Improved Performance of Submicrometer-Gate GaAs MESFET's with an $Al_{0.3}Ga_{0.7}As$ Buffer Layer Grown by Metal Organic Vapor Phase Epitaxy

KENJI HIRUMA, MITSUHIRO MORI, EIJI YANOKURA, HIROSHI MIZUTA, AND SUSUMU TAKAHASHI

***Abstract*—Submicrometer-gate MESFET's were fabricated with a GaAs active layer and an $Al_xGa_{1-x}As$ buffer layer grown by metalorganic vapor-phase epitaxy. To investigate the role of the buffer layer on device performance, FET's with GaAs and $Al_{0.3}Ga_{0.7}As$ buffer layers were compared. Electron Hall mobility in the n-GaAs active layer was found to be uneffected by the Al composition or carrier concentration in the buffer layer. However, a remarkable improvement in the maximum available gain of as much as 5.2 dB was obtained at 26.5 GHz for FET's with a p-$Al_{0.3}Ga_{0.7}As$ buffer layer, which was 1.5 dB higher than those with a p-GaAs buffer layer. The improvement in the maximum available gain is due to a 20–30 percent reduction in both drain conductance and drain–gate capacitance at microwave frequency.**

I. Introduction

GaAs MESFET's with $Al_xGa_{1-x}As$ buffer layers are expected to perform better than those with GaAs buffer layers [1]–[3], because the higher bandgap of $Al_xGa_{1-x}As$ should reduce the injection of channel electrons into the buffer layer and confine carriers within the active layer. Such improved performance should be evident not only by lower output conductance but also by a reduction in short-channel effect, especially in FET's with a submicrometer gate length [2]–[5]. To achieve the desired performance, it is necessary to grow films of good crystal quality with an abrupt heterointerface.

Conventional vapor-phase epitaxy (VPE) cannot grow $Al_xGa_{1-x}As$ of device quality. But molecular-beam epitaxy (MBE) and metalorganic vapor-phase epitaxy (MOVPE) can. Both have good controllability for growing multilayer structures with an abrupt profile for both composition and doping. There have been several reports on GaAs MESFET's with an $Al_xGa_{1-x}As$ buffer layer grown by MOVPE [1], [2] or MBE [3], and improved performance, such as a reduction in drain conductance, was observed in the dc characteristics. However, the electron Hall mobilities of n-GaAs were rather poor when it was grown on $Al_xGa_{1-x}As$ by MOVPE [1], [2]. No strong correlation between the Al composition of the buffer layer and device performance at microwave frequencies has yet been obtained [1]. These difficulties might be due to the gas switching technique of MOVPE. On the other hand, the performance of MESFET's with an $Al_xGa_{1-x}As$ buffer layer is greatly influenced by the $Al_xGa_{1-x}As$ and n-GaAs/$Al_xGa_{1-x}As$ interface quality [1], [3], [6], [7] because Al is a chemically active element that readily incorporates atmospheric oxygen during epitaxial growth. Thus, it is necessary to establish a new growth technique to produce the required device structure.

In this study, epitaxial layers were produced using a newly developed MOVPE growth technique. The electron Hall mobilities of n-GaAs on $Al_xGa_{1-x}As$ grown using this technique were measured to investigate the influence of the $Al_xGa_{1-x}As$ buffer layer. To ascertain the correlation between the Al composition of the buffer layer and device performance, dc and microwave characteristics were also measured for FET's with GaAs and $Al_{0.3}Ga_{0.7}As$ buffer layers. The influence of an oxygen-related deep electron trap on FET performance was also investigated.

II. Epitaxial Growth and Characteristics

The GaAs MESFET considered here is schematically shown in Fig. 1. The epitaxial layers were grown by MOVPE in a vertical reactor, which has two growth zones inside it. One growth zone was used only for GaAs and another for AlGaAs, and a composition and doping profile as abrupt as those grown by MBE could be grown easily by substrate transfer between the two zones. Trimethylgallium (TMG), trimethylaluminum (TMA), and arsine (AsH_3) were used to grow GaAs and $Al_xGa_{1-x}As$, and SiH_4 and Si_2H_6 were used as n-type dopants. These source gases were carried by Pd diffused H_2 gas. The epitaxial layers were grown at a reduced pressure of 2.0×10^4 Pa (150 torr) and the growth temperature was 700°C. The Al composition of the $Al_xGa_{1-x}As$ layers were determined by the peak photoluminescence (PL) wavelength at 77 K. The residual oxygen concentration in the present

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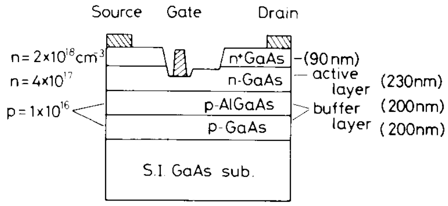


Fig. 1. Schematic diagram of the cross section of GaAs FET with AlGaAs buffer layer.

MOVPE reactor was kept below 0.03 ppm, which is the normal condition for growing $Al_xGa_{1-x}As$ of good PL intensity.

To produce the required FET layers, p-GaAs, p-AlGaAs buffer, n-GaAs active, and n^+-GaAs cap layers were grown successively on a (100) semi-insulating GaAs substrate. The carrier concentration of the p-type buffer layer was around 1×10^{16} cm^{-3}, measured by the van der Pauw method. The growth condition for the p-type buffer layer was determined by chosing an adequate molar flow ratio of AsH_3 to TMG or AsH_3 to (TMG + TMA) to provide proper carbon concentration unintentionally doped by TMG and TMA. Ohmic contact could not be made with the high-resistivity $Al_{0.3}Ga_{0.7}As$ buffer layer grown with a small amount of oxygen contamination (less than 1 ppm) inside the MOVPE reactor. The total thickness of the buffer layer was chosen so that the depletion width extended throughout the buffer layer. Doping of the active and cap layers was around 4×10^{17} cm^{-3} and 2×10^{18} cm^{-3}, respectively, measured by the conventional capacitance–voltage (C–V) method. The thicknesses of active and cap layers were 230 and 90 nm, respectively.

MESFET fabrication was carried out using a new self-alignment quarter-micrometer-gate technique [8]. Ohmic contacts were formed by alloying a thin layer of AuGe and depositing three thin layers of Ni, W, and Au on top. Contact resistivity was around 1×10^{-7} $\Omega \cdot cm^2$. Gate metallization was of Ti/Al. The fabricated FET had a channel length of 3 μm and a gate length of 0.3 μm. The gate recess depth was 0.23 μm and the aspect ratio of the gate length/channel height was around 4. The gate was 0.5 μm offset from the center of the source–drain region for high output operation [8].

It is well known that the degradation of carrier mobility in the active layer limits FET performance [6]. To ascertain the influence of the buffer layer on the electron Hall mobility of the active layer, Hall measurements were performed using a clover-leaf Hall device. Electron Hall mobility versus carrier concentration is shown in Fig. 2. The n-GaAs used was grown successively on each layer of p-GaAs, p-$Al_{0.3}Ga_{0.7}As$ and high-resistivity $Al_{0.3}Ga_{0.7}As$. The curves drawn in the figure indicate theoretical values [9] with carrier compensation ratios of $(N_D + N_A)/n =$ 1, 3, 5, and 10, where N_D, N_A, and n are ionized donor, ionized acceptor, and free-carrier concentrations, respectively. The measured electron Hall mobilities are in quite good agreement with the theoretical curve for the lowest

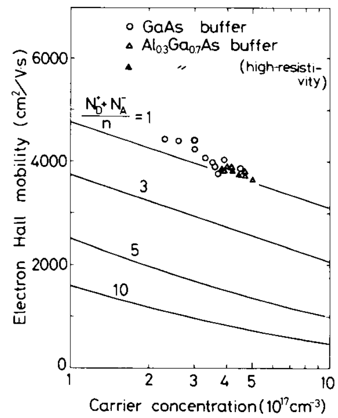


Fig. 2. Electron Hall mobility versus carrier concentration of n-GaAs grown on three different buffer layers.

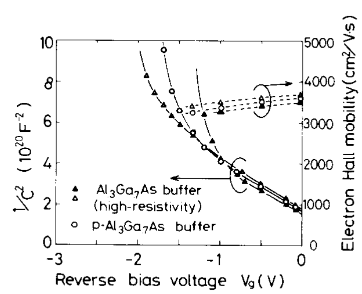


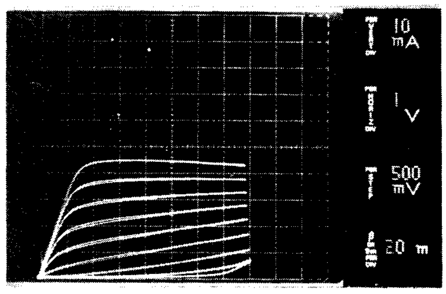
Fig. 3. $1/C^2$ and electron Hall mobility versus reverse-bias voltage (V_g) applied on Schottky contact.

compensation ratio irrespective of the buffer layer. Thus, it can be stated that the active layer has good overall crystal quality.

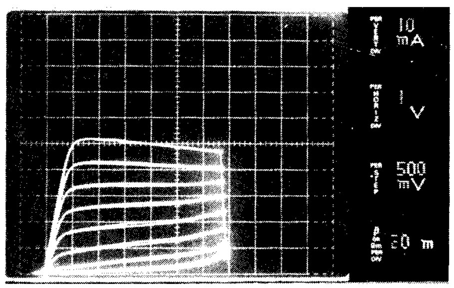
However, Gibod *et al.* [1] have observed degradation of electron Hall mobility in the active layer near the GaAs/AlGaAs heterointerface. In this study, a clover-leaf Hall device with a Schottky contact, made during the FET fabrication process, was used to study the mobility profile through the active layer. A C–V plot with Hall effect measurement shows free-carrier concentration and electron Hall mobility variations for the same applied bias on the Schottky contact. $1/C^2$ and the electron Hall mobility of n-GaAs are plotted in Fig. 3 as a function of reverse-bias voltage. Only a slight decrease in mobility was observed within the range $-1.5\ V < V_g < 0\ V$, where the edge of the depletion region exists within the active layer. From the observed dependence on V_g, it is confirmed that the electron Hall mobility profile is independent of the buffer layer and also reflects the good crystal quality of n-GaAs.

III. DC Characterization

To assess the role of the AlGaAs buffer layer on device characteristics, FET's with different buffer layers have been compared. Typical dc characteristics of the normal FET are shown in Fig. 4. The gate area is 0.3×100 μm^2 for each FET. Fig. 4(a) and (b) corresponds to FET's with a p-GaAs buffer layer and a p-$Al_{0.3}Ga_{0.7}As$ buffer layer,



(a)



(b)

Fig. 4. Drain I_D-V_D characteristics of the FET. (a) p-GaAs buffer layer, (b) p-$Al_{0.3}Ga_{0.7}As$ buffer layer. Vertical scale: 10 mA/div; horizontal scale: 1 V/div; gate step voltage: 0.5 V.

TABLE I

Buffer layer		Active layer			
Al composition	Carrier concentration (cm^{-3})	Pinch-off voltage (V)	Doping ($10^{17}cm^{-3}$)	Electron Hall mobility ($cm^2/V\cdot s$)	Trans-conductance (mS/mm)
0	p~1×10^{16}	-2.5~-3.5	3~6	3500~4500	150~170
0.3	p~1×10^{16}	-2.5~-3.5	3~6	3500~4500	150~170
0.3	high-resistivity	-2.5~-3.5	3~6	3500~4500	150~170

respectively. The doping of the active layer, pinchoff voltage (V_p), and other data corresponding to the identical FET's are listed in Table I. Transconductance was measured at the bias condition for a drain voltage of $V_D = 3.0$ V and at half the saturated drain current. Fig. 4 shows that the p-$Al_{0.3}Ga_{0.7}As$ buffer layer has slightly lower drain conductance than the p-GaAs buffer layer. However, an appreciable difference was observed in I_D versus V_D curves for FET's with a high-resistivity $Al_{0.3}Ga_{0.7}As$ buffer layer. The photo responses of the dc characteristics are shown in Fig. 5. No perceptible change in I_D versus V_D curves could be seen in the FET with the p-$Al_{0.3}Ga_{0.7}As$ buffer layer whether or not it was illuminated, while a significant increase in I_D as well as looping promotion was observed for the FET with the high-resistivity $Al_{0.3}Ga_{0.7}As$ buffer layer when it was illuminated. This is attributed to carrier emission from deep levels at the n-GaAs/$Al_{0.3}Ga_{0.7}As$ interface.

To gain more information about the properties of high-resistivity $Al_{0.3}Ga_{0.7}As$, PL spectra were measured at 4.2 K. The excitation source used in PL measurement was a chopped 514.5-nm line of an Ar ion laser. The typical output power of the Ar ion laser was 0.1 W and the light incident upon the sample was focussed on the sample surface to about 0.2-mm diameter. The detectors used in these PL measurements were a GaAs photocathode for the wavelength range of 500–900 nm and Ge for 900–2000 nm. The PL spectra for p-$Al_{0.3}Ga_{0.7}As$ and high-resistivity $Al_{0.3}Ga_{0.7}As$ are shown in Fig. 6 by solid and broken lines, respectively. In the spectra for p-$Al_{0.3}Ga_{0.7}As$, a band edge emission peak (1.865 eV) and a donor-to-acceptor transition peak (1.833 eV) were observed in the short wavelength range but no other peak in the longer wavelength range. This confirms the good quality of the epitaxial layers grown in our MOVPE technique. In the spectra for the high-resistivity $Al_{0.3}Ga_{0.7}As$, however, significant reduction of the PL intensity and also larger full width at half maximum were observed for the band edge emission peak at 1.873 eV. Moreover, emissions from the oxygen-related deep levels [10] were observed with broad peaks at 1.15 and 0.97 eV. SIMS analysis also showed that the oxygen signal intensity of high-resistivity $Al_{0.3}Ga_{0.7}As$ was larger than that of p-$Al_{0.3}Ga_{0.7}As$, especially at the n-GaAs/$Al_{0.3}Ga_{0.7}As$ heterointerface.

From the dc characterization and the PL measurement described above, the microwave characterization of the FET's with high-resistivity $Al_{0.3}Ga_{0.7}As$ buffer layers was later omitted.

IV. Microwave Performance

To establish a more definite correlation between the Al composition of the buffer layer and device performance, maximum available gains (MAG's) were compared at microwave frequency. The MAG's were obtained from the measured scattering parameters (S-parameters) at 26.5 GHz. The gate width of the FET used in the present S-parameter measurement was 200 μm. The bias conditions were $V_D = 6$ V and half the saturated drain current. MAG's are plotted as functions of the free-carrier concentration in the active layer of the FET in Fig. 7 for FET's with p-GaAs buffer layers and p-$Al_{0.3}Ga_{0.7}As$ buffer layers. Though measured values are somewhat scattered for identical carrier concentrations, a gross interpolation could be performed for each type of FET. From the two interpolated lines, it is deduced that MAG is proportional to the free-carrier concentration. A significant improvement of about 1.5 dB to a magnitude up to 5.2 dB is obtained with the p-$Al_{0.3}Ga_{0.7}As$ buffer layer. MAG's versus V_p are plotted in Fig. 8 for the FET's shown in Fig. 7. It should be noted that the shallower the V_p, the higher the MAG obtained. Thus, both a thinner active layer and a p-$Al_{0.3}Ga_{0.7}As$ buffer layer produce improved FET performance.

Now the roles of the buffer layers are compared through FET microwave performance. The observed improvement is explained as follows: When the FET is operated at the bias condition of the saturated drain current range, current injection into the buffer/substrate from the chan-

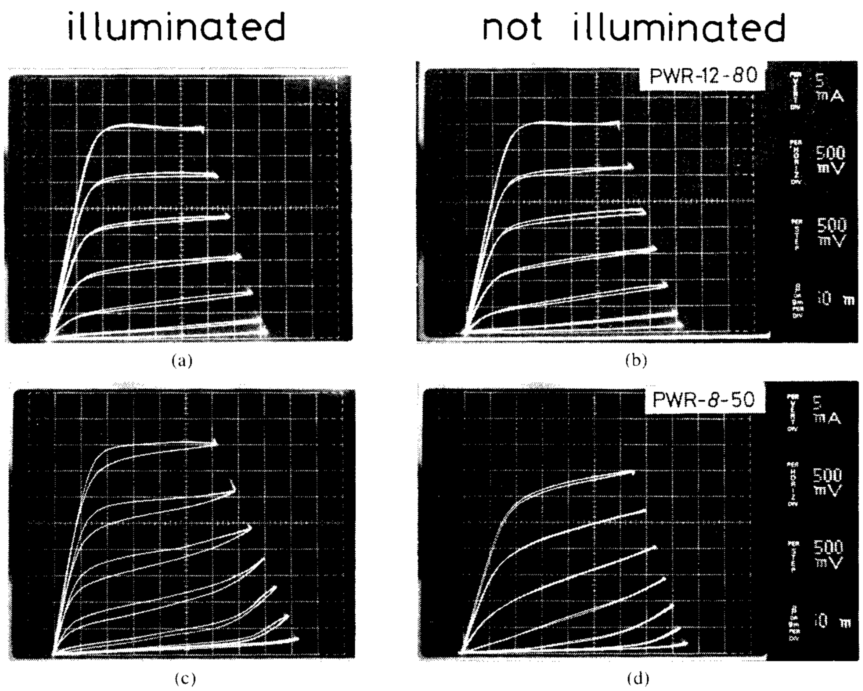


Fig. 5. Photo responses of the FET. (a) and (b) are of the FET with p-$Al_{0.3}Ga_{0.7}As$ buffer layer and (c) and (d) are of the FET with high-resistivity $Al_{0.3}Ga_{0.7}As$ buffer layer. Vertical scale: 5 m A/div, horizontal scale: 0.5 V/div; gate step voltage: 0.5 V.

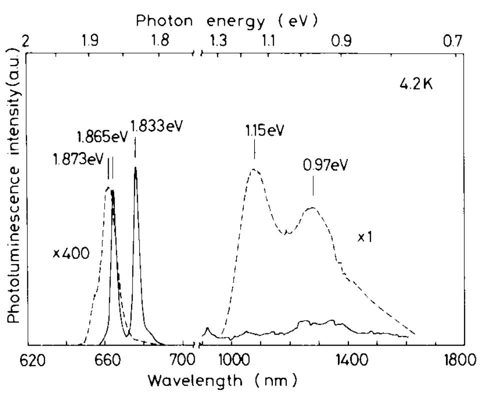


Fig. 6. Photoluminescence spectra for p-$Al_{0.3}Ga_{0.7}As$ (solid line) and high resistivity $Al_{0.3}Ga_{0.7}As$ (broken line).

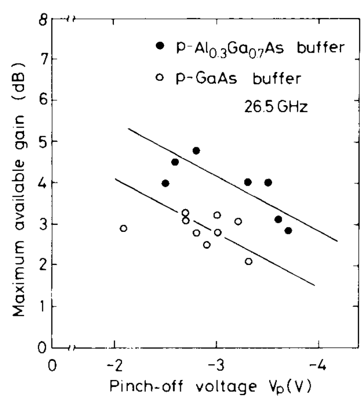


Fig. 8. Maximum available gain versus pinchoff voltage (V_p).

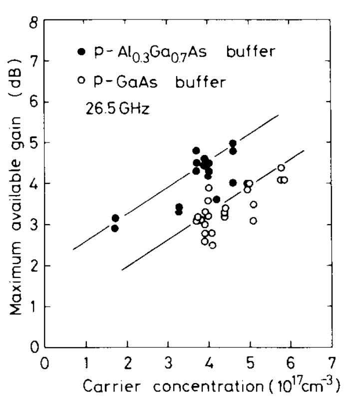


Fig. 7. Maximum available gain versus carrier concentration at 26.5 GHz.

nel region is suppressed by the $Al_xGa_{1-x}As$ buffer layer, and the parasitic increase of the electron concentration in the gate–drain active region is reduced. Thus, smaller drain–gate capacitance, as well as lower drain conductance, can be realized and contributes to MAG enhancement. The drain conductance and drain–gate capacitance for the FET's with a p-$Al_{0.3}Ga_{0.7}As$ buffer layer were around 10 mS/mm and 0.03 pF, respectively, whose magnitudes were found to be 20–30 percent smaller than those magnitudes of the FET's with a p-GaAs buffer layer. On the other hand, both transconductance and gate–source capacitance were almost the same for both types of the FET's in this frequency range.

Further improvement can be expected by optimizing the Al composition of the $Al_xGa_{1-x}As$ buffer layer.

V. Conclusion

GaAs MESFET's with GaAs and $Al_{0.3}Ga_{0.7}As$ buffer layers grown by a newly developed MOVPE technique were fabricated. From the Hall measurements of n-GaAs grown on $Al_{0.3}Ga_{0.7}As$, it was found that there is no degradation of the electron Hall mobility. Improved performance in the microwave range was observed for FET's with p-$Al_{0.3}Ga_{0.7}As$ buffer layers. The correlation between the Al composition of the buffer layer and the microwave performance of the FET was confirmed.

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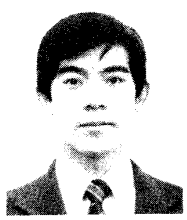

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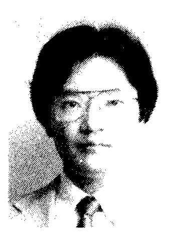

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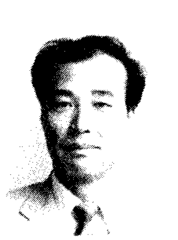

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