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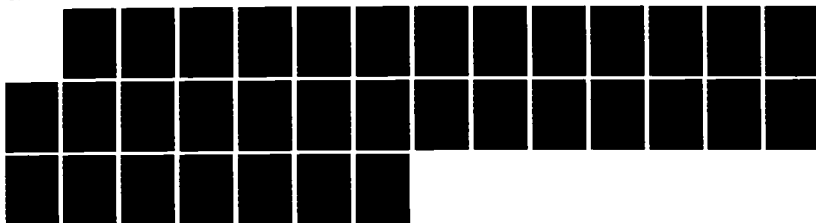
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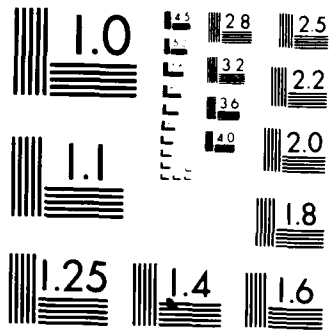
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THE OPTOELECTRONICS JOINT RESEARCH LABORATORY:
LIGHT SHED ON COOPERATIVE RESEARCH IN JAPAN

by

James L. Merz
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106

Professor James L. Merz spent the Fall of 1985 as a Visiting Research Scientist in the Optoelectronics Joint Research Laboratory (OJL) in Kawasaki, Japan. OJL is a joint cooperative laboratory staffed by researchers from nine private electronics companies in Japan through the sponsorship of the Ministry of International Trade and Industry (MITI) of the Japanese government. Professor Merz was the first foreign visiting researcher in this laboratory, and was able to observe first-hand how government/industry cooperative research proceeds in such an environment. In addition, Professor Merz visited the research laboratories of many of the member companies. This report represents an assessment of the effectiveness of a joint cooperative research laboratory such as OJL for optoelectronics research and development in Japan.

Professor Merz is the Director of the Compound Semiconductor Institute at the University of California, Santa Barbara, and a Professor of Electrical Engineering.

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**THE OPTOELECTRONICS JOINT RESEARCH LABORATORY:
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INTRODUCTION

In 1985 a very significant event occurred in the semiconductor industry. The country of Japan sold approximately 10 billion dollars worth of semiconductor devices and integrated circuits, equalling or surpassing the United States' share of the world's market for the first time. Although it is difficult to make an exact comparison between the two countries,¹ sales statistics for a few preceding years suggested that this would eventually happen. The process was accelerated in 1985 because of two factors: 1) the slump during most of 1985 in the semiconductor industry, which appears to have affected the United States more than Japan, and 2) the depreciation of the dollar relative to the yen that occurred dramatically in the fall of 1985 so that constant Japanese sales in yen produced an apparent increase in sales in dollars. Nevertheless, the fact that Japan has finally caught up to the United States in the semiconductor market will have profound effects on the industry in this country, and many people are asking how this happened. Much has been published about the growing strength of the Japanese semiconductor industry; a few examples are given in the references.²⁻⁵ One of the major reasons often given for this dramatic increase in semiconductor technology in Japan has been the establishment of cooperative research projects between industry and the Japanese government through the Ministry for International Trade and Industry (MITI). In particular, the establishment of joint laboratories with personnel shared from member companies has been an innovative approach to research and development in Japan. During the fall of 1985 I had the great fortune to be invited to serve as a visiting researcher in one of those cooperative laboratories, the Optoelectronics Joint Research Laboratory, and in this paper I would like to share some of my observations from that experience.

Optoelectronic devices and the III-V compound materials from which they are fashioned represents only a small portion of the semiconductor industry. Japanese sales for both III-V semiconductors and silicon are compared in Table 1. Two interesting facts are seen in this table. One is that the for both III-V compounds and silicon the substrate sales represent about 10% of the

Table 1. JAPANESE SEMICONDUCTOR SALES, 1985

<u>TOTAL SALES</u>	<u>III-V</u>	<u>Si</u>
SUBSTRATES	\$50. million	\$1.0 billion
DEVICES		
Discrete	\$500. million	\$2.4 billion
ICs	—	\$7.6 billion
Total Devices	\$500. million	\$10.0 billion

Table 2. III-V COMPOUND DEVICES SOLD IN JAPAN (millions of units)

<u>OPTICAL</u>	<u>1985</u>	<u>1990 (est.)</u>
LEDs	3,800	11,700
LDs: Visible (CDs)	2.8	11.4
LDs: IR (Opt. Comm)	.03	0.2
Detectors	.03	
Solar Cells	2.0	
<u>ELECTRONIC</u>		
Wave diodes	0.7	
FETs	7.5	11.7
Hall Elements	243	370

device and circuit sales. Secondly, for both substrates and devices, III-V compounds represent approximately 5% of the total market. Thus, although not a major contributor to semiconductor economics, III-V compound sales are not insignificant. I think, therefore, that my experiences at the Optoelectronics Joint Research Laboratory provide meaningful information about what is happening in the semiconductor industry in Japan. It should be noted that it is estimated that the Japanese have captured approximately 90% or more of the total non-captive market of III-V compound substrates and devices. The rapid development of optoelectronic technology over the last five years in Japan has been described by the Optoelectronic Industry and Technology Development Association.⁶

A breakdown of compound semiconductor devices sold in Japan in 1985 is provided in Table 2. In all cases listed, Japan holds a very large edge over the United States. This is primarily a result of the fact that these devices are used in large numbers in the consumer electronics and optical communications systems for which Japan dominates the world market. A number of interesting facts emerge from this data. The first is that the clear leader in sales are the relatively unsophisticated light emitting diodes (LEDs) which outsell their nearest competitor in this table by nearly three orders of magnitude. Visible LEDs are used in large numbers for displays and indicator lights in consumer electronics, and infrared LEDs are used for many kinds of sensing devices, including camera auto-rangefinders. Thus, although the cost per device is small, a very large number of these devices find their way into the electronics industry. Another surprising fact

is the very large number of visible laser diodes (LDs) that are sold; these are used in compact disks (CDs), a market which is anticipated to increase very rapidly in the next few years.⁷ Even in the area of optical communications, where infrared LDs are used, the Japanese have a large domestic market because the use of optical communications systems is widespread. Their devices are of very high quality so that, even in the United States, Japanese lasers at 1.3 micron are often preferred. For example, the Bell system has chosen to buy Japanese lasers for certain applications, and the Atlantic cable will use Hitachi lasers. It should be noted that there is a large difference in price between visible lasers used in CDs (~ \$10 each), and infrared lasers used for communications (~ \$1000 each). The big market in GaAs solar cells is satellite usage. Just as for optical devices, consumer electronics are again the major force for the sale of electronic devices. For example, the sale of Hall elements, which are needed in video cassette recorders (VCRs), dominates the electronic market by a large amount.

As far as substrates are concerned (which, as shown in Table 1, represent approximately 10% of total semiconductor sales), it is estimated that the United States has approximately half of the substrate market, but that much of it is for internal company use (i.e., captive market) and is therefore not for sale. An example of this is the substrate production by AT&T Bell Laboratories.



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COOPERATIVE RESEARCH IN JAPAN

How did Japan capture so much of the market in III-V semiconductor sales, and take over the lead for semiconductors in general? This is a question that has been hotly debated in the halls and offices of industry in both the United States and Japan, and one for which there is no clear answer. Many people ascribe the growing dominance of Japan in the microelectronics industry to their imaginative use of cooperative research, particularly between industry and the Japanese government in the form of MITI. Table 3 gives a list of current (or recently completed) cooperative research projects in Japan; those dealing with III-V compounds are underlined for emphasis, and the number of companies participating in the project is given. In all cases, the project is of limited duration, with times ranging from four to eight years, and MITI contributes a substantial amount of the budget. Although budget figures are not available in some cases (at least not to me), if one makes reasonable guesses about the level of support in those cases, one sees that an appreciable

Table 3. JAPANESE GOVERNMENT PROJECTS RELATED TO COMPUTER AND COMMUNICATIONS RESEARCH AND DEVELOPMENT

Project	Subject	Comp.	Lab	Budget(\$million)		FY85
				Time	Total	
Optoelectr. Applied System	<u>Optical</u> <u>Loc. Area</u> <u>Network</u>	14 + ETL	OJL (9)	79-85 (OJL to 3:87)	75	14.6
Super- computer	<u>MESFET</u> <u>HEMT</u> JJ	6 + ETL		81-89	96	11.3
Fifth Generation Computer	Artific. Intell.	7+ETL, ECL, NTT	ICOT Res. Lab	82-91	?	20.0
Future Electron Devices	<u>Superlatt.</u> 3D Si Hard ICs	11 + ETL		81-87	?	6.3
Inter- Operability	Interop. between computers	info not available		85-91	63	3.1
System	System software, maint.	info not available		85-88	?	12.5
Advanced Robot Technology	Robotics	ETL, MTL		83-90	83	3.3
Flexible Mfg. System	Manufact. Techn.	ETL, MTL		77-84	57	0.0
<u>TOTAL</u>					600-700	73.1

fraction of one billion dollars is being spent on research and development using this cooperative approach, and over seventy million dollars last year alone.⁸ The cooperative projects listed in Table 3 are only those for microelectronics computer and communication research, and for automated manufacturing; there are cooperative projects in many other areas as well. For example, the Japanese are making major efforts in biotechnology.

The VLSI Project

How effective are these cooperative projects? To try to answer that question, let us look at the first of these cooperative projects (not listed in Table 3), the VLSI project. Information about the VLSI project is given in Table 4. The project had only a four-year lifetime, from 1976-1980. It was established for a specific purpose, to respond to the domination of the integrated circuit memory market that the United States enjoyed; the emphasis, therefore, was on specific technology development. Only five companies, listed in Table 4, participated in this project. Those companies contributed approximately 60% of the three hundred million dollar total budget for the project, while MITI contributed the other 40%.

Table 4. THE VLSI PROJECT, AN EARLY EXAMPLE OF COOPERATIVE RESEARCH IN JAPAN

- 4 years: 1976-1980
- Develop VLSI Technology
- 5 Member Companies*
- Budget
 - Companies: ¥42 billion = \$180 million
 - MITI: ¥28 billion = \$120 million
- VLSI Special Project Laboratory
 - Budget: ¥10 billion (=15% of total)

* Fujitsu, Hitachi, Mitsubishi, NEC, Toshiba

A significant aspect of the VLSI project was the formation of a special project joint laboratory whose personnel came from the research laboratories of the five member companies. Approximately 15% of the total budget was spent in support of this special project laboratory. Researchers from the five member companies worked together on specific projects, and at the end of their project they returned to their companies in good standing. This is made possible by the "lifetime employment" approach that is part of the Japanese system, and would be much more difficult to do in the United States. The limited lifetime of these cooperative research laboratories was a very attractive feature to the member companies, since the commitment made to this research would be limited, and personnel would return at the end of the project. When the project lifetime ended, the doors of the special project laboratory clanged shut, researchers returned to their parent companies and the assembled equipment was divided up through sales to the highest bidder.

Much has been written about the effectiveness of these cooperative research projects. For example, Uenohara *et al*² stated "clearly the VLSI project was a remarkable organizational innovation that essentially succeeded in engendering a new breadth of capability in the Japanese semiconductor industry". In another chapter of the same book Weinstein *et al*² provided a list of 22 specific new products and processes that resulted from the VLSI project. On the other hand, later in the same chapter they state "except for the work using liquid crystals, the Japanese did not appear to have made any major breakthroughs." Nevertheless, when one tries to judge the outcome of such a project by looking at the long-term results, the judgment is quite positive: "By the end of 1981 the Japanese had captured 70% of the 64K RAM market and some industrial commentators declared that Japan had 'won' the battle for the memory market."² Recall that in 1976 Japan had little or no RAM capability!

Thus, although the long range result of the VLSI laboratory appears to be a very positive one, there is still some question as to whether or not the same effects would have been accomplished without the special project joint laboratory. There is a point of view, which was expressed to me by several of the managers of member companies that I visited during my stay in Japan, that, in fact, the money spent on these cooperative laboratories might better be spent by the companies themselves, so that more rapid progress could have been made within the member company laboratories.

THE OPTOELECTRONICS APPLIED SYSTEM PROJECT

The organization of the cooperative research project in optoelectronics was quite different from the VLSI project, as shown in Table 5. In this case, the project lasted for seven years, from 1979-1985, and it was focussed on the research and development of an optical measurement and control system for a specific industrial environment. There are fourteen member companies in this project, plus the Electrotechnical Laboratory (ETL); these are listed in Table 6. MITI's budget was a total of approximately 75 million dollars. The project also included a special project joint laboratory, the Optoelectronics Joint Research Laboratory (OJL), which has received a great deal of favorable publicity.⁹⁻¹¹ OJL was started in 1981 and was intended to have a lifetime of six years, although it has been extended for a seventh year until March, 1987, at a significantly reduced budget. OJL's mission was directed much more towards basic research than was the VLSI laboratory; OJL had the charge of working on generic materials technology that would be of use to all of the companies in developing III-V devices. Thus, OJL did not work on devices themselves, but worked on a broader range of basic materials research which the member companies needed for device development. This approach had a number of advantages; for example, the companies did not have to give away any of their processing and fabrication secrets that are so important in device development and manufacturing, and at relatively low cost, they could participate in materials research that might be considered too expensive for any one company. Along with ETL, nine of the fourteen members of the Optoelectronics Applied System Project joined OJL, and MITI's contribution to OJL's budget was approximately

Table 5. THE OPTOELECTRONICS APPLIED SYSTEM PROJECT, AN IMPORTANT CURRENT EXAMPLE OF COOPERATIVE RESEARCH IN JAPAN

- 7 years: 1979-1985
- R&D of Optical Measurement and Control System
- 14 Member Companies + ETL
- MITI Budget
 - TOTAL: ¥18 billion = \$75 million
 - FY85: ¥3.5 billion = \$15 million
- Optoelectronics Joint Research Laboratory (OJL)
 - 6 years: 1981-1986 (→ March 1987)
 - Generic Materials Technology
 - 9 Member Companies + ETL
 - MITI budget: ¥6 billion = \$25 million
(= 1/3 of total)

Table 6. PARTICIPANTS IN THE OPTOELECTRONIC APPLIED SYSTEM PROJECT (MEMBERS OF OJL ARE UNDERLINED)

GOVERNMENT LABORATORY

- Electrotechnical Laboratory (ETL)

PRIVATE INDUSTRY LABORATORIES

- Fuji Electric
- Fujikura Cable
- Fujitsu
- Furukawa Cable
- Hitachi
- Matsushita
- Mitsubishi
- NEC
- Nippon Sheet Glass
- Okai
- Shimadzu Seisakusho
- Sumitomo
- Toshiba
- Yokogawa Hokushin Electric

1/3 of the total. A breakdown of that budget is given in Table 7, where it can be seen that nearly 60% of MITI's funds were spent on capital equipment for the laboratory. Thus, the effect of MITI's sponsorship of this project was that OJL was a very capital-intensive laboratory; the management of OJL assembled the most impressive collection of high-technology, materials-oriented, state-of-the-art equipment that I have ever seen. The rather small space rented from Fujitsu in their Kawasaki facility was literally crammed with machines for sophisticated crystal growth, such as molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), and the finest characterization and analysis equipment available. In fact, the ratio of occupied to unoccupied floorspace was so large that this somewhat overweight middle-aged professor found it difficult to get around the lab without danger to elbows and shins!

It is interesting to compare certain aspects of the two special project joint laboratories that I have just described, the VLSI lab and OJL. This is done in Table 8. As mentioned before, the VLSI lab had a four year lifetime, whereas OJL was in operation for seven years. On the other hand, the number of technical staff for the VLSI lab exceeded one hundred, more than twice the staff of OJL, so that the total number of man years was approximately the same, and the total budget was approximately the same. The VLSI lab was far more concentrated, and represented a much bigger effort for a short period of time to develop technology, than the more long-range materials research that has been carried out by OJL. The results of these differences are clear from the number of patents, publications and papers that were forthcoming from these labs. In Table 8 it is clear that the VLSI laboratory concentrated on patents, receiving approximately 450 in a period of only four years, whereas more publications have already come out of OJL, and its publication rate is rapidly increasing in its final year. Thus, OJL was a considerably more basic research endeavor, which may contribute to its effectiveness; although it is still in operation, nearly everyone with whom I have spoken considers it to be a resounding success. A measure of that success is the plan for a "second generation" optoelectronics project with a ten-year lifetime (cf. below).

Table 7. OJL BUDGET BREAKDOWN

• MITI		
- Equipment	\$14	M
- Other ^a	\$11	M
Sub-total	\$25	M
• MEMBER COMPANIES		
	\$12.5	M
TOTAL	\$37.5	M

(a) includes 50% of research salaries

Table 8. COMPARISON of VLSI LABORATORY and OPTOELECTRONICS JOINT RESEARCH LABORATORY

	VLSI Lab	OJL
No. of Technical Staff	110	50
Years	4	-
Total Budget	\$40M	\$37.5 M
Patents	450	130
Papers, Publications	460	510

The Optoelectronics Applied System Project had as its goal the research and development of an optical measurement and control system that would be applied to a specific industrial need. It was decided that the first application would be to an oil refinery plant for a number of reasons: (1) Such plants tend to be extremely large and yet closed systems, so that an optical system would be appropriate; (2) There is a need for a large number of sensors for process control, and these sensors could be optical devices; (3) The use of electrical energy for measurement and control raises very serious safety issues; and (4) not insignificantly, there was funding available to MITI through the tax base provided by the oil companies. A total system was targeted for introduction in the Kansai area (Osaka, Kobe, Kyoto) in the fall of 1985. It was actually introduced in the Mizushima Oil Refinery Plant of the Japan Mining Co. (Nihon Kogyo) located about one hour from Osaka during the month of January, 1986.

The optical system was divided into a number of sub-systems which are listed in Table 9. These subsystems have names like "Complex Process Data Subsystem", "Data Control Subsystem", "High-Speed Image Data Subsystem", etc., all of which convey relatively little meaning to me. However, each of these subsystems is centered around a specific optoelectronic device which has a great deal of meaning. Examples are: a multi-wavelength (five different wavelengths) indium phosphide distributed-feedback (DFB) semiconductor laser, a GaAs phase-locked laser array for very high output power, a visible emitting laser diode, etc. In each case, the subsystem device was given to a specific company to develop. The details for these assignments are shown in Table 9. Two of the subsystems listed in Table 9, the High-Speed Process Data Subsystem and the High-Quality Image Data Subsystem, have actually been demonstrated in the oil refinery plant; the others have been demonstrated in the laboratories of the responsible companies. In addition to these subsystems, many optical fiber sensors have been developed through this project.

Table 9. THE FIVE SUBSYSTEMS OF THE OPTOELECTRONICS APPLIED SYSTEM PROJECT

- Complex Process Data Subsystem
 - *Multi-wavelength Laser*
 - 5-wavelength InP DFB
 - Toshiba
- High-Speed Process Data Subsystem
 - *High Power Laser Diode*
 - GaAs phase-locked laser array
 - Mitsubishi
- Data Control Subsystem
 - *Integrated High-Speed Laser Diode*
 - Integrated GaAs driver, modulator detector
 - Hitachi
- High-Quality Image Data Subsystem
 - *Highly Integrated Multi-Channel Optoelectronic Switch*
 - Sophisticated OEIC
 - Fujitsu
- High-Speed Image Data Subsystem
 - *Visible-Emitting Laser Diode*
 - InGaAlP
 - NEC

Let us turn to a few of the devices listed in Table 9, to estimate the progress that individual companies have made on their assigned devices. Before doing this, however, it is appropriate to make an aside.

It is not the simplest task to judge the quality of the research of a group of people, or for that matter, of a large company or even a country. One measure that is frequently used (particularly by the Japanese) is the number of presentations or publications that have been produced by the particular group in question. Although it is clear that this approach has its limitations, it is nevertheless useful, particularly if the yardstick employed is an international conference or a major journal with a critical selection process. The most recent conference that could be considered appropriate for compound semiconductor optoelectronics was the International Conference on GaAs and Related Compounds, held at Karuizawa, Japan, in September, 1985. Clearly, the host country has an advantage at such an international conference; for example, the French had more than their usual number of papers when this conference was held in Biarritz the year before. However, it was the opinion of most of the foreign attendees with whom I spoke that the Japanese contributions totally dominated the Karuizawa conference, and that the progress they had made in both the device and materials areas was no less than spectacular! It seemed that a long-range commitment to III-V compound technology made some years ago by the large electronics companies in Japan had paid off handsomely; the results came pouring out at Karuizawa. It was clear in addition that these same companies had made significant progress on their part of the optoelectronics project as given in Table 9. A few examples should prove the point.

1. Both Sony and NEC announced a high-quality visible laser at the Karuizawa conference, capable of competing with the Xerox PARC device that has been the leader in high-power visible emission. The "scheduled" presentation was a paper by Sony describing progress on a laser using the AlGaInP/GaInP lattice-matched system grown by MOCVD. The active layer was undoped $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$, emitting light at a wavelength as low as 620 nm (bright red). Sony achieved a room temperature threshold of $2 \times 10^4 \text{ A/cm}^2\mu\text{m}$, and CW lasing to $T=33^\circ\text{C}$. Not to be outdone, another researcher leaped to his feet during the discussion to say that NEC (responsible for the visible laser in the optoelectronics project, cf. Table 9) had achieved 4 kA/cm^2 and CW lasing to 50°C with the same material system. I think there are two points to be made here: considerable progress had been made on visible lasers in Japan (an area where the US had been leading), and this was done with a high level of competition between Japanese

companies. Both of these points will be made again in this report.

2. Fujitsu, responsible for a highly-integrated multi-channel optoelectronic switch, indulged in an orgasm of acronyms with its paper on the "SLB-GRIN-SCH-SQW-RW Laser" (Strained-Layer-Buffer GRaded-INdex Separate-Confinement-Heterostructure Single-Quantum-Well, Ridge-Waveguide Laser!!) By combining a technology already recognized for its low-threshold potential ("GRIN-SCH" laser with a single quantum well) with a strained-layer buffer, Fujitsu was able to achieve a threshold current as low as 3 mA, 30 mW output per facet, differential quantum efficiency exceeding 80%, less than 2% change in output power per 1000 hours operating time (tested for 4000 hours at the time of the conference), and nearly single longitudinal mode. More significant than these excellent characteristics of the discrete device, however, was the monolithic integration of four of these lasers with detectors to form a four-channel laser/ photodiode array, all having very similar operating characteristics. A most impressive display of technology!

3. Finally, Hitachi (responsible for integrated high-speed lasers) dazzled the audience with the monolithic integration of no less than 14 separate devices in the form of a source-receiver circuit utilizing a multi-quantum-well (MQW) laser with mirrors fabricated by reactive ion beam etching (RIBE) in order to integrate the laser with other devices on the chip. The rest of the circuit consisted of a driver circuit made by implant technology, having a switching time of 130 psec, and a receiver circuit using a GaAs PIN diode in combination with a high-impedance amplifier (1 FET) and a trans-impedance amplifier (3 FETs). The laser had a threshold current of 31 mA, and its light-current performance characteristics were identical with lasers made from the same chip having cleaved mirrors, indicating the high quality of the etched mirrors. (This RIBE technology, by the way, is one of the areas of intense research at OJL, as we shall see below.)

These few examples should suffice to suggest that the electronic companies are indeed making swift progress on a variety of optoelectronic devices and associated materials problems, and in particular are nearing completion of the specific devices listed in Table 9. More will be said about the research activities of individual companies in a later report; attention here should now be focussed on the special project laboratory for the optoelectronics project, the Optoelectronics Joint Research Laboratory in Kawasaki.

OPTOELECTRONICS JOINT RESEARCH LABORATORY (OJL)

As mentioned above, nine of the fourteen companies that are members of the Optoelectronics Applied System Project have agreed to participate in the special project laboratory that was established in 1981, along with the Electrotechnical Laboratory (ETL). Some of the organizational and administrative details of OJL have already been discussed in this report; it should be clear that OJL is a unique, extremely well-equipped facility working on generic technology research that is of interest to all the member companies, but which allows participation of the companies without compromise of privileged information regarding processing and fabrication techniques and device design concepts. The choice of material for this research has been almost exclusively GaAs (and related, lattice-matched compounds such as AlGaAs). This has been done because OJL's long-range materials research focuses on the concept of optoelectronic integrated circuits (OEICs); that is, the integration of optical devices with high-speed electronic integrated circuits. Since the technology for high-speed electronic devices is expected to be dominated by GaAs for some time in the future (GaAs MESFETs now, high-mobility devices utilizing 2-D electron gases in the future), it was felt by the organizers of OJL that a focus on GaAs would be appropriate.¹²

In what follows I would like to highlight some of the research accomplishments of this laboratory. To do this, it is instructive to look at the structure of OJL in terms of its research-group membership, since I feel that this contains a great deal of information concerning the individual company interests. A summary for all six research groups is given in Table 10.

Group #1: Bulk Crystal Growth

It is clear that Toshiba has a strong interest in bulk growth of high quality GaAs, although many other companies are represented in this effort. Under the capable leadership of Dr. T. Fukuda of Toshiba, this group is one of the best in the world at developing advanced techniques for bulk growth using the liquid-encapsulated Czochralski (LEC) technique. Some of their accomplishments have been:

- The use of magnetic-field techniques (MLEC) to achieve very uniform, striation-free material with a consequent reduction in dislocation density.

• The development of very low temperature gradients to reduce dislocation densities to well below 1000 cm^{-2} without the use of In doping, which has been employed in other laboratories, and which it is felt would be better not done. In order to grow in a low temperature gradient while maintaining visual observation of the solid/liquid interface (considered to be essential for good control of crystal growth) this group developed a unique x-ray imaging system.

• The development of As injection into the melt to accurately control the melt composition and hence the uniformity of wafer resistivity. This is done through the control of the deep compensating center referred to as EL2, for which there is a mass of evidence that an As-antisite defect is involved (and hence requires a slight excess of As in the crystal).

Table 10. ORGANIZATIONAL STRUCTURE OF OJL

DIRECTOR-GENERAL:	T. Iizuka					
TECHNICAL DIRECTOR:	I. Hayashi					
RESEARCH PLANNING:	M. Hirano					
ADMINISTRATION:	A. Okamura					
GROUP:	Bulk Growth	FIBI	Epi Growth	Surf. Phys.	Fabr. Tech.	Charact.
Manager: & company:	Fukuda Toshiba	Hashimoto Fujitsu	Ishii Mitsub.	Nakashima Hitachi	Asakawa NEC	Ishida NEC
	-----Number of Members*-----					
ETL						1
Fujitsu	1	4				1
Furukawa	1				1	1
Hitachi	1			3		
Matsushita		1	1	2		1
Mitsubishi	2		3			2
NEC	2		2		2	1
Oki			1	2		
Sumitomo		1	3	1		
Toshiba	3		1			1
TOTALS:	10	6	11	8	3	8

* Information from Fall, 1985. Some researchers have subsequently returned to their member companies because of the limited remaining lifetime of the laboratory

Utilizing these three techniques in appropriate combination, OJL currently has the best control over defect introduction, and compositional control and uniformity of any laboratory in the world, and hence is in a strong position to carry out a systematic investigation of the principal defects in this material (an activity which is currently in progress; cf. Group #6).

In addition, some work has recently been initiated on the bulk growth of InP, using liquid P as the encapsulant. This is accomplished by allowing vaporized P to condense on the walls of the growth vessel, and run down onto the In melt, encapsulating it with liquid P. OJL was the first laboratory to try this approach, and they have succeeded in growing material at a considerably lower pressure than must be used for direct synthesis (500 atm). A preliminary report of this work was recently given at the Electronic Materials Conference, University of Massachusetts, June 25, 1986.

Group #2: Maskless Ion Implantation (FIBI)

As can be seen from Table 10, this activity at OJL is dominated by Fujitsu; even the group leader, Dr. H. Hashimoto, comes from Fujitsu. At the conclusion of the optoelectronics project, Fujitsu will clearly have a large lead in what could amount to a very important technology in Japan. Maskless ion implantation features a focussed ion beam implanter (FIBI) coupled through a common ultra-high vacuum (UHV) system with a molecular beam epitaxy (MBE) crystal-growth system. An analysis chamber with Auger electron spectroscopy and mass spectroscopy are also part of the UHV system. The FIBI machine can implant Ga, Be, or Si with a spatial beam resolution of 0.1 microns into a UHV surface, followed by MBE growth of additional layers, burying the implanted species in whatever way is desired. The implications of such a technology are tremendous for the development of OEICs. For example, complicated patterns of p-n junctions can be made with precise three-dimensional control of their position, buried-laser active layers can be directly implanted (assuming that implant damage can be eliminated; cf. below) using extremely small dimensions, leading to the possibility of micro-lasers having sub-milliampere threshold currents. Furthermore, these structures (both optical and electronic) can be placed at will anywhere on a wafer, making possible a high level of optoelectronic integration. The potential of this coupled FIBI/MBE system is extremely great, and the investigation of its capabilities represents one of the major contributions of OJL.

Just how good is this system for making defect-free structures? Several experiments have been designed at OJL to answer this question. In one experiment, a 2.4 μm layer of Be-doped GaAs ($p=1 \times 10^{16} \text{ cm}^{-3}$) was grown by MBE, followed by implantation (using FIBI) of Be at a dose of $1 \times 10^{13} \text{ cm}^{-2}$. This corresponds to a Be concentration in the implanted region approximately two orders of magnitude greater than in the conventionally-doped layer. Finally, a second MBE layer of Be-doped GaAs (also $p=1 \times 10^{16} \text{ cm}^{-3}$) was grown to cover the free surface that received the Be implant. This second growth was done in two different ways: in one case, the overgrowth was done after removing the sample from the UHV system, so that the normal defect incorporation at a free surface exposed to atmosphere could take place. In the second case, the entire process was carried out in UHV. Photoluminescence was then measured for both cases by scanning the luminescence excitation beam across a cross-section of the two-layer sample. In the case of the all-UHV sample preparation (made possible by this remarkable apparatus), no reduction of luminescence intensity was observable at the regrowth interface, indicating that a defect-free interface resulted from this procedure. Furthermore, after appropriate annealing of the implant damage, the region implanted with Be showed a strong increase in luminescence due to the Be acceptor, as expected. In the case where the regrowth interface was exposed to air, however, a strong decrease in luminescence efficiency was noted at the position of the interface, showing the usual effect of defect incorporation at such an interface. The results of this experiment are therefore extremely encouraging, suggesting that truly defect-free interfaces can be obtained after implantation when the entire process is carried out in a UHV environment.

Although OJL is not device-oriented, as described above, no Japanese researcher worth his soba can resist the construction of a simple device given the potential of this facility, and OJL researchers are no exception! Several laser devices have been fabricated using maskless ion implantation. By implanting the active layer following standard processing (i.e., cleaved mirrors, etc.), lasers with reasonable operating characteristics have been realized. More recently, novel lasers have been constructed using superlattice disorder (or suppression thereof) by enhanced diffusion; these devices will be described below in conjunction with Group #4.

Group #3: Epitaxial Growth

This group is dominated by two companies, Mitsubishi and Sumitomo, both from the Kansai area of Japan. The group leader is Dr. M. Ishii of Mitsubishi. It is interesting that Sumitomo, long the world leader in bulk GaAs substrates, considers epitaxial growth so important. That leadership is currently threatened by the large number of Japanese companies -- as many as eight of them -- now getting into bulk growth. In addition to Sumitomo Denko (Electric), there are, for example, Sumitomo Kinzoku Kozan (Metal Mining), Mitsubishi Monsanto, and Mitsubishi Kinzoku (Mining). It is clear that Sumitomo and Mitsubishi have a lot at stake in keeping current with crystal growth technology!

The activities of this group are varied, and can only be highlighted here. Both MBE and low-pressure Metal Organic Chemical Vapor Deposition (MOCVD) are investigated. Two themes that run through much of this work are the investigation of growth over patterned wafers for new active device configurations (particularly those that will lead to a planar technology), and the use of novel configurations of quantum wells and superlattices to tailor the properties of devices. Neither of these ideas were originated by the Japanese, but their capital equipment advantages allow them to pursue these ideas in conjunction with other, unusual capabilities, such as FIBI. Growth over patterned substrates has led to the growth of 1- μm stripe-width lasers grown by MBE over grooved substrates (called PGS laser, for pair-groove-substrate), and various MOCVD growth morphologies (including planar) over etched substrate grooves with very different orientations. OJL has MBE machines from all the major suppliers: Varian, Riber, Phi; the opportunity for making comparative assessments in this laboratory is therefore great. Dr. Ishii has considered working on P-based compounds involving the general AlGaInAsP system. Good results have been obtained at Sony, NEC, and Toshiba using MOCVD. He is obviously aware of the problems of growing P compounds by MBE. One of his goals is to begin a program on photo-chemical gas source MBE when he returns to Mitsubishi at the close of this laboratory; the emphasis on III-V compounds is increasing rapidly at Mitsubishi, but the semiconductor industry recession (which has had its effects in Japan, as well as in the U.S.) may make a difference.

OJL has been building a gas-source MBE system for nearly two years, and results are just beginning to come out. Using triethyl gallium (TEG) and arsine, they achieved the lowest

background acceptor concentration produced to that date (late 1985): $p=3 \times 10^{14}$. Just recently, they have made the first observation of the doping enhancement of MBE GaAs using a pulsed excimer laser.

This group has also interacted closely with other groups at OJL on the development of novel structures such as short-cavity lasers and disordered superlattice lasers, which will be described below.

Group #4: Applied Surface Physics

This is the "Hitachi" group, although both Matsushita and Oki (new to III-V technology, but growing rapidly) have strong representation. The group leader is Dr. H. Nakashima of Hitachi. This group works on a large variety of problems, some of which are among the most fundamental problems under investigation at OJL: surface physics and chemistry of Au (and other metals) on GaAs, properties of LaB_6 , a material which may make a superior Schottky gate to GaAs, studies of various interfaces between insulators, metals, and semiconductors using a wide variety of techniques including Rutherford backscattering, proton-induced X-ray emission (PIXE), and synchrotron radiation. However, Dr. Nakashima was a Hitachi laser researcher, and he continues to pursue novel laser concepts within the context of his group and its interactions elsewhere in the laboratory.

One of the most promising of these activities is the investigation of superlattice disordering by enhanced diffusion of Zn and Si. Both conventional diffusion of Zn and the diffusion of Si after implantation (conventional and FIBI) are being investigated. Narrow stripe width ($2.2 \mu\text{m}$) lasers with reproducible light-current characteristics and 25 mA thresholds have been fabricated by diffusing implanted Si through a multi-quantum-well (MQW) layer to produce the lateral confinement for the MQW active layer. When the same procedure is used at the mirrors of a laser, separating the mirror from the active layer, a significant increase in output power is achieved before the threshold for mirror damage is reached. More recently, an even more interesting effect has been observed in Japan and utilized for device formation at OJL. It appears that enhanced diffusion (and hence superlattice disorder) takes place only when the carrier concentration exceeds a certain level. If the material is co-doped (for example, by implanting Be), no disorder takes place, whether the Si is there by implantation or conventional doping. The most recent laser structure fabricated at

OJL makes use of this principal to *prevent* the disorder of a heavily-Si-doped superlattice layer by implanting Be into it. The laser is thus made entirely by maskless techniques.

In addition to the use of superlattice disordering techniques to pursue new device structures, Group #4 is also interested in the fundamental diffusion mechanisms involved. Some very interesting, though not understood, phenomena are currently being investigated. For example, enhanced diffusion occurs when Si is introduced either by conventional implantation or by FIBI. However, there is a "dose window" when FIBI is employed. That is, not only does the dose have to exceed a certain value (to achieve a concentration of approximately 10^{18} cm^{-3} or more, as observed for conventional implants), but if the dose is too great using FIBI, no disorder results. It is not clear if this is a dose or dose-rate effect, although the latter seems to be the case. Further, investigations are under way, and should prove important for any maskless technology.

Group #5: Fabrication Technology

This "group" is not really a group in the usual sense, with only three members; however it constitutes a strong effort in dry etching technology at OJL, under the leadership of Dr. K. Asakawa from NEC. The acting head of this group is Dr. M. Hirano of ETL, who also serves as the laboratory administrator for research planning. The emphasis here has been on Reactive Ion Etching (RIE) and, more recently, Reactive Ion Beam Etching (RIBE) for the microfabrication of a variety of device structures necessary for the formation of OEICs. Although some of the earliest research using RIE techniques was reported by researchers at Bell Laboratories (some of whom are now faculty members at UCSB), the OJL work has made some of the more recent advances in perfecting this technique, with important applications to device fabrication. For better control of the etching characteristics, particularly the directionality of the incident etching plasma, a "beam" of ions is extracted from an electron cyclotron resonance plasma source, and directed at the sample under UHV conditions that are fully compatible with other in-situ processing techniques under development at OJL, such as the maskless implantation described above. By adjusting the source pressure and beam extraction energy, the ratio of chemical/mechanical etching can be controlled so as to minimize surface damage, or maximize etch rate, as required. For example, it has been possible to achieve equal etch rates for GaAs and AlGaAs surfaces, so that no discontinuity occurs when etching through multiple layers of differing composition of these materials as encountered in quantum well or superlattice structures. Finely patterned structures have resulted with extremely

smooth vertical walls, or walls with arbitrary angles with respect to the substrate, by varying the relative orientation of the substrate in the etching system. Using such etching techniques, semiconductor lasers have been fabricated with smooth, vertical etched mirrors; the lasers have operating characteristics essentially identical with lasers made with conventional cleaved mirrors. This group is also exploring the use of electrically-neutral but chemically-reactive radical species for anisotropic etching and damage-free surface polishing.

Recent device work using RIBE in conjunction with the epitaxial growth techniques developed in Group #3 has led to research on very short cavity lasers. The mirrors are made by RIBE, so that the length of these lasers is not limited by mechanical difficulties in cleaving. Cavity lengths as short as 20 μm have been produced, with active layers formed by the PGS technique. At present the threshold current for such lasers is high, but the researchers developing these techniques have found that there is a strong dependence of the device threshold current on the number and thickness of the quantum wells used for the active layer; work is presently underway to optimize these parameters.

Group #6: Materials Analysis and Characterization

Unlike most of the other groups, which tend to be dominated by one or two of the member companies, the characterization group has eight members from seven different companies. Everyone wants to be able to determine the quality of their material! Under the leadership of Dr. K. Ishida from NEC, the major activity of this group is the characterization of bulk LEC material grown by Group #1. In fact, because of the strong concentration of characterization expertise (photoluminescence, DLTS, EPR, TEM, electrical measurements, etc.) in the same laboratory having so strong an effort in bulk growth of GaAs, I believe that OJL stands at the threshold of making a major contribution to the understanding of the principal defects in this material, such as the deep, compensating defect known as EL2 which is responsible for the semi-insulating behavior of undoped GaAs. This is probably the only laboratory in the world currently capable of mounting a systematic study of bulk GaAs with carefully controlled changes in stoichiometry; current activity involves the investigation of the effect of changes in stoichiometry on lattice parameter changes and extended and point defect densities. Very recently (reported at the International Conference on Semi-Insulating III-V Compounds, held in Hakone in May, 1986) the group has reported the first systematic study of the lattice constant of bulk GaAs as a function of stoichiometry. They found

that the lattice constant increases with the amount of As added to the melt of the LEC-grown material, suggesting that the excess As enters the lattice interstitially, a fact that is consistent with recent ENDOR results (also reported at Hakone) that suggest EL2 is a complex consisting of an As-antisite defect (As on a Ga site) and a nearest-neighbor As interstitial.

Another very recent and very important result from this group involves transmission electron microscopy of GaAs grown on Si, one of the more fashionable problems of moment in epitaxial crystal growth. The importance of being able to grow high-quality GaAs on Si substrates is obvious -- such a technology makes possible combining the best of both worlds, high-speed optoelectronic devices in GaAs with the current sophisticated VLSI technology of Si. Many groups in Japan, Europe, and the United States are working on this problem. One such group, at Oki Electric, has succeeded in making device-quality GaAs by first growing an amorphous layer of GaAs on Si at a very low temperature (too low for single-crystal growth), and then increasing the growth temperature to grow the final (device-quality) layers. Excellent results have been obtained by Oki using this approach. Ishida's electron microscope work, published in the Japanese Journal of Applied Physics in April of this year and reported at the Electronic Materials Conference at the University of Massachusetts in June, shows that atoms in the amorphous buffer layer have approximately the correct spacing for the GaAs crystalline lattice, and that after the high-temperature growth of the second layer, the amorphous layer has recrystallized with the proper atomic spacing (if the substrate was properly cleaned). Stress is relieved in this process by the creation of misfit dislocations that run parallel with the layer, and hence do not propagate into the second layer grown. Thus, the mechanism for growth in this case appears to be quite different than that usually obtained for epitaxial GaAs, explaining the unusual results reported by Oki.

The Grand Finale!

At this point it should be clear that truly innovative materials and processing research is underway at OJL, and that progress has been significant during the limited lifetime of this laboratory. As was the case with the VLSI project, it appears that Japan will go from a position behind the United States to virtual domination of the optoelectronic device market during a time span only a little longer than the lifetime of this cooperative project. During the final months of the laboratory (now scheduled to close its doors at the end of the 1986 fiscal year, March 30, 1987), OJL is attempting a daring and truly synergistic experiment which will combine much of the

expertise described above. During my last month at the laboratory a huge UHV system was assembled that incorporated not only the focussed ion beam implanter, MBE, and the analysis chamber described above, but also a new RIBE system, a radical gun for defect-free surface cleaning, and an electron-beam annealing system designed to eliminate the damage resulting from FIBI. This massive vacuum system should be able to "do it all", complete in-situ crystal growth, maskless implantation and/or etching, implant-damage anneal, surface polishing and cleaning, and analysis of the results at any stage of processing, all within a UHV environment! Nothing like this has been (or could be) attempted anywhere else in the world! Dr. Izuo Hayashi, Technical Director of OJL and my host during my visit to OJL, admits that the problems in getting all the components of so complicated a UHV system to work at the same time may be insurmountable. However, should they succeed, the implications are enormous for the future of optoelectronic integrated circuits -- all the growth, fabrication, and processing steps could be done in-situ, in one system, in a completely maskless way, without the need for photolithography, wet chemical processing, or exposure to any other hostile environment! A truly remarkable achievement, well worth the effort, even if success is not realized during the limited remaining lifetime of this laboratory.

COLLABORATIVE RESEARCH -- OJL AND ITS MEMBER COMPANIES

The main thrust of the above discussion should be clear -- the Optoelectronics Applied System Project, and in particular the special project joint laboratory known as OJL, is seen through the eyes of most foreign observers as an extremely successful government/industry cooperative venture. What is the view of Japanese researchers themselves, and how do members of different and highly competitive companies manage to carry off a collaborative activity of this kind? I have already addressed some of these questions briefly in the introduction to this paper, but much more can be written. Although there are no definitive answers, a few specific points can be made.

Success of the Optoelectronic Project

The Japanese themselves consider the Optoelectronics Applied System Project to be a highly successful one. In particular, the government sponsors at MITI have agreed in principal to the establishment of a second, follow-on project in optoelectronics, with a longer lifetime. The (rather sketchy) details as currently known will be given below; suffice it to say that this decision is a strong endorsement of the importance of optoelectronics and the contribution of the project to this technology. It might still be argued by some company managers that they could have proceeded more efficiently if simply given an equivalent amount of funds, but that argument seems to be lost in the political/economic climate of technology in Japan. Thus, there will be another optoelectronics project in Japan!

OJL Researchers and their Interactions

Company loyalties and Japanese group dynamics make a research arena at a laboratory like OJL a complicated one. It is clear that the "lifetime" employment policy of all large Japanese companies provides an advantage for a limited lifetime laboratory such as OJL. That is, the guarantee of a responsible position in the parent company at the end of an assignment at OJL makes it attractive for experienced researchers to take a position there on a temporary basis. Similarly, the companies themselves are much more willing to send their better researchers than would be the case in the United States: a case in point is the MCC, which was initially intended to be staffed by scientists on loan from member companies, but for which a significant fraction of the research staff had to be recruited from the open market. Another factor which contributes to the quality of the research staff at OJL is the redundancy built into the industrial research laboratories -- a good researcher in a particular field can more easily be spared (for a limited time), because there are

others willing and able to work on that project. Nevertheless, Dr. Hayashi, the Technical Director of OJL, admitted that he had to carefully screen all new proposed personnel assignments to the laboratory, and in a number of cases rejected the researcher proposed by his company.

Although company loyalties remain strong, and the researchers return to their parent companies relatively often to report their progress, it seemed to this observer that equally strong, new loyalties had been forged within OJL. The importance of the group, and accompanying respect for the authority of the group leader, was very evident at OJL. Groups met frequently in both formal and informal situations; for example, they would have dinner and drink beer or sake together in a relaxed but informative fashion about once a week. Since the laboratory focus was on generic materials technology of use to all the member companies, and not on devices, there was no need for a high level of inter-company competition, so that communication between researchers was very good. At times when device ideas were investigated, or the quality of the materials was tested by fabricating and evaluating devices made on these new materials, such work was done within the laboratory of the appropriate (i.e., most suitable) member company. Another advantage to the individual researcher of an assignment to OJL is the fact that such an assignment often carried with it an opportunity to do more basic research than had been the case within the parent company.

Technology Transfer to the Member Companies

A number of mechanisms have been established to transfer technology to the member companies. These include (in order of increasing detail of the information transferred): conference papers (which are in the public domain), an annual meeting of the optoelectronics project (at which brief progress reports are given), a written annual report to the project members (considerably more detailed), = quarterly meetings with member companies (at which certain research areas are chosen for in-depth presentations), research collaborations, patents, and written technical reports on specific research areas. These reports may be the natural consequence of the completion of work in a specific area, or they may be a response to a specific company request for technology transfer. Examples of the latter are referred to as OJL Technology Transfer (TT) Reports. MITI clears all such reports, and owns the patents arising from them.

At present the member companies are interested in OJL TT reports on a number of subjects; negotiations are underway between MITI and several companies, who want the royalty-free use of patents which MITI owns (through the optoelectronics project). The companies may have to pay a few percent of the income derived from the patent, if they obtain a detailed TT report.

which describes the so-called "know how" that is essential to the utilization of a new idea.

To date, much of the technology transfer that has taken place has involved bulk crystal growth (Group #1), so many of our remarks will refer to that area. Some examples of techniques that are under negotiation for the transfer of technology developed by this group are: (1) computer-automated crystal shape control; (2) magnetic field LEC (i.e., MLEC); (3) arsenic injection into the LEC growth chamber to control melt composition, and (4) dislocation control through the use of a low temperature gradient.

The two best examples of technology transfer that have already been achieved involve an infrared topograph system, and the standardization of wafer characterization; in both cases the characterization group (#6) worked closely with the bulk crystal growth group to develop these technologies. The infrared topograph system developed for the inspection of GaAs wafers for internal defects was made available to Hamamatsu (not a member company). The system is now commercially available, selling for ≈\$33,000. As of the first of the year, five of these units had been sold, and another 20 sales were expected. MITI receives a royalty of about 1% of the price of each machine. In the case of the standardization of wafer characterization, six companies have agreed to make identical measurements (resistivity, Hall mobility, carrier concentration) on samples taken from the same slice, and to provide their results to OJL for comparison.

There are at least eight ongoing research collaborations between OJL and the member companies. The standardization of wafer characterization involves six member companies, as mentioned above. Hitachi is actively working with OJL to characterize single crystal substrate material by (a) precise measurements of the lattice constant of the wafer, and (b) by the performance of semiconductor lasers fabricated on epi layers grown on these wafers. In the former of these collaborations, the results obtained by Hitachi were so promising that OJL purchased the equipment to do precise lattice-constant measurements in-house; in the latter collaboration, n-type LEC substrate material was used for lasers for the first time, and Hitachi wants detailed information regarding the growth conditions. A similar collaboration is underway with Mitsubishi, whose researchers are using transverse junction stripe (TJS) lasers to characterize semi-insulating (SI) substrate material. Fujitsu is collaborating with OJL to characterize doped layers in SI substrates produced by ion implantation. Toshiba is interested in the use of dislocation-free substrates for the manufacture of LEDs on epi layers grown by MOCVD, and Furukawa is interested in MOCVD epi-growth on In-doped SI substrates for device application. Finally, five companies (Fujitsu, Furukawa, Mitsubishi, NEC, and Sumitomo) are working with OJL on the standardization of Hall

measurements on SI GaAs wafers.

All of the collaborations described above are related to the Optoelectronics Applied System Project. There are also some collaborations with companies involving the "Supercomputer" national project. For example, OJL researchers are involved with Fujitsu and Oki on high electron mobility transistors (HEMTs), and with Hitachi, Mitsubishi, NEC, and Toshiba on field effect transistors (FETs).

Cooperative Research with Universities

OJL researchers are also involved in a number of collaborations with university professors. Examples include Prof. Komatsu and Prof. Sumino at Tohoku University, Prof. Kobayashi at Toyama University, Prof. Nishinaga at the University of Tokyo, Prof. Matsumoto at Keio University, and Prof. Kukimoto at the Tokyo Institute of Technology. In addition, a number of professors serve on OJL's advisory board. All of these collaborations are established on the basis of mutual interest; some were initiated by OJL researchers, and some by the faculty members. However, OJL (as well as any other program funded by MITI) cannot provide research funds to the university for such collaborative research; that is the function of a totally separate ministry within the Japanese government, the Ministry of Culture and Education (MCE). It is clear from numerous discussions that considerable friction exists between this ministry and MITI, with the result that MITI has nothing to do with university research. Industry can and often does fund university research independently, often at the level of $\approx 0.5 - 1.0$ million yen, a very small program by U.S. standards (\$2,000 - 4,000).

Although it is not the intention of this report to evaluate Japanese support of universities, a few additional remarks should be made. University research support through MCE also tends to be in the form of "special project" programs, and the level of support for these projects is quite good. In 1985, total university funding by MCE was of the order of \$175 M (i.e., ¥42 B), \$170 M of which was spent on so-called special projects. The 1985 figure is up 3.6% from 1984 (using yen rather than dollars for comparison). One of these projects is on mixed compounds of the III-V semiconductors, and involves a large number of university researchers working in teams of from two to six faculty members on such subjects as AlGaSb ternaries, EXAFS of InGaAsP, GaAs/AlGaAs metal-organic MBE, and a focussing-type time-of-flight atom probe of these materials. To obtain this funding, a senior professor proposes the overall project or program, and many professors then work on it. One professor might get as much as \$200,000-400,000 (max).

There is also a standard increment of government support for university professors, but it is a very small amount (\approx \$16,000-20,000), about half of which has to go to the university for facilities overhead.

It is this observer's opinion that, whereas cooperative research works extremely well between government and industry in Japan (far better than in the United States), it works badly between university and industry. For example, Japanese industry provides approximately twice as much support to *American* universities as it does to Japanese universities. A case in point is Matsushita, which is providing \$1 M each to Stanford, Harvard and MIT business schools to study US/Japanese relations. What little industrial research support is available tends to be directed to a relatively small number of senior faculty members, who nevertheless do excellent work under conditions that are far from ideal. Should the Japanese rectify this situation and take full advantage of the research talent and capability that exists within their education² system, the United States will really be in trouble!

The New Optoelectronics Project

It now appears quite certain that there will be a new Optoelectronics Project, to begin in 1987 after the termination of the present project. The current thinking for this project (as of mid May, 1986) is as follows, although these plans could still change appreciably before the plan is put into action.

- The project will probably last for 10 years, although the current budget under discussion is felt by many to be insufficient for 10 years.
- There will probably be a special laboratory, although it is not clear that the lab will have a 10-year lifetime.
- There will probably be 13 members of that laboratory; in addition to the nine members of OJL, four new companies are expected to participate: Furukawa, Nippon Glass, Sanyo, and Sharp.
- The charter of the project will broaden to include InP as well as GaAs.

Not many additional details are available at this time. However, the intention of the Japanese is clear -- to continue to dominate both the technology and the market of optoelectronics.

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I first want to thank Dr. Izuo Hayashi, Technical Director of OJL, for arranging my visit to that laboratory, and for his most gracious hospitality during my stay. Hayashi-San showed great sensitivity to my needs and concerns, and spent many hours of his valuable time sharing with me his insights into the technical and social life of Japan. His friendship and help were primary instruments in fashioning our happiness during this visit.

Another person at OJL without whom I would have been totally lost was Mr. A. Okamura, who helped with countless problems involving every aspect of daily life in a totally strange country. His patience and good humor with what must have seemed an endless supply of needs and requests was greatly appreciated.

All of the other officers and managers of the laboratory were also most gracious hosts, particularly Dr. T. Iizuka, the Director General, who was attentive to my needs, enthusiastic about my research activities, and interested in my reactions. Dr. M. Hirano spent countless hours briefing me on collaborative research in Japan, and handling administrative details that my presence created. Finally, all of the group leaders were generous with their time, eager to tell me of the activities of their groups, and interested in my well-being during my visit. All of the staff assisted me with enthusiasm with the many clerical, secretarial, and other needs that a visitor in a strange environment is constantly discovering.

Finally, each and every researcher in the laboratory treated me with kindness, friendliness, and respect. I feel that I have a new circle of close Japanese friends as a result of this experience.

FOOTNOTES AND REFERENCES

1. It is very difficult to make an exact comparison of market sales for the two countries, and therefore to determine when the curves for Japanese and U.S. sales actually crossed (if they have already done so). Japanese market analysts believe that the figures reported for U.S. sales by most U.S. sources do not include so-called "captive" markets (devices produced for use within the company), and that the U.S. figures are therefore underestimates of the total U.S. market. In addition, accurate figures are hard to obtain, because companies tend not to disclose this information. Some examples of the differences between U.S. and Japanese market estimates are given in Table 11. Japanese estimates for 1986 show the U.S. still ahead, whereas the U.S. estimates show Japan in the lead. Note that the Nomura Research Institute figures for 1985 Japanese sales (\$8.2B) are 18% lower than the most recent MITI figures (\$10.0B) which are given in Table 1.

Table 11. WORLD SEMICONDUCTOR MARKET ESTIMATES

	SIA*	NRI†	
	1986	1985	1986
UNITED STATES	\$9.2 B	\$10.0 B	\$11.5 B
JAPAN	9.5	8.2	9.4
OTHER**	6.7	5.6	7.2
TOTAL	25.4	24.8	28.2

* SIA is the Semiconductor Industry Association, an association of US companies.

† NRI is the Nomura Research Institute, a major survey company in Japan.

**Western Europe accounts for 30% of these figures.

2. Daniel I. Okimoto, Takuo Sugano, and Franklin B. Weinstein (editors), Competitive Edge, the Semiconductor Industry in the U.S. and Japan (Stanford University Press, Stanford, CA, 1984). *Specific references in text are to pages 18-20 and 38-39.*
3. Makoto Kikuchi, Japanese Electronics. A Worm's-Eye View of Its Evolution, translated by Simul International (Simul Press, Tokyo, Japan, 1983).
4. Kenichi Ohmae, Triad Power, the Coming Shape of Global Competition, (The Free Press, a Division of Macmillan, Inc., New York, NY, 1985).
5. Jon Sigurdson, Japan's High Technology Race, The Information Technologies (Research Policy Institute, AV-Centralen Press, Lund, Sweden, 1983).
6. Optoelectronic Industry and Technology in Japan, Optoelectronic Industry and Technology Development Association (OITDA), 20th Mori Bldg., 7-4, Nishi Shimbashi 2-chome, Minato-ku, Tokyo 105, Japan.
7. Both Mitsubishi and Sharp have announced the opening of facilities capable of producing one million lasers/month. However, Japanese planners believe that the sale of CDs will not be sufficient to sustain such a rate of production, because the largest market for CDs is expected to be the automobile market, which should saturate at approximately 8 million cars/year. They are therefore eyeing the home computer market, for which a breakthrough in erasable CDs is required.
8. Note that in this and in all other tables in this paper, a currency exchange rate of 240¥ per dollar has been used, a "best estimate" at a reasonably fair average over the lifetime of most of these projects. If today's exchange rate is used, the projects appear to be considerably more expensive.

9. T. Iizuka, T. Fukuda, H. Hashimoto, and K. Asakawa, "Fabrication Technology for Optoelectronic Integrated Circuits", Proc. Int. Conf. on Integrated Optics and Optical Communications (IOOC), Venice, Italy, October 1985.
10. Izuo Hayashi, "Evolution of Optoelectronic Integrated Circuit: OEIC", Proc. International Conference on Integrated and Guided Wave Optics (IGWO), Atlanta, GA, February 1986.
11. Izuo Hayashi, "Research Aiming for Future Optoelectronic Integration", Proc. IEE, to be published.
12. It is not clear that InP-based materials should be totally excluded from consideration. Although the emphasis of OJL's activities have to do with OEIC rather than optical communications (and hence do not require the very low losses available in optical fibers at longer wavelength), InP may have advantages even for the short-haul systems envisioned for OEIC because of the zero-dispersion characteristics of some fibers at these wavelengths, which would lead to higher bandwidth applications. In the final year of OJL some attention is being given to InP, as we shall see, and the next generation optoelectronics project will have more to do with InP.

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THE OPTOELECTRONICS JOINT RESEARCH LABORATORY:
LIGHT SHED ON COOPERATIVE RESEARCH IN JAPAN

Professor James L. Merz spent the Fall of 1985 as a Visiting Research Scientist in the Optoelectronics Joint Research Laboratory (OJL) in Kawasaki, Japan. OJL is a joint cooperative laboratory staffed by researchers from nine private electronics companies in Japan through the sponsorship of the Ministry of International Trade and Industry (MITI) of the Japanese government. Professor Merz was the first foreign visiting researcher in this laboratory, and was able to observe first-hand how government/industry cooperative research proceeds in such an environment. In addition, Professor Merz visited the research laboratories of many of the member companies. This report (Over)

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represents an assessment of the effectiveness of a joint cooperative research laboratory such as OJL for optoelectronics research and development in Japan.

Professor Merz is the Director of the Compound Semiconductor Institute at the University of California, Santa Barbara, and a Professor of Electrical Engineering.

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