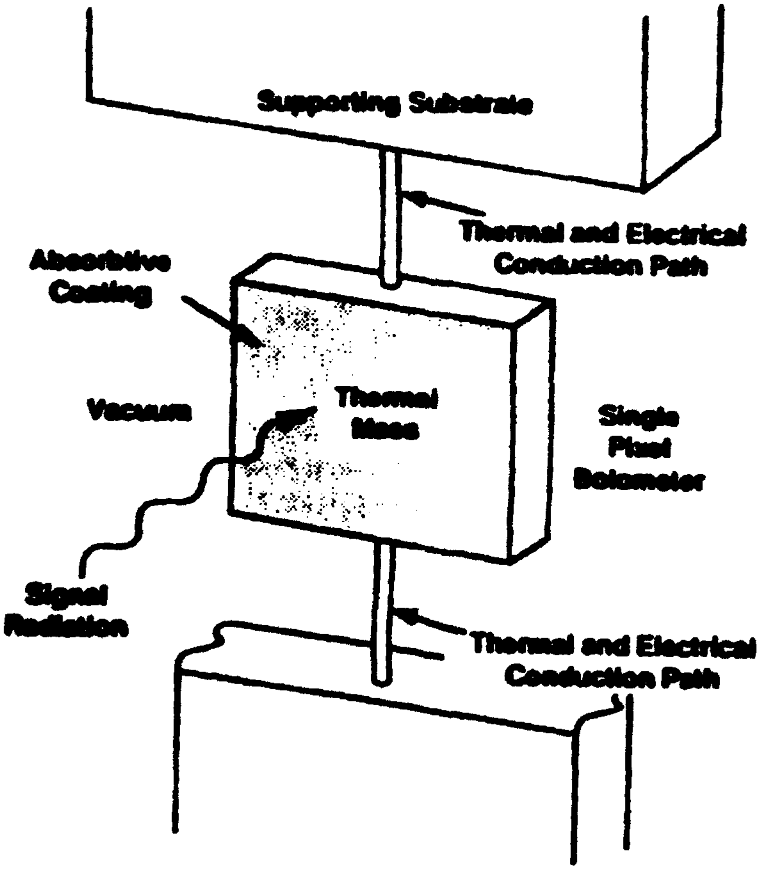
DUAL WAVELENGTH
(4 AND 8-10μM) QWIP DETECTOR



SILICON MICROBOLOMETER

Principle of Operation

- **This figure illustrates the form of a classical bolometer.**
- **It consists of a thermal mass C, suspended by supports of thermal conductance g.**
- **Incident IR radiation will heat up the suspended thermal mass.**
- **The incident IR radiation flux is measured by monitoring the resistance of the thermal mass, which changes with temperature.**



Idealized Bolometer Structure

SUMMARY

- **Multi-spectral infrared imaging shows great promise for providing the military with:**
  - **enhanced target detection,**
  - **threat detection,**
  - **friend or foe identification systems.**
- **The full extent has not been delineated.**
- **Essential to carry out some accurate experimental studies.**
- **Technology could act as an incentive to commercializing infrared systems for:**
  - **earth observation systems**
  - **pollution monitoring**
  - **process control**
  - **other commercial applications**
- **Increased range of interest could lead to a net decrease in cost**
- **The uncooled Si bolometer sensor technologies have potential advantages for ease of use and reduced cost.**

SUGGESTIONS FOR DARPA ACTION

- **Experimental imaging with multi-spectral imagers and accurate simulations to assess the ways it can be employed.**
- **Fabrication of infrared imagers based on the various competing technologies. Our assessment of the order of priority for multi-spectral imaging is HgCdTe, InAs/GaInSb superlattices, quantum well infrared detectors, and thermal imagers.**
- **A program to assess the role for very low cost uncooled sensors in comparison with the other technologies that may require cooling.**

THE FUTURE OF CMOS

Executive Summary

R. Osgood, D. K. Ferry, G. Larrabee, T. McGill

OBJECTIVE:

The objective of this workshop was to ascertain the industrial view of scaling and future directions, including constraints, that will be placed on CMOS advancement over the next decade.

DOD RELEVANCE:

For the foreseeable future, the vast majority of electronic systems will be built primarily with silicon CMOS integrated circuits. A variety of new, non-traditional technologies that DARPA is developing, such as optoelectronics, nanoelectronics, superconductivity, etc., will play an important role in electronic systems of the future, but they will need to interface with and work with silicon CMOS in most applications. For the efforts in new technologies to be as successful as possible, it is critical to have an accurate picture of how mainstream digital silicon CMOS technology will evolve.

SCIENTIFIC AND TECHNICAL SUMMARY:

In the past, the growth in performance in CMOS has mainly been driven by high performance computers. It is expected that, with the onset of a variety of limitations on continued scaling there will be a major paradigm shift to a view, in which the on-chip power dissipation will be the prime constraint for new designs. In work stations, high performance will be achieved by increasing computing speed with tolerable power dissipation achieved by the low power design. In low-end consumer electronics (hand-held systems), low power will be the major attribute of new designs. The high-end systems that have driven the development in the past now will be made with massively parallel aggregates of CMOS processors, each designed under the new paradigm.

Regarding future systems the following comments are applicable:

- Architectural advancements will be required to overcome the onset of limitations by signal propagation across chip.
- It is unlikely that reduced temperatures will be employed to any great extent.
- One IC technology, which appears to be generally of interest for low power applications, is SOI (Silicon on Insulator). This technology provides lower "off" power for MOSFETS and is faster than that of related bulk devices (lower capacitance). Widespread commercial use of SOI would undoubtedly enhance the technology and manufacturing base for DoD rad-hard electronics.
- Interconnect technology is a critical issue that will (could) limit future advancements in CMOS density.

The commercial emphasis on low power CMOS will undoubtedly benefit a large number and variety of DoD systems, particularity for hand-held and small desktop electronic systems, as well as some special purpose computers. Despite this emphasis, however, it is important to keep in mind that the DoD has many applications for ultrahigh performance computer and signal processing. In this case a variety of non-traditional and traditional technologies are likely to be essential despite their attendant power requirements.

Fabrication of future CMOS will be more complicated due to the basic complexity of the advanced processing that is currently used. The need for specific numbers of chips produced at a given design level will drive the industry to larger wafer sizes and more costly fab facilities.

CONCLUSIONS:

Scaled CMOS will continue to be the technology of choice for silicon microelectronics for multiple systems applications. However, design (architecture) paradigm shifts are expected and there is a need to change the basic approach for microelectronics manufacturing. The high-performance needs of DoD may increase the need for application– specific, high-performance chip processing separate from commercial CMOS. A projection of CMOS IC characteristics is given in the table.

Table I

Selected Scaled Cmos Operating Parameters in Year 2007

Power Supply Voltage	1.6-1.0 Volts
I/O Levels	1500 (Logic)
Speed	0.5-1 GH2 (Logic)
Temperature	320° K
Other Digital Technologies	SoI (possibly SiGe:Si)

RECOMMENDATIONS FOR DARPA

1) DARPA needs to continue its programs in creating a scientific base for smart manufacturing in the microelectronics area, since capital costs are otherwise likely to limit manufacturability of CMOS in the next few scaling generations.

2) Support should be provided for the development of new design tools which emphasize the new constraints expected from the projected paradigm shift in chip design; e.g. An emphasis on design procedures for reducing power dissipation.

3) Effort should address new device structures should be developed for memory and logic in the sub-0.1 μm gate length regime, and new local architectures conceived to overcome interconnect limitations in this same scaling region. The current DARPA programs in ultra-dense electronics are therefore needed.

AGENDA
WORKSHOP ON CMOS
July 16, 1992

Thursday, July 16

Welcome	Dr. Richard Osgood, Columbia Univ.
Opening Remarks	Dr. David Ferry, Arizona State
	Dr. Pallab Chatterjee, Texas Instruments
	Dr. Richard Sivan, Motorola
	Dr. Paul Horn, IBM
	Dr. John Carruthers, INTEL
Discussion	

ATTENDEES
WORKSHOP ON CMOS

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Prabhakar, Arati	DARPA/MTO	(703)696-2236
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Srolovitz, David	U of Michigan/DSRC	(313)936-1740

WHITHER CMOS

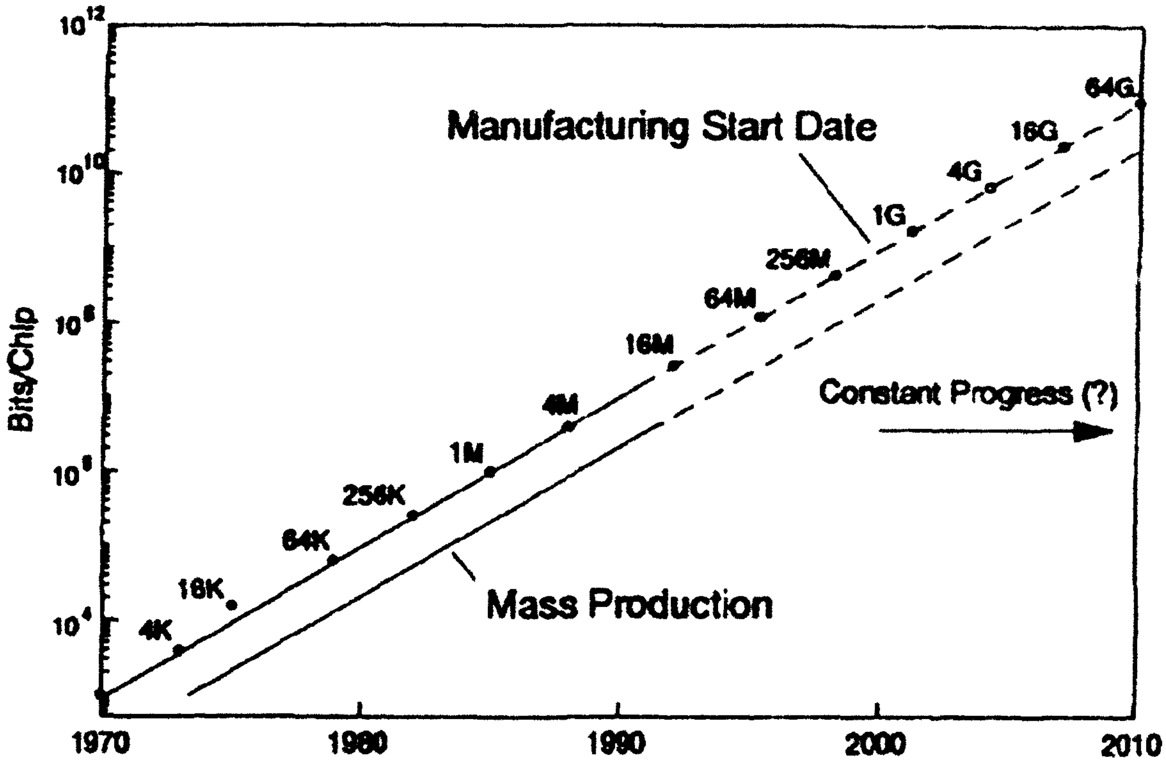
Projections of the Future of Silicon CMOS

R. Osgood, D. Ferry, T. McGill, G. Larrabee

SPEAKERS

Pallab Chatterjee	T. I.
Richard Savan	Motorola
Paul Hom	IBM
John Carruthers	Intel

DRAM EVOLUTION



SILICON ELECTRONIC SYSTEMS

RACK-MOUNTED SYSTEMS

HIGH-PERFORMANCE

DESKTOP SYSTEMS

HIGH DENSITY

HANDHELD SYSTEMS

ULTRA LOW POWER

SILICON FUTURE

SCALED-SILICON CHALLENGES

INCREASING DEMAND FOR HANDHELD PORTABLE ELECTRONICS

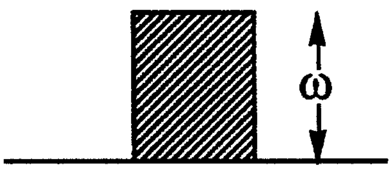
PHYSICAL AND ECONOMICAL LIMITS OF "STANDARD SCALING"

EVOLUTION OF CMOS LOGIC

PARAMETER	1993	2003	2013
Transistors/Die. (Millions)	10	50	500
Mean Fracture Size (Microns)	0.5	0.15	0.10-0.03
Area/Transistor (Microns)	48	18	7
Wafer Diameter	6-8	16-20	30-40
Junction Depth (Angstroms)	500	150	15
Gate Dielectric Thickness (Angstroms)	70	10	1

EXAMPLE OF PHYSICAL LIMITS

PROBLEM



- Cross-section fixed by finite σ (Cu)

- Scaling ω limited by lithography, step coverage, etc.

- Interconnects are wider than cell!

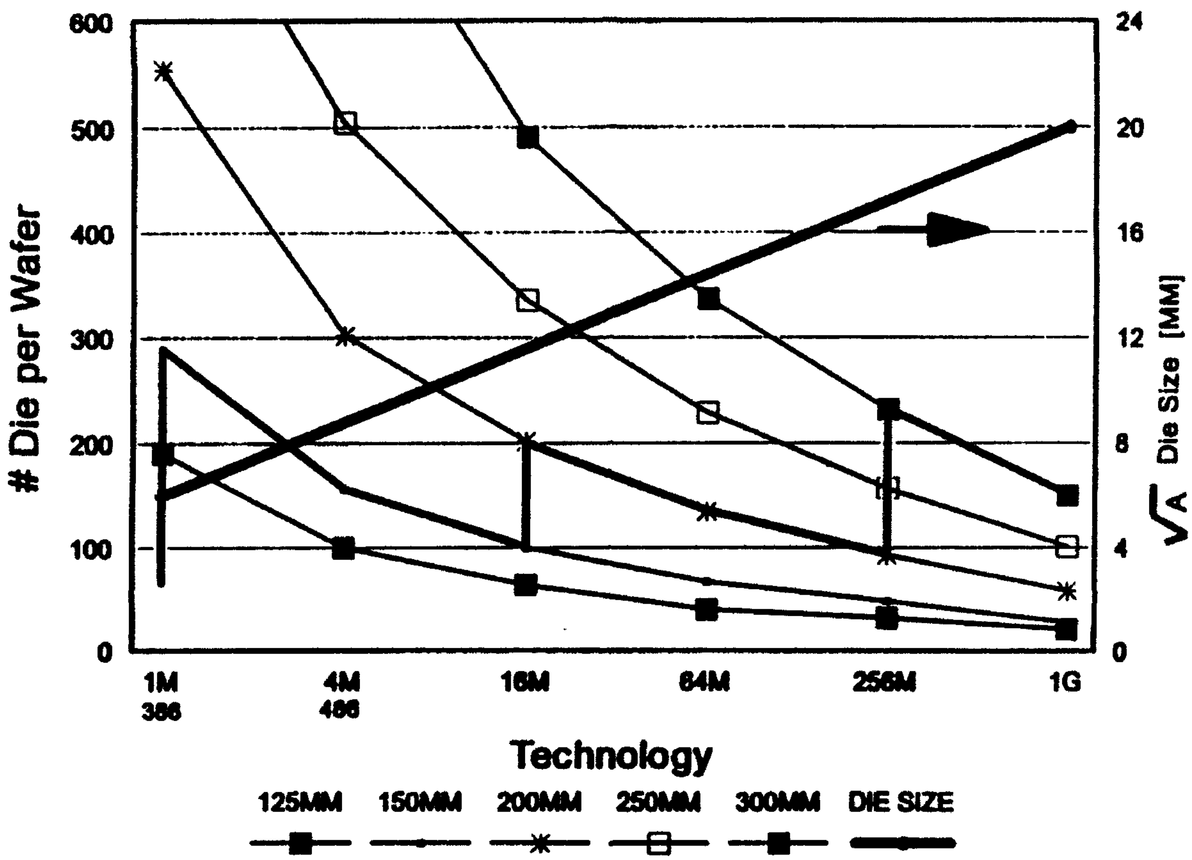
POSSIBLE SOLUTIONS

- Fabrication
  Midwafer interconnects (array)
  Better Package/Chip Design

- Design
  More Local Interconnects
  More pipe-lining

DIE PER WAFER TREND

By Wafer Size



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Speed	0.5-1 GH2 (Logic)
Temperature	320° K
Other Digital Technologies	SoI (possibly SiGe:Si)

RECOMMENDATIONS FOR DARPA

- DARPA'S program in smart flexible manufacturing is essential for future CMOS silicon IC's.

- Support should be provided for the development of new design tools which minimize power dissipation.

- New device structures should be examined for memory and logic using <0.1 μm gate-length devices; new local architectures are needed to deal with the interconnect bottleneck. The current DARPA program in ultra-dense electronics is supportive of these needs.

OPTICAL ARRAYS AND PACKAGING

D. A. B. Miller, R. Osgood, A. Yang and A. Yariv

OBJECTIVES OF THE WORKSHOP

The workshop addressed two topics:

- Optical Arrays - What is the status of technologies for making two-dimensional arrays of "smart pixels" - devices with optical inputs and outputs and smart processing?
- Optical Packaging - Packaging often dominates cost and reliability in optoelectronic modules, especially those using optical fibers. What are the key technologies and research areas?

DoD RELEVANCE

Optical arrays have the potential to avoid basic architectural constraints of purely electronic systems. This is especially true for highly parallel or highly interconnected processors. They are therefore relevant to many DoD processing tasks, including neural processors, signal processing, (convolutions and correlations), image processing and recognition, artificial vision, and array sensor processing. Potential applications exist both for devices running at video frame rates and for ultra-high-speed arrays.

Optical packaging is critical for implementation of optical interconnects inside and between for high-performance digital processors, and for any use of fiber optics.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY

Optical Arrays

Several technologies for making two-dimensional arrays of optical devices exist, and are in various states between research and preproduction. Liquid crystal technology allows integration of optical inputs and outputs with sophisticated silicon integrated circuits. Speeds are moderate, e.g., milliseconds to microseconds speed, but the systems could be arbitrarily "smart". Quantum well self-electro-optic-effect device (SEED) technology now offers high speeds (e.g., 200 MHz) in III-V semiconductor technology. Large arrays (e.g., 128 x 64) of simple devices have been made and used in large system experiments, with as many as 65,000 optical beams. Field effect transistors are now being incorporated for lower energy operation with moderate logical "smartness". Integration of surface emitting lasers with transistors is currently allowing small arrays of simple circuits. Finally, hybrid integration techniques are now emerging, which allow intimate bonding of arrays made in various different technologies.

Real systems require various other technologies to make them work, including array optics, novel opto-mechanical engineering and, for all modulator-based systems, and central optical power sources.

Optical Packaging

Packaging of systems with two-dimensional optical arrays is currently at the prototype stage, with successful demonstrations of large modular experimental systems. Beyond this, practical packaging has not yet been addressed.

Packaging of systems with waveguides and optical fibers involves a difficult mixture of technologies, and often dominates cost. Alignment of optical and optoelectronic components is very critical, with desired tolerances often less than 1 micron. Much of the packaging is done by hand, and active alignment of the components is required for high-performance systems. Manufacturability of such packaging is currently poor. Some work on technologies for interconnection of arrays of fibers exists that can reduce the cost per connection. Approaches to integrate electronic devices, optoelectronic devices and waveguides are being explored, although these do not solve the problems of interconnection to the outside world through fibers.

CONCLUSIONS:

Optical Arrays

The array device technologies themselves are evolving rapidly. They are good enough for systems experiments now, but need continued evolution for real applications. Systems and applications work with real devices is important now; it will generate the specific novel architectures that take best advantage of the features of the arrays, it will clarify the performance levels needed, and will drive the device technology in the most effective directions.

Optical Packaging

There is no single technology that holds the key to packaging. Fiber pigtailing is, however, a key process. Packaging technologies for arrays will be important to reduce cost. A manufacturable passive alignment technique for single mode fiber connection is a critical step in allowing wide-spread use of fiber-optic-based photonics. Research on packaging should be strongly coupled to a manufacturing environment, and should have reduced cost as a major goal.

SUGGESTIONS FOR ACTION BY DARPA

Optical Arrays

- Continued support for smart optical array device technologies.
- A program to stimulate the development of high power central laser power sources in the near infrared.
- A program to demonstrate research prototype systems and applications with existing or imminently available optical array devices.

Optical Packaging

- Stimulate research on low-cost, manufacturable technologies for passive optical alignment of fibers and optoelectronic components, both the signal fibers and arrays.
- Drive the packaging technology to give easy integration with mainstream electronics.

OPTICAL ARRAYS AND PACKAGING

D. A. B. Miller, R. Osgood, A. Yang, and A. Yariv

OBJECTIVES OF THE WORKSHOP:

This workshop addressed two topics:

- The technology for two-dimensional arrays of optical devices, with emphasis on those with both optical inputs and optical outputs;
- The issues in packaging of optoelectronic devices into modules and subsystems, especially those involving connection to optical fibers or waveguides, either singly or in linear arrays.

Key questions for the optical arrays are:

- Is the performance of current devices good enough for real applications?
- If not, can the current devices be evolved to achieve good enough performance? and
- What do we need to do to improve them enough?
- What are the key associated technologies (e.g., novel optics, optical power sources) that we need to advance the use of these arrays?

Key questions for optical packaging include

- What are the key technologies we need to make an impact on packaging?
- What research should be undertaken to advance optical packaging

INTRODUCTION:

Optical Arrays

Optical arrays here means two-dimensional arrays of devices with optical inputs and outputs. Some of the technology for these arrays is common with, e.g., detector arrays and emitter arrays. This workshop concentrated on the current status and future prospects of the array device technologies themselves. The main applications areas of interest for such optical arrays are in information processing and switching. The two-dimensional parallelism and other physical advantages of optics for communicating large amounts of information inside processors may allow new kinds of high-performance machines. Specific examples of potential DoD applications include neural preprocessors (e.g., feature extraction), neural processors (e.g., for pattern classification), signal processing, image processing and recognition, artificial vision, and array sensor processing. There is also considerable research on array devices for telecommunications switching applications, and there may be commercial applications in areas such as medical data analysis, finger print identification, and special digital processors.

Serious technologies for implementing optical arrays of logically smart devices ("smart pixels") are starting to emerge from research now. The main technology groups were each represented by speakers at the workshop. All of these technologies are optoelectronic, and are mostly at the stage of integrating known optical devices with known electronic devices. There are many open performance issues with such devices, including the discussion of the use of modulators rather than emitters, speed, optical and total power requirements and dissipation, thermal stability, the level of integration and circuit complexity possible, uniformity of large arrays, reliability, and ease and cost of fabrication.

Optical Packaging

Optical packaging is concerned with the technology of packaging of optoelectronic devices and systems, especially the interface between the optoelectronic devices and the optics. The workshop focussed mostly on the packaging of one-dimensional arrays or interfaces with single fibers, which is an area of current interest for possible optical interconnections between, and possibly within, high performance digital processors.

Packaging is an issue that has to be addressed now by all suppliers of optoelectronic systems and subsystems. It will be a key issue in any insertion of optoelectronic modules into real applications. Packaging is a often dominant in the cost and reliability of such systems. As a result, it is a key issue of concern for the future success and competitiveness of the US optoelectronics industry. It is also a subject that is difficult to define as an academic research discipline.

Key issues in packaging include cost, manufacturability, reliability, and the degree of integration of packaging with the components. The problem of packaging is compounded by the fact that there is no single technology for packaging; it generally requires the use of many diverse technologies. There are also few standards in packaging, and few agreed platform technologies. Often each different module from a given manufacturer is packaged differently. Hence it is a subject that is currently difficult to separate out into different problems that can be tackled individually.

THE WORKSHOP:

Optical Array Device Technologies

The workshop had four talks on specific areas of optical device array technology. These covered all of the major areas that have strong prospects for arrays with optical inputs and outputs together with some smart processing (analog or digital) (i.e., smart pixel technologies). These have varying degrees of sophistication in terms of performance of the optoelectronic devices and the (usually electronic) smart devices, and varying sizes of arrays.

K. Johnson (University of Colorado) summarized current work on using liquid crystal technology to give optical outputs from conventional silicon integrated circuits. This technology has the advantage that essentially no modification is needed to standard silicon processing, with a liquid crystal layer being added after fabrication of the silicon circuit. Hence relatively complex, smart circuits can be contemplated. The devices run readily at m˙ second speeds in the first systems experiments with early devices, and current individual devices run at microsecond speeds. Array sizes to 1 square centimeter have been demonstrated. One current goal is a 128 x 128 array correlator running at KHz optical rates, which might beat current electronic chips for this problem.

T. Woodward (AT&T Bell Laboratories) discussed the quantum well self-electrooptic-effect device (SEED) technology. This all-semiconductor technology is based on optical modulators utilizing multiple very thin (10nm) semiconductor layers. Large arrays (e.g. 128 x 64) of simple optical logic devices (Symmetric SEEDs) have been made. Individual devices have been operated as fast as 35 ps. Multiple stage switching systems have been demonstrated with this technology, although system clock speeds were limited to 10's of kHz by the available laser power and the moderately high optical input energy of these devices (a few pJ). Recently, field effect transistors have been successfully integrated, which can both increase the logical smartness and reduce the input optical energy (e.g. to < 100 fJ). These devices are operating at 100's of MHz now. The devices currently are GaAs-based. There a.e promising future possibilities for monolithic integration w'th silicon integrated ci.cuits.

J. Cheng (University of New Mexico) showed work on integration of vertical cavity surface emitting lasers with heterojunction bipolar transistors. The use of emitters removes the necessity for the beam distribution optics that is needed by the modulator-based schemes. The emitters are, however, arguably more difficult to integrate, and may have larger total on-chip dissipation. Various simple logic circuits have been demonstrated with this technology. Large uniform arrays remain to be demonstrated, and ultimate performance is not yet clear from these early devices.

N. Jokerst (Georgia Tech.) discussed hybrid technologies for mounting arrays of optical devices onto electronic circuits. Such techniques can avoid process compatibility issues of monolithic integration of opto-electronic and electronic devices, and can do multi-function, multi-material integration. They may also allow replacement of failed devices, improving overall process yield, and may have cost advantages over epitaxial growth technologies. They require handling thin film processed structures, and performance of such hybrid devices may be less than the best integrated devices. Moderate array sizes are routine (e.g. 12 x 16). These thin film techniques, employing metal-metal rapid thermal processed bonds, may have considerable reliability and thermal cycling advantages compared to indium bump bonding techniques, and may be useful for many different kinds of integrations.

Optical Packaging

The second half of the workshop comprised four talks on packaging of optoelectronic devices with associated optics. The first talk discusses the optomechanical systems for "free-space" two-dimensional arrays with optical inputs and outputs. The other three talks discuss packaging of waveguide or fiber devices.

R. McCormick (AT&T Bell Laboratories) discussed the issues and lessons learned from the construction of large free-space optical switching systems. These systems used SEED arrays, with several thousand beams incident on individual arrays. A six stage system with 65000 free-space optical connections was demonstrated. This had involved many novel approaches in optics and opto-mechanics. It had necessitated modular construction, where each part of each stage could be aligned and tested before making the entire system. Standardization was crucial to allow the design of different parts of the systems to be separated from one another. The experience in trying to make such systems had a major influence in the evolution of the devices themselves, often leading to conceptual changes in the devices that would not have been obvious from the point of view of device physics or simple numerical performance goals. In many cases, the system had to be designed to tolerances not normally required in opto-mechanical systems. The work had demonstrated that large free-space systems were feasible.

F. Leonberger (United Technologies Photonics) discussed his experience in making opto-electronic modules, in his case based on lithium niobate opto-electronic devices. He made the general points that performance in real environments and reliability at reasonable cost were important. The module must operate over at least a 40 - 85 C temperature range, be able to withstand 10,000 g shock, and be stable under repeated temperature cycling. From the point of view of the systems designer, the optoelectronic module should look like an electronic component. He emphasized that the cost of fiber pigtailing (connecting the optoelectronic device to an optical fiber) was the dominant cost in many systems. Use of arrays could significantly reduce cost per connection. He also felt that there were many possible options that had not yet been explored for attacking the problem of fiber pigtailing.

C. Armiento (GTE) showed their work on trying to make low cost packaging of linear arrays of electronic and opto-electronic devices with arrays of fibers. He emphasized the importance of integrating opto-electronic and optical components with mainstream electronics if the technology is to receive large scale use. Currently, many modules are essentially hand-crafted, are much bulkier than they need to be fundamentally, are very costly, and have reliability problems because much of the technology is based on submounts. Their approach was to attempt to use a "silicon waferboard" approach, using etched silicon as a single mechanical base for the hybrid integration of electronics, opto-electronics and fibers. An ultimate goal would be also to merge the "silicon waferboard" technology with multi-chip modules. He emphasized also the importance of going to a passive alignment technology for fibers and opto-electroelectronic devices. Passive alignment technology is currently not good enough for single mode fibers.

R. Lytel (Lockheed) discussed efforts to spin deposit and pattern polymer materials that can function both as optical waveguides and as electro-optic switches. Stability of such electro-optic polymers has been a major problem in the past, but this is apparently improving, with stability now up to 350 C in polyimide materials. The goal of such a technology is to build a multilayer technology with electrical interconnect layers, optical waveguides and optical modulators to allow high-performance interconnection on multichip module structures. Such a process also needs a good fiber pigtailing technology to get laser power onto the wafer and to get optical signals on and off the module for module-to-module interconnects.

CONCLUSIONS:

Optical Arrays

We can draw conclusions first of all based on the key questions.

- *Is the performance of current devices good enough for real applications?*

The technologies are generally not well enough developed for full applications in real systems. They are at varying stages between research and pre-production prototypes, depending on the specific technology. The technologies are, however, sufficiently advanced that useful research can be performed on possible systems and applications areas.

- *If not, can the current devices be evolved to achieve good enough performance?*

None of the optical array device technologies discussed at this workshop appears to be near to the end of its evolution. Progress in many aspects of these technologies is rapid at the moment. It is not, however, totally clear what will constitute good enough performance in a device technology because of the early stage of the applications research in most cases. Most of the technologies are untried in serious systems experiments.

- *What do we need to do to improve them enough?*

In most cases, the devices have not yet included much "smartness" between the optical inputs and the optical outputs since most work so far has been to demonstrate the feasibility of the integration technologies. The degree of "smartness" will likely have to continue to improve in order for the devices to find the broadest application. Optical input energy is still a key parameter limiting the size and speed of systems, although recent inclusions of electronic gain have shown considerable reductions in this energy (e.g., to < 100 fJ) that are promising for realistic large systems. Device speed needs to continue to evolve for all technologies, although speeds of 100's of MHz are being demonstrated now. Uniformity of arrays will remain an important issue in most of the technologies. Demonstration of moderately large arrays running fast will be important to stimulate applications.

- *What are the key associated technologies (e.g., novel optics, optical power sources) that we need to advance the use of these arrays?*

There are many associated technologies needed to make optical array systems. These include conventional optics and diffractive optics, which appear at the moment to be under control. Other more demanding technologies requiring novel engineering approaches include modular optomechanical systems for mounting and connecting arrays, two-dimensional fiber bundles, and, for those systems using modulator outputs, medium-high power lasers (e.g., 1 W) providing good mode control both spectrally and spatially at the operating wavelength of the devices. Such optical power supplies would need to be in "shoe-box" or rack-panel mounts, with good lifetimes (e.g., 10,000 hours). In addition, for assembly and diagnostics of such array systems, novel testing equipment will ultimately be required. As the technology advances, CAD tools will become more important to allow design of large or complex systems.

In general, research now into the specific applications of optical array or "smart pixel" technologies is important for two reasons. One reason is that these devices are most likely to be useful in unconventional architectures, such as those best suited either to highly parallel tasks or to highly connected simple processors. Relatively little such systems research has been done in the past with real array components because they generally have not been good enough or widely enough available. It is important that the research focus on building research system prototypes, rather than only theoretical studies, since such prototypes will expose the true benefits and problems of this technology, and will clarify the level of performance needed for practical applications. It is therefore also important that mechanisms to make the advanced devices available to applications researchers continue to be supported and enhanced. A second reason for applications research is that it will stimulate development of the devices by pushing the device technology in the most useful directions.

Optical Packaging

First, we can examine answers to the questions posed.

- *What are the key technologies we need to make an impact on packaging?*

There is no single technology which appears to hold the key to packaging. Rather it is the combined use of several technologies in a manufacturable process that makes successful packaging. Fiber pigtailing is, however, a critical process where much of the difficulty lies. Progress in packaging of arrays of fibers and opto-electronic devices could also be important in reducing the cost per connection.

- *What research should be undertaken to advance optical packaging?*

Programs aimed at packaging modules and subassemblies using novel manufacturable techniques may be important. Research on individual devices outside the context of a packaged system is unlikely to make any impact on packaging problems. A key technological goal would be to develop a packaging process that allowed passive alignment of optical fibers with optoelectronic devices, i.e., without any adjustments required during fabrication. An alternative goal would be a manufacturable process with highly automated active alignment of the fibers. Academic research needs to be strongly coupled to manufacturing to understand the problems most needing research. Cost is a key issue in achieving widespread use of such optics in systems, and cost reduction needs to be a major ultimate goal for research programs in packaging.

Packaging and integration of electronic and opto-electronic components, although still difficult, is easier to envision than the integrated packaging of optoelectronic components to conventional optical components. The path towards integration of electronic and opto-electronic components is made easier by the fact that they both use many similar fabrication techniques, such as layered growth techniques, batch lithographic processing and etching, and the devices are planar in nature. One approach approach to integration of electronics and optoelectronic components is epitaxially to manufacture them both out of the same layer structure, examples being the field-effect transistor/photodetector/modulator integration discussed by Woodward and the bipolar transistor/laser integration discussed by Cheng. A second approach is to make the optoelectronic devices on top of the electronic ones. One example of this approach is heteroepitaxy, growing the layers for the optical devices onto the electronic devices, such as the current research towards GaAs modulators on silicon integrated circuits. Another example is the fabrication of electro-optic polymer waveguides on multichip modules discussed by Lytel, and a third example is the deposition of liquid crystal material on top of silicon integrated circuits discussed by Johnson. A third approach to the integration of electronics and opto-electronics is to fabricate the basic optical devices separately (using planar technology) and transfer and bond them in planar form onto the planar electronics, such as the epitaxial lift-off techniques discussed by Jokerst. There are, therefore many ways of exploiting planar electronic fabrication technologies for such integrations. Optical fibers, however example, represent a completely different, non-planar technology, and alignment is much more critical than is required in hybrid packaging of electronic chips and opto-electronic devices themselves. Hence very precise techniques that lie outside the normal electronic or optical technological domain are needed to package opto-electronics, which is one reason why it is such a challenging problem with few easy solutions. Example technologies that attempt to solve this problem are the silicon V-groove technology discussed by Armiento, and the related lithographically defined groove technology discussed by Leonberger.

Packaging of two-dimensional arrays of optical devices is not yet near to a low cost manufacturable solution. Relatively robust laboratory demonstrations systems involving as many as 65,000 beams have however been constructed and have been successfully operated over periods of weeks. Although construction and alignment of such systems is not trivial, because of the regular form of the arrays it is not a very much more difficult problem to align an entire array than it is to align a single fiber or beam. Hence arrays, both in one dimension and in two dimensions, offer significant prospect of reducing cost per connection.

RECOMMENDATIONS FOR DARPA

Optical Arrays

- Continued support for optical array device technologies, with emphasis on functional smart arrays of quality good enough for systems experiments.
- A program to stimulate the development of laser power sources for high performance array systems. This is one key component that, while requiring no new physical breakthrough, does need technological stimulus now.
- A program on systems and applications research with optical array devices. This should be targeted at finding out the architectures and applications for optical arrays by constructing actual systems demonstrators, albeit simple ones. This will also test the devices and show the performance necessary for real applications.

Optical Packaging

- Stimulate research on technologies for passive optical alignment of fibers and optoelectronic components, both for single fibers and arrays. In all research on optical packaging, ultimate cost and manufacturability should be key criteria.
- Drive the packaging technology to give easy integration with mainstream electronics.

WORKSHOP ON

OPTICAL ARRAYS AND PACKAGING

July 17, 1992

Friday, July 17

Introduction to the Workshop, David Miller and Andy Yang

Introductory Overview of Optical Array Technology, David Miller

"Optical Modulators on Silicon ICs", Kris Johnson (Univ. CO)

Discussion

"Quantum Well SEED Arrays", Ted Woodward (AT&T Bell Labs., Holmdel)

Discussion

"Integrated Surface Emitting Laser Arrays for Optical Logic", Julian Cheng, (Univ. New Mexico)

Discussion

"Hybrid Integration of Opto-electronic Arrays with Electronics", Nan Marie Jokerst (Georgia Inst. of Tech.)

General Discussion

"Optics and Optomechanics for Free Space Optical Systems", Rick McCormick (AT&T Bell Labs., Naperville)

Discussion

"Optical Packaging Requirements for Guided Wave Systems", Fred Leonberger (United Technologies Photonics)

"Optoelectronic-Fiber Packaging Technology", Craig Armiento, GTE Labs.)

Discussion

General Discussion

ATTENDEES

OPTICAL ARRAYS AND PACKAGING

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OPTICAL ARRAYS AND PACKAGING

The Problem:

Optical Arrays - What is the status of technologies for making two-dimensional arrays of "smart Pixels" - devices with optical inputs and outputs and smart processing?

Optical Packaging - Packaging often dominates cost and reliability in optoelectronic modules, expecially those using optical fibers. What are the key technologies and research areas?

DoD Relevance:

Optical arrays suit highly parallel or highly interconnected processors, as in

neural processors
signal processing (convolutions and correlations)
image processing and recognition
artificial vision
array sensor processing

Optical packaging is critical for implementation of optical interconnects inside and between high-performance digital processors, and for any use of fiber optics.

OPTICAL PACKAGING

Packaging for two-dimensional optical arraays

currently prototype state
successful demonstrations of large (e.g., 65,000 beam) modular experimental systems

Packaging of systems with waveguides and optical fibers

involves many technologies
often dominates system cost
alignment of optical and optoelectronic components is very critical (desired < 1 μm) - particularly limiting for single mode systems
packaging often hand-crafted, non-standard
active alignment used for high-performance systems
interconnection of linear arrays of fibers may reduce cost per connection
integration of electronic devices, opto-electronic devices and waveguides (but not fibers) advancing

OPTICAL ARRAYS

"Smart Pixel" technologies

Currently at various stages between research and preproduction

Liquid crystal technology
- Integrates optical inputs and outputs with sophisticated silicon integrated circuits
- Moderate (ms - µm) speeds
- Systems could be arbitrarily "smart"

Quantum well self-electro-optic-effect device (SEED) technology
- High speeds (e.g., 200 MHz circuits now)
- Moderately large arrays (E.g., 128 x 64) of simple devices have been made
- Tested in large system experiments, with as many as 65,000 otpical beams
- Field effect transistors now being incorporated for lower energy operation
  - moderate logical "smartness"
- Surface emitting lasers integrated with transistors
  - currently small arrays of simple circuits
- Hybrid integration by epitaxial lift-off
  - allow integration of many different types of devices and material systems
  - may allow repair during fabrication
  - may be reliable array integration technique

Associated technologies for arrays
- array optics
- novel opto-mechanical engineering
- optical power sources (for modulator systems)

CONCLUSIONS

Optical Arrays

Device technologies
- evolving rapidly
- good enough for systems experiments now
- need continued evolution for real applications

Systems and applications research important now to
- generate specific novel architectures to take advantage of optical arrays
- clarify the performance levels needed
- drive the device technology in most effective directions

Optical Packaging

- Packaging is a major impediment to wide-spread use of fiber optics
- No single key technology for packaging
- Fiber pittailing is a key process
- Packaging technologies for arrays will be important to reduce cost
- Manufacturable passive alignment technique for single mode fiber connection important
- Research on packaging should be strongly coupled to a manufacturing environment
  - have reduced cost as goal
- Packaging should make the system look "electronic to the designer

SUGGESTED DARPA ACTIONS

Optical Arrays

Continued support for smart optical array device technologies.

A program to stimulate the development of central laser power sources.

A program on systems and applications research with optical array devices.

Optical Packaging

Stimulate research on low-cost, manufacturable technologies for passive optical alignment of fibers and optoelectronic components, both for single fibers and arrays.

Drive the packaging technology to give easy integration with mainstream electronics

WORKSHOP ON TERABIT MEMORIES

D. K. Ferry, B. Gilbert, R. Osgood, D. A. B. Miller

OBJECTIVE OF THE WORKSHOP:

To try to understand the trends in the future scaling of memory circuits and systems, and to identify limits to these standard approaches. This memories workshop was held in connection with another workshop on the future of CMOS.

STATEMENT OF DOD RELEVANCE:

The great majority of electronic systems will continue to be implemented with silicon CMOS integrated circuits in the foreseeable future. A variety of new technologies that DARPA is developing will play an important role in advanced performance systems, but these will continue to be interfaced to and work with silicon CMOS in most applications. In understanding system trade-offs, it is necessary to understand how the performance and density of future MOS and magnetic memory systems will evolve over the next decade, and whether there are other possible technologies, such as optical systems.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY:

MOS dynamic memory (DRAM) will continue to evolve over the next decade or so, with chip densities increasing by a factor 4 each three years. It is expected that 4 gigabit (Gb) chips will appear in 2004, although this technology may saturate at a bit density of 1010 bits/cm^2. Magnetic memory density is also continuing to increase, and a 150 gigabyte (GB; 1 byte = 8 bits), 3.5" disc is expected on the same time scale. Current approaches to magnetic memory should achieve terabit/cm^2 (Tb/cm^2) density. Nevertheless, memory access speeds, whether DRAM (10's of nanoseconds) or magnetic (milliseconds), continues to lag further behind processor speed. Consequently, architectures and software are being modified to work around the memory latency problems.

By the year 2000, both semiconductor and magnetic memory will approach densities of 2 billion bits per square centimeter in the actual medium. However, packaged memory density and cost will yield about a one-order of magnitude advantage to the magnetic memory, thus its use in mass memories. Yet, realistic limits may well constrain both of these approaches. In semiconductor memories, cell interconnects and cell architecture (with MOS) may limit the chip density at the 16 Gb level. In magnetic materials, the domain size in thin films may limit the density of bit storage to the order of 1 Tb in a 1" disk package (density 1 Tb/cm^2 on the medium).

Optical memories may have advantages such as a highly parallel access, in which pages of memory are accessed in parallel. Volume holographic storage offers some dense opportunities in the reflection hologram mode, especially when accessed with tunable lasers. However, cross-talk issues between different pages of memory (different individual holograms) may well set limits in storage density to levels below the theoretical limit. As the size of semiconductor storage cells, and logic cells, become smaller, the number of electrons involved also becomes smaller. This suggests that future electronics based upon single-electron transistors will have some opportunity for impact. Also, organic molecules may offer new options in fabrication and in storage media for densities approaching the limit for semiconductor and magnetic media (consideration of these materials at lower storage density is not thought to be competitive).

CONCLUSIONS:

Semiconductor and magnetic memory systems will continue to achieve increased packing densities for at least the next decade. Limits to these technologies appear to lie at densities on the order of 0.01–1.0 Tb/cm^2. Beyond this point, there are a variety of speculative technologies, which offer some promise of continuing the growth of integration density.

SUGGESTIONS FOR ACTION BY DARPA:

DARPA has already begun a program, which contains efforts in ultradense, ultrafast electronic devices. Conclusions of this workshop suggest that this is a proper approach to investigate a number of promising, if speculative, technologies that may provide options to go beyond the expected limit of current semiconductor and magnetic storage technologies. It is highly likely that to reach densities of 1 Tbit/cm^2, especially in semiconductor systems, will require novel approaches. DARPA should pursue the more promising of these novel approaches, but should also pay attention to the needs for advancements in fabrication technology if these approaches are to have any chance of succeeding.

WORKSHOP SUMMARY

The workshop was held on July 20, 1992, with speakers from DSRC as well as from various universities, in order to survey some of the novel approaches to high density memory that are available.

D. K. Ferry (Arizona State University and DSRC) reviewed the scaling progression of VLSI memories and logic, with particular emphasis on DRAM. Each three years brings a new generation of DRAM with a four-fold increase in memory bits. This progression has been relatively continuous since the early 1970's, but there appear to be several problems in the near future (after another decade of growth). One problem is that the cell area has been scaling down faster (3× per generation) than the minimum dimension (the gate length) of the transistor in the cell (1.4× per generation), which means that the cell will be too small to incorporate the transistor soon after the 16 Gb DRAM is achieved. This will require a new device design (vertical transistors?). Similarly, the speed increases in the access time will accentuate the interconnect problem, and available resistivities for metallization will limit these increases. At 16 Gb, continued scaling suggests the bit density in the DRAM will be 6 x 109 bits/cm^2, while the minimum dimension will be 70 nm. At this point, a paradigm shift in DRAM technology should be expected, although several creative approaches could extend the scaling for another generation or so.

B. Gilbert (Mayo Clinic and DSRC) discussed high-speed processors and their impact on memory demand. One aspect finding use today is the concept of parallelism in situations in which the speed can not be increased. In addition, moving seldomly used instructions off-chip has led to the popular RISC architectures. The major problem is memory latency, and considerable effort in compiler design has been expended on alleviating this problem. This means, however, that machine architecture and software are "tuned" to particular memory organizations. Even in massively parallel machines, high-speed, multi-port memory is crucial to achieving performance. The problem is more intense in high-speed cross-bar switches, where very-high speed local memory is required in the switches.

A. Yariv (Caltech and DSRC) discussed the memory applications of reflection holograms, where the memory density could be as high as 1 Tb/cm^3. Here, each "surface" hologram would contribute 108 $bits/cm^2$, and would be one page of memory. These holograms are write-once, read-often memory, with a page (one surface hologram) being read into a semiconductor array and then integrated. Such a memory may be multi-frequency, in which tunable lasers are used. Currently, however, Lithium Niobate is the only material that can be used, and work on new materials is needed. In discussion, it was pointed out that these memories are likely to have a cross-talk problem in which one hologram will cause degradation of data in an adjacent hologram.

K. Likharev (SUNY–Stony Brook) talked about the area of single-electron transistors and single-electron logic. These structures currently work at low temperatures (mK), but advances are being made to raise the temperatures (77 K has already been achieved). The devices work on the correlated transfer of single electrons through very small capacitors, and arrays of these capacitors. Major efforts in single-electron logic are currently underway in his group, in Japan at a variety of laboratories in industry and universities, and in other university groups in the U.S. Problems exist in the control of background charge, lithography of the structures, impedance matching to the outside world, and in software for the design of logic arrays. Nevertheless, the size scale at which these structures begin to be useful (and to have room temperature operation) are expected to be those at which normal DRAM ceases to be usable, so that these may well be the natural step from the normal progression of semiconductor memory to ever increasing density.

M. A. Reed (Yale) discussed the different types of quantum systems. Through the coupling of quantum structures, such as resonant-tunneling diodes, with normal transistor structures, more complicated logical functions are achievable. He gave an example of putting the RTD in the emitter circuit of a heterojunction bipolar transistor to create an exclusive-NOR circuit with one single combined transistor—an effective saving of device numbers and chip area. He pointed out that one needed to find equivalent behavior in Si-based material structures, and that one needed to tune the interaction between size quantization and charge quantization to effectively make quantum device structures. He talked about the limit of processing reliability, in that RTDs cannot be made with uniformity across a wafer [aside: DSRC discussed this in a workshop several years ago, and several examples of more uniform fabrication of RTDs across a wafer were presented at that time, so this problem may be a local one].

G. Whitesides (Harvard and DSRC) discussed self-assembled monolayer organic films. These films can be prepared under ambient conditions and provide very stable films for applications as insulators, resists, and/or charge storage systems. The nature of the chemisorption bond to the semiconductor (or metal) surface seems to actually provide a cleaning behavior at the interface, which desensitizes the process to residual dirt. The films are, in a sense, an example of epitaxial chemistry where the thickness of the film is controlled by the organic chain that is used to create the film. He discussed their sensitivity as a resist, and showed that the damage causing exposure primarily arises from electrons (secondary electrons produced e.g. by incoming X-rays). These films can be especially fruitful for STM lithography due to the controlled thinness of the films.

D. Lambeth (Carnegie-Mellon) discussed magnetic memories. Current levels of integration and density are indicated by the presence of 1 GB magnetic Winchester drives in 3.5" format and available for $2K. Current material is usually Al with a NiCo alloy plated onto the surface. Fly height of the heads is now typically 0.15-0.2 μm. Within the next decade, he expects 150 GB discs to be available in the 3.5" format and 1.5 GB in a 1" format. Ultimate densities are limited by the domain size, which in today's super-paramagnetic limit are about 6 nm—hence about 10^{12} bits/cm^2. New thin film materials prepared from $SmCo_5$, or Co itself, may enhance these levels somewhat, although these advances will lead to head fly heights of only 25 nm. Magneto-optical storage is finding increasing usage, but bit densities are expected to be limited to levels below those of the magnetic memories.

Summary

MOS dynamic memory (DRAM) will continue to evolve over the next decade or so, with chip densities increasing by a factor 4 each three years. It is expected that 4 Gb chips will appear in 2004, although this technology may saturate at a bit density of 10^{10} bits/cm^2. Magnetic memory density is also continuing to increase, and a 150 GB, 3.5" disc is expected on the same time scale. Current approaches to magnetic memory should achieve Tbit/cm2 density. Nevertheless, memory access speeds, whether DRAM (10's of nanoseconds) or magnetic (milliseconds), continues to lag further behind processor speed. Consequently, architectures and software are being modified to work around the memory latency problems.

By the year 2000, both semiconductor and magnetic memory will approach densities of 2 billion bits per square centimeter in the actual medium. However, packaged memory density and cost will yield about a one-order of magnitude advantage to the magnetic memory, thus its use in mass memories. Yet, realistic limits may well constrain both of these approaches to densities below 1 Tb/cm^2. In semiconductor memories, cell interconnects and cell architecture (with MOS) may limit the chip density at the 16 Gb level. In magnetic materials, the domain size in thin films may limit the density of bit storage to the order of 1 Tb in a 1" disk package (density 1 Tb/cm^2 on the medium).

Optical memories may have advantages such as a highly parallel access, in which pages of memory are accessed in parallel. Volume holographic storage offers some dense opportunities in the reflection hologram mode, especially when accessed with tunable lasers. However, cross-talk issues between different pages of memory (different individual holograms) are currently theoretically unclear, and the usable storage capacity may well be below the theoretical limit. As the size of semiconductor storage cells, and logic cells, become smaller, the number of electrons involved also becomes smaller. This suggests that future electronics based upon single-electron transistors will have some opportunity for impact. Also, organic molecules may offer new options in fabrication and in storage media for densities approaching the limit for semiconductor and magnetic media (consideration of these materials at lower storage density is not thought to be competitive).

AGENDA

WORKSHOP ON TERABIT MEMORIES

July 20, 1992

Monday, July 20

Opening Remarks, Jane Alexander, DARPA

Scaling of ULSI and Constraints on New Structures, Dave Ferry, DSRC & Arizona State

Requirements on Very High Speed Memories, Barry Gilbert, DSRC & Mayo Foundation

Prospects for Dense Optical Memories, Amnon Yariv, DSRC & CalTech

Single-Electron Digital Devices, Kostya Likharev, SUNY Stoney Brook

Limitations of Quantum Devices and Circuits, Mark Reed, Yale

Is There a Role for Organics in Terabit Memories, G. Whitesides, DSRC & Harvard

The Future for Magnetic Memories, David Lambeth, Carnegie-Mellon

ATTENDEES

WORKSHOP ON TERABIT MEMORIES

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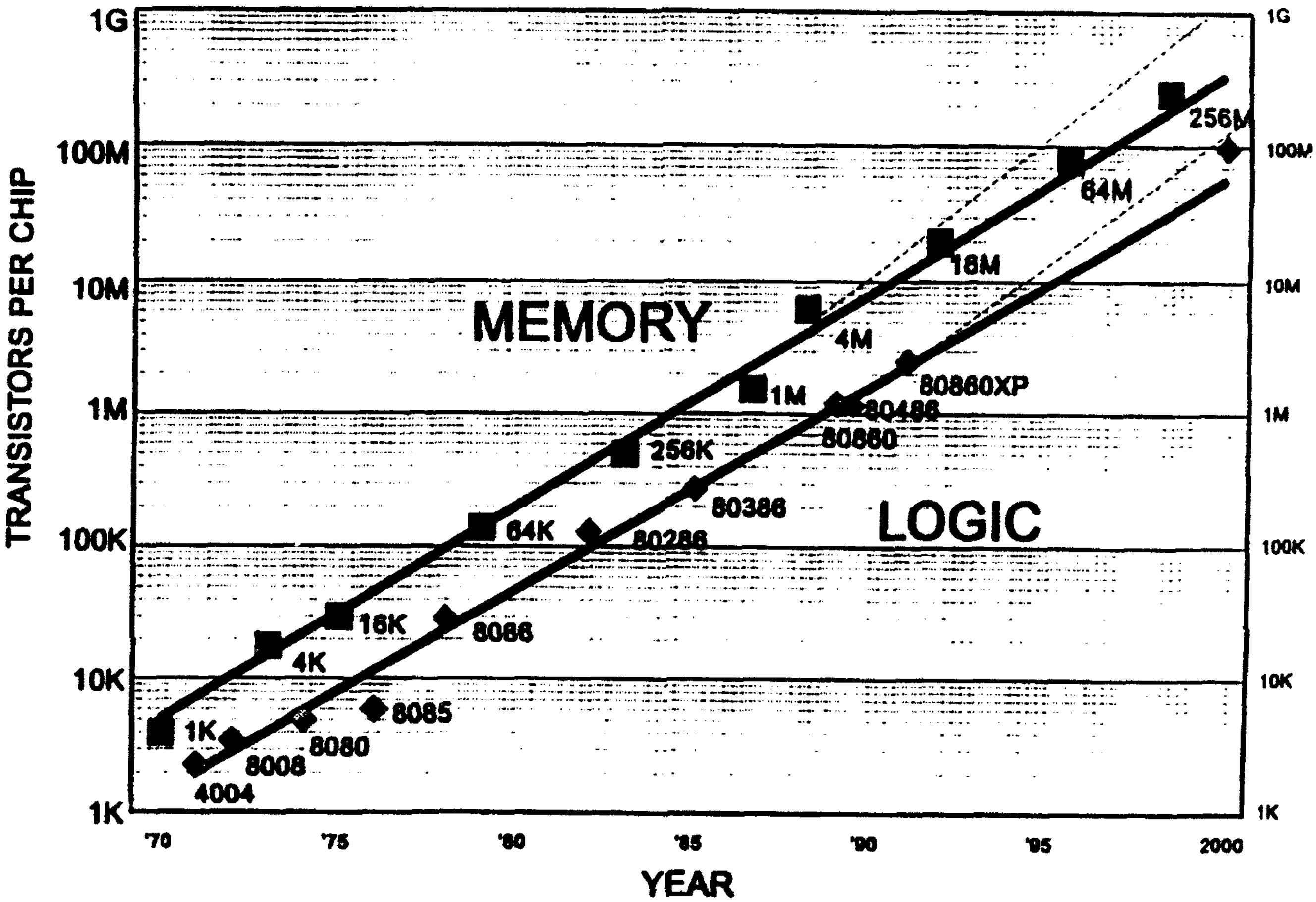
WORKSHOP ON TERABIT MEMORIES

DSRC: D. K. Ferry, B. Gilbert, R. Osgood, D. A. B. Miller

Objectives:	• **Assay future of "standard" memory approaches** • **Look at options for future technologies**

DoD Relevance:	• **Nearly all microelectronics is CMOS or is interfaced to CMOS** • **It is necessary to know the options available to the system designer of future systems.** • **Dominance in advanced microelectronics is needed to maintain force multiplier.**

GROWING NUMBER OF TRANSISTORS



Scaling

- 4× increase in DRAM density every 3 years
- 10× increase in performance every 6-7 years

ULSI > 10^7 devices on a single chip

Factors

- 3× reduction in cell is driver

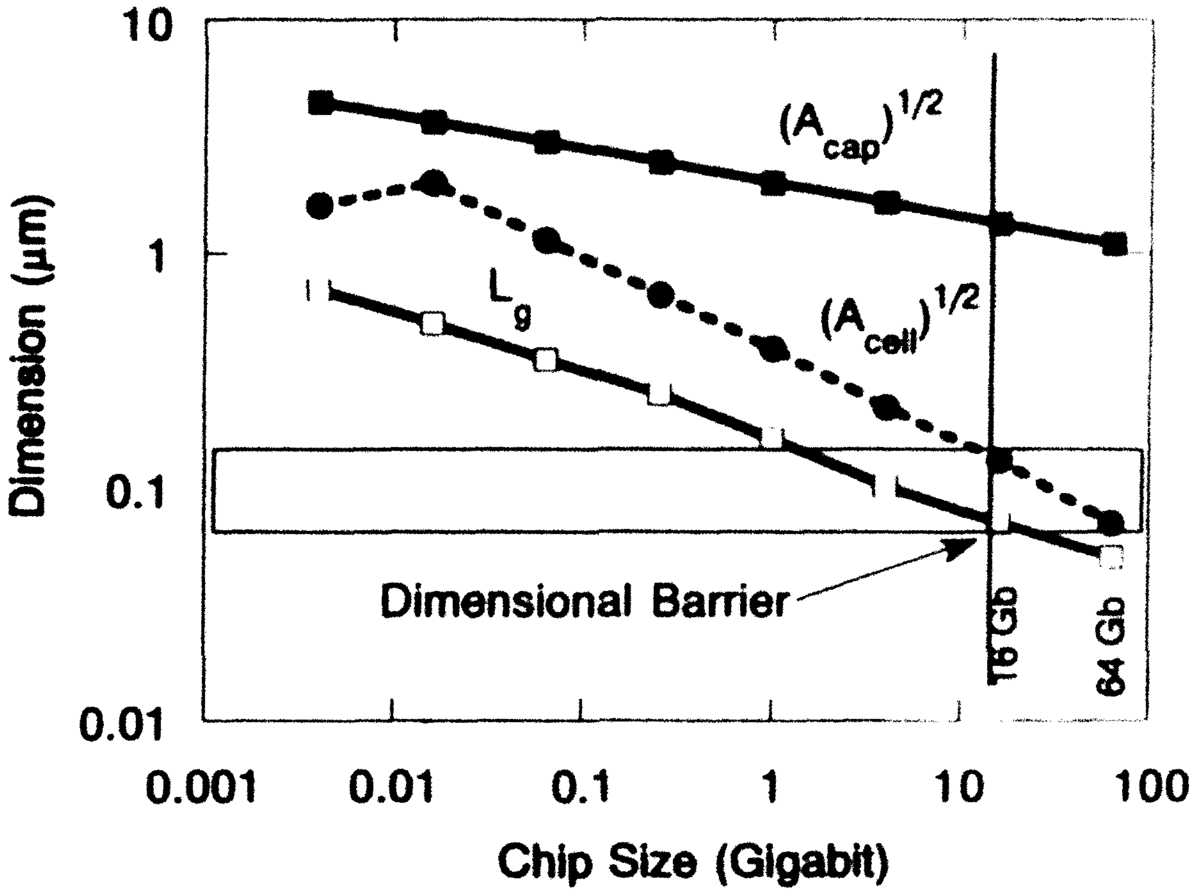
  40% increase in chip size per generation

  1.4× reduction in feature size

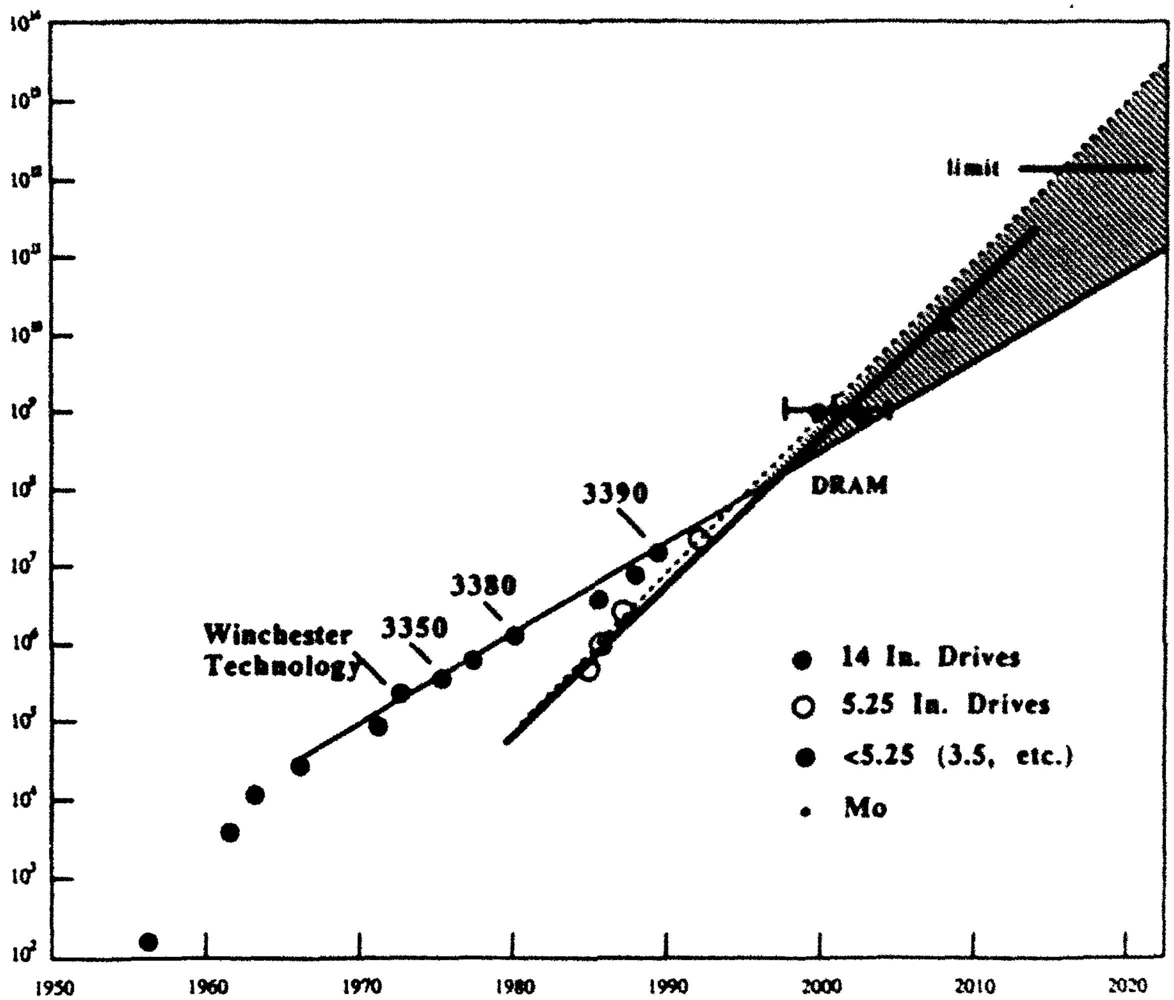
- ε/d has 1.5× reduction per generation

	Design Rule	Cell Area	Capacitor Area
64 MB	0.35	1.3	8.9
256 MB	0.24	0.43	6.0
1 GB	0.16	0.15	4.0
4 GB	0.1	0.05	1.7
	μm	μm^2	μm^2

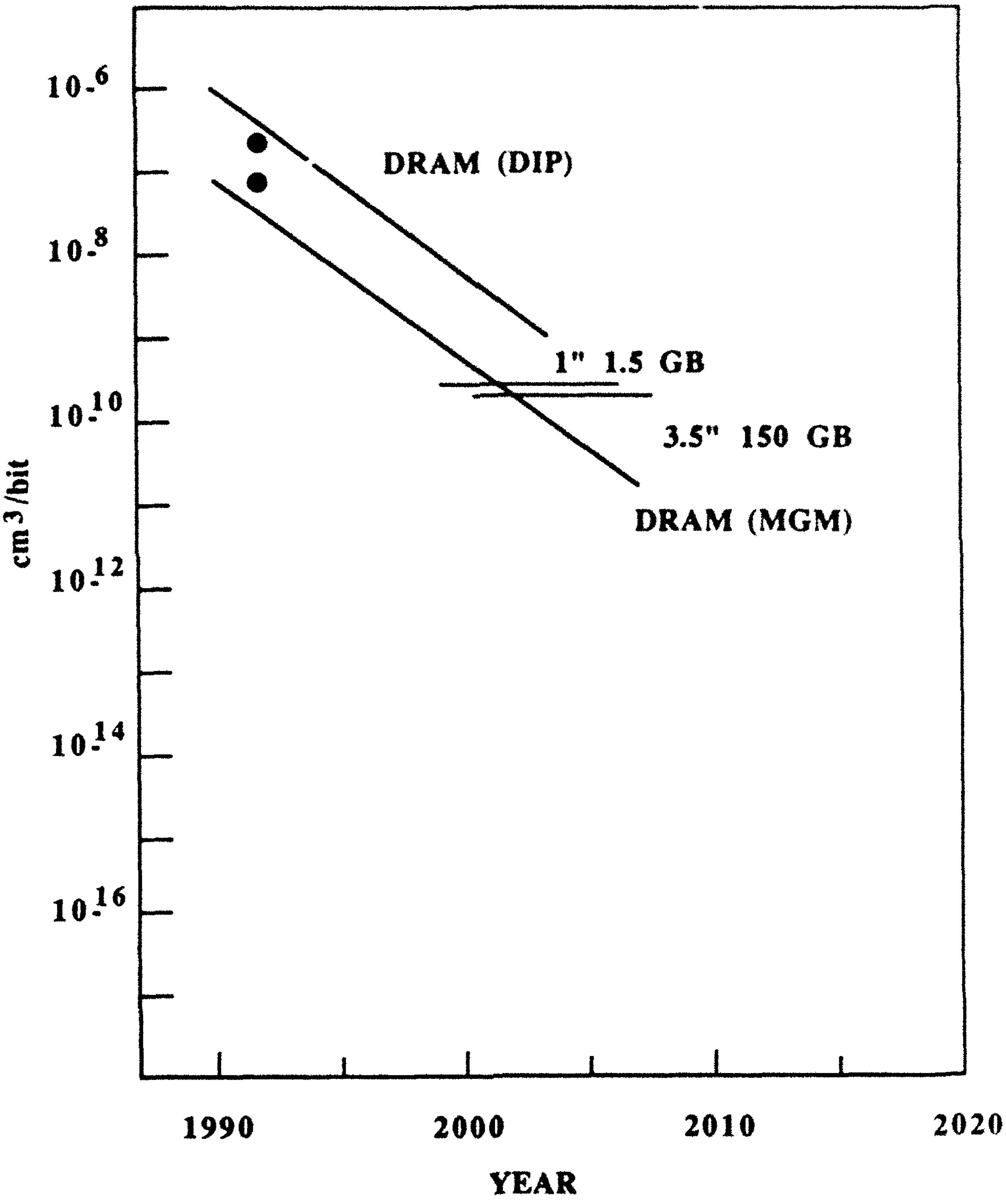
CHIP SIZE (Gigabit)



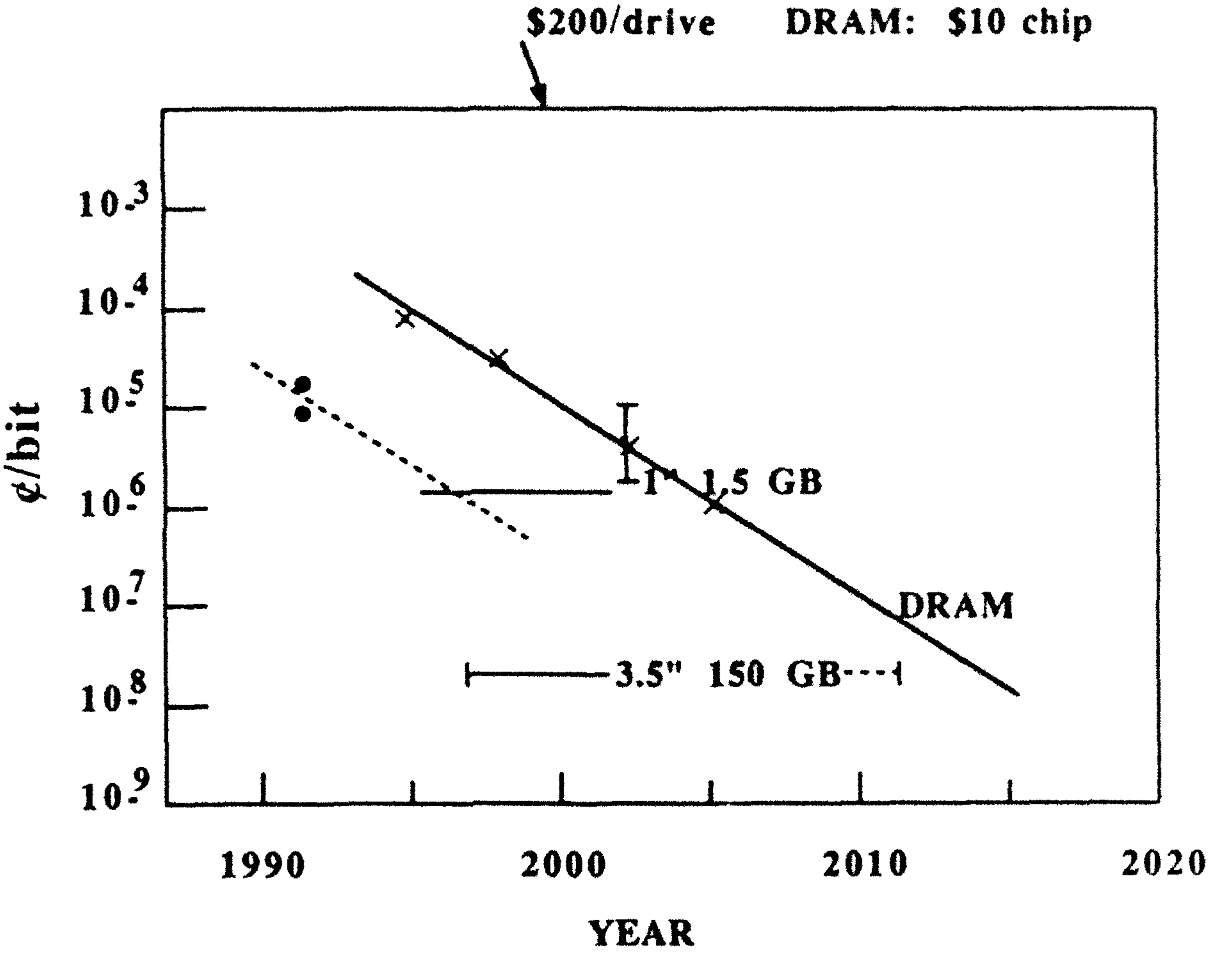
MAGNETIC DISK STORAGE DENSITY



PROGRESS IN BIT VOLUME



MEMORY COST


$200/drive
DRAM: $10 chip
¢/bit
10-3
10-4
10-5
10-6
10-7
10-8
10-9
1" 1.5 GB
DRAM
3.5" 150 GB
1990
2000
2010
2020
YEAR

SUMMARY

- CMOS DRAM scaling will continue until about 2005 (10^9 - 10^{10} bits/cm^2).

- Magnetic memory will continue to scale for a further decade (10^{12} bits/cm^2).

- Magneto-optical and optical memory not likely to be an option for continuation of density increases.

- New approaches are needed to continue the semi-conductor (high speed) memory growth.

- Advancements in lithography and fabrication science will be required for continued increases of memory density.

RECOMMENDATIONS FOR DARPA

- Maintain a program of research into novel memory approaches for the post-CMOS era.

- Coordinate with general CMOS processor work for advances in integration density and logic circuitry.

- Support scientific base necessary for the above research (e.g., architectures of memory/logic, lithography and fabrication technologies/sciences, etc.)

THREE-DIMENSIONAL PATTERNING AND PROCESSING

J. Economy and C. Evans

OBJECTIVES

This workshop was organized to assess the state of the art on three-dimensional patterning and processing of non-planar substrates to which appropriate arrays such as miniaturized actuators, sensors, could be interconnected. Two specific approaches were examined in some detail; namely, direct write on curved surfaces and use of flexible substrates which can conform to non-planar surfaces.

STATEMENT OF DOD RELEVANCE

Information gathering, processing and display increases the the potential for lethality and survivability of the active, forward-deployed military personnel. Light, mobile, low-profile and low power-consumptive electronics and sensors will be required to deliver the personal communication/computation of future systems. The development and affordability of miniature sensors, conformal electronics and microelectronics in vehicle/clothing will all be lead by advances in 1) the fabrication ***of*** three-dimensional structures and, 2) the fabrication ***on*** three-dimensional structures.

SCIENTIFIC AND TECHNOLOGICAL SUMMARY

Traditional use of VLSI technology has concentrated on essentially 2D planar structures with little prominence in the third, z-dimension. For interconnecting and packaging, of conformal electronics and micro-electro-mechanical systems (MEMS), fabricated structures will have increasingly prominent non-planar geometries. These structures are truly three dimensional. Questions that were discussed included fabrication of 3D structures based on development of new technologies (cylindrical lithography, direct-write on non-planar structures), as well as the potential for extensions of traditional, planar lithographic techniques. For example, if we want to put interconnects on non-planar, 3D structures, will it be adequate to write-on final structures or to fabricate on planar, flexible surfaces and then wrap around the arbitrary 3D structures? Alternatively, one could consider developing "stacking technologies" for planar structures to get into the third dimension; e.g., silicon-silicon bonding, multilayer polyimide metal circuitry. . .

A somewhat different and tangential question concerned the effect of miniaturization on material properties, particularly with respect to submicron actuators. Some very preliminary data suggested sharp improvement in mechanical properties at very small dimensions; however, no data was presented to interpret such properties in terms of structural and morphological features. Also, the potential for unexpected self-lubricating surfaces in those specific cases where submicron parts rotated freely was proposed but not substantiated.

Another issue of considerable concern involved the possible need for some form of assembly as part of the three-dimensional fabrication process. At present, insufficient information is available to even begin to assess this specific area.

Several materials opportunities were highlighted, including the potential to greatly improve the current LIGA (Lithographie Galvanoforming Abforming) process which requires 1-1/2 hours of X-ray exposure time in a synchroton to produce satisfactory high aspect ratio profiles. Recent developments in chemically amplified resists could very likely reduce exposure time by two orders of magnitude. Similarly, design of improved photosensitive dielectrics would greatly simplify processing of flexible multi-layered packages.

CONCLUSIONS

Based on this workshop, it is abundantly clear that there are insufficient data to decide on a preferred approach to 3D patterning and processing of conformal systems. In addition, there appear to be a number of related materials questions that require further work. Finally, the need for some kind of automated assembly of miniaturized arrays as part of the the 3D processing was unclear.

SUGGESTIONS FOR DARPA ACTION

1. Various approaches to direct-write interconnect technology should be evaluated and prioritized in terms of their versatility in writing on complex contours and extendibility to finer metal lines.

2. Wrap-around flexible packaging should be explored, particularly with respect to extendibility to fine line multilevel circuitry, robustness and stability to corrosive environments.

3. Mechanical properties of materials at submicron dimensions is poorly understood and requires a more systematic study to optimize variables such as grain size with respect to mechanical properties. In the specific case where miniaturized moving parts are required potential for novel mechanisms of wear and self-lubrication should be studied.

4. Techniques for automated assembly of arrays of MEMS onto appropriate substrates should be pursued in order to achieve cost effective manufacture. Manufacturing processes must be designed for a high level of reproducibility. Simple techniques for mounting these conformal structures into helmets, clothing, etc., must also be developed.

5. Future research on three-dimensional patterning and processing of micro-electro-mechanical systems requires a working knowledge that spans a number of distinct disciplines. It would be helpful if that curricula could be organized that would effectively educate students preparing to work in this area.

AGENDA

WORKSHOP ON 3D PATTERNING AND PROCESSING

July 21, 1992

Tuesday, July 21

Overview - Ken Gabriel, NRL/DARPA

Integrated Sensor Network based on MEMS Techniques - Steve Jacobsen, U. of Utah

Ion Printing for Conformal Interconnects - Dennis Matthies, D. Sarnoff Res.

Polymer Dielectrics for Multilayer Packaging - Jeff Labadie, IBM

3D Polymer/Metal Structures Processing & Mfg. Issues - Gayle Lamer, Techtronics

LIGA - Henry Guckel, U. of Wisconsin

Discussion

ATTENDEES

WORKSHOP ON 3D PATTERNING AND PROCESSING

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THREE-DIMENSIONAL PATTERNING AND PROCESSING

J. Economy and C. Evans

Statement of Problem

Assess state-of-the-art on 3D patterning and processing of non-planar substrates for arrays of miniaturized sensors, actuators...

DoD Relevance

Critical need exists for miniaturized systems (in helmets, clothing) which permit information gathering, processing and display for forward deployed military personnel

KEY ISSUES

- Alternative processes for 3D patterning
- Effect of submicron dimensions on properties
- Potential for automated assembly
- Need for materials innovations

SUGGESTED DARPA ACTIONS

- Evaluate various approaches to direct write on complex surfaces - emphasis on versatility, extendability
- Evaluate flexible packaging with emphasis on fine-line multilevel circuitry, robustness, corrosion resistance
- Characterize mechanical behavior of miniaturized components - submicron structures
- Encourage work in the area of automated assembly of miniaturized arrays onto appropriate substrates
- Encourage curricular development in this general area

OPTICAL INTERCONNECT TECHNOLOGY

A. Yariv, J. Murphy, R. Osgood, D. Ferry

INTRODUCTION

A workshop on Optical Interconnects (OI's) was held on July 22, 1992. The participants drawn mostly from industry are listed in the meeting agenda which forms part of this report. The objectives of the session were to evaluate the present and potential role of optical interconnect technology in computer systems, to determine the optical technologies which are likely to play a role, and to determine what action is necessary to insure the timely availability of these technologies.

The meeting also covered, to a lesser extent, the related issues of radar signal distribution by optical techniques (phased array radar) and, as an example of successful fast growing application of laser interconnect technology, the area of mass distribution of data and video services. The relevance to DoD of efficient high data rate communication within computer systems is obvious and will not be belabored here.

SCIENTIFIC SUMMARY

The conventional electronic interconnect technology becomes progressively problematic as the data rate and/or the communication distance increases. This is due to increasing cross talk (which is proportional to the square of the data rate), the increase in skin effect ohmic losses with the increase in data rate, and the need to drive the larger capacitance associated with long transmission lines.

The power needed to drive an optical link is independent of the path length and, to some extent, of the data rate. This is due to the fact that once launched into a fiber, the optical losses are measured in fractions of db/km, and the equivalent of a line capacitance does not exist.

It follows that OI techniques can play a role at "long" distances and/or "high" data rate communication. The issue before us was to quantify the "long" and "high" limits and relate them to current and future applications.

The ever shrinking size of electronic gates and the advent of multichip modules has led to an increase in the switching speed of individual chips and in the data rate of communication between chips. The distances over which this communication takes place however have also shrunk to typically < 1 cm. In addition, the trend to place cache memories close to the processor has also resulted in short (l < 10 cm) lengths. The consensus of the meeting was that there is no need in the near to intermediate future (< 7 years) for OI on the chip, between chips or even between between multichip modules (MCM) since the distances involved are < 10 cm and the data rates < 500Mbit/s. The crossover where OI becomes advantageous was taken to be approximately at f > 500 Mbit/s and l > 50 cm. The two main applications of OI are:

(1) Communication with low speed archival memories, such as magnetic discs, and peripheral data transfers (to printers LANs, etc.). Here, multiplexed data structures on single fibers can effectively reduce the number of copper wires running between the two ends (or onto the fan of a network). Hand-shaking and synchronization of data transfer must be addressed.

(2) Data transfer to/from main memory. Here, the bandwidth of the overall bus must be as high as possible and the typical distances are much larger. The immunity from crosstalk will allow greater bundling of fibers into compact cables than is currently possible with copper.

Another message that came across during the meeting was that OI technology had to become cost effective. "Communication in computers should not exceed 10% of the total cost." The consensus about the role of OI in computer networks caused the meeting to switch gear and concentrate on the type of OI technology which will be needed.

As far as the types of optical components needed for OI, the consensus was that the main component identified by the meeting was the monolithic laser array shown in Fig. 1. In this configuration a large number of ultra low threshold lasers, say 32, are driven directly by the logic levels on the data buses. The individual lasers are operated typically at f < 500 Mb/s and require Ith < 1 ma to turn on. What is needed is a near standard design for these laser modules which includes the optical coupling to fiber pigtails. Needed is an integrated optical receiver for recovering the data stream on the receiver side. These components should be highly standardized so as to be manufacturable at low cost and serve a large and diverse group number of customers.

A second approach which might play a role in OI is that of multiplexing the electronic data and then using the interleaved data stream to modulate a single laser. Such a system could operate at intermediate data rates, say 1 < f < 10 Gb/s, where the parallel laser array will constitute an overkill. This approach is demonstrated in Fig 2. It requires electronic multiplexing in the transmitting side and demultiplexing in the receiver. These are highly power hungry and problematic at the data (up to 10 Gb/s) which are envisaged.

Another technology which was considered to be important for OI was that Wavelength Division Multiplexing (WDM) which will enable a large number of users, each with its own wavelength, to share the same optical fiber. What hinders this technology is the fact that at the moment, there is no consensus even about the nature of the basic building blocks.

CONCLUSIONS

(1) Optical Interconnect Technology will play an important, possibly an indispensable, role in future computer systems.

(2) The OI role is seen limited to "box" to "box" communication and will not be applied to chip to chip or even MCM to MCM communication. Typical distances and data rates for OI is l > 50 cm, f > 200 Mb/s. Typical applications are :

communication with peripherals and main memory and between computer systems.

(3) The lack of inexpensive high frequency 1 GHz $< f <$ 15 GHz semiconductor lasers is slowing the wide scale application of microwave application of OI technology. One main example of an application crying out for such a development is that of phased array radars. (Fig. 3)

(4) There is a need to develop a generic wavelength multiplexing technology for combining many optical fibers and for stripping ("dropping") them selectively.

SUGGESTIONS FOR DARPA

(1) There is an obvious need for a generic low cost monolithic laser array system for OI. The DARPA sponsored OETC program involving GE, ATT (and others) is directed toward this end. It is recommended that the program be re-evaluated to determine if it is supported at a level which is commensurate with its importance and that it addresses the issues of generic technology and low cost manufacturability sufficiently.

(2) There is a need for a generic low cost serial, single laser, OI product. DARPA should launch a project to develop such a product including the MUX and DEMUX modules. Typical data rates are 1 Gb/s $< f <$ 5 Gb/s.

(3) Need to develop generic microwave laser arrays for phased array lasers for frequencies $\leq$ 15 GHz.

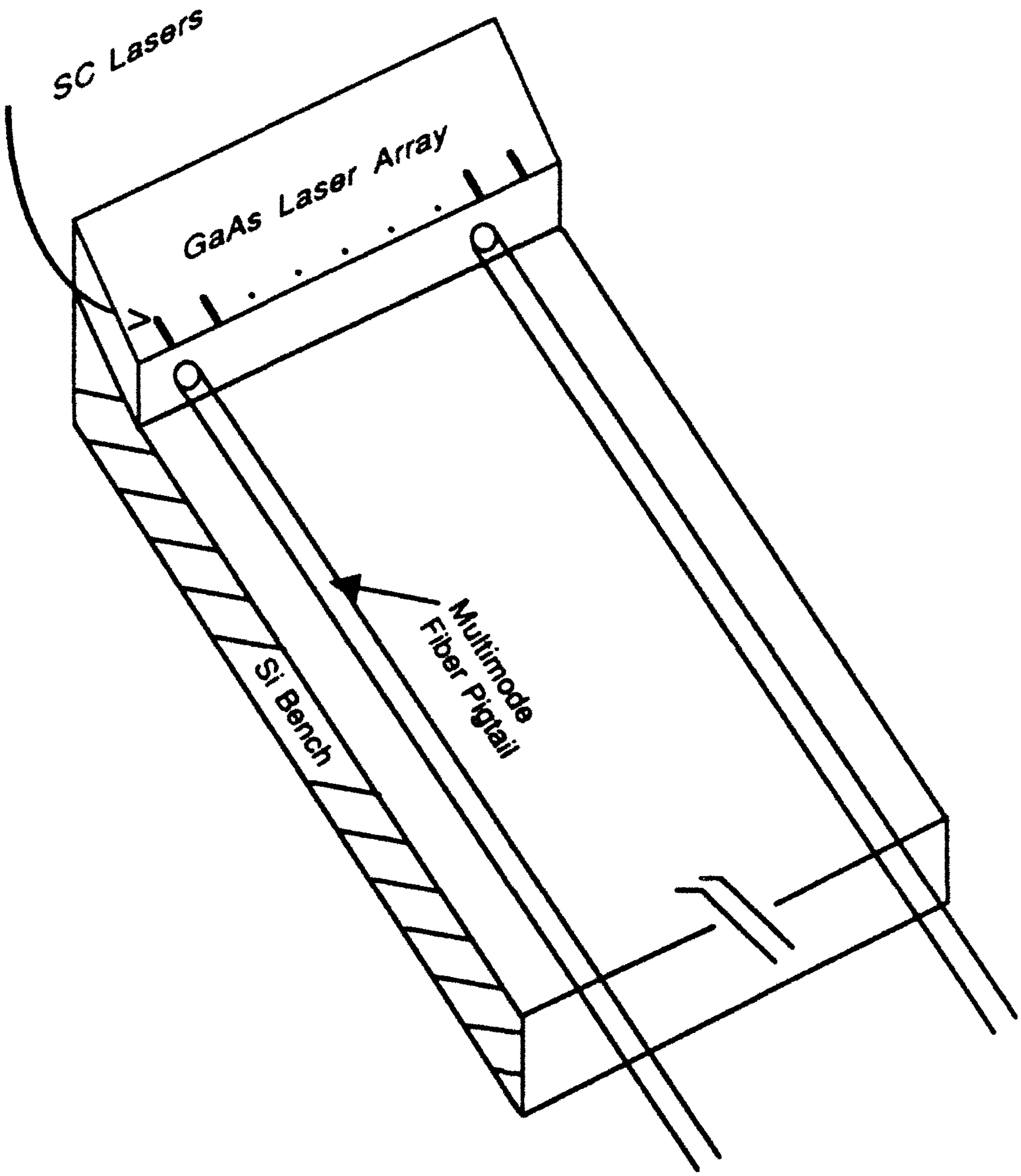

Figure 1. Monolithic SC Laser Array

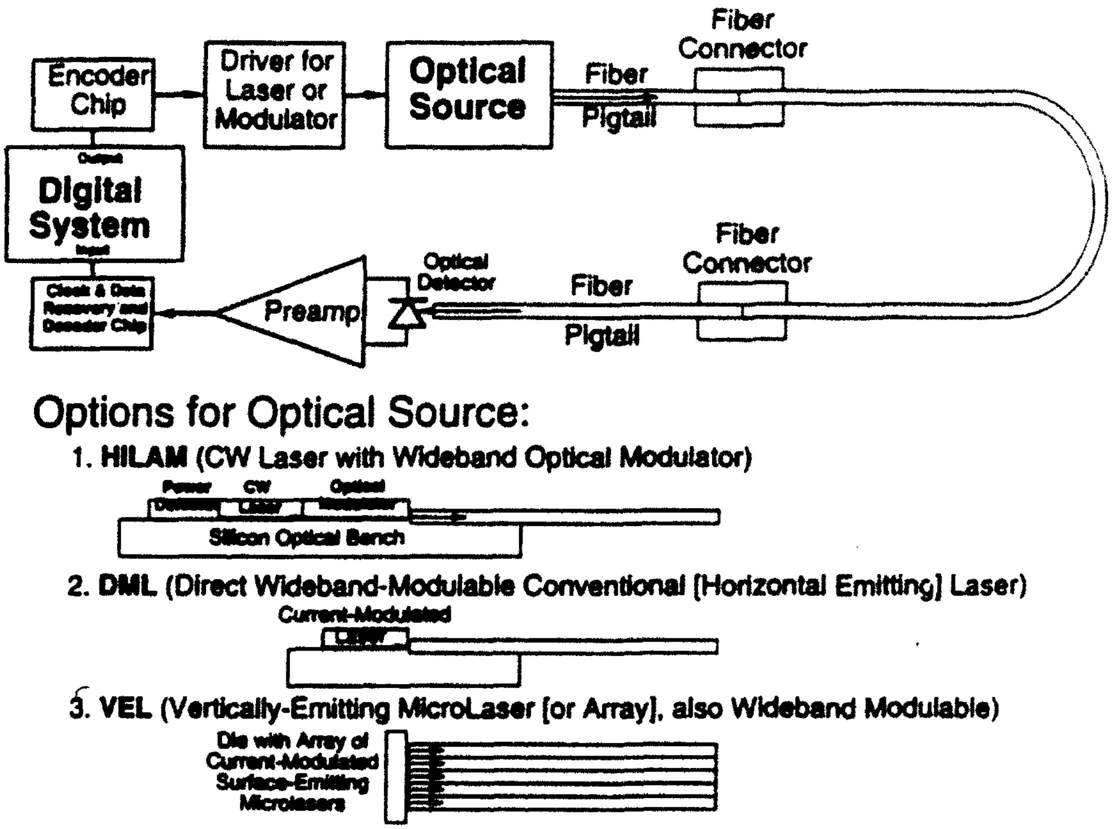

Figure 2. Typical Digital Optical Interconnect Link Elements

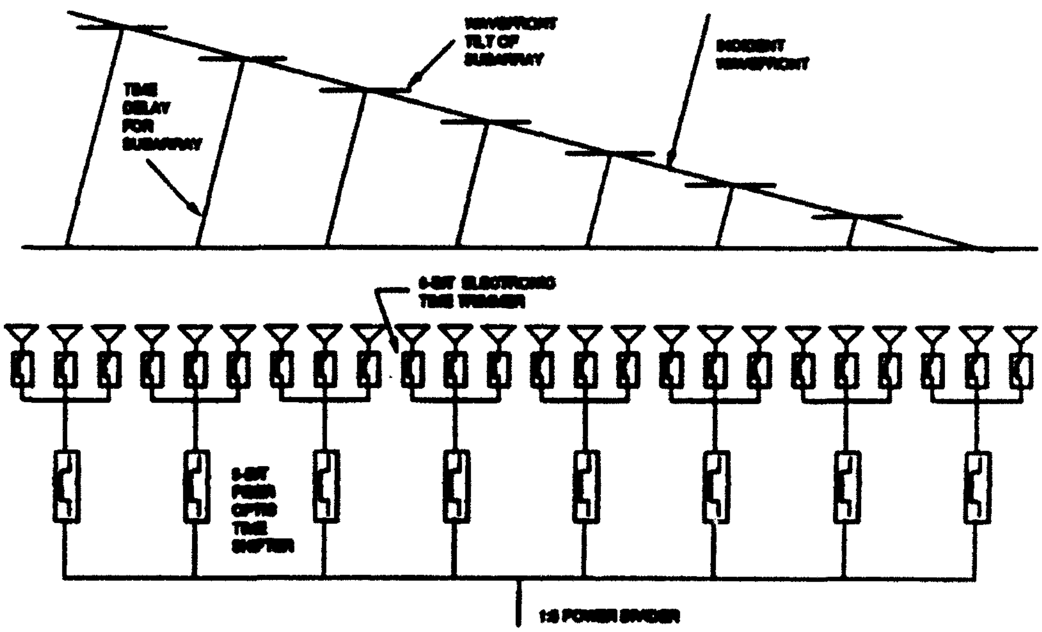

Figure 3. Sub-array Time Shift Network

AGENDA

OPTICAL INTERCONNECT TECHNOLOGY

July 22, 1992

Wednesday, July 22

Opening Comments - J. Murphy, A. Yariv

Phil Anthony, AT&T Bell Labs, "Photonic Connection of Electronic Processing"

R. Lasky, IBM, "Optoelectronic Packaging Needs for Data Communication"

C. Harder, IBM/Zurich, "The Merit of Optical Interconnect in the Case of Latency, Power and Bandwidth Limit"

S. Kasturia, AT&T Bell Labs, "Optical Interconnection in Switching Systems"

H. Yen, Hughes Research, "Distribution of Microwave Radar Signals by Fiber Networks"

H. Blauvelt, ORTEL, "Broadband Coaxial-Fiber Distribution Systems"

H. Davidson, SUN, "Optical Interconnect for Computers"

R. Eden, title to be announced

Summary Session

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OPTICAL INTERCONNECT TECHNOLOGY

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RECOMMENDATIONS

Need to develop generic products for OI, specifically:

(1) Low cost monolithic laser array at 0.85μ and/or 1.3μ, directly modulatable up to f ~ 1Gb/s

(2) Matching detector and receiver array

(3) Low cost, serial high frequency, semiconductor laser with associated MUX/DEMUX electronics

(4) Monolithic laser arrays for microwave (2 < f < 2O GHz) phased array radar applications

(5) Generic wavelength multiplexing and demultiplexing components

CONCLUSIONS

- OI will play a crucial role in computer systems
- Main areas of application will be in "box" to "box" interconnect f > 200 Mb/S, l > 50cm
- There do not exist today laser products aimed at OI
- There does not exist laser technology aimed at microwave OI for radar signals

HEAD-MOUNTED DISPLAY

George M. Whitesides and E. C. Urban

This workshop was organized to help establish a technology road map leading to key components of new head-mounted display systems. "Head-Mounted Displays" in this context refers to systems for the visual presentation of information that can be used by individual, mobile, non-tethered personnel. A representative application for a head-mounted display system would be to goggles (or other display systems) that could be fitted to the helmet of an individual soldier. Sensors in the helmet would track the position of the helmet and the direction in which it was pointing with high accuracy. This information would be relayed in real time to a remote communications center, which would calculate the field of view of the goggles based on other information (satellites, photo-imagery, radar, reconnaissance reports) and then communicate to the soldier information that would help him to interpret the field of view that he was observing. The information could be displayed in a number of ways, but it would, ideally, be correlated spatially with the visual information perceived by the soldier looking directly through the goggles or visor to the helmet. Thus, in this application, the soldier would be aware only of looking through the goggle of his helmet, and of seeing, in real time, visual information that would identify targets and threats.

The system would be related to the head-up displays essential in the operation of aircraft and helicopters, but would have much more stringent requirements in weight, cost, power consumption and ruggedness.

This kind of mobile head-mounted display would have a broad range of applications, ranging from those similar to aircraft applications (e.g., for operators of tanks or other vehicles with ample power, in which weight was of modestly lower concern than for helmets for the individual soldier), through assistant systems for maintenance personnel, to systems for use in training or in virtual reality. The range of applications is sufficiently broad that it is not useful to set firm, general specifications for certain characteristics of these head-mounted display systems: for example, some could operate with wire or optical fiber connections to the supporting computers, and others would have to be entirely untethered; some would require very high data rates, while others could be used with lower data rates for accessing archival or documentary information; some would require high-resolution visual information over a broad visual field, and others could pass information limited to simple icons. All systems would share, however, certain characteristics:

There must be sensors that track position and direction;

The system must be comfortable, easy to use and rugged;

There must be an appropriate display, capable of generating the visual information to be projected on the visor or goggles;

There must be an optical system that conveys this information to the retina of the wearer, in a way that superimposes it on the real-time visual field;

The power requirements of the system must be compatible its intended application (clearly more of an issue for an individual combatant than for a vehicle operator);

The cost of the system must be low, if it is to have widespread application;

The system must take into account the characteristics of the human visual system, and must not induce vertigo or motion sickness, or require extensive habituation to be useful.

Examination of this list of requirements suggested that there were three technologies for which the available base was clearly inadequate for the intended applications, and in which it might be necessary to develop new technology: sensors for tracking and ranging; robust, inexpensive optical systems capable of displaying information in a useful form; technology (or knowledge) necessary to control the psychological aspects of the system (particularly interactions between the visual and the vestibular system of the ear). The workshop focused on these three issues.

SENSORS

Drs. Gobetz (UTC) and Eddy (GM) reviewed the current technology in advanced position sensors. There was general agreement that the rapid advance in the technology of micro-machining structures in silicon provided the basis for new types of micro-sensors having the required small size and (potentially) low cost. These technologies are still sufficiently early in their development cycle that it is difficult to compare them directly in terms of their technical performance, or to choose between them for the applications in head-mounted displays. There are, however, several obvious technical contenders that seem to have the potential to meet the requirements of head-mounted display systems. All share the characteristic of having a (small) mass of silicon (the "proof mass") semi-isolated from the rest of the system (the reference mass) and capable of responding to accelerations by changes in position relative to the reference mass (that is, ultimately, to the helmet). The best method of analyzing this change in relative position is not yet clearly established. The method that is technologically most advanced at present is to use a capacitance-based measurement, since this type of measurement is readily integrated into a microelectronic circuit. Other possibilities involve measurement of strain (using a piezoelectric element or an element in resonant vibration) or one of several optical methods.

An independent but technologically related and important contending technology is to measure the relative positions of the proof mass and the reference mass using a micro-machined electron tunneling element (similar to that used in a scanning tunneling microscope). This technology is being developed in several laboratories, most prominently at JPL, but was not explicitly reviewed in this workshop.

A number of important technical issues were raised by the speakers and in discussions that cannot presently be answered based on current information:

Which of the technologies for sensing the positions of the proof and reference masses are best for which applications? (Current technology for the capacitance-based systems is projected to be able to measure 1 milligravity (1 mg) for a total price, including the package, of approximately $10. This type of device is strongly influenced by the potential for use in the automotive market, for position sensing and intelligent highway applications).

Which technologies are the most rugged? There is a tendency to believe that elaborate vibrating-beam micro-machined structures cannot be rugged, but this belief may be wrong: certainly it is not based on performance tests in a system of this type that has been designed to be rugged. Ruggedness is also a concern in STM-like systems.

Should the sensors for any particular application be designed to have very low drift so they do not need to be recalibrated or updated (by GPS or some other technology) or is periodic updating acceptable? If so, how often and in what manner? For certain applications, high accuracy in measuring accelerations will be important. Is this accuracy best achieved by building more sophisticated devices (especially those operating with positive nulling, so that the position of the proof and reference masses never, in fact, change position), or is it best achieved by using multiple sensors and relying on statistics to improve accuracy?

What type of accuracy, stability, cost, weight, volume and ruggedness are required for the most important or most immediate applications?

How can the cost of packaging be minimized? There was broad agreement that, with development, the cost of the micro-machined sensors alone was likely to be relatively low, but that the cost of the complete package including the sensor or sensors could be much higher. This issue raises the question of the extent to which the microelectronic systems for interpreting the signals from the sensors should be incorporated into the fabrication of the sensor, and to what extent these systems should be fabricated separately.

OPTICAL SYSTEMS

Two speakers discussed approaches to the optical problems posed by the head-mounted display systems: Dr. Ansley (Hughes Training) discussed classical optical solutions; Dr. Veldkamp (Lincoln Laboratory) discussed binary optical solutions. The constrained geometry of the helmet and visor, and the geometry of the eyes, makes the transfer of information from display devices (presumably located on the side of the top of the helmet) to the eye an exceptionally difficult job. The existing systems for accomplishing this task all have deficiencies. It is, however, clear that conventional optical design is capable of producing technically acceptable solutions to the problem. What is not clear is the cost, manufacturability, ruggedness and practicality of these solutions. For example, one plausible solution to the optical problem requires using the inside surface of the goggle or visor as a projection/reflection surface. How probable is it that the inside surface of a goggle used in the field can be kept in acceptable optical condition to be a component of a demanding optical path?

In any event, it is certainly practical, based on the current level of technology in conventional optics, to begin to develop prototype systems for the configuration of various optical systems, to test concepts.

An alternative technology that seems to hold substantial promise in this problem is binary optics. This technology for directing beams, forming complex images in complex focal surfaces and correcting for optical distortions (especially chromatic distortions) is still in its infancy, relative to classical optics. Its attractiveness in the application of head-mounted displays is two-fold: First, although the design of an optical element, and the production of the tools necessary to produce the appropriate optical elements is complex, once these steps are completed these elements are much less expensive to manufacture than lenses and mirrors. Second, since binary optics relies on diffraction for its optical effects, the optical information is usually "distributed" over the element, and is thus much less likely to suffer irreversible degradation of content or performance from localized surface defects (dirt or damage). (We note that the diffraction effects are also claimed to lie at the origin of one of the major defects of binary optical systems: that is, artifacts such as glare, clouding or formation of "ghost" images in the visual field due to the undiffracted primary beam.)

It seems possible that the best system will combine conventional optical and binary optical solutions. The relatively small experience base in binary optics should not be allowed to keep this technology from competing: its low cost and ruggedness may make it the preferred solution for certain vital classes of problems and it seems the most plausible solution for low-cost and rugged systems.

PSYCHOLOGICAL ISSUES

Dr. Daily (Hughes) presented an outline of the visual design issues to be considered in presenting information visually. Professor Howard (York University) discussed engineering issues related to the design of visual systems that are psychologically acceptable and functional to the user. At the heart of the problem in "psychoengineering" is understanding the interaction between the visual and vestibular systems. These two systems are linked by reflex: Motion in the head is sensed by the balance organs in the ear, and used to redirect the eyes, on the assumption that the object being observed is not moving in concert with the head. If this assumption is incorrect, a number of undesirable consequences--from motion sickness and headache to disorientation and phantom sensations of motion--can result. Understanding and controlling these interactions depends, in part, on understanding the engineering aspects of these systems: How rapidly do the eyes scan? What types of motion can they accommodate? What are the motions to which the vestibular system is sensitive, and how is information that is perceived by the vestibular system coupled to automatic reorientation of the eyes? What are the cues used by the visual system to process information about motion and position?

Although this type of information is central to the design of a variety of display systems, quantitative data are only now beginning to be available. The experimental work required to collect this information is, apparently, not exceptionally difficult, but quantitative experimental psychology is not a large field, and the number of research groups (essentially all in universities) actively working in it is small.

SYSTEMS ENGINEERING: THE COMANCHE

Perhaps the most highly developed head-up display system now in development is that for the Comanche helicopter (LHX). Dr. Hamilton (Sikorski) described the range of considerations necessary to build a successful system (as opposed to a helmet or to a collection of elements). Many of the requirements for the Comanche helmet-mounted display are irrelevant or contrary to those contemplated in the DARPA program, but the systems thinking required to integrate the Comanche helmet into the Comanche helicopter has much of value for the DARPA project.

SUMMARY

Micro-machining in silicon and other materials provides a plausible technological route to low-cost sensors. Packaging these sensors with their accessory electronics is the probable high-cost problem.

There are several optical solutions to the problem posed by the head-mounted display, but none is simultaneously optically optimal, rugged and low-cost. A possible solution may be to combine conventional and binary optical elements.

Psychological issues are vital to the acceptability and usefulness of the systems. The information necessary to develop a head-mounted system can be developed empirically, but would be better developed through a systematic program in basic experimental psychology.

The systems aspects of the problem have not yet been seriously considered, and it would be premature to do so until more information is available about the components. There is, however, a potential treasure of experience in the Comanche project, and the DARPA project would be well-advised to try to keep active contact with this project.

SUGGESTED DARPA ACTION

Examine the range of applications proposed for head-mounted display, and try to identify the most plausible of them as immediate targets. Use these applications to try to set at least tentative specifications against which to evaluate the results from programs designed to produce comparative data for the various early-stage technologies.

Evaluate the possible alternative technologies in micro-machined silicon micro-sensors using these prototype systems, before launching a large-scale development effort in any one. Emphasize packaging, ruggedness and manufacturability in these programs. Include a program that evaluates STM/AFM-based sensors.

Evaluate both conventional and binary optical solution to the problems posed by head-mounted display, with a particular effort to use binary optics to add manufacturability, lower cost and increase ruggedness of the more exposed parts of the optic·l train.

Institute programs to obtain the necessary data to design and engineer appropriate psychological characteristics into the function of the system.

Coordinate/cooperate with the groups developing sensor systems for the automotive applications: these applications will be the ones most likely to develop high-volume, low-cost technology, and are the civilian application most likely to benefit from spin-off from a DARPA program in advanced technology.

Take advantage of the systems engineering expertise in tne Comanche helicopter project.

AGENDA

HELMET MOUNTED DISPLAYS

July 23, 1992

Chairman: George M. Whitesides

Objectives: To provide information useful in constructing a technology roadmap leading to a mobile helmet-mounted display. The foci of the workshop will be: i) tracking and ranging; ii) optics; iii) perceptual/psychological issues.

Thursday, July 23

George Whitesides; Dick Urban: Introduction to the workshop

Frank Gobetz, United Technologies Research Center: "Advanced Technologies: Tracking and Ranging Sensors"

David Eddy, General Motors: "Motion Sensors for Automotive Systems"

Mike Daily, Hughes: "Presentation of Visual Information"

Wilfred Veldkamp, Lincoln Laboratory: "Binary Optics"

David Ansley, Hughes Training, Inc.: "Optical Design Considerations"

Bruce Hamilton, Sikorsky: "Human Factor Considerations in the Development of the Comanche Helmet Mounted Display"

Ian Howard, Dept. of Psychology, York University: "Visual-Vestibular Relationships in Relation to Helmets"

Summary and Discussion

ATTENDANCE

HEAD MOUNTED DISPLAYS

NAME	ADDRESS/AFFILIATION	TELEPHONE
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Ferry, David	ASU/DSRC	602/965-2570
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Glasser, L.	DARPA	703-696-2213
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Keicher, Bill	MIT/Lincoln	617/981-7522
Larrabee, G.	DSRC	214/239-0008
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Miller, David	AT&T/DSRC	908/949-5458
Murphy, J.	DARPA	703/696-2250
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Rapp, R.	Ohio St. Univ/DSRC	614/292-6178
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Whitesides, G.	Harvard/DSRC	617/495-9430

HEAD-MOUNTED DISPLAYS

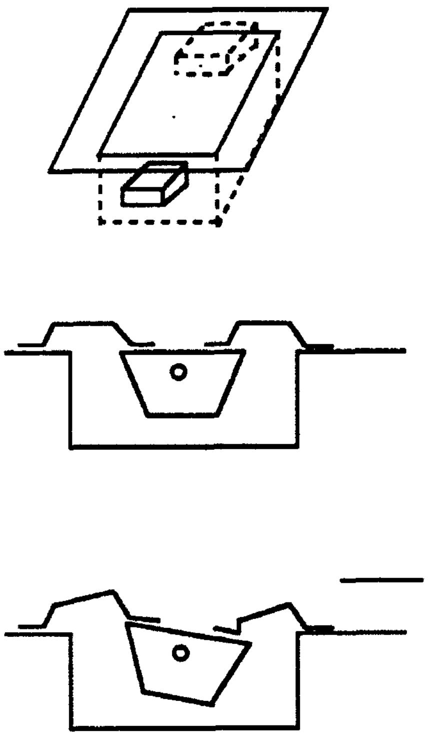
PROGRAM OBJECTIVE: To develop technology for providing high-resolution information in real time to individual, mobile personnel.

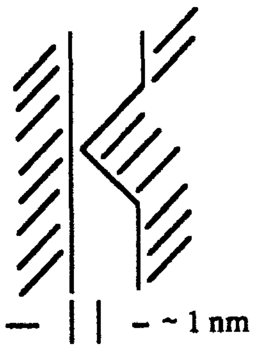
WORKSHOP OBJECTIVE: To develop a technology roadmap in three key areas ranging and tracking systems; optical elements for visual display; control of psychological/visual interactions

(Not discussed: displays; power supplies; remote computation; 3-D sound and other modalities)

Ranging and Tracking

Key technology: Micromachined Silicon





Scanning
Tunneling
Microscope

Capacitative Vibratory
Microbeam

Sensitivity: 1 mg now ($10)
1 μg attainable
1 ng ?

Issues: **Fit to need specifications shock tolerance updating (GPS) or gauging packaging (cost) coupling to automotive**

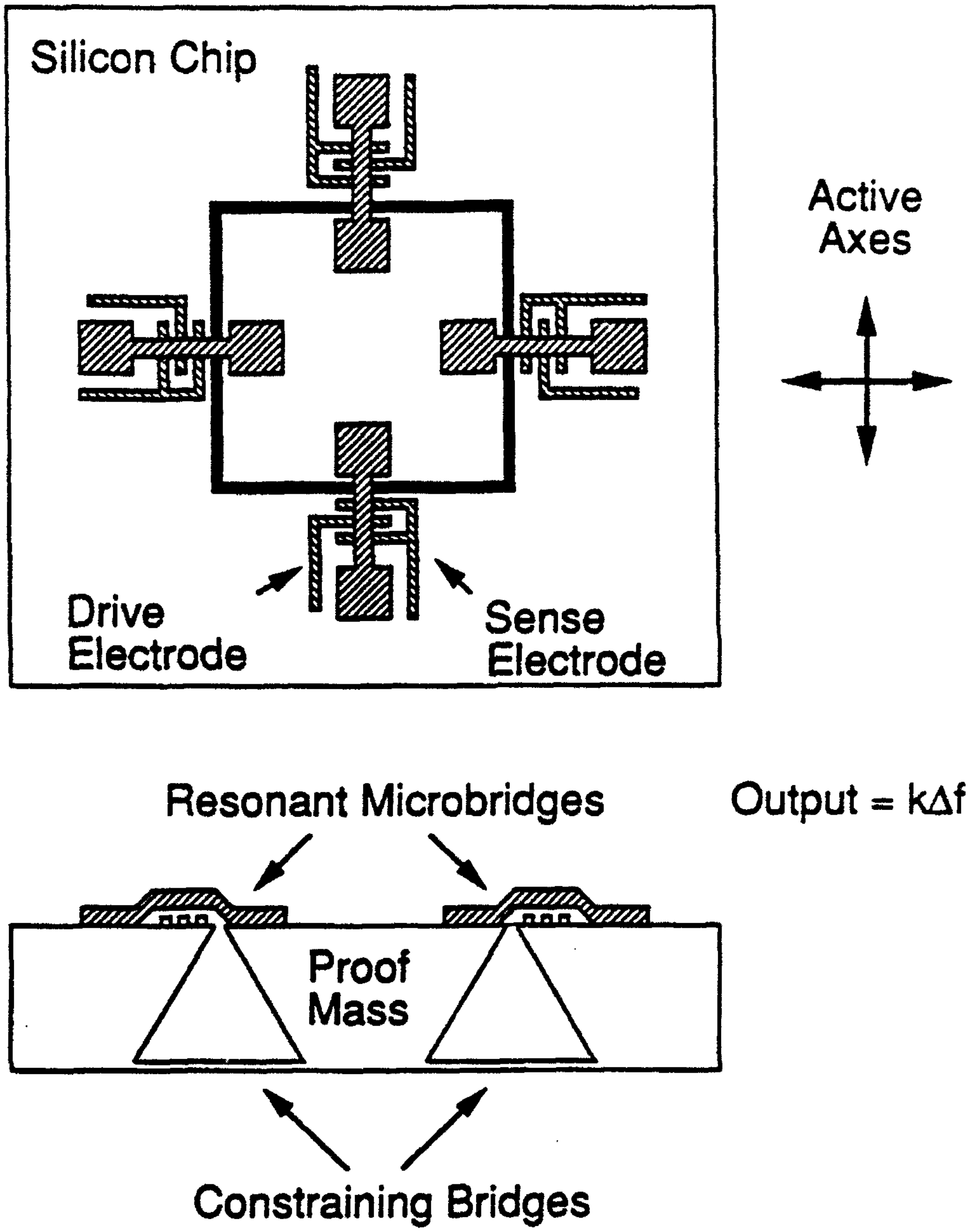
OPTICS

Difficult Optical Problems

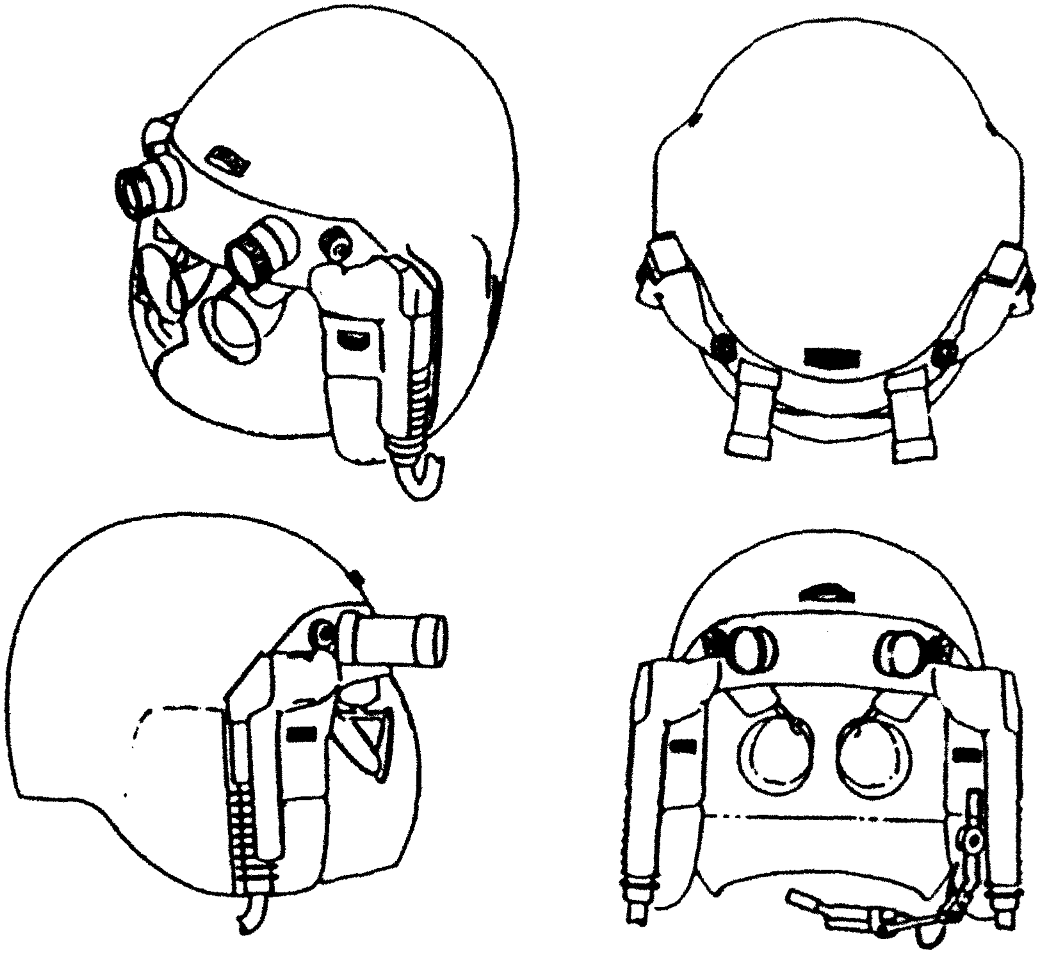
Conventional Optics
Expensive; Difficult to manufacture

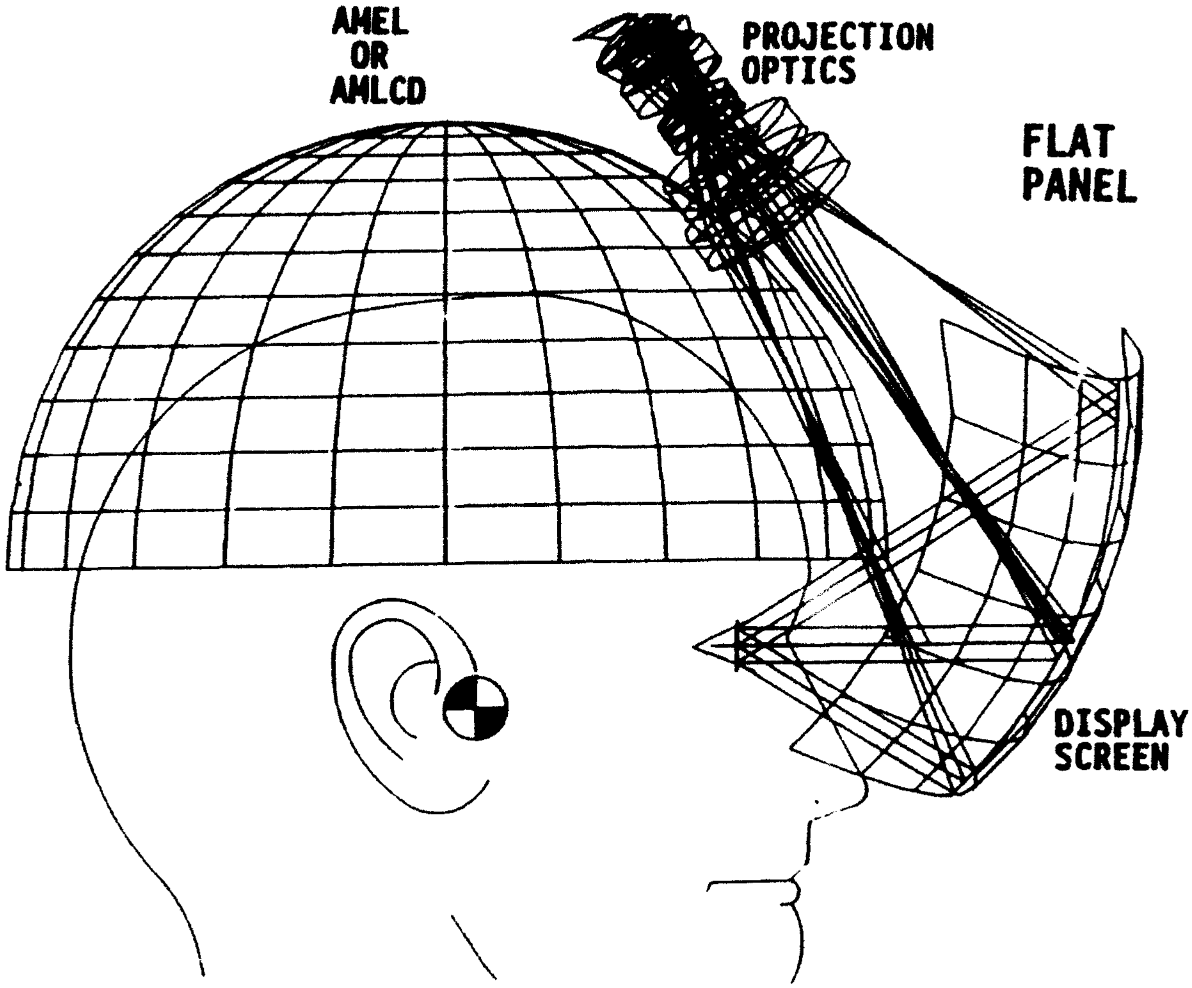
Binary Optics
Diffractive system; glare from primary beam

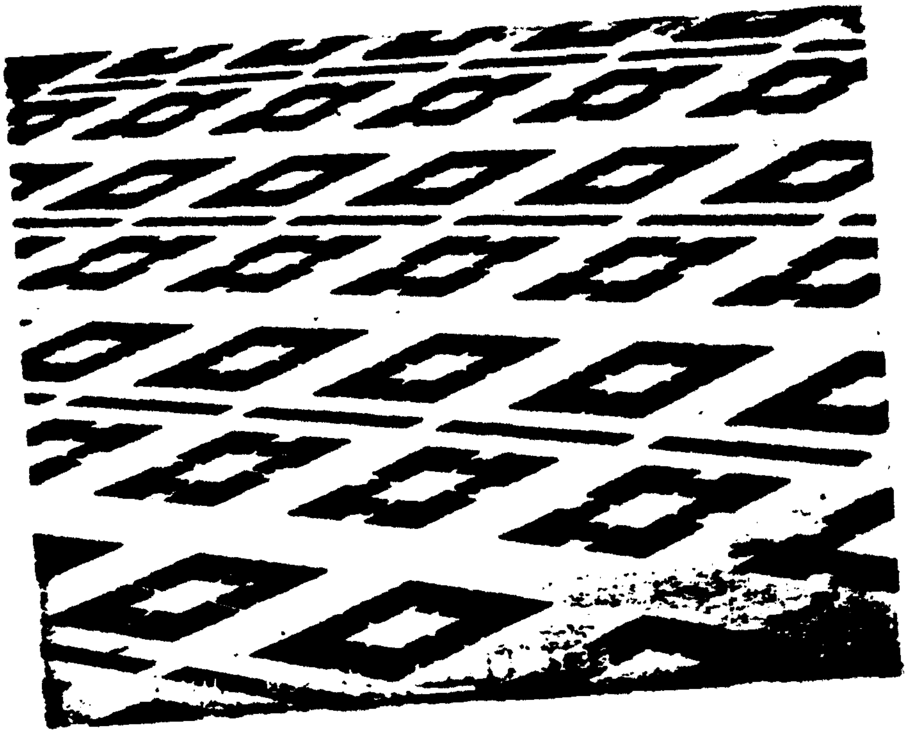
RESONANT BEAM ACCELEROMETER

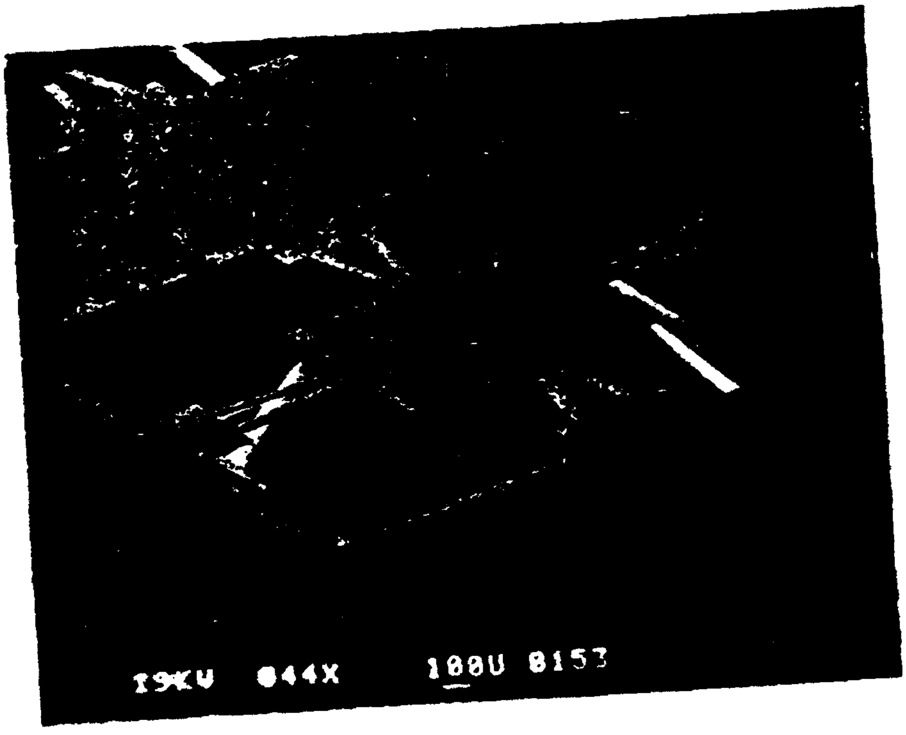


Comanche HMD




AMEL
OR
AMLCD
PROJECTION
OPTICS
FLAT
PANEL
DISPLAY
SCREEN

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SUGGESTED DARPA ACTIONS

- Establish tentative requirements for representative applications
- Evaluate competing technologies in micro-machined silicon (including STM/AFM), emphasizing solutions that include packaging; develop appropriate specific technologies in prototypes
- Evaluate conventional and digital optical solutions to prototype components
- Initiate a program to obtain psychoengineering parameters
- Coordinate/cooperate with automotive developments
- Take advantage of systems engineering experience on Comanche/LHX

TUTORIAL ON PERCEPTION AND COGNITION

G. M. Whitesides

This tutorial was intended to provide an introduction to some of the research being done in the area of cognitive science. This area is one of the most actively growing areas of modern science, and one in which DARPA might wish to develop an active interest. Military systems consist of both machines and men, and tasks such as decision making, instruction and training, communications and many others require the efficient transfer of information to and among individuals, and depend on their ability to assimilate and act on this information. Although the tutorial was intended primarily as an introduction to the field, one of the tutorials--that dealing with visual psychology--outlined a number of subjects directly relevant to concerns in DARPA.

The first participant--Floyd Bloom (Scripps)--outlined the ionic, molecular and cellular systems used in the brain to process and to transfer information at the level of individual synapses and neurons. These systems depend on propagating excitations within the neurons based on ion gradients across cell membranes to convey information over long distances (nm), and on the diffusion of low molecular weight molecules (neuro-transmitters) to convey information over short distances (Angstroms). Biological systems (in clear contrast to current computational model systems based on so-called artificial neural networks (ANNs) rely extensively on feedback as well as feed forward in information processing in the network, and are densely connected in three dimensions. Biological information processing systems and systems based on silicon are remarkably different in their modes of operation. The importance and potential value of these major differences between biological information-processing elements and man-made computational elements as a source of new ideas for algorithms for information processing or for computational architectures for DARPA is not clear. (We note, however, that primitive considerations of the brain led to the development of ANNs; these types of computational systems are becoming increasingly important in non-biological information processing.) The architectures that have developed in the brain have done so at least in part because of the constraints imposed by the necessity for function in a living organism--that is, the system must be obtainable from biological components, and must operate in water at approximately ambient temperature. They may, therefore, have been evolved for reasons having nothing to do with their efficiency in information processing or storage, or with their utility in solving particular classes of problems. Nonetheless, the strategies used by the brain in information processing are deeply interesting both in their own right and as a possible source of new ideas. There is, however, no pressing reason for DARPA to be actively involved in the area of molecular neurobiology at present, and work in it is already adequately funded (primarily by NIH).

The second participant--Dr. Jerry Edelman (Scripps)--discussed views of the higher-level organization of the brain. A central point of this discussion was that the brain is not a "computer" in the sense of having a fixed instruction set and architecture, but rather a system capable of great plasticity in morphology, structure and detailed organization. Since current computers do not, in general, employ these characteristics, the concept of plasticity is a potentially important one to explore as the basis for new types of computer architectures.

Edelman also described work now in progress at Scripps to build simple machines modeling the behavior of small networks of neurons. This project has produced several working models having different levels of complexity, of which the most sophisticated exhibits substantial complexity and the ability to "learn". The results of these programs are relevant to several DARPA programs, including ANNs and autonomous vehicles.

The third participant--Dr. Patrick Cavanagh (Harvard)--discussed the psychology of the visual system. He emphasized that the processing of visual information by the brain is emerging as a remarkable and complex fusion of quasi-independent visual systems: one for black-and-white, one for motion, one for texture, one specialized in detecting angular features, etc. The unitary information that is the result of perception is, in fact, the largely seamless result of fusion of these semi-independent streams of visual information.

Since so much of the current work in DARPA is focused on areas of technology (such as flat-screen display) that involve the interface between man and machine, this area of research seems a gold mine of potentially useful information for use in designing display systems to interact efficiently in transferring computer-generated information to people.

Cavanagh also emphasized the importance of certain complex instrumental/analytical technologies now emerging in cognitive science for further understanding of the function of the brain. Perhaps the one with the greatest potential to change the pace of research is a specialized form of magnetic resonance imagery (MRI) designed to image thin two-dimensional slices through the brain, with an acquisition time per slice of approximately 30 msec. These images give remarkably detailed information about the areas of the brain that are active metabolically, and thus aid in the localization of the physical areas of the brain involved in various information processing tasks in real time. This information promises to provide a wealth of information about the architecture of the brain, and suggesting pathways for coupling the information in different processing channels of the brain. This information could be useful in applied programs such as the design of efficient flat-panel display systems in suggesting ways of coupling different types of information (contrast, color, texture, sound,...) for maximum comprehensibility.

Cavanagh gave a number of examples of unexpected behavior in the visual system. For example, an image presented in red on a green field was uninterpretable, while the same image with the colors reversed was readily recognizable as a face. These counter-intuitive behaviors could either provide the basis for new stratagems for visual display, or could confound existing ones (unless recognized).

The wealth of new science emerging in this area, and the relevance of this science to areas of technology of direct interest to DARPA, suggest that it is timely to carry out a careful survey of the work being done in this area, and of its possible application to DARPA-sponsored projects. A conference/workshop in applications of visual psychology to information transfer using flat-panel displays would be a plausible, specific, low-cost starting point for such an effort.

The area of experimental visual psychology is one which it is particularly appropriate for DARPA to consider work, because:

- It is highly dependent on computation, and on concepts of information processing that have evolved in non-biological systems; these areas are areas of central competence in DARPA.
- It is especially relevant to flat-screen display: it is applicable to improving the efficiency of tasks such as pattern recognition/target recognition/IFF and training.
- The new technologies in the field--MRI, computer modeling of complex systems of "neurons", synthesis and study of autonomous systems and the use of unsupervised learning--rely on instrumentation and techniques familiar to DARPA.
- The field is relatively underfunded in Universities: It gets some support from NIH (but its strongly physical chemical aspects makes it fall outside the central focus of NIH) and NSF does not have a large enough budget to make an impact on the field.
- Participation in the field would position DARPA to take advantage in the research in cognitive science broadly.

AGENDA

TUTORIAL IN PERCEPTION AND COGNITION

July 24, 1992

Chairman: George M. Whitesides

Objectives: To outline current concepts and techniques in cognitive science, for nonspecialists in the field.

Friday, July 24

Check-in and breakfast

George Whitesides; Ira Skurnick: Introduction to the workshop

Floyd Bloom, Scripps: "How Nerve Cells Work Together to Provide Mental Activity

Jerry Edelman, Scripps: "Is It Possible to Build a Perception Machine?"

Patrick Cavanaugh, Dept. of Psychology, Harvard University: "Functional Architecture in Human Vision"

ATTENDANCE

TUTORIAL IN PERCEPTION AND COGNITION

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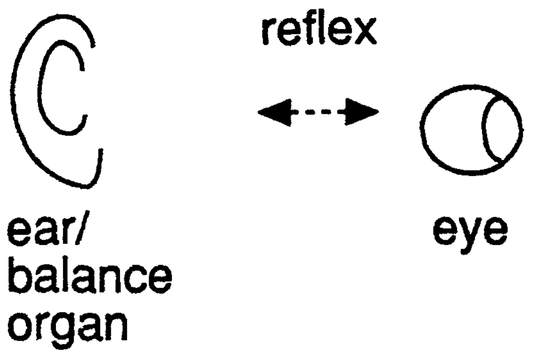
Veldkamp, Wilfrid	MIT/LL	(617)981-7526
Wagner, Abe	SRDC	(310)552-3931
Whitesides, George	Harvard/DSRC	(617)495-9430

Psychodynamics: Visual-Vestibulary Interactions

Bioengineering Database is spotty and Empirical

Immediate Problem



Broad Issue

Efficient, acceptable, robust protocols for presenting

PERCEPTION AND COGNITION: PSYCHOLOGY OF VISION

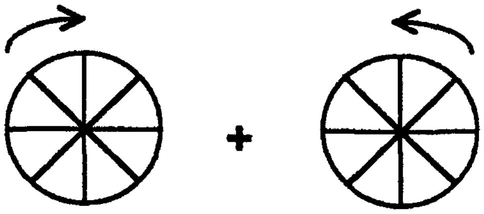
The visual system fuses a number of different "tracks" with different functions, specialization sensitivity, and response time

Presentation of Information

**Efficiency of visual presentation:
color bar > movement > ...**

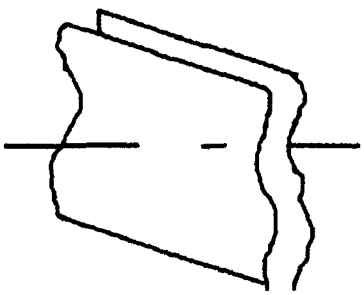
**Psychoengineering data: tracking rates, stability, interactions, edges, color, texture -- sound -- touch
central/peripheral; color/black and white**

**red/green recognizable
green/red unrecognizable**



color **b/w**

b/w dominates



"far" is "stationary"

BENEFITS OF A PROGRAM IN SCIENCE/TECHNOLOGY OF PERCEPTION/COGNITION

- Efficient Transfer of information from machine to man
  More information with less computation
  More rapid assimilation of information; improved decision making

- Data compression and storage; encryption

- New algorithms for pattern/target recognition; IFF

- Improved training methods

WHY DARPA

Maximizes return on DARPA investment in displays, AI/"Assistant" systems; neural nets

Strong computation/information/display component (DARPA competence)

Increasingly heavily dependent on instrumentation (MRI and other brain imaging modalities now make possible real-time imaging of brain activity at the mm scale)

Undersupported in Universities (low-level support from NIH, NSF)

Positions DARPA to take advantage of advances in cognitive/brain science

Ponder technology base for civilian use in communications; education; entertainment; driver alert systems

ON NEUTRAL HOLES IN TAILORED, LAYERED SHEETS

B. Budiansky, J. W. Hutchinson, and A. G. Evans

It has been suggested that multilayered sheets, in which alternating layers have different elastic moduli, might lend themselves to *tailoring* to reduce, or even eliminate, harmful stress concentrations at holes or other stress raisers. Such tailoring could be implemented by making the sheet thickness spatially non-uniform, varying the *number* of layers, but keeping the layering pattern unchanged; or, keeping the total thickness unchanged, by varying the pattern of layer locations and thicknesses; or by a combination of these two approaches. We will call the first method "thickness tailoring", and the second "modulus tailoring". Tailored fabrication of such non-uniform layered sheets seems particularly well suited to masked deposition techniques.

This note provides a preliminary analytical assessment of the theoretical feasibility of designing a tailored, layered sheet that would alleviate the stress concentration induced by a circular hole in a field of balanced biaxial tension (see Fig. 1). If the stress concentration is actually eliminated, the result is a so-called "neutral" hole. It should be emphasized at the outset that reducing the *average* circumferential stress at the boundary of the hole is definitely not necessarily the desired goal. As we shall see, if modulus tailoring with constant overall thickness is exploited, and only the relative volumes of the layer constituents are changed, the stresses within the individual layers can be reduced while the average stress goes up! (This seemingly paradoxical result takes a little getting used to; the reason it's right is that while the stress in the stiffer material drops, there is more of it, so the average rises.) Conversely, a misguided reduction of the average hole-boundary stress by means of modulus tailoring can lead to higher stress concentrations within the layers.

We consider a two-constituent layered sheet, with Young's moduli E_α (α=1,2) in the alternating layers, and for simplicity, we assume the same Poisson's ratio ν in each layer. The effective sheet modulus is $E = f_1E_1 + f_2E_2$, where the f's are volume fractions. At each r, denote the average radial and circumferential stresses by σ_r and σ_θ, and let $\sigma_r^{(\alpha)}$, $\sigma_\theta^{(\alpha)}$ ($\alpha=1,2$) be the stresses in the layers. The stress-strain relations are

$$\varepsilon_r = \frac{\sigma_r^{(\alpha)} - \nu\sigma_\theta^{(\alpha)}}{E_\alpha} = \frac{\sigma_r - \nu\sigma_\theta}{E(r)}$$
$$\varepsilon_\theta = \frac{\sigma_\theta^{(\alpha)} - \nu\sigma_r^{(\alpha)}}{E_\alpha} = \frac{\sigma_\theta - \nu\sigma_r}{E(r)} \tag{1}$$

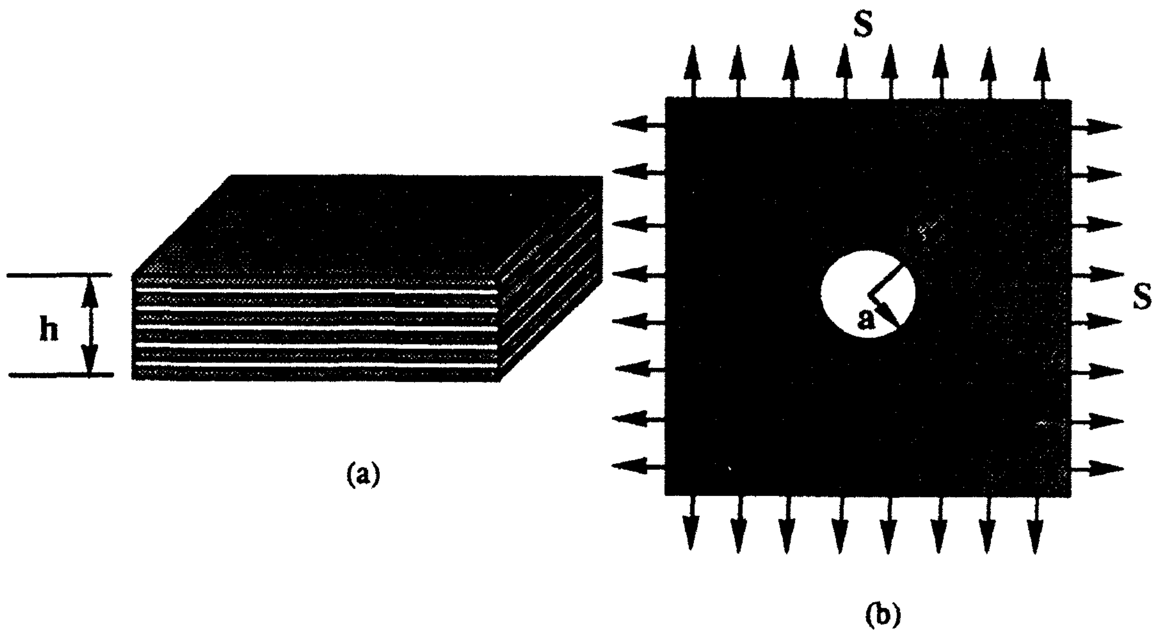


Fig. 1 (a) Layered sheet. (b) Hole in sheet under balanced biaxial tension.

Let
$$\sigma_r = \frac{E(r)}{E(\infty)}s_r, \quad \sigma_\theta = \frac{E(r)}{E(\infty)}s_\theta \tag{2}$$

where $E(\infty)$ is the untailored sheet modulus far from the hole. Then

$$\sigma_r^{(\alpha)} = \frac{E_\alpha}{E(\infty)} s_r, \; \sigma_\theta^{(\alpha)} = \frac{E_\alpha}{E(\infty)} s_\theta \tag{3}$$

and so the layer stresses are proportional to s_r and s_θ. Hence, it is the value of s_θ at r=a that we must seek to lower by tailoring E(r), or the sheet thickness h(r), or both. Note that while the stress concentration factor (SCF) for the *average* sheet stress σ_θ is $\sigma_\theta(a)/S$, the *layer* concentration factors are

$$\frac{\sigma_\theta^{(\alpha)}(a)}{\sigma_\theta^{(\alpha)}(\infty)} = \frac{s_\theta(a)}{s_\theta(\infty)} = \frac{s_\theta(a)}{S} \tag{4}$$

For a *uniform* layered sheet, these layer concentration factors are equal to the classical stress concentration factor $\sigma_\theta(a)/S = 2$.

The equations of equilibrium and compatibility are

$$\frac{d(rh\sigma)_r}{dr} = h\sigma_r \tag{5}$$

and

$$\frac{d(r\varepsilon_\theta)}{dr} = \varepsilon_r \tag{6}$$

respectively. These may be rewritten as

$$\left[\lambda\rho s_r\right]' = \lambda s_\theta \tag{7}$$

$$\left[\rho(s_\theta - \nu s_r)\right]' = s_r - \nu s_\theta \tag{8}$$

in terms of $\rho \equiv r/a$, and the *tailoring function* defined by

$$\lambda(r) \equiv \frac{E(r)}{E(\infty)} \frac{h(r)}{h(\infty)} \tag{9}$$

Primes denote derivatives with respect to ρ.

We proceed in a semi-inverse fashion by asserting the spatial distribution

$$s_r = S\left(1 - \rho^{-n}\right) \tag{10}$$

and solving the compatibility equation (8) for s_θ to get

$$s_\theta = S\left[1 + \frac{1 - \nu(n-1)}{(n-1-\nu)\rho^n} - \frac{C}{\rho^{(1+\nu)}}\right] \tag{11}$$

where C is a constant. The only value of C that leads to a bounded tailoring function is

$$C = \frac{2n - n^2}{n - 1 - \nu} \tag{12}$$

and this gives the *layer* stress concentration factor $s_\theta/S=n$ at $\rho=1$. The tailoring formula

$$\lambda(r) = \exp\left[\frac{n(2-n)}{n-1-\nu}\int_0^{a/r} \frac{x^\nu - x^{n-1}}{1-x^n} dx\right] \tag{13}$$

follows from the equilibrium equation (7). In all cases the peak value of λ(r), as expected, occurs at r=a, and is given by

$$\begin{aligned} \lambda(a) &= \exp\left[\frac{n(2-n)}{n-1-\nu}\int_0^1 \frac{x^\nu - x^{n-1}}{1-x^n} dx\right] \quad (n \neq 1+\nu) \\ &= \exp\left[-(1-\nu^2)\int_0^1 \frac{x^\nu \log x}{1-x^n} dx\right] \quad (n = 1+\nu) \end{aligned} \tag{14}$$

For $\nu=0$ this last result equals $\exp(\pi^2/6)$.

Fig. 2 shows how the peak tailoring magnitude varies with the layer stress concentration factor n, for several values of ν. We remark that if only thickness tailoring is used, the SCF for average stress is the same as that for the layers, and so is also reduced below 2. But for pure modulus tailoring, the SCF for the average stress is given by $n\lambda(a)$, and this always exceeds 2 for $n<2$.

To get a neutral hole, we set n=1 in the formula for $\lambda(r)$, and find

$$\lambda_{neutral}(r) = \exp\left[\frac{1}{\nu}\int_0^{a/r}\frac{1-x^\nu}{1-x}dx\right] \quad (15)$$

For $\nu=0$, this result becomes

$$\lambda_{neutral}(r) = \exp\left[-\int_0^{a/r}\frac{\log x}{1-x}dx\right] \quad (\nu=0) \quad (16)$$

Fig. 3 shows how $\lambda_{neutral}$ varies with r/a for $\nu=0, 1/4$, and $1/2$.

We should check the values of $\sigma_\theta^{(\alpha)}(r)/\sigma_\theta^{(\alpha)}(\infty) = s_\theta(r)/S$ away from the hole. In the case of the neutral hole, we find

$$\begin{aligned} s_\theta/S &= 1-\left(\rho^{-1}-\rho^{-(1+\nu)}\right)/\nu \quad (\nu\neq 0) \\ &= 1-\rho^{-1}\log\rho \qquad (\nu=0) \end{aligned} \quad (17)$$

and so the peak layer stress does indeed occur at the hole.

Acknowledgements

This work was supported by DARPA's Defense Sciences Research Council, under contract to the University of Michigan, by a DARPA URI grant to the University of California at Santa Barbara, and by the Division of Applied Sciences, Harvard University.

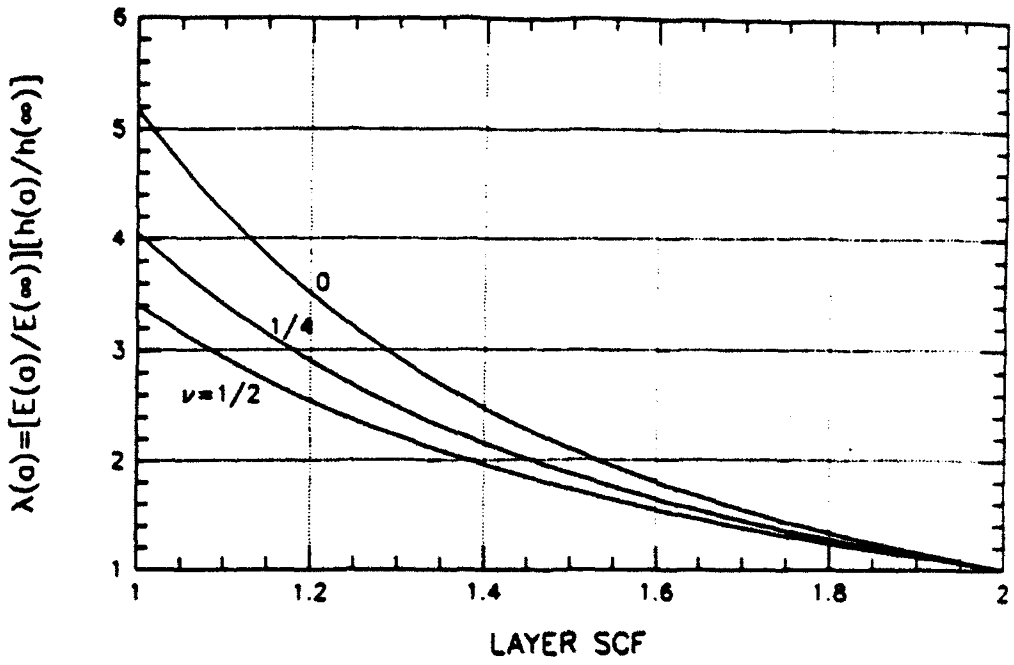


Figure 2. Tailoring function at hole boundary vs. layer stress concentration factor.

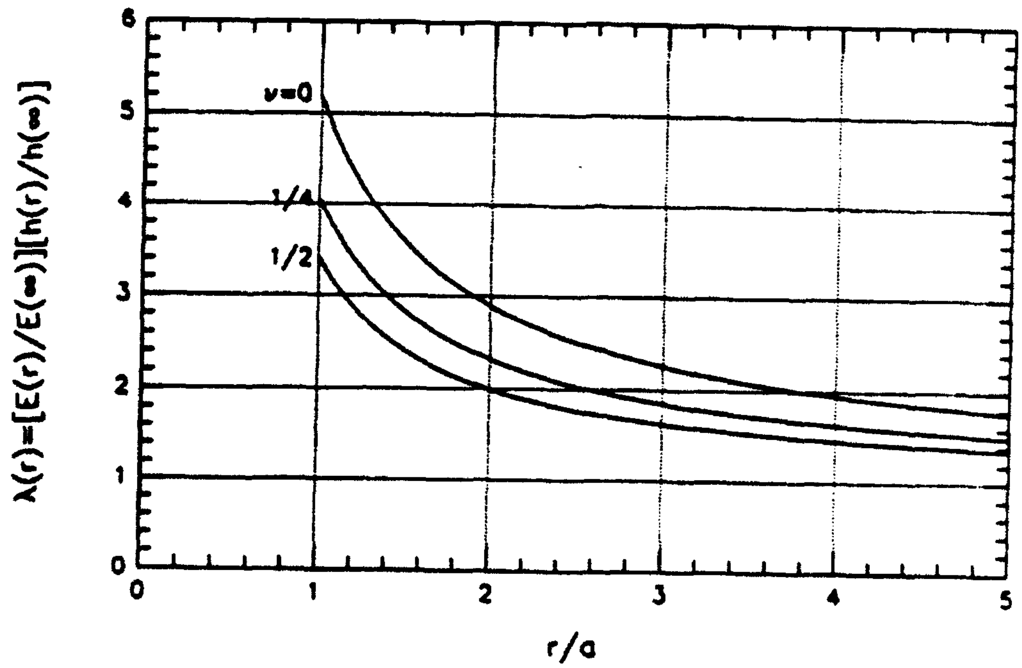


Figure 3. Spatial variation of tailoring function for a neutral hole.

CROSSTALK AND ERROR PROBABILITY IN COUNTER-BEAM λ-MULTIPLEXED DIGITAL HOLOGRAMS

Amnon Yariv, Lance Glasser, George Rakuljic, Victor Leyva

Wavelength multiplexing of volume holograms recorded with counter-propagating beams has been suggested recently as a method for recording large amounts of data(1). This method, in contrast to the conventional angular multiplexing, distributes the holograms uniformly in the grating K space, thus reducing crosstalk.

In this note, we will try to quantify the issue of crosstalk. To do so, we consider first a volume hologram which stores a large number of plane wave holograms recorded and is reconstructed using the geometry of Fig. 1. Each hologram is recorded with its own unique wavelength.

The holograms are represented by their index distributions

$$\Delta n_1 = \Delta n_{01} \sin K_1 z$$

$$\Delta n_2 = \Delta n_{02} \sin K_2 z$$

$$\vdots$$

$$\Delta n_i = \Delta n_{0i} \sin K_i z \qquad (1)$$

where the Bragg condition relation

$$K_i = \frac{4\pi}{\lambda_i} n_{0i} \qquad (2)$$

holds with λ_i being the wavelength used to record (and read) hologram i and n_{0i} is the index of refraction at λ_i

The reflection coefficient of a given, say i, hologram is[2]

$$r_{ii} = \frac{-i\kappa_i e^{ik_i L/2} \mathrm{Sinh}(SL)}{\Delta_i \mathrm{Sinh}(S_i L) + iS\cosh(S_i L)} \tag{3}$$

where L is the length of the hologram and

$$\kappa_i = \frac{\omega_i}{c}\Delta n_{oi}\,,\ \Delta_i = 2\frac{\omega_i n_{oi}}{c} - K_i\ (\equiv \text{Bragg Mismatch}),\ S_i \equiv \sqrt{\kappa_i^2 - \Delta_i^2} \tag{4}$$

The situation considered here is one involving a large number of stored holograms (this number can reach a few thousands) so that $|r_{ii}|<<1$ (say ~10^{-2}). We will also use a wavelength separation λ_i-λ_{i+1} between neighboring holograms sufficiently large so that $\Delta_i L>>1$ and assume that $\Delta_i>>\kappa_i$ except for the case when a hologram is read with its "own" wavelength in which case $\Delta_i = 0$. We will take $\kappa_i = \kappa_{i+1} \equiv \kappa$.

Under the restrictions just stated, the crosstalk, i.e., the undesired field (amplitude) reflection off a hologram when its nearest neighbor is read off, is

$$r_{i,i+1} \cong e^{i\Delta_{i,i+1}L}\frac{\kappa_{i+1}}{\Delta_{i,i+1}}\sin \Delta_{i,i+1}L \tag{5}$$

where $\Delta_{i,i+i} = 2\frac{\omega_i}{c}n_{oi} - K_{i+1}$ is the deviation from the Bragg condition which is involved in the crosstalk between two neighboring holograms.

If the "good" field reflected from, say, hologram #1, i.e., the (output) reflected field which results when the incident beam λ is that used to record hologram #1, is taken as E_o, then the total reflected field is

$$E_R = E_o\left(1 - \frac{\kappa}{\Delta_{1,2}}\sin \Delta_{1,2}Le^{i\Delta_{1,2}L} - \frac{\kappa}{\Delta_{1,3}}\sin \Delta_{1,3}Le^{i\Delta_{1,3}L}\ldots - \frac{\kappa}{\Delta_{1,N}}\sin \Delta_{1,N}Le^{i\Delta_{1,N}L}\right) \tag{6}$$

The unity inside the square brackets represents the "signal" while the remaining terms represent crosstalk from all the other N-1 holograms. In what follows we will consider the effect of the crosstalk on the signal fidelity.

To quantify the argument, consider the case where each hologram records a page of spatial bits so that each pixel is either a "1" ($=E_o$) or a "0". The sequence of terms

$$E_N = \kappa E_o \left(\frac{\sin \Delta_{1,2} L e^{i\Delta_{1,2}L}}{\Delta_{1,2}} + \frac{\sin \Delta_{1,3} L e^{i\Delta_{1,3}L}}{\Delta_{1,3}} + \ldots\ldots \right) \tag{7}$$

in (6) can be viewed a random walk with an ever diminishing step size ($\Delta_{1,i+1} > \Delta_{1,i}$) since the arguments ($\Delta_{1,2} L$, $\Delta_{1,3} L$) are randomly distributed.

Since the number of holograms is large and each term in (7) small, we apply Gaussian statistics to E_N with a probability distribution function

$$p(E_N) = \frac{1}{\sqrt{2\pi \langle E_N^2 \rangle}} e^{-\frac{E_N^2}{2\langle E_N^2 \rangle}} \tag{8}$$

where < > denotes an ensemble average. To facilitate the numerical calculation, assume that the Δ's in (7) are evenly distributed. In this case

$$\langle E_N^2 \rangle = \frac{\kappa^2}{\Delta^2} E_o^2 \left\langle \left(\frac{\sin \Delta L}{1} e^{i\Delta L} + \frac{\sin 2\Delta L}{2} e^{i2\Delta L} + \ldots \frac{\sin N\Delta L}{N} e^{in\Delta L} \right)^2 \right\rangle \tag{9}$$

$$= \frac{\kappa^2 E_o^2}{\Delta^2} \left\langle 2x \sum_{1}^{N} \frac{\sin^2(n\Delta L)}{n^2} + \sum_{i\neq}^{N} \sum_{j}^{N} \frac{\sin(i\Delta L)\sin(j\Delta L)\, e^{(i+j)\Delta L}}{ij} \right\rangle$$

Taking $\langle \sin^2(N\Delta L) \rangle = \frac{1}{2}$ and neglecting the double summation (N>>1) leads to

$$\langle E_N^2 \rangle = \frac{\pi^2}{6} \frac{\kappa^2}{\Delta^2} E_o^2 \tag{10}$$

where we allowed for negative values of Δ as well as positive ones and approximated

$$\sum_{n=1}^{N} n^{-2} \cong \sum_{1}^{\infty} n^{-2} = \frac{\pi^2}{6}.$$

The reconstruction of a "1" as an example will lead to an error if at that particular location $E_N < -E_o/2$ and to an erroneous reading of a "zero" if $E_N > E_o/2$. (This assumes that the detection threshold is set at $E_o/2$.) The error probability in this case is given by

$$EP = \int_{E_o/2}^{\infty} p(E_N)\, dE_N$$

$$= \frac{1}{2} \operatorname{erfc}\left[\frac{E_o}{2\sqrt{2}\left(E_N^2\right)^{1/2}}\right]$$

$$= \frac{1}{2} \operatorname{erfc}\left[0.276\ \Delta/\kappa\right] \qquad (11)$$

where erfc(x) is the complimentary error function of x. It is noted that the crosstalk depends on just two parameters: the grating "strength" κ and the Bragg mismatch parameter Δ.

Fig. 2 shows a plot of the error probability as a function of Δ/κ.

From this plot, we find, as an example, that an error probability of 10^{-15} requires a value of Δ/κ of 26.2 db $(\Delta/\kappa = 20.4)$.

The value of Δ/κ of a multipage hologram can be determined from a measurement of the crosstalk in the case when only two holograms are recorded. The amount of (power) crosstalk between nearest neighbors is given according to Eq. (6) by κ^2/Δ^2.

Fig. 3 shows an experimental plot of (power) reflectivity vs. wavelength in the case of a wavelength multiplexed hologram. The crystal employed is $LiNbO_3$ which was fixed after recording twenty holograms with a nearest neighbor wavelength separation $\Delta\lambda = 8Å$ near

$\lambda = 5000\text{Å}$. The measured peak reflectivity of 10^{-2} yields $\kappa = 50\text{m}^{-1}$. From the relation $\Delta = \left(-4\pi n/\lambda^2\right)\Delta\lambda$, we obtain $\Delta = 10^5\text{m}^{-1}$. This validates our working assumption $\Delta >> \kappa$. The calculated crosstalk for this case is $\kappa^2/\Delta^2 = 5\text{x}10^{-4} = -33\text{db}$. The measured crosstalk is seen to vary between -32db and -45db. Our calculated value falls consistently on the low side indicating some effective apodization mechanism. This aspect will be considered in a separate paper.

We had no convincing way to quantify the error probability calculated in this paper except to note that the crosstalk (i.e., the depth of the minima) in Fig.3 essentially the same when the recorded holograms contain no information and when the holograms are modulated with the image information of lithography masks with feature sizes down to 1μm. This bears qualitatively the assertion[1] that in counter beam λ-multiplexed holograms, the crosstalk is nearly independent of the information content.

References

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(2) Amnon Yariv "Optical Electronics" Holt, Rinehart and Winston, Phil. 1991 p. 503.

The authors are indebted to C. Tyler and B. Carnahan for helpful discussions and numerical help.

(a) California Institute of Technology and Defense Advanced Research Projects Agency (DARPA) Defense Sciences Research Council

(b) Defense Advanced Research Projects Agency

(c) Accuwave Corp., Santa Monica, CA

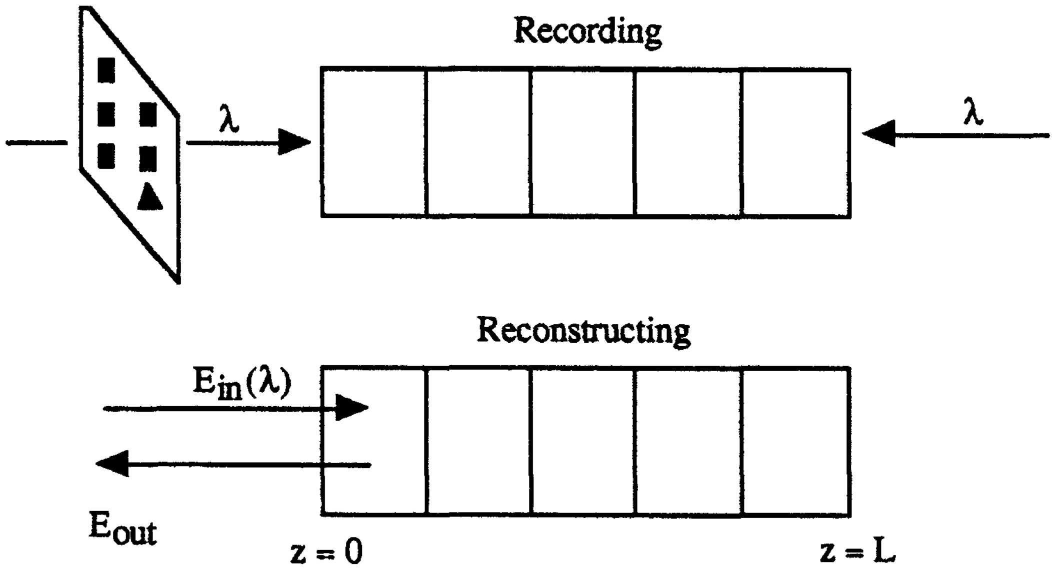

Figure 1. Basic geometry of recording and counter beam λ-multiplexed holograms.

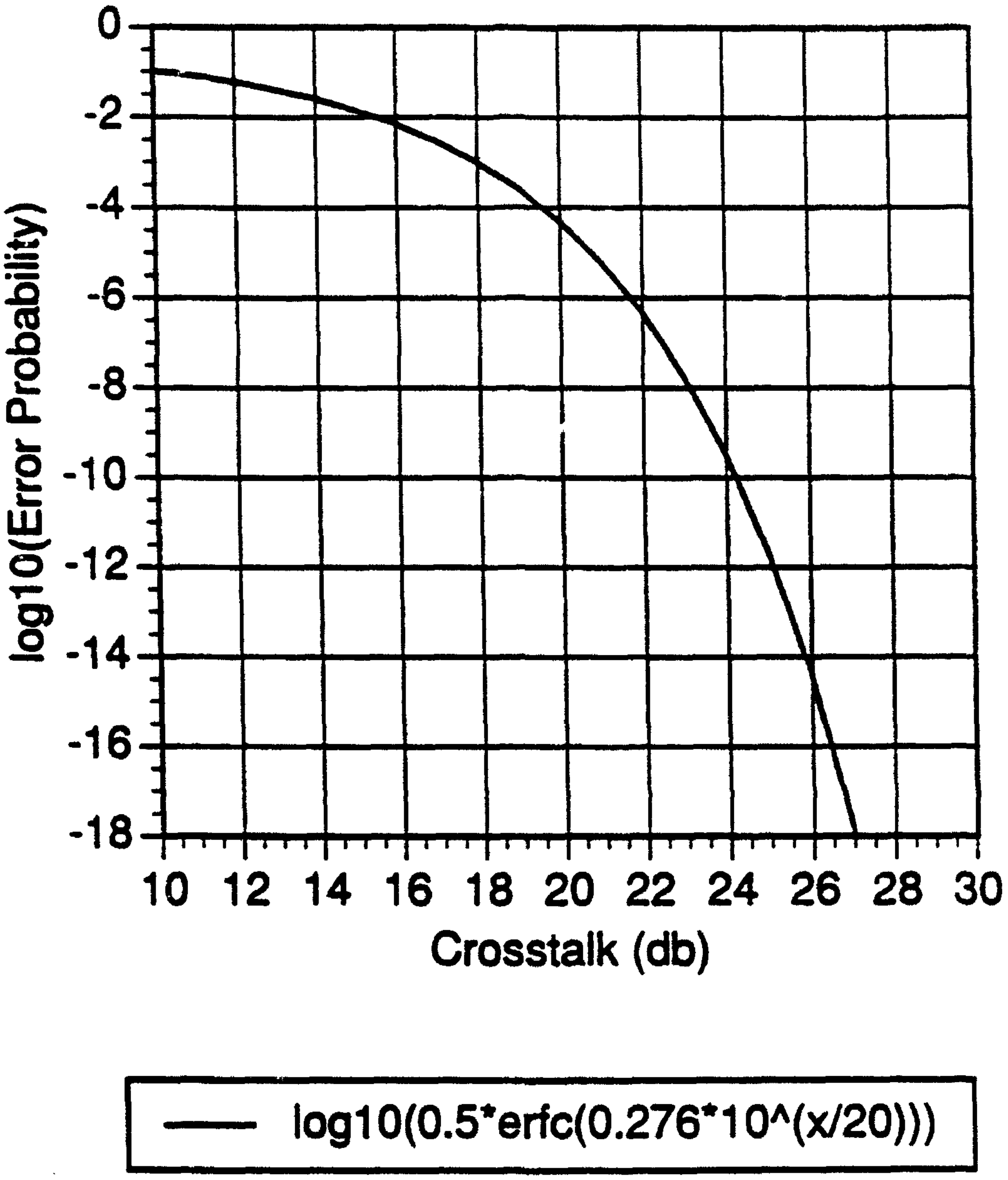

Figure 2. Calculated error probability as a function of the crosstalk expressed in db $\left(10 \log (\kappa/\Delta)^2\right)$.

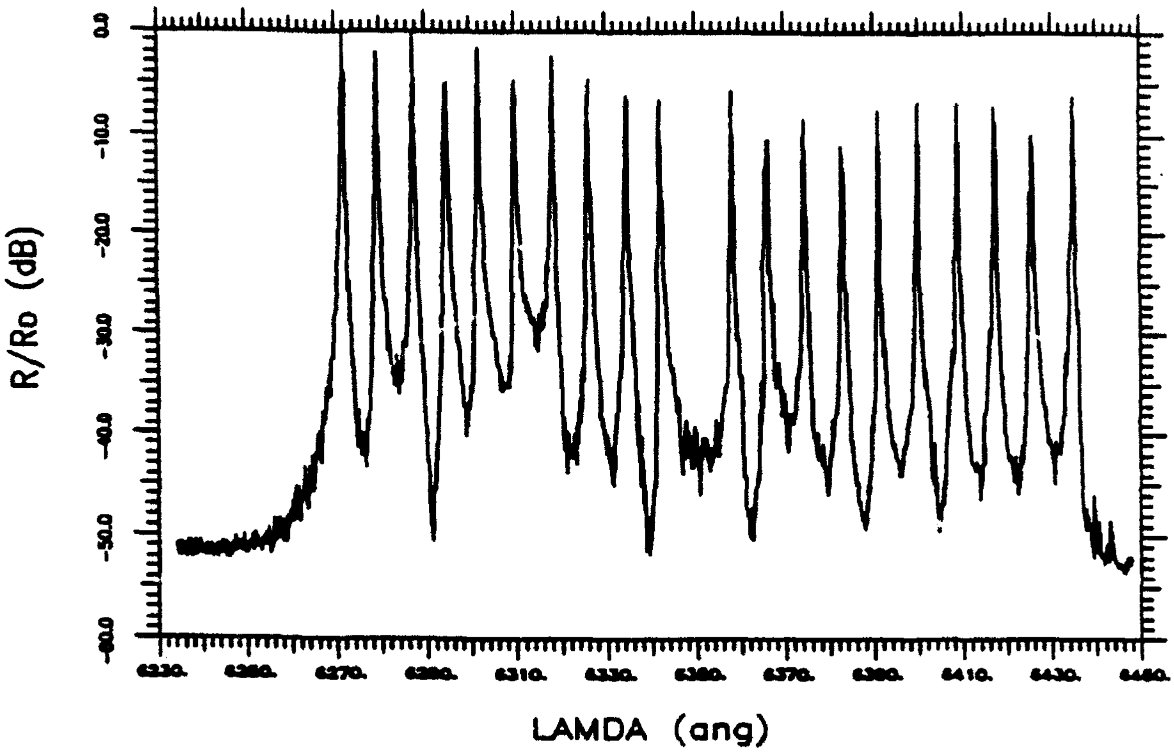

Figure 3. Measured reflection characteristic vs λ off a multi hologram ($\lambda_1,\lambda_2 ... \lambda_{20}$) recorded and fixed in $LiNbO_3$.

DARPA SUPERCRITICAL WATER OXIDATION PROJECT (GA)

J. P. Hirth and R. A. Rapp

A DARPA-funded project has been initiated with General Atomics to achieve the destruction of hazardous waste by its oxidation to completion in supercritical water. The oxidation would require residence times on the order of a minute or more at a "gas" temperature as high as 600C. But very acidic, oxidizing aqueous solutions are involved in the heat-up and cool-down of the solution on each side of the supercritical reactor. It seems practical to consider that certain materials problems must be anticipated in both types of reactors, i.e. by gaseous reactions in the contaminated supercritical steam and by electrochemical corrosion attack by the hot acidic, oxidizing liquid solutions. In fact, the environmental conditions estimated for both types of reactors are probably more severe than those experienced elsewhere in industrial practice. We want to list briefly a few concerns about potential materials problems in the hope that these comments might be helpful.

"PEST" OXIDATION

For nickel-base alloys, intermetallics, and some other alloys, a "pest" oxidation problem occurs at intermediate temperatures. For example, nickel suffers a ductility minimum after exposure to an oxidizing environment of 600-900C. The mechanism involves oxygen penetration along grain boundaries in some cases. In other cases, hydrog is thought to be absorbed during the reduction of the steam, and the hydrogen penetrates the grain boundaries. In either case, a severe loss of ductility at room temperature can ensue the following such an exposure.

Simple tensile tests or even bend tests of coupons of potential container materials after expcsure would provide a check for this possibility.

HYDROGEN EMBRITTLEMENT

Aside from the above mentioned effect, embrittlement by hydride formation is a possibility for Zr, Ti, Nb, and Pt among the proposed containment materials. Again the source of the hydrogen would be water reduced in the oxidation of the metal surface. The time scale for this form of embrittlement is longer than that for the "pest" phenomenon. Again, mechanical tests would reveal the embrittlement.

GENERAL AND GALVANIC AQUEOUS CORROSION

The estimated compositions (acidity and oxidizing potential) for the aqueous solutions in the heat-up and cool-down chambers are far more aggressive than those for the familiar pressurized- or boiling-water nuclear reactors. In these reactors, the water chemistry is carefully controlled to achieve a neutral solution lacking in oxidants to support an electrochemical reduction reaction. For these conditions, a protective passive film based on a hydrated chromium oxide is stabilized. For the hot, acidic, oxidizing aqueous solutions intended for this waste disposal system, alloys based on Ni or Co will not prove to be resistant. If they are needed to form the external walls for an autoclave protected by an internal noble metal liner, then galvanic cells created by pairs of dissimilar metals in contact with the electrolytic solution must be absolutely avoided, since the base metal will suffer accelerated attack. The electrical isolation of the two metals, with a means to protect the base metal (e.g. cathodic protection using the Ti-base dimensionally stable anode), can be considered.

MIXED OXIDANT GASEOUS ATTACK

In the proposed autoclave for the oxidation by supercritical water, both oxygen and chlorine would be available to serve as oxidants. Most metals exhibit relatively high vapor pressures for their volatile chlorides at temperatures of 500-600C. As a severe complication, the chloridation of an alloy (composed of components with different reactivities with chlorine) does not result in a flat receding external interface; rather the most volatile component is leached out of the alloy preferentially, along grain boundaries or other defects, so that a deep penetration occurs. If the chlorine vapor species is unstable in the presence of oxygen, then a conversion to oxide will occur and the chlorine can be recycled within the pores of the alloy to achieve rapid localized attack.

If requested, we could provide some further discussion, or references to literature, etc. We hope that the comments might be helpful.

DARPA/DSRC WARGAMING

R. C. Lytikainen, B. A. Wilcox

EXECUTIVE SUMMARY

The Defense Research Projects Agency (DARPA) has for over 25 years, derived considerable and tangible benefit from the scientific advice and assistance provided via the Defense Research Science Council (DSRC). In the past three years, the rapid, if not breath-taking changes occurring in our world, coupled with a continuing draw-down in the defense budget and the need to be doing things smarter with less, has led us to believe that we should be doing a better job in exposing our DARPA Program Managers and DSRC scientists to the military decision making process, and to military operations and exercises. At the end of the 1991 DSRC Summer Conference, the Steering Committee made the recommendation (joined by DARPA management), to conduct a pilot "wargaming" project designed to "build an intuition for military application of technology".

ACTIVITIES

During the past year, DARPA Program Managers and DSRC members have participated in or been observers of several military war games and exercises. In pre-conference activities, a total of 12-DARPA and 1-DSRC members visited various Army (National Training Center, Ft. Irwin, CA), Navy (NAS Whidby Island, WA, and Naval Bases in Norfolk, VA), and Marine Corps (29 palms, CA) activities and exercises, and 2-DARPA people participated in an Air Force wargame at the AFWARCOL, Maxwell AFB, AL. During the 1992 DSRC Summer Conference in La Jolla, 13-DARPA and 11-DSRC observed Marine Corps amphibious operations at Camp Pendleton, CA, and 10-DARPA and 2-DSRC members participated in a Navy Tactical Wargame at Point Loma, CA. The above activities are described in further detail on following pages.

In keeping with the idea of providing greater focus upon application of new technology to solving current, practical military problems, 8-DARPA and 18-DSRC members participated in a session on "Helicopter Failure Problems" with the Navy, on 8-9 July 1992.

CONCLUSIONS AND RECOMMENDATIONS

The DARPA/DSRC Wargaming Pilot Project has proven to be a highly successful venture towards "building an intuition" in our program managers and scientists, and is also beginning to reap specific returns with respect to application of new technology.

The overwhelming consensus among DARPA program managers and DSRC members who have participated, is that exposure to wargaming, military operations, exercises and field trips to other military installations should be an integral and continuing part of our program. A summary of planned activities for the next year are provided below.

Since any meaningful interface with or involvement in defense/military-related programs, projects and/or operations requires a DoD clearance, any DSRC member who would be directly involved in military application research, must obtain a Secret clearance. (A Top Secret clearance is desirable, but not necessary).

WARGAMING

(Expose DARPA/DSRC to Military Operations & Decision Making Process)

- CHANGING WORLD
- GAIN INSIGHT-MILITARY APPLICATION OF TECHNOLOGY
- BETTER BANG FOR THE BUCK
- LINKAGES/BUILDING AN INTUITION

WARGAMING

(Expose DARPA/DSRC to Military Operations & Decision Making Process)

- **WAR GAMES (on, off-conference)**
  - **Seminar (TIG) < Immersion**
  - **Operational/Tactical < Observation**

- **EXERCISES & FIELD TRIPS (on, off-conference)**
  - **Where rubber hits the road**
  - **Soldiers/Sailors/Marines/Airmen**

- **CAMEO APPEARANCES (during conference)**
  - **Specific Problems (e.g., Helicopter Failure Problems)**
  - **Discussion/Seminar/Round Table**
  - **Sea Stories**

WAR GAMES - COMPLETED

- AIR FORCE - AFWARCOL - Maxwell AFB, AL
  - Mar 92, "Global Reach"
  - 3-1/2 days 2-DARPA
    - < Strategic/Regional/Air Power

- NAVY - TACTRAGRUPAC - San Diego, CA
  - 19-21 Jul 92, Fleet Exercise
  - 2-1/2 days 10-DARPA, 2 DSRC
    - < Operational/Tactical

WAR GAMES - PLANNED

- AIR FORCE - AFWARCOL - Maxwell AFB, AL
  - 30 Nov-3 Dec 92, "Global Reach"
  - 3-1/2 days 8-12 DARPA/DSRC
    - < Strategic/Regional/Air Power

- NAVY - NAVWARCOL - Newport, RI
  - 16-20 Nov 92 "SEACON",
  - 4-1/2 days 1-4 DARPA/DSRC
    - < Operational (two-sided)

- Jul 93, "Global War Game"

  5-12 days 6-8 DARPA/DSRC
    - < Technology Cell/Strategic

- AIR FORCE - AFWARCOL - Maxwell AFB, AL
  - Feb-Jun 93, Technology Game
  - 3-4 days each 1-4 DARPA/DSRC
    - < Operational/Technology

EXERCISES & FIELD TRIPS - COMPLETED

- ARMY - National Training Center - Ft. Irwin, CA
  - Apr/May 92, "OPFOR"/armor/artillery/air/infantry
  - 2 days 2-DARPA

- NAVY - Naval Air Station - Whidby Island, WA
  - May 92, electronic warfare/EA6B Simulator, fly a/c
  - 5 days 2-DARPA

- MARINE CORPS - 29 Palms, CA
  - May 92, Combined Arms Exercise (CAX) in Desert
  - 3 days 5-DARPA

- NAVY - Naval Base, Air Station - Norfolk, VA
  - June 92, maint. & repair - SIMA/USS Shenandoah (AD-44)
  - 2 days 3-DARPA, 1-DSRC

- MARINE CORPS - Camp Pendleton, CA
  - July 92, Tandem Thrust/Marine amphibious landing
  - 1/2 day each 13-DARPA, 11 DSRC

- GRUNION - Mission Beach, La Jolla Shores, CA
  - 16 July, leuresthes tenuis landing
  - 1047 - 1247P (high tide) 6-DARPA, ??-DSRC

EXERCISES & FIELD TRIPS - PLANNED

- NAVY - Norfolk, Puerto Rico, San Diego, San Francisco
  - Sep-Nov 92, at-sea aboard variety of ships
  - 3-4 days each 1-3 DARPA/DSRC

- NAVY - Naval Air Station - Whidby Island, WA
  - Sep-Oct 92, Electronic warfare/EA6B Simulator
  - 3-1/2 days 2-DSRC

- AIR FORCE - Colorado Springs, CO
  - Oct 92-Jun 93, STRATCOM/NORAD/CINCSPACE/ AFSCN
  - 2-3 days each 4-8 DARPA/DSRC

- AIR FORCE - Nellis AFB, NV
  - Jan-Jun 93, Red Flag/fighter/bomber/stealth
  - 2-3 days each 1-3 DARPA/DSRC

- MARINE CORPS - 29 Palms, CA
  - Oct 92-Jun 93, Combined Arms Exercise (CAX) in Desert
  - 3 days each (monthly) 3-4 DARPA/DSRC

- ARMY - National Training Center - Ft. Irwin, CA
  - Oct 92-Jun 93, "OPFOR"/armor/artillery/air/infantry
  - 2 days each (monthly) 2-6 DARPA/DSRC