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私の半導体研究

東北大学教授　西 澤 潤 一

Profile of Lecturer

Professor Jun-ichi Nishizawa

1926 Born in Sendai, Japan

1960 Received the Doctor of Engineering degree, Tohoku University

1962～ Professor of Research Institute of Electrical Communication, Tohoku University

1968～ Director, Semiconductor Research Insitute, Semiconductor Research Foundation

1981～1986 Project Director, Nishizawa Perfect Crystal Project, Exploratory Research for Advanced Technology, Research Development Corporation of Japan, Science and Technology Agency

1983～1986 Director of Research Institute of Electrical Communication, Tohoku University

1984～ Honorary Member, the Institute of Electronics and Communication Engineers of Japan and the Institute of Electrical Engineers of Japan

1986～ Managing Director, Semiconductor Research Foundation

Honour

Many awards, such as a Person of Cultural Merits, the Purple Ribbon Medal, the Japan Academy award, and Director's Award of Japanese Science and Technology Agency (twice), and Jack A. Morton Award

Recent Monograph

"How to See Ten Years Ahead,"
Kodansha Ltd., 1985.
"Simplicity, Honesty and Stubbornness — The Story of My Life,"
Nihon Keizai Shimbun Inc., 1985.
"The Age of Science: A Personal View,"
Kodansha Ltd., 1985.
"Jun-ichi Nishizawa's 'Opinions for Development': An Original Concept,"
Kogyo Chosakai Publishing Co., Ltd., 1986.
"My/The Battle for Exploration,"
President Inc., 1986.

講師略歴

西澤潤一

●学歴および経歴

1926　仙台市生まれ
1960　工学博士
1962～　東北大学教授（電気通信研究所）
1968～　(財)半導体研究振興会　半導体研究所長
1981～1986　科学技術庁創造科学技術推進事業　完全結晶プロジェクト総括責任者
1983～1986　東北大学電気通信研究所　所長
1984～　(社)電子通信学会　名誉員
1984～　(社)電気学会　名誉員
1986～　(財)半導体研究振興会　常務理事

●栄　誉

紫綬褒賞を受けられた他、日本学士院賞、科学技術庁長官奨励賞(２度)、ジャック・A・モートン賞など多数の賞を受賞する。

●近年発表の論文・著作

『「十年先を読む」発想法』
1985年、講談社

『愚直一徹―私の履歴書』
1985年、日本経済新聞社

『科学時代の発想法』
1985年、講談社

『西澤潤一の独創開発論』
1986年、工業調査会

『独創は闘いにあり』
1986年、プレジデント社

このレポートは昭和61年11月17日、ホテル・オークラにおいて行なわれた1986年度本田賞授与式の記念講演の要旨をまとめたものです。

MY STUDIES OF THE SEMICONDUCTOR

Lecture at the Conferring Ceremony on the 17th of November 1986, in Tokyo

Professor Jun-ichi Nishizawa
The Winner of the Honda Prize 1986

I. Science and Technology and Mankind

Until very recently, mankind was a parasite on earth, whose activities only left tiny marks on the great works of nature. But today, the activities of mankind even cause the change of weather conditions. Mankind is, so to speak, on a beautiful flying object named "Earth." Mankind must co-exist with nature, keeping the integrity of its beauty.

Professor M. Matsudaira, an Emeritus Professor of Tohoku University and a scholar internationally noted for his study on hydro-acoustics, said that when the ancient Chinese created the character "工," meaning engineering, they signified the heavenly natural phenomena with the upper horizontal line, the people and the society on earth with the lower horizontal line, and connected the two lines with a vertical line to signify the effective use of nature for the benefit and of human society and mankind.

Science and technology never destroy nature. They are what improve human life and its society, keeping the negative impact on nature to a minimum. Without advancement in science and technology we would still be hunting for meat, barking trees, and felling forests for firewood. In no less than a few days, the beauty of our earth would be devastated. But, thanks to science and technology, the natural integrity has been maintained to the extent as it exists today.

But we must remember that the resources that are available on earth are all limited. Resources are roughly classified into material resources such as food, and energy resources such as fossil fuel — for example coal and oil — besides atomic energy. Whatever the resource, be it food or water, until relatively recent times we have been blessed with sufficiency. Hydraulic power generation provided enough power supply for mankind. Today, however, the energy resources that nature has stored from prehistoric times are being exhausted rapidly due primarily, perhaps, to the population increase.

If indeed population increase has been the primary factor, mankind has wasted many resources at leisure, and has even inflicted direct damage upon nature at times. From the economic point of view, many welcome a business upturn. But the fact is that, on the other hand, this causes a further waste of energy.

Mankind can no longer afford the luxury of satisfying its desires as it pleases. We have arrived at a point where we must try to advance science and technology to satisfy our desires while taking into consideration the long history of mankind that lies behind us and the long future that lies ahead of us.

Is it true that science and technology are really the cause of natural destruction, as often argued? It appears true because fields, forests and mountains are often destroyed when factories are built. But as I mentioned before, it is crystal clear that without agriculture and the manufacturing industries the very survival of mankind on spaceship "earth," with such a large population, would have been at stake. Despite criticism, the criticizers themselves would not be able to live a day without the benefit of science and technology.

Such criticisms arise from confusing science and technology with some profit-making industries. The task of science and technology originally lies in satisfying more desires with less resources. Desires are influenced by the mentality of a given person and how he or she views life. Be that as it may, there are differences in the significance of a given desire, and classification and evaluation of such significance are dealt with in the realm of ethics, and balancing of desires is a matter of economics. Science and technology today have entered into the realm of politics — a world of poli-technology.

This tendency will grow in the years ahead, first and foremost due to the population explosion. The world's population is increasing at such speed that if it continues to grow at the present rate, it will be phenomenal by the year 2000. The El Niño phenomenon is said to have died down, and it is quite possible that food production will be increased before the advent of the next phenomenon. Even so, under the current situation the world will be faced with a serious food shortage in the near future. In the light of such a possible worldwide food scarcity, development of bio-technology is called for.

Generally speaking, resources of a material nature can be recycled; that is, recycled from what would otherwise be disposed of, so we can recover them. The question is the energy which is consumed in this process. Elements even burned out are still consumed, therefore original molecules can be recovered with energy: however, dissipated energy resources cannot be recovered to its original molecules. For resources that are no longer available on earth, the only alternative is to bring them from other planets. That not being possible, the only option is to conserve resources.

On second thought, mankind has hitherto explored and exploited resources that lie only a few kilometers below the ground and slightly deeper below the sea bed. What lie beyond this depth have been practically untouched. There remains tremendous work still to be done.

Lastly, I refer to energy resources. It is said that oil and coal will be depleted. The impact of the "oil shock" which occurred in 1973 is still fresh in our memory. Nuclear energy probably cannot last very long in view of its reserves. Both solar heat energy and tidal energy hold little prospect. Wind, tidal-level and wave energies are all at the threshold of the break-even point, and too dependent on geographic conditions. And in almost all cases, the heavy investment on facilities cannot be recovered.

Perhaps the most feasible one is solar ray energy. The energy the sunlight brings to earth is so enormous that the sunlight that shines over the area within the Yamanote Line (circular railway line) in Tokyo is said to suffice to meet the total electric power demand in Japan. In reality, of course, such an area would be far too small considering the fact that the efficiency of a solar battery is only 15 percent. Be that as it may, it is the most feasible means and reminds us that mankind is indeed the child of the sun.

The only other feasible means is nuclear fusion power generation, which we can call man-made sun. Unless the unit cost of solar batteries using sunlight can be reduced, their commercial application is not feasible.

Energy being totally a consuming item, it cannot be reserved, let alone recovered. Energy is indeed an indispensable and essential element in our lives. Securing energy and more efficient use of it is, therefore, of overriding necessity. Energy cost accounts for a fairly large portion of the production cost of industrial products and even of agricultural products. The producers of such products and their employees also spend a large proportion of their household expenditures on energy. It is regrettable that I have no concrete figures to endorse the above.

In other words, energy is like water in life and production in that its cost accounts for quite a large proportion of the total cost or expenditure, and not to mention the fact that it is indispensable. Provision of inexpensive and readily usable energy is the most vital factor in so-called modern life.

II. Science and Technology for the Japanese People

Longing for the good old days when life was easier is shared by those who live in a highly sophisticated modern society. But a return to the good old days seems almost impossible now with such high population density and harsh competition.

Assuming it were possible, where would these "out-of" people live? Obviously, they would lose out in international competition. And as a peculiar case, what would happen to their livelihood if the Japanese people — living in a country with practically no natural resources and with a population density close to the highest in the world — should they be totally deprived of their competitive spirit? While this is not my field, I believe that the task of we scientists is to secure a constant reserve of strength for the Japanese people to stay duly viable in international competition.

The value of resources will probably continue to rise in the future. Given this prospect, science and technology in Japan will be required to be high as a vital role in the interests of maintaining our lifeline necessary to stay independent. More important, such science and technology must be essential, indispensable and not available elsewhere, for such people lacking natural resources.

Hitler once said that Germany had only air, water and coal. But Japan is not even blessed with much coal. The challenge of supporting a huge population with just air and water is a new experiment for mankind which is to be found nowhere else. We cannot afford to sit back and wait for someone to render us wisdom.

It should also be remembered that the level of the Japanese today ranks among the top in the world, and hence Japan is required to play a leading role in the world community whether we like it or not.

Racial egoism cannot be condoned. At the same time, one is not qualified to speak of other people or of mankind if one is unable to solve the problems of one's own people, and at the same time if one has to depend on others. Also, establishing a true and lasting stability for the Japanese would be a contribution to the well-being of all mankind, and this can be achieved by each person setting a model way of life for himself. And these two roles can be accommodated by further advancing science and technology for the benefit of all mankind.

As for Japan, a country with little natural resources, its remarkable economic success after World War II was possible because it found a solution to the transportation problem by developing its coastal industrial regions. Today, however, similar methods and similar technologies are being used throughout the world. As a result, geographical advantages and lower wage levels are once again becoming the determining factors for industrial siting.

Considering the geographical factor, large and heavy products other than those for domestic consumption are generally losing their position of importance in Japan. Instead, small, lightweight products are gaining momentum due to their transportability. They must not only be small and lightweight, but also must be such products that are not produced elsewhere if they are to sell in distant countries.

In sum, it becomes apparent that the products capable of supporting the Japanese today and in the future are those that require a relatively small amount of material, but still require substantial processing.

As a people who have very limited natural resources, we have no option but to develop sophisticated technologies if we are to survive, let alone if we wish to maintain our current standard of living which is among the highest in the world. It means that the Japanese are a people who are destined to co-exist with sophisticated high technology — and such technology must contribute to the conservation of resources and to energy-saving in the interests of mankind.

III. Development of Energy-Saving Devices

My honorable teacher, Professor Yasushi Watanabe, was dedicated to raising engineers capable of exploiting physics after World War II. Before that, Professor Hidetsugu Yagi shared the same sentiment. Professor Yagi was the first to introduce communications engineering to Japan, at that day a neglected discipline. He is also one of the international founders of electronics.

For Professor Watanabe, who studied the vacuum electron tube in which he had directly wound grid on oxide-coated cathode, the disclosure of the transistor must been a real breakthrough. He immediately instructed my seniors, Namio Honda and Tomoyasu Nakano (now President of Toyohashi College and Emeritus Professor of Tokyo Electrical College), to commence research. Six months later, I was instructed to join the team. We first attempted to identify the phenomenon that was observed when one needle was erected in order to identify the phenomenon observed with two needles. Hence study on the diode was initiated.

We failed, however, to produce a quality diode with gold and platinum needles contacted on *n* type germanium as was supposed to be the case according to the theory of that time. Although our measurements were taken using iron pyrite ore and galena ore — which were kindly provided to us by Dr. Ichiro Sunagawa (now Professor of our university) — instead of germanium as it was not available, this would have had no influence on the content of the study.

Again, we were to devote ourselves to developing a procedure to make a quality diode. In effect, it was one of the papers of Dr. Hartmann combined with an accidental happening during experiments that led us to confirm that the quality diode was produced when metallic needles made contact in the presence of a thin insulator film on the surface of a semiconductor.

Why is the quality diode produced under such conditions? The only possible explanation was that electrons rush into insulating material only when the voltage is applied in a certain direction. Should this be interpreted to mean that electrons are accelerated within the semiconductor and then rush into the insulating material? If so, the optimum insulating material should be that into which electrons can easily rush. If this is the case, the same semiconductor could be used for the insulating material when it contains very little or no impurities. To confirm the above, the ion implantation method — which became the key technology of today's integrated circuit — was developed, and every thinkable method was tested in various ways. In all results, the quality diode was confirmed. It meant that a new theory for the rectification phenomenon had been established.

The new theory was published and a patent application was filed. We succeeded first of all on September 11, 1950, and by the end of that year, had developed the world's first pin diode and ion implantation method which are still actively used in industrial applications. The phenomenon of accelerated electrons rushing into the film on the surface of insulating material is today termed hot-electron injection.

Soon after, the amplification phenomenon in which electrons were fed into insulating semiconductor film and the electric current was varied, was proposed. This finding was published as the pnip transistor and pnip drift transistor (which are applied to almost all bipolar transistors of today), and electrostatic induction transistor. In those days, only point contact transistors were in existence, and none of today's transistors had yet been realized.

With very little financial resources, we produced only pin diodes in our laboratory. In 1958, we were able to enhance the capacity to 2300V, 100A. No one believed our accomplishment. The pnip transistor was realized by Dr. J. Early, and the pnip drift transistor was realized by RCA Labs ahead of us. Only the static induction transistor was left yet to be realized.

During the same period, we were the first to publish the existence of an avalanche breakdown in semiconductors which became evident through my study to identify reverse current in diodes. Also the existence of the space charge conduction phenomenon, and that deep level capturing was observed once in the event of recombination, were proposed theoretically, identified from the analytical results of study on forward current.

From around 1940, study on vapor phase crystal growth was initiated. In 1961, I discovered that the crystal quality was improved as a result of the species which had been adsorbed on the surface moving actively, being stimulated to migrate by the irradiation of the ultraviolet rays. This discovery was published the following year. The result was found that the silicon and the III-V compound semiconductors displayed magnificent two dimentional layer growth as explained by Kossel's theory. As a result, we succeeded in producing high grade crystals.

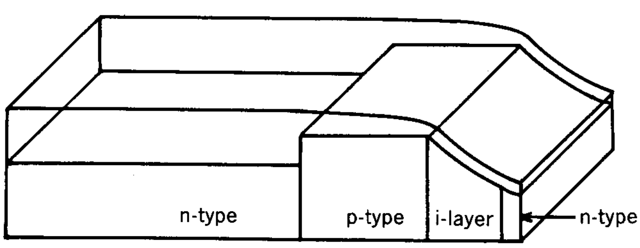
We already had doubts about the theory for FET at that time. We decided to verify our doubts by testing the operational theory of FET by channel resistance. Crystal growth technology made it possible to prepare short channel FET. The result revealed that the FET theory was indeed totally wrong, and that static induction transistors were associated with small channel resistance. This transistor is what is today called SIT.

Dr. Yasunori Mochida et al. have produced excellent SIT for audio use, and Tohoku Kinzoku Corp. is producing a large power SIT of 1KW. Drs. Kitsuregawa, Oka, Shirahata and their colleagues at Mitsubishi Electric have developed SIT of 1G Hz, 100W output. During the same period in 1971, we were successful in producing a thyristor in our laboratory. It deserves to be mentioned that this device, static induction thyristor (SI Thy), is to a large extent responsible for the introduction of electronic technology in power engineering.

The development of SIT resulted in substantial improvement in the efficiency of high frequency generators and power amplifiers. A high frequency generator with a total efficiency of 97 percent has been realized. Recently, GTE Corporation has developed its prototype of 8GHz, 20W output. Dr. K. Muraoka et al. of Toyo Electric Co. Ltd. have confirmed a 99 percent efficiency for an SI Thy oscillator of up to 20KHz, enabling to about 20KHz as power sources, which enables a substantial reduction in the size of motors and transformers theoretically as small as five percent. In the future, long distance transmission of electric power will become possible using direct current transmission, and converting it to alternating current in urban areas using the SI Thy. It has also been confirmed that when an optical pulse is fed to one of the two connected optical fibers, electrical current starts to run, and when the optical pulse is fed to the other fiber, the electrical current is shut off.

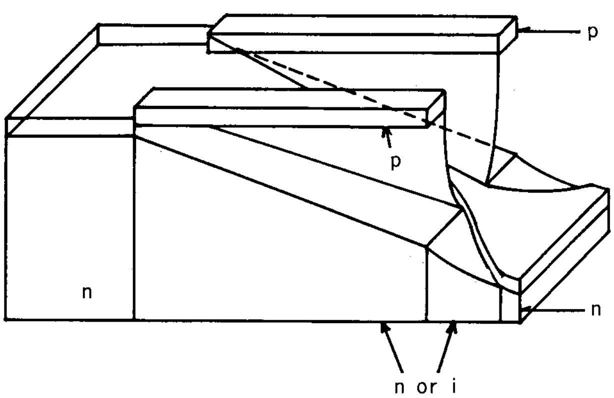
Fig. 1 SIT Operational Theory

(A)



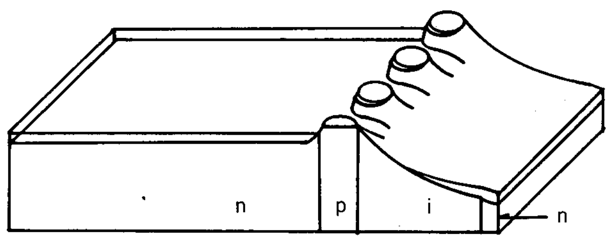
Bipolar Transistor (BPT)

(B)



Field Effect Transistor (FET)

(C)



Static Induction Transistor (SIT)

(D)

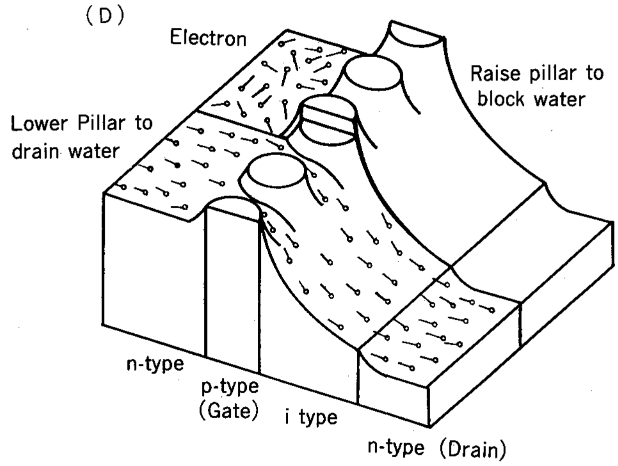


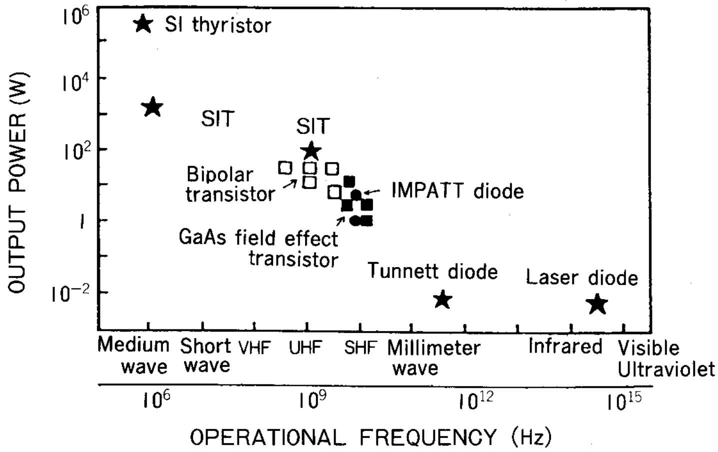
Fig. 1-A represents the watercourse model of the bipolar transistor (BPT) invented by Dr. Shockley in 1949 and realized two years later. The level of the base layer-the narrow p-type area-is varied to control the flow, i.e. raised to reduce the flow and lowered to increase the flow from the emitter on the left. Narrowing the width of the base layer (the lateral distance in the figure) shortens the time required for the water from the emitter side to flow to the collector on the opposite side, resulting in shorter switching time.

Fig. 1-B shows the watercourse model of the field effect transistor (FET) invented in 1926 and realized at last in 1952. The model has such a structure that a thin rubber film is attached to two parallel rods. The water flow between the two rods is varied by moving the rods up and down: When the rods are raised, and hence the rubber film is raised, the channel becomes narrower, and vice versa. Naturally, the shorter the channel, the faster the flow volume change.

Fig. 1-C The watercourse model the static induction transistor (SIT) developed by both Watanabe and Nishizawa in 1951 and realized later in 1969 is shown in Fig. 1-C. Neither BPT nor FET have realized in 1951. The model has such a structure that the pillars placed under the rubber film push up the film and create channels through which water flows. The flow is controlled by vertical movements of the pillars. While the depth of the channel is varied such as BPT to control the flow, the width of the base layer of SIT is very narrow. Also, the width of the channel (almost perpendicular to the paper) is varied such as FET, but the length of the p-type parallel rods of SIT have been shortened as much as possible. Therefore, the current velocity of SIT is faster than that of both BPT and FET.

Fig. 1-D shows the theory of SIT by showing the change in flow with the change in pillar height.

Fig. 2 Output Power Versus Operational Frequency of Semiconductor Device

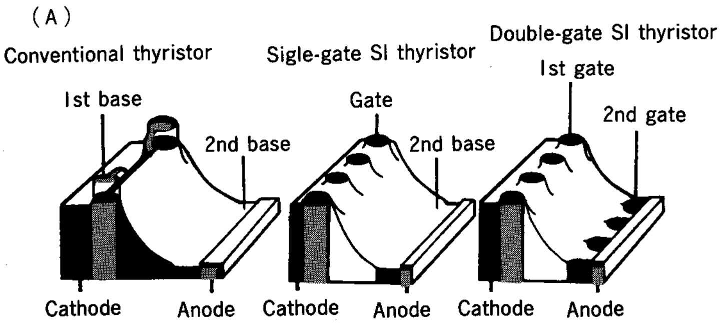


In 1954, the infrared spectrometer was improved to extend of handling 150μm and producing 0.1mm higher harmonic frequency waves by applying microwaves to the semiconductor diode. Despite such accomplishments, the frequency gap between infrared rays with interference (laser light) and microwaves, which is far from being a high frequency, remained three orders of magnitude.

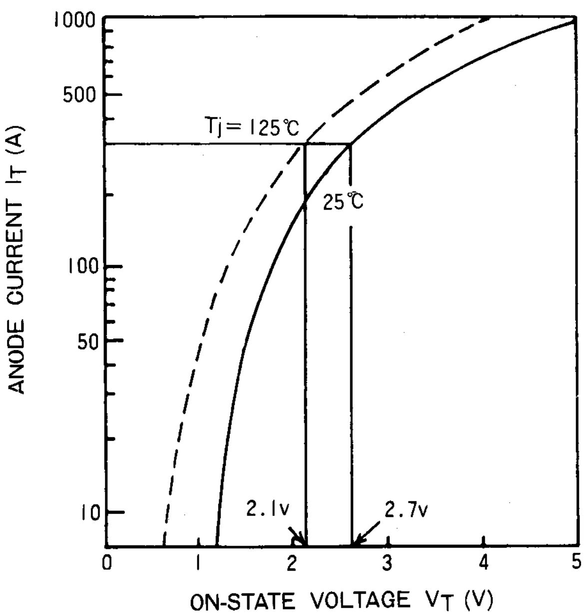
The starry marks denote that devices were invented or already realized at our laboratory. The Tunnett diode has been oscillated at 338GHz.

Fig. 3 Static Induction (SI) Thyristor

(A)



(B) ON-state voltage characteristics



(C) Controllable power versus operational frequency of the power semiconductor device

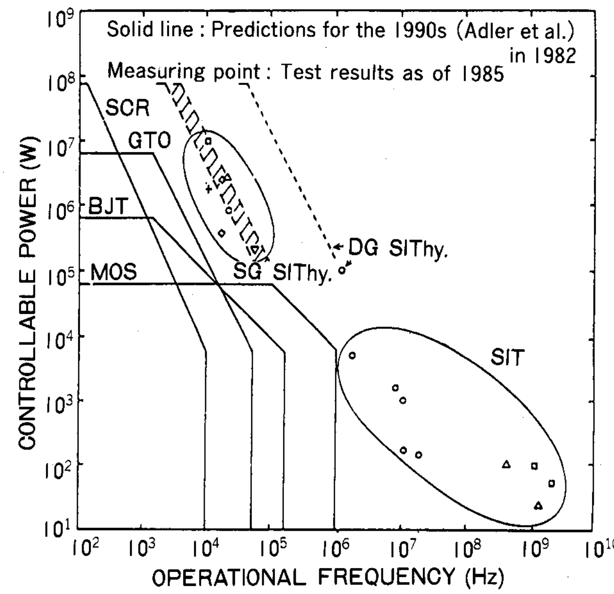


Fig. 3-A shows the schematical potential diagrams of three types of thyristors (an electrical power switch made of a semiconductor): Conventional thyristor, single-gate SI thyristor and double-gate SI thyristor. The single-gate SI thyristor is a variant of the conventional thyristor in that one of the bases is replaced by a gate of the same structure as that of SIT. The double-gate SI thyristor has two such gates, hence switching time gets faster and the system more efficient.

Fig. 3-B shows the measured value indicating the level of the forward voltage drop observed in a switch when the rated current is conducting. The figure implies that the voltage drop of the SI thyristor is about two-thirds of the conventional thyristor.

Fig. 3-C represents the predictions for the 1990s made by Dr. Adler and his associates.

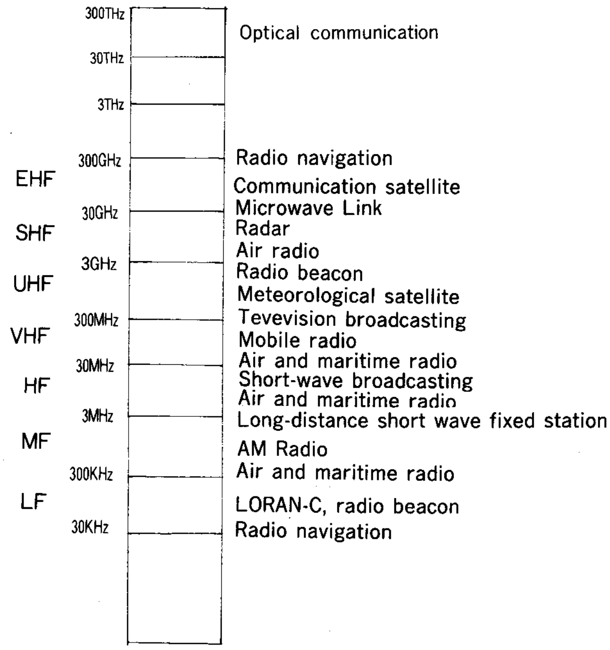
The figure shows that experimental results for the single-gate SI thyristor (SG SI Thy), double-gate SI thyristor (DG SI Thy) and SIT were already beyond the speculated criteria up to 1985. The DG SI Thy shows better properties than SG SI Thy in view of the operational frequency.

Mankind is in need of energy today. But the future availability of energy resources is gloomy. It is also a fact that mankind employs many types of equipment, yet their efficiency is extremely low. There had been for many years, however, only one type of equipment with 99 percent efficiency — the transformer. The accomplishment of developing the two other 99-percent-efficient devices — the pin diode for conversion of AC to DC and the SI thyristor, which is also equipped with the DC-to-AC conversion capability — gives me great pleasure for I could find and clarify basic phenomena regarding the semiconductor itself.

IV. Optical Communications and the Life of Mankind

The semiconductor integrated circuit is inducing fundamental changes in the life of mankind. It goes without saying that the original aim of such technology is to improve the efficiency of our lives. I am proud of the fact that many pnip drift transistors are involved in the operation of accomplishing this aim. And I look forward to the day when the SIT will play the principal role, in particular what was called the ideal SIT proposed in 1971. This is a sort of SIT with a thickness of less than the length of the carrier mean free path, and is being developed under different names throughout the world over recent years.

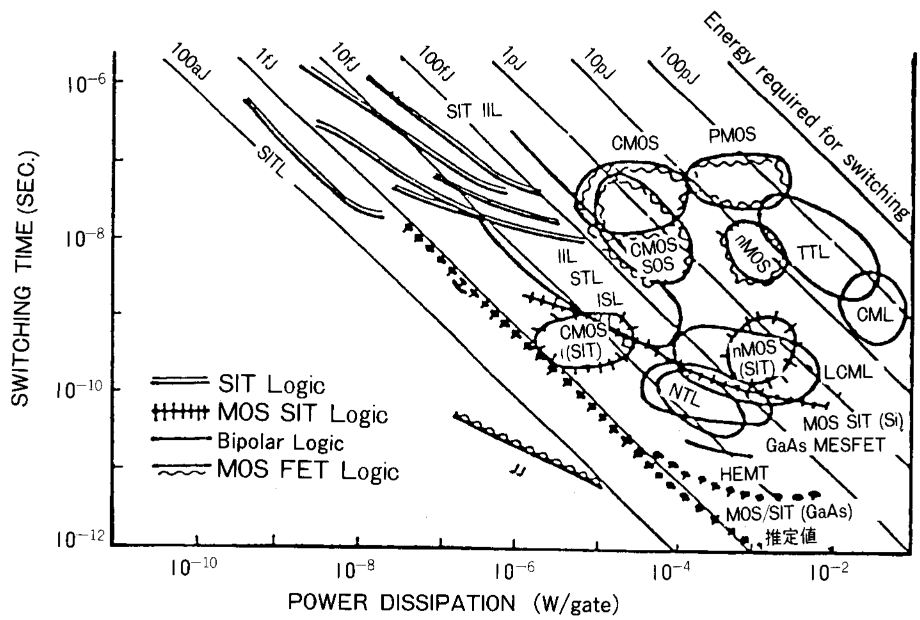
Fig. 4 Utilization Spectrum of Electromagnetic Waves



The same frequency cannot be used by different radio stations due to the interference. Therefore, frequencies are allotted so that a given frequency is used only for a given purpose by a given user. As a higher frequency has become exploitable, the corresponding radio frequency has been allotted for more advanced usages. Yet the frequency range is not available enough to satisfy the demand of users. Suddenly, however, communications have become possible in the optical area. An ordinary light flickers by nature, therefore an artificially created flicker did not make clear the fact of communication. On the contrary, since a laser beam is flicker-free, the presence of a slightest flicker of it would indicate that some information is sended.

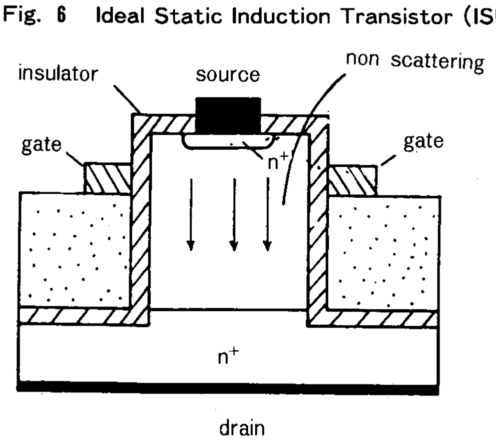
Despite the technological advancement, the state-of-the-art technology cannot amplify the frequency between radio frequency and light, thus these frequency bands have not yet been used for communications as of today.

Fig. 5 Comparison of Some IC Properties



Transistors available on frequencies somewhere between light wave and radio wave have been employed for high-speed computers. The shortest switching time today is a few picoseconds achieved by HEMT in Fujitsu, Ltd..This value is equivalent to that of a superconducting device marked JJ as shown in Fig. 5. The ideal SIT (ISIT), which we are attempting to realize, would theoretically reduce the switching time to less than one picosecond. In other words, semiconductor devices are just as good as superconducting devices in terms of switching time. However, unfortunately semiconductor devices are apt to consume more power. It might be interesting to note that the switching time is reduced by half when power is doubled in the same circuit. Consequently, the energy required for one switching operation remains nearly constant, running parallel with the slant lines shown in Fig. 5. SIT logic-the-left-most line on the chart-requires the least level of energy. 200 aJ is a world record. A circuit switch functioning with a power of as low as a few picowatts is also a world record. If switching time comes to be verified as being the shortest in the world, SIT will hold three world records, enabling production of a computer with super high speed at such a level as has been considered impossible in the past.

Fig. 6 Ideal Static Induction Transistor (ISIT)



Electrons are injected from the source (or emitter) at the top toward the drain (or collector), giving out the electric current. With a thin transistor, the electrons collise very few crystal grids which are under thermal vibration during this course. Therefore the transit time is very short and switching is substantially shortened-theoretically to one picosecond or less for the switching time. The ideal thickness of the transistor should be a few hundred Å, or tens of molecule on the assumption that it is made of GaAs. We should be fully aware that the transistor should be made thinner to this extent.

Meanwhile, in response to the rapid advancement of IC technology, which can be signified as one of the two wheels of a car, optical communication is beginning to play an important role as the other wheel in our lives.

Professor Yagi taught us to strive to arrive light through explore on to higher frequency in order to provide means of communications available to many individuals.

In Japan, Dr. T. Seki initiated the idea of using the quartz glass rod for optical communications in 1936. In 1926 or 1927, the idea of using optical fiber to transmit light existed in Britain and the U.S.A. a, however, could not be applied to communications without improvements.

When I invented the pin diode under Professor Watanabe, I also published that it could be applied to light detection. In my paper to report the existence of carrier avalanche in semiconductors published in 1952, I also included the basic formula of APD. In sum, the two light detectors that are practically used today were already in my papers during the 1950 — 1953 period.

In 1957 I read a paper on the possible amplification of a microwave pulse when impurities such as phosporus are added to silicon and have the idea of creating a continuous amplified oscillation of light using the pn junction of an external resonance type semiconductor. I proposed this idea, but all journals refused to publish my paper. Nevertheless, I did get only a patent. I also got a patent for the internal resonance type semiconductor laser in 1959. Due to our financial restraints, it was left behind to the realization by Dr. Robert Hall in 1962.

In 1964, I thought out and made public that when a glass fiber had a distribution of refractive indices within it with the maximum refractive index placed in the center, the light beam was concentrated within the glass fiber. Later, with the cooperation of Dr. Shojiro Kawakami, performed the analysis of the optimum distribution as well as some tests.(The same idea in US Patent was by CIP, and is later than ours, and that applied before was abandoned.)

In 1970, I proposed the polarization type fiber. By these proposals, I could be said to discovered the three essential elements of optical communications first in the world. Single mode fiber, which I believe, was proposed by Dr. Dyott and large core step index fiber was proposed by Dr. Van Hell.

Through my experimental work of growing crystals for compound semiconductors, I studied deviation from stoichiometric composition. The study indicated that the conventional saturated solubility was not constant and that chemical potential was constant through the solid, liquid and vapor phases. It was Drs. Shinichi Akai and Takashi Suzuki of Sumitomo Electric Co. who succeeded in applying corresponding technology to the production of the world's highest quality GaAs crystal, and late the same method in the Czochralski method is also succeeded by our group. And it was Prof. Junichi Chikawa who applied it to the general production process.

Meanwhile, we were successful in applying this technology to produce a bright light emitting diode using liquid phase epitaxial growth. While one paper had indicated a theoretical external quantum efficiency of 3% at most, Mr. Toru Teshima et al. had already accomplished the production of that of 29%. The key to all these technologies lies in preventing crystalline defect generation by applying the appropriate vapor pressure to restrain the evaporation of the component atoms. We elucidated that GaP could produce a green emission of 550nm prepared without adding nitrogen but with application of optimum vapor pressure on and that II-VI compound can be both p and n types, when it was prepared with controlled vapor pressure of the component. Thus, we were able to contribute in the area of the study about the compound fundamental science.

However, the electric bulb has shortcomings: its efficiency is extremely low, the filaments are prone to break, and identification from reflected light is difficult due to the use of colored glass. The light emitting diode can compensate for these shortcomings.

We are still working to improve the characteristics of optical devices which employ this superior material such as the laser.

Such development of communication engineering may be appeared to be totally outside the field of material resources. However, it is a grave mistake. Not only is the thinking activity a key activity of the human being, it also induces tremendous advantage on the dissipation of resources, as very often observed in our day to day life. If visual telephone conversations between the heads of states were to result in the prevention of war, it is indeed making a great contribution to the lives of the people. It will, at the same time, have a huge impact on the amount of goods consumed.

Communications and information will become more important in the years ahead. And the core of such development will be the thin glass fiber line of about a 10-micron diameter that holds tens of thousands of telephone lines enabling simultaneous transmission.

V. Technology of the Future

I had no intention of being in the limelight. What had kept me going was my determination to help the Japanese people, who are not blessed with natural resources, to find means of life to keep them viable, and a conviction that has taken root in me recently — that Japan must contribute to mankind if it is to remain viable. If the above could be expressed as my left hand, my right hand was the spirit to identify the unknown, even if it were in a modest way. I have believed that I could not have lived any other way. To my surprise, it appears that the society will be walking in the same direction for some time to come.

Enjoying this much wealth, we Japanese have lived by just copying and modifying others' inventions. So it is understandable that the other races came not to tolerate us. It goes without saying that we must contribute to the global community by developing our own new products. However, the current economic situation presents a grim outlook for accomplishing this task. While appreciation of the Japanese yen might be welcomed from the perspective of Japanese peoples' livelihood as such, it causes an extremely difficult situation from the perspective of international balance of payments. Imported resources will become less expensive, but export prices of products will go up and hence become more difficult to sell.

In effect, Japanese manufacturers will have to produce abroad. Already, the threat of hollowing of industries is being observed in Japan. Overseas production by Japanese corporations should be seen as a great advancement in that the Japanese are leaving behind their ethnic egoism and assuming an international position.

What, then, will be left in Japan? There will remain research and development, laboratories and pilot plants for production facilities. All industries in Japan — from agriculture to medical care — are faced with the need to transform themselves into highly sophisticated technology-oriented levels. Failure to accomplish this task is for the Japanese industries synonymous to losing their raison d'être. They will go back, and no longer be able to stand on their own feet as industries because the age of limited resources, and hence high resource prices, creeps up on them. It will mean days of hunger for the Japanese.

In other words, it is the first step towards the creation of a new era for the world, because the Japanese people are suffer the double handicap of high population density and extraordinarily little resource availability. Japan is obliged to challenge to the trial of the coming new era as the first of the world.

It is a challenge for survival with only air and water available. But today, we all are aware that even air and water are not guaranteed for us. Even air and water are polluted. Eventually there will come a time when polluted air and water will have to be cleaned by men, not only by the natural system.

What will be the threat to man's life if mankind continues to live in the same way as today? In my view, such a threat stems from population growth. It might take the form of food shortage, or increase of carbon monoxide and nitrogen oxide. Some fear the increase of carbon dioxide. Oxygen shortage and water shortage may threaten our livelihood.

It is said that cancer may be eradicated in the near future, and this is a welcome development. On the other hand, what would happen if mankind were to get eternal life? The earth would be overcrowded; securing air and water would become even more difficult.

China is perhaps the only country that decides on and implements a population policy today.

Man will look desperately for and continue to look for means of survival in science and technology. However, it is unfortunately apparent that science and technology alone will not provide the answer.

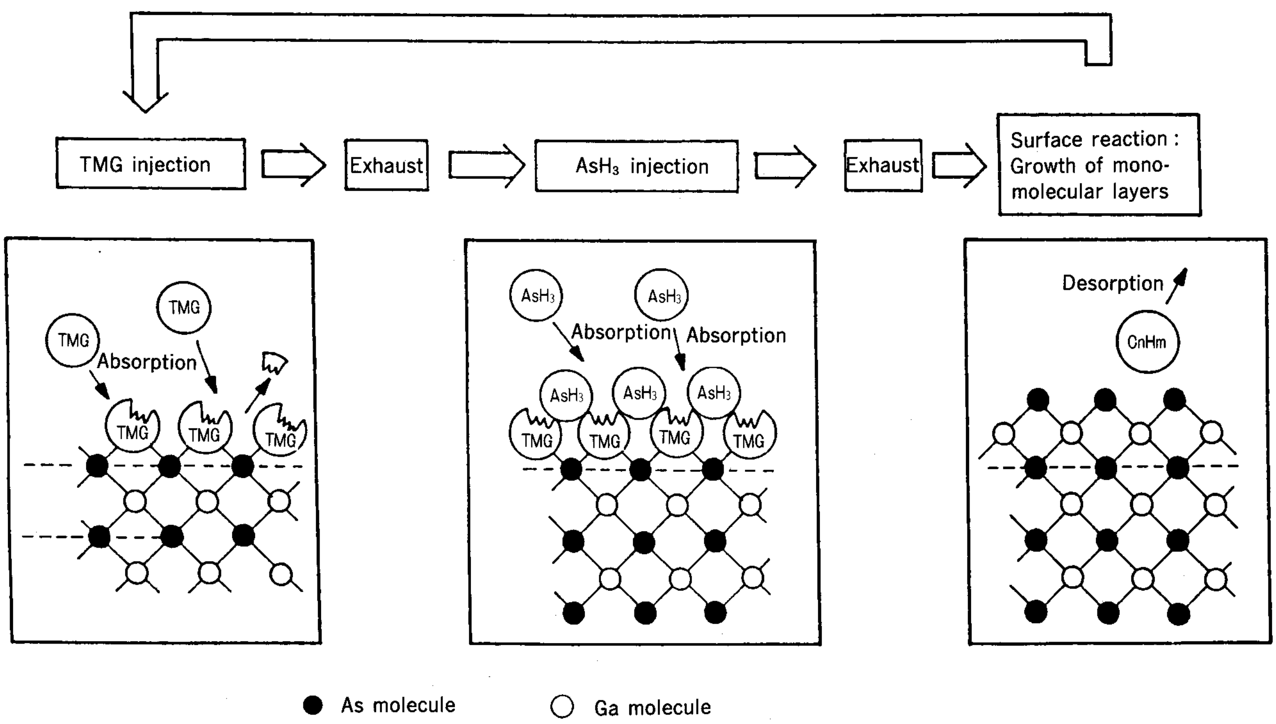
Some criticize the rush in the development of science and technology. Science and technology were always a double-edged sword. We cannot afford to delay their development for fear of its abuse. We Japanese, who are born in a country of no resources, are destined to develop an all-mighty, all-time science and technology. For Japan to secure its living, we must put essential technology demanded by the world into commercial application a little ahead of others.

The tendency to rush may stem from anxiety and excessive desire. Extra deposit will dissipate anxiety. If our deposit of science and technology has filled extra room, we will feel comfortable because we know we are ready. Then, we would not rush to commercialization too early being seized by fear. This will avoid us making unexpected mistakes, such as discharging of pollutants, through being too hasty.

To put it another way, I think we make haste because we are behind. The proper process of industrial application should be, first, to make selection from a wide spectrum of science and technologies taking into consideration economic, ecological and ethical factors, second, to formulate policy, and then to proceed to industrial application. If the technology involved is that which the world is truly welcoming for, being too hasty will only result in maldistribution of wealth.

Deceleration of development of science and technology is not the answer; sharp acceleration and higher efficiency is what is required.

Fig. 7 Types of Molecular Layer Epitaxial Growth



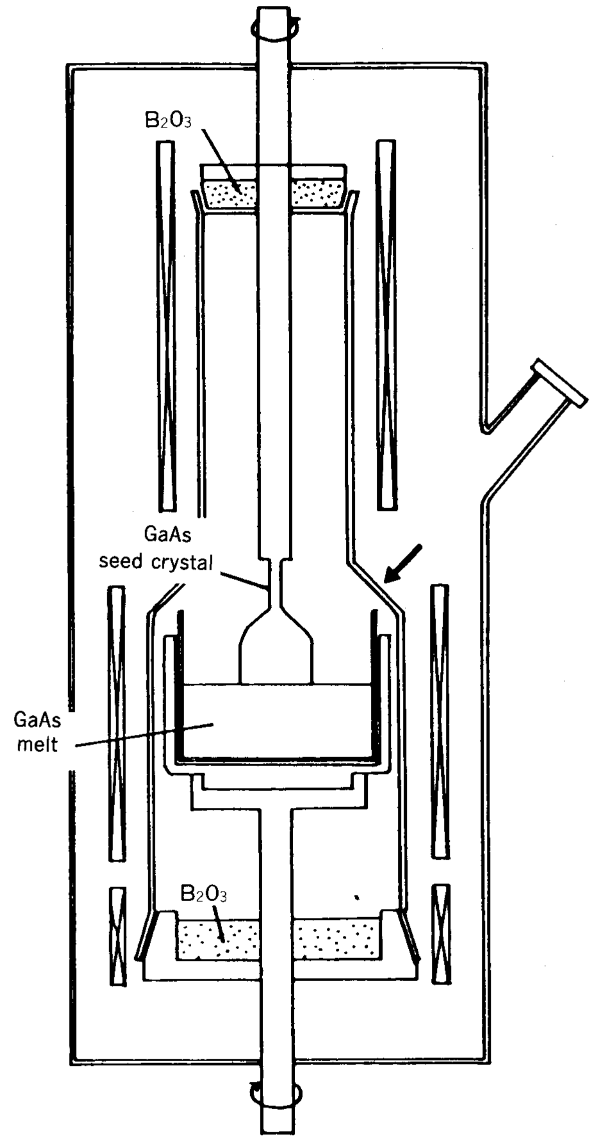
We succeeded in producing GaAs monocrystal line film by applying the procedure for making ZnS polycrystal film which was developed by Dr. Suntola of Finland. TMG gas is supplied onto a GaAs crystal to be adsorbed. In about two seconds, the firmly adsorbed TMG gas forms a monolayer, and excessive gas is exhausted. Then AsH_3 gas is injected, which in about 10 seconds is adsorbed over the previously adsorbed TMG layer.

By the reaction of the adsorbved AsH_3 layer and the adsorbed TMG layer, the growth of monomolecular layer of GaAs and the adsorption of by product such as hydrocarbons are caused. Repeat the same process again and again to make each molecular layer, i.e. 50 times to produce 50 layers of GaAs single crystal film. The ultraviolet-ray exposure during the crystal growth enables a growth of high quality crystal film at about 300°C. When TMG gas is adsorbed,it decomposes and becomes $GaCH_3$, and this further turns into Ga which is fixed as the substrate temperature rises. We discovered that the exposure of ultraviolet rays activates the molecular migration on the GaAs surface. This finding may serve as an important lead in probing the mechanism of catalysis.

Is this problem only a problem for Japan? No, it is a common problem for the entire global community. Let me say repeatedly that Japan has no resources and our population density is extraordinarily high. So perhaps we are experiencing this problem slightly ahead of everyone else.

I am close to my retirement age. There are many things I must do in the remaining few years. Using activated cataphoresis of surface adsorbed particle employing ultraviolet ray exposure, I was the first to translate the idea of Dr. Suntola into crystal. As a result, I succeeded in monomolecular lazer crystal growth utilizing adsorption reaction on the surface of semiconductor crystal. My research now touches the very essence of catalytic chemistry and the mystery of crystal growth. I hope to develop new technologies to produce materials of high perfection at very low temperature, and materials that have not been realized due to difficulties to compose.

Fig. 8 Example of Perfect Techiques for GaAs Crystal Growth



We discovered that the extremely high-quality GaAs crystal growth can be grown when the optimum vapour pressure of As is applied in the process of solidification of GaAs from the liquid Ga or other substances. Judging from this discovery, we also found that the optimum vapour pressure at the solidification point of 1237°C for the molten GaAs, is, to our convenience, about 1 atmospheric pressure. Drs. Shin-ichi Akai and Takashi Suzuki demonstrated corresponding procedure using a horizontal-type electric furnace. Fig. 8 represents a vertical-type furnace capable of producing crystal which is close to circular shape. Molten B_2O_3 or Ga are used to prevent As gas leakage from the rotating parts of the growth apparatus. A vessel heated up to 617°C containing As is connected to the equipment through quartz tube to feed optimum vaporer pressure.