Half a Century's Journey in Research:
Applying Physics for the Benefit of Society [photo 1]

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As a researcher in advanced technology, I am greatly pleased and honored to be awarded the Kyoto Prize at the dawn of a new century.

First, I would like to talk about my parents. The story goes that my father was born into a family of priests in Seto, Aichi Prefecture, and at the age of eight he was adopted into the Hayashi family. For several generations the Hayashis had apparently practiced medicine in Edo (now Tokyo), and the house in Azabu where I was born was in the typical style of a doctor's house. My mother was born in Koji-machi as the second daughter of a man who had come from a farming family named Tsuchida in Niigata Prefecture and moved to Tokyo to establish himself in business. My father majored in basic medicine, pharmacology, in the medical department of Tokyo Imperial University. He also spent two years studying in Germany, then the world leader in medical science. The college he went to is still in existence in Strasbourg.

Both of my parents were widowed when they married each other, so they were not young when they had me. This may be part of the reason they were such loving parents.

I was born the fourth son in Azabu, Tokyo in 1922. Although our house had survived the inferno of the Great Kanto Earthquake, we left it when I was six for the newly developed town of Denen Chofu, which was to be our home for a long time to come. One of the few memories I have from the time in Azabu involves going with my father to a vacant lot once occupied by an astronomical observatory. There, I would enjoy toying with the pools of mercury remaining on a huge slab of stone that had apparently supported some instrument. I vividly remember the pleasure of touching that wobbly surface, with no one around to warn me of its toxicity.

My fascination with science began in my early childhood, but I was not content just to gather plants or catch insects. It seems that "science and engineering" better defines my field of interest, which set me apart from my father, who was a pure "scientist" in basic medicine. One area of scientific knowledge that he imparted to me and that still lives fresh in my memory concerns the solar system. On summer evenings, we would stand on the second-story terrace of our house after a bath, when my father would help me make out the planets in the solar system—Jupiter, Mars, and so on—somehow ignoring the fixed stars that make up the constellations. I also remember the story he recounted of how Pluto had come to be discovered as the farthest planet orbiting the Sun. Having expounded to me on the relative positions of the planets, from Venus, Mars and Jupiter to Uranus and Neptune, he said that the irregular movement of Neptune, considered theretofore to be the outermost planet of the system, gave away the presence of another planet beyond it.

When I started school, my father and I took a daily cold-water bath together as a way of increasing our physical toughness. Throwing a bowlful of icy water over my shoulders in chilly winter required courage. I dropped the habit sometime in adulthood, but I still see traces of it in my morning exercises, done with my pajamas off, without which I cannot start my day.

In 1930, I entered Gakushuin, where I would spend a total of 14 years, from elementary school through high school. My father seemed to like the educational style of this institution. Some of the highlights of my school days include the service learning program through physical labor, such as weeding the expansive playground; dormitory life in my first year of both junior and senior high school; and the summer swimming camps at the beach of Numazu with its few weeks of rigorous training. Particularly grueling was the long-distance swimming over a distance of several kilometers. Reaching the goal gave me such immense satisfaction that I still cannot forget it. I am truly grateful to have been given such wonderful experiences as a student.

I think that the foundations of my belief in not succumbing to selfish desires throughout my long research career were laid at Gakushuin. In my case, it means not thinking about my research projects in terms of how much power and money they will bring me.

Going back a little in time, I decided perhaps while in junior high school that I wanted to be able to visualize the laws of physics at work. In other words, I wanted every object in my mind's eye to behave exactly the way it would in the physical world.

For example, if you push a stone across an ice surface that is completely flat with no resistance or obstacles, it should keep going in the same direction indefinitely.

An image of the basic physical principles can be envisaged, according to which, changing the speed or direction of a moving object requires a force, and the change in speed, acceleration, increases in proportion to the strength of the force and in inverse proportion to the weight of the stone, its mass. When I began dealing with microwaves in my college days, I also wanted to be able to picture their behavior in my mind. Because, unlike mechanics, it was an invisible phenomenon and, furthermore, a complex occurrence involving electric and magnetic processes, it proved to be quite a challenge.

After graduating from high school in 1943, I went on to study in the Physics Department of the University of Tokyo. Those being the closing days of World War II, upon enrollment I was assigned to work on "wartime research" in a laboratory in addition to attending lectures. Under the guidance of Dr. Hiroo Kumagai, I had the opportunity to work with microwaves [photo 2], short radio waves with wavelengths in the order of centimeters, for the first time in my life. Microwaves were the core of the radar system of that time, traveling straight, just like light, until they collide with an object and reflect. This behavior permits the spotting of ships and other objects easily at night, and many Japanese ships were sunk by the United States, which was making advances in this technology. Dr. Kumagai's laboratory studied the generation and reception of microwaves, and I once participated in a project to develop a device for measuring the radar wavelength of B29s. We actually tried to measure it during an air raid.

In the days following the lost war, when there was virtually no funding for the Science and Engineering Institute of the University of Tokyo, we bought a vacuum-tube receiver from a B29 on the black market in Kanda, and experimented with it. We toyed with the microwaves, and vigorously discussed such topics as their basic similarities to light waves and the relative directions of radio waves and electric force. We learned so many things in those days. We also handcrafted microwave circuits to observe their characteristics.

In the meantime, construction of "cyclotrons" received approval in Japan. A cyclotron is a machine used to accelerate hydrogen nuclei and other positively charged particles. After having assembled a miniature cyclotron by hand under Dr. Kumagai, I joined a project to construct a large-scale cyclotron at the Institute for Nuclear Study. We employed the principle of microwaves to design cyclotron oscillators, and understood the mechanics well because the small cyclotron had been practically handcrafted. The large cyclotron was to be shared by researchers from around the country, and featured a function that enabled us to choose different rates for accelerating particles. Therefore, it had the unique capability to adjust the voltage frequency within a higher range. While working with the laboratory, I was able to make a number of close friends, including Dr. Tadashi Kikuchi, the head of the Institute. It was also at the Science and Engineering Institute in Komaba that I met my future wife, Keiko.

After doing all I could in the development of cyclotrons, I worked on developing better designs for radiation measurement instruments for use in nuclear research, but then decided that I go to the United States to experience the research scene of the electronics superpower. With an introduction from Dr. Minoru Oda, I transferred to the Nuclear Science Laboratory of the Massachusetts Institute of Technology in Boston. A year later I moved to Bell Laboratories, where I became a Member of the Technical Staff, joining a project to develop prototype radiation detectors for use on satellites. Because the University of Tokyo permitted studying abroad no longer than three years, I was eventually faced with the difficult choice of whether to return to Japan or give up my position there. But thanks to Dr. W. L. Brown, the section chief of Bell Laboratories, I secured a new position and I quit the University of Tokyo to become a regular researcher at Bell Laboratories in 1966. Dr. J. K. Galt, the department chief, had been considering “semiconductor lasers” as his research theme, which was the very subject that I myself had been hoping to explore.

He had always regarded light as the vital component of communication technology of the future and believed that the technology could be revolutionized by accomplishing continuous operation of semiconductor lasers at room temperature. I think that his forecast for semiconductor lasers, which were still in their infancy at the time, was very farsighted.[*1] Having already tapped Dr. M. B. Panish as the chemistry expert for his project, he had been looking for a physics specialist to work in combination with him. Dr. Galt was seeking people with experience in chemistry and physics, not expertise in semiconductor lasers, and that was what made Dr. Panish and me an ideal choice for him. We were both anxious to get ready for the project, only we were clueless as to what approach to take.

Dr. Panish started to develop techniques for growing GaAs crystals from a Ga solution, while I was to analyze the output characteristics of the crystals he produced [photo 3]. As we groped about together in the dark, we happened upon the fact that the crystal in combination with Al made a very clean joint surface with the regular GaAs crystal*1 and hit upon the idea that perhaps we could use it to dam the outflow of electrons from the GaAs [photo 4]. Encouraged by the possibility that such an arrangement might facilitate the continuous operation of semiconductor lasers at room temperature, we immediately set to work on designing a new laser structure. Pursuing this line, we were able to reduce the threshold current density at room temperature to 10 KA/cm^2, which was one-tenth of the former level. As of December 1968, however, it was clear that we could expect no further reduction.*1 Then we concluded that if using a single heterojunction did not confine electrons sufficiently, we needed a three-layered structure wherein another heterojunction was attached on the opposite side of the GaAs light-emitting layer. We concentrated all our efforts on realizing this design, even to the point of building a new apparatus for growing crystals. Even with this new machine, however, it was not easy to make any further reduction in the threshold current density. While Dr. Panish, together with his enthusiastic assistant, Sumski, persevered through numerous obstacles to improve the laser structure, we made progress in the quality of devices, and at 10 a.m. on June 1, 1970, finally succeeded in getting one to operate continuously at room temperature!*1 Seeing this success, many people working at Bell Laboratories, including the vice president, rushed into the room to congratulate the team.

Although the continuous wave operation at room temperature was clearly a major breakthrough, it was also true that semiconductor laser technology was still in its infancy, with any practical application a distant prospect at best. Besides, Bell Laboratories had largely committed itself to the study of millimeter wave technology as the foundation of the next-generation of communications: it could not simply and suddenly shift its attention to light.

Meanwhile, many companies in Japan were taking serious notice of our success with lasers, and, encouraged by the arrival of low-attenuation optical fibers, began a race to realize optical communications systems. This development made me think of going back to my home country, this time to work with private enterprise instead of a college. Following a friend's recommendation, I returned to Japan in the fall of 1971 to assume a position as a fellow at NEC.

That was a time when no one in the world knew whether a semiconductor laser would ever have any practical applications at all. At Bell Laboratories, a small proportion, less than ten percent of the devices produced were free of defects, and even the non-defective products exhibited an output degradation. Although semiconductor devices were supposed to be long-lived, that did not necessarily seem to apply to those that emitted light. We needed to make sure that they would last at least tens of thousands of hours if we were going to use them for communications. How could we give such a long lifetime to our devices, which now lasted only a few minutes? I can never forget those moments when I persisted in my efforts with overwhelming anxiety. I just had to keep telling myself that we could achieve long-lived devices. Our project had become an act of faith. Members of our group at Dr. Nannichi Yasuo’s laboratory examined every possible cause of degradation.

Our continuous search led to a great discovery in 1973, when a dark line was found in a degraded laser. This breakthrough was made possible by the tenacity of Hiroo Yonezu, who insisted on looking into the inside of degraded lasers no bigger than a grain of rice. We took measures to examine what would happen if our crystal had fewer defects, which were marked by the presence of dark lines extending from dark spots, minute flaws in the crystal structure. Working in this manner, we extended the lifetime of our lasers little by little, and when eventually I cited 2000 hours of operation in a presentation at the Device Research Conference, the presenters who were to follow me, researchers from Bell Laboratories, were visibly upset: they had prepared a presentation very similar to ours, but with data 200 hours shorter. Our data were a world record!

In the days following my return from the United States, when I was working on the development of practical applications for lasers, I befriended many researchers from other companies, and suggested that we should discuss basic issues together, even though we were at rival organizations. This kind of attitude might have played a role in making Japan’s laser research scene such a lively one. Once, members of the “semiconductor laser family,” who established close relations through these discussions, threw a party for me. It was a heart-warming occasion after my many years of efforts. We still get together regularly. It also makes me grateful for my Gakushuin days, where I learned the value of friendship.

Japanese companies thus began together to develop practical applications for lasers. I remember feeling extremely proud of being part of the leading pack, rather than chasing overseas competitors, as Japan-made semiconductor lasers dominated the world market. Such inter-company relationships, highly competitive yet cooperative as I mentioned, were a major contributing factor to this success.*2 Meanwhile, the application of lasers eventually expanded to include optical communications systems, compact disc players, and laser printers.

In the 1980s, two research institutes opened in Japan: Optoelectronics Joint Research Laboratories and Optoelectronics Technology Research Laboratory. The Optoelectronics Joint Research Laboratories set a goal of developing an optoelectronic integrated circuit called OEIC and began research on the materials for it. It was concluded that attaching a compound semiconductor device like GaAs onto a Si substrate would involve nearly insurmountable difficulties. Meanwhile, what was construed to be an OEIC in those days was a switching circuit positioned at each node of an intricate network of optical fibers. With this simple design, all we needed to do was to assemble optical and electronic circuits individually and then package them together in one box. That would spare us the trouble of making an OEIC from scratch.

The "optoelectronic integration system" made by a real combination of optical and electronic circuits is necessary only at a high performance level where the system cannot be accomplished without this combined integration, even if it is difficult to make it. This applies to single-chip computers or microprocessors. In an electronic IC, signals between electronic devices, or transistors, travel through metal wires. Steady progress in production technology for electronic devices has been miniaturizing them, and microprocessors have been more highly integrated and require more acceleration. A dilemma arises because the thinner the wire is, the stronger is the resistance to the electrons passing through it, meaning that the signal transmission speed will not increase as much as expected. Extensive calculations have revealed that no matter what we do, metal wires will not meet the requirements for the "long" stretch wiring, which runs several centimeters on a microprocessor.*3 If we could use light to relay signals, however, we should be able to substantially reduce the connection time. An "optical connection" would cover the distance of three centimeters in less than one-tenth of the time required with a conventional arrangement. What would happen in an "optical connection" is that signals are first converted from electronic to optical form through optical devices, such as lasers, and then sent along the "paths of light," or optical fibers, to their destination, where they are converted back to electronic form by a photon detector. The speed I mentioned takes into account the time required for the electron-to-photon-to-electron conversion. However, the number of "long" stretch wires that require such optical connection in a single-chip computer amounts to thousands. Given the complexity of computers, this is only to be expected, but realizing it is quite a tough challenge.

Prices of light-emitting devices will have to come down substantially, and there is the challenge of mounting them on a Si substrate. This will require a breakthrough technology which seems impossible to achieve within the current view of single-chip computers. Such an invention, however, promises enormous application potential. For example, it would enhance our ability to process high-speed moving images. Research has already begun in this field in Japan, with a method of breaking a moving image into smaller pieces, receiving them simultaneously in photonic devices, and contrasting them. Tadashi Ishikawa is now attracting worldwide attention for a proposal of his that employs a sophisticated technology to achieve this with only a few chips. He has already conducted preliminary experiments.[*4] The material and device technologies required for high-speed image processing are almost the same as those needed for "optoelectronic integrated circuits." I am hopeful these efforts will lead to many more applications that contribute to humanity.

Conclusion [photo 5]

Following the evolution of optical technology, mainly for lasers, over many years, I have begun to envision a future where light will be used in completely different ways and for a greater variety of purposes than it is now. I have come to believe that, instead of just generating visual pictures like TV and video images, the combination of "photons and electrons" can achieve a lot more through further integration, such as a drastic improvement in computer performance and even the development of a "robotic elderly caretaker," complete with the eyesight and intelligence of a real human. It could perhaps be termed "Photo Electronic Integration." It is a great dream of the 21st century.

Looking back over my career in research, I see a few points that seem important. One is the fact that my work has always been greatly influenced by the people I have met. It was while working at Dr. Hiroo Kumagai's laboratory, for example, that I discovered what was to become the central theme of my life-long career:

"microwaves and light." And the encounter with Dr. Galt led me to spend the bulk of the latter half of my life on research in semiconductor lasers.

Later, while working on the development of practical applications for lasers, I and researchers of my "semiconductor laser family" encountered some serious problems that were totally unfamiliar, but managed to overcome them all thanks to the dedicated efforts of young colleagues.

I am an ordinary researcher, not a great man. I just like to make the laws of physics work for the "real world," as in taking advantage of the characteristics of semiconductor lasers for their practical use, and have simply applied myself to my research.

Indeed, "research is the exploration of the unknown." I consider myself fortunate to have been faced with some very tough questions, one of them being "is it possible to make semiconductor lasers operate continuously at room temperature?" I also ran into serious difficulties in the development of practical applications. There was no other choice but to keep on believing in myself. Later, while exploring applications for the optoelectronic integrated circuit in a study group dedicated to this theme, I reached the conclusion that the core problem with a computing system that uses only electronic circuits is the delay in the speed of the internal signal transmission. This could only be solved through the introduction of optical circuits on a massive scale. A vital part of this solution, "Photo Electronic Integration," is something that we should regard as one of the most important challenges in the 21st century. Furthermore, achieving this goal will open up a wide field of practical applications. So let us continue dreaming and keep striving towards our dreams. I believe anything is possible when we join hands across generations in the service of humanity.

Lastly, again, it is a great honor to see my lifetime of research activities recognized with such a prestigious prize. It marks another turning point in my life. I would like to thank all of the many people who have supported me to this day.

＊1　I. Hayashi, "Heterostructure Lasers," *IEEE Electron Devices*, Vol. ED-31, No.11 (1984), pp. 1630-1642.

＊2　Ryoichi Ito, "Semiconductor Lasers," *Kogaku*, Vol. 24, No. 8 (1995), pp. 486-494.

＊3　Izuo Hayashi, “Optoelectronic Integration,” Oyo Buturi Vol. 65, No. 8 (1996), pp. 824-831.

＊4　Masatoshi Ishikawa, “Massively Parallel Processing Vision System―General Purpose Vision Chip and Optoelectronic Vision System,” *Oyo Buturi* Vol. 67 (1998), pp. 33-38.

Acknowledgements [photo 6]

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・ The Japan Society of Applied Physics

・ The Engineering Academy of Japan

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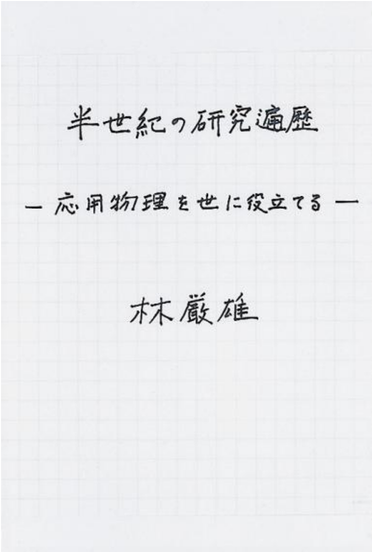
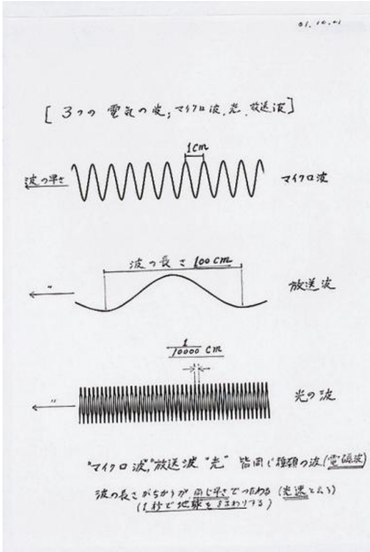


photo 1



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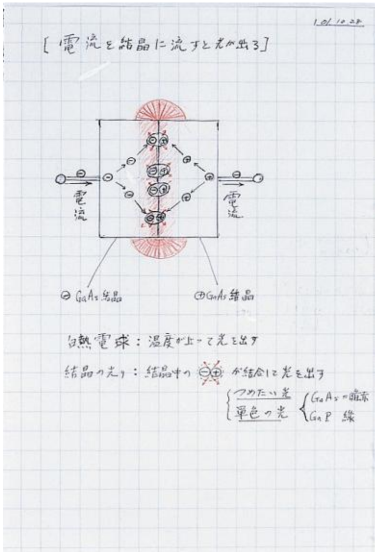

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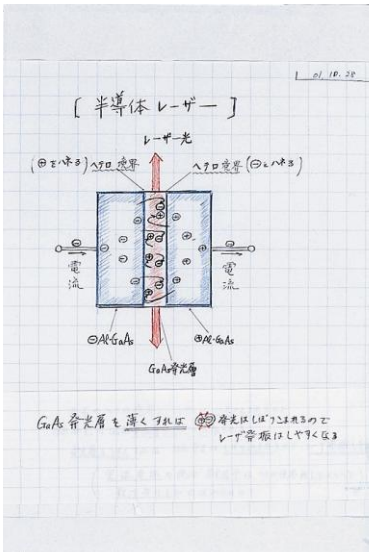

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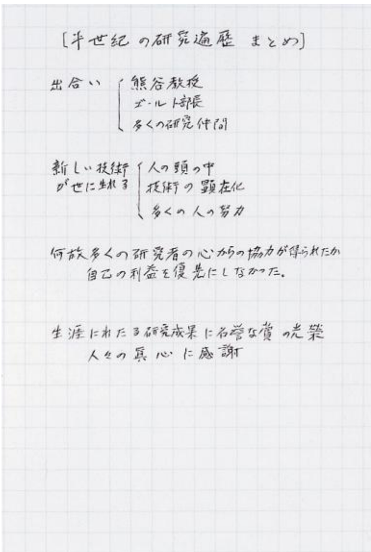

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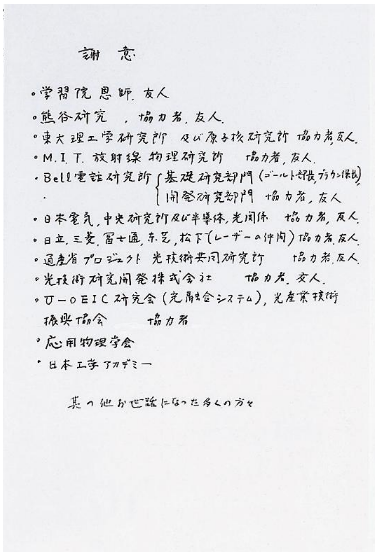

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