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MOLECULAR BEAM EPITAXY:
A MESOVIEW OF
JAPANESE RESEARCH ORGANIZATION

Lennart Stenberg

Massachusetts Institute of Technology

MITJP 91-12

Center for International Studies
Massachusetts Institute of Technology

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Research Policy Institute
University of Lund, Sweden

1. Introduction

In recent years much attention has been given to Japanese science and technology policy. Japanese programs involving cooperation between the government and technologically advanced companies have come to be seen as an efficient means of industrial policy and been a source of inspiration for the establishment of similar programs in other countries.

High regards for the technological strength of Japanese industry and related policies are routinely contrasted with correspondingly low appreciation for the level of basic research in Japan as compared to the United States and Europe. In particular, many Japanese and western commentators alike have expressed highly critical views of the research capabilities of Japanese universities.[1] Although a gradual increase in the Japanese contribution to scientific research is recognized there is still scepticism that Japan will ever seriously rival the United States and Europe in their position in science.[2]

Since around 1980 there has been a shift in policy focus in Japan in the direction of a stronger emphasis on "basic research".[3] As a consequence

[1] Okimoto (1987, p 416-17), for example, writes about the "second-rate quality of university-based research" in Japan.

[2] Narin (1988), while providing data showing that Japanese scientists increased their share of papers in the Science Literature Indicators database from approximately 5 percent in 1973 to 7.5 percent in 1984, points to factors that may keep Japan from "ever developing the kind of scientific hegemony that the Europeans had in the early part of this century, and the U.S. had in the middle years".

[3] Although basic research has moved to center stage in Japanese discussions of R&D-policy,

government policies for support of R&D in firms, government research establishments, and universities have all undergone far-reaching changes during the last decade. New visionary R&D-programs have been launched, new mechanisms for funding of cooperative efforts in basic research have been introduced, research priorities at government institutes have begun to be changed in the direction of more basic research, and initiatives have been taken to strengthen research and graduate education at universities.

In the corporate sector the establishment of new research laboratories for fundamental, or similarly labelled, research by a large number of companies has been the most visible sign of a new policy in Japanese industry to take a leading role in the development of new basic technologies. There has also been a mushrooming of new research organizations operated and staffed jointly by several companies. These joint research firms, which in the R&D-statistics are classified as "private foundations", represent a new component in the Japanese research system.

In Japan the R&D-system is dominated by the business sector to a higher extent than in any other country with the exception of Switzerland, the latter being a special case due to the concentration of research-intensive pharmaceutical firms in that country. An exceptionally rapid expansion of R&D in Japanese industry during the 1980s coinciding with a much slower growth in government R&D-expenditure has further shifted the center of gravity in the Japanese R&D-system towards the business sector. As industry has increased basic research at a rate somewhat higher than that for product-oriented R&D the dominance of the business sector is beginning to extend even to basic research leading to concerns in both Japan and abroad about an unbalanced institutional structure for the performance of basic research in Japan.[4]

Figure 1, based on official R&D-statistics, gives a quantitative estimate of the expansion and institutional diversification of the Japanese research system that have taken place over the last decade. It needs to be pointed out, however, that the data provided by the R&D-statistics is unreliable in

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the share of basic research in total R&D-expenditure in Japan has hardly shown any noticeable change during the 1980s as all types of R&D have grown at a rapid rate.

[4] Arguments have been put forward, for example, in conncetion with the negotiations of a new science agreement between the United States and Japan in 1988, that Japan is not contributing its fair share to openly accessible basic research. While the main point seems to be that the Japanese government is not funding sufficient research at universities there is an additional fear that expanded basic research in Japanese firms will increase their ability to take advantage of basic research in other countries while not making their own research sufficiently available. For a Japanese discussion of the desirability of a leading role for universites in basic research see Sakakibara (1988).

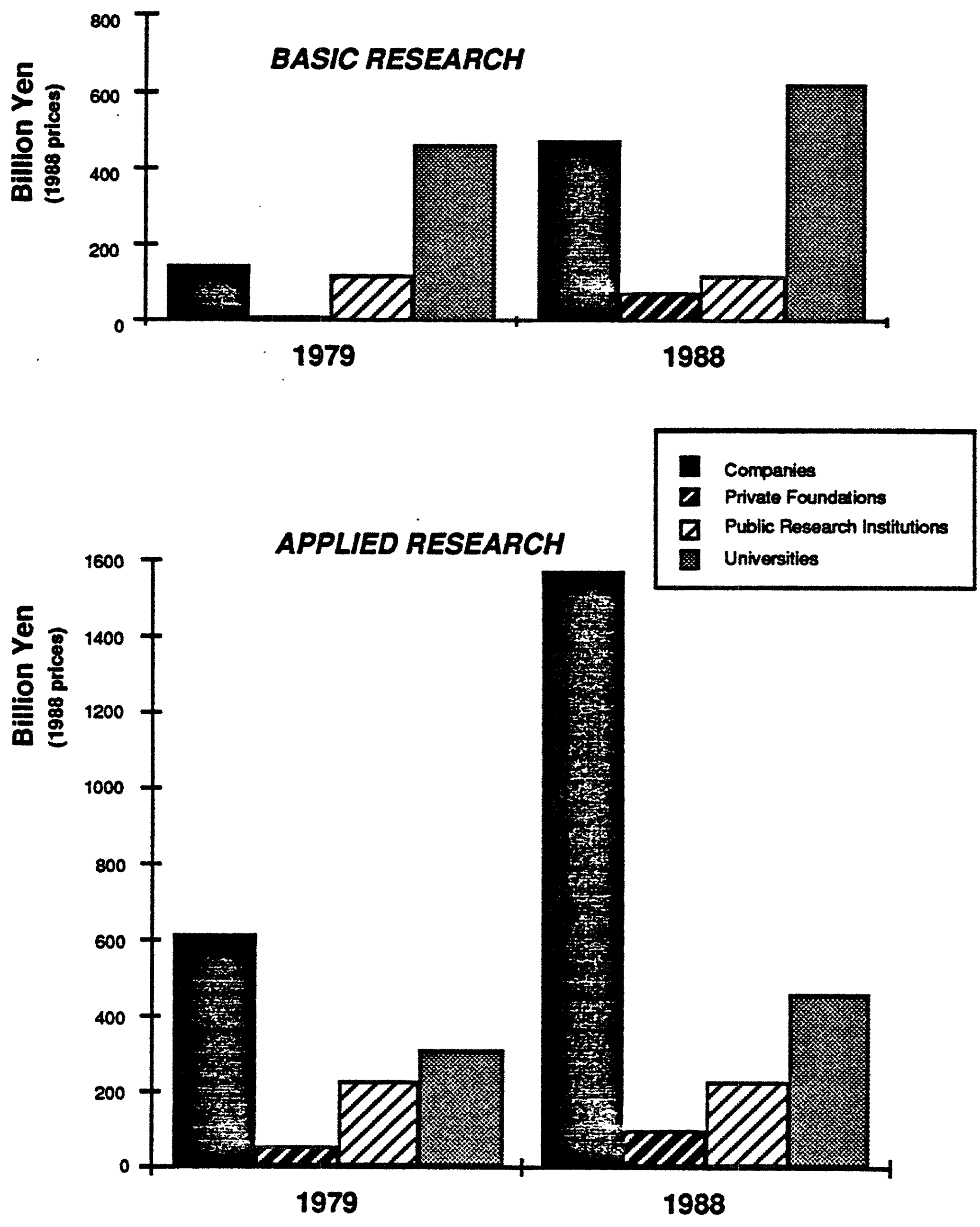

Figure 1 *Expenditure for Basic and Applied Research (physical, agricultural and medical sciences and engineering) in Japan 1979 and 1987 by Type of Research Organization*

Source: *Report on the Survey of R&D, 1980 and 1989* several respects. The concepts of basic and applied research have proven to be very ambiguous and therefore less suitable as a basis for surveys of R&D.[5] In the special case of universities the problem may be less one of distinguishing between different categories of R&D than distinguishing research from teaching and other non-R&D-activities. This problem is particularly large in Japan where separately budgeted research is a very small part of total research expenditure.[6] Finally, disaggregation of research activity according to scientific or technical field is not possible beyond a very crude level and can even at this level as a rule not be done using the same field classification for different types of research organizations.

The extensive participation of industrial firms in long-term research and the establishment of a large number of joint research firms give the Japanese research system a structure rather different from that in most other countries. Whether this difference will become further pronounced or whether it represents only a temporary aberration from more traditional models according to which universities or, in some countries, other types of publicly funded research institutes are seen as the natural centers for basic research is presently very difficult to judge. The outcome will depend on many factors, most of which defy predictions, such as how deeply Japanese industrial firms will remain committed to investments in basic research, how the joint research firms in the end will be evaluated by their corporate members, the scale of public and private resources that can be made available to universities, and what kind of cooperative relations that can develop between different types of research organizations.

The present paper aims at revealing qualitative aspects of the ongoing changes in the Japanese research system through detailed study of developments in one specific field, Molecular Beam Epitaxy (MBE). The objective is to clarify the role played by companies, universities and other types of research organizations during the course of the evolution of MBE research in Japan, seeking insights that might be generalizable also to other fields. The focus is on the organizational context of the research performed rather than on its scientific and technological content, although the latter aspect will be considered in broad terms.

MBE was chosen because it satisfied several criteria:

* MBE, being one of the most advanced technologies for engineering of

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[5] Stokes (1982) has for example suggested that basic and applied represent different dimensions and therefore are not mutually exclusive. Work is underway in many places to develop new categories which would be better guides to describing current realities.

[6] This problem is discussed in Irvine (1990). The same problem exists for data measuring R&D personnel as there is no data allowing calculation of full time equivalents.

materials on an atomic scale, represents a basic technology with a wide variety of possible applications

* MBE has great relevance both scientifically and from a practical technical point of view: development of MBE technology requires scientific research which to a large extent is quite basic in nature; MBE is also used as a tool in basic research of physical phenomena

* The MBE field has attracted the attention of researchers in universities as well as in industry

* The MBE field is a fairly well delineated field in both substance and time and is of suitable size for an intensive case study

* The research community in the field has exhibited very fast growth, making the field suitable for studying questions of recruitment and training of researchers

The approach taken, was to study the evolution of the community of MBE-researchers in Japan. Using bibliometric data, Japanese researchers active in the MBE-field and the organizations for which they worked were identified for different time periods . Similar data were gathered also for other countries to permit comparison of the institutional structure of the research communities in Japan and in other countries.

Information on qualitative aspects of the development of MBE-research in the leading Japanese organizations was obtained through interviews. These focused on the broad evolution of MBE-research in cognitive and technical terms, the validity of the bibliometric data, the mechanisms for acquiring and diffusing expertise in MBE, the primary research targets and motives for starting up MBE-research, and comparisons of MBE research carried out in different organizations and in different groups within a specific organization. After analysis of the interviews, additional bibliometric searches were performed to study subfields of MBE-research and also to obtain some data for the evolution of competing technologies.

As a result a fairly coherent picture of the evolution of MBE-research in Japan over the last 15 years was obtained. The quantitative data also allows some limited comparisons with other countries.

This paper first attempts a characterization of the basic features of MBE-technology and the general pattern of its development, including some bibliometric data showing the institutional structure and dynamics of MBE-research in the United States and worldwide as a reference for analysis of developments in Japan. The bulk of the paper discusses the evolution of MBE-research in Japan in some detail, and pays special attention to the objectives and research targets for different organizations, the role of government programs, sources of research funds for universities, and recruitment, training and careers of MBE-researchers. Finally some conclusions are drawn from the MBE case study.

2. Sketch of MBE technology and its development

Molecular Beam Epitaxy (MBE) is a technology for growing crystals in a highly controlled fashion making possible the growth of very thin layers of high quality crystals, that is crystals of well defined and very uniform composition.[7] The composition of the layers can be varied during the growth process allowing the fabrication of sandwiched structures, so-called heterostructures, which if repeated yield superlattices. Such structures give a high degree of freedom for designing semiconductor materials with desirable electronic and optical properties of a great variety by exploiting what has been termed bandgap engineering. An essential requirement is, however, that crystals of sufficiently high quality, with few impurities and abrupt interfaces between different materials, can be grown.

Different types of materials may be used, although the technology is currently more developed for some than for others. Initially research concentrated on III-V semiconductor materials, especially structures combining gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs). This materials system is still the most widely used and researched, but, increasingly, other III-V materials as well as II-IV semiconductors, for example zinc selenide (ZiSe), and elemental semiconductors such as Silicon (Si) and Germanium (Ge) have attracted attention. Also other materials have been grown by MBE, for example certain organic materials and, very recently, high temperature superconducting materials.

MBE-grown materials are used both in basic solid state physics research and for the fabrication of electron devices, for example various types of transistors or lasers. The artificial materials and structures that can be created with the help of MBE produce in many cases physical effects of great scientific interest, effects which may also be exploited in devices for practical use. Some discrete devices, especially high electron mobility transistors (HEMTs) and certain lasers, are already produced commercially using MBE while integrated circuits (ICs) and optoelectronic ICs (OEICs), that is circuits which combine optical and other devices on one substrate, have been available experimentally for several years but still have

7 For a technical overview of MBE see for example Sakaki (1989). For a more detailed account of current topics see Shiraki (1989). Takahashi (1989) provides a useful summary of recent trends in MBE.

uncertain commercial prospects.

MBE requires ultrahigh vacuum (UHV) and the technology for achieving this has been gradually perfected since the beginning of MBE-research 20 years ago in the United States. The first MBE-machines were designed by the researchers themselves and built to custom order by various vacuum companies. In the late 1970s equipment manufacturers began to market the first standard systems. To contain costs some researchers, especially in universities, continued to design their own systems also after that.

Instrumentation to study the samples during the growth process (so called in-situ measurement) is an important part of most MBE-machines used in research.[8] The attachment of such instrumentation means that almost all MBE-systems to some extent are custom-made as the instrumentation typically will vary from one machine to another. The development of methods for in-situ surface analysis has been and continues to be an important area of MBE-research. Needless to say the instrumentation has successively become more varied, plentiful and sophisticated as MBE-technology has evolved.

Initially more or less all MBE systems used solid source materials which were heated in crucibles to generate vapor which in turn, when let into the vacuum growth chamber, formed "molecular beams". Since the beginning of the 1980s different types of gas source MBE have been developed which, depending on which element is supplied in gas form, go under the names of gas source MBE (GSMBE), metal-organic MBE (MOMBE) or chemical beam epitaxy (CBE). One of several factors which has prompted the development of gas source MBE is the higher throughput that can be achieved with this method as compared with conventional MBE. MBE has been seen as having a disadvantage in this respect in comparison with other crystal growth techniques, which has been one reason why metal-organic chemical vapor deposition (MOCVD) has tended to be preferred to MBE for volume production. Gas source MBE is also better suited than conventional MBE for growth of certain materials, for example those containing both arsenic (As) and phosphorous (P).

In a sense gas source MBE can be seen as combining certain features of MBE and MOCVD, thereby contributing to the distinction between the two becoming less sharp, something which is also reflected in a growing overlapping of the two research communities with an increasing number of researchers using both MBE and MOCVD and various hybrid or related techniques such as atomic layer epitaxy (ALE).

The MBE technology has been modified also by the addition of auxiliary

[8] The fact that MBE operates under UHV is the reason in-situ monitoring can be used with MBE, something which has not been possible with other crystal growth processes such as MOCVD. This is one key advantage of MBE as a research tool.

processes such as laser or electron beam excitation to the basic growth method, thus making possible selective growth, reduction in growth temperature, and increase in chemical adsorption at the sample surface.

The use of photonic beams in combination with a growing repertoire of reactive chemicals introduced through gas source MBE processes gives a range of new options to manipulate the growth process, most of which have so far only marginally been explored. Of particular interest is the possibility that methods could be developed to control the growth process in the lateral direction in order to produce low dimensional structures such as quantum wires and quantum boxes, structures seen as holding the promise of a whole new field of physics as well as of new classes of devices.

Traditionally the growth of crystals and fabrication of microstructures have been distinct processes using different and separate equipment. Recently it has become common to integrate these processes into one piece of equipment combining MBE, electron beam lithography, reactive ion etching, etc., thus making it possible to perform all processing steps without breaking the UHV condition. Just as in the case of gas source MBE this closer integration of different growth and processing technologies also contributes to a blurring of the distinction between MBE researchers and researchers who are involved in the development of microfabrication processes.

The ease with which different materials can be grown epitaxially, that is with the crystalline structure preserved while changing from one material to the other, is dependent upon how well the crystal structure of the two materials are matched to each other. The greater the difference in lattice constants between the materials - the lattice constant being the distance between atoms in the crystal plane perpendicular to the growth direction - the greater are the difficulties in growing high quality heterostructures. As MBE-equipment has become more versatile and the understanding of growth mechanisms for different materials systems has increased, ever more challenging combinations of materials have successfully been grown. Since the mid 1980s there has for example been much research concerning the growth of GaAs on Si. So far most MBE research has aimed at growth of semiconductors on semiconductors. There are, however, visions, articulated by, among others, Professor Furukawa at Tokyo Institute of Technology, that it will become possible to grow semiconductors, metals and insulators on each other with a high degree of freedom in how they are combined.

For an outside observer the impression is that there is presently considerable uncertainty as to the future direction(s) that MBE research will take. This is partly related to the, at best, unclear, and according to some rather bleak, commercial potentials of MBE for any large volume products, a subject which will be discussed further later. In a situation where near-term commercial prospects, outside certain niche markets for which the technology has partly already been developed to a mature stage, are not so promising it seems that the interest of many researchers is beginning to converge on the vision of developing MBE for the realization of what loosely may be referred to as "quantum devices".

In a way the very identity of an MBE researcher is also becoming open to question as the different crystal growth and fabrication technologies are becoming increasingly integrated with each other. The identity is also becoming confused for another reason. There is growing number of researchers who use MBE without having any intention of contributing to the development of MBE technology as such. As the MBE technology has become perfected for some materials it has become possible to automate the operation of MBE-equipment for these materials so fully that someone with very little experience of MBE can grow materials which may not have the quality required for fabrication of devices but which may still be useful for studies of various physical effects. As the use of MBE in commercial contexts is increasing, there is also a growing use of MBE for routine growth of wafers for device development.

Summarizing the development of MBE technology, one can say that after MBE-research was started at Bell Labs in the late 1960s it took around a decade to establish the basic process technology for the most common materials system, GaAs/AlGaAs, to a level which permitted the realization in a laboratory setting of the first practical devices. After further development efforts some devices were put in commercial production during the latter part of the 1980s.[9] Gradually the technology has branched out, as described above, from its initial core, both in terms of the configuration of the equipment and the materials systems to which it has been applied, with a certain increase also in the variety of device applications. The diversity of research themes and approaches have thus multiplied especially in the last 3-5 years.

Through the counting of of publications it is possible to get some quantitative measure of the growth of MBE-research and its institutional structure.[10] Of a total of some 6500 publications indexed in the INSPEC database during the period 1969-1989, 48 and 19 percent came from

[9] It should be noted that material for the same device usually can be grown by alternative methods. Lasers are mainly produced by Liquid Phase Epitaxy (LPE), except for sophisticated devices for which MOCVD and MBE compete, with the former so far being the one usually preferred. In the case of HEMTs it appears that MBE is favored over MOCVD by most, but by no means all, firms.

[10] For a discussion of the use of bibliometry to study research communities see foe example Granberg (1989) and Rappa (1988).

organizations in the United States and Japan respectively (Figure 2).[11] In all parts of the world there has been a very rapid growth in MBE-publications. In absolute numbers most of that growth has occurred since the early 1980s. The growth was slower in Japan than elsewhere during the indexing period 1981-83 and more rapid during the next three-year period. Publications indexed in a certain year can be assumed to correspond, on average, to research being performed two to three years earlier.

In order to broadly compare the evolution of the MBE research communities in Japan and the United States each research organization was categorized into one of the following six groups:

1. Telecommunications research organizations
2. Three largest industrial firms in terms of total number of MBE publications (excluding those covered in group 1)
3. Other firms
4. Government laboratories/research institutes and cooperative research organizations
5. Three largest universities in terms of total number of MBE publications
6. Other universities (and other higher education institutions)

Figure 3 shows how the number of publications developed for each group over three-year periods in the United States and Japan respectively. It should be noted that the scale for the United States is twice that for Japan, roughly corresponding to the ratio between the two countries' populations. Somewhat more detailed data of a similar type for the period 1987-89 is exhibited in Figure 4. Here the scales are kept the same in order to facilitate direct comparison of publication counts between individual organizations, a kind of comparison which, should be interpreted with great caution.

[11] Molecular Beam Epitaxial Growth was introduced as a "controlled term" in the Inspec database in 1979. In order to capture MBE publications prior to 1979 the search was performed to include also MBE, and alternative expressions, as uncontrolled terms. The publication set thus obtained was for the period 1979-89 in the case of Japan around 40 percent larger than that retrieved using the controlled term and for all countries together 50 percent larger. An additional reason for choosing a generous search strategy was the fact that the data were to be used to identify as many organizations as possible with any degree of involvement in MBE. The time from publication to indexing in the INSPEC database varies. Most publications are indexed within one to one and a half year. For papers presented at conferences the time to prepare conference proceedings, which varies widely, must also be taken into account. It appears that on average it takes longer to index Japanese publications than publications from the United States. Publications in the INSPEC database are only given one address even if the authors belong to different organizations and this is indicated in the original publication.

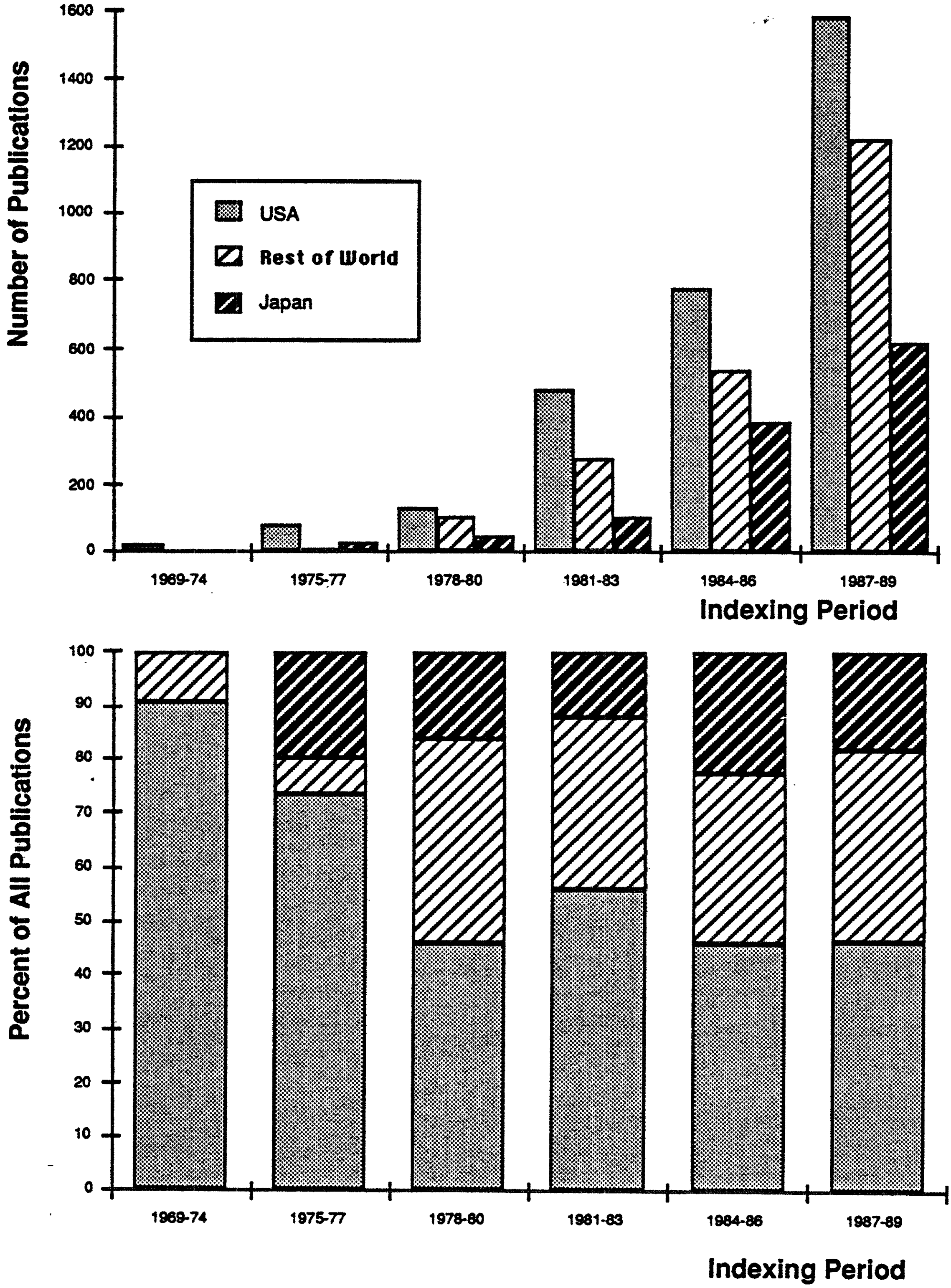

Figure 2 *Distribution among USA, Japan, and Rest of World of Publications in the Field of MBE according to Source of Publication*

Source: *Data from on-line search in Inspec processed by the author*

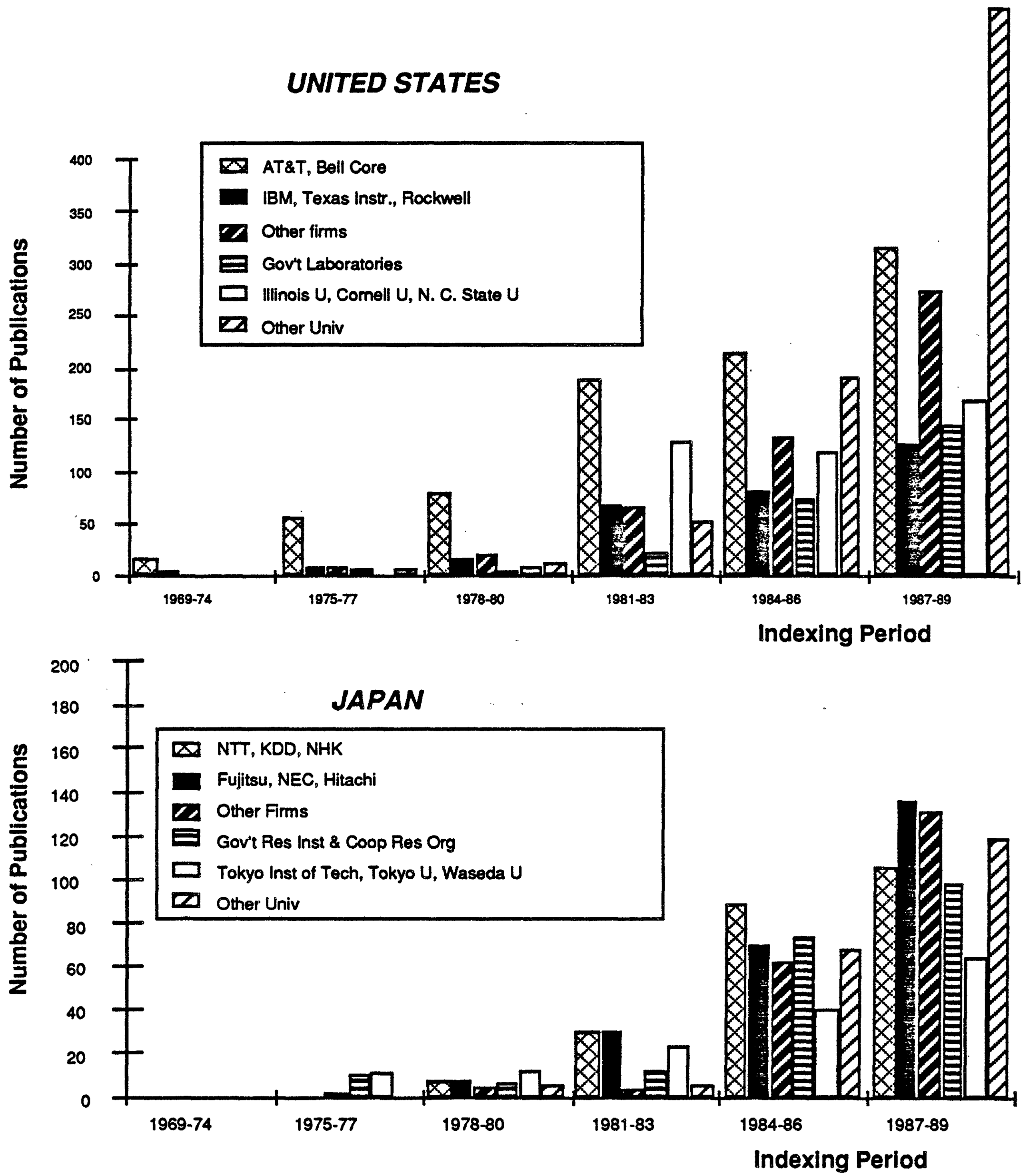

Figure 3 *Distribution of Publications in the Field of MBE among Organizations in the United States and in Japan*

Source: *Data from on-line search in Inspec processed by the author*

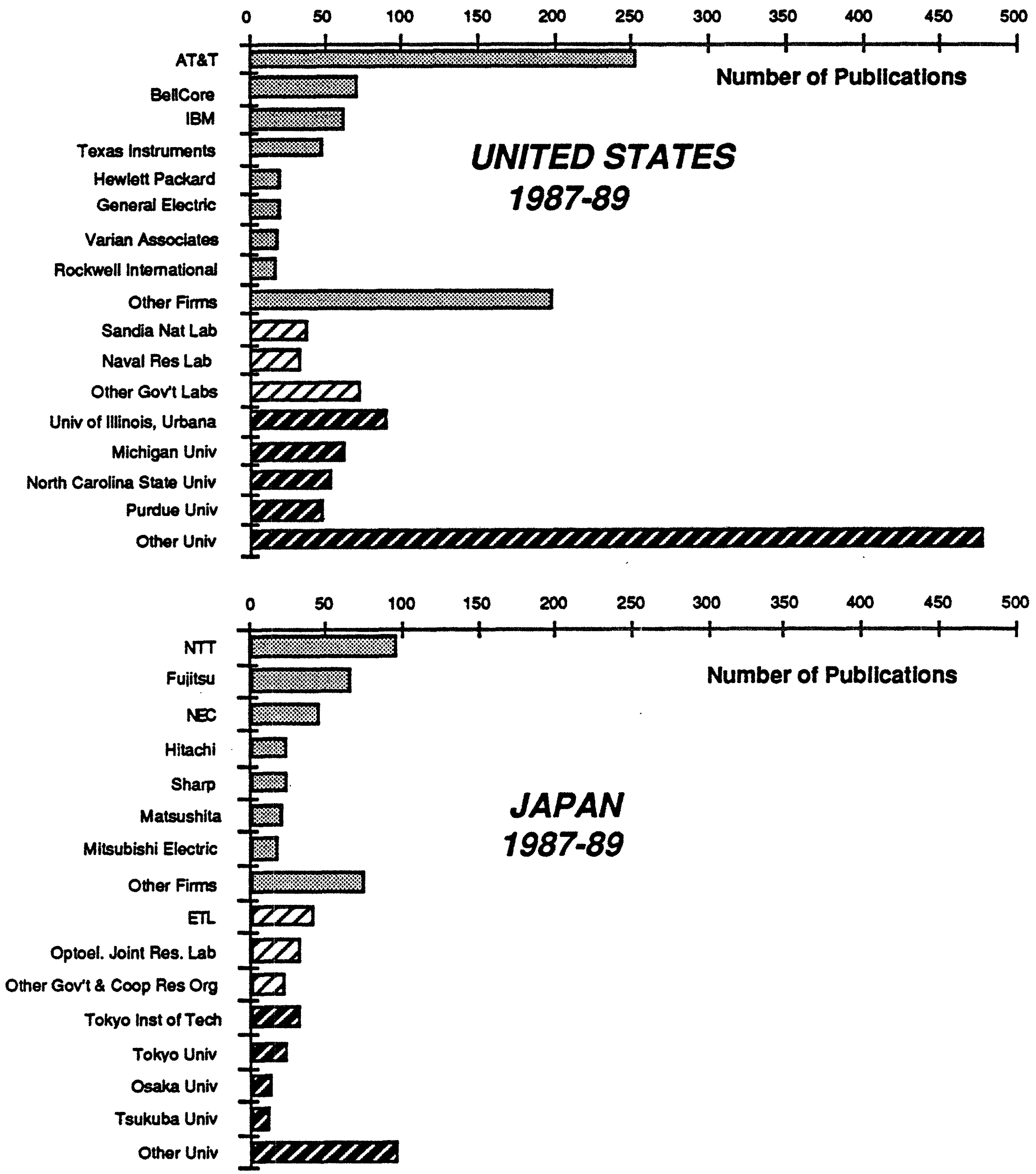

Figure 4 *Distribution of Publications in the Field of MBE that were Indexed in Inspec 1987-89 from U.S. and Japanese Organizations*

Source: *Data from on-line search in Inspec processed by the author*

Overall the research communities of the two countries exhibit rather similar development with a strong concentration to only a few organizations during the 1970s and then a rapid broadening of the participation in the 1980s. On a per capita basis the Japanese business sector has a stronger publication record than its American counterpart, while the university sector is weaker. The leading Japanese industrial firms compare well with American firms even in absolute terms while the same cannot be said for the universities. Similar data for European countries, which can not be displayed here for reasons of space, reveal, however, that in the field of MBE, American universities are exceptionally strong. In terms of per capita publication counts Japanese universities fall somewhere between the United Kingdom and West Germany and far ahead of France. In absolute numbers of publications the three largest Japanese universities are about 50 percent larger than their counterparts in the United Kingdom and West Germany. MBE research in the corporate sector is much more limited in the European countries than in either of Japan and the United States.

3. Evolution of the institutional structure of MBE research in Japan

3.1. The pioneers

1980 represented a turning point for MBE technology. Around this time it became clear that the technology had to be taken seriously while this had previously been very much an open question. In fact around 1978/79 the outlook for the possibility of commercial applications of MBE had, at least in Japan, been at a pessimistic low. Efforts to turn a visionary concept into a useful technology had been underway in the United States for almost a decade, and in Japan a few years less, without yet producing any results that had not already been achieved more easily in other ways.

Prior to 1980 only a handful of companies, three universities and ETL had at all been involved in MBE research in Japan. ETL and Tokyo Institute of Technology (Professor Takahashi) had pioneered the Japanese efforts in the very early 1970s. They were soon joined by Mitsubishi, Matsushita and Fujitsu and around 1977 also Hitachi and NTT started MBE research. Some of Professor Kimata's students at Waseda University had joined the research group at ETL very early for their thesis work and somewhat later Kimata's group at Waseda University started MBE research on very simple equipment that had been built from the meagre funds available. At Tokyo University, Professor Sakaki returned in 1978 after having worked one year with Dr. Esaki at IBM in what was one of the two leading MBE research groups in the United States and in the world. Sakaki was determined to establish MBE research at the Institute for Industrial Science where he had been working since 1974. This seemed to him a good time for a university to get involved in MBE research as Japanese industry was apparently in the process of scaling down its already fairly small MBE research.

Mitsubishi and Matsushita were about to dissolve their MBE groups and management at Fujitsu was also becoming impatient. Hitachi and NTT had started later and therefore might be expected to hold out longer. At Hitachi compound semiconductor research was under general pressure and severely cut. By reorienting MBE research towards growth of silicon crystals instead of the more commonly studied compound semiconductors the researchers at Hitachi were able to obtain management support for continuation of MBE research.

NTT as a public or semi-public organization was expected and able to carry out more long-term research than regular companies and consistent with this does not seem to have been strongly affected by the generally pessimistic views on MBE in the late 1970s. NTT was primarily interested in materials and devices with potential use in telecommunication and therefore set out to explore crystal growth for various kinds of optical devices, more precisely long wavelength lasers, visible light lasers and optical modulators. MBE research on long wavelength lasers and optical modulators was already underway at Bell Laboratories when NTT started up its own efforts. Visible light lasers, a field which Japanese companies dominate today, are mainly used in CD-players and laser printers and thus fall outside NTT's primary interest. Research on MBE growth of visible light lasers was therefore later discontinued while the other two themes are still being pursued at NTT. The research just described was carried out in the Optical Device Division. At about the same time MBE research was also started up in the Basic Research Division. This research initially focused on growth of GaSb and GaSbAs and was later to emphasize growth of AlGaAs for multiple quantum well physics and its application to optical devices.

The Electrotechnical Laboratory (ETL), the main electronics laboratory under MITI, played a key role in the launching of the second wave of MBE research in Japan. Its role in the planning and monitoring of three major MITI R&D-programs, each begun around 1980 and supporting MBE research in a different way, may have been more important for MBE in Japan than its own specific research contributions. The two functions are, however, so closely intertwined that they should be viewed together.

ETL's first experience with MBE went back as far as the early 1970s when research on visible light lasers was started as part of the Pattern Recognition Large Scale Project. This project was mainly concerned with software but Dr. Sakurai at ETL who was planning the project had decided to include research on optical elements, including semiconductor lasers, in the project. Semiconductor laser research had more or less stopped in Japan around 1966-67 as a result of a growing conviction that it would be impossible to realize semiconductor lasers that could operate at room temperature. In 1970, Dr. Hayashi, then working at Bell Labs, had instilled some new hope when he demonstrated a double heterostructure (DH) GaAlAs laser at room temperature. [12] As a result semiconductor laser research was resumed in Hitachi, NEC and Toshiba. By including lasers in the pattern recognition project Sakurai was able to provide early encouragement for these research programs at NEC and Toshiba, while Hitachi preferred to stay out of the laser part of the project. NEC was given the task of developing single mode lasing and Toshiba to develop long-life lasers.

ETL's task of developing a visible light laser was more challenging and speculative than the tasks allotted to the companies, a division of tasks which was in line with the role defined for ETL. While semiconductor research in the Japanese companies relied on LPE as the growth method, ETL decided to begin experiments also with MBE. As later became clear, the chosen material, GaAsP, due to its content of phosphorous, caused erosion in the growth chamber which seriously reduced the efficiency of the vacuum pumps and made it difficult to grow high quality crystals. Nevertheless GaAsP was successfully grown on GaAs and when the work was discontinued around 1978 a lot of MBE know-how had been accumulated through hard and sometimes frustrating work. New MBE research activities had also been launched, all of them on somewhat unusual materials. The second MBE group to be formed, around 1975, began research on II-VI compound semiconductors, mainly ZnSe and ZnTe. This was followed by the establishment of other groups trying to grow wide band-gap semiconductors (initially AlN and later GaN) and Si respectively.

The fairly hesitant and small-scale MBE research in Japan, and elsewhere, prior to 1980 reflected uncertainty about both whether MBE would be technically successful and if it would be needed considering the availability of alternative crystal growth technologies. Optical devices was not an important target for any of the four industrial companies doing MBE research prior to 1980. The market for optoelectronic devices hardly existed[13] and LPE seemed a more reliable crystal growth technology than

[12] This laser, which had been grown using Liquid Phase Epitaxy (LPE) and represented a new concept (GaAlAs heterojunctions had been introduced as late as around 1968) still was far from a practical device. Its lifetime was limited to a few hours which would have to be improved to somewhere in the order of one million hours to allow practical use.

[13] LEDs were put on the market around 1976/77 but were still in 1980 a little too expensive compared to alternative solutions for a real market take-off. Semiconductor lasers were still plagued by too short a life time. Continuously working semiconductor lasers operating at room temperature were therefore not yet commercialized. LPE still showed low reproducibility. Ion implantation had not yet been introduced so the cost of producing lasers was high. The problems of laser life-time were solved around 1981/82 and then the laser market

MBE. The usefulness of MBE for transistors and other electric transport devices[14] was by no means obvious either. One could argue that the existence of a large market for ICs and discrete electric transport devices gave an economic base for exploratory research on basic technologies for future devices, the size of which was infinitely much larger than that for research on optoelectronic devices. MBE grown materials were, however, expected to be used primarily in high speed devices, which represent but a small portion of the total market for electron transport devices. Furthermore, at the time military applications (microwave devices) almost totally dominated the market for high speed electronics and Japanese firms did not have a strong position in the U.S. or any of the other major military markets. As a consequence MBE researchers in the Japanese companies found it increasingly difficult to defend their research.

Apart from the need to argue their case with management, the researchers themselves were not so concerned with what devices might ultimately be produced with the help of MBE. They were still struggling to master the basic technology of growing high-quality crystals. The general concept of superlattices, band gap engineering, etc., that had been introduced by Esaki and others around 1970 were so intriguing to most researchers that these visions more than anything else motived efforts to master the technologies that were required to realize the visions and open up a new world of physics and most likely also of device engineering.

The Japanese researchers were by no means alone in having difficulties in growing good crystals, but there seems to be some agreement that until the early 1980s they were behind at least the best research groups in the United States, including Bell Labs and IBM. There was one very good reason for this. The various research organizations in Japan simply had not put the same amount of resources into MBE research as their major contesters in the United States. Another factor which slowed the progress of MBE research in Japan and which only gradually became obvious was that the infrastructure of equipment and materials suppliers in Japan was not up to standards. The vacuum companies had less experience with ultra high vacuum (UHV) equipment than the leading companies in the United States and Europe. The latter typically were more discriminating in the materials they used, thereby eliminating many sources of contamination during growth. When Dr. Cho, the pioneer of MBE from Bell Labs, visited Japan in 1978 it was revealed that different and better crucibles were being used in the United States than in Japan. The Japanese had used "composite BN" crucibles while Union Carbide supplied IBM and AT&T with "Pyrotic BN (PBN)". After the Japanese researchers shifted to the Union Carbide crucibles they were able to obtain much improvement in their crystal

took off.

14 The term transport device is used here to denote electron devices other than optical devices.

quality.

After MBE growth technology became established around 1980 for at least AlGaAs, standard MBE machines became available and traded internationally. Before that, the MBE researchers themselves had usually done the basic design for each MBE machine, and solved the detailed design problems in cooperation with a local vacuum company, the latter subsequently building the machine to order. It is worth emphasizing that the physicists who became involved in MBE, contrary to what would have been their natural inclination, had to pay a lot of attention to technical problems in the design and operation of their machines.

Whatever capabilities were lacking on part of the Japanese suppliers probably was to a large extent a reflection of the as yet less developed market in Japan for the most advanced equipment as compared to, for example, the United States. Today, equipment from the top Japanese companies, Ulvac and Anelva, is considered to be comparable to that from Varian, Vacuum Generator and Riber, the leading foreign suppliers.

In line with the general career patterns in Japan there was basically no mobility of MBE researchers between the different organizations prior to 1980. The only exception we encountered is Dr Naganuma, who graduated from Professor Takahashi's research group at the Tokyo Institute of Technology and then in 1976 moved to NTT's Basic Research Division where he became one of the early MBE researchers.

In 1976 Dr Gonda, leader of the first MBE group at ETL, took the initiative to establishing an informal group of the main MBE researchers in Japan for discussing common problems and exchanging ideas. The group met at least three times a year until around 1981-82.

International exchange appears to have been rather limited during the 1970s. Professor Sakaki had been abroad doing research in the field of MBE, but did not return from IBM until 1978, and Dr. Kawai, after having worked at IBM and Cornell University with MBE and related questions of superlattices , was hired by ETL around 1980. During the 1970s, Japanese MBE researchers, of course, read what was published, especially from IBM and Bell Labs, and some researchers made short visits abroad. The occasional visits to Japan of Cho and Esaki were experienced as important events. They were however short encounters. By and large in these early years each research group learnt MBE the hard way through its own trial and error with only rather general guidance from what could be sifted out of the scientific papers published abroad and a few, probably very welcome, opportunities to discuss with other MBE groups in Japan.

3.2. The invention of HEMT at Fujitsu

Starting in 1979 the momentum began to build for a second wave of MBE research both internationally and in Japan. The Japanese research community responded particularly intensely to the new research opportunities that were opening up as a consequence of a number of technical breakthroughs. Although they may in some sense only have represented the tip of an iceberg that was ready to come up to the surface, three developments had a particularly strong impact on the perceptions of the potential of MBE technology, two coming out of Bell Labs and a third from Fujitsu.

Dr Tsang, a young researcher at Bell Labs, in 1979 flooded journals with papers showing dramatic improvement in MBE-grown lasers. Inspired by his recent work with LPE, Tsang had used a growth temperature some 100°C higher than what was conventionally considered recommendable. He also used a new technique for cooling the growth chamber which resulted in a better vacuum and lower contamination by oxygen and carbon dioxide during growth. Finally he used Be as p-type dopant. The importance of Tsang's results was that they demonstrated that results of practical interest could be achieved by MBE, and such concrete evidence was much more convincing to management than ever so exciting visions lacking material proof. This therefore raised the spirits not only of the MBE researchers directly involved with optical materials but for those working with transport device materials as well, although there would soon be concrete results also in that field.

In 1978 Dingle and his coworkers at Bell Labs had introduced a new concept, modulation doping, through which it was possible to grow heterojunctions, where electrons that could move long distances without being scattered (high mobility electrons) were confined in a thin layer, forming a so called two-dimensional electron gas (2 DEG). This ability to create high mobility electrons presented opportunities for design of new types of high speed devices and researchers in several groups in both the United States and Europe began to explore these opportunities, but Fujitsu was the first to demonstrate a working device. A patent application for the new device called HEMT (High Electron Mobility Transistor) was filed in early 1980. In May the same year the results were presented at the spring meeting of the Japan Society of Applied Physics and a month later a presentation was made to an international audience at a conference in the United States.

Development of the HEMT had progressed extremely fast at Fujitsu. Dr. Mimura[15], who had been doing basic research in device physics at

[15] Mimura received his doctoral degree from Osaka University in 1982.

Fujitsu, had read about Dingle's concept of modulation doping for the first time in the spring of 1979 and began to give some thought to what kind of new device might be built on this principle. In July his ideas had matured to the point where he had a concrete device concept. He approached Dr. Hiyamizu, who had been leading the MBE group since 1975, to discuss the possibilities of realizing the device design. A formal project was started in which Mimura and Hiyamizu worked close together in an iterating process of development of the crystal growth technology and modification of the design of the device. Major problems of reproducibility were encountered until an "air locked system" had been developed early in 1980. The first devices were, however, produced already in October 1979.

A major reason for Fujitsu's success appears to have been the close cooperation between an MBE researcher and a device physicist. Fujitsu was more or less the only company in Japan at the time with an active research program on MBE growth of GaAs GaAlAs heterostructures. Abroad, most of the groups working on HEMT-like devices seem to have consisted almost entirely of MBE researchers with very little input from device-oriented researchers.

3.3. Three MITI-projects

It took a little while before the dust had settled from the scientific debate about the invention of the HEMT and its genuine novelty was generally acclaimed. This of course eliminated the threat that had earlier been felt that MBE research at Fujitsu might be discontinued. In fact Fujitsu took steps to enlarge its MBE research. A new group was established with the singular task of perfecting crystal growth technique for HEMTs; both discrete devices and ICs. Hiyamizu's group then soon became free to pursue other avenues of MBE research. The momentum to expand MBE research was further aided by Fujitsu taking a leading role in MBE related research in no less than three MITI projects that were started around 1981.

The MITI-projects referred to were the Supercomputer Project, the OEIC Project[16], and the Superlattices Devices Project[17]. MITI had already earlier been involved in encouraging MBE research in Japanese companies, mainly through financial support for the acquisition of MBE equipment. At

[16] The official names of these two Large Scale projects were "High Speed Computing System for Scientific and Technological Uses" (1981-89) and "Optical Measurement and Control System" (1979-85). The total budgets of the projects were around $ 120 million and $ 100 million respectively. (Throughout this paper $ 1= ¥ 150 is used as conversion rate)

[17] The Superlattices Devices Project (1981-90), with a total budget of around $ 25 million, was part of a new scheme "Research and Development Project on Basic Technologies for Future Industries" launched by MITI in 1981 and initially including 12 projects three of which dealing with new electron devices. Plans for the three electron devices projects are described in Sakamoto (1982).

least two companies benefitted from such support, Fujitsu being one.

The Supercomputer Project most directly followed up on the invention of the HEMT. The development of various types of high speed LSIs was an important aspect of this project. Each of the participating six companies received financial support to develop production technology for one or two of three main types of ICs. Fujitsu and Oki were contracted to work on HEMT ICs and reverse HEMT ICs respectively. GaAs MESFETs and ICs based on Josephson Junction devices were the other two types.[18] The target for Fujitsu's and Oki's work was to develop 16 Kbit SRAMs for random number generators and this target has been successfully achieved. In spite of this success and continuing research at both Fujitsu and Oki it remains unlikely, or at least highly uncertain, that HEMT LSIs will ever be used commercially, as they exhibit some operating characteristics (for example, poor drivability) which are very unfavorable compared to alternative ICs.

Discrete HEMTs, that is components consisting of only one transistor, have however found commercial applications. The most important is in tuners for satellite TV broadcasting receivers which make good use of the very low noise characteristic of the HEMT. It is estimated that in 1989 around one million tuners were produced in Japan, each containing five HEMTs. When considering that as many as 10 000 HEMTs may be fabricated on one wafer it becomes clear that the market for discrete HEMTs is still fairly limited in value terms, even if it is expanding at a rapid rate.

The Superlattices Devices Project also focused on electron transport devices but was more speculative in nature than the Supercomputer Project. Its objective was to demonstrate new device concepts. Most of the research, however, actually concerned the development of new basic technologies for crystal growth and device fabrications, with MBE as one of the prime examples of such technologies. Four companies and ETL were involved in the Superlattices Devices Project, and all but Sony would have MBE growth as a crucial part of their research. Sony, which had pioneered MOCVD, a crystal growth technique competing with MBE, remained faithful to its past accomplishments.

The other three companies, Hitachi, Fujitsu and Sumitomo Electric, each worked on different devices and materials systems. Hitachi was supported to direct its already existing Si MBE research to the development a Permeable Base Transistor (PBT) which didn't build on the conventional concept of superlattice, but under the label of "lateral superstructure device" was nevertheless accepted. Fujitsu was charged with developing a Resonant Tunneling Hot Electron Transistor (RHET) in InAlGaAs and

[18] The six companies were: Hitachi, NEC, Toshiba, Mitsubishi Electric, Fujitsu and Oki. Fujitsu worked both on HEMT ICs and Josephson Junction ICs.

succeeded in fabricating not only an individual transistor but an IC with a new function. Sumitomi Electric, which had no previous experience with MBE was given the task of developing a HEMT in $(InAs)_3(GaAs)_1$ with AlInAs as channel layer.

Within the framework of the 3-Dimensional IC Project, running in parallel with the Superlattice Devices Project, there was still another project involving MBE, namely an effort by Oki to grow GaAs on Si. Already in the mid 1980s Oki managed to grow good crystals and is today considered the leader in Japan in the technology of growing GaAs on Si.[19]

It deserves to be emphasized that although all the just mentioned four projects had the demonstration of devices as their targets, these targets were not so important in themselves but served a useful function in directing and setting a standard for the development of the basic technologies of crystal growth and device fabrication.

The Supercomputer and the Superlattices Devices projects both ran over a very long period, nine and ten years respectively. The companies which got engaged in these projects effectively committed themselves to maintain viable research groups for that long a time. For the MBE researchers at Hitachi and Fujitsu, who had very recently worried about the viability of their research, and for researchers in the new groups at Sumitomo and Oki the future must have seemed very bright. Even without the MITI programs it is likely that the prospects for MBE research would have improved, given the recent breakthroughs, but hardly to the extent achieved by the stability and extra funding of the MITI-programs.

The Superlattices Devices Project also gave a strong boost to MBE research at ETL. As customary in MITI's electronics R&D-programs, ETL had been intimately involved in the planning of the project, with Gonda drawing up the plan, including research at ETL itself. Researchers from three or four different groups at ETL were drawn into the project. A new Riber MBE-machine, considered much superior in reliability to the machines already installed at ETL, could be acquired with the new funding made available and was used for growth of AlGaAs superlattices. Another machine, acquired by the VLSI Joint Research Laboratory towards the end of its existence and then transferred to ETL around 1979, was used for Si and Ge MBE. The research at ETL included both the study of the basic mechanisms of crystal growth and exploration of some new device concepts. An important result was the development of a technique for nearly atomic layer by layer controlled growth, so called phase-locked epitaxial growth, based on intensity oscillations in Reflection High Energy

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19 Also MBE-research at Sanyo has been performed with support from the R&D-project of Basic Technologies for Future Industries (Shiraki, 1989, p. 504), but it is unclear under which sub-project.

Electron Diffraction (RHEED), the latter a technique usually employed for monitoring of the growth process in real time.

The R&D Project on Basic Technologies for Future Industries, of which the Superlattices Devices Project has been a part, is gradually being renewed as the early projects are phased out and new projects take their place. A Bio-electronic Devices Project was, for example, introduced in 1986 when the Fortified ICs for Extreme Conditions Project was completed.[20] The other two initial electron device projects will both be completed in 1990. There is an interest both at ETL and in some companies in the launching of a new project, which would be a natural continuation of the Superlattices Devices and the Three-Dimensional ICs projects, centering around the concept of quantum devices but it remains unclear whether such a project will be able to compete with other proposals. The fact that similar projects have already been started with support from other ministries is one factor speaking against the project.

The OEIC-project aimed at the development of OEICs, that is electric transport and optical devices integrated on one chip, and their application in various systems for control of industrial processes using optical signals. The systems applications came only towards the end of the project while the bulk of the project concerned the development of crystal growth and device fabrication technology for OEICs. The latter was divided into two distinct activities, one being the development of specific OEICs contracted to five companies[21] and the other being research on basic technologies for future OEICs in a laboratory jointly operated and staffed by the five companies receiving special contracts, an additional four companies[22] and ETL. The projects in the individual companies were started already in 1979 while the Optoelectronics Joint Research Laboratory (OJRL) began its operation first in 1981.

The company projects relied for the most part on already established technologies which in terms of epitaxial growth meant LPE. MBE was however included in OJRL's research program. In the early stages of the planning of the OJRL, which was set up only after considerable resistance from the five leading companies, the idea had been to have one of the six research groups work on MBE. As time went on the interest in MBE grew among the companies, not surprisingly considering the breakthroughs already described. There was still considerable hesitancy in most companies to launch any major in-house MBE research programs especially in the optical materials field. As MBE was beginning to show some promise, the opportunity to explore the technology without having to make

20 The Superconducting Materials and Devices Project (1988-97), and Non-linear Photonics Materials Project (1989-98) also have relevance for electron devices.

21 Hitachi, Mitsubishi Electric, Toshiba, NEC and Fujitsu

22 Matsushita, Oki, Furukawa Electric and Sumitomo Electric

any own long term commitments, therefore seemed a very appealing proposition. Several companies expressed a desire to work on MBE in the OJRL.[23]

When OJRL started its operation there were only rather rough plans for the research to be carried out leaving much discretion to the group leaders in their choice of research direction. The group leaders from Fujitsu (Dr. Hashimoto), Mitsubishi (Dr. Ishii) and Hitachi (Dr. Nakashima) all wanted to be involved in MBE research. However MITI/AIST did not want the different research groups to overlap too much. To satisfy MITI/AIST somewhat artificial distinctions had to be made between the groups. As it turned out the three groups doing MBE-work naturally focused their work in such a way that their work mixed nicely and became more complimentary than duplicating. Ishii's group had the study of epitaxial growth, mainly MBE but also some MOCVD, including fundamental study of growth mechanisms as its main objective. Hashimoto had a background in ion implantation research and combined MBE and Focused Ion Beam equipment in one machine so that crystal growth and implantation could be done without breaking the UHV condition. Nakashima who, like Ishii, was a laser specialist, decided to develop a multiple quantum well laser, which used a new device structure ("index guided"). This required development of MBE technology and brought Nakashima's group into quite basic studies of surface physics.

The OJRL was a very important step in the evolution of joint research in Japan.[24] Most of the Large Scale Projects have since the beginning of such projects in the 1960s included the establishment of joint laboratories. Their function has, however, almost always been limited to the very end of the projects and consisted in the final integration of the various technologies or subsystems developed during the main part of a project into a demonstration system. The widely discussed VLSI Project (1975-1979) therefore represented something new in that a joint laboratory was established from the beginning of the project. There were, however, several research sections in the joint laboratory and each was

[23] A major cost of participating in the OJRL as seen by the companies was that they had to send some of their own researchers, which could be a very significant sacrifice considering the scarcity of qualified researchers, especially in dynamic fields. At the same time the most effective way of gaining a benefit of research in a joint laboratory was to have own researchers work there and later return to the company. The OJRL seldom received the most ideal researchers from the companies in terms of their immediate research experience. This, however, doesn't seem to have held back the research to any significant extent. The group leaders, and the specially selected coworkers one of whom each group leader brought from his own company constituted a strong enough backbone, which complemented by a few additional experienced researchers quickly could guide the whole organization to perform very impressive research.

[24] Interesting accounts of the operation of the OJRL can be found in Hayashi (1989), Merz (1986), and Shimada (1986).

largely staffed with researchers from only one company with the result that the research was joint only to a limited degree. The reason was that the research work carried out was rather close to the market making it difficult for the companies to cooperate in earnest. The OJRL, by contrast, focused on more basic research and therefore could, and did, mix researchers from several companies freely in each section; and there was also a lot of interaction between the groups as they all had their desks in one big room.

The OJRL is generally considered to have been very successful in its mission. It was extremely well equipped and with almost 50 researchers it represented a much larger and more comprehensive research effort than any of the participating companies could muster in the OEIC field at the time. As MBE was one the main topics of research OJRL naturally had a strong impact on the development in Japan of this field. That influence took many forms. An important mechanism for transmitting results from the OJRL to the member companies was the upgrading of the capabilities of the researchers who worked at OJRL and then went back to their companies.[25] Approximately ten researchers, none of whom had any experience with MBE when they came to OJRL, are now actively pursuing MBE research in their companies. Research at OJRL also gave the companies something to lean on when they made decisions about their own MBE research. The research at OJRL set challenging goals and sought innovative solutions, thereby often laying out fruitful directions for future research.

3.4. New organizations for joint research

The Optoelectronics Technology Research Laboratory (OTL), which was set up soon after the discontinuation of the OJRL in 1986, is in many respects carrying on OJRL's mission but is also taking the concept of joint research one step further. It is one of the first of a large number of joint research firms that have been established since 1986 with financial support from Japan Key Tech Center, a quasi-governmental organization. OTL is planned to operate during 10 years.

The Key Tech Center, operated under the joint supervision of MITI and the Ministry of Post and Telecommunication (MPT), has several tasks but the most significant is to finance joint research between groups of firms. Through equity investment in, or loans to, joint research firms it provides

[25] While almost all of the researchers went back to their companies, the situation was different for the group leaders. As many as four of them became professors immediately or soon after leaving OJRL. Two went back to their companies but only one to work in the semiconductor field. Iizuka first went back ETL, then joined a company. (One of the group leaders left OJRL early and was replaced which explains why the number of group leaders add up to seven).

up to 70 percent of the financing necessary to carry out specific research program. The Key Tech Center, which has the legal status of a non-profit foundation, relies on a capital fund built up from several sources, the most important of which are dividends from government ownership of NTT shares. The way the Key Tech Center is funded means that it can operate free from the constraints of the government's annual budget. The real strengths and weaknesses of this mechanism for support of joint research, compared to for example the long standing Large Scale Projects, will only become clear when some of the joint research firms have concluded their work and the results of their work as well as the financial arrangements be evaluated by the member firms. There still seems to be only vague notions what will happen financially when the joint research firms have exhausted their initial financing.

The OTL consists of one big group of 20 researchers[26], all looking from different angles at the problem of how to fabricate low dimensional structures, for example quantum wires and quantum boxes. Epitaxial growth, mainly using MBE of one or another kind, is an important research component which is studied in its most fundamental aspects. For this purpose the most advanced analysis equipment has been combined with the crystal growth chambers in ways which, in several cases, have not been tried anywhere before. The research is as basic as that which can be found in any university but carried out under much more favorable conditions. The researchers, widely ranging in age and the research fields and research cultures in which they have worked, have no other obligations than their research while at OTL. The material resources leave little more to be desired. The leadership, represented by the Dr. Hayashi, Director, and Dr. Katayama, the Technical Director, has a deep knowledge of the topics being researched. With each researcher coming from a different background and many complementary approaches being taken to study the same physical phenomena the OTL seems to be an ideal place for creative research.

One might ask what the member companies expect to get out of OTL. As the utility of quantum wires or the like for practical devices is uncertain at best, the most convincing answer is that the companies are seeking access to high quality basic research. The role of the objective to fabricate structures such as quantum wires is mainly to focus the research program. The expectation on the part of OTL's management is that in the process of reaching for this objective a deep understanding of quantum crystal materials and structures will be gained, an understanding which will be useful also for fabrication of more mundane semiconductor devices in the near term. In developing this philosophy, Dr Hayashi has

[26] All but one on assignment from one of the 13 member firms: Mitsubishi Electric, Hitachi, Sanyo, Matsushita, Furukawa Electric, Japan Sheet Glass, Oki, Toshiba, Fujikura, Fujitsu, NEC, Sharp, Sumitomo Electric. The Director and the Technical Director are not counted among the 20.

built on his experience from the OJRL, where he served in a special technical advisory position. The philosophy therefore reflects what he considers to have been the most essential contribution of OJRL.

The Advanced Telecommunications Research Laboratories (ATR), established in 1986 and located in the new Culture and Science City under development near Nara in the Kansai area, is an additional example of a joint research organization which is doing MBE research and which is supported by the Key Tech Center. For several reasons it is likely to have less of an impact in the field of MBE, the main simply being that MBE research is a smaller activity at ATR than at OTL. ATR, formally consisting of three laboratories, has several hundred researchers in total but the great majority of these are studying systems and software oriented matters. In the ATR Optical and Radio Communications Research Laboratory, the Optical & Electronic Devices Group has around ten researchers most of whom are involved in research on semiconductors materials and physics of advanced devices, with MBE as one of the primary technologies. ATR is, like OTL, generously funded and well equipped, but short on researchers. Although ATR probably may have set somewhat less ambitious research targets than the OTL, the differences between them in research organization are probably larger than differences in the nature of the research. The main difference lies in the weaker continuity at ATR than at OTL. While the researchers at OTL are semi-permanent and seldom stay less than three years, three years is considered the upper limit at ATR and frequently researchers stay an even shorter time. The fact that also the group leaders at ATR change every three years must cause great problems in setting and adhering to long term research goals.[27]

Japanese electronics companies have almost all their R&D laboratories in the area around Tokyo or in the Kansai area, with a strong and growing dominance by the former. The establishment of ATR is part of a conscious effort to enhance the environment for companies to do R&D in the Kansai area. While OTL draws its members from both regions, the Optical & Electronic Devices group at ATR has so far only attracted, and maybe only tried to attract, members from the Kansai area, the exceptions being NTT and NHK which are special cases.[28] Notably, the leading Kansai electronics companies are also members of OTL. Considering the small scale of ATR's semiconductor research, its success will critically depend on how close a cooperation it can develop with research in its member companies and maybe also with research in the universities in the Kansai area. It has a greater need to develop such links than OTL and the development of close cooperation with research in Kansai universities and companies may offer

[27] The head of the whole Optical and Radio Communications Laboratory is appointed for ten years, the originally planned lifetime of ATR.

[28] Among the members of ATR's Optical & Electronics Devices Group are NTT, NHK, Sumitomo Metals & Mining, Sumitomo Electric, Murata, Toyobo, Mitsubishi, Rohm, Sanyo and Sharp.

a special opportunity for ATR consistent with the reason for its establishment.[29]

3.5 Device development and basic research in companies

Although the MITI-supported projects in all likelihood helped accelerate the second wave of MBE research, this effect became increasingly less important as more and more companies built up and expanded their MBE research.

In the cases of Fujitsu and Hitachi, MITI funding, as already described, contributed to strengthening already existing activities by providing additional funding and guaranteeing stability over a longer term than could typically be taken for granted for research funded purely by internal corporate funds. At Oki and Sumitomo Electric, on the other hand, the MITI projects were launched more or less at same time as new MBE research groups were being started up. Judging from their publication records MBE research in the latter two companies appears not to have expanded very much beyond the topics covered by the MITI projects.

Other companies which began MBE research did so without any direct financial support from MITI programs. Mitsubishi Electric and Sanyo were among the earliest to start up MBE research in the second wave, both companies primarily focusing on optical devices. A large number of companies started MBE research around 1982-84. NEC and Matsushita developed rather diverse research programs with optical devices representing a minor part while Sharp, Rohm and Omron almost totally concentrated on laser development. At Sony and Toshiba MBE research never developed beyond rather small research programs as both companies early became strongly committed to the development of MOCVD, an alternative technology to MBE. In the latter part of the 1980s an additional 5-10 companies, some, for example Toyota, outside the electronics industry, have initiated MBE research for the most part on a limited scale. Japanese suppliers of MBE-equipment - Ulvac, Anelva and to a lesser extent Seiko Instruments - have invested resources in the development of MBE technology, usually in cooperation with customers, but do not appear to have had major internal research programs.

MBE research in the companies cover a broad range of activities which can be characterized in different ways, for example in terms of the materials studied or the device applications at which the research is aimed. Although the ultimate justification for more or less all MBE research in companies is the prospect of new or better practical devices of one or

[29] In its major fields of research, ATR is likely to be relatively much stronger and for those the situation would therefore be quite different from that in semiconductor research.

another kind, the link between material growth by MBE and the development and fabrication of devices takes on different forms. On the one extreme crystal growth by MBE is done simply to supply, on a routine basis, wafers for further fabrication of devices aiming at development of devices with improved characteristics. On the other extreme, crystals are grown for the purpose of discovering or exploring some new physical effect which may open up as yet unknown possibilities for new device concepts. Most of the research related to low-dimensional quantum confinement structures can be put in this latter category. HEMTs and certain types of lasers based on MBE-grown crystals have already been commercialized, so MBE research related to such devices has, for the most part, well defined and near term objectives of improving device performance. Most of the MBE research in the Japanese companies falls, as might be expected, between the two extremes.

NTT is generally considered to be the leader in MBE research among Japanese companies with Fujitsu being a good second.[30] From the start NTT has been emphasizing optical devices and Fujitsu been particularly interested in transport devices for ICs, first HEMTs and later resonant bipolar transistors (RBT) and resonant tunneling hot electron transistors (RHET). Already in the early 1980s, Fujitsu, however, began to use MBE also for research on optical devices and was one of the first Japanese companies using this technology for the realization of OEICs. Correspondingly, NTT around 1983, in its LSI Laboratories, began research on various transport devices, the most important of which would become hetero-bipolar transistors (HBT) which have been developed to the level of ICs.

Fujitsu's MBE research has been almost totally limited to III-V compound semiconductors and these have also dominated at NTT. Although NTT has had several groups working on Si MBE, the clear leaders in this field are NEC and Hitachi. Hitachi, which pioneered Si MBE in Japan in the late 1970s, did not begin MBE for III-V semiconductors until around 1983 and then primarily for transport devices. NEC which started its MBE research rather late, around 1984, has since developed a broader and larger research program than Hitachi with extensive research of Si as well as III-V materials. Although optical devices were initially an important target for III-V MBE at NEC it appears that MOCVD soon became the favored technology for such devices.

Electronic companies in the Kansai area[31] have traditionally been considered as having a more pragmatic view of R&D than the major electronics

[30] NTT was, for example, among the first to develop gas-source MBE in the early 1980s and Horikoshi at NTT has developed a modified version of MBE, labelled Migration Enhanced Epitaxy (MEE), which yields extremely high quality crystals at low substrate temperatures by interrupting the flow of As during the deposition of Al and Ga.

[31] E g Matsushita, Mitsubishi Electric, Omron, Rohm, Sanyo, Sharp and Sumitomo Electric.

companies in and around Tokyo[32] and as putting less emphasis on long term research. The fact that both Matsushita and Mitsubishi discontinued their MBE research in the late 1970s and later developments in these and other Kansai companies seem broadly consistent with this view although the distinction must should not be overdrawn. Matsushita, Mitsubishi and Sharp are well ahead of other Kansai companies in terms of the number of MBE publications. Both Mitsubishi's and Sharp's MBE research have focused on III-V laser materials, while Matsushita has mainly worked on various transport devices. For a while Matsushita had a Si MBE group but that was discontinued. Both Matsushita and Sharp have groups for II-VI MBE.

Three of the top four laser manufacturers[33] in Japan are located in the Kansai area. Rohm Co., which has only published a handful of papers on MBE, all around 1985 and concerning lasers grown by MBE, captured in 1988 the position as the second largest laser producer in Japan after Sharp. Rohm is said to be the only company in Japan using MBE for commercial production of lasers. Sharp has been very successful in producing lasers by LPE, a fact which delayed its start up of MBE research. Research on MBE-grown quantum well lasers which has resulted in practical devices has recently been transferred from the Central Research Laboratory to one of the product divisions. As Sharp has not been very active in MOCVD, judging from the company's publication record in this field, there seems to be a good chance that Sharp will begin commercial manufacturing of sophisticated lasers by MBE. Mitsubishi is unique among the laser manufacturers in that it has had strong laser research programs for both MBE- and MOCVD-grown crystals, while other companies, as for example Matsushita which has selected MOCVD, have tended to emphasize one or the other of the two crystal growth methods for development of sophisticated lasers. There is however no evidence that Mitsubishi uses MBE for commercial production of lasers.

Many Japanese electronics companies have commercial production of discrete HEMT devices and monolithic microwave ICs (MMICs) and several are using MBE for at least part of this production, with MOCVD and LPE making up the balance. Mitsubishi is known to have developed very effective MBE production technology for these types of devices. Interestingly, a key person in developing this technology has been Dr Sonoda, who was one of the pioneers of MBE at Mitsubishi in the 1970s,

[32] Fujitsu, Hitachi, NEC, NTT and Toshiba.

[33] The market share data, derived from on-line search in Nikkei Telecom refers to the number of lasers produced and ranks the top nine laser manufacturers in 1989 as follows: Sharp, Rohm Co, Sony, Mitsubishi Electric, Toshiba, Matsushita, Hitachi, NEC and Sanyo. Short wavelength lasers which are used in e g CD-players and laser printers are produced in much larger quantities than long wavelength lasers but exhibit a much lower unit price. The rank ordering of laser manufacturers in terms of value of shipments may therefore be different from the rank ordering referred to here.

but then left the field as the company discontinued its MBE research. Sonoda has later, at Mitsubishi's semiconductor works, revived his interest in MBE, applying MBE to the production of HEMTs. Fujitsu has pushed beyond discrete HEMTs to Large Scale Integrated Circuits (LSI) with several thousand transistors and is the leader in manufacturing technology for HEMT LSIs. There is, however, considerable doubt whether HEMT LSIs will ever become commercially viable products. Hitachi has also made efforts to develop MBE into a production technology and has developed its own production equipment, which although intended for sale on the open market, so far probably is only used by Hitachi itself.

Generally for transport devices that are currently being researched with MBE, HEMTs being just one example, the future commercial prospects of their use in LSI are very uncertain and many observers are sceptical that MBE will have any role in manufacturing of LSI in the next 20 years worth mentioning. Although upsets in this assessment cannot be excluded - devices based on Si-Ge heterostructures is a possible case - the evaluation of the potential of MBE as commercial production technology can be made with greater confidence today than in the early 1980s and as just mentioned it tends to be rather negative, which does not exclude that there may be opportunities for the development of niche markets.

The difficulty in identifying device concepts which offer a really promising commercial potential, may to some extent promote a shift towards more basic and long term MBE research in industry, especially at the present stage when the technology for some of the most obvious candidates for MBE grown devices, such as HEMTs and certain types of lasers, is becoming well established and presenting fewer challenges for the researchers. The currently strong interest in new concept devices among MBE-researchers in Japanese companies could be interpreted in this light.

One of the persons interviewed in this study even suggested that there are too many company researchers in Japan working on what still amounts to very speculative device concepts and that this was producing a risk that research on more realistic GaAs transport devices is being left undone, possibly contributing to GaAs technology declining further in relation to Si technology. This in turn could lead to a new "cold winter" for compound semiconductor research similar to the one experienced in the late 1970s with the result that compound semiconductor technology will effectively have disappeared from the companies before any new concept devices have been realized.

When the expected time horizon for realization of practical devices is long or when there is no conscious link at all with device development it would seem appropriate to classify the MBE research in question as "basic research". With this definition, a rather large part of MBE research in Japanese companies which shows up in scientific publications can be classified as basic research. There has been a general trend among Japanese companies since the early 1980s to expand their basic research. The case of MBE gives some basis for examining the question of why Japanese companies do basic research.

The utility of the specific research results that may be obtained is only one of several factors. The positive image created from pursuing research at the scientific frontier is seen as a powerful means of building confidence in the company among customers as well as among employees and also makes it easier to attract new qualified scientists and engineers. For image creation it is probably more important that a field can be associated with visionary thinking that sets one company apart from the mainstream than that it shows a large commercial potential.

Of course a strong program of basic research will not be set up to create illusions alone. It will usually be expected to generate basic patents which can be used in different ways, not least in negotiations with other companies, when the latter have patents with the power to block development. Basic research can also be seen as a way of developing competence in a field, a function which may be particularly important in those cases when a field has not yet been well established in the universities and therefore expertise can not easily be introduced in the companies through recruitment of new graduates. Having research competence in a field before it is well established yields a preparedness to sudden breakthroughs in the field. It gives the ability to identify and correctly evaluate such breakthroughs both through the competence built up in the company and through the social network relations to expertise in other organizations that are often easier to build around basic research topics than commercially more sensitive R&D. The existence of an in-house research group of course also means that a company can respond much faster to a new development than if it has to start from scratch, in terms of actually exploiting the new opportunities that are opening up, something which could be of great importance for establishing a prominent position in a new field.

Returning to the specific case of MBE, the technology is continuously undergoing change through an interactive process involving a broadening of the range of materials successfully grown by MBE, experiments with new device applications, changes in MBE-equipment and growth methods, and a deepening of the understanding of growth mechanisms. Increasing use of gas sources in MBE, the use of various beams to enhance or localize the MBE growth process, and the combination of MBE, electron beam lithography and reactive ion etching and a growing number of sophisticated analysis instruments in the same UHV-equipment are some of the most prominent trends in the most tangible aspects of MBE technology. Together these developments open up a multitude of possible new combinations, the practicality and utility of which are uncertain and quite difficult to evaluate at the present time. In this situation it may be more appropriate to pursue rather basic research than to attempt to organize a research program around a specific device application. Of course conceivable device applications will to some extent direct the choice of research focus, but considering the motives for corporate basic research, discussed above, the uniqueness of the research target and approach may be as important.

The fact that a company is pursuing a particular research direction more aggressively than other companies, thus cannot automatically be interpreted as a sign that the company evaluates the economic opportunities in this area more optimistically than other companies. It may simply mean that the company has discovered that it has developed a strong research position in this direction and judges that it can receive a high visibility from nurturing that position.

Some of the confusion surrounding definitions of basic research stems from attempts to define categories of research according to the guiding motives of the research. A company which is ultimately interested in producing devices nevertheless will in may cases carry out research which is more or less identical with that pursued by academic researchers who are primarily seeking recognition within the scientific community. This difference in motives is likely to have some impact on what questions are given priority and how the research is carried out. In simplified terms one can argue that the industrial researcher will be content to achieve a practical result, for example to grow a certain material to specified quality, while the academic researcher will want to know how the result is achieved, which in the case mentioned means to understand the growth mechanisms. In a science-intensive field like MBE such a distinction, however, tends to get blurred. Many academic researchers, especially in engineering faculties, orient their research with a clear recognition of its potential impact on device development. Correspondingly, industrial researchers, while being aware of corporate objectives, will often share the interest of academic researchers in obtaining a scientific understanding of the phenomena they are trying to control, partly because scientific understanding may be necessary for achieving practical results and partly because they value such understanding highly. The intertwining of the academic and the industrial research communities is further aided by the fact that some of the most advanced experimental research is carried out in industrial laboratories. There are examples of industrial laboratories being the first to provide experimental evidence of quite basic theories.

3.6. Universities strengthening their relative position

MBE research was first established primarily in industrial laboratories and, with only a few exceptions, rather late started up at academic institutions. In this regard the development in the United States and in Japan has been rather similar. In both countries there has been a strong surge of interest in MBE among university researchers during the latter half of the 1980s. Judging from the bibliometric data discussed earlier, the size of the MBE research community in American universities is however around five times as large as that in Japan, reflecting the much larger number of "research universities" in the United States as compared to in Japan.

Until mid 1980s only half a dozen universities were doing significant MBE research in Japan. Mentioned in approximately the order of establishment they were: Tokyo Institute of Technology (two groups), Waseda University, Tokyo University, Tsukuba University, Kwansei Gakuin University and Shizuoka University. The different groups grew up with little contacts between them, one exception being contacts between Professor Sano at Kwansei Gakuin University and Professor Sakaki when the former started his MBE research.

During the first half of the 1980s universities also seem to have had rather limited contacts with companies in the MBE field. For one thing the few universities active in the field were for the most part in the process of building up their research so there was still only a very small number of students who had received a doctoral degree for MBE research. Prior to 1985 only a handful new PhDs specializing in MBE moved from universities, largely from Tokyo Institute of Technology and Waseda University, to pursue MBE research in companies. Although there were in addition some MBE researchers who moved to companies after taking a masters degree, and there were some company researchers who spent a year or so at a Japanese university to learn MBE, it seems fair to say that universities until the mid 1980s contributed only marginally to the development of MBE research competence in Japanese companies. The influence from companies to universities does not seem to have been very significant either during this time. This should not be interpreted to mean that academic and industrial researchers were unaware of each others work. There were conferences and other opportunities for researchers to stay abreast of MBE research activities in Japan.

In recent years universities have become a more vital part of the Japanese MBE research community. The number of research groups has expanded considerably, both through the addition of new groups at universities which were already active in the MBE field and through additional universities becoming involved in MBE research. MBE research is today actively pursued at some 25-30 universities in at least 35 different research groups. At Tokyo University alone there are around half a dozen groups. Osaka University, Tokyo Institute of Technology and Tsukuba University each has three or more groups. It is still too early to judge how many of all the new groups will ultimately carry any weight.

While university researchers in Japan often maintain that they try to avoid competing head on with research groups in industry there still is a very considerable overlapping in research topics between these two parts of the Japanese research communities. There are university groups performing significant research in all important materials systems and with most types of equipment configurations. II-VI compound semiconductors and other "exotic" materials are more commonly researched in universities than in industrial laboratories but university groups are well represented also in those areas where industry is putting most of its research efforts. An important exception is device-oriented research which has seen little participation from academic groups. Device research usually require very high quality crystals, an area in which universities, with only a couple of exceptions, have not come up to the same level as industry, partly due to the latter's superior material resources and partly, and in the final analysis maybe more importantly, because industry has much stronger motives to pursue device research and development. There are, however, examples of some of the leading university groups playing an important role in the early stages of new device development in firms through demonstration of basic features of new device concepts or as discussion partners. As much as device research is not very prominent at universities, there are few pure theoreticians in industry.

A very interesting recent development is that several of the top MBE researchers in industry and at ETL have been recruited as professors to build up new research groups. The most striking case is Osaka University which has hired during a short period no less than four prominent researchers from ETL (Gonda), Fujitsu (Hiyamizu), Hitachi (Nakashima, one of the group leaders at the OJRL) and NTT (Asahi) respectively. Three of them are now working in close cooperation at the Institute of Industrial and Scientific Research. Similarly Tokyo University and Hiroshima University have each hired leading researchers from Hitachi (Shiraki) and ETL (Yao).

This movement of researchers from industry and ETL to universities can be viewed as a result of the strong build up of basic research capabilities in Japanese industry and career choices on the part of industrial researchers. Several companies have dual career systems for their researchers, one leading through the management ranks and the other allowing the researchers to continue with research also at a relatively high age. In practice, however, the latter career seems to be perceived as having less status than a management career and somehow usually not be a natural choice for an able researcher. For industrial researchers who prefer to continue to be directly involved in research rather than proceed to management positions increasingly distant from such involvement, a position as a professor may therefore be attractive when they reach a certain age and have to make career choices. As Japanese industry has expanded its basic research the number of candidates for academic positions among highly qualified industrial researchers has greatly increased.

At the same time there has emerged a growing consensus at Japanese universities that they need to catch up with the research carried out in industry in many new fields. To hire some of the researchers who have been instrumental in building up the strong research capabilities in industry is an effective way of addressing this need. Not only will it directly strengthen the research capabilities of universities but it also significantly improves the conditions for their effective communication with industry. The hiring of industrial researchers to academic positions seems to be on the increase in the electronics field as a whole and not just apply to the MBE field, and could well be an even more general trend.

It cannot be excluded that, in the case of MBE, the movement of researchers from industry to universities also reflects a perception that firms are becoming less the committed to MBE as an important basic technology.

Judging from interviews, there seems little risk that a growing number of professors with industrial background will make university research more short-sighted than otherwise would be the case. If anything the new professors coming from industry appear determined to exploit the freedom of academic research to pursue basic research problems, which they may have had to forego in their industrial career, not because research on such problems was not permitted, but because such research had low priority and had to be set aside when more pressing needs made themselves felt.

Just as there has been a movement of researchers from the leading industrial research groups to universities, the early academic MBE groups have increasingly contributed their competence to other groups in universities and companies, through the supply of new graduates and through training of special students from companies in universities. Some of these university trained researchers have come to play a key role in new groups being set up in companies embarking for the first time on MBE research.

Through a combination of bibliometric searches and interviews, the number of doctoral degrees granted for research in the field of MBE was estimated for six early established university research groups.[34] In total, almost 30 doctoral degrees were granted for MBE research in these

[34] Professor Takahashi's and Professor Furukawa's at Tokyo Institute of Technology, Professor Kimata's at Waseda University, Professor Sakaki's at Tokyo University, Professor Kawabe's at Tsukuba University, and Professor Sano's at Kwansei Gakuin University.

groups, just over half of which in the two groups at Tokyo Institute of Technology and the rest divided equally between Tokyo University and the remaining three universities taken together. Around two thirds of the degree recipients are continuing MBE research and half of these are working in companies. The degrees referred to are so called course doctorates (*katei hakase*) which presuppose attendance at a university, usually for three years after a master's degree, including certain course work.

In Japan there exists, however, also another type of doctoral degree, thesis doctorate (*ronbun hakase*) which is granted on the basis of a thesis being presented to and accepted by a professor at a university. The research work underlying the thesis is usually performed in non-university research laboratories, mostly in companies. Significantly, in engineering, during the decade 1976-86, the number of thesis doctorates approximately doubled while the number of course doctorates remained about level, bringing the thesis doctorates to a level almost twice that of course doctorates. This development suggests that a large and increasing part of the advanced research training associated with the expansion of industrial research in Japan has occurred in the firms. The picture is somewhat modified by the frequent dispatching of company researchers as special research students to universities.

During the latter half of the 1980s, enrollment in doctor course studies has increased notably. In Electrical and Communications Engineering, more than 50 percent as many doctoral degrees were granted in 1989 compared to 1986. As the number of first year doctoral students was 30 percent higher in 1989 than in 1986, some further expansion in doctoral degrees should be expected. (Monbusho, 1987 and 1990). Part, and possibly most, of the increase, however can be ascribed to foreign students. At Tokyo University the number of doctoral students in engineering increased from 579 in 1986 to 653 in 1989. Foreign students made up all but three of the increase bringing the percentage of foreign students as high 42 percent. (The University of Tokyo, 1987 and 1989).

The difficulty of attracting a sufficient number of doctoral students is generally perceived to be a very serious problem for Japanese universities. It is not unusual for a research group to lack doctoral students altogether. In order to improve the situation there have been some suggestions that a new doctoral degree be introduced, representing a compromise between the course and thesis doctorates. According to this idea, the requirements regarding attendance at the university would be relaxed in comparison with the current doctor course, but sufficient to assure that the doctoral student would make a real contribution to the research environment at the university before he was granted his degree.[35] If

[35] A new type of doctorate, a *gakujitsuhakase*, is for example being discussed at the Research Center for Advanced Science and Technology (RCAST) at Tokyo University. Professor Furukawa at Tokyo Institute of Technology has suggested a one year minimum residence requirement for

implemented these ideas could have quite far-reaching effects on the research capacity of Japanese universities. Considering the already established system of special research students from companies to universities, and the competition among companies in recruiting new graduates, it is quite possible that Japanese firms would be willing to let their researchers be enrolled in such a new type of doctoral studies while remaining on the firms' payrolls. Some professors have already perceived that management in many companies has begun to show a more generous attitude to their researchers' spending company time to complete doctoral theses.

It is interesting to note, and maybe not surprising, that those three research groups which have been most successful in producing doctorates also have made many of the most original research contributions among the university groups. Professor Takahashi was, for example, among the first internationally to work on MOMBE and has since developed this process further to so called photo-MOMBE. Professor Sakaki first discussed the feasibility of using quantum wires and other low dimensional structures as materials for electron devices and has continued to develop these ideas. Professor Furukawa has used various techniques, including electron beam exposure, to establish growth methods for a number of semiconductor/fluoride/semiconductor structures and used them for realization of new devices.

One major factor deterring universities everywhere from embarking on MBE research has been the high cost of the equipment needed. Operating costs, including costs of wafers, large quantities of low temperature nitrogen and other materials also represent an obstacle. The price of an MBE-machine will vary depending on specifications, guarantee clauses, etc., but is in the order of one million dollars. A university department strapped for funds, choosing a simple design with less guarantee of reliable operation, and contracting with a small vacuum company to manufacture the equipment may be able to press the price down to half a million dollars or possibly even less. Even the large suppliers may be willing to offer universities a lower than normal price as a good-will gesture.

Insufficient equipment funds has been experienced as a serious problem at universities in most countries but the situation has often been described as particularly bad in Japan. Generally speaking it appears, however, that the availability to Japanese universities of funds for equipment has improved considerably in the last ten years, to a point where the lack of such funds now appears to represent less of a bottleneck for development of research, particularly in the most prominent national universities, than ten years ago. Although there has been some increase in the total funds for

thesis doctorates. (Furukawa, 1989)

equipment, of more importance may be a seemingly growing willingness on the part of Monbusho and other involved parties to concentrate research funds so as to, for example, facilitate the purchase of expensive equipment.

As the mechanisms for research funding constitute a major determinant of of the development of university research we will discuss them in rather much detail and attempt to place the conditions for MBE-research in the wider context of university research funding in Japan.

The sources of research funds for Japanese universities may be divided into four categories:

* general university funds from the Ministry of Education (Monbusho)
* grants-in-aid from the Ministry of Education
* donations or research contracts from companies or private foundations
* research grants from other ministries

Each chair (koza) in a national university is every year allocated a fixed sum for research expenses, the sum varying between subjects and according to whether there is a doctoral program or not, but limited to a few ten thousand dollars. These koza funds are used for travel, various office expenses, purchase of literature, materials and small equipment, etc., but are obviously totally inadequate for the acquisition of an MBE-machine. They are usually not even sufficient for covering the operating costs associated with MBE-research.

Another type of general university funds more important for the acquisition of research equipment is included in the budget for "new requests" which each university annually negotiates with Monbusho. "New requests" may cover everything from funds for a new piece of equipment or a new professorial chair to the establishment of a whole new faculty. As the budgets available for new requests are usually very limited each faculty or attached research institute prepares priority lists of new requests. Facilities and equipment for semiconductor research have increasingly come to be viewed as high priority items in many universities, MBE-equipment being but one example.

The establishment of new chairs, individually or as part of new departments, is usually associated with the allocation of special start-up funds, which can be used for the purchase of new equipment. Such start-up funds, amounting to around ¥ 50 million, that is around one third of a million dollars, per chair, enabled Professor Kawabe to start MBE-research at Tsukuba University in the early 1980s. When a new professor takes up an already existing chair he may also receive special equipment funds as has, for example, happened in the case of the recent expansion of

MBE-research at the Institute of Scientific and Industrial research (ISIR) at Osaka University.

Recognizing the increasing difficulty of furnishing each chair (koza) with adequate facilities and equipment there has been a growing trend in Japan during the last decade of establishing Research Centers representing a major investment in equipment and facilities to be shared by faculty and students from different departments[36] and occasionally even from different faculties. Several new facilities for semiconductor research with large clean-rooms have been established in this way during the latter half of the 1980s. These centers typically contain a variety of semiconductor lithography, crystal growth, fabrication and characterization equipment.

The Research Center for Ultra-High Speed Electronics at Tokyo Institute of Technology (TIT) which was completed in 1986 at a cost of $ 10 million dollars, equally divided between building and equipment, is an example of how the establishment of a research center has greatly improved the conditions for MBE-research. The center houses research by six different research groups, most of which are involved in growth of high quality crystals by MBE or MOCVD or their modified versions and microfabrication of nanometer-structures for quantum effect devices. It should be pointed out that there are also other MBE-machines at TIT, both on the Ookayama campus where the research center is located and on the Nagatsuda campus of the Graduate School of Science and Engineering.

Individual MBE-machines have been installed at research centers also at other universities, without necessarily being the focus of the research. At Hiroshima University a Research Center for Integrated Systems (RCIS) recently became fully operational. It resembles the CIS at Stanford University which has provided a model, not only in name, but also in that it puts strong emphasis on both design and fabrication of integrated circuits. The RCIS, which focuses on silicon technology, has initially been equipped with one MOMBE for growth of GaAs on Si. This process is needed for growth of the light-emitting diodes and photoconductors included in the "optically coupled three-dimensional common memory", a novel design which is the first major research target of the RCIS. As at TIT, MBE-research is also performed outside the center.

Research centers of the type mentioned became popular during the 1970s. They were planned for a life of ten years, after which period there were no guarantees for their further existence in order to give real leverage for Monbusho, and maybe also for the concerned university, in negotiations regarding new research themes for a center or redirection of its research funds to other needs. Some of the early centers have been up for review. In

[36] Each department usually has several koza.

the semiconductor field, the Research Center for Ultrafine Beam Microfabrication at Osaka University, has been formally discontinued and instead a new Research Center for Extreme Materials been set up in new facilities. The Division for Nanometer Structure Science and Technology in the new center, however, continues the research from the previous center. Electron and ion beam technology, fields in which the group has long standing expertise, are developed and used together with other processing and crystal growth technologies, including MBE. Of special interest is the development of a low energy focused ion beam system for doping, etching, and metal deposition to be combined with an MBE to allow uninterrupted ultra-high vacuum growth and fabrication of quantum effect devices.

The Technological Development Center at the Technological University of Nagaoka has a more general mission than the centers mentioned so far. Being a small university, opened in 1978 with a charter to emphasize graduate education, many of the research facilities were organized for joint use from the start. The Technological Development Center, which has an MBE-facility for research on blue light emitting devices, has been built to further interdisciplinary research in and out of the university, including joint projects with private companies.

Research centers differ from the so called attached research institutes, which have long been in existence at many Japanese universities, in that the former almost totally rely on faculty and students in the regular teaching departments while the latter have their own permanent organization with professorial and other positions. The new centers, which resemble the research centers and interdepartmental laboratories common at American universities, are seen as a more more flexible, and therefore presently favored, alternative to the attached research institutes. The attached research institutes nonetheless remain a very important part of the Japanese universities, not least in the field of MBE-research.

There are altogether 37 research institutes attached to national universities working in the field of natural or engineering sciences, most of which were established during the period 1935-1965. They vary in size, The Institute of Industrial Science (IIS) at Tokyo University with a total of 350 permanent staff and another 450 graduate students and visiting researchers being the largest. The IIS and at least two other attached research institutes, The Institute of Scientific and Industrial Research (ISIR) at Osaka University and the Research Institute of Scientific and Industrial Research at Shizuoka University are carrying out significant MBE research.

The (ISIR) (on a different campus of Osaka University than the above mentioned Research Center for Extreme Materials) has, as earlier discussed, in recent years built up a very strong capability in the MBE field. Two MBE research groups, working closely together, have no less than five MBE-machines, two of which represent used equipment donated from NTT and the OJRL respectively. One of the new machines is a gas source MBE which is being combined with focused ion beam implantation, chlorine gas etching, and a scanning tunneling electron microscope furnishing a very powerful tool for research on quantum devices.

At Tokyo University MBE research started at the IIS in the late 1970s and has more recently been expanded to the Research Center for Advanced Science and Technology (RCAST), to several groups within the Department of Electronic Engineering and one or two additional groups. RCAST, established in 1987, is a special case in the stream of new research centers. It represents an experiment in university research organization which is monitored attentively by many other universities in Japan.

Like the other centers it aims at encouraging interdisciplinary research and the sharing of costly research facilities. In its staffing policy RCAST falls however somewhere between the old attached research institutes and the typical new research centers by having its own research staff but limiting the time period for appointments. Non-permanent positions are meant to help increase mobility of faculty both inside Tokyo University and to and from other research organizations. Consistent with this philosophy RCAST has also pioneered the practice of endowed chairs which only recently became permitted in Japanese national universities. The endowed chairs at RCAST are established for five years at a time and funded through donations from business firms. As a rule foreign researchers are invited to take up the endowed chairs. Also other universities have begun to establish endowed chairs. In the field of MBE, Hitachi has donated $ 700 000 to Tokyo Institute of Technology to invite a foreign professor to do research on quantum effect devices in cooperation with Professor Takahashi during a three-year period from 1991.

At RCAST there are presently a total of 27 chairs, four of which are endowed. At the start of RCAST it was decided to establish a coordinated research facility, The Process Center, for research on electronic or optical materials and devices, fields which represent around a fourth of all the chairs. The Process Center, mainly paid for by institutional funds and housed in old buildings, is well equipped for crystal growth, device fabrication and characterization. For crystal growth there are three MBE-machines and one MOCVD-equipment, one of the MBEs being connected with an etching chamber and an other with a focused ion beam implanter. The third MBE is used for growth of silicon crystals. By the fact that Professor Sakaki has appointments at both RCAST and the IIS, good communication is guaranteed between MBE and quantum device research at the two places.

In addition to the research centers and research institutes attached to individual universities, a new system of 14 Inter-University research institutes has been built up under Monbusho, starting with the establishment of the National Laboratory for High Energy Physics (KEK) in Tsukuba in 1971. KEK and the Institute for Molecular Science in Okazaki have become involved in MBE-research. These institutes are the only likely candidates for MBE-research among the seven Inter-University institutes which are working in areas of science and engineering. The Institute for Molecular Science has recently started research on MBE-growth of phthalocyanine polymer films. During the early part of the 1980s, researchers at KEK cooperated with an equipment manufacturer in trying to develop vacuum chambers for MBE in aluminum, utilizing expertise gained from the use of aluminum in nuclear research. More recently the synchrotron radiation facility at KEK has begun to be used for high-intensity X-ray diffraction studies of MBE-grown materials by researchers from a variety of research organizations. ETL is, for example, installing an MBE-machine directly at a port of KEK's Photon Factory for in-situ Extended X-Ray Absorption Fine Structure (EXAFS) measurements, initially for characterization of Ge grown on Si.

Complementing the system of institutional support to universities, research funds are also distributed more selectively on a project by project basis through the grants-in-aid system administered by Monbusho. There are many different types of research grants under this system which has grown very rapidly at the expense of general koza-funds which have gradually decreased in real terms. Presently the grants-in-aid system amounts to around $ 350 million which, considering that it serves all fields of science as well as the humanities, looks rather small in international comparison. This is true even if one accounts for the fact that hardly any salaries or overheads are paid out of the grants in contrast to the situation in for example the United States where these cost items may make up as much as 60-70 percent of a grant.

The regular grants to single investigators may be as high as $ 100 000 per year but are usually much smaller and therefore usually too small to finance expensive equipment. Some simpler MBE-machines were, however, financed this way during the 1970s and early 1980s. To meet the needs of today's scientific research Monbusho has devoted an increasing portion of the grants-in-aid budget to larger research grants. In the early 1980s grants for "specially promoted distinguished research" (SPDR) were introduced and more recently a scheme for "priority areas research" replaced and expanded earlier programs for special project research. Especially the former type of grant has been a very important source of funds for the acquisition of high quality MBE equipment, for example at Hokkaido University (Hasegawa), Tokyo Institute of Technology

(Furukawa), Tokyo University (Sakaki), and at Hiroshima University (Yamanishi). SPDR projects are defined by Monbusho as those "requiring an especially large amount of research expenditures, but expected to make significant contributions in research in view of the international recognition of the topic as important for research". (NSF, September 1988). Around ten new grants are distributed every year, each grant amounting to some $ 1-2 million distributed over a period of three to five years.

While the SPDR grants are given to single principle investigators and their research groups, "priority areas research" is designed to combine the capabilities of several groups to accelerate the development of research in emerging new fields judged to have a high potential both intrinsically and in terms of their effects on the development of other fields or for the solution of important social problems. (NSF, October 1988). Altogether research has been initiated on 62 project themes since the start of this grant category in 1987, some of which have had some content of MBE research.

A particularly interesting case from the point of view of MBE is the project "Basic Studies on Electron Wave Interference Effects in Mesoscopic Structures" begun in 1990 under the leadership of Professor Namba, director of the Research Center for Extreme Materials at Osaka University (Namba, 1990).[37] The project "aims to investigate a new field of physics called mesoscopic physics and establish a basis for applications to electron wave electronics". Mesoscopic physics is a term used to describe the study of quantum effects in one- or zerodimensional nano-structures. A unique feature of the project is the wide range of competences gathered from theorists of quantum physics to electron device engineers. With a total budget of around $ 4 million over three years, the project is at the high end of the priority areas research themes in terms of size. Given that as many as 35 research groups participate, the scale of funding available to each group is nevertheless fairly limited, even for those groups receiving an above average share of the funds made available through the project. At least a third of the participating research groups employ advanced methods for crystal growth in their sub-projects, MBE being the most commonly used. Consequently a majority of

[37] "New Functionality Materials - Design, Preparation and Control" started in 1987 and " Metal-Semiconductor Interfaces: A key problem for Ultimate Microelectronics" started in 1989 are examples of earlier priority area projects which also involved MBE researchers. Even earlier, MBE researchers could obtain funds from "Alloy Semiconductor Physics and Electronics", an example of so called special project research, a grant category which along with part of another category, special long term research, was transformed into priority areas research. The priority area "Fundamental Research on Photo-Induced Process in Semiconductors" started in 1990 under the leadership of Professor Takahashi at Tokyo Institute of Technology also includes crystal growth as an important component, but other growth processes than MBE dominate.

the leading university MBE research groups participate in the project.

Specially distinguished research and priority areas research appear to be important vitalizing factors for research at Japanese universities. The former gives a few select researchers exceptionally good working conditions for a limited time period, while the latter gives strong incentives for organization of networks and task sharing within the academic community. With respect to the priority areas research projects one may question how innovative and well integrated the projects really are. It would seem that the usual project period of only three years is too short to allow the establishment of effective collaborative structures, not to mention achievement of the typically extremely ambitious research targets. In this respect some of MITI's research projects extending over a ten year period provide a striking contrast. Researchers taking the initiative to organize and propose such projects naturally have to compromise in trying to achieve the necessary support from potential participants and other researchers who could influence funding decisions. There is therefore a risk that the research plans become *pro forma* aggregations of research already underway and that the selection of themes and the distribution of resources will reproduce already entrenched academic power structures. If these problems can be dealt with, and there is for example some indication that the project periods might become longer, the priority areas research could significantly add to the strength of Japanese academic research.

The proliferation of research centers and the diversification and growth of the grants-in-aid system means that there is more room for initiatives by Japanese university researchers that could influence the material resources available to them for research. The entrepreneurial energies that this more open and hopeful situation is unleashing are probably many times larger than the growth in research funding.

Growing opportunities for research support from the business sector and other private sources work in the same direction. Such support which takes different forms has grown fast during the last decade. Donations are the most important. Money gifts alone amounted to over $ 200 million in 1988, up from less than $ 50 million a decade earlier. There is no statistics over the value of materials, equipment and services given to universities free or sold at high discounts by enterprises. However, judging from acknowledgements in scientific papers such gifts are quite common.

There are several examples of MBE equipment, or funds for the purchase of MBE equipment, being donated from private sources. One of the most significant examples concerns the Kwansei Gakuin University, a private university which has a very small science faculty and no engineering faculty. It became the first university in the Kansai area to seriously get involved in MBE research after receiving a major donation from the Yamada Foundation in 1980. Dr. Esaki at IBM, who felt that there was a need to build up a widely accessible resource for MBE research in the Kansai area to promote the diffusion of the MBE technology among Kansai electronics companies, played an important role in bringing about the donation. Professor Sano and his colleagues at Kwansei Gakuin University has built up a well respected MBE research activity and developed important links with many local companies and universities thus to a large extent fulfilling Esaki's vision.

Professor Kimata who started MBE research already during the 1970s at Waseda University had to manage with inadequate equipment funds for a long time. To build the first machine he had only $ 8000 at his disposal which was of course not at all sufficient even for the very simplified design chosen. After some pressure Anelva nevertheless agreed to build the machine as a goodwill gesture. The next two machines were very much better than the first but still had serious drawbacks, for example no preparation chamber, due to shortage of funds. Only around 1987 could really satisfactory equipment be obtained through a donation from the Shimazu company, which has later donated still another machine.

Until the latter half of the 1980s, Waseda University and Kwansei Gakuin University appear to have been the only private universities involved in MBE research. More recently a handful of other private universities have begun to publish in the field.[38] This may reflect the general improvement in the financial situation of private universities which has occurred during the 1980s. Private universities receive some institutional support for research from Monbusho through the "Private University Foundation". This however only makes up 10-15 percent of total general funds for research at private universities, with the remainder covered by income from other sources, primarily tuition fees.[39] Decisions on the use of general funds for purchase of equipment at the private universities are not negotiated with Monbusho, as in the case of the national universities, but left to the discretion of each university.

In a reversal of policy, Monbusho in 1983 began to actively encourage

[38] For example: Hokkaido Institute of Technology, Sophia University, Nippon Institute of Technology, Osaka Institute of Technology, Okayama University of Science

[39] Self-financed R&D at private universities in the fields of physical sciences and engineering in 1987 amounted to 174 billion yen according to official Japanese R&D-statistics. As discussed in Irvine (1990) a significant part of these funds, maybe as much as a third or more, in reality cover salaries for non-R&D-activities on the part of university researchers. For the same fields, in 1987 private universities received funds for R&D totalling 21 billion from national and local governments. Most of these funds were provided through the Private University Foundation and a smaller part represent grants-in-aid from Mombusho (For all fields grants-in-aid represent around 5 percent of all government research support to private universities).

university-industry research cooperation by introducing a "System of Joint Research with Industry".[40] Under this scheme Monbusho finances a part, usually between a fourth and a third, of the cost of research projects carried out at universities with support from industry. In 1988 there were around 600 joint projects underway at a total cost of almost $ 20 million.[41] (Monbusho, No date). One of the most ambitious joint research projects, "Mesoscopic Electronics", is being carried out under the leadership of Professor Ikoma at the Institute of Industrial Science (IIS) at Tokyo University.[42] At a total cost of $2.5 million for the period 1988-90, two thirds of which from ten leading electronics firms and the rest from Monbusho, it is much larger than most other joint projects and is seen as a test case for developing the concept of joint research. The project, which includes MBE crystal growth as an important component has already served to establish the concept of mesoscopic electronics in the Japanese research community.

Most of the research is being performed in the Research Group on Semiconductor Heterostructure Materials and Devices, one of nine inter-disciplinary groups at IIS. The group received a large (around $ 4 million) institutional equipment grant during the period 1984-87 which was partly used to acquire an MBE equipped with a large number of advanced instruments for in-situ measurements. The joint research project repre-sented a welcome new source of research funds when the institutional grant had run out. Some researchers from Tokyo Institute of Technology and Hiroshima University also have participated in the project. All in all nine professors, including Professor Sakaki, have been involved in the project.

Much effort is spent in the project to achieve effective communication

[40] Monbusho also supports university-industry cooperation in other ways. Special Centers for Cooperative Research have, for example, been established at 18 national universities since 1987. The decision to permit national universities to establish donated chairs has been mentioned earlier. Without support from Monbusho, universities also perform contract research for industrial firms. In 1988 around 2000 contracts brought in almost $ 30 million to national universities. The practice of Japanese companies to send young researchers to universities, in Japan or abroad, as special research students is another very important mechanism for university-industry cooperation. These other avenues of university-industry cooperation may well have been operative in the case of MBE, especially in recent years when the number of universities doing research in the field has multiplied, but the extent remains unclear. As far as the leading university MBE groups are concerned it appears that special research students from companies have mainly been sent to Professor Sakaki at Tokyo University and Professor Sano at Kwansei Gakuin University, but even in these cases the number has been limited to little more than a handful, the two groups taken together.

[41] There is some possibility that this figure only includes the contribution from Monbusho, in which case the total amount would be three to four times larger.

[42] Cooperation between Toyohashi University of Technology and Toyoko Kagaku Co. regarding laser-assisted metal-organic molecular epitaxy of gamma-sapphire on silicon is another joint project involving MBE research that has been identified.

between the university research groups and the participating firms. Each firm has assigned a "cooperating researcher" and several of these worked for some period at IIS. Half-day technical meetings are being held once a month with the involved university professors, the cooperating researchers and other persons selected by the firms. Research results are also being presented to a wider audience through a number of so called forums.

The reversal of Monbusho's policy regarding industry-university cooperation from a rather sceptical view to one of active encouragement is strongly related to the strengthened research potential of Japanese industry. With their increasing involvement in rather basic research it became desirable for Japanese firms to cultivate their relations with academic research groups. Foreign universities, and especially those in the United States, were perceived as more attractive partners than the Japanese universities, in terms of the research level as well as the attitudes and regulations concerning cooperation with industry. Many deals were struck between Japanese firms and research groups at American universities often involving donations of large amounts of money for the construction of new laboratories or the establishment of new chairs. It seemed to many that Japanese universities faced a strategic choice: either they actively tried to become a partner to Japanese industry and thereby derive benefit from its growing resources and research capabilities or they ran the risk of becoming an increasingly marginal factor in the Japanese research system.

There are still sharply conflicting views within the Japanese academic community and seemingly also within Monbusho as to how responsive universities should be to the research needs of industry. Nevertheless, determined efforts are obviously being made to put Japanese university research in touch with and if possible ahead of the development of leading edge industrial technology.

While Monbusho is presently encouraging industrial presence on university campuses, Monbusho still does not welcome other ministries to engage university researchers in their research projects. While in most other countries universities derive funds from many different government bodies, Monbusho very nearly totally monopolizes government funding of universities in Japan. One would expect that the current policy of the Japanese government to strengthen basic research should favor universities. The unwillingness of Monbusho to give up any control of university research to other ministries, however, forces the latter to spend their funds for basic research elsewhere than at universities. Naturally there are some exceptions, but taken in total they represent an extremely small part of university research funding. In the next section are described some activities of the Science and Technology Agency and ways in which these involve universities. MITI has so far mainly used university professors as advisors in its various research programs. In one case, solar cell development under the Sunshine Program, MITI has directly funded university research in a major way. The New Energy and Industrial Technology Development Organization (NEDO), which only a couple of years ago had its mandate broadened to include development of industrial technology more generally, is currently trying to involve Japanese universities in its efforts to organize international research cooperation.

The growing involvement of universities in MBE research is not only a question of improved economic opportunities but also relates to changes in the substance of MBE research. On the one hand MBE is becoming a tool for many physicists who are not interested in MBE *per se* but employ MBE to produce materials or structures suitable for the exploration of interesting physical phenomena. For the most common materials systems this can often be accomplished without any particularly deep expertise in MBE as the demands on crystal quality may not be so high and the MBE-machines since a few years back have become simple to operate. On the other hand the research opportunities for "real MBE-research" are expanding at a rapid rate as the MBE process is becoming more versatile through the introduction of gaseous sources, the use of various energetic beams, etc.. As a consequence the range of materials and combination of materials that can successfully be grown is steadily increasing to include not only broader range of semiconductors but also metals, insulators, high temperature superconducting materials, and organic materials. There is furthermore the whole new field of the physics and electronics of low-dimensional structures barely beginning to open up.

These new directions of MBE research are well suited to universities. One reason is that they put a premium on combining expertise from several scientific fields and on integrating theoretical knowledge and experimental research. Understanding of growth mechanisms in photo-assisted MOMBE and analysis of quantum phenomena in low dimensional structures can be cited as examples. Under proper conditions of organization, such as exemplified above, this should give universities a stronger position in MBE research.

Another characteristic of the new areas of MBE research is that no approach has clearly established itself as the dominating one. There is therefore plenty of room for novel ideas, which for the most part can be tried out and demonstrated with the equipment available today at at least the leading universities. Once a new concept is shown to be promising, however, it is quite likely that industrial groups with larger resources will be able to push forward at a higher speed and take a lead.

Until fairly recently there has been a strong tendency among Japanese researchers, in industry as well as in universities, to define research targets by looking at the leading research groups abroad, especially those in the United States. As both the level and the quantity of science and technology in Japan is reaching a par with, and not seldom moving ahead of, the rest of the world Japanese researchers will increasingly themselves have to define new directions of research. This is a particularly suitable role for universities as they have great freedom in generating and exploring new concepts, an activity which is necessary for setting out new research targets. Comparing the situation around 1980 when MBE research began to take off in Japanese industry and the situation during the last couple of years it seems undeniable that Japanese universities are much more prominent in laying out the agenda for future research.

3.7. STA launches research programs to increase mobility of researchers

Accounting for a fourth of all government R&D-expenditure, the Science and Technology Agency (STA) is, after Monbusho, the second largest ministerial level body in Japan in terms of R&D-funding and twice as large as the better known MITI. STA is most noted for its promotion of science and technology in prestigious areas such as nuclear power, aerospace and ocean technology. While, these areas still consume the bulk of STA's funds, the agency has become increasingly active in more normal fields of basic research, especially those related to life science and materials science, a development which is also reflected in the case of MBE.

STA is currently supporting at least two major research efforts that contain MBE as a key element.[43] One is the Quantum Materials Project which has been part of the Frontier Research Program (FRP) at the Institute of Physical and Chemical Research (RIKEN) since the start of that program in 1986. The other is the Sakaki Quantum Wave Project started in 1985 as part of the Exploratory Research for Advanced Technology (ERATO) scheme in operation since 1981 under the auspices of the Research and Development Corporation of Japan (JRDC).

The ERATO program was designed as a response to concerns that established ways of organizing research in Japan did not sufficiently encourage and support creative research. The program therefore set out to experiment with new concepts of research organization which challenged ingrained traditions. An individualistic style has been sought by investing a strong leadership role with the Directors of each project and further emphasized by the practice of naming the projects after their Directors. It has also been an ambition to gather under the Directors researchers with heterogeneous backgrounds in terms of disciplines, sector of employment, and country of origin, while at the same time concentrating on young PhD-

[43] In addition MBE-research concerning ferromagnetic semiconductors is taking place at the National Research Institute for Metals (NRIM), one of STA's institutes.

level researchers in their early thirties. Flexibility in organization has been achieved by renting laboratories, sometimes at several locations in one project, from participating or other organizations, in either case adjusted to where talented people can be found.

On the whole ERATO gives the impression of being a very successful program. Although the participation of researchers permanently employed at universities and government laboratories, other than the project Directors, seems to have been very limited, important steps have nevertheless been taken to increase the mobility of researchers in the Japanese research system.

Of the 21 projects that had been started before the end of 1989, 14 of which are still running, two thirds are directed by university professors. Around half of the research staff have come from private industry, another third have participated as individuals, and most of the rest have been foreign nationals. Individuals for the most part refers to persons who have just earned their doctorate but are not yet permanently employed. For these researchers ERATO has in effect introduced a system of postdoctoral research positions which has earlier been more or less totally lacking in Japan. As there is no tradition in Japan of postdoctoral positions, it has no doubt been felt risky to accept these positions. The attractiveness of the ERATO projects, in terms of their substance, leadership, resources and stimulating research environment, has nevertheless been sufficient to motivate many researchers to take this risk and thereby contribute to an opening up of the Japanese research system.

Various ERATO projects have been concerned with semiconductor epitaxial growth. Two projects directed by Professor Nishizawa at Tohoku University, Perfect Crystal Project (1981-86) and Terahertz Project (1987-92), have dealt with the development of photostimulated molecular layer epitaxial (PMLE) growth of compound semiconductors, representing an alternative technology to MBE. The Kuroda Solid Surface Project (1985-90) has investigated new techniques for epitaxial growth of Si films.

The Quantum Wave Project (1988-93) directed by Professor Sakaki of Tokyo University, already identified as one of the leading personalities in the Japanese MBE community, is the first ERATO project to include MBE as an important element. The project, having an annual budget of $ 2 million, is performed at three locations, at the Research Center for Advanced Science and Technology (RCAST) at Tokyo University, at NEC's Tsukuba Research Laboratories and at Matsushita Giken in the Tokyo area. Work at NEC focuses on atomic layer epitaxy (ALE)[44] while work at Matsushita

[44] A technology based on self-limiting features of certain chemical reactions occurring when a solid surface is exposed to vapor during material growth. ALE was pioneered in Finland by T. Suntola to meet the needs of improved ZnS thin films and dielectric thin films for electro-

Giken deals with novel quantum material systems including MBE growth of organic materials[45]. The group at RCAST has acquired an MBE combined with etching equipment for fabrication of structures that will permit the study of quantum wave effects. In addition to the two companies mentioned as providing laboratories, another six companies dispatched researchers to the project in 1990, four of which to RCAST.[46] Two postdocs from Tokyo University, a master degree holder from Tohoku University and a researcher from the United States add to the research team at RCAST. Additional scientists, especially from foreign countries, are expected to join the three research teams.

The Frontier Research Program (FRP) employs a somewhat more permanent research organization than ERATO. Firstly, the projects may last as long as 15 years if found to make sufficient progress in the reviews done every five years. This compares with a maximum duration of five years for the ERATO projects.[47] Even if continued, however, the FRP-projects are meant to be re-staffed after each five-year period. Full-time researchers are hired on a one-year basis but contracts are renewed for up to five years if performance is satisfactory. Secondly, the FRP-projects are all being carried out at RIKEN. While almost all the research in the ten first established laboratories is performed on RIKEN's main campus in Wako near Tokyo, any new FRP-laboratories will be set up outside the Tokyo area. The first example of this policy is the establishment in October 1990 of a Photodynamics Research Center with four laboratories in Sendai under the directorship of Professor Nishizawa. Parts of the new center build on and extend some of Nishizawa's earlier work in two ERATO-projects. The laboratories in Wako benefit from being able to use the resources of RIKEN, a well equipped research institute with almost 500 research staff and many visiting scientists.

80 researchers worked full-time in FRP as of May 1990, and about as many part-time. Foreign scientists, employees of firms and RIKEN research

luminescent thin film display devices, ALE has in the 1980s been applied to epitaxial growth of III-V and II-VI compounds, especially layered structures, such as superlattices and superalloys, applications which currently dominate ALE. ALE has also been extended to the growth of single crystals of elemental semiconductors. Japanese research organizations today dominate ALE. According to a publication count done by Suntola, 81 out of 155 papers published during the period 1977-88, came from Japan. The leading Japanese organizations are RIKEN, NEC, ETL, NTT, and the Semiconductor Research Institute in Sendai. The last is a private foundation directed by Professor Nishizawa. His MLE is classified as ALE by Suntola. (Suntola, 1989)

[45] NEC also does research on growth of organic materials using MBE, but this is not part of the ERATO-project.

[46] The six companies are Matsushita Electric, Ulvac, Sumitomo Electric, Toyota, Shimazu, and Asahi Chemicals, the last a producer of Hall effect sensors using MBE.

[47] The two projects directed by Professor Nishizawa are largely in the same area and can probably be considered a ten-year project.

staff, mentioned in order of their numbers, together represented slightly over one third of the full-time researchers. Of the remaining two thirds around 30 percent were postdocs and the rest new graduates with less than a doctor's degree or researchers permanently resigned from other jobs, mostly in government laboratories. There are hardly any cases of employees of government institutes working full-time in FRP on leave from their institutes. FRP thus even more than ERATO offers temporary employment for researchers who not yet or no longer have a stable job. The laboratory heads, most of whom work only part-time at FRP, are for the most part foreign scientists or Japanese university professors, several of the latter retired from Tokyo University.

Research in the Laboratory for Quantum Materials (LQM) deals with optical properties of quantum well structures of III-V materials, electron transport in quantum wire structures and the development of new evaluation techniques for quantum materials, such as laser spectroscopy of exitons found in quantum well structures. The Laboratory Head, Professor Namba, was until 1988 also Head of RIKEN's Laser Science Group where he around 1980 started a microprocessing project which has functioned as a platform for the establishment of the Quantum Materials Project, which in turn was part of the very early core of FRP. Growth of very high quality crystals is a very important part of the project and several different approaches are used. An MOCVD-system acquired in 1984 has been adapted for laser assisted Atomic Layer Epitaxy (ALE) with good results. No less than three MBE-systems have been acquired during the last two or three years, one of which is using both gas and solid sources and being employed for Chemical Beam Epitaxy (CBE) to study growth kinetics and photochemical reactions in laser assisted growth of GaAlAs and GaInAs. The other two MBEs are designed for the development of growth technique of new quantum materials, such as $CuCl/CaF_2$ quantum wells[48], and for physics research respectively.

The LQM and the Laser Science Group at RIKEN cooperate very closely with Osaka University. Professor Namba has for two decades had a double appointment as Chief Scientist at RIKEN and Professor at the Faculty of Engineering Science of Osaka University. His successor as Head of RIKEN's Laser Science Group Dr. Aoyagi, who has also a key position as Coordinator in the LQM, is furthermore a Visiting Professor at Osaka University, something which gives him an opportunity to work with graduate students. A great number of papers have consequently been coauthered by researchers from Osaka University and RIKEN in the areas of laser assisted crystal growth, microprocessing and nanometer physics. Three postdocs in the LQM have received their doctorates from Osaka University under Professor Namba, while a fourth postdoc obtained his doctorate from

[48] The Laboratory for Photophysics at the new Photodynamics Research center in Sendai will research the same materials. (RIKEN, 1990)

Tsukuba University under Professor Kawabe, who initiated MBE-research at that university.

Many foreign scientists have worked in the LQM for periods varying from a month to a year which has given the laboratory an extensive network of international contacts. The experiences reported by Gerhard Fasol from Cavendish Laboratory, Cambridge University, gives the impression of the LQM as being well integrated in the Japanese research system. He worked two summers in Japan, partly at the LQM and partly in Professor Sakaki's group at Tokyo University. On the first occasion he also collaborated with Dr. Horikoshi at NTT, who supplied him with high quality quantum well samples and during his second visit Toyota Central Research laboratory provided samples. (RIKEN,1988; RIKEN, 1989). It should also be noted that formally Sakaki is participating in the LQM on a part time basis.

In the two MBE-related projects described above, like in other ERATO- and FRP-projects, STA and its related organizations JRDC and RIKEN obviously collaborate in a significant way with prominent university researchers. Whether these programs will remain isolated cases or lead the way towards a greater role more generally for STA and other ministries at Japanese national universities is difficult to judge. Universities clearly could benefit from an injection of resources from other ministries than Monbusho, but the latter appears still to resist such a development. University researchers would also benefit from being able to use the often superior facilities and equipment in government and corporate laboratories. Arrangements of this kind are, however, still unusual, especially for professors of national universities, although the cases of informal cooperation appear to outnumber those that are officially recognized and sanctioned.

STA is charged with a special role to coordinate government science and technology policy, a role which has gained in importance partly due to the fiscal austerity of the 1980s and partly due to the perceived needs for structural change in the Japanese research system. While Mombusho and its support of university research falls outside STA's coordination mandate, policy measures designed to strengthen the ties between industry, government and universities are included. STA's coordination role is closely tied to the policies set forth by the Council for Science and Technology (CST), for which STA provides the secretariat, and the economic resources made available through the Special Coordination Funds for Promoting Science and Technology (SCFPST) which was established in 1981 as a means for promoting cooperation among different sectors in the Japanese research system and is managed by STA. Although the amount distributed through the SCFPST, in 1988 around \$ 60 million, is fairly small it introduces a new feature into the Japanese research system by offering funding which in principle does not respect ministerial boundaries. The SCFPST was encountered in the MBE community only once when it helped fund the purchase of characterization equipment by a university professor who cooperated with one of STA's institutes as part of a larger materials research project, but there could well be additional cases.

4. Conclusions

The MBE study supports the notion of a growing basic research effort in Japanese industry during the 1980s and demonstrates how this has allowed the Japanese firms to keep abreast of, and actively contribute to, the evolution of a new basic technology which has a close linkage with scientific research. The character of MBE as a basic technology is underlined by the fact that all the major Japanese electronics firms have had some serious programs of MBE-research. The volume and orientation of MBE-research varies greatly among firms and is dependent on each firms overall product market profile and its evaluation of, and relative success with, alternative crystal growth technologies. While NTT and Fujitsu have mustered the most impressive MBE-research efforts overall, Hitachi and NEC have dominated in Si MBE, Sharp developed high performance short-wavelength lasers and Rohm and Mitsubishi Electric excelled in MBE manufacturing technology, just to mention some examples.

The MBE case also usefully illustrates the supportive role of MITI during the take-off of MBE-research in the early 1980s through the timely launching of three new research programs as well as the importance of ETL in organizing these programs, a role which was dependent on ETL's own early involvement in MBE research.

The expansion of long-term research in Japanese firms has undoubtedly reduced the leverage of MITI's research support to individual companies. The creation of joint research laboratories appears to offer better leverage for government research funds than subsidies to individual firms as the resources of one such laboratory, if well focused, can yield a research capability that is stronger than that of any single firm. The Optoelectronics Joint Research Laboratory (OJRL) and the Optoelectronics Technology Research Laboratory (OTL) are good examples of how organizations for joint research have evolved during the last decade into a new powerful element in the Japanese research infrastructure, combining a strong commitment to basic research characteristic of universities and very ample material resources usually found only in a few industrial laboratories. The joint research laboratories, although so far seemingly successful, still have to be considered experiments and their permanence will depend on many factors, not least on how research cooperation between universities and industry develop.

It seems unavoidable that the relative importance of ETL will diminish as the number of researchers there are, at best, maintained at a constant level, while the corporate sector, including the joint research firms, is expanding its research rapidly. At the same time the number of research specialties which ETL is trying to cover is increasing. Reduced importance for MITI's research programs will also tend to undermine the pivotal role ETL has had so far. The official policy is to put increasing emphasis on ever more fundamental research, but it is not clear that this in itself will be sufficient to give ETL a profile which really distinguishes its research from that in industry or in universities. ETL may continue as a very respectable research institution in the electronics field, but it will be constantly challenged by a host of other research organizations in Japan and can probably no longer assume that it has a unique position.

The Japanese university system is actively responding to the opportunities offered by the development of new fields like MBE and to the challenges imposed by the growing strength of company research in Japan. The research funding system has become more diverse and better capable of meeting the demands posed by ever more expensive equipment and the need to achieve critical mass in research efforts. It therefore seems likely that the real research capacity of Japanese universities has grown faster than one would be left to believe from looking at aggregate R&D-statistics.[49] Recruitment of highly qualified researchers from companies to become university professors is an interesting mechanism for universities to rapidly catch up with industry in new fields, a side-effect of which is to improve the universities' contact net-works with industry. A remaining problem, although there may have been some improvement in very recent years, is the difficulty many research groups have of recruiting doctoral students. Proposals have been put forward to address this problem by introducing a new system for doctoral studies.

While universities played a minor role in MBE-research in the early 1980s in Japan, they are ten years later contributing very actively, especially in research related to quantum materials and quantum-effect devices. The pattern is similar in other countries and partly a consequence of changes in MBE technology and related research topics. The development of MBE technology has, for example, become increasingly dependent on an understanding of the basic mechanisms of the MBE growth process and as the sophistication of MBE technology has grown it has become possible to grow materials and structures which can be used to study scientifically increasingly more interesting physical effects, changes which both have served to attract academic scientists to MBE-research. Although Japanese universities have responded vigorously to the new challenges opening up, their response has been weaker, in quantitative terms, than that of the American universities but comparable to that of European universities.

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[49] A similar conclusion is drawn in Okimoto (1987) for the period 1965-1981 based on study of a sample of catalogues and reports of academic institutions.

As illustrated by the case of MBE, but valid also on a more general level, the Science and Technology Agency (STA) has stepped forward as an important actor on the Japanese scene of basic technology research. It has introduced several innovative schemes aimed at increasing mobility and cooperation among organizations from different sectors in the Japanese research system, and in the process introduced what *de facto* amounts to postdoc positions, something which earlier hardly existed in Japan.

As the Japanese research system in the MBE field has expanded it has simultaneously become more differentiated and more integrated. Not only has the number of research groups grown but there has also been a creation of new types of research organizations. As the number of research groups has increased, the potential for organizing research cooperation and mobility of researchers has naturally increased. Although mobility is still low by international standards it has been high enough to create many new linkages between different research groups, linkages which have been further strengthened and multiplied by research cooperation in a number of forms, often promoted by MITI, Monbusho or STA. One important remaining barrier to integration of the Japanese research system is the great difficulties for other ministries than Monbusho to work with universities, a situation which, if it persists, can have a distorting effect on the Japanese government's policies to strengthen basic research.

Some twenty years ago Joseph Ben-David discussed the "scientific gap" between the United States and Western Europe and concluded that this was due to structural inadequacies of the European organization of scientific research. (Ben-David, 1968). In trying to explain why the United States seemed better able to exploit the fruits of scientific research, he proposed that "practical uses of science should be conceived as the result of chance interactions between fundamental discoveries on the one hand and practi-cal interests on the other, which can occur in an infinite variety of ways". From such a perspective the emerging structure of the Japanese research system with a growing multitude of intertwined networks containing a great variety of research organizations, including a particularly good representation of "practical interests", certainly deserves continued attention.

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