A New Field-Effect Transistor with Selectively Doped GaAs/n-$Al_xGa_{1-x}As$ Heterojunctions

1980 Jpn. J. Appl. Phys. 19 L225

(http://iopscience.iop.org/1347-4065/19/5/L225)

JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 19, NO. 5, MAY, 1980 pp. L225–L227

A New Field-Effect Transistor with Selectively Doped GaAs/n-$Al_xGa_{1-x}As$ Heterojunctions

Takashi MIMURA, Satoshi HIYAMIZU, Toshio FUJII and Kazuo NANBU

Fujitsu Laboratories Ltd.,
1015, Kamikodanaka, Nakahara-ku, Kawasaki 211

(Received March 24, 1980)

Studies of field-effect control of the high mobility electrons in MBE-grown selectively doped GaAs/n-$Al_xGa_{1-x}As$ heterojunctions are described. Successful fabrication of a new field-effect transistor, called a high electron mobility transistor (HEMT), with extremely high-speed microwave capabilities is reported.

One of the most interesting phenomena in heterojunction structures is the mobility enhancement behavior first reported by Dingle *et al.*[1)] in MBE (molecular beam epitaxy)-grown modulation-doped GaAs–$Al_xGa_{1-x}As$ superlattices. In these structures, alternate layers of GaAs and $Al_xGa_{1-x}As$ with the $Al_xGa_{1-x}As$ layers selectively doped with Si are involved. Because of the higher electron affinity of GaAs, free electrons in $Al_xGa_{1-x}As$ layers are transferred to the non-doped GaAs layers where they form a quasi two-dimensional Fermi gas. The measured Hall mobilities parallel to the layers are higher than that of uniformly doped GaAs of equivalent doping concentration. The mobility enhancement behavior is attributed to the spatial separation between electrons and their parent donor impurities. In this paper we report our studies of field-effect control of the high mobility electrons in selectively doped GaAs/n-$Al_xGa_{1-x}As$ heterostructures and describe fabrication of a new field-effect transistor, called a high electron mobility transistor (HEMT), with extremely high-speed microwave capabilities.

The heterostructure used in this experiment consists of non-doped GaAs epilayers and a Si-doped n-type $Al_xGa_{1-x}As$ ($x=0.32$) epilayer, as illustrated in Fig. 1(a). The epilayers, 1 μm thick, were grown successively by MBE on a Cr-doped semi-insulating GaAs substrate. The doping level in $Al_xGa_{1-x}As$ is $6.6\times10^{17}/cm^3$. A schematic energy band diagram of a non-doped GaAs/n–$Al_xGa_{1-x}As$ heterojunction is shown in Fig. 1(b). An electron layer is formed at the GaAs side of the interface, while the

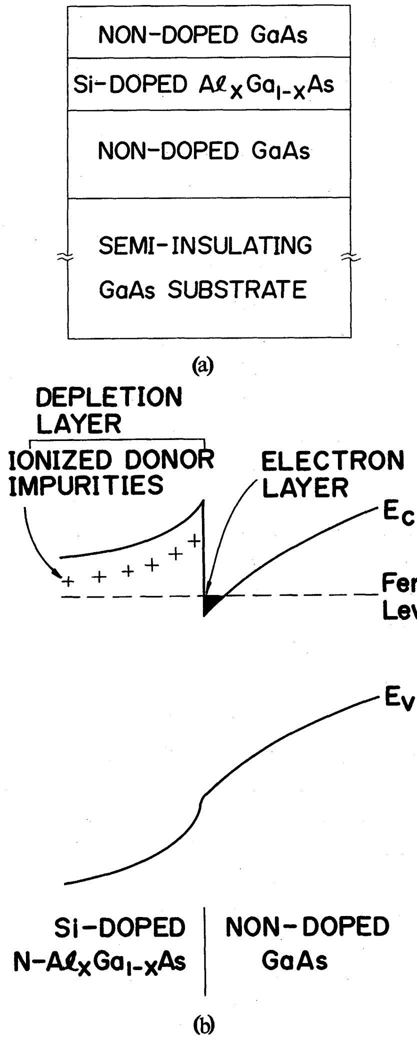

Fig. 1. (a) Heterostructure used in field-effect experiments. (b) Schematic energy band diagram of a selectively doped GaAs/n-$Al_xGa_{1-x}As$ heterojunction.

$Al_xGa_{1-x}As$ layer is depleted towards the interface.

Device fabrication starts with the etching of mesa islands down to the non-doped GaAs layer adjacent to the semi-insulating substrate to localize the active region. The source and drain ohmic contacts are made with gold-germanium eutectic alloy and gold overlay. Rectifying contact for the gate is provided by the deposition of aluminum on the surface of non-doped GaAs of the top epilayer. We have simultaneously fabricated HEMT's, Hall bridges and diodes for capacitance-voltage measurements in the wafer.

Figure 2 shows the apparent carrier profile measured at 77 K with a differential capacitance feedback profiler. Simple profiling theory suggests that the obtained carrier profile should give the true electron distribution except for minor Debye-length smearing.[2] In the case of GaAs for carrier concentrations of 10^{17} and $10^{18}/cm^3$, the Debye lengths at 77 K are 68 and 21 Å, respectively. In Fig. 2 we can observe a spike-like carrier profile with the spreading width of 85 Å at the carrier concentration of $2\times10^{17}/cm^3$. The spike-like carrier profile may result from the two-dimensionality of electrons confined to the GaAs layer. The two-dimensionality of the electron layers was first demonstrated by Shubnikov-de Haas measurements in modulation-doped superlattices.[3]

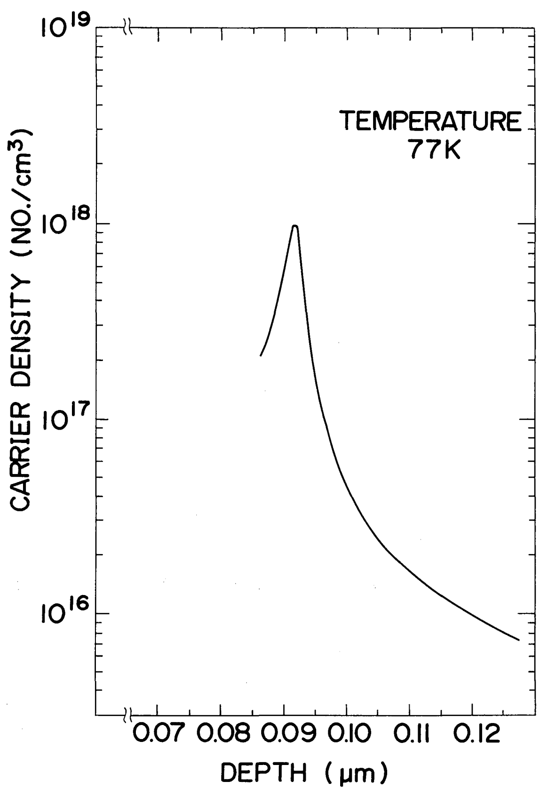

Fig. 2. Carrier profile obtained for the heterostructure at 77 K.

Figure 3(a) shows 300 K and 77 K drain current-voltage characteristics of the HEMT, measured with a 100 Hz curve tracer. Complete pinch-off of the drain current from the gate is observed. The drain current saturates at the drain voltage V_{DS} where $V_{DS}=V_{GS}-V_P$, as expected from the Shockley model.[4] Here V_{GS} represents the source-to-gate voltage and V_p the pinch-off voltage. In Fig. 3(a) we can observe a dramatic increase in saturated transconductance G_m by a factor as much as 3, when the HEMT is cooled to 77 K. This increase in G_m is partly due to the increase in the electron mobility at low temperatures. The Hall mobility measured at 77 K was 32500 $cm^2/V\cdot s$, which is higher than what has been reported in modulation-doped superlattices.

Conventional Schottky-gate GaAs field-effect transistors (MESFETs) were fabricated using VPE (vapor phase epitaxy)-grown active layer with the carrier concentration of $1.0\times10^{17}/cm^3$. The geometry and zero gate-bias drain saturation current of the MESFETs are the same as those for the HEMT.

Figure 3(b) shows 300 K and 77 K drain current-voltage characteristics of the MESFETs. In contrast to the HEMT, the MESFET does not exhibit any significant increase in 77 K transconductance.

In Table I we compare the parameters of the HEMT with those of the GaAs MESFET. The 300 K mobility of the HEMT is 30 percent higher than that of the MESFET. The mobility advantage of the HEMT over the MESFET increases by a factor of 5 to 6 by lowering the temperature to 77 K. 77 K transconductance of the HEMT is 3 times higher than that of the MESFET. The intrinsic high-speed capability of the transistor depends on the current gain-bandwidth product f_T, which is given by $f_T=G_m/2\pi C_{GS}$. Here C_{GS} denotes the gate-to-source capacitance. If we assume that the C_{GS} values for the HEMT and the MESFET of the same geometry are similar, high-speed capabilities depend principally on the G_m values.

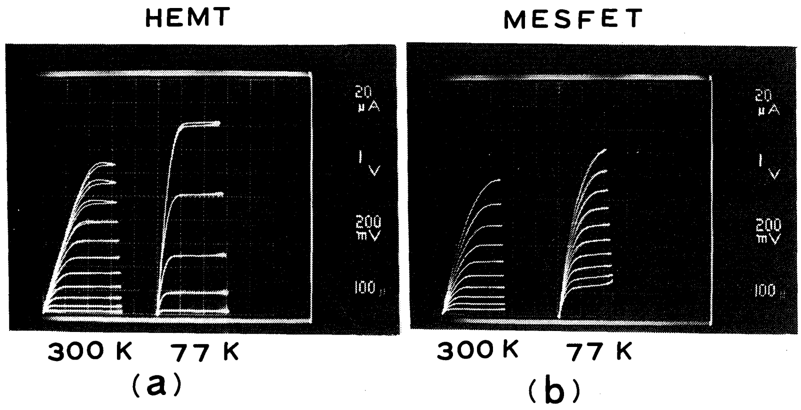

Fig. 3. 300 K and 77 K current-voltage characteristics of the HEMT (a) and the GaAs MESFET (b). Both devices have the same geometrical dimensions: Gate length=400 μm, Gate width=50 μm. Scales: Drain current, 20 μA/div.; Drain voltage, 1 V/div.; Gate voltage, 0.2 V/step.

Table I. Parameters of the HEMT and the GaAs MESFET.

	Carrier concentration	Hall mobility, μ_H (cm^2/V·s)		Mobility advantage at 77 K, μ_H(HEMT)/μ_H(MESFET)	Transconductance advantage at 77 K, G_m(HEMT)/G_m(MESFET)
		300 K	77 K		
HEMT	0.7×10^{12}/cm^2	6200	32500	5.5	3
MESFET	1.0×10^{17}/cm^3	4700	5800		

Therefore the HEMT should attain 3 times higher speeds than the MESFET at 77 K.

Recent calculations have predicted that the maximum attainable mobility at low temperature limited by Coulomb scattering from donor ions should exceed 10^5 cm^2/V·s.[5] The HEMT with improved electron mobility may attain at least 10 times higher speed than the GaAs MESFET.

In summary, we have described a new field-effect transistor, called a high electron mobility transistor (HEMT), with selectively doped GaAs/n–Al$_x$Ga$_{1-x}$As heterojunctions. 77 K and 300 K mobilities of the HEMT are significantly higher than those of the GaAs MESFET with similar drain saturation current. Dramatic increase in transconductance of the HEMT has been observed when the HEMT was cooled to 77 K. Crude estimation has shown that the high-speed performance of the HEMT should be 3 times superior to that of the MESFET at 77 K. Further substantial improvements in high-speed capability of the HEMT are expected with improved electron mobilities at low temperatures.

The authors would like to thank to M. Fukuta and T. Hashimoto for supporting this work.

References

1) R. Dingle, H. L. Störmer, A. C. Gossard and W. Wiegmann: Appl. Phys. Lett. **33** (1978) 655.
2) H. Kröemer and W. Y. Chien: IEEE Trans. Electron Devices **ED-26** (1979) 1839.
3) H. L. Störmer, R. Dingle, A. C. Gossard, W. Wiegmann and M. D. Sturge: Solid State Commun. **29** (1979) 705.
4) W. Shockley: Proc. IRE **40** (1952) 1365.
5) S. Mori and T. Ando: Proc. Yamada Conf. II, LAKE YAMANAKA, 1979, p. 44.