HIGH-BREAKDOWN-VOLTAGE $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ I-HEMT AND I^2HEMT WITH A GaInP PASSIVATION LAYER GROWN BY GAS SOURCE MOLECULAR BEAM EPITAXY

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Abstract—The first $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ inverted-structure high electron mobility transistors (I-HEMT) and insulated-gate inverted-structure high electron mobility transistors (I^2HEMT) grown by gas source molecular beam epitaxy (GSMBE) have been fabricated and measured. Very high drain-to-source breakdown voltage was obtained in the I-HEMT (23 V) and I^2HEMT (13 V). The maximum g_m s achieved for I-HEMT and I^2HEMT were 120 and 100 mS/mm at room temperature, respectively. No I - V collapse was observed at 77 K. The high breakdown characteristics were attributed to the use of a high band gap GaInP passivation layer between the gate and drain. These results indicate that $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ I-HEMT and I^2HEMT are promising to be used as high breakdown (high power) devices.

NOTATION

GSMBE	Gas Source Molecular Beam Epitaxy
I-HEMT	Inverted High Electron Mobility Transistor
I^2HEMT	Inverted structure Insulated gate High Electron Mobility Transistor
MESFET	Metal Semiconductor Field Effect Transistor
I - V	current-voltage
BV_{ds}	drain to source breakdown voltage
I_{DSS}	drain to source saturation current
g_m	transconductance
DX center	deep level unknown center
Γ valley	gamma energy valley in k space
L valley	L energy valley in k space
RHEED	Reflection High Electron Energy Diffraction

1. INTRODUCTION

Recently there has been growing interest in the material system of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ lattice matched to GaAs because of its potential applications in many electronic and optoelectronic devices. $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ has a wide direct bandgap (~ 1.92 eV) and hence can be used to fabricate visible light laser diodes and light-emitting diodes. Moreover, because of the large Γ - L valley separation (300 meV), $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ has been found to have a very low concentration of DX centers and therefore the DX related problems like the persistent photoconductivity effect, I - V collapse at low temperature and threshold voltage shift were either not observed or greatly reduced[1,2]. Due to the small surface recombination velocity of GaInP , reduced low frequency noise in the HEMT device is expected[3]. The GaInP has very low reactivity with oxygen, which means high reliability. The wet/dry etching selectivity between GaAs and GaInP is very high, which implies high uniformity and yield. These

features make GaInP a favorable material to replace AlGaAs in the AlGaAs/GaAs heterostructures. GaInP/GaAs normal-structure HEMTs grown by MOCVD[12] and GSMBE[2] have been reported with excellent performance. While most studies have been concentrated in the normal-structure HEMTs, the inverted structure HEMTs (I-HEMT), in which the small bandgap channel is on top of the large bandgap supplying layer, have also been proposed and investigated theoretically and experimentally by Lee and Shur[4], Morkoc *et al.*[5] and Cirillo *et al.*[6]. There are several advantages of the I-HEMT structure. It has been shown that the transconductance of the I-HEMT is nearly independent of the doping level in the high bandgap material, while in the normal HEMT the transconductance decreases with reduced doping[7]. Enhanced electron mobility[5] and extremely high transconductance[6] were also observed, which was attributed to the smaller distance between the 2D electrons and the gate in the I-HEMT compared with that of the normal HEMT. For power applications, high breakdown characteristics are also needed. Although the breakdown mechanism in a FET is still not totally understood, it is generally believed that breakdown occurs at the gate edge nearest the drain where the electric field is highest or along the surface between the gate and the drain[8–11]. One way to improve the breakdown voltage is the use of a passivation layer. The passivation layer can be a low-temperature-grown GaAs layer[12–14] or an undoped high bandgap AlGaAs layer[15–17]. Because of the high resistivity and the low avalanche rate of the passivation layer, these devices show high breakdown voltage characteristics and thus high power transistors are obtained.

In this paper, the first $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ inverted-structure HEMTs grown by gas source molecular beam epitaxy (GSMBE) have been fabricated and measured. High drain-to-source breakdown voltage ~ 23 V and gate-to-drain breakdown voltage ~ 26 V were achieved by using the GaInP passivation layer. We also measured mobility and transconductance of these layers. $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ insulated-gate inverted-structure HEMTs (I^2HEMT)[18,19] were also fabricated for comparison.

2. CRYSTAL GROWTH AND DEVICE TECHNOLOGY

The heterostructures were grown by gas source MBE on semi-insulating (100) GaAs substrates. First, *in situ* reflection high energy electron diffraction (RHEED) was used to calibrate the growth rate of InP and GaP. The growth rate of GaP was calibrated by growing GaAs on a GaAs substrate, assuming the rate for growing GaAs for a given Ga flux is the same

as that for GaP. The growth rate of InP was calibrated by growing InP on an InP substrate. Since the lattice constant of InP is different from that of GaAs, corrections were made to calibrate the growth rate. Then the GaInP was grown on GaAs according to the above RHEED rate calibrations. X-ray diffraction of the sample was used to determine the mismatch. With this mismatch data, the Ga cell temperature was adjusted to fine tune the lattice mismatch while the InP growth rate was kept unchanged. A lattice mismatch typically less than 1×10^{-3} was obtained. Schematic diagrams of the layer structures and cross sections of an I-HEMT and an I^2HEMT are shown in Figs. 1(a) and (b), respectively. They consisted of a $1 \mu\text{m}$ undoped GaAs buffer followed by a $500 \text{ \AA}$ undoped GaInP layer, a $200 \text{ \AA}$ n^+ -doped GaInP supplying layer, a $70 \text{ \AA}$ undoped GaInP spacer, and a $300 \text{ \AA}$ undoped GaAs channel layer. A $200 \text{ \AA}$ undoped GaInP layer on top of the channel layer was used as the passivation layer between gate and drain to increase the breakdown. Finally, an n^+ -GaAs cap layer was grown to facilitate ohmic contacts. Conventional photolithography and wet chemical etching techniques were used to fabricate the devices. First, the mesa isolation etch was done. Then, AuGeNi ohmic contacts were thermally evaporated, patterned by lift-off and rapid thermal annealed. Next, optical gate lithography followed by gate recess were done. The gate length of the transistor is $1.5 \mu\text{m}$. Due to the high etching selectivity between the GaInP and GaAs, the fabrication processing is much easier than the AlGaAs/GaAs system. Specific contact resistance of $4 \times 10^{-6} \Omega \cdot \text{cm}^2$ was obtained from transmission line patterns.

Fig. 1. Schematic diagrams of the layer structures and the cross sections of the (a) I-HEMT and (b) I^2HEMT .

3. RESULTS AND DISCUSSION

3.1. Hall measurement

Hall measurement was done with the n^+ GaAs cap layer etched. The Hall mobility was 2400 and $11,100 \text{ cm}^2/\text{V} \cdot \text{s}$ at 300 and 77 K, respectively, while the corresponding value for the sheet charge was 2.2×10^{12} and $1.6 \times 10^{12} \text{ cm}^{-2}$. The mobility was lower than the previous reports ($3200 \text{ cm}^2/\text{V} \cdot \text{s}$, 300 K, and $17,700 \text{ cm}^2/\text{V} \cdot \text{s}$, 77 K)[2] of the normal GaInP/GaAs HEMT grown by the same techniques (GSMBE) while the sheet densities were higher than the previous results (9.8×10^{11} and $5.6 \times 10^{11} \text{ cm}^{-2}$) of the normal HEMT. A possible explanation for the lower mobility of GaInP/GaAs compared to that of conventional AlGaAs/GaAs is the interface roughness resulting from switching PH_3 to AsH_3 gas during the growth of GaAs on top of GaInP[1].

3.2. I - V characteristics of I-HEMT with and without GaInP passivation layer between gate and drain

The typical d.c. I - V characteristics of I-HEMT is shown in Fig. 2. It showed a very small leakage

Fig. 2. The common-source current (I)-voltage (V) characteristics of the I-HEMT.

current I_{DS} in the pinch-off region even for drain bias V_{DS} up to 19 V. A drain-to-source breakdown voltage $BV_{DS} \approx 23$ V was obtained, which is defined as the drain voltage where drain current I_D reaches one-tenth of the saturation current I_{DSS} . This result is comparable to that (22 V) obtained from GaAs MESFETs with a low-temperature-grown GaAs passivation layer[14]. The gate-to-drain breakdown voltage was ~ 26 V as shown in Fig. 3, where the gate-to-drain breakdown voltage is defined as the voltage at which the gate current reaches 1 mA/mm. This value is also comparable to that (25 V) obtained from GaAs MESFETs with a low-temperature-grown GaAs passivation layer[14] and that (19–20 V) from GaAs MISFETs with undoped AlGaAs as an insulator[16]. The g_m s found from all samples on a 2" wafer ranged from 80 to 120 mS/mm at room temperature. The

Fig. 3. The gate-to-drain breakdown characteristics of the I-HEMT. Solid line: with the GaInP passivation layer between the gate and drain; dotted line: without the GaInP passivation layer between the gate and drain.

Fig. 4. The transconductance (g_m) vs. gate voltage (V_G) transfer curves at different temperatures. Solid line: room temperature; dotted line: 77 K.

variation of g_m was due to variation of access resistance. The $I_{DS}-V_G$ and g_m-V_G transfer curves at different temperatures (300 and 77 K) for the particular device shown in Fig. 1 are shown in Fig. 4. The maximum g_m was around 80 mS/mm at 300 K and increased to 120 mS/mm at 77 K.

As a control experiment, the GaInP passivation layer (see Fig. 1) of the I-HEMT was etched and the electrical characteristics were measured. The gate-to-drain breakdown $I-V$ characteristics (dotted line) are shown in Fig. 3. It is clear that the gate-to-drain breakdown voltage (8 V) obtained without GaInP passivation layer between the gate and drain regions is much lower than that with the GaInP passivation layer (26 V). A similar reduction in drain-to-source

Fig. 5. The common source $I-V$ characteristics of an I-HEMT at different temperatures. Solid line: room temperature; dotted line: 77 K.

Fig. 6. The common-source I - V characteristics of the I^2 HEMT.

breakdown voltage was also observed in the common-source I - V characteristics. From this experiment we conclude that the presence of the undoped GaInP passivation layer between the gate and drain effectively reduced the electric field near the gate and therefore the breakdown voltages were increased. The increase of g_m from 80 mS/mm at 300 K to 120 mS/mm at 77 K can be attributed to the increase of drain current at lower temperatures as shown in Fig. 5. The increase of current may be due to the increase in mobility at lower temperatures as mentioned previously. Note that no I - V collapse at 77 K was observed under bias-stress test. This is consistent with the report of Chan *et al.*[1].

3.3. I - V characteristics of I^2 HEMT with GaInP passivation layer between gate and drain

The common-source and gate-to-drain I - V characteristics of I^2 HEMT are shown in Figs 6 and 7, respectively. The g_m s of all the devices fabricated on a 2" wafer ranged from 80 to 100 mS/mm, which

Fig. 7. The gate-to-drain breakdown characteristics of the I^2 HEMT.

is, on the average, lower than that of I-HEMT. From Figs 6 and 7, we found that the drain-to-source and gate-to-source breakdown voltages were 13 and 14 V respectively. That is, both values are lower than those of the I-HEMT with passivation layer, but still higher than those of I-HEMT without passivation layer. This conclusion is true for all the devices that we have fabricated from two 2" wafers. These results seem to imply that the gate-to-drain passivation layer is more important than the gate-to-channel insulated layer, at least for a thin insulating layer (200 Å). It is unclear to us now why GaInP/GaAs I-HEMT has higher breakdown voltage than GaInP/GaAs I^2 HEMT. Electrical characteristics of I^2 HEMT at 77 K showed similar behavior to those of I-HEMT: higher current level, higher g_m , no I - V collapse, and no persistent photoconductivity effect.

4. SUMMARY

We have fabricated the first GSMBE-grown GaInP/GaAs I-HEMT and I^2 HEMT with a GaInP passivation layer between the gate and drain. It is found that the drain-to-source and gate-to-drain breakdown voltages are very high (23 and 26 V, respectively). However, the breakdown voltages dropped markedly once the GaInP layer was taken out and this unequivocally demonstrated that the GaInP passivation layer was the key reason for the increase of the breakdown voltages. The I^2 HEMT showed lower drain-to-source and gate-to-drain breakdown voltages (13 and 14 V) than the I-HEMT, which is unclear to us now. Both I-HEMT and I^2 HEMT with a passivation layer had higher breakdown voltages than those without a passivation layer. By further optimization of the layer structures, high g_m and high power I-HEMT or I^2 HEMT should be realizable.

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