Plasma-Induced Fluorine Damage in P-HEMT Caused by C_2F_6/CHF_3 RIE Plasma

Hiroyuki Uchiyama^{a)} and Takafumi Taniguchi

Central Research Laboratory, Hitachi Ltd.,

1–280 Higashi-Koigakubo, Kokubunji-shi, Tokyo 185–8601, Japan

a) h-uchiya@crl.hitachi.co.jp

Abstract: Fluorine atoms intruded into the channel layer in P-HEMT and degraded its carrier density and electron mobility during the SiO_2 RIE process. Thermal annealing at 300°C for 10 minutes was rather effective for recovering from this plasma damage. Our SIMS investigation revealed that the mechanism of this recovery was the removal of fluorine atoms from the channel layer and their accumulation in the δ -doped Si layer. Ionized impurities in the channel layer were removed, and electron mobility was significantly recovered. However, the carrier density was recovered to a lesser degree than that of the electron mobility because of the neutralization of Si donors in the δ -doped layer caused by the fluorine accumulation.

Keywords: RIE, plasma, damage, fluorine, P-HEMT, SIMS

Classification: Electron devices

References

- [1] S. Salimian, C. Yuen, C. Shih, and C. B. Cooper, “Damage studies of dry etched GaAs recessed gates for field effect transistors,” *J. Vac. Sci. Technol. B*, vol. 9, no. 1, pp. 114–119, 1991.
- [2] C. -W. Kuo and Y. -K. Su, “Photo reflectance and C-V Measurement Investigations of Dry Etched Gate Recesses for GaInP/InGaAs/GaAs Pseudomorphic High Electron Mobility Transistors (HEMTs) Using BCl_3/Ar Plasma,” *Jpn. J. Appl. Phys.*, vol. 36, pp. L1651–L1653, 1997.
- [3] C. Juang, K. K. Kuhn, and R. B. Darling, “Selective etching of GaAs and $Al_{0.30}Ga_{0.70}As$ with citric acid/hydrogen peroxide solutions,” *J. Vac. Sci. Technol. B*, vol. 8, no. 5, pp. 1122–1124, 1990.
- [4] R. Grundbacher, I. Adesida, Y. -C. Kao, and A. A. Ketterson, “Single step lithography for double-recessed gate pseudomorphic high electron mobility transistors,” *J. Vac. Sci. Technol. B*, vol. 15, no. 1, pp. 49–52, 1997.
- [5] T. Kitano, S. Izumi, H. Minami, T. Ishikawa, K. Sato, T. Sonoda, and M. Otsubo, “Selective wet etching for highly uniform GaAs/ $Al_{0.15}Ga_{0.85}As$ heterostructure field effect transistors,” *J. Vac. Sci. Technol. B*, vol. 15, no. 1, pp. 167–170, 1997.

1 Introduction

The plasma dry etching process is an essential technology for the manufacture of compound semiconductor devices. However, it is known that the plasma-induced damage degrades most device characteristics, and is caused by implantation of reactive particles and destruction of surface crystal structures. In particular, HEMTs (High Electron Mobility Transistors) are greatly influenced by plasma induced damage because the gate recessing performed by the dry etching process is necessary to control the threshold gate voltages. Some reports discussed the influence of gate recess dry etching in HEMTs [1,2]. Recently, highly selective chemical wet etching was developed and used for gate recessing of HEMTs for avoiding plasma damage [3-5]. Even then, we were aware of the degradation of carrier density and electron mobility in P-HEMTs by our experience. Because C_2F_6/CHF_3 RIE (Reactive Ion Etching) was usually used for the fabrication of the SiO_2 gate recess mask, we thought that this degradation was caused by the SiO_2 RIE before the gate recess etching process. In this work, we have investigated the SiO_2 RIE plasma-induced damages and revealed the intrusion mechanism of fluorine atoms in P-HEMT (Pseudomorphic-HEMT). We have also examined the effect of thermal annealing on the fluorine damage.

2 Experimental

A P-HEMT structure was grown on semi-insulating GaAs wafers by molecular beam epitaxy (MBE). The P-HEMT structure, shown in Table I, was composed of an undoped GaAs buffer layer, an undoped $Al_{0.3}Ga_{0.7}As$ buffer layer (50 nm), an undoped GaAs buffer layer (50 nm), an undoped $In_{0.25}Ga_{0.75}As$ channel layer (8 nm), an undoped $Al_{0.3}Ga_{0.7}As$ layer (2 nm), a Si-doped $Al_{0.3}Ga_{0.7}As$ layer (5 nm), a δ -doped Si layer ($5.0 \times 10^{12} \text{ cm}^{-2}$), an undoped $Al_{0.3}Ga_{0.7}As$ Schottky layer (25 nm), and an undoped GaAs cap layer (10 nm). The sample was exposed to a C_2F_6/CHF_3 RIE plasma generated by a Lam Research TE-580 dry etching system. The equivalent etching time was the same as that of a SiO_2 etching of 250 nm. The RIE plasma-exposed P-HEMT

Table I. P-HEMT sample layer structure

Layer structure	Thickness
(1) un-GaAs cap layer	10 nm
(2) un- $Al_{0.3}Ga_{0.7}As$ Schottky layer	25 nm
(3) δ -doped Si layer	$(5.0 \times 10^{12} \text{ cm}^{-2})$
(4) n- $Al_{0.3}Ga_{0.7}As$ layer	5 nm (Si: $2.3 \times 10^{18} \text{ cm}^{-3}$)
(5) un- $Al_{0.3}Ga_{0.7}As$ layer	2 nm
(6) un- $In_{0.25}Ga_{0.75}As$ channel layer	8 nm
(7) un-GaAs	50 nm
(8) un- $Al_{0.3}Ga_{0.7}As$	50 nm
(9) un-GaAs buffer layer	400 nm
(10) Semi-insulating GaAs substrate	600 μm

sample was annealed at 300°C for 10 minutes. We checked the sample at every process step by taking Hall measurements and using secondary ion mass spectroscopy (SIMS). Before the Hall measurements, undoped GaAs cap layers of all samples were removed with a pH-adjusted citric acid selective wet etchant in order to control the surface state of each sample.

3 Results and Discussion

3.1 Behavior of carrier density and mobility during processing

The carrier density and electron mobility behaviors after RIE and thermal annealing in the P-HEMT sample are shown in Fig. 1. The behaviors are expressed as a proportion of their values before processing. The carrier density decreased to 0.22 after RIE plasma exposure and recovered to 0.49 after thermal annealing. The electron mobility had the same behavior as that of the carrier density and was 0.45 after RIE plasma exposure and 0.74 after annealing. This demonstrates that the C_2F_6/CHF_3 RIE process caused considerable damage to the P-HEMT, but the thermal annealing process was effective in repairing the damaged layers to some extent.

Fig. 1. Changes in carrier density and electron mobility after RIE and after thermal annealing (N_s : carrier density, N_{s0} : default carrier density, μ_s : mobility, μ_{s0} : default mobility)

3.2 Behavior of plasma induced impurities in P-HEMT

The SIMS profiles of hydrogen, carbon, oxygen and fluorine at every process step, that is before processing, after RIE, and after thermal annealing, are shown in Fig. 2 (a) - (d). We were not able to find obvious distinction among all the process steps in hydrogen, carbon and oxygen concentrations. However, only fluorine exhibited significant changes, as shown in Fig. 2 (d). This

Fig. 2 (a). SIMS profiles of hydrogen atoms in P-HEMT before processing, after RIE, and after thermal annealing ((1)–(7) indicate the layer structure of P-HEMT, as shown in Table I.)

Fig. 2 (b). SIMS profiles of carbon atoms in P-HEMT before processing, after RIE, and after thermal annealing ((1)–(7) indicate the layer structure of P-HEMT, as shown in Table I.)

was the evidence for the RIE plasma-induced damage observed in Fig. 1. Before processing, there was no fluorine atom in P-HEMT and the background fluorine concentration was very low. After RIE, fluorine atoms penetrated to about a 15 nm depth into the P-HEMT and the background fluorine concentration was higher than that before processing. It seems that the fluorine ions reached deeper than the depth of the $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ channel layer as a result of the RIE process. We considered that the penetrated fluorine atoms, which caused ionized impurity scattering in the channel layer and carrier neutralization in the δ -doped layer, were the main reason for the degradation of carrier density and electron mobility caused by RIE, as shown in Fig. 1. After thermal annealing, fluorine atoms diffused and accumulated at the GaAs/ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ hetero interface and in the δ -doped Si layer. Moreover, the background fluorine concentrations at depths under 45 nm were the same as those before processing. In particular, a lot of fluorine atoms, even those that had existed under the $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ channel layer, accumulated in the δ -doped Si layer. The fluorine concentration in the upper channel layer after the thermal annealing was seemingly the same as that after RIE, because the peak of the SIMS depth profile at the 35 nm depth tailed to deeper layers. If the fluorine atoms had existed such a high concentration in the channel layer, the carrier density and electron mobility might have degraded seriously due to a formation of electron-scattering centers. However, the carrier density and electron mobility practically recovered from 0.22 and 0.45 to 0.49 and 0.74, respectively as shown in Fig. 1. Then we assumed that the fluorine atoms caused ionized impurity scattering in the channel layer were removed

Fig. 2 (c). SIMS profiles of oxygen atoms in P-HEMT before processing, after RIE, and after thermal annealing ((1)-(7) indicate the layer structure of P-HEMT, as shown in Table I.)

Fig. 2 (d). SIMS profiles of fluorine atoms in P-HEMT exhibited different behavior from other profiles ((1)-(7) indicate the layer structure of P-HEMT, as shown in Table I.)

by the thermal annealing process. The recovery of background fluorine concentration above mentioned also supported this consideration. Moreover, this recovery occurred in spite of the fluorine accumulation that was likely to cause carrier neutralization in the δ -doped Si layer. Thus, we supposed that most of the accumulated fluorine atoms existed as neutral impurities and barely affected Si donors in the δ -doped layer. Estimated from results of the SIMS and the Hall measurements, we expected that about 20% of fluorine atoms stacked in the δ -doped layer neutralized the Si donors. We also supposed that the strained interface, like the GaAs/Al_{0.3}Ga_{0.7}As hetero and δ -doped interfaces, caused this fluorine accumulation by thermal diffusion.

4 Conclusion

In conclusion, we found plasma induced fluorine damage in P-HEMTs using Hall measurements and secondary ion mass spectroscopy. The damage was caused by the penetration of fluorine ions into the In_{0.25}Ga_{0.75}As channel layer and the formation of electron-scattering centers and carrier neutralization in the δ -doped Si layer. The thermal annealing process was rather effective in repairing this fluorine damage by removing fluorine atoms from the channel layer and accumulating them in the δ -doped layer. We also expected that most of the fluorine atoms accumulated by thermal annealing existed in the neutral state in the δ -doped layer.