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Sub 0.1 μm Asymmetric Γ-gate PHEMT Process Using Electron Beam Lithography

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ABSTRACT

In this paper, we have studied on the fabrication of GaAs-based pseudomorphic high electron mobility transistors (PHEMT's) for the purpose of millimeter-wave applications.

To fabricate the high performance GaAs-based PHEMT's, we have developed unit processes, such as 0.1 μm Γ-gate lithography, silicon nitride passivation, and air-bridge process to achieve high performance of device characteristics. The DC characteristics of the fabricated PHEMT was measured at a unit gate width of 70 μm and 2 gate fingers, and showed a good pinch-off property (V_P = -1 V) and a drain-source saturation current density (I_{dss}) of 373.53 mA/mm. Maximum extrinsic transconductance (g_m) was 522.4 mS/mm at V_{gs} = -0.3 V, V_{ds} = 1.5 V, and I_{ds} = 0.5 I_{dss}.

The RF measurements were performed in the frequency range of 1.0 ~ 50 GHz. For this measurement, the drain and gate voltage were 1.5 V and -0.3 V, respectively. At 50 GHz, 9.2 dB of maximum stable gain (MSG) and 4.2 dB of S_{21} gain were obtained, respectively. A current gain cut-off frequency (f_T) of 113 GHz and a maximum frequency of oscillation (f_{max}) of 180 GHz were achieved from the fabricated PHEMT with a 0.1 μm gate length.

INTRODUCTION

Millimeter-wave resources, of which frequency is greater than 30 GHz, have been used for the military applications, such as radars, electronic warfares, guided missiles and measurements of the nuclear radioactivity. However, the role of millimeter-wave resource in commercial business is recently emphasized because a great demand emerges in commercial applications in the high-speed broadband wireless communications [1]. The rapid improvement in device performance for millimeter-wave applications can be attributed to progress in both the epitaxy of heterostructures and processing technology. Therefore, much effort is being made aggressively on the technology development for the millimeter-wave modules and systems. Recently, new material-based HEMT's, such as InAlAs/InGaAs/InP HEMT's, show the highest cut-off frequency and the lowest microwave noise of all three terminal semiconductor devices [2-4].

For this reason, it is widely believed that they are one of the promising devices for millimeter-wave low-noise applications, and however, are still under research stage because of the high production cost, the technology immaturity and low breakdown voltage. Therefore, conventional GaAs-based PHEMT's are still one of the key active devices for millimeter-wave circuits, and modules [5]. In this paper, we report the DC and RF characteristics of the fabricated PHEMT using the asymmetric Γ-shaped gate structures with a 0.1 μm gate-length.

FABRICATION TECHNOLOGY

The PHEMT epitaxial structure was grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate and consists of the following layers: a 1 μm undoped GaAs buffer, a 120 Å undoped $In_{0.2}Ga_{0.8}As$ channel, a 40 Å undoped $Al_{0.25}Ga_{0.75}As$ spacer layer, delta doping plane (5×10^{12} cm $^{-2}$), a 250 Å undoped $Al_{0.25}Ga_{0.75}As$ Schottky contact layer, a 300 Å n-type doped GaAs cap (5×10^{18} cm $^{-3}$). A schematic cross-section view of the PHEMT's structure is given in Fig. 1.

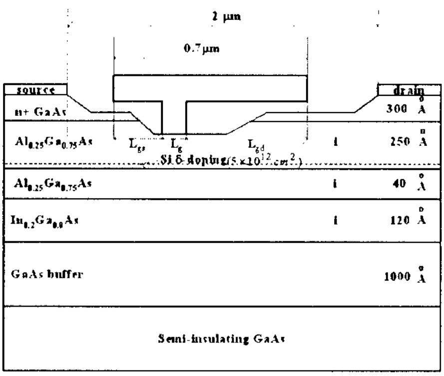

Fig.1 Schematic cross-sectional view of the PHEMT's.

The epitaxial layers showed a 2 dimensional electron carrier density of 2.1×10^{12} cm^2 and Hall mobility of 6670 cm^2/V-s at the room temperature. The PHEMT's were designed to have the off-set gate structures, which normally exhibit the high transconductance and the low gate-source resistance. The relation between the intrinsic transconductance(g_m) and the measurable transconductance(g_m') of the PHEMT's is given by equation 1. Therefore, it is expected that an enhanced g_m' can be achieved at a low gate-source resistance of the Γ-shaped gate.

The gate-source resistance can reduce by minimizing the source-gate spacing [6].

$$g_m' = \frac{g_m}{1 + R_{gs} g_m} \qquad (1)$$

As shown in Fig. 1, the Γ-shaped gate structures were employed to obtain a sufficient space-margin between the source and the gate-heads. For this purpose, the design parameters of 0.1 μm gate length, 2.0 μm source-drain spacing, 0.7 μm gate-head length, and 0.75 μm source-gate spacing were adopted, respectively, for the transistor structure. The PHEMT's were fabricated 3500 Å mesa for electric isolation using the etchants of $H_2SO_4/H_2O_2/H_2O$ (1 : 8 : 160) and AuGe/Ni/Au (1150/280/1600 Å) ohmic metallization with a specific contact resistance of around 1~2 × 10^{-7} Ω·cm. Ohmic alloy was performed by the two-step rapid thermal annealing at 300 and 350 °C for 10 and 20 seconds, respectively. 0.1 μm offset Γ-gate patterning was done by electron beam lithography using a Leica Microsystems Ltd Electron Beam Pattern Generator (EBPG-4HR system) operating at an acceleration voltage of 50kV, a beam size of 50 nm and a beam current of 1 nA. Resist profiles with an overhang structure for metal liftoff and 0.1 μm offset Γ-gate with electron beam resists of a tri-layer structure consisting of PMMA 4%+MCB/ P(MMA-MAA) / PMMA 4% (1000/6000/2000 Å). Selective etching is an important step in processing GaAs/AlGaAs structures because the etched depth is limited within a few hundred angstroms and critically affects the threshold voltage of devices. The gate recess profiles were controlled by a two-step wet-etching method using the 50 % citric acid solution $/H_2O_2/H_2O$ (1 : 3 : 1). Fig. 2 shows the surface quality on the etched samples by using an AFM and SEM.

In our AFM results, the surface etched by the selective etchant of 50 % citric acid solution $/H_2O_2/H_2O$ (1 : 3 : 1) solution is smoother than that by another volume ratio etchants.

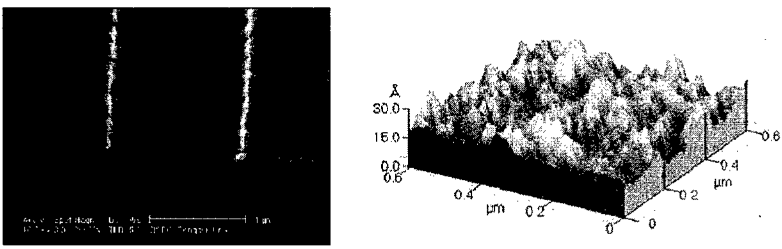

Fig. 2 SEM and AFM images taken from the surfaces etched by a solution of 50 % citric acid solution$/H_2O_2/H_2O$ (1 : 3 : 1).

After Ti/Au (500/4500 Å) gate metallization , the devices were fully passivated by 800 Å Si_3N_4 deposited at the RF plasma enhanced CVD (PECVD) system. A SEM micrograph of 0.1 μm offset Γ-gate after lift-off and passivating with a Si_3N_4 film is shown in Fig. 3.

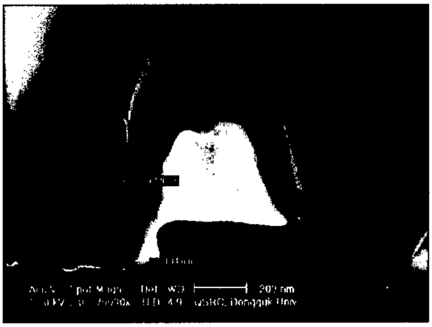

Fig.3 SEM micrograph showing 0.1 μm offset Γ-gate after lift off and passivating with a Si_3N_4. film.

As shown in Fig. 4, air-bridge metals of the Ti/Au (200/15000 Å) were then formed after patterning the dielectric and photo-resist to interconnect the isolated electrodes [7]. Fig. 5 shows the micrograph of the fabricated PHEMT's of 70 μm unit gate width and 2 fingers.

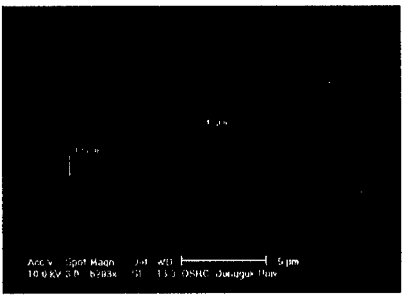

Fig.4 SEM micrograph of the air-bridge interconnections.

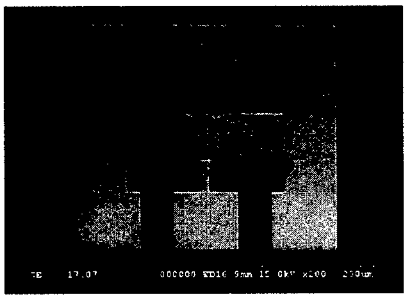

Fig.5 Plan view SEM micrograph the fabricated 70 μm × 2 PHEMT's.

RESULTS AND DISCUSSION

The DC and RF characteristics of the fabricated PHEMT's were measured by a HP 4156A DC parameter analyzer and a HP 8510C network analyzer. The DC characteristics of the offset PHEMT's with L_{gd} = 1.15 μm and L_{gs} = 0.75 μm are shown in Fig. 6, 7. The current-voltage characteristics of the 70 μm unit gate width with 2 gate fingers are given in Fig. 6. From this measurement results, we obtained a pinch-off property (V_P = -1 V) and a drain-source saturation current (I_{dss}) of 52.3 mA. The maximum drain current density that is defined as the saturation current density measured at a gate-to-source voltage (V_{gs}) of 0V is 373.53 mA/mm.

The maximum extrinsic transconductance (g_m') is 522.4 mS/mm at V_{ds} = 1.5 V and V_{gs} = -0.3V, as shown in Fig. 7.

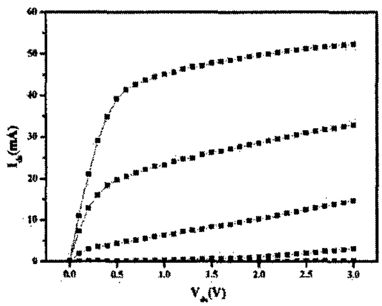

Fig. 6 I_{ds} Vs. V_{ds} characteristics of PHEMT's.

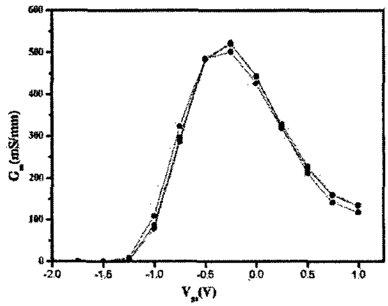

Fig. 7 Transconductance characteristics of PHEMT's.

The RF measurements were performed in a frequency range of 1.0 ~ 50 GHz. For this RF measurement, the drain and gate voltages of 1.5 V and –0.3 V were used, respectively.

At 50 GHz, a maximum stable gain (MSG) of 9.2 dB and a S_{21} gain 4.2 dB were obtained.

A current gain cut-off frequency (f_T) of 113 GHz and a maximum frequency (f_{max}) 180 GHz were achieved from the fabricated PHEMT's of 0.1 μm gate length. Fig. 8 shows a plot of S_{21} gain, the current gain H_{21}, G_{ms}(maximum stable gain), U(Unilateral power gain) versus the frequency. The f_T and f_{max} were calculated using the H_{21} and the G_{ms} values at 50 GHz by an extrapolation of -6 dB/octave.

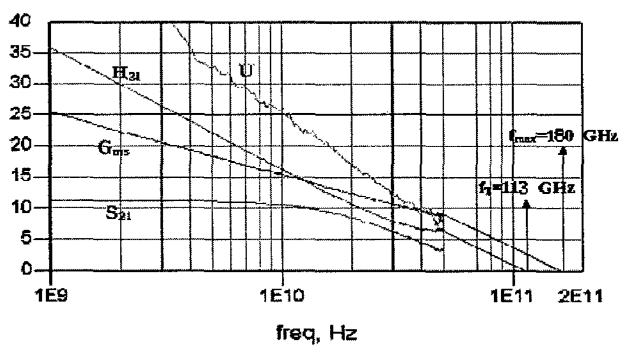

Fig. 8 RF characteristics of the fabricated PHEMT's.

CONCLUSIONS

We have fabricated the GaAs-based 0.1 μm Γ-gate PHEMT's for millimeter-waves. To fabricate the PHEMT's we carried out development of unit processes such as 0.1 μm Γ-gate lithography, gate recess, silicon nitride passivation and air-bridge process. f_{max} of 180 GHz, f_T of 113 GHz and good DC characteristics such as the pinch-off property (V_p = -1V) were achieved by applying an offset Γ-gate and recess technology using an electron beam lithography and the mixed etchant of 50 % citric acid solution/H_2O_2/H_2O (1 : 3 : 1) for PHEMT's grown by MBE.

ACKNOWLEDGEMENT

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