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Design and Fabrication of the 0.1 μm Γ-Shaped Gate PHEMT's for Millimeter-Waves

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Abstract

We studied 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 performed the simulation to analyze the designed epitaxial-structures. Each unit processes, such as 0.1 μm Γ-gate lithography, silicon nitride passivation and air-bridge process were developed to achieve high performance device characteristics. The DC characteristics of the PHEMT's were measured at a 70 μm unit gate width of 2 gate fingers, and showed a good pinch-off property (V_P = -1.75 V) and a drain-source saturation current density (I_{dss}) of 450 mA/mm. Maximum extrinsic transconductance (g_m) was 363.6 mS/mm at V_{gs} = -0.7 V, V_{ds} = 1.5 V, and I_{ds}=0.5I_{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 -0.7 V, respectively. At 50 GHz, 9.2 dB of maximum stable gain (MSG) and 3.2 dB of S_{21} gain were obtained, respectively. A current gain cut-off frequency (f_T) of 106 GHz and a maximum frequency of oscillation (f_{max}) of 160 GHz were achieved from the fabricated PHEMT's of 0.1 μm gate length.

Ⅰ. 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]. 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 show highest cut-off frequencies 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, 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 for the 0.1 μm gate-length PHEMT gates fabricated using the Γ-shaped off-set gate structures.

Ⅱ. DESIGN OF THE PHEMT'S

The epitaxial structure of the GaAs PHEMT's used in this studies was grown as follows. A top the 4-inch semi-insulating GaAs substrates, 10000 Å undoped GaAs buffers, 120 Å undoped $In_{0.2}Ga_{0.8}As$ channels, 40 Å undoped $Al_{0.25}Ga_{0.75}As$ spacers, silicon delta doped ($5 \times 10^{12} cm^2$) layers, 250 Å undoped $Al_{0.25}Ga_{0.75}As$ layers and 300 Å highly n-type doped GaAs caps ($5 \times 10^{18} cm^3$) were sequentially grown. These epitaxial layers showed a 2 dimensional electron carrier density of $2.1 \times 10^{12} cm^2$ and Hall mobility of 6670 cm^2/V-sec at room temperature.

The PHEMT's were designed to have the off-set gate structures, which normal exhibit the high transconductance and the low gate-source resistance. The relation between the intrinsic transconductance(gm) and the measurable transconductance(g_m') of the PHEMT's is given by equation (1). Therefore, it is expected that an enhanced gm' can be achieved at a low gate-source resistance of the Γ-shaped gate. The gate-source resistance can be reduced by minimizing the source-gate spacing[6].

$$g_m = \frac{g_m}{1+R_{gs} g_m} \tag{1}$$

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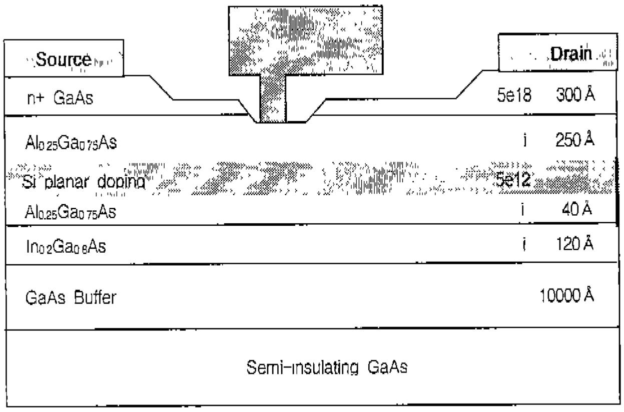


Fig. 1. A cross-sectional schematic of the 0.1 μm Γ-gate PHEMT's.

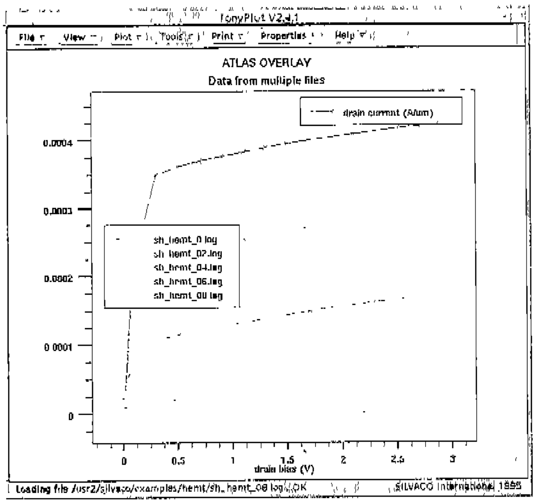
As shown in Fig. 1, the Γ-shaped gate structures were employed to obtain a sufficient space-margin between the source and the gate-heads. For this purpose, the design parameter of 0.1 μm gate length, 2.0 μm source-drain spacing, 0.8 μm gate-head length, and 0.65 μm source-gate spacing were adopted, respectively, for the transistor structure.

Fig. 2 shows the simulation results for the Γ-shaped gate PHEMT's of 0.1 μm gate length. In Fig. 2(a), I_{dss} of 420 mA/mm, pinch-off voltage(V_p) of −0.8 V, transconductance (g_m) of 625 mS/mm and knee voltage(V_k) of 0.5 V were obtained, respectively, from the ATLAS simulation. At 60 GHz, a current gain of 7.5 dB was calculated from the S-parameter extraction simulation, and a 150 GHz of cut-off frequency(f_T) was obtained, as shown in Fig. 2(b).

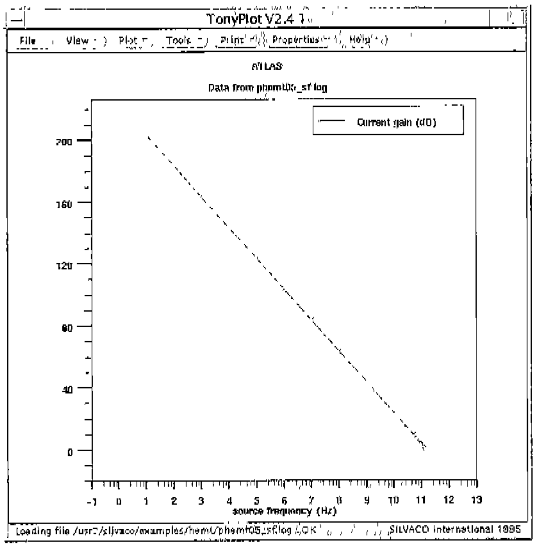
Ⅲ. FABRICATIONS OF THE PHEMT'S

To the fabricate 0.1 μm off-set gate PHEMT's, we developed the following key unit processes; 0.1 μm Γ-shaped gate lithography, Si_3N_4 passivation and air-bridge process.

AuGe / Ni / Au and Ti / Au (1150 / 280 / 1600 and 500 / 4500 Å, respectively) metals were used for the drain/source and the schottky contacts for the gate electrode, respectively. Prior to the ohmic formation, 3500 Å mesa etching was carried out to isolate the devices by using $H_2SO_4 / H_2O_2 / H_2O$ (1 : 8 : 160). Ohmic alloy was performed by using the two-step rapid thermal annealing (RTA) (at 300 / 350 ℃ for 10 / 20 seconds), and a low specific contact resistance of $1 \times 10^{-7}\ \Omega \cdot cm^2$ was obtained. The 0.1 μm Γ-gates, as shown in Fig. 3, were patterned by the triple-layer resist PMMA(4%+MCB) / P(MMA-MAA) / PMMA(4%) (1000 / 6000 / 2000 Å) at an 50 KeV electron-beam lithography system (Leica EBPG-4HR). The gate recess profiles were controlled by a two-step wet-etching method using the citric acid / H_2O_2 / H_2O / FC-93 (1 gr : 1 ml : 310 ml : 0.4 ml). After the gate fabrication, the devices were fully passivated by 800 Å Si_3N_4 deposited at a RF plasma enhanced CVD (PECVD) system.



(a) Simulation results of the Ids vs. Vds (V_{gs} = −0.8 ~ 0 V, step = 0.2 V)



(b) Simulation results of the current gains

Fig. 2. Simulation results of the 0.1 μm Γ-gate PHEMT's.

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

Ⅳ. MEASUREMENT/RESULTS

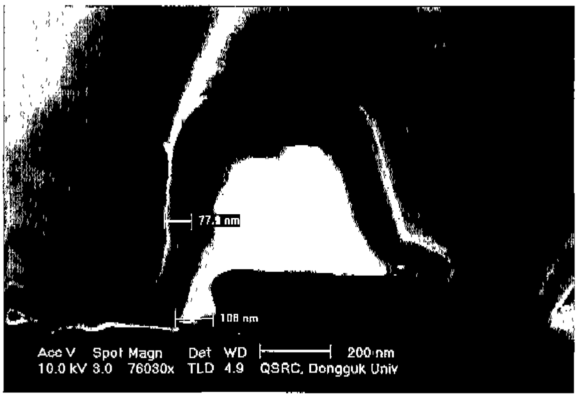


Fig. 3. SEM micrograph of the 0.1 μm Γ-shaped gate.

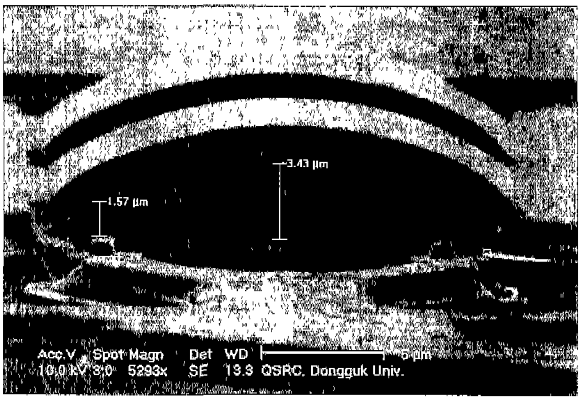


Fig. 4. SEM micrograph of the air-bridge interconnections.

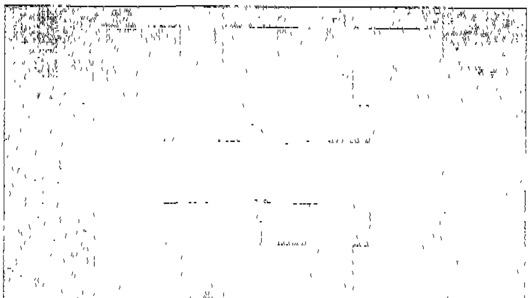
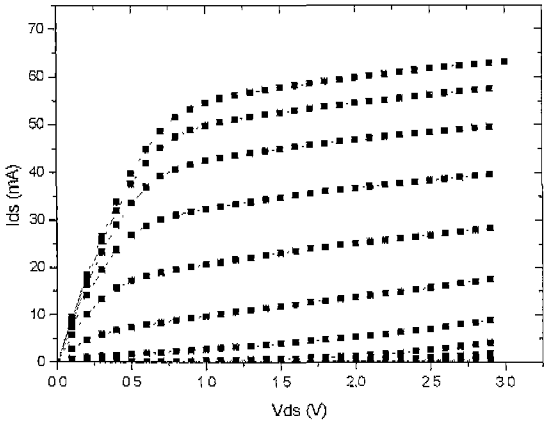
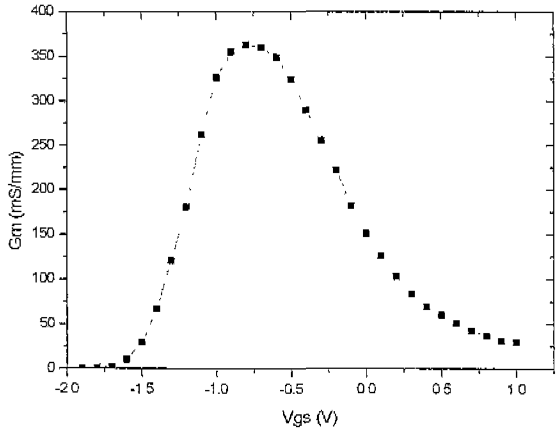


Fig. 5. Plan-view SEM micrograph of the fabricated 70 μm ×2 PHEMT.



(a) Ids vs. Vds characteristics of PHEMT's (70 μm × 2) (V_{gs} = −2.5 ~ 0 V, step : 0.25 V)



(b) Transconductance characteristics of the PHEMT's (V_{ds} = 1 V)

Fig. 6. DC characteristics of the fabricated PHEMT's.

DC and RF characteristics of the fabricated PHEMT's were examined by a HP 4156A DC parameter analyzer and a HP 8510C network analyzer. The DC characteristics of the devices were measured at 70 μm unit gate width of 2 gate fingers. From this measurement, and we obtained a good pinch-off property (V_P = −1.75 V) and a drain-source saturation current (I_{dss}) of 64 mA and drain-source saturation current density (I_{dss}) of 450 mA/mm. A maximum extrinsic transconductance (g_m) of 363.6 mS/mm was measured at $V_{gs} = -0.7$ V and $V_{ds} = 1.5$ V, and 0.5 Idss. Fig. 6 shows the DC characteristics of the fabricated PHEMT's. The RF measurements were performed in a frequency range of 1.0 ~ 50 GHz. For this RF measurement, the drain and gate voltage of 1.5 and −0.7 V was used, respectively. At 50 GHz, a maximum stable gain (MSG) of 9.2 dB and a S_{21} gain 3.2 dB were obtained. A current gain cut-off frequency (f_T) of 106 GHz and a maximum frequency of oscillation (f_{max}) of 160 GHz were achieved from the fabricated PHEMT's of 0.1 μm gate length. Fig. 7 shows a plot of S_{21} gain, the current gain H_{21}, G_{ms}(maximum stable gain), U(unilateral power gain) versus the frequency, and Fig. 8 the variation of show stability factor obtained by the measured

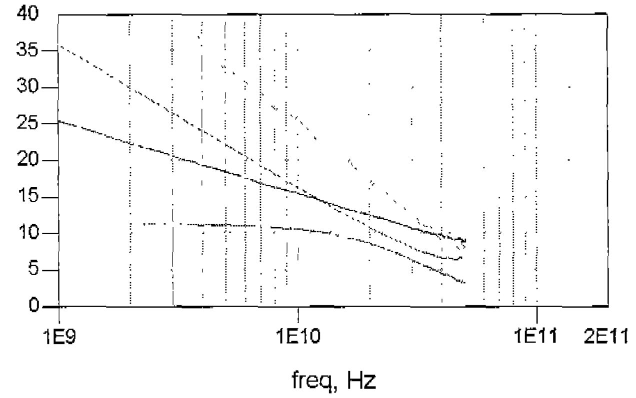


Fig. 7. RF characteristics of the fabricated PHEMT's.

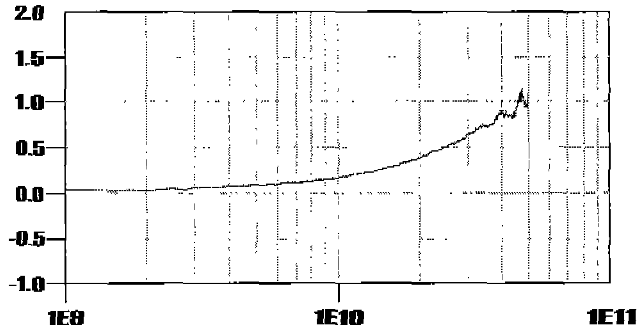


Fig. 8. Stability factor of the fabricated PHEMT's.

S-parameters. The f_T and f_{max} were calculated using the H_{21} and the Gms values at 50 GHz by an extrapolation of 6 dB/octave.

V. CONCLUSION

We have fabricated the GaAs-based 0.1 μm Γ-gate PHEMT's for millimeter-wave. To fabricate the PHEMT's, we carried out development of unit processes such as 0.1 μm Γ-gate lithography, silicon nitride passivation and air-bridge process.

The follow is DC characteristics from the fabricated 0.1 μm Γ-gate PHEMT's (70 μm unit gate width and 2 gate fingers); V_p of −1.75 V, I_{dss} of 63 mA, maximum g_m of 363.6 mS/mm(at V_{gs} = −0.7 V and V_{ds} = 1.5 V and 0.5 I_{dss}). From RF measurement, at 1.0 ~ 50 GHz, MSG of 9.2 dB, S_{21} gain of 3.2 dB, cut-off frequency(f_T) of 106 GHz, and f_{max} of 160 GHz were obtained. We consider that fabricated PHEMT's have good characteristics and possible millimeter application.

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