Special Contribution
Invention of High Electron Mobility Transistor (HEMT) and Contributions to Information and Communications Field

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1. Introduction

More than 30 years have passed since Fujitsu's announcement of the high electron mobility transistor (HEMT) in 1980.[1] Since then, the HEMT has achieved widespread use as a fundamental technology driving innovation in the field of information and communications. Applications include satellite broadcasting receivers, mobile phone systems, millimeter-band automobile radar, GPS navigation systems, and broadband wireless access systems. Furthermore, with a goal to achieve even higher speeds in information and communication technologies in the future, HEMT R&D is becoming extremely active throughout the world. Today, in addition to conventional gallium arsenide (GaAs) HEMTs, the development of ultra-high-frequency indium phosphide (InP) HEMTs[2),3)] and low-power/high-efficiency gallium nitride (GaN) HEMTs[4)] is progressing.

In this paper, I would like to present a retrospective on HEMT R&D based on my personal experiences from its invention to commercialization. I will explain some background on its invention and describe factors that contributed to its successful implementation.

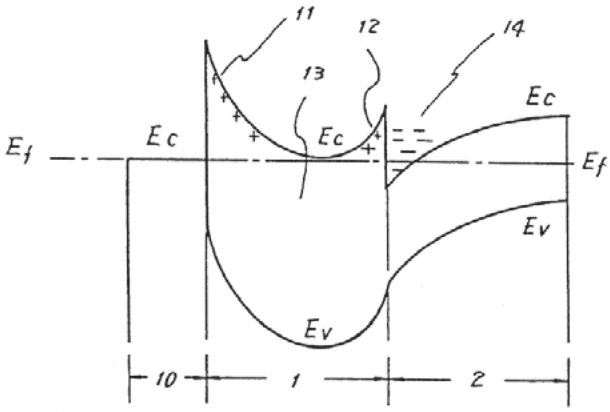
2. Idea of HEMT

During the initial development of the HEMT in 1979, I belonged to a research group developing GaAs metal semiconductor field effect transistor (MESFET) devices. The GaAs MESFET invented by C. A. Mead in 1966 is a high-speed device featuring extremely high cost performance.[5)] For me, who was pursuing high-speed devices, I wondered whether improving the GaAs MESFET was the only work left. However, I was not interested in any follow-up research themes, so I participated in research on the GaAs metal oxide semiconductor field effect transistor (MOSFET) for about two years. The MOSFET is widely known as an indispensable device for LSIs, and the purpose of my research was to explore the possibility of achieving LSIs with GaAs MOSFETs. Specifically, my aim was to eliminate the interface state near GaAs and the gate oxide film to achieve an electron accumulation layer. Unfortunately, despite a number of attempts with a variety of techniques, I could not decrease the interface state density to a level that would cause accumulation to occur.

Consequently, in February 1979, concerned about continuing GaAs MOSFET research, I developed an interest in a "modulation-doped superlattice structure," in which donor-doped aluminum gallium arsenide (AlGaAs) layers and non-doped GaAs layers are alternately stacked. In this structure, electrons accumulate in the non-doped GaAs layer between n-type AlGaAs layers on both sides. This phenomenon would make sense for researchers in this field, however for me, this was a surprise. This was because it was clear there was an accumulation of electrons here, which is something that I could not achieve in GaAs MOSFETs. I was quite impressed, however, since this was a phenomenon in a modulation-doped superlattice structure that I was not especially familiar with, no ideas came to mind at that time.

I conceived the idea of the HEMT in July 1979. My aim here was to establish a heterojunction structure between n-type AlGaAs and GaAs layers while introducing a Schottky barrier junction at the surface of the n-type AlGaAs layer to create a depletion layer. This scheme eliminated electrons within the n-type AlGaAs layer and enabled a field effect to govern a 2D electron gas within the GaAs layer.

Figure 1 shows the energy band diagram expressing the HEMT operating principle as it appeared in the patent specification. If we treat the depleted n-type AlGaAs layer as a gate-insulating film in the manner of silicon dioxide (SiO_2), the device concept of the HEMT can be understood to be structurally similar to the MOSFET. At the same time, the Schottky barrier junction used to deplete the n-type AlGaAs layer has the function of the gate electrode in GaAs MESFETs.



Source: Journal of the Institute of Image Information and Television Engineers, Vol. 52, No. 4 (1998)

Figure 1
HEMT energy band diagram.

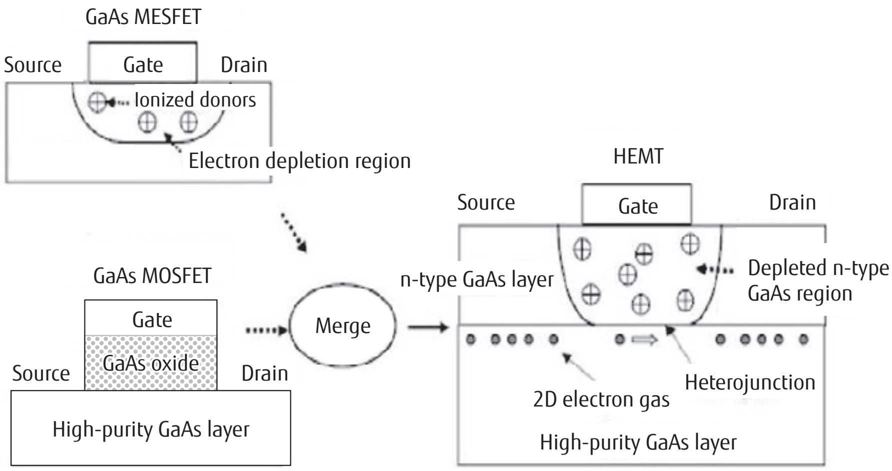
Merging existing device concepts embodied by GaAs MESFET and MOSFET formed a new type of junction, resulting in the creation of a new device concept called the HEMT (**Figure 2**).

3. Demonstration of HEMT operation

An idea by itself is no more than a fantasy—it is meaningless if it cannot be shown to be feasible by experiment. Such experimental verification requires a variety of techniques. In setting out to construct an HEMT prototype, an advanced crystal growth technique was indispensable. At that time, however, I was working in a department developing devices, and there were no techniques available for fabricating crystal at the level of precision required for HEMTs.

The 2D electron gas serving as the HEMT current channel lies near the GaAs and AlGaAs heterojunction. It is a small region having the breadth of an electron wave function, or in terms of atomic layers, an extremely narrow region of a dozen of atomic layers. Consequently, for crystal growth, there was a need for a technique having precise control to create a heterojunction on the order of atomic layers. At that time, however, molecular beam epitaxy (MBE) was the only method that could satisfy such a demanding level of precision.

MBE has two key features: a crystal growth rate that, at approximately one atomic layer per second, is



Source: IEICE Transactions Vol. J100-C, No. 10 (2017)

Figure 2
HEMT creation from merging existing device concepts.

more than ten times slower than that of conventional crystal growth methods; and the use of mechanical shutters that enables successive growth of different types of semiconductors.

I therefore sought out the cooperation of an MBE group outside my department and established an HEMT prototype "circle," consisting of only of two researchers from the MBE group and myself, the former of whom participated out of personal interest. We were able to initiate research activities through this format of an informal prototype circle, which I believe was one important factor in our successful development of the HEMT. If this work had been taken up as an official research theme at the idea stage, I think it would have been exposed to various types of interference while losing flexibility in development activities, all of which could have increased the risk of failure.

Immediately after starting up this prototype circle, I received a letter. To my surprise, it was from Dr. R. Dingle of Bell Laboratories, the author of papers on modulation-doped superlattices, who expressed a desire to talk with me about the GaAs MOSFETs that I had been researching. He visited Fujitsu Laboratories on August 30, 1979. We discussed his modulation-doped superlattice and our MOSFETs, but our work on HEMT development that we had just started was naturally confidential. To my relief, I learned through these discussions that they had not yet reached the point of having a clear device concept of the HEMT.

However, in early September soon after his visit, I learned from the program of that year's GaAs IC Symposium that his group was announcing experimental results on the control of electrons in a modulation-doped superlattice. Clearly, they were moving in the direction of research pointing to some type of device. Presumably, it was something different from the HEMT, but I could not help but feel that they could become a formidable competitor in this area.

This prompted us to step up our research. In November 1979, the technical level of the MBE group caught up with that of Dr. Dingle's group. In addition, as head of the device fabrication process at that time, I was faced with difficulties in etching technology. Operation of an HEMT device requires a semiconductor layer only a few nm thick sandwiched between the gate electrode and heterojunction interface. However, given the technology at that time, this would require etching at an unbelievably high level of precision. We therefore prepared a variety of etching solutions and tried them out with a series of simple experiments, but reproducibility of etching precision was still a problem.

We decided not to miss the most honorable moment of announcing the first HEMT device by taking too much time to improve the device fabrication process. We therefore decided to put aside this problem of reproducibility for the time being and start working on a prototype. We were intent on realizing a functioning HEMT before our competitor, and to this end, even a single working prototype would suffice. Towards the end of December 1979, after two or three failures, we succeeded in finding a chip operating as an HEMT in a low-yield wafer. This took place about four months after forming our informal HEMT prototype circle.

The results of this HEMT research were presented at the 38th Device Research Conference (DRC) held in June 1980. After giving my presentation, I was handed a document by a researcher unknown to me. To my surprise, it was a copy of a paper on a device similar to our HEMT (called an "inverted HEMT" in which the HEMT AlGaAs and GaAs layers were upside down). Listening to what he had to say later, I found out that he was a researcher at the Thompson-CSF company in France and that, much to his disappointment, they had been beaten by our presentation. At any rate, we were the first to be recognized for the invention of the HEMT, but only by a hair. This type of occurrence happens frequently in competitive technology development. It is essential that the existence of a strong competitor be considered and never ignored.

4. Achieving practical HEMTs

The HEMT began to show signs as a potential high-frequency device soon after its creation. As I mentioned above, however, etching technology and other techniques that could achieve precise control of device dimensions were still immature. As a consequence, I myself was unsure as to whether we could achieve crystal growth to the point of a practical device. I feared that our device would simply become a "laboratory curiosity" without ever reaching the production stage. I was the only one in charge of the device fabrication process, but I was unable to resolve this low reproducibility of the HEMT prototype process.

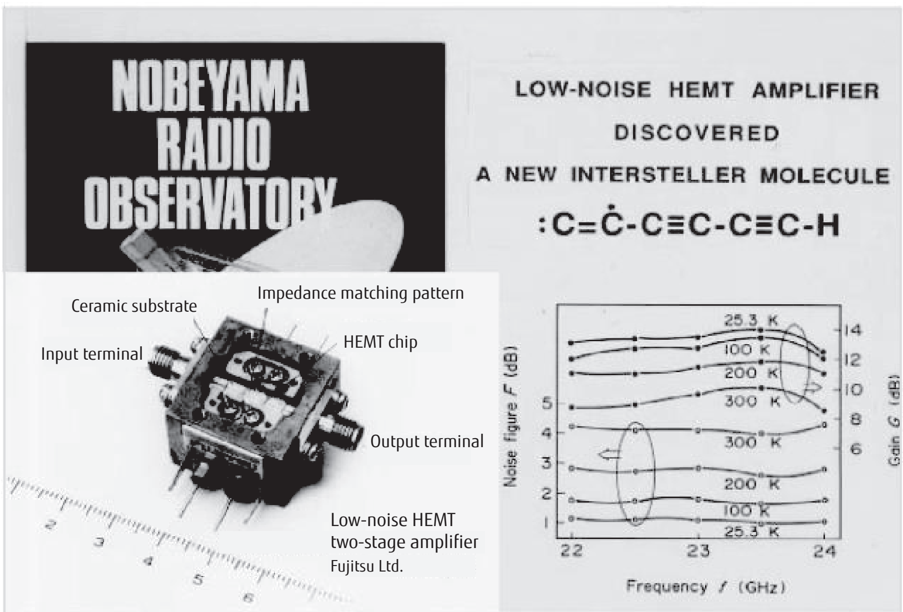
An HEMT features an extremely thin AlGaAs layer under the control electrode, and the desired threshold voltage must be obtained by controlling the thickness of this layer with a precision of several atomic layers. However, since AlGaAs includes Al, it is extremely active compared with GaAs. As a result, simply exposing AlGaAs to air will cause natural oxide film consisting mostly of Al_2O_3 (aluminum oxide) to form on its surface, thereby changing the thickness of the AlGaAs film. This phenomenon was truly fatal for achieving a practical HEMT device.

The breakthrough to this difficult technical problem arrived in the structure of a GaAs cap layer deposited on the AlGaAs layer and the use of reactive ion etching (RIE) technology. Specifically, the GaAs cap layer would protect the AlGaAs surface from oxidation and an RIE process would be used to selectively remove only the electrode portion of the cap layer prior to setting the control electrode. In this way, we thought that high precision in the thickness of the AlGaAs film could be maintained during crystal growth, thereby greatly simplifying HEMT fabrication. This method could be used since the HEMT is fabricated from AlGaAs and GaAs, two types of materials with chemically different properties. In the end, this technology enabled us to produce HEMT devices with uniform characteristics and good reproducibility for the first time, which helped to strengthen our conviction that our HEMT could be a practical device.

5. Commercialization of HEMT

The commercialization of our HEMT unexpectedly took place at the IEEE International Solid-State Circuits Conference (ISSCC) held in 1983. It was here that a person associated with the National Radio Astronomy Observatory (NRAO) in the United States took notice of our presentation on an HEMT low-noise 4-stage amplifier[6] for application to satellite communications in the microwave band. The reason for this interest was that the noise characteristics of the presented HEMT in a low-temperature environment that could replace existing parametric amplifiers or GaAs MESFET amplifiers. Taking this opportunity, low-noise amplifiers for radio telescopes became the first HEMT target product.

In this regard, the HEMT amplifier installed at the Nobeyama Radio Observatory of the National Astronomical Observatory of Japan in 1985 contributed to the discovery of an unknown hydrocarbon molecule in a dark nebula (**Figure 3**).[7] This was followed by the installation of HEMT amplifiers in major radio



Source: Society of Semiconductor Industry Specialists, Encore, No. 66 (2010)

Figure 3
Low-noise HEMT amplifier for radio astronomy (first commercial product) and noise characteristics.

observatories around the world. In this way, a fortunate discovery in the early stages of development of even a niche market that could leverage HEMT performance under low-temperature conditions became an extremely important step toward innovation in HEMT development. The emergence of this market initiated business activities, which in turn enabled successive improvements to device-related technologies. It also helped to enhance competitive power in the market with respect to existing GaAs MESFET technology and to pave the way to new application fields.

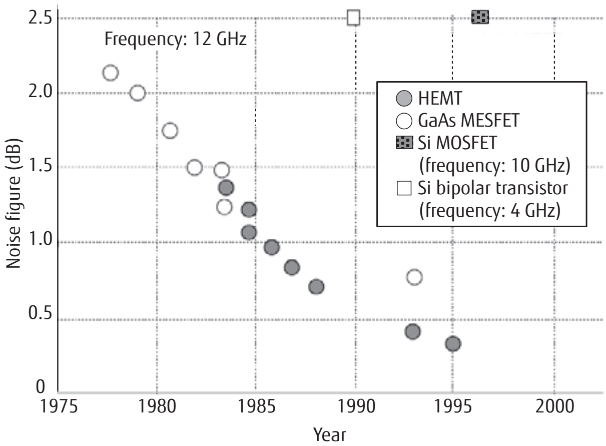
6. Widespread use of HEMTs

The use of HEMTs began to take off in 1987 when they came to replace conventional GaAs MESFETs as low-noise amplifiers in converters for satellite broadcast receivers. The use of HEMTs enabled parabolic antennas to be downsized to less than half of the conventional ones and contributed to the explosive growth of satellite broadcasting in Japan, Europe, and elsewhere.

To give some background to this rapid spread of HEMTs, the development of mass-production process technologies unique to HEMTs such as selective dry etching made a big contribution in addition to high-quality crystal growth techniques and high throughput. Furthermore, as another important factor, base technologies used in GaAs MESFET development such as circuit design technologies and measurement evaluation technologies could be used in practically the same form in HEMT development. This made for extremely efficient gains in performance as in factor analysis for achieving low-noise HEMTs. Changes in GaAs MESFET and HEMT noise figures over time at 12 GHz (satellite broadcasting frequency) are plotted in **Figure 4**. Noise figures for Si bipolar transistors and Si MOSFETs at different frequencies are plotted for reference.

At the 1983 time point, there was no significant difference in performance between HEMTs and GaAs MESFETs. Later, however, as HEMTs began to be evaluated by users, progress in low-noise technology accelerated due to user feedback as well as economic market principles. As a result, the HEMT minimum noise figure dropped to approximately 0.3 dB and the downsizing effect in parabolic antennas used for receiving satellite broadcasts reached its limit, both of which contributed greatly to the expansion of satellite broadcasting.

Another feature of HEMTs is the ability to be applied to a variety of compound semiconductors. In addition to conventional GaAs HEMTs, the research and development of ultra-high-frequency HEMTs using InP and high-efficiency/high-output HEMTs using GaN is progressing at a lively pace. It is expected that InP-type HEMTs will be applied to high-speed downloaders,[note)] image sensing used in security checks, etc., and other applications that can make use of their ultra-high-frequency characteristics. As for GaN-type HEMTs, they are already being used in base stations for mobile phones and contributing to power savings and downsizing. Going forward, we can expect HEMTs to be applied to millimeter-wave wireless communications in fifth-generation (5G) mobile communications and to power supplies for servers.



Source: IEICE Transactions Vol. J100-C, No. 10 (2017)

Figure 4
Transition in HEMT and GaAs MESFET noise figures at 12 GHz.

7. Conclusion

In this paper, I explained some background to the invention of the HEMT that I personally experienced and described the history of its commercialization.

The contents of the individual themes presented

note) KIOSK-type equipment from which large volumes of data, such as 4K/8K video, can be download to a smartphone at a high speed of tens of Gbps through close contact with the equipment and smartphone.

in this paper, while naturally unique to HEMT development, are somewhat universal in nature as they have much in common with past examples of technology development. The essence of the idea behind the HEMT is the merging of existing concepts. In this regard, I believe that the ability to find ways of merging existing concepts is a form of creativity. I also feel that I have been able to nurture my creative abilities through many and varied experiences including failures.

As young researchers confront future challenges in this field, I expect the HEMT to become an increasingly popular device that drives innovation not only in information and communications and the high-efficiency use of energy but also in medical treatment, borderless wireless communications including outer space applications, and other fields.

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