The Early History of the High Electron Mobility Transistor (HEMT)

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Invited Paper

***Abstract*—The early history of the high electron mobility transistor contains a good illustration of the way a new device idea happens and develops toward commercialization. These events that took place in our laboratory are described in this paper.**

***Index Terms*—Cryogenic low-noise amplifier, depletion-mode HEMT, enhancement-mode HEMT, GaAs MESFET, GaAs MOSFET, HEMT, HEMT IC, high electron mobility transistor, inverted HEMT, radio telescope.**

I. Path to High Electron Mobility Transistor Ideas

WHEN THE high electron mobility transistor (HEMT) idea occurred to me in 1979, I belonged to a section that developed GaAs MESFETs. I was researching GaAs MOSFETs. The research was motivated by the expectation that GaAs MOSFETs would offer high-speed performance superior to that of Si MOSFETs. My primary intention was to demonstrate inversion- or accumulation-type n-channel devices. To do so, my colleague and I developed a low-temperature plasma oxidation technique to grow a stoichiometric native oxide of GaAs. Results, however, were discouraging. No electron inversion or accumulation was possible with the GaAs MOS system. High density of the surface states near the interface captured electrons, thus, there was no accumulation of electrons. I had worked for about two years on improving the interface, but without much success. In the spring of 1979, interesting work of a somewhat different technical field was brought to my attention. This was the modulation-doped heterojunction superlattice developed by Dingle *et al.* at Bell Laboratories, Murray Hill, NJ [1]. The superlattice consisted of many alternate thin layers of n-type AlGaAs and undoped GaAs. With this technology, electrons supplied by donors in the AlGaAs layers move into the GaAs potential wells, suffer less from ionized donor scattering, and achieve high mobility. More impressive, however, was that electrons accumulated in undoped GaAs potential wells. This was significant because, as noted earlier, I had failed to achieve electron accumulation in the GaAs MOS system. Although impressive, the technology was unfamiliar and did not jog me with any new ideas at the time.

A few months later in June 1979, I presented a paper on depletion-type GaAs MOSFETs at the 37th Device Research Conference. Due to the low density of surface states near the bandgap center, the surface Fermi level was movable within a narrow energy range of the bandgap. Therefore, depletion-type MOSFETs operated by modulating the width of a depletion region in a doped bulk channel. While talking with a conference attendee immediately after my presentation at the conference, I was suddenly seized by the will to look for ways to control electrons accumulated in the superlattice. Although I cannot exactly explain this unexpected change of direction, it probably came about because I had wanted to research more feasible subjects than GaAs MOSFETs.

For the next two or three weeks, I concentrated my thoughts on the superlattice structure hoping for creative ideas. I came up with the idea of using a field effect to control electrons at the interface of a single heterojunction consisting of a pair of undoped GaAs and n-type AlGaAs; the field from a Schottky gate placed on the AlGaAs surface controls the electrons at the interface. Fig. 1 presents my sketch depicting the device principle of HEMTs, which was submitted to the patent division of our company on August 16, 1979. Based on this sketch and an additional memorandum, a patent was completed and filed at the end of the same year [2].

The sketch shows how the energy band diagram of the system changes with the n-type AlGaAs layer thickness. Where AlGaAs is thick, as in the leftmost drawing of Fig. 1, there are three regions in the n-type AlGaAs layer: the surface depletion region formed by a Schottky junction, a charge neutral region, and the interface depletion region at the heterojunction. In this configuration, we cannot fully control the electron accumulation layer because the charge neutral region effectively shields the electric field from the gate. Due to this limitation, successful HEMT operation is not possible. With AlGaAs of medium thickness, as in the middle of Fig. 1, the two depletion regions merge, the entire AlGaAs layer is depleted, and the electron accumulation layer remains at the interface. In this profile, the electric field from the gate reaches and controls the electron accumulation layer at the interface. This results in depletion-mode HEMTs (called D-HEMTs). The first demonstration of D-HEMTs was published in May 1980 [3]. When the AlGaAs is thin, since the pinning point of the Fermi level on the AlGaAs surface is below the conduction band of the GaAs layer, the electron accumulation layer disappears, as shown in the rightmost drawing. When positive gate voltages higher than the threshold voltage are applied, an electron accumulation layer is induced at the interface. This explains the operation principle of enhancement-mode HEMTs (called E-HEMTs). The first re-

Manuscript received June 20, 2001.

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Publisher Item Identifier S 0018-9480(02)01993-2.

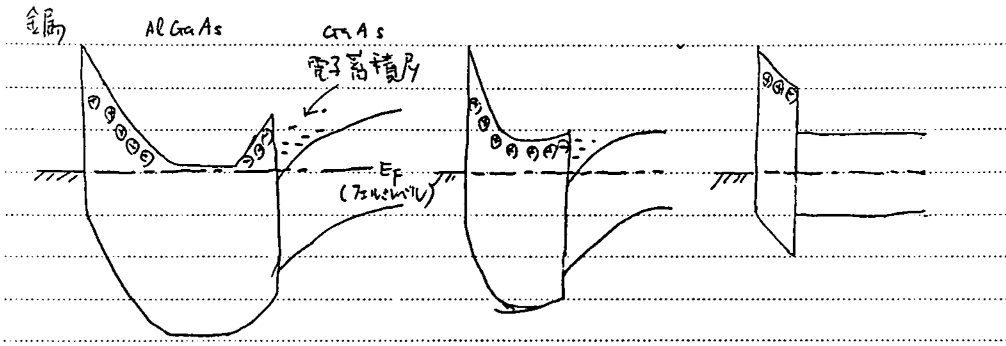

Fig. 1. Sketch of the energy band diagrams explaining the operation principle of HEMTs.

port on E-HEMTs was presented in August 1980 [4], [5]. Since the E-HEMT requires only a single positive voltage, circuitry is simple. This feature gives E-HEMTs an advantage in such applications as mobile phone power amplifiers and digital integrated circuits.

Taking into account that the depleted AlGaAs can be considered a gate insulator in a MOSFET, it is easy to see that the device concept of the HEMT is similar to that of a MOSFET. It may even be the case that our failure to develop accumulation-type GaAsMOSFETs contributed most to the invention of HEMTs. Failures sometimes sharpen our attention, prodding us to find something valuable in everyday incidents, such as reading papers and talking with others.

II. Implementation

A few weeks after I completed the HEMT idea, I explained it to a colleague who was working on MOCVD in the same laboratory, and expected his cooperation. He reasoned, however, that the HEMT structure I proposed was beyond the scope of MOCVD at that time and declined to cooperate in growing the structure. On August 7, 1979, I introduced the idea to people working on molecular beam epitaxy (MBE) in a different section of our laboratories. The MBE group agreed to cooperate in growing the heterostructures. Around that time, they were eagerly searching for device applications for their technology, since they were struggling to convince company management of the importance of their MBE research. A number of companies in Japan had already stopped MBE research because it lacked promise in device applications. That lack of promise was why our HEMT development team was successfully formed; it was also why our team was strongly motivated to bring HEMT to reality. I received a letter immediately after the development team was formed. To my surprise, it was from Dingle. He wanted to discuss GaAs MOSFETs and came to visit us on August 30, 1979. We discussed his modulation-doped superlattice and our MOSFET. Naturally, I kept our activity on the HEMT development confidential and did not discuss it. Through our discussions, I felt secure that his group had not come upon a device concept like the HEMT. However, at the beginning of September 1979, I learned from the program of the GaAs IC Symposium that same year that his group would release the results of their experiments in controlling electrons in the modulation-doped superlattice. I believed that the device differed from HEMT, but knew his group would be a tough competitor.

This event accelerated our activity. By around November 1979, our MBE technique had improved to the level of growing the high-quality epilayers required for HEMT structures. Before that, a problem arouse as to which structure would have priority for development. I had an idea for another possible structure, which is now called an "inverted" HEMT, in which a Schottky gate is placed on the undoped GaAs channel layer grown over the doped AlGaAs layer. Putting aside the relative advantages of potential ultimate performance from each type of structure, it was enough at the initial stage of development to check the minimum characteristics required of an FET. From this perspective, both types of structures seemed to have equal possibility of implementation. I chose the "inverted" HEMT for priority development. What brought me to this decision was simple: the device structure of an "inverted" HEMT is similar to that of a conventional GaAs MESFET, which was very familiar to me. We grew the "inverted" structure on November 13, 1979, and then fabricated a device for two days. The structure did not, however, exhibit any FET characteristics, and the result was a complete failure. We thought the failure might be caused by errors in the manufacturing process and attempted fabrication again with almost the same structure. The result was the same. In spite of investigating possible causes for the failure, we were unable to determine the actual cause. I then decided to avoid taking too much time at this stage so as not to miss the chance of being the first to release an HEMT. I declared a moratorium on the "inverted" structure and turned to the "normal" HEMT structure.

On December 24, 1979, we completed crystal growth of the structure, and finally obtained several operational HEMT chips on a low-yield wafer at the end of December of that same year. This was about four months after our HEMT development team was formed. Fig. 2 is a photograph of Satoshi Hiyamizu, leader of the MBE group, and Takashi Mimura testing the first HEMT integrated circuits [6] in 1981. Incidentally, we do not know why the "inverted" structure failed. I think it probably had something to do with the quality of the interface of the "inverted" structure grown by our MBE machine at that time. The first report on the "inverted" HEMT was given by Delagebeaudeuf *et al.* at Thomson-CSF, Orsay, France, in August 1980 [7].

III. First User

Commercialization of HEMTs significantly increased in Japan and Europe around 1987 when HEMTs began to replace GaAs MESFETs in broadcasting satellite receivers. HEMTs made it

Fig. 2. My colleague, Satoshi Hiyamizu, and Takashi Mimura testing the first HEMT IC.

possible to reduce the size of a parabolic antenna by one-half or more. This particular opportunity for commercialization, however, was not in the original plan. Early HEMT technology was still in a primitive stage of development, thus, it had many weak points, especially from the standpoint of cost performance. Our marketing studies led us to decide that HEMTs were best suited for applications in the microwave satellite communications field. We, therefore, developed a prototype HEMT amplifier for satellite communications and introduced it at the 1983 International Solid-State Circuit Conference [8]. When my colleague returned to his seat at the end of his talk, a conference attendee asked to buy the HEMT that had just been presented. That person was doing work for a radio astronomical observatory. The HEMT amplifier seemed efficient enough to detect weak microwave signals from dark nebula.

Soon after this unexpected event, Nobeyama Radio Observatory (NRO), Nagano, Japan, also asked our factory division to develop low-noise HEMT amplifiers. Fig. 3 shows the first HEMT used commercially as a cryogenic low-noise amplifier. This amplifier was installed in the NRO 45-m radio telescope in 1985. In 1986, the telescope equipped with the HEMT amplifier discovered new interstellar molecules in the Taurus Molecular Cloud about 400 light years away [9]. In detecting very weak microwave signals from the molecules, people at the NRO continued observing the signal for 150 h. The amplifier must be very stable for such prolonged observation. Stable operation is the top priority for radio telescopes and was a significant HEMT strong point at that time, compared to the parametric amplifiers being used. After discovery of the new interstellar molecule at NRO, HEMTs were successfully installed in radio telescopes throughout the world.

After being introduced to the marketplace, HEMT technology started to receive feedback from the marketplace. People wanted higher performance and less expensive HEMTs. Responding to these demands, many electronics companies invested in the technology and, eventually, the cost-performance of the HEMT improved. Since then, the HEMT has found wider and wider applications.

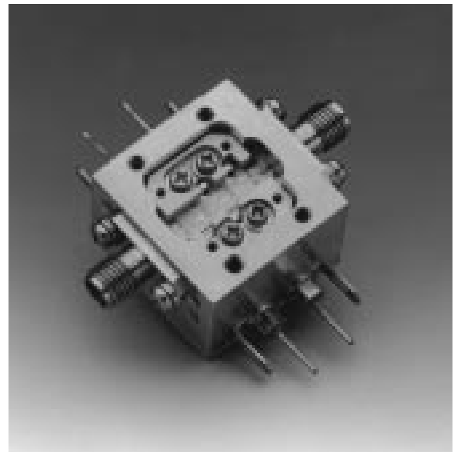

Fig. 3. First commercial HEMT: a cryogenic low-noise amplifier for the radio telescope at Nobeyama Radio Observatory, Nagano, Japan.

References

[1] R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegmann, “Electron mobilities in modulation-doped semiconductor heterojunction superlattices,” *Appl. Phys. Lett.*, vol. 33, no. 7, pp. 665–667, 1978.

[2] T. Mimura, “Semiconductor device,” Japanese Patent 1 409 643, Nov. 24, 1987.

[3] T. Mimura, S. Hiyamizu, T. Fujii, and K. Nanbu, “A new field-effect transistor with selectively doped GaAs/n–$Al_xGa_{1-x}As$ heterojunctions,” *Jpn. J. Appl. Phys.*, vol. 19, no. 5, pp. L225–L227, 1980.

[4] T. Mimura, S. Hiyamizu, H. Hashimoto, and H. Ishikawa, “An enhancement-mode high electron mobility transistor for VLSI,” in *Proc. 12th Solid-State Devices Conf.*, Tokyo, Japan, Aug. 1980, p. 364.

[5] ——, “An enhancement-mode high electron mobility transistor for VLSI,” *Jpn. J. Appl. Phys.*, vol. suppl. 20-1, p. 364, 1981.

[6] T. Mimura, K. Joshin, S. Hiyamizu, K. Hikosaka, and M. Abe, “High electron mobility transistor logic,” *Jpn. J. Appl. Phys.*, vol. 20, no. 8, pp. L598–L600, 1981.

[7] D. Delagebeaudeuf, P. Delescluse, P. Etienne, M. Laviron, J. Chaplart, and N. T. Linh, “Two-dimensional electron gas MESFET structure,” *Electron. Lett.*, vol. 16, no. 17, pp. 667–668, 1980.

[8] M. Niori, T. Saito, K. Joshin, and T. Mimura, “A 20 GHz high electron mobility transistor amplifier for satellite communications,” in *Int. Solid-State Circuits Conf. Tech. Dig.*, 1983, pp. 198–199.

[9] H. Suzuki, M. Ohishi, N. Kaifu, S. Ishikawa, and T. Kasuga, “Detection of the interstellar C_6H radical,” *Publ. Astron. Soc. Japan*, vol. 38, pp. 911–917, 1986.

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In 1970, he began his professional career as a Technical Staff Member with Fujitsu Ltd., Kobe, Japan, where his research centered around the development of microwave Si bipolar transistors and GaAs power MESFETs. In 1975 he joined Fujitsu Laboratories Ltd., Kawasaki, Japan, where he was involved with III–V compound semiconductor high-frequency high-speed devices including the heterostructure HEMT. He is currently a Fellow of Fujitsu Laboratories Ltd.

Dr. Mimura is a Fellow of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of many awards for his pioneering work on HEMTs, including a 1998 Purple Ribbon Medal presented by the Japanese Government, the 1998 H. Welker Award presented at the International Symposium on Compound Semiconductors, the 1992 Imperial Invention Prize presented by the Japan Institute of Invention and Innovation, and the 1990 IEEE Morris N. Liebmann Memorial Award.