Japanese Journal of Applied Physics

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To cite this article: Takashi Mimura 2005 *Jpn. J. Appl. Phys.* **44** 8263

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Japanese Journal of Applied Physics
Vol. 44, No. 12, 2005, pp. 8263–8268
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Invited Review Paper

Pioneering Contributions to Applied Physics in the Last Half Century

Development of High Electron Mobility Transistor

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(Received June 16, 2005; accepted August 6, 2005; published December 8, 2005)

The development of the high electron mobility transistor (HEMT) provides a good illustration of the way a new device emerges and evolves toward commercialization. This article will focus on these events that the author feels might be of interest to young researchers. Recent progress and future trends in HEMT technology are also described.
[DOI: 10.1143/JJAP.44.8263]

KEYWORDS: high electron mobility transistor (HEMT), HEMT IC, E-HEMT, D-HEMT, inverted HEMT, GaAs-based HEMT, InP-based HEMT, GaN-based HEMT, modulation-doped superlattice, radio telescope

1. Introduction

It has been more than 25 years since the high electron mobility transistor (HEMT) was first proposed in 1979.[1] The key concept of the HEMT is the field-effect modulation of the high-mobility two-dimensional electron gas (2DEG) at the heterostructure consisting of one of the selectively doped semiconductor pairs, such as n-AlGaAs/GaAs and n-InAlAs/InGaAs. The first demonstration of the HEMT was made by our group in 1980.[2] In the same year, we reported the first microwave performance, which was superior to that of a GaAs metal–semiconductor field-effect transistor (MESFET).[3] Nineteen eighty-one saw the first HEMT digital integrated circuit with the highest switching speed in any semiconductor device at that time.[4] Since our demonstration, worldwide efforts to develop high-speed, high-frequency HEMTs have begun. In 1985, for the first time, HEMTs were used commercially as a cryogenic low-noise amplifier, for a radio telescope to detect microwave signals from a dark nebula, leading to the discovery of a new interstellar molecule.[5] Mass production of HEMTs for the first consumer application was started around 1986, when low-noise HEMT amplifiers were exclusively used in broadcasting satellite receivers, providing the technology a foundation for further development in microwave and millimeter-wave applications such as cell-phone handsets[6] and automotive radars.[7]

In this article, I first describe the path that led to the concept of the HEMT and then the few milestones that I feel are important in the development of HEMT technology.

2. How HEMT Emerged

The history of the development of the HEMT at our laboratories began with research into GaAs metal–oxide–semiconductor field-effect transistors (MOSFETs) in 1977. The research was motivated by the expectation that GaAs MOSFETs would offer superior high-speed performance over Si-based counterparts. At about this time, considerable research was being carried out in major semiconductor companies and universities in the United States, Europe, and especially Japan. My primary intention for the GaAs MOSFET research was to demonstrate an n-channel device, vital to high-speed LSI circuits. To do so, my colleague and I grew a stoichiometric native oxide on GaAs by low-temperature plasma oxidation. However, we found no accumulation of electrons at the interface between the oxide and GaAs, due to the high density of the surface states.

In the spring of 1979, the interesting work of a somewhat different technical field was brought to my attention. This was the modulation-doped heterojunction superlattice demonstrated by Dingle *et al.*[8] The original concept of the modulation-doped superlattice was proposed by Esaki and Tsu.[9] The superlattice consists of many alternate thin layers of n-type AlGaAs and undoped GaAs. 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, we had failed to achieve electron accumulation in the GaAs MOS system.

Inspired by the superlattice structure, I came up with the idea of using a field effect to modulate electrons at the interface of a heterostructure 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. Figure 1 shows 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.

The sketch illustrates how the energy band diagram of the system changes with the n-type AlGaAs layer thickness. When 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 barrier, 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 modulates 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.[2] When the AlGaAs layer 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

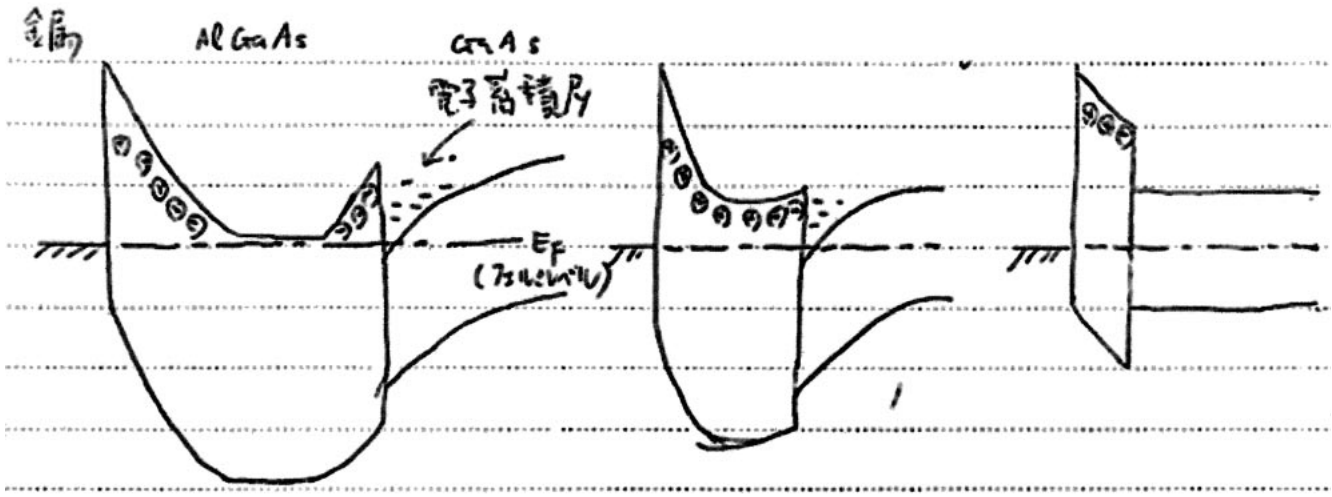

Fig. 1. Energy band diagrams explaining field-effect modulation of two-dimensional electron gas.

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 report on E-HEMTs was presented in August 1980.[10] Since the E-HEMT requires only a single positive power supply, circuitry is simple. This feature gives E-HEMTs an advantage in such applications as mobile phone power amplifiers[6] and digital integrated circuits.

After completing the HEMT idea, I explained it to a person who was working on molecular beam epitaxy (MBE) in a different section of our laboratories. The MBE group kindly agreed to cooperate in growing the heterostructures. Prior to this, I had the idea of another possible structure, which now is called an "inverted" HEMT, in which a Schottky gate is placed on the undoped GaAs channel layer grown over the doped AlGaAs layer. 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. However, the structure did not exhibit any FET characteristics, and the result was a complete failure. We thought that the failure might have been caused by errors in the manufacturing process and attempted fabrication again with almost the same structure. The result was the same. In spite of investigations on the 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 a HEMT. I declared a moratorium on the "inverted" structure and turned to the "normal" HEMT structure.

On December 24, 1979, we completed the crystal growth of the structure and finally obtained several operational HEMT chips on a low-yield wafer at the end of that same month. 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.* on August 1980.[11]

3. Integrated Circuits for High-Speed Systems

In this section, the evolution of the HEMT technology for digital IC applications is described. In 1981, the first HEMT integrated circuit was demonstrated.[4] Figure 2 shows an enlarged view of the HEMT ring oscillator, which is a conventional test circuit for measuring the switching performance of a basic logic gate. The measured switching delay was 17 ps at 77 K and, in spite of a relatively long gate length of 1.7 μm, was the shortest in any semiconductor device at that time. Since then, the levels of integration and switching performance rapidly increased. In 1983, Lee *et al.* fabricated 1-μm-gate HEMT ring oscillators and obtained a switching delay of 12.2 ps at room temperature.[12] HEMT 1 k, 4 k and 64 kbit static random-access memory (SRAM) chips were successfully developed.[13–15] The main factors that made such advances possible are as follows: First, the current-gain cutoff frequency f_T of the HEMT is much higher than that of conventional devices because of the superior transport properties of the HEMT channel. Second, the HEMT structure has an inherently large channel aspect ratio (gate length to distance between the gate and 2DEG at the heterointerface), facilitating scaling down of the device without significant short-channel effects. In a conventional FET such as a GaAs MESFET, the aspect ratio can be improved by increasing the doping level in the channel. However, high doping gives rise to an undesirable degradation of the electron mobility, and therefore, of the high-speed capability of the device. In contrast, because the 2DEG in the HEMT channel is spatially separated from donors in the AlGaAs barrier layer, the doping concentration can be increased to avoid short-channel effects without any significant decrease in electron mobility. Thus, the HEMT structure has an inherent advantage with respect to short-channel effects.

Figure 3 shows a cross section of a typical HEMT direct-coupled FET logic (DCFL) circuits, consisting of E- and D-HEMTs. The gate metal of a D-HEMT is formed on a GaAs cap layer to set the threshold voltage negative. The key process technology for the integration of E- and D-HEMTs

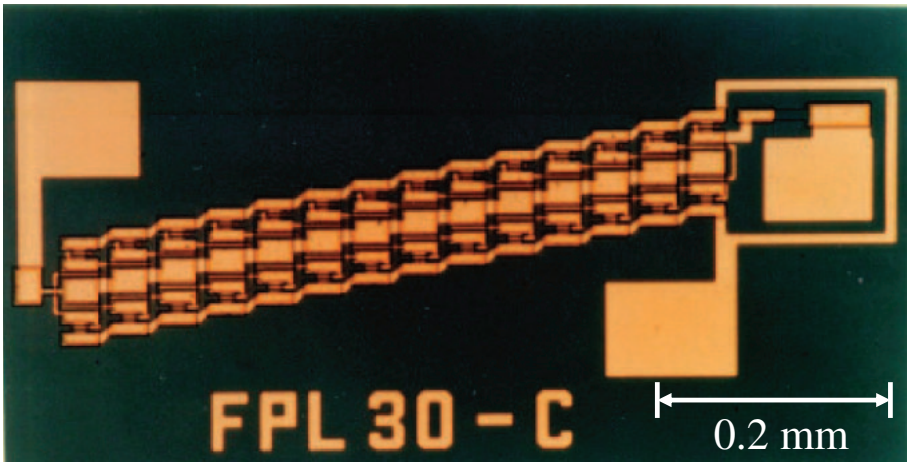

Fig. 2. First HEMT integrated circuit: 27-stage ring oscillator.

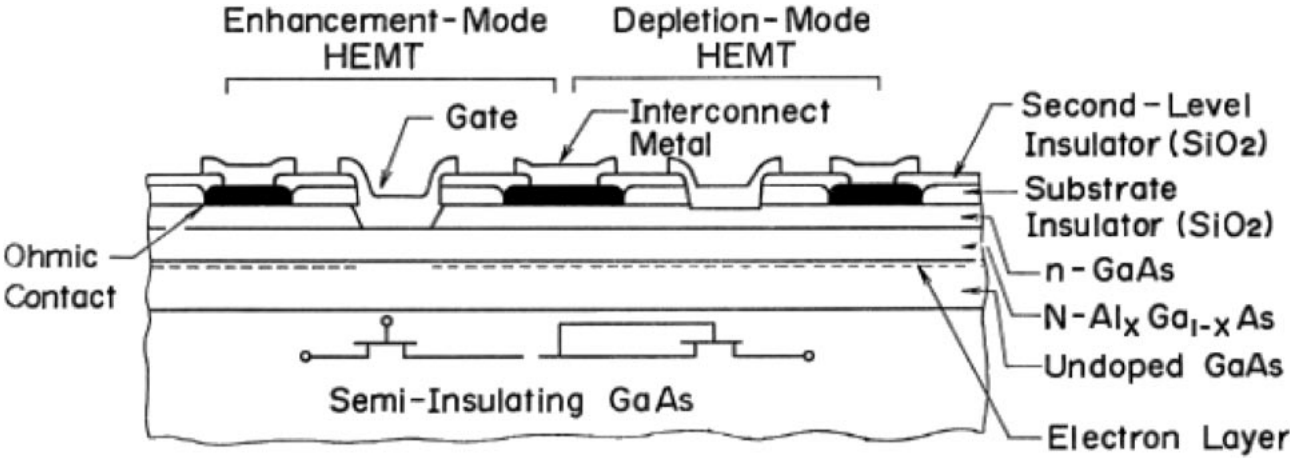

Fig. 3. Schematic cross section of logic gate consisting of E- and D-HEMTs.

in the same epiwafer is selective dry etching to achieve precise control of the threshold voltage of E-HEMTs. The GaAs cap layer was selectively removed from the gate region of E-HEMTs. Selective dry etching using CCl_2F_2 and He achieved a high selectivity ratio of more than 260.[16] Once the AlGaAs surface is exposed, the etching stops almost automatically, minimizing the threshold voltage variation of the device. Selective dry etching was really a breakthrough for LSI circuits fabrication and is mandatory for mass production of recessed gate structures widely adopted into low-noise HEMTs.

In 1988, HEMT multibit data registers[17] were developed for the supercomputer of the National Research and Development Program of Japan. Figure 4 shows the packaged HEMT multibit data register, which consists of 0.5 µm DCFL circuits (1.1 kbit gates) and measures $6.1 \times 6.2\,mm^2$. The register synchronizes the 36-bit data signals with a clock signal at high clock rates, resolving the skew problem in a high-speed parallel architecture supercomputer. Four HEMT mulitibit data registers were installed in the emitter-coupled-logic-based supercomputer system, which successfully operated with a machine cycle time well below 1 ns.[18] Figure 5 shows the packaged HEMT multibit data registers mounted on a printed circuit board of the system.

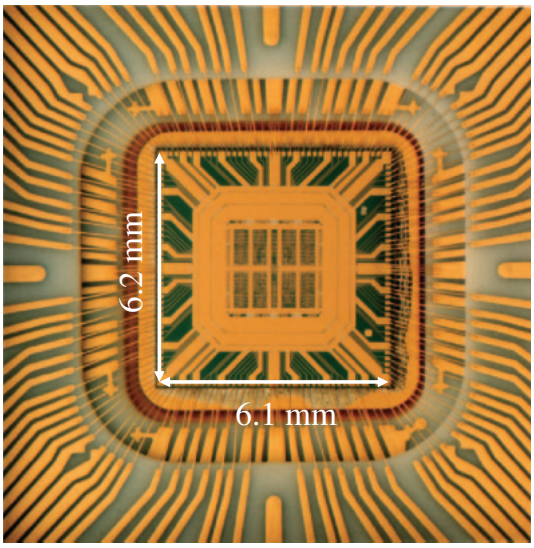

Fig. 4. Packaged HEMT multibit data register.

Recently, impressive results obtained with InP-based IC technology were reported. Suzuki *et al.* reported the highest speed ICs fabricated by a 0.10 µm InAlAs/InGaAs/InP

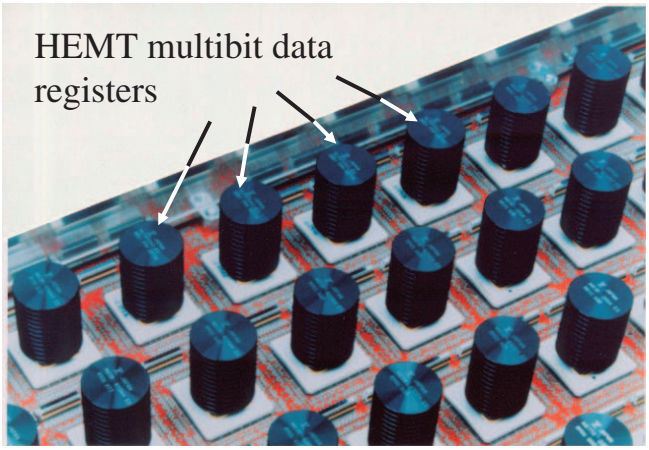

Fig. 5. HEMT multibit data registers mounted on circuit board of supercomputer.

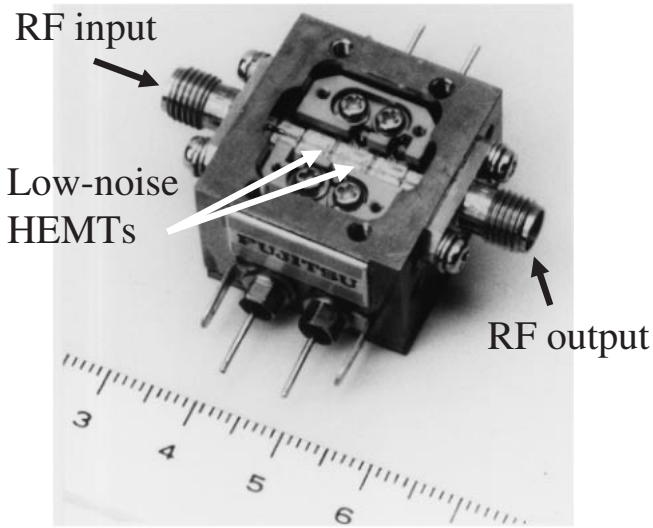

Fig. 6. First commercial HEMT: cryogenic low-noise amplifier for radio telescope at Nobeyama Radio Observatory.

HEMT technology, achieving 144 Gbit/s operation in a selector circuit and 100 Gbit/s operation in a 4 : 1 multiplexer.[19] Murata *et al.* also demonstrated 100 Gbit/s multiplexing and demultiplexing operation using production-level InP-based HEMT technology.[20] These performances are very promising for future high-speed optical communication systems.

4. Early Commercialization

Commercialization of HEMTs significantly increased in Japan and Europe around 1987 when HEMTs began to replace GaAsMESFETs in broadcasting satellite receivers. HEMTs made it possible to reduce the size of a parabolic antenna by one-half or more. However, this particular opportunity for commercialization was not in the original plan. Early HEMT technology was still in a primitive stage of development; 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.[21] When my colleague returned to his seat at the end of his talk, a conference attendee offered to buy the HEMT that had just been presented. That person was doing work for a radio astronomical observatory. The cryogenic noise performance of the HEMT amplifier seemed efficient enough for detecting weak microwave signals from dark nebulae.

Soon after this unexpected event, people at Nobeyama Radio Observatory (NRO), Nagano, Japan, also asked our factory division to develop low-noise HEMT amplifiers. Figure 6 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 Taurus Molecular Cloud about 400 light-years away.[5] In detecting a very weak microwave signal from the molecules, people at NRO continued to observe 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 with the parametric amplifiers being used. After discovery of the new interstellar molecule at NRO, HEMTs were successfully installed in radio telescopes throughout the world. Cryogenically cooled HEMT low-noise amplifiers have been continuously improved. InP-based HEMTs are now coming close to competing with the microwave amplification by stimulated emission of radiation (MASER). At the X-band (~8.4 GHz), an InP-based HEMT cooled to 6 K had a noise temperature of 4.5 K and the MASER had a noise temperature of 2 K when cooled to liquid He temperature.[22]

After being introduced to a small marketplace, HEMT technology gradually attracted the attention of potential users in many different fields of application. Potential customers wanted higher-performance and less-expensive HEMTs. Responding to these demands, many companies invested in HEMT-related technologies. MBE machine vendors started to develop mass-production systems, and a high-throughput metal-organic chemical vapor deposition (MOCVD) growth technique was successfully developed. A recessed-gate structure, which was originally developed to demonstrate the E-HEMT,[10] was adopted to reduce parasitic access resistance.

The minimum noise figure $F_{\min}$ for microwave FETs can be described as[23]

$$F_{\min} = 1 + K(f/f_T)\{g_m(R_s + R_g)\}^{1/2},$$

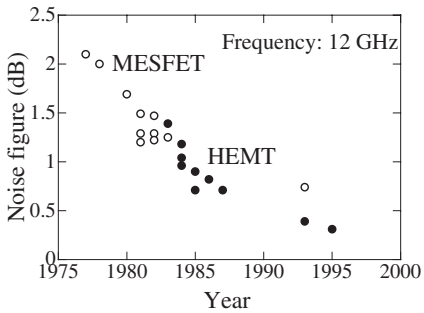

Fig. 7. Evolution of noise performance of GaAs MESFETs and HEMTs.

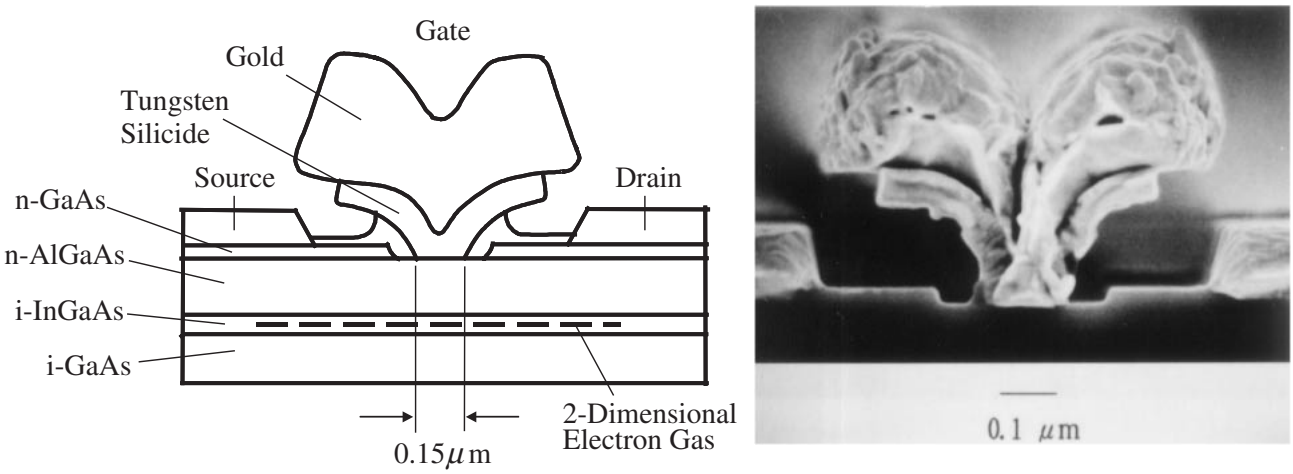

Fig. 8. SEM photograph and schematic diagram of recessed-gate pseudomorphic low-noise HEMT.

where K is a fitting factor, f the measurement frequency, f_T the current-gain cutoff frequency, g_m the transconductance, R_s the source resistance, and R_g the gate resistance. K experimentally obtained for the HEMT and GaAs MESFET was around 1.5 and 2.5, respectively. f_T has been increased over the years as we moved from GaAs MESFETs, to HEMTs, and then to pseudomorphic HEMTs with a higher-mobility InGaAs channel. The evolution of the noise performances of GaAs MESFETs and HEMTs at the satellite broadcasting frequency of 12 GHz is shown in Fig. 7. Around 1984, the noise figures of both devices were almost the same. As the HEMTs improved, the achievable noise figure was continuously lowered. In 1995, a noise figure of 0.3 dB was achieved, signifying the lowest noise figure for size-reduced parabolic antennas for satellite broadcasting. Figure 8 shows a schematic diagram and a scanning electron microscopy (SEM) photograph of the commercially available recessed-gate pseudomorophic HEMT.

5. Concluding Remarks and Future Trends

In the future, the scaling down of HEMTs is expected to improve their high-speed high-frequency performance. When reducing the horizontal dimensions of the device such as gate length, we should reduce the vertical dimensions at the same time to suppress the so-called short-channel effect. This is well known as a scaling rule for FETs. From a scaling viewpoint, InP is preferable over GaAs in that the barrier layer of InP-based HEMTs can be made thinner than that of GaAs-based counterparts at the same threshold voltage and the same donor concentration in the barrier layers. This is because the difference in energy between the Schottky barrier height of the gate and the conduction band offset at the heterointerface for InP-based devices is smaller than that for GaAs-based ones; typically 0.1 to 0.2 eV for InP- and 0.4 to 0.5 eV for GaAs-based HEMTs. Recently, the state-of-the-art performance with InP-based HEMT technology was reported. With a barrier layer (InAlAs) of 4 nm, the thinnest value yet reported for HEMTs, and a gate length of 25 nm, f_T's of up to 500 GHz for a lattice-matched HEMT and 562 GHz for a pseudomorphic counterpart have been achieved.[24] Development efforts are continuing to find a scaling endpoint of HEMTs for various materials systems.

In recent years, there has been interest in the development of HEMTs based on wide-band-gap III–V nitrides because of their high critical electric field for breakdown (2×10^6 V/cm). Since the first demonstration of AlGaN/GaN HEMTs in 1993,[25] GaN-based HEMTs have been successfully implemented for use in microwave power amplifiers. Kanamura *et al.* reported an output power of 101 W at 2.14 GHz from a 36-mm-gate-width AlGaN/GaN HEMT on a low-cost n-SiC substrate.[26] GaN-based HEMTs show promise for various high-power applications, including wireless base stations.[27]

We have seen a dramatic evolution of the HEMT since the first demonstration in 1980. The present widespread availability of HEMTs, particularly in microwave and millimeter-wave applications, is far beyond my wildest dreams. Future developments will focus on scaling down the devices and using wide-band-gap III–V nitrides to improve fundamental device performance and there is much work to achieve significant cost savings.

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