Low-Noise Metamorphic HEMTs With Reflowed 0.1-μm T-Gate

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***Abstract*—A 0.1-μm T-gate fabricated using e-beam lithography and thermally reflow process was developed and applied to the manufacture of the low-noise metamorphic high electron-mobility transistors (MHEMTs). The T-gate developed using the thermally reflowed e-beam resist technique had a gate length of 0.1 μm and compatible with the MHEMT fabrication process. The MHEMT manufactured demonstrates a cutoff frequency f_T of 154 GHz and a maximum frequency $f_{\max}$ of 300 GHz. The noise figure for the 160 μm gate-width device is less than 1 dB and the associated gain is up to 14 dB at 18 GHz. This is the first report of a 0.1 μm MHEMT device manufactured using the reflowed e-beam resist process for T-gate formation.**

***Index Terms*—Cutoff frequency, e-beam, gate length, maximum frequency, metamorphic high electron-mobility transistors (MHEMTs), noise figure (NF), T-gate, thermally reflow.**

I. INTRODUCTION

FOR THE high-frequency wireless applications, metamorphic HEMTs (MHEMTs) using an $In_xAl_{1-x}As$–$In_xGa_{1-x}As$ heterostructure grown on GaAs substrate [1], [2] constitutes a good alternative to pseudomorphic AlGaAs–InGaAs–GaAs HEMTs (PHEMTs) and to lattice matched InAlAs–InGaAs–InP HEMTs (InP-HEMTs). For the MHEMT devices, a strain relaxed, compositionally graded metamorphic buffer layer is used to accommodate the large lattice mismatch between the top layers and the substrate. The MHEMT has received much attention recently due to its capability to combine the advantage of the InP-based structure and the GaAs substrate and has demonstrated excellent electrical performance for high-frequency applications [3], [4]. In order to achieve superior RF performance for high-frequency applications, short gate length is required for the compound semiconductor field effect transistors. The gain and noise characteristics of the MHEMTs at high frequency are strongly dependent on the gate length (Lg) and the gate resistance values. T-shaped gates are generally used for the HEMTs to maximize the device performance.

Manuscript received January 12, 2004. This work was supported by the National Science Council of Taiwan, R.O.C., under Contract NSC912215E009036. The review of this letter was arranged by Editor D. Ritter.

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Digital Object Identifier 10.1109/LED.2004.829027

Different lithography methods have been developed for the submicrometer T-gates in recent years [5], [6]. For example, multilayer photo resist processes have been used to obtain submicrometer T-shaped gates [7]. In order to further improve device performance, dielectric deposition process with etching back technology have been widely used to form dielectric sidewall and shrink the gate length that is originally limited by the lithography resolution [8]. However, tightly controlled process and relatively complicated steps with long process time are required for these processes.

The thermally reflowed resist process is another approach for gate shrinkage and has previous been reported [9], [10]. However, thermally reflow of e-beam photo resist to achieve sub-0.1-μm T-gate for MHEMT application has never been reported. In this study, resist profile for 0.1-μm T-shaped gate was achieved by thermally reflowing the bilayer e-beam resist using hotplate and the 0.1-μm T-shaped gate was achieved by the standard lift off process and was applied to the MHEMT manufacture. Comparing with a two-step lithography of hybrid T-shaped gate [11] and Y-shaped gate [12], the reflowed gate process is a much simpler, relatively inexpensive and flexible process. Additionally, it is also free of plasma damage and is compatible with the MHEMT process for high-frequency application.

II. PROCESS FLOW

The $In_{0.53}Al_{0.47}As$–$In_{0.53}Ga_{0.47}As$ MHEMT uses $In_xAl_{1-x}As$ as the buffer layer between the GaAs substrate and the InP lattice-matched HEMT structure and was grown by the molecular beam epitaxy (MBE) method on the 3-in diameter GaAs substrate. The sequence for the device fabrication is as follows. The mesas were isolated by wet chemical etch and the ohmic contacts were formed by evaporating Au–Ge–Ni–Au on heavily doped InGaAs layer and then alloyed at 320 °C using rapid thermal annealing. The contact resistance as measured by the transmission line model method was 0.04 Ωmm. For the reflowed T-gate process, the bi-layer resist which consist of polymethylmethacrylate (PMMA) and polymethyl methacrylate-methacrylic acid P(MMA-MAA) was exposed first by e-beam lithography (Leica EBML300) with an opening of 0.25 μm, and then went through thermally reflow treatment at 115 °C on a hotplate for 60 s to reduce the opening to 0.1 μm. The liftoff profile was obtained due to the bottom resist PMMA was successfully shrunk to form the desired footprint opening of 0.1 μm without any obvious change on the top P(MMA-MAA) layer after thermal treatment. In addition, the reflow condition was optimized after testing different

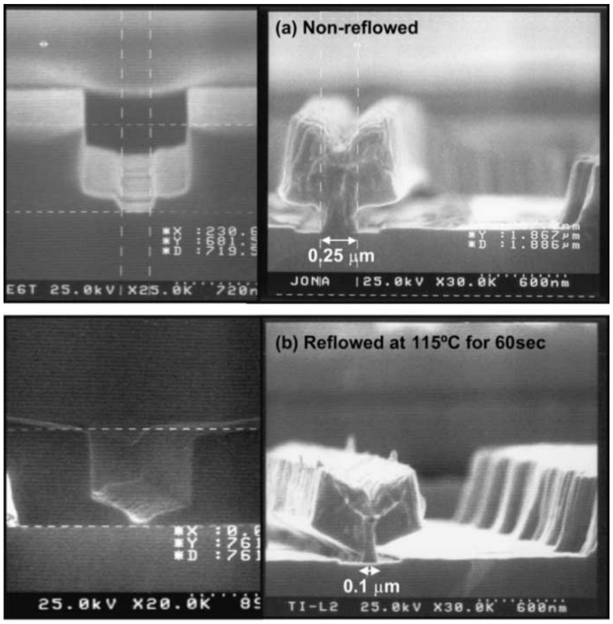

Fig. 1. Scanning electron microscopy micrograph. (a) Conventional e-beam resist and its 0.25-μm T-gate. (b) The resist after shrinking by thermally reflow and its 0.1-μm T-gate.

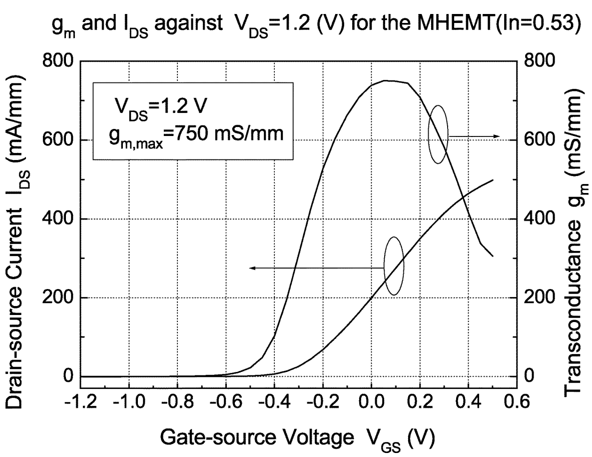

Fig. 2. Transconductance of the $0.1\ \mu\text{m} \times 160\ \mu\text{m}$ MHEMT.

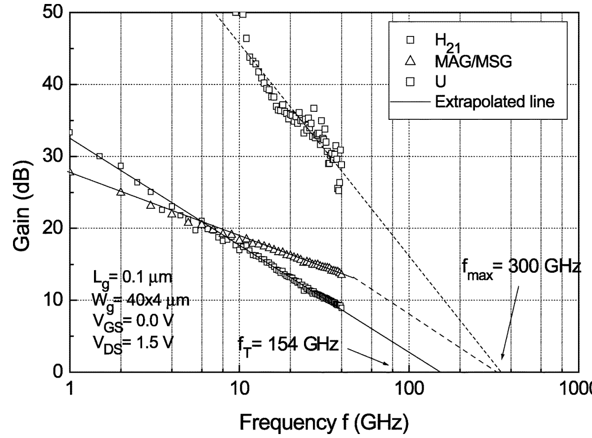

Fig. 3. Typical current gain H_{21}, MAG/MSG, and unilateral gain U as a function of frequency of the $0.1 \times 160\ \mu$m MHEMT.

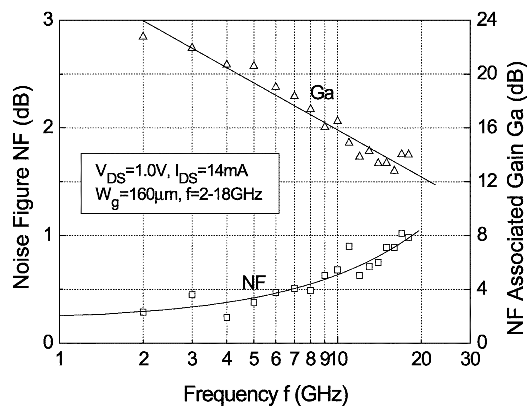

Fig. 4. Noise figure and associated gain as a function of frequency at $V_{\rm DS} = 1$ V and $I_{\rm DS} = 14$ mA of the $0.1 \times 160\ \mu$m MHEMT.

temperatures (from 105 to 135 °C, per step = 10 °C) and time (20, 40, 60, and 80 s). The detailed process optimization has been published in [10]. Although the reflowed temperature over 125 °C will obtain shorter gate length, there is a risk of footprint opening being closed by high temperature and long time reflow. Therefore the optimized reflow condition of 115 °C for 60 s was decided. In order to verify the reflow effect, MHEMTs with nonreflowed T-gate were also fabricated. Fig. 1 illustrates the cross sections of the two types of T-gate profiles. Fig. 1(a) is the e-beam resist after exposure and its 0.25 μm T-gate after liftoff. Fig. 1(b) is the resist after thermal reflow and its 0.1-μm T-gate after liftoff. As shown in Fig. 1(b), the e-beam resist profile after thermal reflow was very ideal for liftoff and T-gate formation.

After gate lithography process, gate recess was performed using succinic-base solution and Ti–Pt–Au (100–100–300 nm) were deposited as the Schottky gate metal and liftoff process was performed to form the T-shaped gate. As shown in Fig. 1, the recess width on the devices was about 0.13 μm for both with and without reflow samples. After T-gate formation, 100-nm-thick silicon nitride film was deposited by PECVD as the passivation layer. Finally, the airbridges were formed with 2 μm of plated Au.

III. Device Performance

The drain current and transconductance versus gate bias of the $0.1 \times 160\ \mu\text{m}^2$ MHEMT fabricated using the thermally reflowed T-gate are shown in Fig. 2. The device exhibits a good pinchoff characteristics and the saturation drain current $(I_{\rm DSS})$ is 200 mA/mm. The transconductance of the device at 1.2-V drain-source voltage is 750 mS/mm and the pinchoff voltage is -500 mV. The gate to drain breakdown voltage measured was 10-V at a gate reverse current of -1 mA/mm. The high breakdown voltage is due to lower Idss target caused by longer recess.

The *S*-parameters for the MHEMT devices were measured from 1–40 GHz and current gain H_{21}, MAG/MSG, and unilateral gain U as a function of frequency are shown in Fig. 3. The f_T and $f_{\max}$ obtained for the $0.1 \times 160\ \mu\text{m}^2$ MHEMT were 154 and 300 GHz, respectively. In addition, the measurement of the noise figure (NF) and associated gain have been performed in the frequency range between 2 and 18 GHz, and the results are shown in Fig. 4. The NF is less than 1 dB up to 18 GHz with an associated gain of 14 dB at 18 GHz.

TABLE I
SUMMARY OF DEVICE PERFORMANCE OF THE MHEMT WITH NON-REFLOWED AND REFLOWED T-GATE

T-gate type of the MHEMT	Lg(μm)	gm(mS/mm)	V_{BR}(V)	f_T(GHz)	f_{max}(GHz)	NF@18GHz (dB)
Non-reflowed T-gate	0.25	700	8	105	180	1.18
Reflowed T-gate	0.1	750	10	154	300	0.99

Table I summarizes the measured electrical performance of the $0.1 \times 160\ \mu m^2$ MHEMT and the performance was compared with the performance of the nonreflowed $0.25 \times 160\ \mu m^2$ MHEMT. Although the transconductance of the MHEMT with reflowed T-gate increased only slightly, the f_T and $f_{\max}$ were improved substantially from 105–154 GHz and from 180–300 GHz, respectively. However, the increase in transconductance is less pronounced (from 700–750 mS/mm). In other words, carriers are at their saturation velocity when current saturates and this is evident by the fact that the knee voltage at Idss is less than the pinchoff voltage in the current–voltage curve. Thus, the transconductance has less dependence on gate length and the increase in cutoff frequency mainly comes from gate–source capacitance. The improved RF performance was due to the T-gate shrinkage from 0.25 to 0.1 μm after the thermal reflow process.

IV. CONCLUSION

A thermal reflow process for e-beam bilayer resist to achieve 0.1-μm T-gate formation was successful developed and applied to the MHEMT fabrication. The $0.1 \times 160\ \mu m^2$ MHEMT fabricated demonstrated a cutoff frequency f_T of 154 GHz and a maximum frequency $f_{\max}$ up to 300 GHz, the noise figure of the fabricated MHEMT was less than 1 dB with 14 dB associated gain at 18 GHz. The excellent device performance of the 0.1 μm MHEMT manufactured demonstrated that the reflowed T-gate process is compatible with the MHEMT process and can be practically used for the MHEMT manufacturing.

ACKNOWLEDGMENT

The authors would like to thank National Nano Device Laboratories RF group for *S*-parameter measurements.

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