Quarterly Report

Analysis of Cost:
CVD Diamond Deposition and Finishing

Contract Number: N00014-93-C2044

IBIS Associates, Inc.
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2nd Quarter 1993

IBIS

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Executive Summary

IBIS Associates has updated its predictive spreadsheet model of the DC Arc diamond deposition technology. This report presents the results obtained with the new model and a revised set of baseline inputs for diamond heat sink manufacture. The cost of producing 1,000 six inch, 1mm thick, polished and metallized diamond wafers, 1 mm thick, by the DC Arc deposition technology is estimated to be $4,357 per wafer in the long run. Sixty-four percent of this cost is due to the deposition step, which is capital and labor intensive. Overall, the equipment cost of 23.4% and materials cost of 20.6% are significant factors in the total cost. Assuming an annual production volume greater than 1,510 and argon recycle equipment cost less than $200,000, compressed argon recycling in diamond deposition is economical relative to diamond deposition with liquid source gases.

The major revision of the DC Arc Model is the inclusion of alternative polishing technologies. It was determined from industry interviews that abrasive lapping remains the prevalent polishing technology for CVD diamond films. This method is typically carried out with a polishing rate of 1 um per hour. Using only abrasive lapping, with new input data, the total production cost per wafer is $4,357. Using only hot iron polishing, which is characterized by a polishing rate of 5 um per hour, the production cost reduces to $3,479 per wafer. Oxygen Plasma Polishing occurs at an average rate of 3.3 um per hour, which results in a total cost of $4,544 per wafer. Oxygen ion beam polishing incurs a high cost of $6,146, which is due to the material removal rate of 0.24 um per hour.

The capital cost of metallization equipment for coating diamond films wafers varies with the throughput per batch. New regressions are incorporated into the DC Arc model to more accurately predict the price of metallization equipment. Both sputtering and evaporation operations remain severely underutilized with 95% and 97% idle times, respectively. In order to fully utilize one sputtering metallization machine, for example, the production volume must reach 20,000 wafers per year. Less expensive, lower throughput machines do not lead to reductions in idle time significant enough to justify metallization in-house; therefore, the outsourcing of the metallization operation to third party vendors remains the most economical option, at 1,000 wafers per year production volume.

New information relating to the inspection operation is incorporated into the DC Arc Model. The addition of microscopic inspection and thermal conductivity inspection however, has minimal impact on the cost. The contribution of each inspection step to the overall production cost remains negligible at less than 2 percent.

To be investigated further are the relationships of deposition rate with DC Arc power, substrate shape, gas flow rate, and desired quality.

Polishing of CVD Diamond Films

This report describes several methods for polishing CVD diamond films, which can be applied separately or in conjunction with each other. These technologies are shown in Figure 1. From industry interviews, IBIS determined that the required surface roughness for the subsequent metallization operation is on the order of 0.1 um, and polishing operations must be chosen to meet this specification while maximizing material removal rates. According to the experts surveyed, conventional abrasive lapping still remains the prevalent technology for polishing CVD diamond films, although Hot Iron Polishing, Reactive Plasma, and Ion Milling approaches have been considered. The IBIS Technical Cost Model, therefore, assumes only abrasive lapping as the finishing operation, but allows exploration into other technologies. In general, the polishing rate attained with each technology depends greatly on the quality of the deposited diamond films, as measured by the original flatness and surface roughness. The chemical state of the diamond films, with respect to amorphous carbon content and doping levels, can also influence the polishing rate significantly. Unfortunately the quantitative relationships between purity and polishing rate remain to be determined for the different methods.

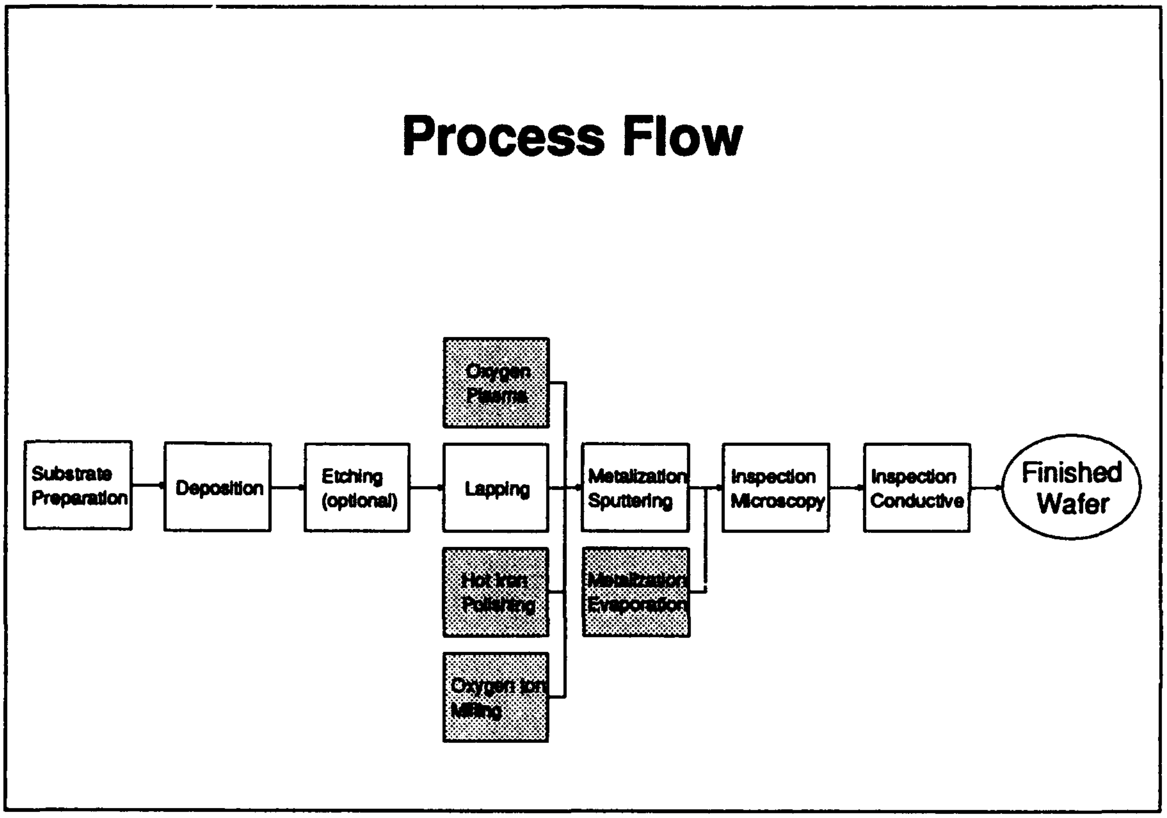

Figure 1

Abrasive Lapping

In the lapping operation wafers are placed in holders (typically three to five wafers per batch) and are made to travel in an elliptical pattern on the surface of a rotating circular plate. During this process, a diamond grit slurry flows through grooves in the plate, lapping the surface of the diamond films. The size of the chosen grit depends on the initial and desired surface roughness. In the production of electronic substrates, it is necessary to lap only one side of the wafer, since its underside is already smooth and flat from the original contact with the growth substrate. This underside, however, is not suited for use in heat sinks, because the fine grains there produce inferior thermal and electrical properties in the film. The side being lapped contains both microscopic roughness attributable to the growth of diamond crystals, as well as a macroscopic bulging or "crowning", due to unequal growth rates across the face of the wafer. The tendency has been to use small wafer sizes for abrasive lapping, because larger specimens may crack under higher loads. For samples of one square centimeter in area, the linear material removal rates in abrasive lapping have been reported at about 1 um/hr.

Hot Iron Polishing

It is well known in industry that diamond materials are ineffective as grinding agents for ferrous metals due to the graphitization of carbon in contact with hot iron. This mechanism is the basis for hot iron polishing of diamond, where the graphite produced is removed by diffusion into a cast iron polishing plate. The plate is held stationary in a vacuum of 0.1 Pa. As reported by Yoshikawa at the Tokyo Institute of Technology ("Development and Performance of a Diamond Film Polishing Apparatus with Hot Metals," SPIE Diamond Optics III, 1990), the hot plate polishing process is characterized by a linear polishing rate of 7 um/hr at 950C in vacuum, with little surface and sub-surface damage. Other sources, such as Harker at Rockwell International ("The Polishing of Polycrystalline Diamond Films," SPIE Diamond Optics III, 1990), suggest a more conservative polishing rate of 5 um/hr. This polishing rate can be controlled by introducing an atmosphere with varying hydrogen content into the polishing chamber. The hot iron process is still developmental, but its potential low cost and ease of scaling make it a likely candidate for large throughput batch processing.

Oxygen Plasma Polishing

Reactive Plasma polishing is an area technique where a plasma discharge is generated above the wafer in a reactive atmosphere, typically a mixture of oxygen and argon. The discharge ionizes the gaseous species, which etch away carbon material through a combined process of graphitization and sputtering. For this process Harker ("The Polishing of Polycrystalline Diamond Films," SPIE Diamond Optics III, 1990), has reported polishing rates from 1 to 5 um/hr on samples one square centimeter in area, at substrate temperatures from 450-650C. The smooth diamond films in these experiments were finished using the Hot Iron Plate technique or abrasive lapping. Harker's group reported problems with preferential etching at the diamond grain boundaries. This difficulty was alleviated by depositing gold coatings to shield the grain boundaries, while still exposing the high points on the film. In the industrial sector, Oxford Plasma Technology, a manufacturer of plasma processing systems, has used one of its plasma reactors to pattern etch diamond thin films. In this effort, linear etch rates of 3.3 um/hr over one square centimeter samples were reported. It was suggested that to optimize material removal rates for polishing, more argon should be added to the plasma.

Oxygen Ion Milling

In Oxygen Ion Milling processes, a reactive ion beam is rastered across the sample surface, with the energy flux and beam direction being independently controllable. The removal of carbon atoms occurs primarily through sputtering, the efficiency of which depends largely on the ion beam's angle of incidence. In most cases, however, the micro-surface is not leveled as the macro-surface geometry becomes more flat. By filling the cracks and valleys of the micro-surface with a material which etches at the same rate as diamond, it is possible to significantly reduce this micro-surface, or surface roughness, on the wafers. One such planarizing material has been found in a mixture of photoresist and titanium-silica emulsion. This coating also keeps the ion beam incident on one surface rather than a multitude of facets, thereby improving the efficiency of material removal.

Six or eight inch diameter ion beam sources are available. Nordiko Plasma Systems, for example, holds the patents on a filamentless ion source architecture which produces reactive ion beams. In relation to oxygen plasma polishing, ion milling is reported to be a slow process, attaining only about 0.24 um/hr. This means ion milling is better suited to final polishing, rather than bulk material removal.

Diamond Polishing - Miscellaneous Issues

There are other polishing techniques which are developmental, or are mostly used for specialty applications like high performance optics. Tribochemical polishing is one such process, which has recently attracted interest in the semiconductor industry for producing highly polished surfaces, without the damage common in abrasive techniques. In one version of this method, a lapping grit is used, which under the action of load and friction, catalyzes the conversion of diamond to carbon monoxide gas. This method achieves linear polishing rates from 2 to 15 um/hr, depending on applied pressure and the detailed chemistry of the silica based lapping grit. The exact configuration of this lapping system, in terms of equipment requirements, was not disclosed. The different tribochemical processes are not covered in this report and should be investigated further, including data on polishing rates, equipment requirements, and costs.

It should be emphasized that the polishing rates given above are process specific, and were obtained with samples on the order of one square centimeter in area or smaller. Polishing rates for larger samples are often difficult to determine from these small-substrate values, especially in the case of lapping and tribochemical polishing, where the mechanical loads associated with a given polishing rate depend on the sample flatness and on interface area. Reactive plasma approaches are limited by the ability to generate uniform plasma discharges over a large area, which depends on the power used to drive the plasma discharge. The effective polishing rates possible with oxygen ion beams depend on the area covered and the beam's dwell time per unit area. By choosing the large diameter beams available today, large samples can be almost continually exposed in single wafer systems with minimal displacement of the ion beam for uniformity. Hot iron polishing is the only process not limited by the sample area; polishing rates with this technique depend only on the ability to uniformly heat a large polishing plate and the diffusion rate of carbon into the plate material. This independence of removal rate with area facilitates scale-up. For the purpose of cost modeling, IBIS has assumed that all reported polishing rates remain constant with increasing sample area.

The possible throughput for a given polishing technology also depends whether the process can accommodate multiple wafers or is a single wafer technique. As reported here, lapping and hot iron polishing are the only processes for multiple substrates. Oxygen ion beam polishing is a single wafer method with one ion source covering one wafer completely. Oxygen Plasma Polishing is a process where a single wafer is placed into the process chamber at a time, although cycle times can be reduced with a load lock arrangement and automatic wafer handling. Single wafer processes can, in general, be converted into multi-wafer processes using a cluster tool arrangement of separate process chambers connected to a central wafer handling mechanism. Both of these possibilities however, entail a corresponding increase in equipment cost.

Metallization

The ninth operation in the diamond wafer manufacturing process as modeled is the metallization of the diamond film surface. The most common means of metallizing is DC vacuum sputtering, a momentum transfer process where argon ions ablate metal atoms from a sputtering target. The metal deposits on the chosen substrate, resulting in films with good adhesion. For processing, bare wafers are placed in a carousel and loaded into the sputtering system. The sputtering chamber contains an anode and a cathode between which the diamond film passes; the cathode being the sputtering target. A variety of sputtering targets can be accommodated in the process chamber, for successive deposition of metal layers. In the updated DC Arc model, electron beam evaporation is added as an alternative to sputtering. In this technology an electron beam melts the surface of a metal charge. As this occurs, the metal evaporates in the chamber and deposits on the substrate by vapor condensation.

In previous versions of the DC Arc model, metallization equipment for coating wafers was assumed to be multi-station equipment valued at $500,000 per station. At current levels of diamond wafer production, such a scale of machine would be severely underutilized. Instead, single chamber systems with a single load lock are most appropriate, as they are available at about half of that cost. The updated TCM, however, no longer requires the machine cost as an explicit input, but calculates the cost of both sputtering and evaporation systems with regressions obtained through industry interviews.

DC Arc Baseline Cost Model

IBIS Associates, through the use of Technical Cost Modeling (TCM), has created a predictive spreadsheet of the DC Arc diamond film technology. Portions of this model are still undergoing active investigation and modification. This section presents both the input assumptions and the cost estimates derived for each unit operation as currently simulated. Key input data were obtained primarily through discussions with industry personnel. In the new baseline analysis each operation is assumed to have "dedicated equipment" (i.e. the equipment is not being used for other manufacturing jobs). Additionally, standard default values are applied for equipment downtimes, rejection rates, number of laborers per operation and building space requirements. IBIS will continue to investigate values for these factors. Recognizing that there are no commercial scale production facilities for making diamond films, establishing definitive values for these parameters will not be possible. Instead, IBIS will rely on experience gained from modeling other, similar manufacturing processes. As is shown in Model List 1, the modeling effort assumes the production of six inch diamond wafers, each being one millimeter thick and produced at an annual volume of one thousand pieces.

DC Arc Economics: Product Specifications

PRODUCT SPECIFICATIONS

Part Name	6 in. substrate	NAME
Wafer Diameter	15.24 cm	WAFER
Finished Wafer Thickness	1,000 um	THIK
Annual Production Volume	1 (000/yr)	NUM
Length of Production Run	5 yrs	PLIFE

Model List 1

Surface Preparation Inputs

The substrate is assumed to be a six inch diameter silicon wafer with a thickness of 0.15 inches (3810 um). The price for such wafers is listed at $43 each in the spreadsheet's material database. These substrates are assumed to be polished in batches of five, for one hour, to create a mirror quality finish. The batch size was chosen to be representative of a small scale polishing mechanism which could easily accommodate 1,000 silicon wafers per year. The model assumes that the same type of polishing equipment is used for polishing silicon as is used for the diamond wafers. The capital costs for polishing equipment are predicted based on a statistical relationship derived from the analysis of collected industry data.

The input assumptions for the surface preparation operation are summarized in Model List 2. Changes made from the previous version of the model include a change in the number of direct laborers per polishing station, from a value of one to a value of 0.5. This is designed to reflect a situation where one laborer oversees two pieces of equipment. In addition, the building space requirement per station is increased from 150 square feet to 250 square feet to more accurately reflect equipment and working space footprints.

DC Arc Economics: Surface Preparation Inputs

PROCESS RELATED FACTORS - SURFACE PREPARATION			
Process In Use?	1	[1=Y 0=N]	USE1
Dedicated Investment	1	[1=Y 0=N]	DED1
Process Rejection Rate	5%		REJ1
Average Equipment Downtime	20.0%		DOWN1
Direct Laborers Per Station	0.5		NLAB1
Substrate Material	11	[menu #]	MATL1
Pieces Per Batch	5	pcs/batch	PCS1
Process Time	60	min/batch	PTIME1
Building Space Requirement	250	sqft/sta	FLR1

Model List 2

Surface Preparation Cost Estimates

With the preceding inputs, the total operation cost for surface preparation is found to be $109 per wafer. As shown in Model List 3, the largest element of this cost is the silicon material at $65.66 per wafer, or 60.0%. The price of the clean silicon substrates, however, is listed at only $43.00 per wafer. The discrepancy between this price and the material cost in the unit operation cost summary is attributable to the method in which scrap losses are accounted. Because each step in the prccess involves some losses or rejects, 1,511 silicon wafers must be prepared in order to produce 1,000 good diamond wafers. The cost all 1,511 wafers is distributed over the 1,000 good wafers ultimately produced.

DC Arc Economics: Surface Preparation Cost Estimates

DC ARC CVD TCM: SURFACE PREPARATION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$65.66	$65,660	60.0%	
Direct Labor Cost	$3.40	$3,400	3.1%	
Utility Cost	$0.06	$64	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$5.23	$5,233	4.8%	$26,166
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$1.25	$1,250	1.1%	$25,000
Maintenance Cost	$4.09	$4,093	3.7%	
Overhead Labor Cost	$25.00	$25,000	22.8%	
Cost of Capital	$4.72	$4,725	4.3%	
TOTAL FABRICATION COST	$109.42	$109,425	100.0%	$51,166

Model List 3

Deposition Inputs

Model List 4 presents the input assumptions used in estimating the costs of the deposition operation. The inputs listed involve equipment assumptions, gas concentrations, flow rates, and recycling rates. The process rejection rate is changed to 12.5% (from 1% in the previous report) while the number of direct laborers per station is set to 0.4 (from 0.25). The concentrations of reactant gases is reset from 24% hydrogen, 1% methane, and 75% argon, in the first quarterly report, to 65.75% hydrogen, 1% methane and 33% argon. These changes reflect new information on gas composition, as well as a change from compressed gas to liquid gas sources. The recycle rates remain at 0% for hydrogen and 0% for argon, because recycling reduces gas consumption to levels where liquid gas deliveries are not economical for gas suppliers. With a production volume significantly higher than 1,000 wafers per year, gas recycling could be warranted. If the gas recycling option is activated in the model, the equipment cost is increased by $250,000. This recycling expenditure would provide for equipment that adsorbs carbon based gases, converts residual hydrogen to water, dries the gas mixture, and recirculates the recovered argon.

In the updated baseline process the deposition rate is removed from the inputs, to be calculated instead from the deposition equipment power. The carbon capture factor is increased to thirty percent from a value of twenty percent, to better reflect information about the efficiency of developmental deposition systems. The model, as updated, uses a correlation equation to calculate equipment costs based on the power rating of the deposition machine. The power is increased from 90kW to 350 kW. The cooling water entry is replaced with inputs for the coolant temperature rise and the heat capacity of the coolant. The input value for the building space requirement was changed from 1,000 square feet to 1,500 square feet per deposition station.

DC Arc Economics: Deposition Inputs

PROCESS RELATED FACTORS - DEPOSITION

Process In Use?	1 [1=Y 0=N]	USE2
Dedicated Investment	1 [1=Y 0=N]	DED2
Process Rejection Rate	12.5%	REJ2
Average Equipment Downtime	15.0%	DOWN2
Direct Laborers Per Station	0.4	NLAB2

	Menu #	vol%	
Hydrogen	1	65.7%	GASA VOLA
Carbon Containing Gas	15	1.0%	GASB VOLB
Carrier Gas	4	33.3%	GASC VOLC
Other Gas	0	0.0%	GASD VOLD
		100.0%	

Hydrogen Recycle Rate	0.0%	RECYC
Carrier Gas Recycle Rate	0.0%	RECYC2
Gas Recycle Equipment Cost	$250,000 /sta	MCH2A
Machine Power	350 kW	POW2
Carbon Capture Factor	30.0%	CCF2
Machine Load/Unload Time	120 min/cyc	PTIME2
Available Deposition Time	8,640 hrs/yr	DAYHR2
Cooling Water Temp Rise	50.0 C	TEMP2
Heat Capacity of Water	1.0 cal/g/C	CP2
Building Space Requirement	1,500 sqft/sta	FLR2

Model List 4

Deposition Cost Estimates

The total cost of the deposition operation is found to be $2,787 per wafer. As shown in Model List 5, the largest contribution to this cost is the equipment cost at 32.3% of the total. This high equipment expenditure per wafer is due to the large capital investment for each station and the low throughput of the deposition process, which necessitates multiple deposition stations. Unless one or both of these factors is changed in the future, DC Arc based diamond films will remain costly to produce. The material cost accounts for 3.4% of the total process cost, which represents a large decrease from the 25% value reported in the 1993 First Quarter Report, due to the switch to liquid gases. Utility costs account for 21.7% of the total manufacturing cost, up from the 10.6% value previously reported. This underscores reducing utility costs as an important cost cutting strategy.

DC Arc Economics: Deposition Cost Estimates

DC ARC CVD TCM: DEPOSITION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$95.11	$95,108	3.4%	
Direct Labor Cost	$308.77	$308,770	11.1%	
Utility Cost	$603.68	$603,680	21.7%	
FIXED COST ELEMENTS				
Equipment Cost	$900.00	$900,000	32.3%	$4,500,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$37.50	$37,500	1.3%	$750,000
Maintenance Cost	$420.00	$420,000	15.1%	
Overhead Labor Cost	$100.00	$100,000	3.6%	
Cost of Capital	$322.22	$322,222	11.6%	
TOTAL FABRICATION COST	$2,787.28	$2,787,280	100.0%	$5,250,000

Model List 5

Etching Inputs

Model List 6 presents the inputs for the etching process. Etching rates are tabulated in the Material Database, where a rate of 20 um/min is listed for silicon. The etching operation assumes a capacity of twenty wafers per batch per station, which is a change from fifty wafers per batch. The rinse time remains set at thirty minutes, while the machine and etchant costs stay at $6,000 per station and $70 per liter respectively. The cost of etchant disposal, when made a separate input, becomes $30 per liter, while the etchant capacity per station is taken to be one liter per batch.

DC Arc Economics: Etching Inputs

PROCESS RELATED FACTORS - ETCHING

Process In Use?	1	[1=Y 0=N]	USE3
Dedicated Investment	1	[1=Y 0=N]	DED3
Process Rejection Rate	1.0%		REJ3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1		NLAB3
Load/Unload and Rinse Time	30	min/batch	PTIME3
Pieces Per Batch	20		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost	$70	/liter	ETCH3A
Etchant Disposal Cost	$30	/liter	ETCH3B
Mashine Etchant Capacity	1	l/batch	CAP3
Machine Power	0	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3

Model List 6

Etching Cost Estimates

The total cost of the etching operation is $64.57 per wafer. Overhead labor costs account for 77.4%, while direct labor and equipment costs account for 7.1% and 2.8%, respectively. Model List 7 reviews the costs of the etching operation.

DC Arc Economics: Etching Cost Estimates

DC ARC CVD TCM: ETCHING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$3.98	$3,980	6.2%	
Direct Labor Cost	$4.62	$4,616	7.1%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.80	$1,800	2.8%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.50	$500	0.8%	$10,000
Maintenance Cost	$1.52	$1,520	2.4%	
Overhead Labor Cost	$50.00	$50,000	77.4%	
Cost of Capital	$2.16	$2,157	3.3%	
TOTAL FABRICATION COST	$64.57	$64,574	100.0%	$19,000

Model List 7

Lapping Inputs

The inputs for the Lapping operation are shown in Model List 8. Among the important process parameters are the number of sides to be polished, the number of lapping steps, and the size of the lapping machine. For the production of electronic heat sinks, it is typical to lap only one side of the wafer, using a two step lapping process.

The material to be removed is set to 10% of the original weight. The input for the load/unload time remains at 40 minutes per cycle. In the revised baseline analysis, it is assumed that one station can lap five wafers uniformly with a linear polishing rate of 1 um/hr. This lapping rate replaces the 0.017 cubic centimeters per minute value previously used. The lapping machine uses a diamond grit slurry, priced at $53 per liter, with a flow rate through the system of 0.5 liter/hour. The lapping plate life for polishing diamond films remains set at 320 hours, while the building space allocated to the lapping machine stays at 400 square feet.

DC Arc Economics: Lapping Inputs

PROCESS RELATED FACTORS - LAPPING

Process In Use?	1 [1=Y 0=N]	USE4
Dedicated Investment	1 [1=Y 0=N]	DED4
Process Rejection Rate	10.0%	REJ4
Average Equipment Downtime	15.0%	DOWN4
Direct Laborers Per Station	0.25	NLAB4
Lapped Material Removal	10.0% by wgt	TLAP4
No of Lapping Steps	2	LAPS4
Pieces Per Batch	5	PCS4
Load/Unload and Clean Wafers	40 min	PTIME4
Average Lapping Rate	1.0 um/hr	RATE4
Lapping Slurry Cost	$53 /liter	LAP$4
Lapping Slurry Usage Rate	0.5 liter/hr	LAPR4
Lapping Plate Life	320 hrs	PLAL4
Available Lapping Time	8,640 hrs	DAYHR4
Building Space Requirement	400 sqft/sta	FLR4

Model List 8

Lapping Cost Estimates

As shown in Model List 9 the total cost of the lapping operation is found to be $1,103/wafer, with the main contribution being the lapping grit at 66.4%. This value represents an increase from 50.9% previously reported. The long cycle time particularly affects the slurry usage and the direct labor cost (13.4%).

DC Arc Economics: Lapping Cost Estimates

DC ARC CVD TCM: LAPPING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$732.33	$732,333	66.4%	
Direct Labor Cost	$148.06	$148,060	13.4%	
Utility Cost	$5.84	$5,845	0.5%	
FIXED COST ELEMENTS				
Equipment Cost	$14.33	$14,327	1.3%	$71,634
Tooling Cost	$75.11	$75,110	6.8%	$375,550
Building Cost	$8.00	$8,000	0.7%	$160,000
Maintenance Cost	$18.53	$18,531	1.7%	
Overhead Labor Cost	$50.00	$50,000	4.5%	
Cost of Capital	$51.06	$51,065	4.6%	
TOTAL FABRICATION COST	$1,103.27	$1,103,269	100.0%	$607,184

Model List 9

Hot Iron Polishing Inputs

The baseline scenario assumes lapping is used exclusively for the finishing of the diamond wafers. If the Hot Iron Polishing operation is used, the inputs for this operation are shown in Model List 10.

The number of direct laborers per station is set at one-fourth, since handling requirements are assumed to be similar to those in the lapping operation. Material removal is set to 10% of the original weight of the diamond films. If Hot Iron Polishing is chosen, the baseline scenario uses one polishing step with three pieces per batch. The average linear polishing rate is fixed at 5 um/hr. In IBIS's investigations, very little information was obtained on the life of the polishing plate. It is therefore assumed that after ten cycles of surfacing, heating, and cooling, the iron plate will need to be replaced. The machine power requirement and equipment cost are calculated from a data regression based on the capacity input. The building space requirement is fixed at 400 square feet.

DC Arc Economics: Hot Iron Polishing Inputs

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PROCESS RELATED FACTORS - HOT IRON POLISHING
              Process In Use?          1 [1=Y 0=N]    USE5
         Dedicated Investment          1 [1=Y 0=N]    DED5
        Process Rejection Rate      10.0%              REJ5
     Average Equipment Downtime     15.0%              DOWN5
    Direct Laborers Per Station     0.25               NLAB5

             Material Removed      10.0% by wgt       TLAP5
         No of Polishing Steps         1              LAPS5
              Pieces Per Batch         3              PCS5

  Load/Unload and Clean Wafers        40 min          PTIME5
        Average Polishing Rate         5 um/hr        RATE5
    Useful Polishing Plate Life       10 cycles       PLAL5

      Available Polishing Time     8,640 hrs          DAYHR5
    Building Space Requirement       400 sqft/sta     FLR5
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Model List 10

Hot Iron Polishing Cost Estimates

The total cost of the Hot Iron Polishing step is $224.78, of which 22.3% is due to direct labor costs. By using a non-baseline value of 100 cycles for the hot iron plate life, the operation cost is found to be $169.77, which is a 25% reduction. If, instead, the plate must be replaced after each cycle, the cost of this operation increases to $773.37, which is still significantly less than the cost of conventional lapping. A comprehensive cost summary of the Hot Iron Polishing is given in Model List 11.

DC Arc Economics: Hot Iron Polishing Cost Estimates

DC ARC CVD TCM: HOT IRON POLISHING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$50.23	$50,231	22.3%	
Utility Cost	$13.77	$13,773	6.1%	
FIXED COST ELEMENTS				
Equipment Cost	$39.60	$39,605	17.6%	$198,024
Tooling Cost	$33.00	$33,003	14.7%	$165,017
Building Cost	$4.00	$4,000	1.8%	$80,000
Maintenance Cost	$22.24	$22,242	9.9%	
Overhead Labor Cost	$25.00	$25,000	11.1%	
Cost of Capital	$36.92	$36,923	16.4%	
TOTAL FABRICATION COST	$224.78	$224,778	100.0%	$443,041

Model List 11

Oxygen Plasma Inputs

The inputs for the Oxygen Plasma Polishing operation are shown in Model List 12. This polishing process runs one wafer at a time, in a reactive atmosphere of pure oxygen. The amount of material removed is ten percent of the diamond wafer's original weight. The number of polishing steps is fixed at one. In the polishing inputs, the oxygen gas consumption is assumed to be 500 standard cubic centimeters per minute (sccm), and the machine power ten kilowatts. The building space requirement is 400 square feet per station, while the equipment cost is chosen to be $300,000 per station, a value typical for industrial plasma etching equipment.

DC Arc Economics: Oxygen Plasma Polishing Inputs

```
PROCESS RELATED FACTORS - OXYGEN PLASMA POLISHING
             Process In Use?          1 [1=Y 0=N]   USE6
        Dedicated Investment          1 [1=Y 0=N]   DED6
      Process Rejection Rate      10.0%             REJ6
  Average Equipment Downtime      15.0%             DOWN6
 Direct Laborers Per Station      0.25              NLAB6

                              Menu #        vol%
                            ------------------------
                     Oxygen      25       100.0%  GAS6A VOL6A
                  Argon Gas       4         0.0%  GAS6B VOL6B
                  Other Gas       0         0.0%  GAS6C VOL6C
                            ------------------------
                                          100.0%

            Material Removed   10.0% by wgt     TLAP6
         No of Polishing Steps        1             LAP6
            Pieces Per Batch          1             PCS6

      Oxygen gas Consumption        500 sccm        TFLOW6
 Load/Unload and Clean Wafers        40 min         PTIME6
       Average Polishing Rate       3.3 um/hr       RATE6

               Machine Power         10 kW          POW6
                Machine Cost   $300,000 /sta        MCH6
      Available Lapping Time      8,640 hrs     DAYHR6
  Building Space Requirement        400 sqft/sta    FLR6
```

Model List 12

Oxygen Plasma Cost Estimates

The cost of the Oxygen Plasma Polishing is $1,290/wafer. The capital equipment and maintenance are the majority of this cost, at 42.0% and 18.3% respectively, while direct labor accounts for 17.5%. The costs for this process are summarized in Model List 13.

The key parameter affecting the cost of oxygen plasma polishing is its high equipment cost, low capacity, and its average polishing rate of 3.3 microns per hour. However, a small improvement in any of these factors decreases the operation cost significantly. For instance, if the capacity increases only to two wafers per batch, the cost reduces to $466.

DC Arc Economics: Oxygen Plasma Polishing Cost Estimates

DC ARC CVD TCM: OXYGEN PLASMA POLISHING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$3.56	$3,562	0.3%	
Direct Labor Cost	$226.06	$226,062	17.5%	
Utility Cost	$21.35	$21,350	1.7%	
FIXED COST ELEMENTS				
Equipment Cost	$541.80	$541,800	42.0%	$2,709,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$12.00	$12,000	0.9%	$240,000
Maintenance Cost	$235.92	$235,920	18.3%	
Overhead Labor Cost	$75.00	$75,000	5.8%	
Cost of Capital	$174.08	$174,082	13.5%	
TOTAL FABRICATION COST	$1,289.78	$1,289,777	100.0%	$2,949,000

Model List 13

Oxygen Ion Milling Inputs

The inputs for the Oxygen Ion Milling operation are shown in Model List 14.

The process of Oxygen Ion Beam Milling processes 3 wafers per batch. The reactant gas is assumed to be 100% oxygen. The material removal is set to ten percent of the wafer's deposited mass. Oxygen gas consumption is fixed at fifteen sccm. The machine consumes roughly one kilowatt and the ion source life is assumed to be 1,000 hours, with a cost of $1,000 per source. For the linear polishing rate, a value of 0.24 um/hr is used, while the building space requirement is estimated at 400 square feet per station. The equipment cost is $500,000 per station, due to the three wafer capacity.

DC Arc Economics: Oxygen Ion Milling Inputs

```
PROCESS RELATED FACTORS - OXYGEN ION MILLING
             Process In Use?          1 [1-Y 0-N]    USE7
         Dedicated Investment         1 [1-Y 0-N]    DED7
       Process Rejection Rate      10.0%             REJ7
   Average Equipment Downtime      15.0%             DOWN7
  Direct Laborers Per Station      0.25              NLAB7

                                 Menu #        vol%
                               -----------------------
                       Oxygen       25       100.0%  GAS7A VOL7A
                    Argon Gas        4         0.0%  GAS7B VOL7B
                    Other Gas        0         0.0%  GAS7C VOL7C
                               -----------------------
                                             100.0%

             Material Removed   10.0% by wgt     TLAP7
        No of Polishing Steps        1               LAPS7
             Pieces Per Batch        3               PCS7
      Oxygen Gas Consumption        10 sscm          GASA7

              Ion Source Life     1000 hrs           SOUL7
              Ion Source Cost   $1,000 /ea           SCOST7

Load/Unload and Clean Wafers        40 min           PTIME7
                 Preheat Time        5 min           PREHT
      Average Polishing Rate      0.24 um/hr         RATE7

                 Machine Cost  $500,000 /sta         MCH7
                Machine Power        1 kW            POW7
     Available Polishing Time    8,640 hrs           DAYHR7
   Building Space Requirement      400 sqft/sta      FLR7
```

Model List 14

Oxygen Ion Milling Cost Estimates

The cost of polishing with an oxygen ion beam is $2,892. Of this value, 46.7% and 19.7% represent the capital equipment and maintenance costs, respectively. The direct labor contribution is 11.7% of the total cost. All costs for this operation are summarized in Model List 15.

DC Arc Economics: Oxygen Ion Milling Cost Estimates

DC ARC CVD TCM: OXYGEN ION MILLING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.35	$346	0.0%	
Direct Labor Cost	$339.22	$339,215	11.7%	
Utility Cost	$9.61	$9,611	0.3%	
FIXED COST ELEMENTS				
Equipment Cost	$1,350.00	$1,350,000	46.7%	$6,750,000
Tooling Cost	$64.20	$64,200	2.2%	$321,000
Building Cost	$18.00	$18,000	0.6%	$360,000
Maintenance Cost	$568.80	$568,800	19.7%	
Overhead Labor Cost	$112.50	$112,500	3.9%	
Cost of Capital	$429.57	$429,565	14.9%	
TOTAL FABRICATION COST	$2,892.24	$2,892,238	100.0%	$7,431,000

Model List 15

Sputter Deposition Inputs

As shown in Model List 16 the Sputtering operation assumes the sequential deposition of titanium, platinum, and gold, to a thickness of 0.1 um each. The capacity of the metallization chamber is set to 3 pieces per batch, which is a change from the 6 pieces per batch value previously used. The machine cost is derived from this capacity input. The building space requirement is 400 square feet per station.

DC Arc Economics: Sputtering Inputs

```
PROCESS RELATED FACTORS - METALLIZATION - SPUTTERING
             Process In Use?           1 [1=Y 0=N]   USE8
        Dedicated Investment           1 [1=Y 0=N]   DED8
      Process Rejection Rate         1.0%            REJ8
  Average Equipment Downtime        20.0%            DOWN8
   Direct Laborers Per Station       0.1             NLAB8
        Load/Unload Laborers           1             LLAB8

     Metal Layers                Menu #                Thick (um)
     ----------------------------------------------------------
     Titanium                          1 MET8A           0.10 THK8A
     Platinum                          2 MET8B           0.10 THK8B
     Gold                              3 MET8C           0.10 THK8C
     ----------------------------------------------------------

                   Load Time          15 min/batch   PTIME8
         Target Preheat Time           1 min/kW      HTIME8
            Pieces Per Batch           3 pcs/batch   PCS8

             Evaporator Power          3 kW          POW8
  Building Space Requirement         400 sqft/sta    FLR8
```

Model List 16

Sputtering Cost Estimates

The Sputtering operation contributes $128 per wafer to the overall production cost. As presented in Model List 17, the significant cost drivers for sputter metallization are related to equipment cost. Included in these costs are the investment in the equipment at 52.7% (down from 58.1%), its maintenance at 23.6%, and the cost of capital at 17% (up from 16.6%). At 1,000 wafers/yr, the metallization station is idle 95% of the time. In order to fully utilize this machine, the annual production volume must reach 20,000 wafers. Given this throughput, it seems sensible that a production facility making only 1,000 wafers per year would outsource metallization.

DC Arc Economics: Sputtering Cost Estimates

DC ARC CVD TCM: METALLIZATION - SPUTTERING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$1.36	$1,358	1.1%	
Direct Labor Cost	$0.24	$242	0.2%	
Utility Cost	$0.02	$16	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$67.65	$67,655	52.7%	$338,274
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$2.00	$2,000	1.6%	$40,000
Maintenance Cost	$30.26	$30,262	23.6%	
Overhead Labor Cost	$5.00	$5,000	3.9%	
Cost of Capital	$21.84	$21,842	17.0%	
TOTAL FABRICATION COST	$128.37	$128,374	100.0%	$378,274

Model List 17

Evaporative Deposition Inputs

The baseline assumptions for evaporative deposition are the same as sputtering; the sequential deposition of titanium, platinum, and gold, to a thickness of 0.1 um each. The assumptions are presented in Model List 18. The capacity of the metallization chamber is set to 5 pieces per batch and the machine cost is computed from the input using a regression relationship. The building space requirement is changed from 100 to 400 square feet per station.

DC Arc Economics: Evaporation Inputs

```
PROCESS RELATED FACTORS - METALLIZATION - EVAPORATION
             Process In Use?             1 [1=Y 0=N]   USE9
        Dedicated Investment             1 [1=Y 0=N]   DED9
      Process Rejection Rate           1.0%            REJ9
  Average Equipment Downtime          20.0%            DOWN9
 Direct Laborers Per Station           0.1             NLAB9
        Load/Unload Laborers             1             LLAB9

     Metal Layers                 Menu #             Thick (um)
     -----------------------------------------------------------
     Titanium                          1 MET9A          0.10 THK9A
     Platinum                          2 MET9B          0.10 THK9B
     Gold                              3 MET9C          0.10 THK9C
     -----------------------------------------------------------

                   Load Time            15 min/batch   PTIME9
         Target Preheat Time             1 min/kW      HTIME9
            Pieces Per Batch             5 pcs/batch   PCS9

             Evaporator Power            7 kW          POW9
  Building Space Requirement           400 sqft/sta    FLR9
```

Model List 18

Evaporation Cost Estimates

The evaporation operation is found to cost $52.16 per wafer, when substituted for sputtering. As shown in Model List 19, significant cost drivers for evaporative metallization are related to equipment cost. These include the investment in the equipment at 43.0% and its maintenance of 23.3%. The cost of capital is also significant at 17.5%.

At 1,000 wafers/yr, this metallization station is also idle 97% of the time. In order to fully utilize this machine, an annual production volume of 29,000 wafers must be realized. Given this capability, it is probable that any production facility making only 1,000 wafers per year would outsource metallization. At the higher production volumes, it would become economical to purchase the metallization equipment in the model.

DC Arc Economics: Evaporation Cost Estimates

DC ARC CVD TCM: METALLIZATION - EVAPORATION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$1.28	$1,277	2.4%	
Direct Labor Cost	$0.18	$177	0.3%	
Utility Cost	$0.03	$27	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$22.41	$22,412	43.0%	$112,060
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$2.00	$2,000	3.8%	$40,000
Maintenance Cost	$12.16	$12,165	23.3%	
Overhead Labor Cost	$5.00	$5,000	9.6%	
Cost of Capital	$9.10	$9,103	17.5%	
TOTAL FABRICATION COST	$52.16	$52,162	100.0%	$152,060

Model List 19

Inspection Inputs

The two inspection steps that process finished diamond films were recently added to the DC Arc Deposition model. The main inputs for microscopy are the machine cost, which is fixed at $50,000 per station, and average inspection time of 15 minutes/wafer. The number of direct laborers per station is assigned to be one. The percent inspection is set to 100%. The building space requirement per inspection station is fixed at 50 square feet per station. These inputs are shown in Model List 20. All settings described for the Microscopic investigation apply for the Thermal Conductivity Inspection operation.

DC Arc Economics: Inspection Inputs

```
PROCESS RELATED FACTORS - INSPECTION - MICROSCOPY
                Process In Use?            1 [1-Y 0-N]    USE10
           Dedicated Investment            1 [1-Y 0-N]    DED10
         Process Rejection Rate          5.0%             REJ10
     Average Equipment Downtime          5.0%             DOWN10
    Direct Laborers Per Station            1              NLAB10

        Average Inspection Time           15 min/batch    PTIME10
             Percent Inspection          100%             INSP10
                   Machine Cost      $50,000 /sta         MCH10

                  Machine Power         0.10 kW           POW10
     Building Space Requirement           50 sqft/sta     FLR10

PROCESS RELATED FACTORS - INSPECTION - THERMAL CONDUCTIVITY
                Process In Use?            1 [1-Y 0-N]    USE11
           Dedicated Investment            1 [1-Y 0-N]    DED11
         Process Rejection Rate          5.0%             REJ11
     Average Equipment Downtime          5.0%             DOWN11
    Direct Laborers Per Station            1              NLAB11

        Average Inspection Time           15 min/batch    PTIME11
             Percent Inspection          100%             INSP11
                   Machine Cost      $50,000 /sta         MCH11

                  Machine Power         0.10 kW           POW11
     Building Space Requirement           50 sqft/sta     FLR11
```

Model List 20

Inspection Cost Estimates

The cost of microscopic examination of diamond films is calculated at $82.38 in the baseline scenario. The equipment cost for this operation accounts for 18.2% of this total cost, while 6.4% is due to the direct labor cost. The largest contributor to the total production cost is overhead labor at 60.7%. The cost of thermal conductivity inspection is almost identical to optical examination, with a per wafer contribution of $82.11. The equipment is calculated at 18.3% of total operation cost, while direct and indirect labor are 6.1% and 60.9%, respectively. These costs are summarized in Model Lists 21 and 22.

DC Arc Economics: Microscopy Cost Estimates

DC ARC CVD TCM: INSPECTION - MICROSCOPY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$5.25	$5,249	6.4%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$15.00	$15,000	18.2%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.25	$250	0.3%	$5,000
Maintenance Cost	$6.40	$6,400	7.8%	
Overhead Labor Cost	$50.00	$50,000	60.7%	
Cost of Capital	$5.48	$5,482	6.7%	
TOTAL FABRICATION COST	$82.38	$82,382	100.0%	$80,000

Model List 21

DC Arc Economics: Thermal Conductivity Cost Estimates

DC ARC CVD TCM: INSPECTION - TEERMAL CONDUCTIVITY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$4.99	$4,986	6.1%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$15.00	$15,000	18.3%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.25	$250	0.3%	$5,000
Maintenance Cost	$6.40	$6,400	7.8%	
Overhead Labor Cost	$50.00	$50,000	60.9%	
Cost of Capital	$5.48	$5,477	6.7%	
TOTAL FABRICATION COST	$82.11	$82,115	100.0%	$80,000

Model List 22

Cost Summary

The baseline cost to produce six inch, metallized, diamond heat sinks is $4,357 per wafer. As shown in Model List 23, equipment costs are the largest contributing factor, at 23.4% of the cost. The high equipment costs per wafer are characteristic of many operations, including the deposition step. Because the analysis assumes dedicated equipment, and because production volumes are low, the underutilized capital, such as metallization chambers, figures significantly in the cost per wafer. Material costs, which account for 20.6% of the total, are mainly due to the cost of the gases consumed in the deposition step. Direct labor accounts for 10.9% of the total production cost, while utility costs are 14.0% of the total. Equipment and its maintenance together constitute 34.6% of the total cost.

DC Arc Economics: Cost Summary

DC ARC CVD TCM: COST SUMMARY
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$898.44	$898,439	18.1%	
Direct Labor Cost	$919.50	$919,502	18.5%	
Utility Cost	$609.61	$609,608	12.3%	
FIXED COST ELEMENTS				
Equipment Cost	$1,019.01	$1,019,015	20.5%	$5,095,074
Tooling Cost	$75.11	$75,110	1.5%	$375,550
Building Cost	$49.75	$49,750	1.0%	$995,000
Maintenance Cost	$487.21	$487,206	9.8%	
Overhead Labor Cost	$480.00	$480,000	9.7%	
Cost of Capital	$422.90	$422,900	8.5%	
TOTAL FABRICATION COST	$4,961.53	$4,961,529	100.0%	$6,465,624

Model List 23

Sensitivity Analysis

Gas Recycle

The effect of compressed gas recycling on deposition cost is studied by determining the annual production volume needed to offset the added cost of recycling equipment. As seen in Figure 2, by producing 1,510 diamond films a year, the diamond wafer cost equals the baseline cost at 1,000 wafers with liquid hydrogen and argon, assuming the argon recycle equipment can be obtained for $200,000. This argon recycle equipment is assumed to recover 99% of the process gases. Higher production volumes are seen to be even more economical. The material cost for deposition with compressed gases and recycling producing only 1,000 wafers per year was found to result in more expensive diamond wafers than the baseline case using liquid gases.

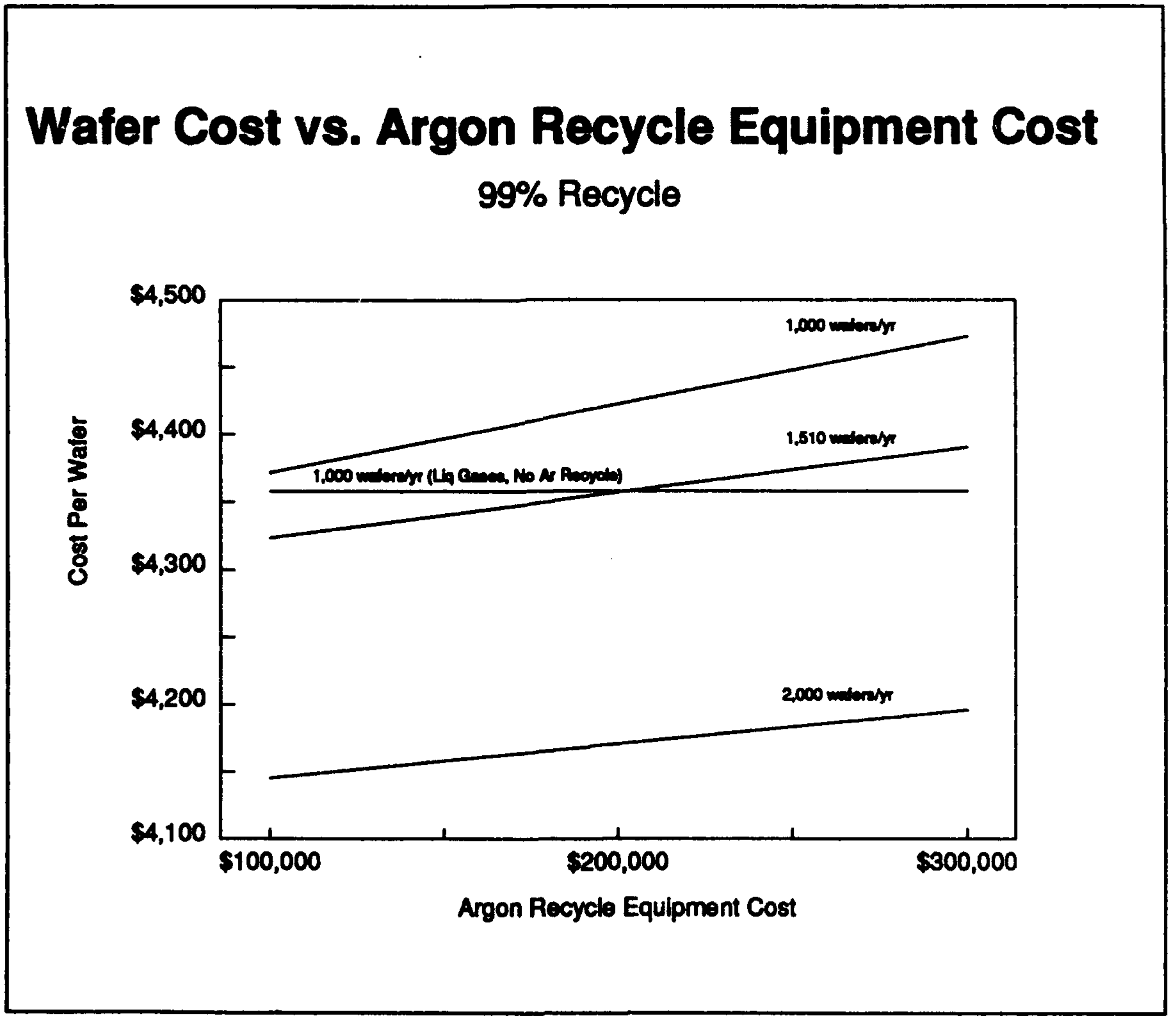


Figure 2

The Effect of Machine Capacity on Finishing Costs

The cost associated with alternative polishing processes are all found to be more than the baseline cost with traditional lapping technology, except for hot iron polishing, which has a higher material removal rate than the other technologies.

Abrasive Lapping

Figure 3 shows the total production cost per wafer using Abrasive Lapping as a function of the polishing batch size used. The batch size employed in the baseline scenario is indicated. The optimal capacity to be used for abrasive lapping is twenty wafers per batch. For capacities lower than twenty, the lapping machine must operate for a longer period of time, therefore requiring more man-hours, machines, and electricity. For

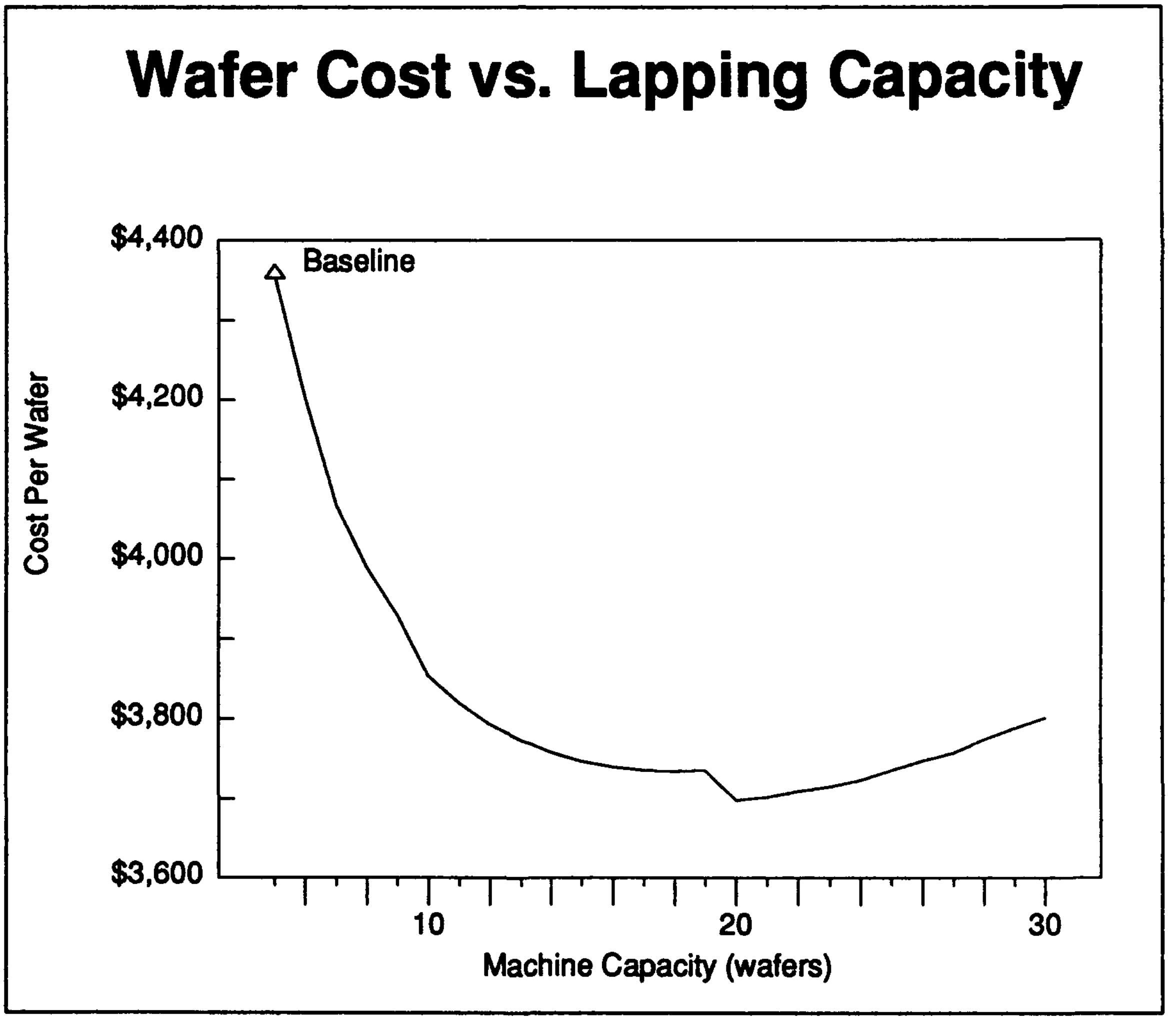


Figure 3

capacities higher than twenty wafers per batch, the lapping plate cost increases significantly, preventing these higher capacities from being economical.

For both lapping and hot iron polishing, the cost per wafer reaches a minimum. As the capacity increases from this minimum (twenty wafers per batch for lapping, six wafers per batch for hot iron polishing), the cost of the iron plate (for the lap plate or the hot iron sciathe) becomes more amplified, causing the cost per wafer to increase dramatically. Therefore the cost per wafer increases with these larger capacities, and there is an optimal value for machine capacity.

Hot Iron Polishing

When the Hot Iron Polishing operation is used exclusively, the total production cost per wafer is calculated to be $3,323. Figure 4 shows the variation of wafer cost with polishing batch size using the Hot Iron Polishing operation. The wafer cost decreases as the capacity increases until the capacity reaches ten wafers per batch. This cost reduction is due to the drop in run time for the hot iron polishing machine.

In both the lapping and hot iron polishing analyses, a statistically derived relationship is used to estimate equipment cost as a function of the number of pieces per batch. The data this relationship is derived from included costs for machines capable of handling up to 20 six inch diameter wafers.

Oxygen Plasma Polishing and Oxygen Ion Milling

Figures 5 and 6 show the total production cost per wafer using Oxygen Plasma Polishing and Oxygen Ion Milling as a function of polishing batch size. In constructing these curves, the appropriate number of single chamber systems are linked together in a cluster tool configuration. Each chamber adds $50,000 and $100,000 to the total cost of the Plasma and Ion systems respectively, which have base costs of $300,000. As can be seen by comparing Figures 4, 5, and 6, Oxygen Plasma Polishing and Oxygen Ion Milling are more expensive than Hot Ion Polishing.

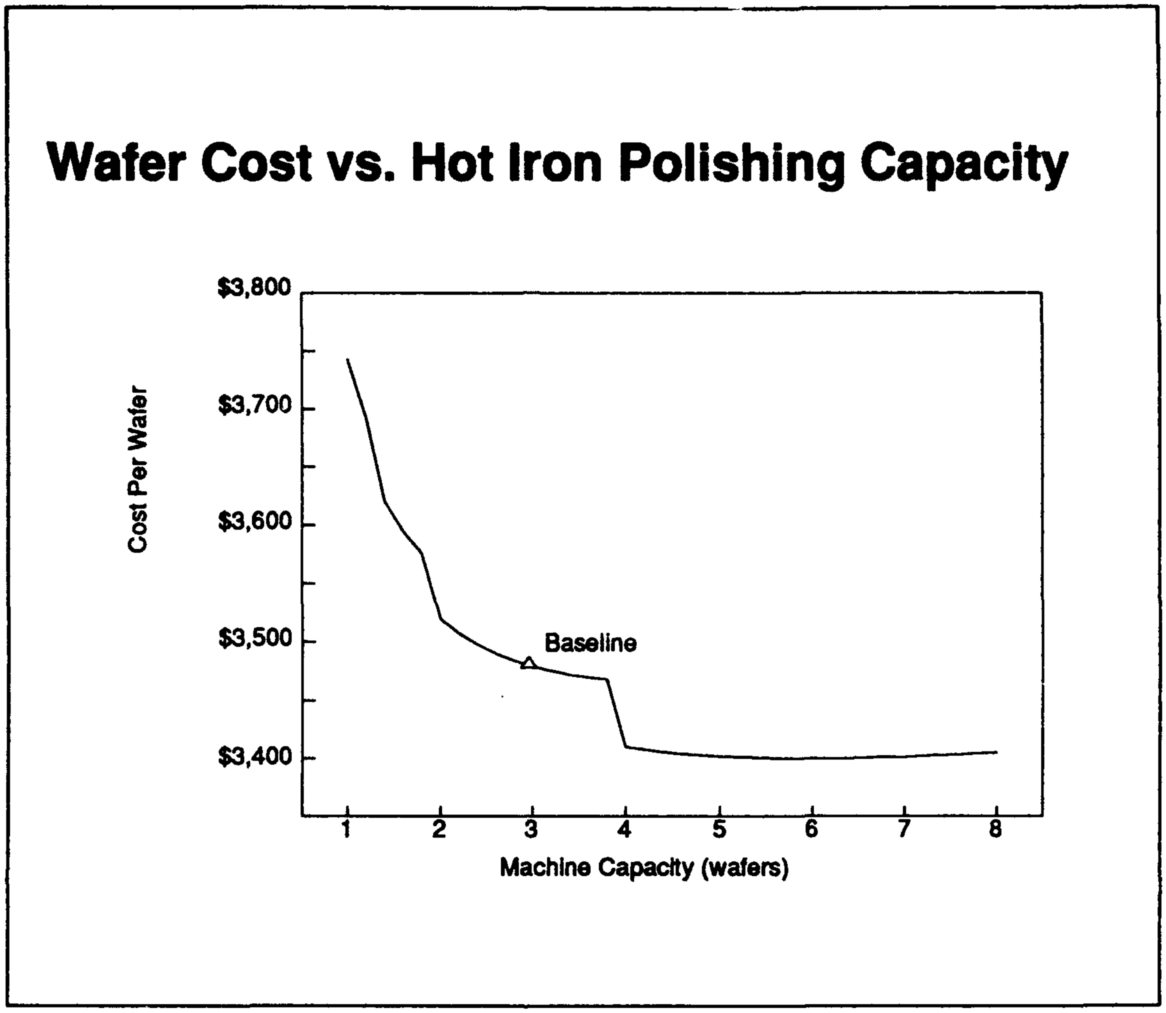
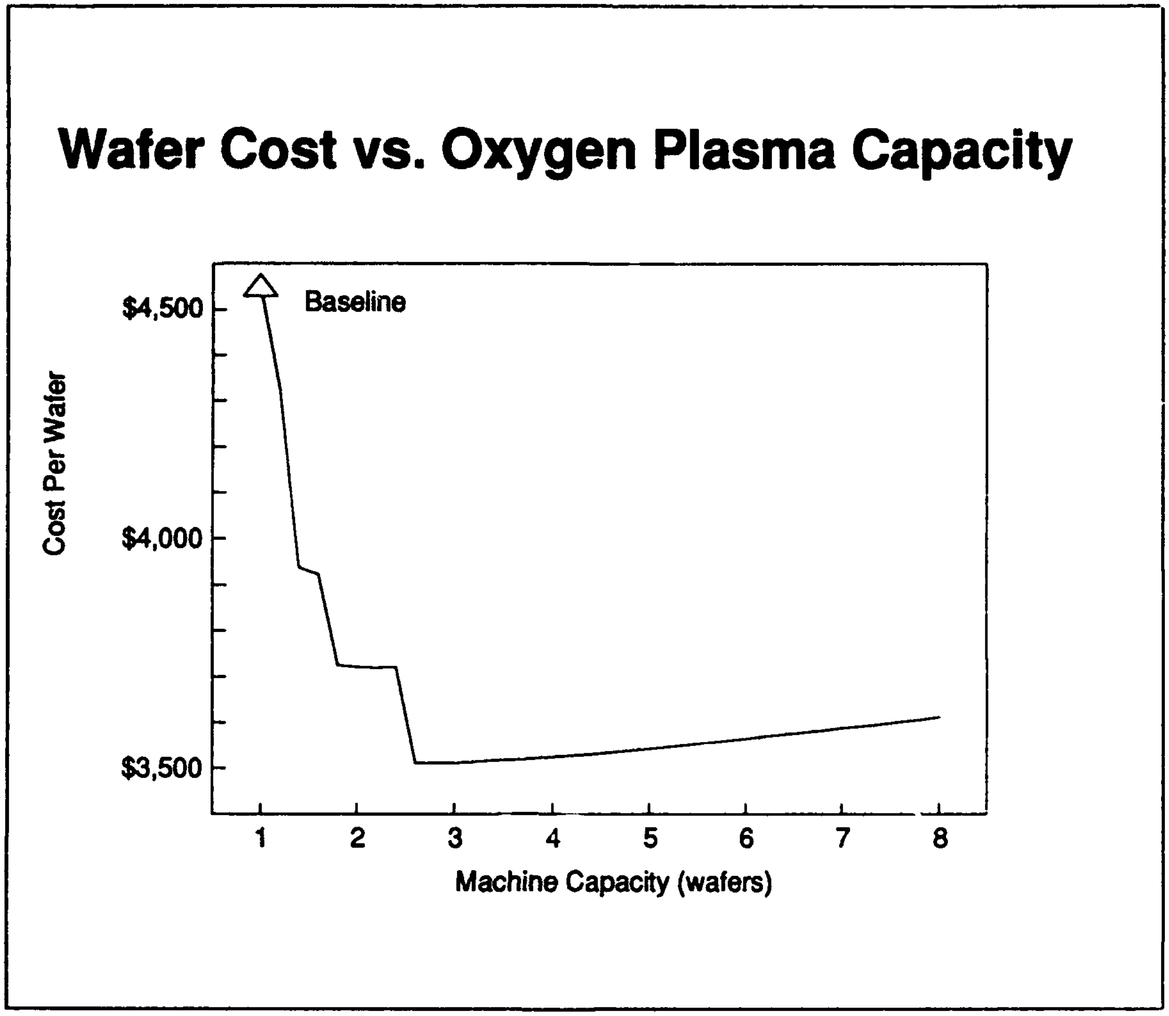

Wafer Cost vs. Hot Iron Polishing Capacity
$3,800
$3,700
$3,600
$3,500
$3,400
Cost Per Wafer
Baseline
1
2
3
4
5
6
7
8
Machine Capacity (wafers)

Figure 4



Wafer Cost vs. Oxygen Plasma Capacity
Baseline
$4,500
$4,000
$3,500
Cost Per Wafer
1
2
3
4
5
6
7
8
Machine Capacity (wafers)

Figure 5

The Effect of Combining Finishing Technologies

Combinations of two or more polishing processes are found to be more expensive than the unit operations of which they are composed, as illustrated in Figure 7, where the price per wafer is plotted against a percentage measure of the partition between the processes. For all polishing combinations, it is assumed that a total of 10% of the deposited diamond is removed, regardless of polishing combination. The weight percent of diamond removed by the first operation is shown on the horizontal axis, while the vertical axis indicates the cost per wafer. At 10%, the second process is removing no material and therefore is not in use. The top curve shows a combination of Abrasive Lapping and Oxygen Plasma Polishing. The wafer cost is seen to decrease only slightly as the Lapping percentage increases from zero weight percent to ten weight percent. The combination of Hot Iron Polishing and Plasma Polishing becomes cheaper as the contribution of Hot Iron Polishing increases. For all polishing combinations the large drops in price at the extremes (0% and 10%) are included to indicate the costs of these

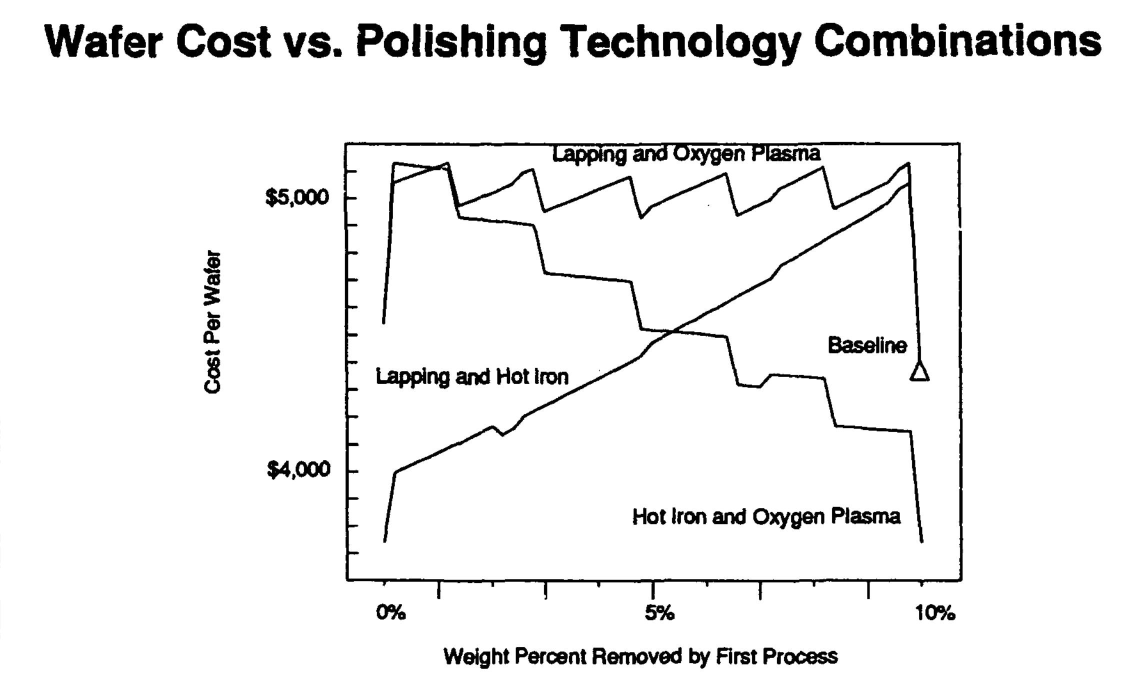


Figure 6

individual polishing operations. The step-like jumps in these graphs are due to increases in the number of parallel polishing stations.

The Effect of an Increasing Material Removal Percentage

It is possible to evaluate the different polishing methods by comparing wafer cost to the weight percent of diamond that is removed. Figure 8 shows cost per wafer as a function of the deposited material removal percentage. The greater the mass of diamond polished or lapped, the more diamond must initially be deposited. This, in turn, adds to the total cost by increasing the cost of the deposition operation. In comparing polishing technologies, therefore, the best technique yields the final surface finish while removing diamond at a high rate. In Figure 8, this translates to flat or shallow sloped curves. Abrasive lapping, for small diamond removal, is relatively inexpensive due to low capital costs but increases quickly due to its slow removal rate. With higher removal rates, the Hot Iron Polishing and Oxygen Plasma Polishing operations remain relatively inexpensive with increasing mass removal percentages, and therefore have the shallower slopes. The step-like jumps in these graphs are due to increases in the number of parallel polishing stations.

Wafer Cost vs. Polish Weight Removal

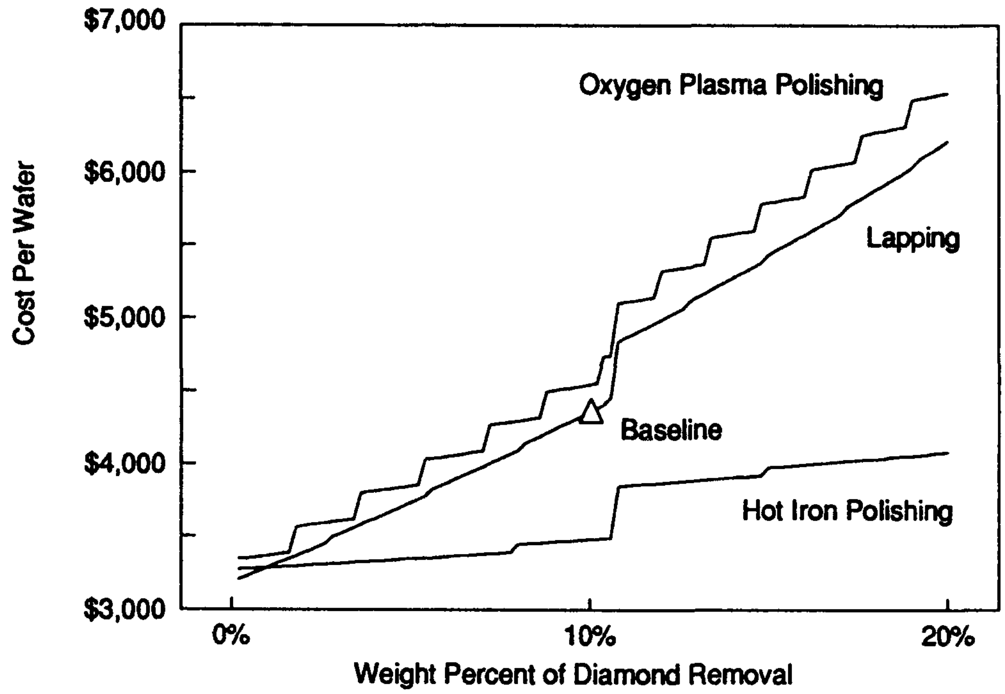


Figure 7

The Effect of Metallization Technology and Capacity

The dependence of total production cost on the type of metallization is determined. Figure 9 illustrates the dependence of diamond film production costs on the batch size used in the sputtering and evaporation operations. By comparing these curves, it is evident that small batch sizes favor the evaporation equipment. Due to the rapid rise in cost with increasing evaporation capacity however, sputtering equipment is the preferred technology for baseline metallization.

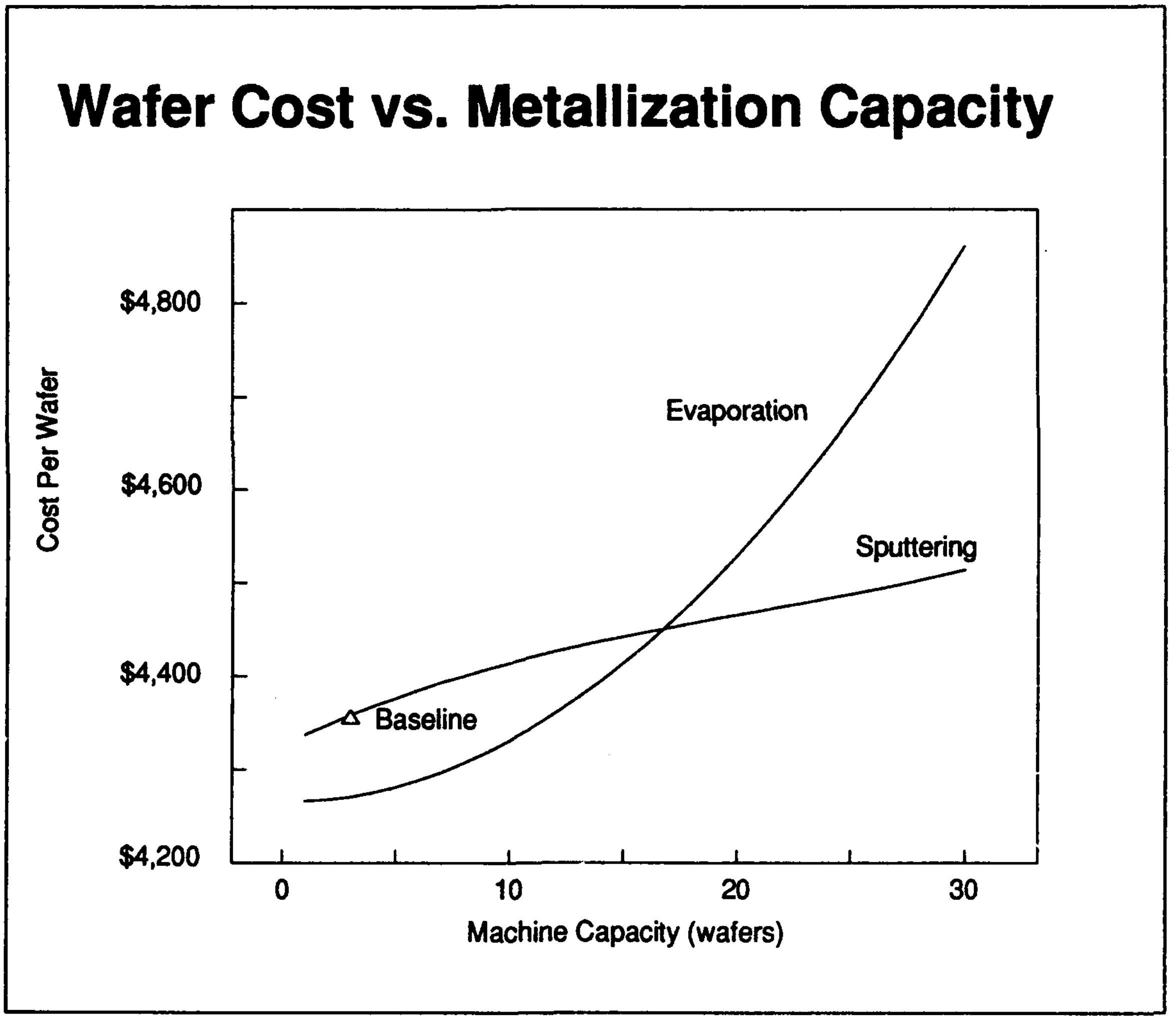


Figure 8

Summary & Conclusions

IBIS Associates, through Technical Cost Modeling (TCM), has updated its predictive spreadsheet model of the DC Arc diamond deposition technology. This report presents the results obtained with the new model and a revised set of baseline inputs for diamond heat sink manufacture. The cost of producing 1,000, six inch, polished and metallized diamond wafers, 1 mm thick, by the DC Arc deposition technology is estimated to be $4,357 per wafer. Sixty-four percent of this cost is attributable to the deposition step, which is capital and labor intensive. The cost of finished diamond wafers is also dominated by equipment costs, at 23.4%, and material costs, at 20.6% of the total production cost.

It is found that the implementation of an argon recycling system makes diamond deposition with compressed gases economical relative to diamond deposition with liquid source gases, if the annual production volume for compressed gas operation is 1,525 diamond wafers per year, increased from 1,000.

The major revisions to the DC Arc Model over this reporting period are the alternative polishing technologies, which can be used exclusively or in conjunction with each other. More updated information is also added to the abrasive lapping operation.

Using only abrasive lapping, with new input data, the total production cost per wafer is determined to be $4,357. Using only Hot Iron polishing this cost is reduced to $3,479 per wafer. Oxygen Plasma Polishing alone results in a cost of $4,544 per wafer, while Oxygen Ion Milling yields a cost of $6,146 in the baseline case. This increase in the wafer cost is due to the slow material removal rates characteristic of Oxygen Ion Milling. By using a 5 capacity polishing system this cost is reduced to $4,909.

It is determined that any combinations of faster processes are more expensive than the individual processes and that the exact cost varies with the contribution of each process. For instance, the combination of Hot Iron (4% removal) and Oxygen Plasma Polishing (6% removal) costs $4,709 per wafer as compared to $3,479 for Hot Iron Polishing and $4,544 for Oxygen Plasma polishing alone.

The capital cost of metallization equipment for coating diamond film wafers varies with throughput. New regressions are incorporated into the DC Arc model to more accurately estimate the cost of metallization equipment. It is found that both sputtering and evaporation operations remain severely underutilized with 95% and 97% idle times, respectively, for the production of 1,000 metallized wafers per year. Less expensive, lower throughput machines do not lead to reductions in idle time significant enough to justify metallization inhouse. Instead, the outsourcing of the metallization operation to third party vendors remains the most economical option.