Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 767-769 **PD-3-16**

Simple Kinetic Model of ECR-RIBE Reacor for the Optimization of GaAs Etching Process

M. Sugiyama, T. Yamaizumi*, M. Nezuka**, Y. Shimogaki, Y. Nakano*, K. Tada* and H. Komiyama
Department of Chemical System Engineering, Faculty of Engineering, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan
*Department of Electronic Engineering, Faculty of Engineering, University of Tokyo
**Plasma System Corporation

In order to obtain the optimum performnce for the ECR-RIBE process of GaAs, we studied the kinetic mechanism of the process. We examined the effect of Cl_2 flow rate by observing ething profiles and estimating Cl concentration with optical emission spectroscopy. We also introduced a simple model of ECR-RIBE reactor and considered the mass balance of reactive species to explain the observed flow rate dependency. Our method of analysis and kinetic constants obtained here will contribute to the optimization of the dry etching process.

Introduction

Dry etching of GaAs is an important technology for the fabrication of high-speed electronic devices and optoelectronic devices. The reactive ion beam etching method combined with high density ECR plasma (ECR-RIBE) has attracted much attention for its ability to realize highly anisotropic and low damage etching. Asakawa et al. already optimized the process parameters in the ECR-RIBE of GaAs such as microwave power, Cl_2 pressure and ion acceleration voltage to obtain the vertical sidewall and smooth surface morphology[1)]. In order to understand the reaction mechanisms of this process, we made the kinetic study of the ECR-RIBE process for GaAs by noticing the effect of Cl_2 flow rate. First, we examined how the etching performances were affected by Cl_2 flow rate, and then we tried to explain this trend in terms of the effect of Cl_2 flow rate on Cl radical concentration. To interpret the observed tendencies, we introduced a simplified model of our ECR-RIBE reactor and considered the kinetics of the etching reaction macroscopically. Thus we obtained kinetic parameters, such as rate constants of gas phase and surface reaction, based on our model. Our method of analysis and kinetic rate constants obtained here will contribute to establising a guiding principle for the optimization of the reactor design and its performances.

Experiment

In order to examine the effect of Cl_2 flow rate on the etching performances, we etched GaAs substrates with Cl_2 discharge in ECR-RIBE reactor (Fig. 1) at Cl_2 flow rates ranging from 0.5sccm to 10sccm, while other etching conditions were kept constant: 70W microwave power, 0.25mTorr Cl_2 pressure, and DC self bias of -35V was created on the substrate holder by applying 13.56MHz RF bias. Lines of various widths and an open space were patterned on $1cm^2$ GaAs substrate with SiO_2 mask. The etched profiles were observed by scanning electron microscopy (SEM). For the better understanding of the mechanism, we also examined the relation between the Cl_2 flow rate and the concentration of Cl radicals by utilizing optical emission spectroscopy (OES). The emitted light was observed through the quartz plate window near the substrate holder and analyzed by utilizing the plasma monitor, HAMAMATSU PMA-11.

Results and discussion

First we examined the effect of Cl_2 flow rate on the etching performances. At lower flow rates, the etching rate of an open space on GaAs substrate increased as Cl_2 flow rate

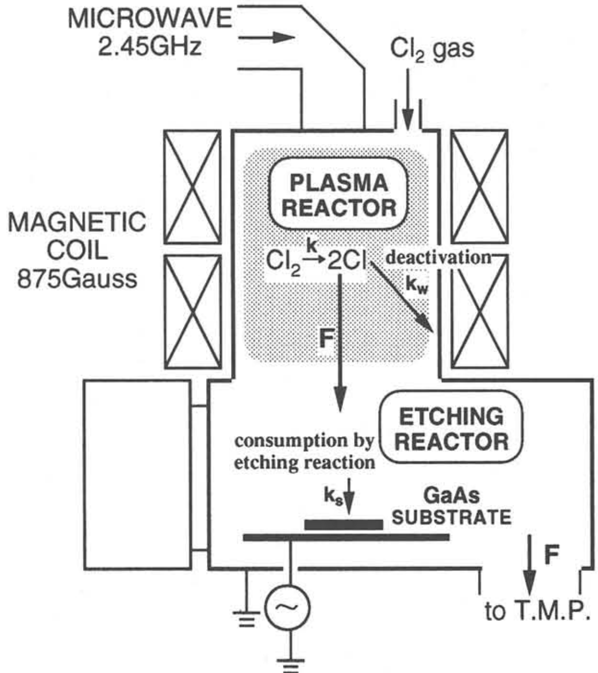

Fig. 1: Schematic diagram of our ECR-RIBE reactor and the modeling chart. The arrows indicate the transport of Cl radicals.

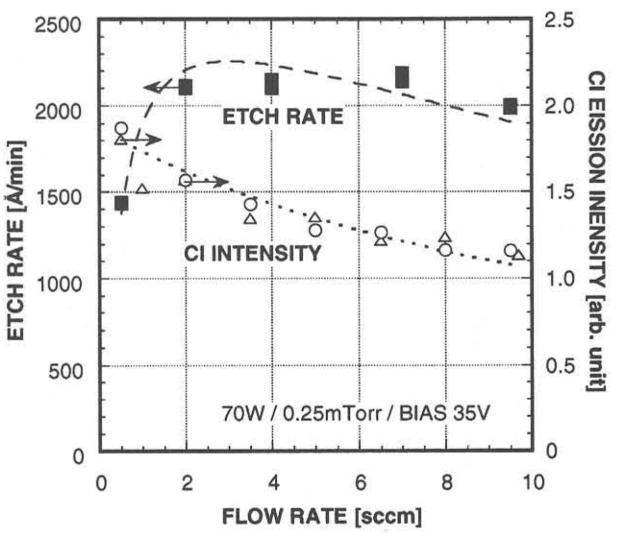

Fig. 2: Flow rate dependency of the etching rate of the open space on GaAs substrate and the corresponding emission intensity of Cl radicals.

increased, and seemed to reach a plateau at higher flow rate. (Fig. 2) The etching rates of trenches on GaAs substrate became slower as their width decreased, and this trend (so-called RIE-lag[2)]) was more obvious for larger Cl_2 flow rate. (Fig. 3) The increase in Cl_2 flow rate also made the sidewall of trenches more rounded. (Fig. 4) Since the radical etching reaction proceeds without ion bombardment, the sidewall etching can be caused by the radical etching reaction. We can attribute the observed RIE-lag also to the radical etching reaction, because a radical flux becomes smaller at the bottom of the trench of higher aspect ratio[3)]. Therefore we assumed that the increased Cl_2 flow rate caused the increase in the Cl radical flux on the GaAs substrate and thus accelerated the radical etching reaction. To confirm this, it is necessary to examine the effect of Cl_2 flow rate on the concentration of Cl radicals that is assumed to be almost proportional to the flux of Cl radicals on the GaAs substrate.

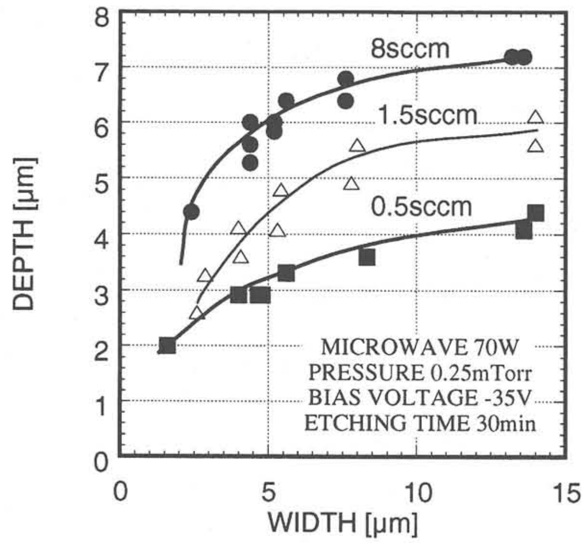

Fig. 3: Dependence of the trench etching rate on Cl_2 flow rate and the trench width.

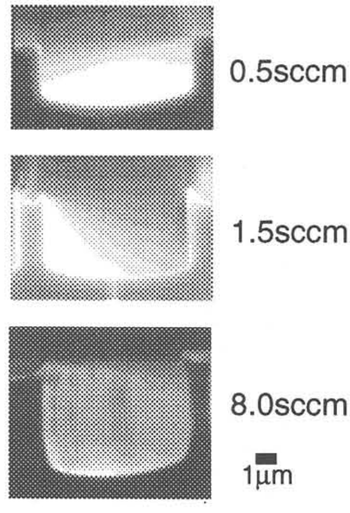

Fig. 4: Cross sections of the etched trenches observed by SEM.

Hence, we employed OES and estimated the effect of Cl_2 flow rate on the Cl concentration with the assumption that the Cl emission intensity is almost proportional to the Cl concentration. The obtained spectra (Fig. 5) included strong emission peaks from Cl radicals (700-800nm)[4)]. When the GaAs substrate was introduced into the system, the peak intensity of Cl radical decreased, while strong peaks of Ga atoms appeared at 403nm and 417nm[5)]. The peak intensity of Cl radical (725nm) decreased monotonically as the flow rate increased when no GaAs substrate existed in the reactor, but we observed the decrease of the Cl intensity particularly at lower flow rates when GaAs substrates were introduced into the reactor. (Fig. 6) On the other hand, the Ga peak intensity exhibited flow rate dependency that is different from that of Cl. (Fig. 7) The emission intensity depended also on the area of the etched substrate as shown in Figs. 6 and 7. In order to explain these dependencies, we need to consider the macroscopic mass balance of reactive species in the reactor.

Thus, as a first approximation, we introduced a simplified model of our ECR-RIBE reactor to consider the mass balance of Cl radicals in the reactor. The model divides the reactor into two Continuous Stirred Tank Reactors (CSTRs) in witch the concentration of every chemical species is assumed to be uniform. They are called PLASMA REACTOR and ETCHING REACTOR as shown in Fig. 1. In the PLASMA REACTOR, Cl radicals generated from Cl_2 molecules are either flow into the ETCHING REACTOR or deactivate at chamber walls. In the ETCHING REACTOR, Cl radicals from the PLASMA REACTOR are either consumed by the etching reaction or pumped out of the reactor. For simplicity, the Cl consumption rate by the etching reaction is assumed to be proportional to the Cl concentration in the ETCHING REACTOR. With these assumptions, we considered the mass balance of Cl radicals and obtained the expression of the Cl emission peak intensity:

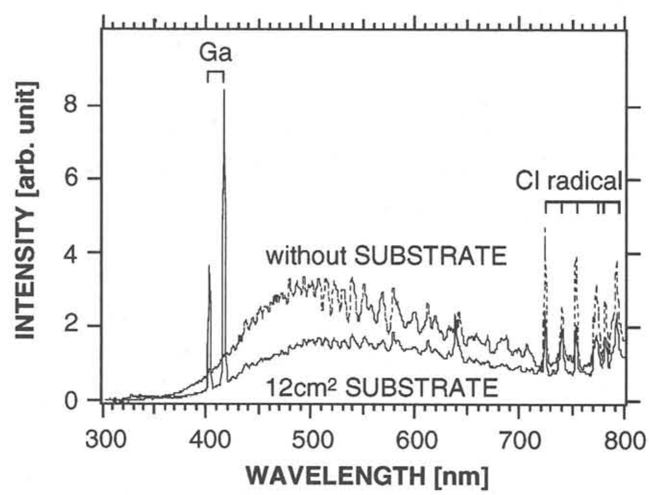

Fig. 5: Optical emission spectra obtained both without a GaAs substrate and with a $12cm^2$ GaAs substrate.

$$I_{Cl} = \frac{\alpha V_p k C_0}{F + Wk_w} \cdot \frac{F}{F + Sk_s} \cdots\cdots\cdots (1),$$

where F is the Cl_2 flow rate, V_p is the volume of the PLASMA REACTOR, k is the rate constant of the Cl generation, C_0 is the inlet concentration of Cl_2, W is the chamber wall area of the PLASMA REACTOR, k_w is the rate constant of the Cl deactivation, S is the surface area of the GaAs substrate, k_s is the rate constant of the Cl consumption by the etching reaction, and α is a constant. We evaluated k and k_w from the Cl intensities observed without a substrate, and then fitted the eq. (1) to the intensities observed with substrates, with k_s being a fitting parameter. The fitting curves in Fig. 6 show a good agreement with the experimental data. The values of k_s shown in Fig. 6 are nearly the same for different substrate area, which confirms the validity of our model.

Next we explain the flow rate dependency of the Ga emission intensity. We assume that the emission is from the excited Ga atoms (Ga^*) generated by the dissociation of the etching products, $GaCl_x$ molecules. With this assumption, we considered the mass balance of Ga^* and $GaCl_x$ in the ETCHING REACTOR and obtained the expression of Ga emission intensity:

$$I_{Ga} = \frac{\beta k_d}{k_q} \cdot \frac{V_p k C_0}{F + Wk_w} \cdot \frac{F}{F + Sk_s} \cdot \frac{Sk_s}{F + V_e k_d} \cdots\cdots (2),$$

where, k_d is the rate constant of $GaCl_x$ dissociation, k_q is the rate constant of Ga^* relaxation, and β is a constant. We fitted eq. (2) to the Ga emission intensities utilizing the values of k, k_w and k_s obtained with the Cl emission intensities. The fitting curve in Fig. 7 shows a good agreement with the experimental data. The values of fitting parameters, k_d and k_q, shown in Fig. 7 are nearly independent of substrate area. These observations lend further evidence to the validity of our model.

Then we examined the relation between the etching rate of the GaAs substrate and the emission peak intensity of Cl radicals. (Fig. 2) The decrease in Cl emission intensity with increasing Cl_2 flow rate suggests that Cl radical flux on the substrate should decrease with increasing flow rate, which is contradictory to the observed flow rate dependency of etching rate, sidewall etching and RIE-lag. Thus we took into account the effect of the etching products that is expected to supress the etching reaction. At lower flow rates, the concentration of etching products is assumed to be larger, so the supression by etching products is expected to be more effective. In this way we can explain the flow rate dependency of the etching rate as the fitting curves in Fig. 2 illustrate. We can attribute also the flow rate dependency of sidewall etching to the supression by etching products. The flow rate dependency of RIE-lag can be explained qualitatively in terms of the supression by etching products. The concentration of etching products is considered to be larger at the bottom of the trenches because of their conductance[3]. The trench of higher aspect ratio has larger conductance, so the concentration of etching products should be larger, which leads to slower etching reaction. This trend is expected to be more obvious at higher pumping speed, that is, higher Cl_2 flow rate.

Conclusion

We have examined the effect of Cl_2 flow rate on etching performances. The etching rate and the profile of etched trenches depended on Cl_2 flow rate, which implied that the radical etching reaction was accelerated as Cl_2 flow rate increased. We attributed that effect to the increase of Cl radical flux on the substrate. Thus we examined the effect of Cl_2 flow rate on Cl concentration in the reactor by employing OES. The observed Cl emission intensity implied that the Cl concentration in the reactor depended on Cl_2 flow rate and the area of the etched GaAs substrate. We introduced a simplified model of our ECR-RIBE reactor and considered the mass balance of Cl radicals in the reactor, and we succeeded in explaining the observed dependency. We could also explain the flow rate dependency of the observed Ga emission intensity with our model. These facts reveal that the optimization of the etching performances at the micron level requires the insight into the macroscopic transport of reactive species in the reactor. By utilizing the method of analysis presented here and the kinetic parameters we have obtained, we should be able to obtain the desired etching performances for the ECR-RIBE process.

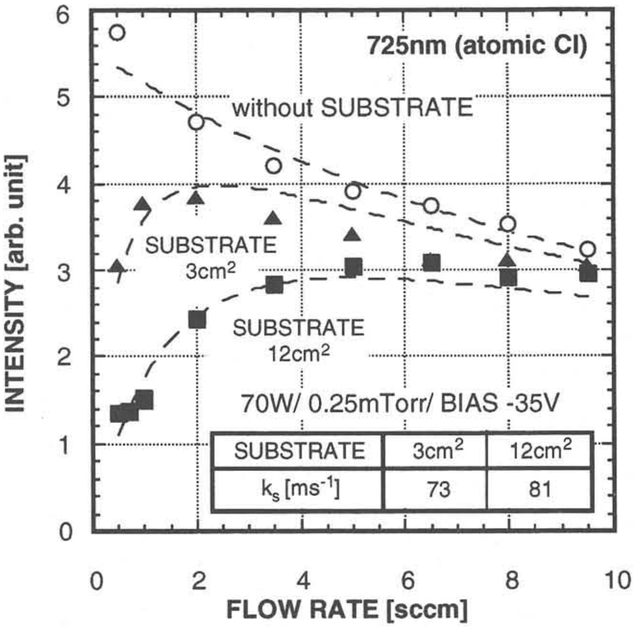

Fig. 6: Flow rate dependency of Cl peak intensity. The dashed lines indicate the fitting curves besed on our model.

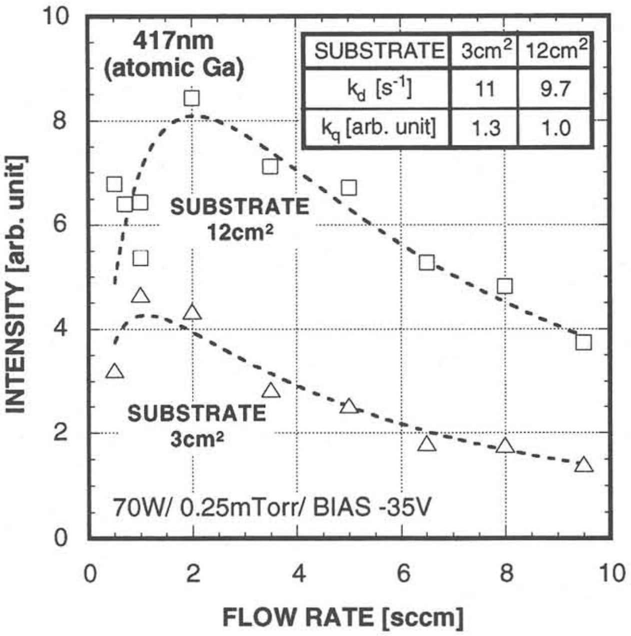

Fig. 7: Flow rate dependency of Ga peak intensity. The dashed lines indicate the fitting curves besed on our model.

References

1) K. Asakawa and S. Sugata: J. Vac. Sci. Technol. **B3** (1985) 402

2) R. A. Gottscho and C. W. Jurgensen: J. Vac Sci. Technol. **B10** (1992) 2133

3) J. W. Cobern and H. F. Winters: Appl. Phys. Lett. **55** (1989) 2730

4) *CRC Handbook of Chemistry and Physics*, ed. R. C. Weast (CRC Press, Florida, 1988)

5) *Coincidence Tables for Atomic Spectroscopy*, ed. J. Kuba (Elsevier Publishing Company, Amsterdam, 1965), p. 10