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History of HEMT Transistors

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1. Prologue

The High Electron Mobility Transistor (HEMT) is a kind of field effect transistor that the Japanese invented and successfully commercialized. According to semiconductor theory, the semiconductor layer needs to be doped with n-type impurities to generate electrons in the layer. However, this procedure causes the electrons to slow down because they end up colliding with the impurities residing in the same region, that were used to generate them in the first place. HEMT is a smart device that was designed to resolve this contradiction.

HEMT accomplishes this by use of high mobility electrons generated using the hetero-junction of a highly doped n-type AlGaAs thin layer and a non-doped GaAs layer. The electrons generated in n-type AlGaAs drop completely into the next GaAs layer to form a depleted AlGaAs layer, because the hetero-junction created by different band-gap material forms a steep canyon in the GaAs side where the electrons can move quickly without colliding with any impurities.

HEMT is a superior device for building a low noise amplifier at a high frequency such as 12GHz. Already nineteen years have passed since HEMT was invented. HEMT is now widely used as an extremely low noise device in terrestrial and space telecommunications systems, radio telescopes in the area of astronomy, direct broadcasting satellite television (DBS) receivers and a car navigation receivers. As I was one of the fortunate enough to be there and serve as a "midwife" during the birth of HEMT, I would like to recount some episodes in the history of HEMT from its dawn to its commercialization.

2. Mimura and Yokoyama

Dr. Takashi Mimura, the inventor of HEMT, is currently a fellow of Fujitsu Laboratories. At that time, he was a researcher who reported to me. In 1977, I was assigned to head the compound semiconductor device research section. Our research activities were then confined to high power GaAs FETs and GaAs ICs because we believed "Concentration, the best measure for success, could provide us with a great deal of gain, even through failure".

I asked Dr. T. Mimura and Dr. N. Yokoyama to work on developing as soon as possible the GaAsMOSFET (Metal Oxide Semiconductor Field Effect Transistor) which was necessary for a GaAs IC. Dr. Mimura had a genius for uncovering the essence of a phenomenon from the

limited results data from a few experiments, and Dr. Yokoyama had a talent for quickly moving through experiments. Although articles on the GaAs MOSFET, introducing a low-temperature plasma oxide film as the gate insulator, were published in many papers in English, it was far from being practical.

Sometime in the spring of 1978, Dr. Mimura explained to me why the GaAs MOSFET was not acceptable and advised me to change the direction of our research, to turn to another device utilizing the surface effect of GaAs. At that time, we discontinued our MOSFET research. After that, Dr. Yokoyama was engaged in a process for developing the GaAs LSI. Afterwards, he went on to develop the RHET (Resonant tunneling Hot Electron Transistor), applied electron resonance effect of quantum mechanics.

3. A near miss to Nobel Prize

In the U.S., there was a rumor to the effect that Dr. Mimura got the hint regarding the invention of the HEMT from a discussion he had with Dr. Dingle of Bell Laboratories. This discussion was supposedly held in a car when Dr. Dingle visited our Laboratory at the end of August in 1979. But the facts are different. He wrote the manuscript for a patent, that was dated August 16, two weeks before Dr. Dingle visited there.

In the fall of 1979, the first data was obtained. I cannot imagine how he came up with the idea for HEMT, but when an n-type AlGaAs is substituted for GaAs oxide film, the discontinued MOSFET becomes very similar to HEMT in terms of structure, as referred to in Figure 1. So I think that my "selfish" requirement, that he "develop the GaAs MOSFET" ended up having a positive effect on the invention of the HEMT.

In February 1980, Dr. Klitzing of West Germany measured the two-dimensional electron gas of MOSFET in an environment exposed to ultra low temperatures and high magnetic fields, at Grenoble Research Center, France. As a result of taking these measurements, Dr. Klitzing discovered "the quantum Hall effect" whereby the Hall voltage of semiconductors changes quantum-theoretically. He published his findings in the Physical Review Letter. (1) Dr. Klitzing was awarded the 1985 Nobel Prize in Physics for this achievement.

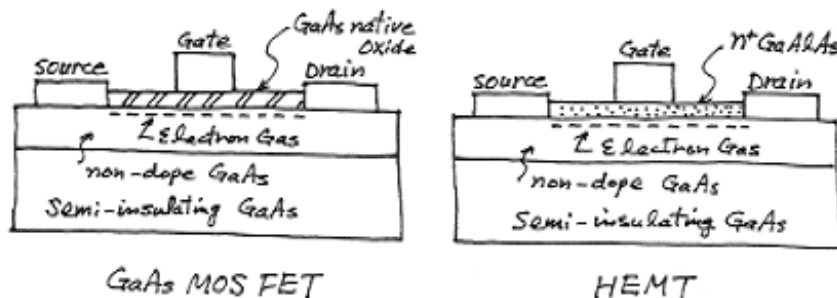


Fig 1. Structural comparison between MOSFET and HEMT (Sketch of Fukuta)

Also, in March 1982, researchers led by Dr. Tsui of Bell Laboratories measured the properties of electron gas on a two-dimensional plane in GaAs/AlGaAs heterojunctions using extremely powerful magnetic fields and extremely low temperatures. Then, they discovered "the fractional quantum Hall effect" and published their findings in Physical Review Letter for

1982. (2) Dr. Laughlin, Stomer, and Tsui were awarded the 1998 Nobel Prize in Physics for this achievement.

From 1979 through 1980, we studied the behavior of two-dimensional electron gas generated by the HEMT structure. However, we didn't hit on the idea that its characteristic changed quantum-theoretically. I had directed our researchers to focus more on examining how HEMT displayed microwave device and IC characteristics, instead of considering this basic measurement of the two-dimensional electron gas. Although I had excellent researchers, I was not likely to be leading my team to creating anything as successful as Nobel Prize-class works.

4. Inspiration to perspiration

In January 1980, we confirmed that we had successfully come up with a microwave amplifier characteristic of the HEMT. I had enough confidence to believe that it would succeed. I explained the fruits of our results, which were then secret, to the Fujitsu executives, and asked them to fully support this development up to its completion. The paper submitted to JJAP in the fall of 1979 was accepted and published in May of 1980. (3) Late in June, Dr. Mimura made a presentation concerning HEMT at the DRC meeting in the United States, and on June 20, Fujitsu decided to inform the news media via a news release about the HEMT invention on June 20. The next day, June 21, I was transferred from the research laboratory to the business division.

There is a mission that for all workers in the factory to be able to make many devices, of which only one is a device from our research laboratory. One percent of inspiration is necessary to the invention; equally ninety-nine percent of perspiration is required to the business. It's the business that we have to win to guarantee the volume, the characteristics, the reliability, and the price of products which customers want, and then to deliver and to make profit.

The process of manufacturing new semiconductor devices is much like the process of advance through a minefield, by groping in the dark. After we are figuratively blown apart by the mine, which represents the failures we experience with our processes, and make sacrifices in terms of yield loss, we finally make our way to a broader and more reliable road to the manufacturing process. The battle to complete the HEMT project ended successfully, thanks to the work of many people.

In 1985, HEMT was announced as a unique microwave semiconductor device with the lowest noise characteristics in the world. Initially, HEMT was used for a radio telescope (45 meters in diameter) in Nobeyama Japan, where it replaced the parametric amplifier that had been used up to then. When HEMT is cooled to liquid-helium temperature, we can pick up a signal from an interstellar molecule in NGC2024, which is 1,000 light-years away from the earth. The universe is filled with 3K noise that was generated by the "Big Bang" that marked the birth of the universe, whose remnants have remained since then. HEMT can actually pick out, from a sea of noise, minor 10K signals sent out by interstellar molecules.

5. Leave them to think

From the summer of 1987, NHK Japan broadcasting corporation started its satellite broadcasting service for 24 hours a day. The service using a Direct Broadcast Satellite (DBS) originated in the United States. In the United States, people have sufficient space in their garden to set up a parabolic antenna that may be as large as 2 meters in diameter, and are able to enjoy more than 50 channels of TV programming. I'm afraid the Japanese do not have enough "real estate" to set up an antenna of this size. And if we were to set up an antenna 2

meters in diameter on the roof, it would probably end up getting blown away by a typhoon. HEMT allowed us to solve this rather pressing problem.

By using HEMT we can receive TV programs from satellites 36,000Km above the ground. The antenna used for this type of broadcasting, is less than 30 centimeters in diameter, and can be set on the roof or the veranda with ease. Accordingly, it has proven to be very popular. Figure 2 shows schematically an example of a DBS receiver. HEMT made its way into our homes. HEMT also made its way into the homes of the East Europeans. The collapse of the Berlin Wall in 1989 is said to have been brought about by internal pressure built up by dissatisfied East Europeans who were exposed to Western information made available through satellite broadcasting using our HEMTs.

It is written in the Analects of Confucius, the ancient Chinese philosopher, that "A youth is to be regarded with respect. How do we know that his future capabilities will not exceed the ones we possess at present?" I interpret this to mean that, "A youth is always capable of new thinking. Leave them to think." We should expect much from young researchers and engineers. Recently, we have been exposed to criticism whenever the economic condition of Europe and the US wasn't good and trade imbalances with Japan grew significantly. At such times, we often heard criticism to the effect that "The principle function of products is conceived in Europe or the US, and after the workings of such products becomes clear, they end up being produced in Japan." While this idea can be debated, it is time for Japanese companies to seek the free and open exchange of ideas with the West.



Fig.2 an example of a DBS receiver

This is the best way to promote, on both sides, the maximum opportunity for new functions to be realized. This must be done, of course, within a framework that respects each side's intellectual property.

6. Epilogue

Some persons feel disappointed that people aren't trained to be creative in Japan. But I disagree. While it will be necessary to encourage more creativity in the education system, to look positively on one's differences with others from childhood, many promising persons have made it through the current system successfully. If we accept their interesting points of view, and prepare circumstances that will present them with opportunities to use their talents in fields that require creativity, Japanese creativity will be encouraged and flourish.

By the way, in 1990, the above-mentioned Dr. Mimura, the inventor of HEMT, received from IEEE the "Morries.N.Liebmann Memorial Prize " which is awarded to contributors to the progressive technique development in the field of electronic devices. As you may know, IEEE is a world-famous electric and electronic association. Dr. Yokoyama, who developed a new

electrode structure of the GaAs LSI, received the same prize in 1998. There have been only eight Japanese winners of this prize, and of those only two-Mimura and Yokoyama-work in private industry.

In October 1979, we took over all of the functions related to compound semiconductors within Fujitsu. These include development, production, and sales. These function were taken over by the new Fujitsu Quantum Devices Limited (FQD), which was established at this time. Our products are indispensable to this high speed network system market, microwave devices, opto-electronics devices and super high speed GaAs LSIs. While each of these represents a niche market, we hold a high position (1st,2nd,or 3rd) in terms of global market share for each category. We are determined to continue as the worldwide leader in the development of compound semiconductor devices and succeed as a business by translating such developments into practical and affordable products.

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