A High Electron Mobility Transistor with a Mushroom Gate Fabricated by Focused Ion Beam Lithography.

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Abstract

A super low noise HEMT with a mushroom-shaped quarter micron gate was fabricated by using focused ion beam lithography. The mixed exposure of Be^{++} and Si^{++} focused ion beams was used to form T-shaped resist profiles. This method has the advantages of a high reproducibility and controllability of resist profiles. The gate resistance was extremely reduced by mushroom-shaped gate. As a result, the fabricated HEMT showed a minimum noise figure (NFmin) of 0.68dB with an associated gain (Ga) of 9.7dB at 12GHz. This device also showed an NFmin of 0.83dB with a Ga of 7.7dB at 18GHz.

Introduction

The need for low-noise microwave and millimeter-wave receivers has prompted extensive research in the field of high electron mobility transistors (HEMT's). For low-noise performance, it is required to make the gate length as short as possible. The performance of the HEMT with the gate length below 0.3μm, however, does not necessarily become improved because of the increase of gate resistance. One approach to obtain a gate with both low resistance and short length is the adoption of a mushroom-shaped gate structure, which is typically fabricated by multilevel resist process using electron beam lithography[1],[2]. Although this method has succeeded in obtaining the mushroom-shaped gate[3], there still remain problems of the process complexity and the reproducibility for fine pattern delineation.

In the focused ion beam lithography, patterns as fine as the beam size can be obtained because the region which is affected by scattered ions in the material is extremely small. Moreover, ion beams have another advantage of desirable resist profile control by means of the mixed exposure of different ion species[4].

In this paper, a newly developed fabrication process for a mushroom-shaped gate using focused ion beam lithography is described. A mixed exposure of Be^{++} and Si^{++} focused ion beams in a single level resist process makes it possible to form the mushroom structure, which can be realized very uniformly and repeatedly. As the result, the fabricated HEMT showed excellent noise performance.

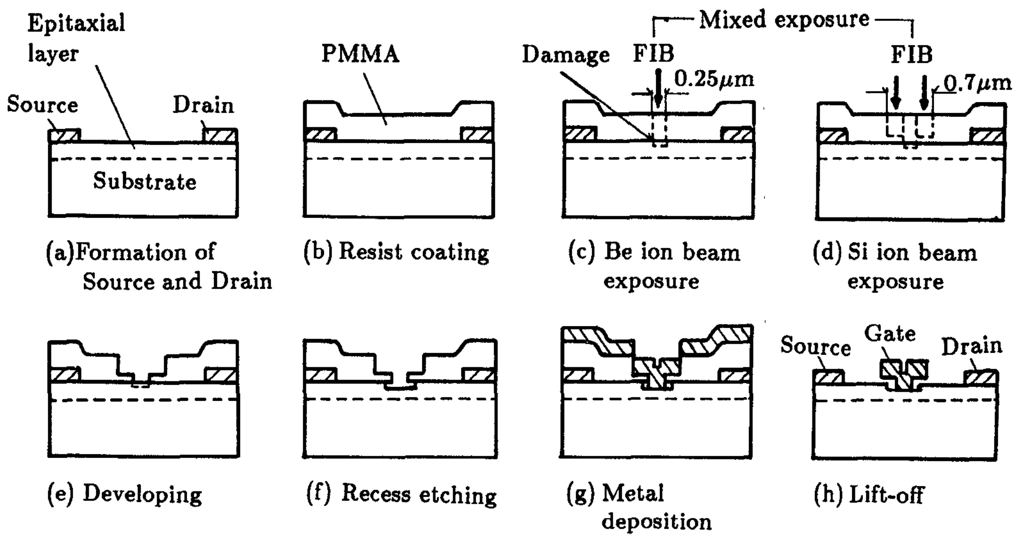

Fig.1 Process flow of mushroom shaped gate fabrication using FIB.

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Fabrication Process

Epitaxial wafers for the HEMT were grown by molecular beam epitaxy (MBE) technique. About 1μm thick undoped GaAs buffer layer was grown on 3"ϕ semi-insulating LEC GaAs substrate, followed by a 400Å thick n-$Al_{0.3}Ga_{0.7}As$ layer and a 1500Å thick n-GaAs cap layer, which was usually 500–600Å thick. The rather thick cap layer was adopted in order to minimize source-to-gate parasitic resistance and to remove damaged layer thoroughly by recess etching. The n-GaAs and n-$Al_{0.3}Ga_{0.7}As$ layers were Si-doped with a concentration of $2 \times 10^{18}/cm^3$ and $1.5 \times 10^{18}/cm^3$, respectively.

In the device fabrication, almost all of resist patterning was carried out by conventional optical lithography except for the gate definition. The mixed exposure of different kinds of focused ion beams was adopted to form mushroom-shaped resist profiles. Fig.1 shows the detailed gate fabrication process flow of the mushroom gate HEMT. After the source and the drain electrodes were formed on a substrate, PMMA with the thickness of 1.05 μm was coated [Fig.1 (a) (b)]. Then the 'stalk' region and the 'cap' region of the gate were exposed with 192keV Be^{++} and 260keV Si^{++}, successively, with a dose of 2.0×10^{13} ions/cm^2 [Fig.1 (c) (d)]. The exposure dose was determined so as to get the pattern width with a good agreement with the desired width. The exposure was performed by using a device-fabrication system (JIBL-200S). Au-Si-Be alloy was used for the ionization material of the liquid metal ion source. Ion beams can be switched easily by changing the parameter of the mass filter and the accelerating voltage. Prior to the exposure, the ion beam was programmed to scan an alignment mark in order to adjust the offset between the beam position and the wafer. The alignment mark was a cross shaped ohmic metal on the substrate, previously fabricated in the drain electrode. At intervals, a calibration grid was scanned by the beam in order to correct the gain and the rotation of the beam deflection. The exposed depths of 192keV Be^{++} and 260keV Si^{++} were 1.05μm and .7μm respectively.

The development of the resist was carried out by immersing the wafer in a 2:3 mixture of methylisobutylketone (MIBK) and isoprophyl alcohol (IPA) for 10 minutes at room temperature. The resist profiles were stable during this development, therefore, T-shaped resist profiles can be controled precisely by changing accelerating energy and species of ions. After the top surface of the epitaxial layer was recessed to the optimum depth by wet chemical etching , a Schottky metal (Ni/Al) was deposited with a thickness of 6000Å, [Fig.1 (e)], and the gate fabrication process was completed by a lift-off procedure[Fig.1 (f)].

Fig.2 shows an SEM micro-photograph of the mushroom-shaped gate fabricated by using the mixed exposure technique. Quater-micron gate with mushroom shape, which had 0.7μm width at the 'cap', was obtained. The 1000Å thick SiN film was coated on the whole gate area to ensure high reliability of this device. Fig. 3 shows the chip pattern of the mushroom gate HEMT. The total gate width was 200μm and the size of the fabricated chip was 350×380μm^2. The cross mark at the drain pad was the alignment mark for the FIB direct exposure.

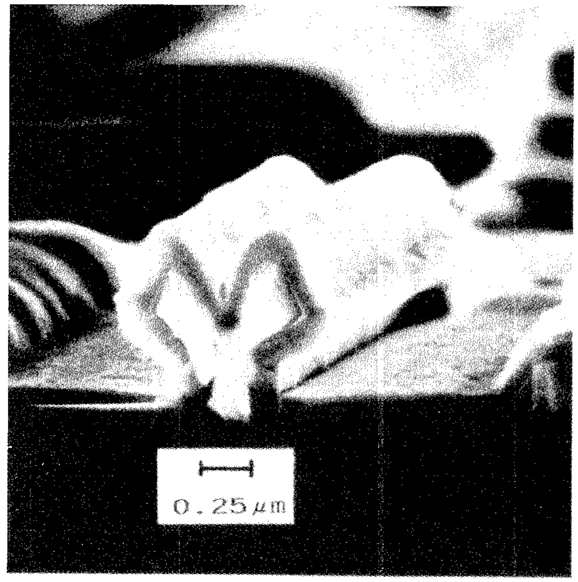

Fig.2 Cross sectional SEM micrograph of the mushroom gate HEMT.

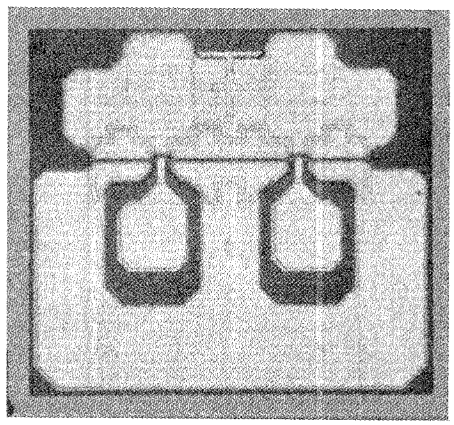

Fig.3 Photograph of the HEMT.

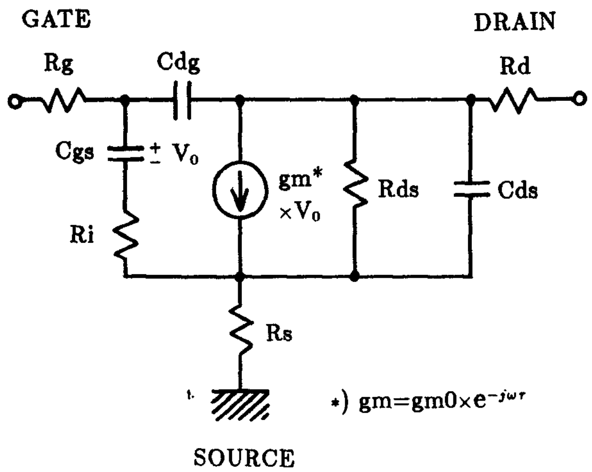

Fig.4 Equivalent circuit.

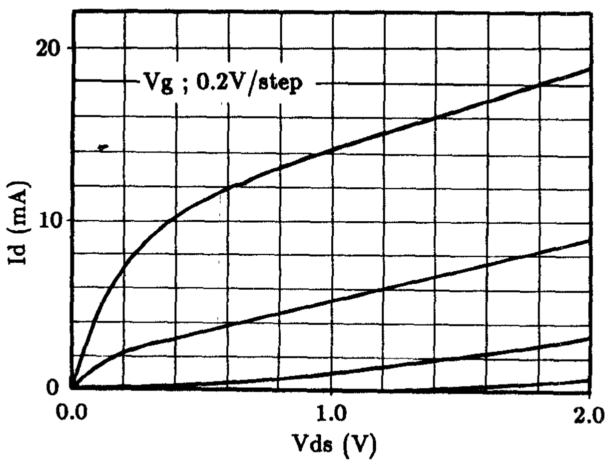

Fig.5 Drain current versus voltage characteristics.

Table 1 Comparison of equivalent circuit parameters of three type HEMT's.

Parameter	Conventional HEMT (a) (Lg=0.5μm)	Mushroom HEMT (b) (Lg=0.5μm)	Mushroom HEMT (c) (Lg=0.25μm)
Cgs(pF)	0.151	0.148	0.078
Cdg(pF)	0.030	0.038	0.037
Cds(pF)	0.042	0.049	0.036
Rin(Ω)*1	8.27	3.81	4.0
Rd(Ω)	4.02	3.87	6.10
Rds(Ω)	569	527	267
gm0(mS)	32.5	37.1	34.1
τ(ps)	2.6	2.7	1.7

*1) Rin = Rg+Ri+Rs

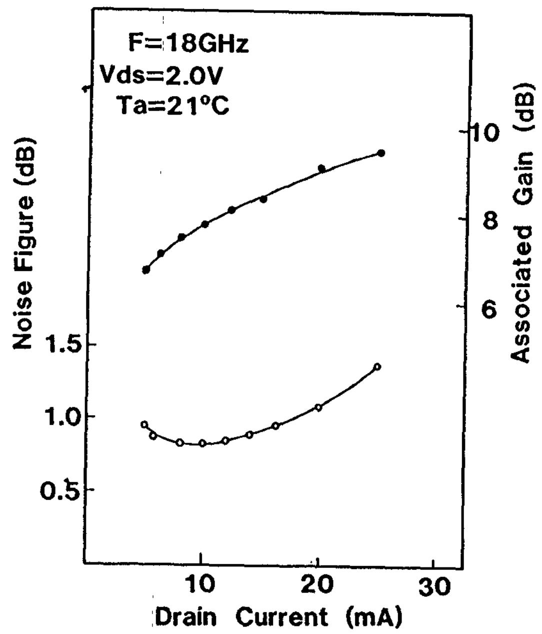

Fig.6 Noise figure and associated gain versus drain current at 18GHz.

Performances

In order to confirm the effectiveness in the performance due to the gate structure, three kinds of devices were fabricated. Device (a) had a conventional gate structure with 0.5μm gate length. Device (b) and Device (c) had the mushroom gates with 0.5μm and 0.25μm gate lengths, respectively. These three devices had a gate width of 150μm and a unit gate width of 75μm. Based on small signal RF characteristics, parameters of an equivalent circuit were determined for each device [Table 1, Fig. 4]. As shown in this table, the input resistance (Rin=Rg+Ri+Rs) varied remarkably and there existed small differences between the Device (a) and the Device (b) for other parameters. The Device (c) had about half value of the gate-to-source capacitance (Cgs), remaining close value of Rin. Moreover, the resistance measurement was carried out on the mushroom-shaped line and the conventional line, which had delta-shaped cross-section. The resistances were 70Ω/mm and 470Ω/mm for the mushroom-shaped line and the conventional line, respectively. It was confirmed that the mushroom gate structure yielded a decrease of the gate resistance by a factor of seven, compared with the resistance of the conventional gate. Minimum noise figures of these three devices were 1.2dB, 1.0dB and 0.68dB at 12GHz for the Device (a), the Device (b) and the Device (c), respectively. These results showed that the mushroom-shaped gate structure fabricated by focused ion beam lithography successfully improved the device performances.

Fig. 5 shows drain current/voltage characteristics observed at room temperature. Maximum transconductance of about 300mS/mm and good pinch-off characteristics were obtained. Fig. 6 shows the noise figure and the associated gain versus the drain current of the mushroom-shaped gate HEMT at 18 GHz. A minimum noise figure (NFmin) of .83 dB with an associated gain (Ga) of 7.7dB was obtained at the drain current (Id) of 10mA. This device also showed an NFmin of .68dB with a Ga of 9.7 dB at 12GHz.

Conclusion

In order to obtain a super low noise HEMT, mixed exposure process of two kinds of focused ion beams was optimized and applied to form mushroom-shaped gate. The fabricated device showed good noise figure of .83dB with the associated gain of 7.7dB at 18GHz. The result implies that this technology is useful in realizing super low noise performance and also has the benefit of fabricating mushroom gate structure accurately and reproducibly.

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