

Fabrication and Characterization of 0.2 μ m InAlAs/InGaAs Metamorphic HEMT's with Inverse Step-Graded InAlAs Buffer on GaAs Substrate

Dae-Hyun Kim, Sung-Won Kim, Seong-Chul Hong, Seung-Won Paek, Jae-Hak Lee, Ki-Woong Chung, and Kwang-Seok Seo

Abstract— Metamorphic InAlAs/InGaAs HEMT are successfully demonstrated, exhibiting several advantages over conventional P-HEMT on GaAs and LM-HEMT on InP substrate. The strain-relaxed metamorphic structure is grown by MBE on the GaAs substrate with the inverse-step graded InAlAs metamorphic buffer. The device with 40% indium content shows the better characteristics than the device with 53% indium content. The fabricated metamorphic HEMT with 0.2 μ m T-gate and 40% indium content shows the excellent DC and microwave characteristics of $V_{th}=-0.65V$, $g_{m,max}=620$ mS/mm, $f_T=120GHz$ and $f_{max}=210GHz$.

Index Terms— GaAs, HEMT, InGaAs, metamorphic, M-HEMT, Power

I. INTRODUCTION

While InAlAs/InGaAs HEMT's (High Electron Mobility Transistors) on InP substrates exhibit the high gain and low noise characteristics at millimeter-wave frequencies, their small on-state breakdown voltages have limited their use in power applications [1-2]. Conversely, GaAs P-HEMT's show the excellent power and gain performance at microwave frequencies, but

their millimeter-wave performances are limited by the relatively small f_T (unity gain cut-off frequency) and f_{max} (maximum oscillation of frequency). These limitations can be solved by using metamorphic HEMT technologies: the growth of high In content on GaAs substrate.

For the recent years, there has been considerable interest on the development of metamorphic-based HEMT (M-HEMT) devices [3-5]. The metamorphic structures using graded In(Ga)AlAs buffer or AlGaAsSb buffer can give a free choice of lattice constant and indium composition. M-HEMT's provide the ability to tailor the lattice constant to any indium content desired, and therefore allow the device designer an additional degree of freedom to optimize the device performance with respect to high frequency gain, power, and noise.

In this paper, we show the excellent performance of InGaAs/InAlAs M-HEMT's with 40% and 53% Indium content. The device with lower indium content (40%) offers several advantages over InP-based HEMT. The relatively high band-gap of the InGaAs channel ($\sim 1eV$) reduces the impact ionization effects in the channel, and the high bandgap of the InAlAs Schottky barrier layer increases the gate turn-on voltage. These two features can improve the device power performance with the increase of the drain breakdown voltage and the operational gate voltage swing.

II. MATERIALS AND PROCESSING

Metamorphic InGaAs/InAlAs HEMT layers were grown by solid-source molecular beam epitaxy on 3 inch semi-insulating GaAs substrates. The metamorphic

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buffer consists of a 1- μ m thick inverse step-graded InAlAs layer. The InAlAs /InGaAs MHEMT epitaxial structures are shown in Fig. 1. The results of Hall measurements indicate the 2-DEG density of $3.93 \times 10^{12} \text{ cm}^{-2}$ with the mobility of $7,780 \text{ cm}^2/\text{V}\cdot\text{s}$ at 300K for sample-A (40% indium) and the 2-DEG density of $4.53 \times 10^{12} \text{ cm}^{-2}$ with the mobility of $8,000 \text{ cm}^2/\text{V}\cdot\text{s}$ at 300K for sample-B (53% indium). These results are superior to those reported for GaAs P-HEMT's, confirming the superiority of the electron transport characteristics of M-HEMT's over GaAs P-HEMT's.

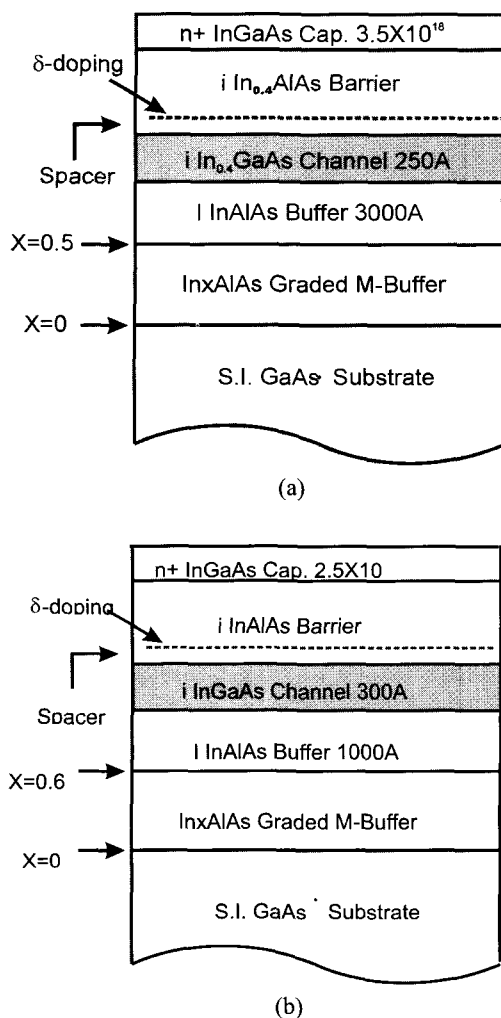


Fig. 1. Cross-section of the InGaAs/InAlAs M-HEMT structures on GaAs substrate. (a) 40% Indium Content : Sample-A (b) 53% Indium Content : Sample-B.

Device fabrication begins with mesa isolation down to the InAlAs buffer layer by the wet chemical etching using $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ mixture. For the ohmic contact formation, an image reversal photo-resist (AZ5214) was

used to achieve a well-defined profile for lift-off. To obtain the lowest contact resistance, various Ni/Ge/Au ohmic metal structures were evaporated and annealed at different temperatures and the transmission line measurements were made to extract the ohmic contact resistance. As shown in Fig. 2, the 300/800/1000Å Ni/Ge/Au metal structures, annealed at 320°C for 20 seconds in H_2 ambient, drastically lowered the contact resistance to 0.1 $\Omega\cdot\text{mm}$ for InAlAs/InGaAs metamorphic structure. The double e-beam exposure method was applied to define 0.2 μ m T-gate with PMMA/P(MMA-MAA)/PMMA tri-layer photo-resist in order to improve lift-off [6]. After the wet gate recess using diluted citric acid, the gate Schottky metals were e-gun evaporated with Ti/Pt/Au(5000 Å). In the final step, RPECVD Si_3N_4 and thick Ti/Au contact were deposited for device passivation and microwave probing pads [7].

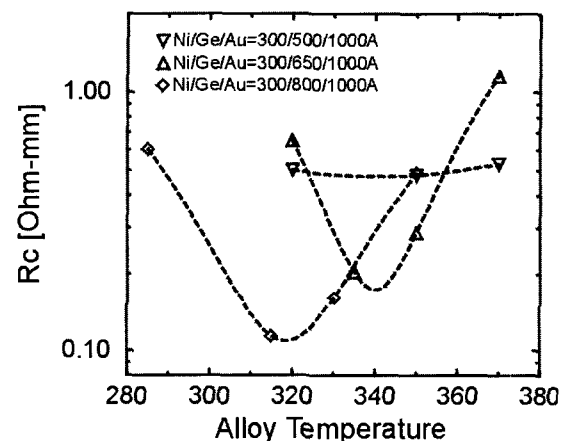


Fig. 2. Contact resistance (R_c) versus the alloy temperatures for the various Ni/Ge/Au structure.

III. DC AND RF CHARACTERISTICS

The 0.2 μ m T-Gate metamorphic HEMT's were characterized on-wafer for dc and microwave performance. The output I-V transfer characteristics are shown in Fig. 3. The M-HEMT's with 40% indium content exhibit I_{dss} of 400mA/mm and $g_{\text{m,max}}$ of 630mS/mm with low output conductance ($G_o=5\text{mS/mm}$ @ $V_{\text{gs}}=0\text{V}$ & $V_{\text{ds}}=1.5\text{V}$). The M-HEMT's with 53% indium content show somewhat higher $g_{\text{m,max}}$ of 700mS/mm, but output conductance ($G_o=60\text{mS/mm}$ @ $V_{\text{gs}}=0\text{V}$ & $V_{\text{ds}}=1.5\text{V}$) is about twelve times higher

than that of 40% indium content's device. This means that as the indium content increases the carrier transport property is improved but the device gain characteristics are mainly limited by the impact ionization in the InGaAs channel. All devices show little kink effect that is often observed in the LM-HEMT's on InP substrate [8].

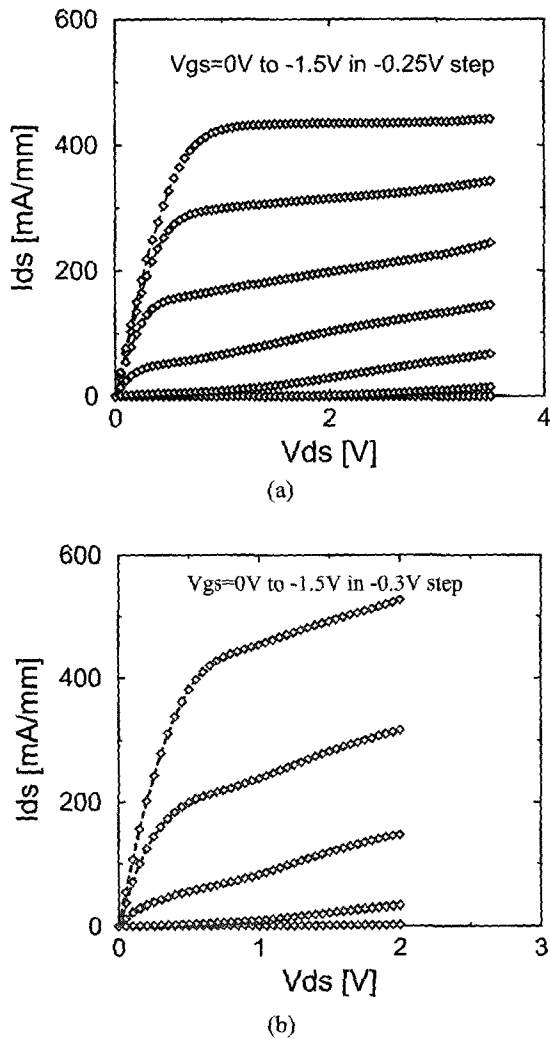


Fig. 3. Typical DC transfer I-V characteristics of the M-HEMT's. A 40% In M-HEMT's show that low output conductance and little kink effect. (a) 40% Indium content : Sample-A (b) 53% Indium content : Sample-B

Fig. 4 shows the performance of the Schottky gate device in the reverse bias and forward bias. When the indium content is reduced to 40%, the device exhibits a high gate reverse breakdown voltage of -5.2V measured at 1mA/mm of gate current. In addition, the significant improvement in the forward gate diode characteristic

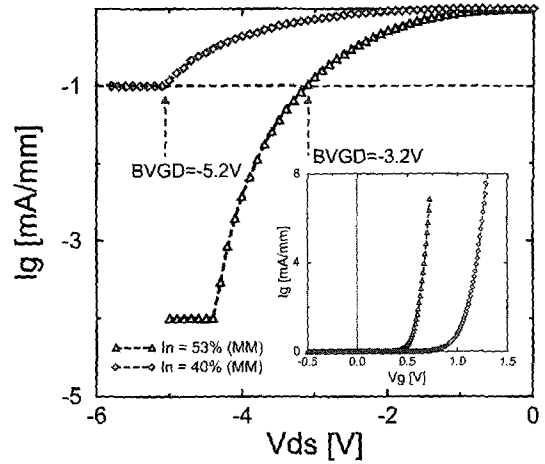


Fig. 4. The Schottky Gate characteristics. A 40% In M-HEMT's show BVGD of -5.2V and turn-on voltage of 1.0V .

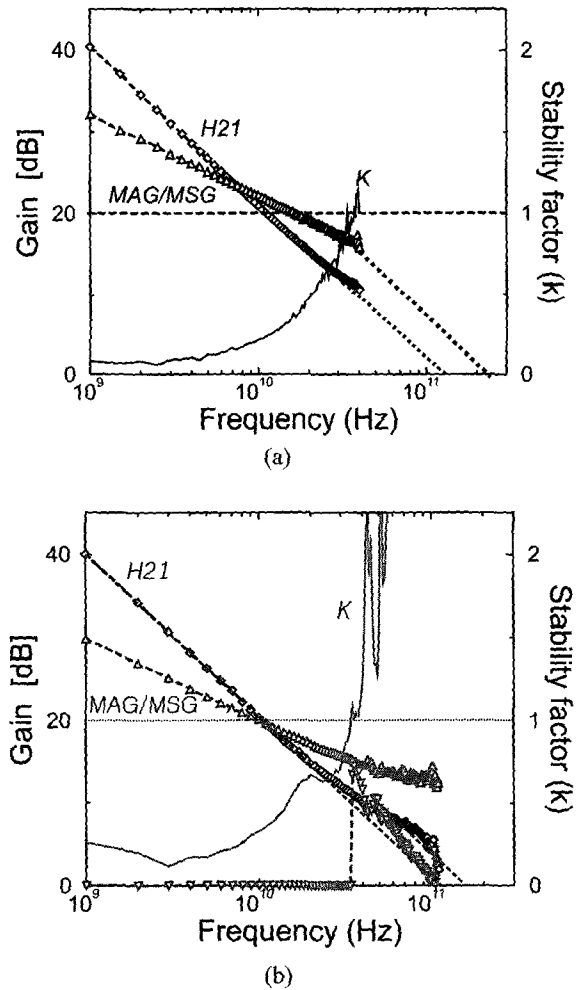


Fig. 5. Current gain H_{21} and Power Gain MAG/MSG versus frequency for the $0.2\mu\text{m}$ M-HEMT's biased at the peak transconductance.

occurs with the Schottky turn-on voltage of 1.0V . These are related to the increase of the Schottky barrier height.

These two features enable to increase the operating gate voltage swing and therefore give rise to higher output power density, especially in the enhancement-mode power device.

The small-signal scattering parameters (S-parameters) of 2x100 μ m wide M-HEMT's were measured using on-wafer probing and network analyzer (1 ~ 50GHz). With 40% indium content in the InGaAs channel layer, the better microwave performance is observed. Fig. 5. (a) shows the microwave characteristics for the sample-A (40% indium). A current gain cut-off frequency f_T of 120GHz and an f_{max} of 210GHz are extrapolated from the H_{21} and the maximum available gain (MAG) for a 0.2 μ m device biased at the peak transconductance. Fig. 5. (b) shows the microwave gain characteristics for the sample-B (53% indium). A f_T of 110GHz and an f_{max} of 160GHz are extrapolated from the H_{21} and the MAG. As similar to the dc characteristics, the microwave gain is also improved as the indium content decreases due to the reduced impact ionization in the channel layer.

IV. CONCLUSION

In summary, we have successfully demonstrated the InGaAs/InAlAs M-HEMT's on GaAs substrate grown by MBE. The fabricated M-HEMT's have the channel indium content of 40% and 53%, respectively. The M-HEMT with 40% indium content exhibits an f_T of 120GHz and an f_{max} of 210GHz. This device also exhibits a high reverse breakdown voltage of -5.2V and forward gate turn-on voltage of 1.0V. These two results indicate that a higher output power density would result for the M-HEMT with 40% indium content due to the increased gate voltage swing. From the above results, the M-HEMT with 40% indium content would be a good compromise between the GaAs P-HEMT and LM-HEMT on InP substrate for power application at millimeter-wave frequency, because it enables to obtain excellent high-frequency performance, high current density, high breakdown voltage, and high gate turn-on voltage simultaneously.

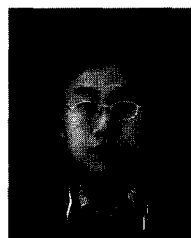
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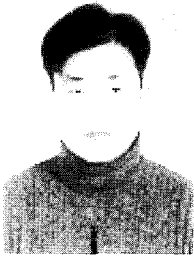
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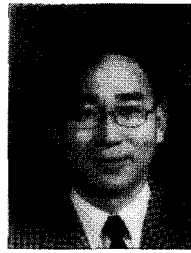
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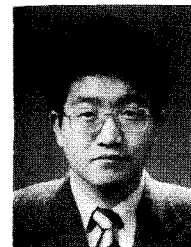
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