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A Newly Developed Two Mode Channel FET (TMT) Suited for Super-Low-Noise and High-Power Applications

Minoru Sawada, Daijiro Inoue, Kohji Matsumura, and Yasoo Harada

Semiconductor Research Center, SANYO Electric Co., Ltd.,
1-18-13 Hashiridani, Hirakata, Osaka 573, Japan

A super-low-noise two mode channel FET (TMT) with high and plateau-shaped transconductance (g_m) characteristics has been developed, which has two electron transport modes against the applied gate voltage (V_{gs}). That is, the electrons mainly drift in a highly-doped channel region at a shallow V_{gs} and in an undoped channel region at a deep V_{gs}. A plateau g_m region and the maximum g_m were achieved at a V_{gs} range of −0.25~+0.5 V and 535 mS/mm, respectively. The minimum noise figure and associated gain for the TMT were superior in the low drain current (I_{ds}) region and nearly equal in the middle and high I_{ds} region to those of an AlGaAs/InGaAs pseudomorphic HEMT fabricated using the same wafer process and device geometry.

I. Introduction

To realize microwave or millimeter-wave monolithic integrated circuits (MMIC's) for both reception and transmission, it is necessary to develop a new discrete device with both super-low-noise and high-power performance. One promising device for MMIC elements is the high electron mobility transistor (HEMT), for which various wafer structures have been developed for super-low-noise applications. However, because these structures are generally unable to provide excellent power performance, another HEMT wafer structure is usually required for power applications [1]. In addition to this, it is difficult to grow both of the above mentioned HEMT wafer structures on the same GaAs substrate without compromising the performance of either.

Another promising device is the highly-doped channel FET [2]. Doped-channel MIS-like FET's (DMT's) [3] showed higher transconductance (g_m) than the HEMT's and a plateau-shaped g_m against the gate voltage (V_{gs}). These characteristics are essential for achieving excellent high-power performance, such as high power-added efficency and low distortion [4]. Concerning the low-noise performance of the highly-doped channel FET's, the minimum noise figure (NF_{min}) reported for pulse-doped and ion-implanted GaAs MESFET's has been 0.72 dB at 12 GHz [5] and 0.56 dB at 10 GHz [6], respectively, and that for ion-implanted $In_xGa_{1-x}As$ MESFET's and AlGaAs/InGaAs/GaAs doped-channel heterojunction FET's (DC-HFET's) has been 2.8 dB at 60 GHz [7] and 0.65 dB at 12 GHz [8]. This noise performance is somewhat inferior to that of AlGaAs/GaAs HEMT's or AlGaAs/InGaAs pseudomorphic HEMT's (P-HEMT's). Therefore, the noise performance must be improved in these highly-doped channel FET's.

We have developed a new heterojunction FET, which can overcome the noise problem while maintaining the excellent performance of highly-doped channel FET's such as the high and plateau-shaped g_m. The new FET has two electron transport modes (ETM's) against the V_{gs}. That is, the electrons mainly drift in a highly-doped channel region at a shallow V_{gs} (MESFET-like ETM) and in an undoped channel region at a deep V_{gs} (HEMT-like ETM), so we call it a two mode channel FET (TMT). Whereas n-GaAs/InGaAs or n-AlGaAs/InGaAs HEMT systems have a basic wafer structure that enables them to produce the two ETM's, these HEMT's are practically operated using only the HEMT-like ETM and are designed not to operate in the MESFET-like ETM or to suppress the parallel conduction. So the design and practical operating principles of the TMT, which is operated using the two ETM's, are different from those of the HEMT's.

In this paper, we report on the TMT structure, fabrication process and electrical characteristics, and demonstrate that the noise performance of the TMT is superior to that of P-HEMT's fabricated by the same wafer process, especially in the low drain current (I_{ds}) region.

II. Device Structure and Fabrication Process

Figures 1 and 2 show the device structure and conduction energy band diagram for the TMT, respectively. The wafer for the TMT consists of an undoped GaAs buffer layer, an undoped InGaAs channel layer (In mole fraction 0.2, 50 Å), an undoped graded $In_xGa_{1-x}As$ channel layer (In mole fraction 0.2(lower side)~0(upper side), 70 Å), an n-GaAs electron-supplying and channel layer ($n=2\times10^{18}$ cm^{-3}, 200 Å), an n-AlGaAs barrier layer (Al mole fraction 0.22, $n=2\times10^{18}$ cm^{-3}, 500 Å) and an n-GaAs cap layer ($n=3\times10^{18}$ cm^{-3}, 800 Å). The wafer for the P-HEMT, which was fabricated in order to compare its device characteristics with the TMT, consists of an undoped GaAs buffer layer, an undoped InGaAs channel layer (In mole fraction 0.2, 100 Å), an undoped AlGaAs spacer layer (Al mole fraction 0.22, 20 Å), an n-AlGaAs electron-supplying layer ($n=2\times10^{18}$ cm^{-3}, 500 Å) and an n-GaAs cap layer ($n=3\times10^{18}$ cm^{-3}, 1000 Å). These wafers were grown by the molecular beam epitaxy (MBE) method at a GaAs substrate temperature of about 510 ℃.

These devices were fabricated by using our improved dummy-gate technique, in which the reverse dummy-gate patterns were fabricated by a lift-off process using a combination of single-layered resist and SiO_2 film deposited by the ECR-plasma-CVD method instead of the double-layered [9] or triple-layered [10] resist system. As shown in Fig. 3, the devices were fabricated as follows. After device isolation through mesa etching, an optically exposed single-layered PMMA resist pattern was thinned by oxygen plasma for dummy-gate pattern fabrication (Fig. 3(a)). After SiO_2 deposition using the ECR-plasma-CVD method followed by selective wet-etching (Buffered HF) of the SiO_2 deposited on the side wall of the dummy-gate resist (Fig. 3(b)), the reverse dummy-gate pattern was formed by removing the resist. Alloyed AuGe/Ni/Au metal was used for the source and drain ohmic contacts (Fig. 3(c)). After wet-recess etching, the T-shaped gate electrode was fabricated by lift-off of the evaporated Ti/Al metal (Fig. 3(d)). The gate length and width were 0.2-μm and 200-μm, respectively.

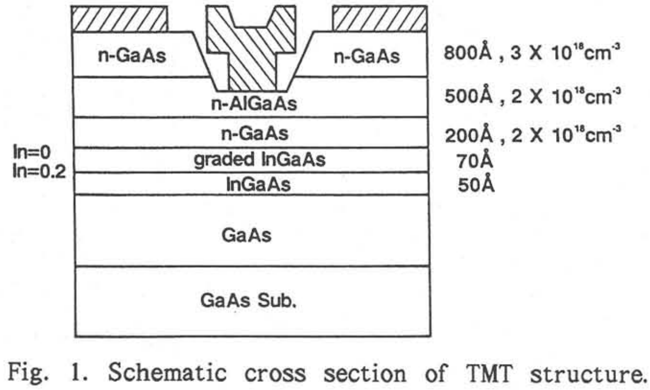

Fig. 1. Schematic cross section of TMT structure.

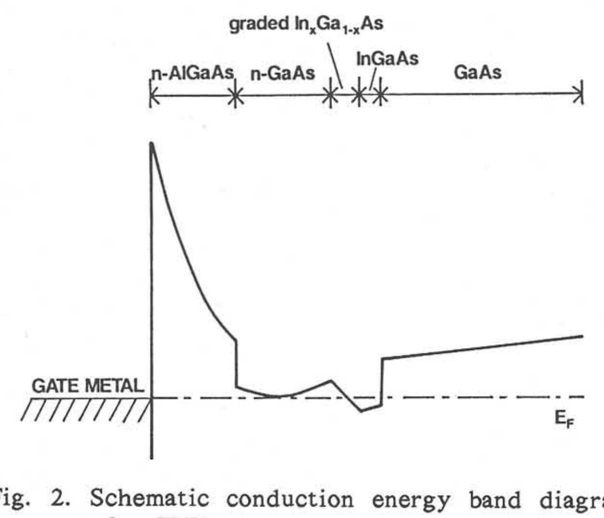

Fig. 2. Schematic conduction energy band diagram for TMT.

III. Device Characteristics

The electron mobility of the TMT and the P-HEMT wafers, obtained from Hall measurements, was about 2500 and 5000 $cm^2/V\cdot s$ at 300 K, and about 3500 and 15000 $cm^2/V\cdot s$ at 77 K, respectively. The electron mobility of the TMT wafer was nearly equal to that of the above mentioned highly-doped channel FET's [5], [8], and about half that of the P-HEMT at 300 K and a quarter at 77 K. Figure 4 shows the g_m and I_{ds} as functions of V_{gs} for the TMT and the P-HEMT. For the TMT, a rapid increase in g_m in the low-I_{ds} region was obtained and a g_m of 385 mS/mm was achieved at a I_{ds} of 50 mA/mm (for the P-HEMT, a g_m of 380 mS/mm). The maximum g_m reached 535 mS/mm at a I_{ds} of 175 mA/mm, which was comparable to that of the P-HEMT (550 mS/mm at

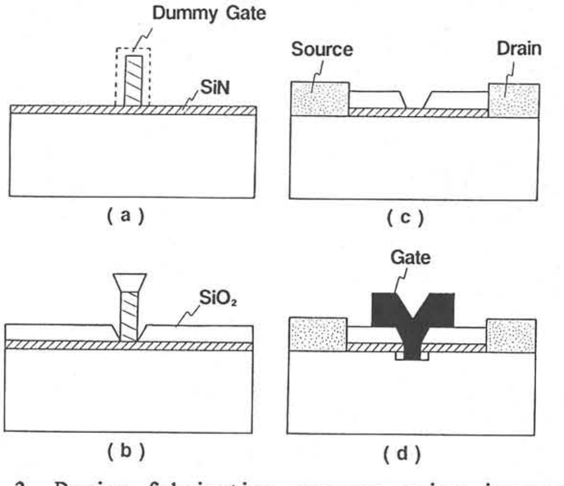

Fig. 3. Device fabrication process using improved dummy-gate technique.

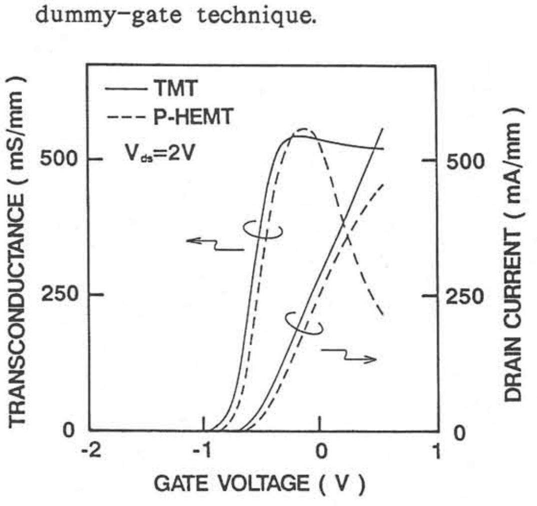

Fig. 4. Transconductance and drain current as functions of gate voltage for 0.2-μm×200-μm TMT and P-HEMT.

a I_{ds} of 200 mS/mm). The TMT had a plateau-shaped g_m-V_{gs} characteristic in the extended V_{gs} range from −0.25 to +0.5 V, instead of the sharply convex characteristic of the P-HEMT. These excellent g_m characteristics were brought about by a newly designed channel structure consisting of (i) the undoped InGaAs and graded $In_xGa_{1-x}As$ quantum-well layers which act to enhance the electron confinement in the undoped channel layer while suppressing an increase in the source series resistance, and (ii) the highly-doped n-GaAs layer which acts not only as the electron-supplying layer to the undoped channel but also as the channel layer at a shallow V_{gs}.

Figure 5 shows the NF_{min} and associated gain (Ga) at 12 GHz as functions of the I_{ds} for the TMT and the P-HEMT. The NF_{min} in both devices was nearly equal and remained less than 0.65 dB throughout a large I_{ds} region (50~150 mA/mm). The NF_{min} of the TMT was superior to that of the P-HEMT in the low-I_{ds} region, and NF<0.9 was obtained at a I_{ds} of 10 mA/mm. We believe that this superior NF_{min} [5] for the TMT is due to the fact that the TMT has a sharper electron probability density distribution at the low-I_{ds} bias condition than that of the P-HEMT, which was obtained from the following calculation. That is, the full width at half maximum (FWHM) of the electron probability density distribution in the quantum well layer for the TMT and the P-HEMT was calculated by using both (i) the effective mass approximation, and (ii) a self-consistent method for solving Poisson's equation and Schrodinger's equation. Figure 6 shows the FWHM as a function of the sheet carrier concentration (N_s) for the TMT and the P-HEMT. With reductions in N_s, the FWHM for the TMT reduced and that for the P-HEMT slightly increased, and the former and the latter were about 62 Å and about 70 Å at the N_s of 1×10^{11} cm^{-2}, respectively. These results showed that the FWHM for the TMT was smaller than that for the P-HEMT in the low-I_{ds} bias condition. On the other hand, the Ga was nearly equal throughout a large I_{ds} region (25~150 mA/mm) for both devices.

IV. Conclusions

We have successfully developed a new heterojunction device, the two mode channel FET (TMT), which had highly-doped GaAs, undoped graded $In_xGa_{1-x}As$ and undoped InGaAs layers as the channel. The NF_{min} and Ga for the TMT were superior in the low-I_{ds} region and nearly equal in the middle and high-I_{ds} region to those of the P-HEMT. The g_m versus V_{gs} characteristic showed a plateau region through a V_{gs} range of −0.25~+0.5 V, and a maximum g_m of 535 mS/mm.

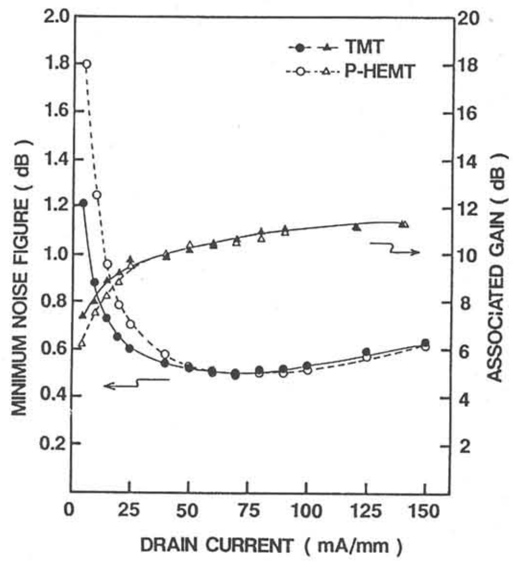

Fig. 5. Minimum noise figure and associated gain at 12 GHz of 0.2-μm×200-μm TMT and P-HEMT.

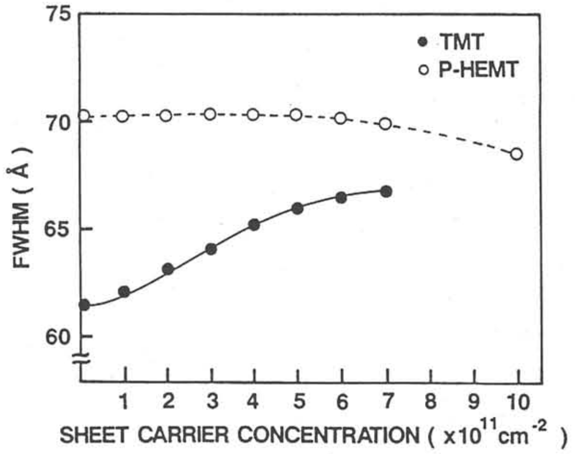

Fig. 6. FWHM of electron probability density distribution in quantum well layer as functions of N_s for TMT and P-HEMT.

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