# A Half-Century Journey in Research
## — Applying Physics for the Benefit of Society —

Izuo HAYASHI


## Abstract

This is an outline of my technical activities during the past half century, during which I examined ways to apply physical concepts into photo-electronic devices for the benefit of society. The original story was presented last year at the Kyoto Prize Ceremony, describing my activities to the general public in layman's terms.


My deeply ingrained interest in natural sciences was clearly influenced with my father. My favorite way of thinking about natural science, which I adopted during my high school years, is to create an active physical image in my mind without using mathematical calculations.

My true academic activities began when I joined the Tokyo University Physics Department. This was during Japan's war years, and my studies of "microwaves" under Professor Kumagai were affected by wartime technology. However, these studies remained with me for a long time, changing shape, and eventually expanding into the study of "lightwaves", which became the seeds for my first visions of semiconductor lasers.

A coincidental meeting with Dr. J. K. Galt was the most important link between my background in microwaves and his idea on semiconductor lasers.

My interest in "electronics" began around the same time as my research in microwaves, when I used electronic systems such as vacuum tube amplifiers and primitive computers. An equal interest in "microwave-light waves" and "electronics" led me to the idea of "Photo-Electronic Integration" later in my life, which will be described as my "dream for the 21st century" in the last part of this paper.

## 1. Visualizing physical concepts

As I described in the abstract, I wanted to visualize the law of physics working independently in my mind.

Suppose a piece of heavy stone is sitting on a flat ice plain. If the stone started to move in one direction, it will keep sliding on the ice indefinitely in the same direction. If I want to change the direction of the stone's movement, a force is needed (Figure 1). This is a "Law of Mechanics".

"Microwave" was my focus of interest for many years. Microwaves are electro magnetic waves with very short wavelengths. Here I focus the electromagnetic wave of about one centimeter used for radar application (Fig.2). US bombers used microwave-based radars during the war. Wavelength measurement of bombers was my first job during my wartime research.

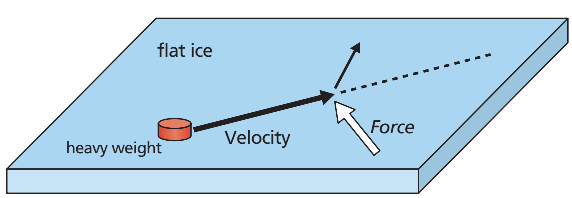


Fig. 1: An example visualizing laws of physics. This is a law of Mechanics.

After the end of the war, I joined a laboratory of Tokyo University. There was almost no budget for research. Somehow we obtained a small microwave tube, which was used by the US bombers, in downtown Tokyo (at the famous Kanda black market).

In the laboratory we conducted various experiment using this tube, and learned about the characteristics of microwaves. Using a handmade grating (parallel wires), we were able to measure the electric field direction (Fig.3). And using a metal plate, we could also determine the magnetic field direction. We discussed our findings with colleagues, and obtained a pretty good "visual image" of microwaves.

Because the basic laws of physics are unchanging, the microwave image was useful in designing the cavity for a high power radio frequency oscillator that was used in a cyclotron for nuclear particle experiments. Years later, this image was also useful in understanding the characteristics of light waves in semiconductor lasers.

## 2. Experience in the United States
### — Room Temperature Operation of Semiconductor Lasers —

After nearly 20 years working with Tokyo University, I decided to go to the U.S. to study electronics technology and to gain experience in laboratory work over there, knowing that significant advances in electronics must have made during the war.

I spent the first year at MIT and the next year at Bell Telephone Laboratories (BTL). During my first few years at BTL, I studied nuclear particle radiation detectors for satellite experiments under Dr. W. L. Brown, a department head.

Three years was the limit for overseas studies set by Tokyo University. Dr. Brown kindly introduced me to a few laboratories to see if there was a place for me in BTL. After visiting several facilities, I finally met Dr. J. K. Galt, a laboratory head in the solid state electronics research division. Coincidentally, he was looking for an experienced physicist to work with semiconductor lasers. This came as a most unexpected surprise for me.

Dr. John K. Galt had an idea that "if continuous operation of a semiconductor laser is achieved at room temperature, it will have a major impact on communication technology".

I was surprised and at the same time very much delighted. I immediately resigned

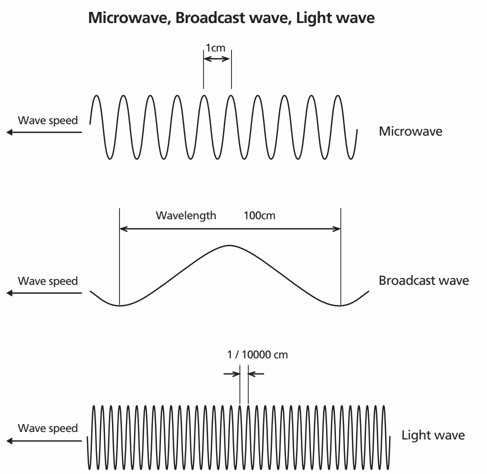


Fig. 2: Electro Magnetic Wave of different wave length

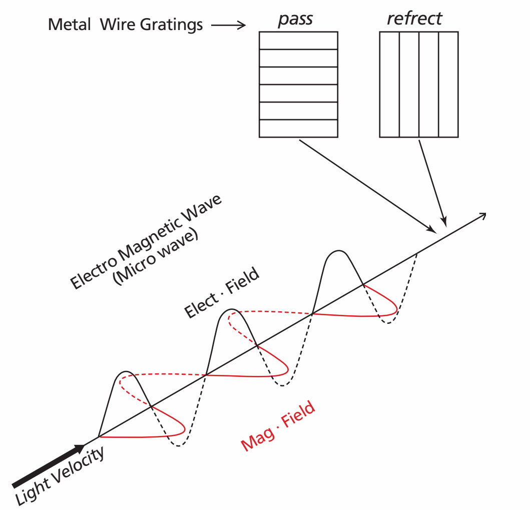


Fig. 3: Electromagneticwave, shape of Electric and Magnetic field. Metal wire grating experiment using the microwave.

from Tokyo University and joined Dr. Galt's group in BTL. I started working with Dr. M. B. Panish, who was a chemist in the group. I conducted measurements, and he handled crystal growth for semiconductor lasers using GaAs. However, we did not have any idea of how to proceed with studies targeting room temperature lasers.

At the Semiconductor laser Conference (1967), fellows from IBM presented a study on visible lasers using AlGaAs grown on GaAs. Dr. Panish started immediately to grow the new material and I began studying its luminescence.

Surprisingly, a very strong luminescence of GaAs was found underneath a thin AL-GaAs layer. This was a great discovery. Instinctively I felt that this phenomenon might be useful in the room temperature operation of semiconductor lasers. The interface between GaAs and AlGaAs must be ideally clean! (ref 1)

We started to put an AlGaAs on a GaAs active layer, using the old growth technique (tipping Fig.2 in ref 1). The lasing threshold came down almost one tenth of the previous value. This is called a Single Hetero Structure (SH). But this threshold was not low enough to achieve room temperature operation (Fig.4 in ref 1). We started to install another Al-GaAs layer on the other side of the active GaAs layer, called a Double Hetero Structure (DH)(Fig.5) (ref 1).

A great deal of effort went into this DH growth. Panish, with his assistant S. Sumsky, had to prepare a new type of growth technique, call the "sliding boat structure" (Fig.4)(ref 1). It required many delicate adjustments, and improvements were gradually achieved. My assistant P. Foy made laser devices from this wafer for laser threshold current measurement (Fig.5).

One and a half years later, he found a pretty good wafer. We came to the laboratory even on "holiday mornings."

We finally achieved "Continuous wave operation (cw)"! This was a big event at BTL. Many people came to see us. The Vice President of Bell came in the next day.

## 3. Back to Japan

### – Challenge for practical usage –

I came back to Japan the next fall, in 1971. This time I chose a private company, Nippon Electric Co. Ltd. (NEC), as the working place for developing applications. I was a leader, and conducted no research by myself.

A very short laser lifetime, and several other problems were awaiting us. In addition to the large amount of work required, some

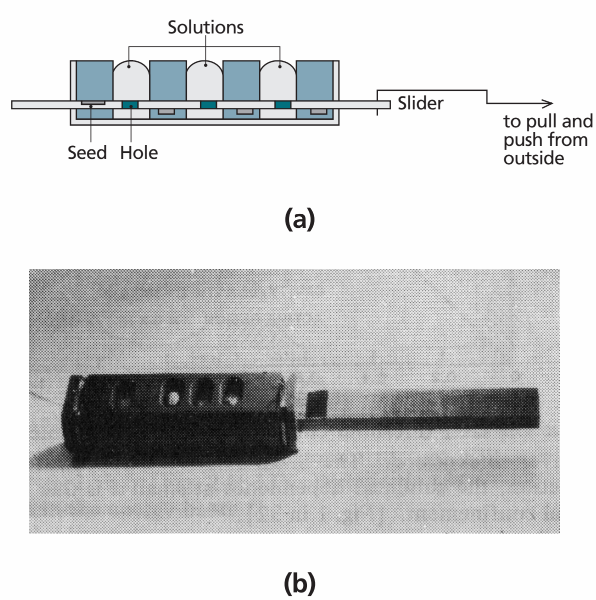


Fig. 4: (a) A new "moving seed" multiple layer solution growth apparatus (Dec. 25, 1969). With this apparatus three DH epitaxial layers can be grown in succession from three solutions. A slider will be moved (push-pull) from outside. All parts are graphite. (b) A photograph of an early sliding boat. The top and the bottom part inserts were tied by platinum wires.

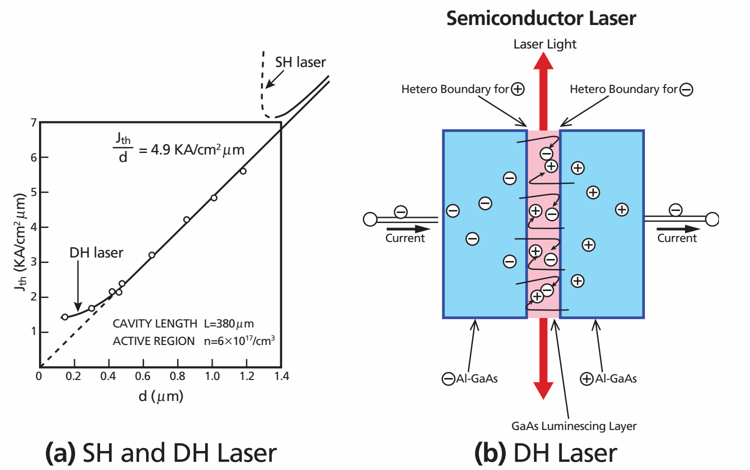


Fig. 5: The DH laser threshold current density $J_{th}$ as a function of the active layer thickness $d$. The linear relation demonstrates an ideal DH function, the sublinear dependence at small $d$ is due to the loss of optical confinement. (ref 1)

technical breakthroughs were also necessary before we could achieve practical applications.

In the beginning, the lifetime of the lasers was about one minute. We conducted many trials, changing impurities, dopings, contaminations, and other factors, but with no major effect.

This was a very difficult time for me, not knowing why we were making so little progress. I just kept telling myself, "We should be able to achieve a long life laser."

A breakthrough occurred in 1973, when a young colleague, H. Yonezu, found "dark lines" in a degraded laser (Fig.6). These lines appeared in a small laser structure. Degradation is always associated with narrow dark lines, which run along a certain crystalline orientation. Dark lines grow from dark spots, which are caused by dislocations in the crystal. We used better substrate crystals and improved growth techniques, and as a result the lifetime increased gradually, from minutes to hours and days.

At the Conference on Laser Engineering and Application (1973), I announced a record laser life that had exceeded the 2000-hour mark by a few hundred hours. At the conference, I met a researcher from BTL. had also achieved a record life of about 2000 hours. This was an astounding revelation (ref 1). The same progress had occurred at the same time in two places across the Pacific, independently!

"Competition and Collaboration"

While I was in NEC, I made many friends in other companies. At meetings I was observing their activities, and noticed that discussions were not as productive as they could have been. I suggested that we should discuss basic issues, even among researchers at rival organizations.

A "Semiconductor laser family" has arisen in this field, made up of a group of people who have developed many of application systems during 1980s. They get together every fall and spring, around the times when Applied Physics meetings are held.

## 4. Dream in the 21st century

In large scale Si LSIs (finer pattern size, DR < 0.1 μm) and higher operating speeds (f > GHz), an interconnection crisis occurs due to the increased resistance of metal wirings. Results of calculations are shown in Fig 7 (Fig.2 in ref 2). Optical interconnections decrease the delay effectively for long connections over 10 μm.

A large number of optical interconnections ($10^3$ – $10^4$) will be required for the ULSI system. Small size and low power of semiconductor lasers is essential. A μm size surface emitting laser with μ-watt power has already been reported (P. D. Dapkas, ref. 9 in ref 2). Furthermore, the cost of these lasers must be much lower than those available today.

In the abstract, I described my interest in both "Electronics" and "Microwave → Light" in the early stages of my research. Later, this led me to the idea of Photo-Electronic-integration as a dream for the 21st century.

Many problems related to devices, processes, and system structures must be solved to make this system valuable for practical usage.

Process compatibility must be achieved. High temperature ranges in the Si process must be clearly delineated from low temperature zones of III-Vs and metal wire evaporation.

Several studies are being done to overcome the problem of lattice mismatches between Si and (III-V)s. H. Yonezu and others achieved dislocation-free GaAs on Si through the skillful use of interface layers (ref. 4). M. Tamura showed that a remarkable decrease of dislocation in GaAs could achieved by annealing (Fig. 8 in ref 2).

An important message that must be reported relates to the study of optical interconnection, which was conducted by a group of people carefully selected from different specialties between 1990 and 1994 (the U-OEIC study group). The report was very insightful, and is still valuable today (ref. 3). An example of optical interconnection is the structure shown in Fig.8 (ref.2), where an optical plate is separated from an LSI substrate. Optical paths can be installed freely from LSI circuits.

It will take time to achieve practical applications using these photo-electronic integrated system. A variety of new techniques must be developed to complete the system, and this will require the collaborative effort of en-

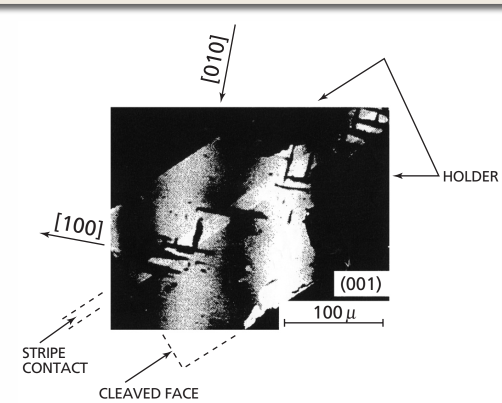


Fig. 6: "Dark-line" defect pattern in a degraded DH laser e. $I_j$ pattern was taken with an SEM. The stripe contact is removed after aging. (H.Yonezu et al.: A.P.L, Jan. 1974)

gineers from different fields of specialization. But when this goal is finally realized, the system will be of great benefit for society in 21st century.

## Summary

Looking back, my meetings with significant people defined milestones of my life long career.

Hiroo Kumagai was my life-long teacher. He introduced me not only to techniques such as those related to microwaves, but also provided me with my physics background in the laboratory.

John Galt provided me with the theme of semiconductor lasers. This has become a central part of my career in photo-electronics integration.

I also learned from many colleagues about important techniques for practical applications.

I am an ordinary researcher, not a great inventor or a scholar. However, I have always enjoyed the highest level of collaboration, because I have tried to give of myself without asking much in return.

Even so, I have reaped many great rewards, not only in terms of physical gain, but also in the human relationships with the people with whom I have collaborated. The "semiconductor laser family" described in section 3 still meets every year. This is the best time for me to reflect on my many years of research activity.

Finally, I would like to say that it is a great honor to have my lifetime research activities recognized by the very prestigious "Kyoto Prize." I would like to thank all the people supported me during this 50 years of study.

Thank you very much.

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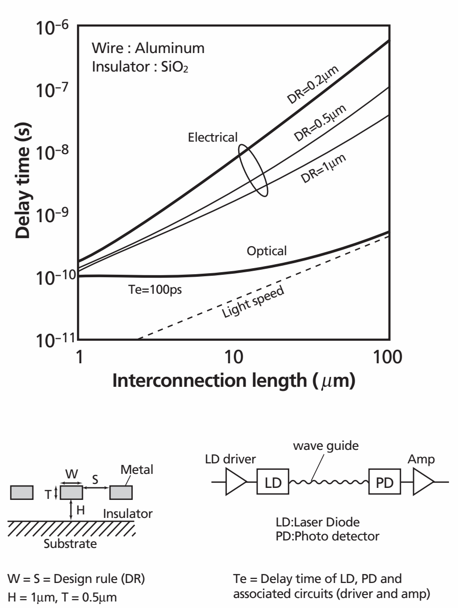


Fig. 7: Signal Delay of Optical versus Electrical Interconnections on the microprocessor. Optical interconnection delay includes electrical circuits delay Te=100ps in addition to that of the light. (A. Iwata)

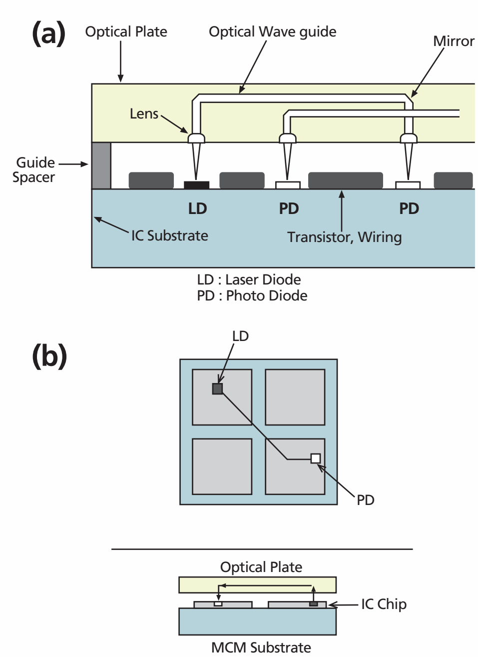


Fig. 8: Optical interconnection circuits can be installed freely from LSI circuits in MCM substrate.