Extended Abstracts of the 18th (1986 International) Conference on Solid State Devices and Materials, Tokyo, 1986, pp. 233-236

A-6-2

Double-Source Excited Reactive Ion Etching and Its Application to Submicron Trench Etching

Masaaki Sato and Yoshinobu Arita

NTT Electrical Communications Laboratories

3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

Double-source Excited Reactive Ion Etching (DERIE) was developed in order to control submicron trench shape. With DERIE, gas dissociation and ionization can be increased in the upper discharge space without increasing incident ion energy to the sample in the low pressure region. Accordingly, DERIE leads to side wall deposition control preventing undercutting without lowering etch rate and selectivity. Using a chlorine and $SiCl_4$ mixture, submicron single crystalline silicon trenches (0.23 μm wide, 2.64 μm deep) with a tapering side wall can be realized reproductively.

1. Introduction

Reactive Ion Etching (RIE) has been widely accepted as a useful method for microlithography in LSI processes. It has been used to realize 1 μm resolution LSI's.[1] However, when it is applied to submicron trench etching, the etch rate decreases,[2)3)4)5] and the point width of the trench becomes narrower with increasing trench depth.[3)6]

Lowering the pressure is one solution to these problems.[6)7)5] However, this would result in a decrease in the etch rate and in the selectivity to the mask and underlayer. This is because of the decrease in radical concentration. In addition, undercutting of the trench side wall becomes a serious problem in submicron trench formation.[7]

In our previous single crystalline silicon trench etching experiment,[7] undercutting of the trench side wall was suppressed by mixing a depositing species in the etching gas. However, in this procedure where hydrogen and $SiCl_4$ were mixed in chlorine, the silicon etch rate and the selectivity (silicon etch rate/SiO_2 etch rate) are sacrificed for shape controllability. It has also been indicated that more deposition is required to suppress undercutting of narrower trenches. There was no stable method previously developed for submicron trench etching with high aspect ratio (depth/width) with high shape controllability.

In this paper, Double-source Excited Reactive Ion Etching (DERIE)[8] is proposed as a submicron trench etching method. DERIE leads to deposition control in the low pressure region without lowering etch rate and selectivity. It was shown that a quarter micron wide silicon trench etching with high aspect ratio can be achieved using a chlorine and silicon tetrachloride ($SiCl_4$) mixture.

2.Experimental Procedure

A schematic diagram of DERIE is shown in Fig. 1. This is essentially a triode reactor,[9] in which the upper discharge space is enclosed and separated from the lower discharge space by a carbon grid with ground potential. Gas dissociation and ionization increases in the upper space with increasing rf power to the upper

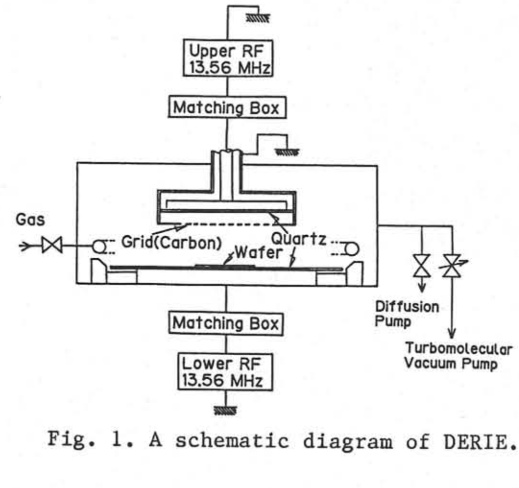


Fig. 1. A schematic diagram of DERIE.

electrode. Through the diffusion of upper space radicals and ions, high radical and ion density is maintained in the lower discharge space. Incident ion energy to the sample is controlled by rf power applied to the lower electrode. Accordingly, ion current/radical concentration can be increased without increasing ion energy.

In this experiment, chlorine gas was introduced as the main etching gas in the lower space. In addition, $SiCl_4$ was mixed for shape control. A turbomolecular vacuum pump and a rotary pump functioned as the evacuation systems.

The samples were P type (111) silicon wafers on which thermal silicon oxide was patterned as an etching mask using RIE. Optical emission spectra were measured to analyze the discharge condition change in DERIE.

3. Results and Discussion

Undercutting the trench side wall becomes a serious problem in the etching of submicron trenches as shown in Fig. 2. This undercutting is thought to be caused by divergent ions scattered by ion-molecule collisions. In spite of the relatively lower pressures (0.15 Pa) where an ion mean free path is larger than the ion sheath width, nevertheless a few tens percent of ions must be scattered in the ion sheath.

In order to prevent undercutting, side wall protection by simultaneous deposition is required. It was indicated that hydrogen and $SiCl_4$ mixed in chlorine is effective for the deposition. However, the silicon etch rate and the selectivity decrease with increasing $SiCl_4$ and/or hydrogen flow rate.

In DERIE, chlorine and $SiCl_4$ were used respectively as the etching gas and deposition gas. Compared to conventional RIE, $SiCl_4$ becomes completely dissociated in the upper discharge space because of high electron density. It also causes an increase in the deposition species. Hydrogen mixing was not needed in DERIE. In addition, the simultaneous deposition rate can be controlled by applying power to the upper electrode without changing ion energy. Optical emission spectra of the discharge, in conventional RIE and DERIE are shown in Figs. 3 (a) and (b), respectively. Si and SiCl peaks, which are estimated to be the deposition species, were 6 times larger in DERIE than in conventional RIE.

The silicon and SiO_2 etch rate as well as the selectivity (silicon etch rate/SiO_2 etch rate) are shown in Fig. 4 as a function of $SiCl_4$ flow rate, where chlorine flow rate is fixed at 10 SCCM. The etch rate is two to ten times larger than in conventional RIE. This is because ion current density increases as upper rf power increases. Also, the etch rates of both silicon and SiO_2 increase with the mixing of $SiCl_4$, and the selectivity is almost independent of the $SiCl_4$ flow rate.

This result contrasts with conventional RIE, where the silicon etch rate decreases with the

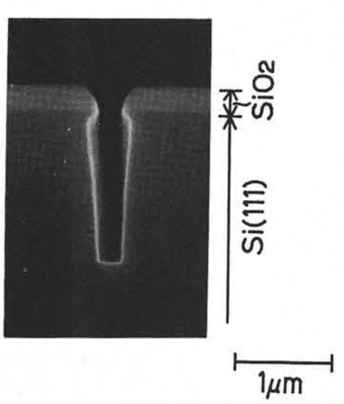


Fig. 2. The submicron silicon trench cross section etched by conventional RIE in 10 SCCM of chlorine at 0.15 Pa and 0.13 W/cm^2.

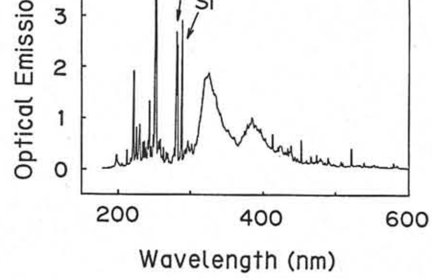


Fig. 3. The optical emission spectra of the discharge, where gas flow rates were 10 SCCM of chlorine and 8 SCCM of $SiCl_4$.

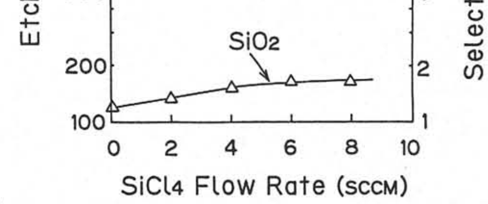


Fig. 4. The silicon and SiO_2 etch rates as well as the selectivity (silicon/SiO_2), as a function of $SiCl_4$ flow rate, where the upper and lower power were 200 W and 80 W (0.13 W/cm^2), respectively.

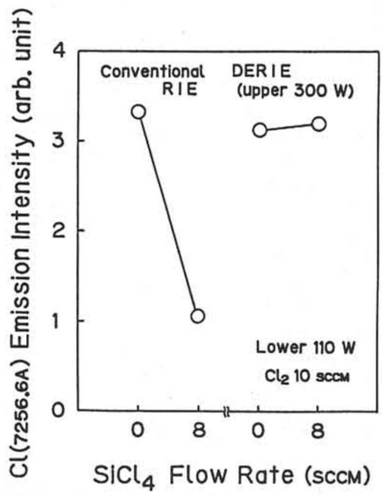
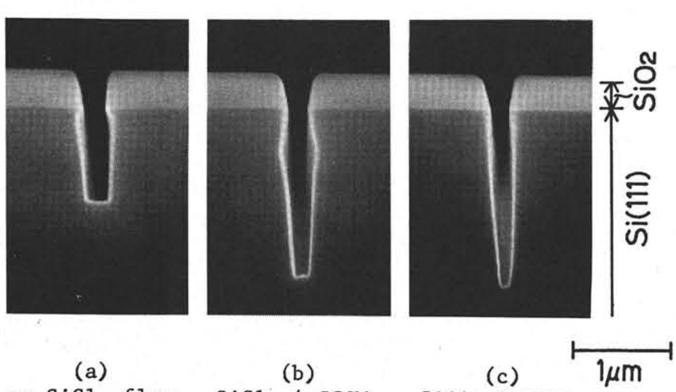


Fig. 5. Optical emission intensity of chlorine atoms (7256.6 Å) as a function of $SiCl_4$ flow rate.

mixing of the deposition species. This can be interpreted by the optical emission intensity change of chlorine atoms (7256.6 Å)[10] as shown in Fig. 5. In conventional RIE, Cl intensity (i.e., chlorine radical concentration) decreases with the increasing $SiCl_4$ flow rate. This is due to $SiCl_4$ and its dissociated species acting as a recombinant of chlorine radicals. This causes a decrease in the silicon etch rate only. The SiO_2 etch rate is limited only by ion current density. Therefore, it does not change with the chlorine radical concentration, as a result, the selectivity decreases.

In DERIE however, chlorine radical concentration does not change with the mixing of $SiCl_4$. This must be due to high electron density in the upper discharge space. The gas dissociation is so complete in the upper space that



(a) no $SiCl_4$ flow (b) $SiCl_4$ 4 SCCM (c) $SiCl_4$ 8 SCCM

Fig. 6. SEM cross sections of silicon trenches etched in DERIE in 10 SCCM of chlorine and 8 SCCM of $SiCl_4$ at 200 W of the upper power and 80 W (0.13 W/cm^2) of the lower power for 10 min..

recombination does not affect chlorine radical concentration.

The relationship between the etched shape and $SiCl_4$ flow rate for 0.23 µm wide silicon trenches etched in DERIE are shown in Fig. 6. It can be observed that the etched depth increases and undercutting of the side wall is suppressed with increasing $SiCl_4$ flow rate. A tapering trench without undercutting is obtained at 8 SCCM of $SiCl_4$ (Fig. 6(c)).

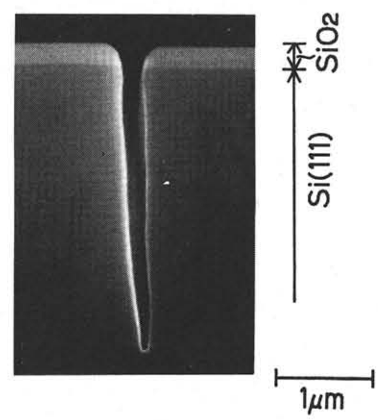
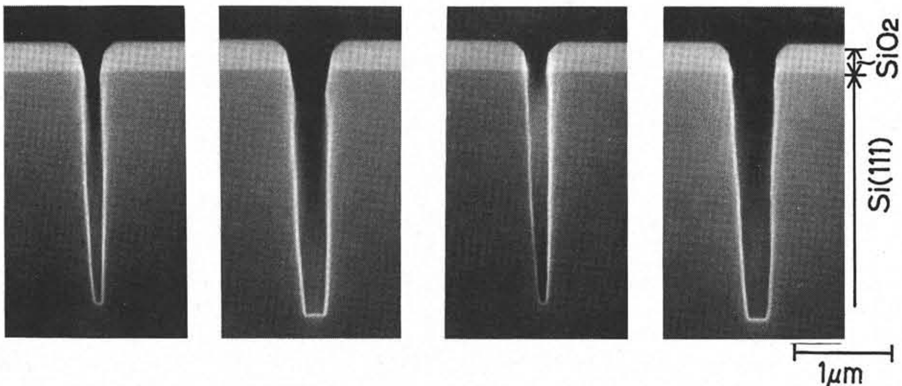


Fig. 7. SEM cross section of a silicon trench etched in DERIE for 17 min..

The SEM cross section of the trench after etching in the same condition as Fig. 6(c), but for 17 minutes is shown in Fig. 7. The trench begins to meander with increasing trench depth. To control the etched shape of the deeper trench etching and to prevent meandering, applying higher power density to the lower electrode is effective.[7] The SEM cross sections of the silicon trenches etched at 110 W (0.18 W/cm^2) of the lower rf power, are shown in Fig. 8. The samples are immediately after etching (Fig. 8(a)(b)) and after buffered HF (BHF) treatment (Fig. 8(c)(d)). After etching, deposited films can be observed on the side walls, but these films are removed after BHF treatment. The silicon tapering trenches with high aspect ratio (11.5) can be obtained without undercutting and meandering.

It can be observed in Fig. 8 that the etched depth of the narrower trench (0.23 µm wide, 2.64 µm deep, Fig. (a)) becomes shallow compared with the wider trench (0.46 µm wide, 2.82 µm deep, Fig. 8(b)). Normalized etched depth as a function of aspect ratio was measured from the SEM cross sections after etching of 12 minutes, as shown in



(a) 0.23 μm wide (b) 0.46 μm wide (c) 0.23 μm wide (d) 0.46 μm wide
after etching after BHF treatment

Fig. 8. SEM cross section of silicon trenches etched in DERIE in 10 SCCM of chlorine and 8 SCCM of $SiCl_4$ at 0.29 Pa, 300 W of the upper power, and 110 W (0.18 W/cm^2) of the lower power for 12 min.

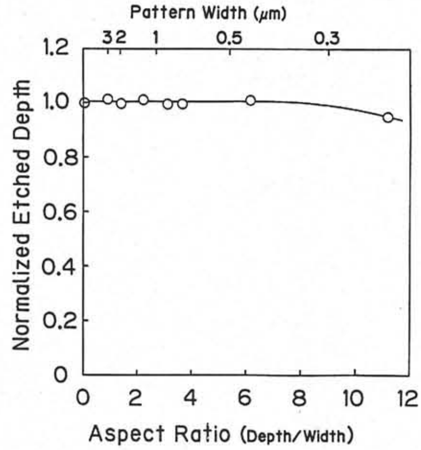


Fig. 9. Normalized etched depth of silicon trenches as a function of aspect ratio. Etching time was 12 minutes.

Fig. 9. The etch depth does not change untill the aspect ratio exceeds six, then it decreases slightly. However, the depth decrease is only 6 % when the aspect ratio is 11.5, which is a profound improvement over conventional RIE.[3)4)5)] This result is due to the etching/deposition balance in the trenches. Both the etch rate and the simultaneous deposition rate decrease with decreasing trench width. This is because of the incident direction restriction of ion and deposition species by the mask opening range. This controls the change in the net etch rate of the trench.

4. Conclusion

Double-source Excited Reactive Ion Etching (DERIE) is proposed as a submicron trench etching method. In submicron trench etching, undercutting the trench side wall becomes a serious problem. Gas dissociation and ionization can be increased in the upper discharge space without increasing ion energy. Accordingly, DERIE features side wall deposition control to prevent undercutting without lowering etch rate and selectivity.

Submicron single crystalline silicon trench etching was performed in DERIE. Chlorine and $SiCl_4$ were used as the etching gas and deposition gas for side wall protection, respectively. Undercutting was suppressed with the increasing $SiCl_4$ flow rate. High power density applied to the lower electrode was effective in preventing trench meandering. The final result is that 0.23 μm wide, 2.64 μm deep silicon trenches with tapering side wall can be realized reproductively.

DERIE has been shown to be a promising method for use in the next generation of ULSI processes with patterns of lower submicron to sub-100 nm wide. This is because of the high controllability of gas dissociation, ionization, and ion acceleration in the low pressure region.

Acknowledgements

The authors wish to express their appreciation to T. Sakai for his encouragement and support throughout this endeavor. They also wish to thank H. Nakamura and A. Yoshikawa for their invaluable advice at the beginning of this project. The authors wish to thank K. Sakuma for preparing samples.

References

(1) T. Mano, K. Takeya, T. Watanabe, N. Ieda, K. Kiuch, E. Arai, T. Ogawa, and K. Hirata, IEEE J. Solid-State Circuits, SC-15, 865 (1980)
(2) M. Oda, H. Namatsu, S. Ohki, H. Akiya, and T. Shibata, Proc. 6th Symp. on Dry Processes, Tokyo, October, 115 (1984)
(3) D. Chin, S. H. Dhong, and G. J. Long, J. Electrochem. Soc., 132, 1707 (1985)
(4) T. Arikado, K. Horioka, M. Sekine, H. Okano, and Y. Horiike, Proc. 7th Sympo. on Dry Processes, Tokyo, October, 114 (1985)
(5) Y. Horiike, M. Sekine, T. Arikado, and H. Okano, Proc. 53rd meeting of the Electrochemical Society of Japan, Tokyo, April, (1986), in Japanese
(6) M. Sato and Y. Arita, Proc. 6th Symp. on Dry Processes, Tokyo, October, 109 (1984)
(7) M. Sato, K. Sakuma, and Y. Arita, Proc. 7th Symp. on Dry Processes, Tokyo, October, 102 (1985)
(8) M. Sato and Y. Arita, Proc. 44th Autumn Meeting of the Japan Society of Applied Physics, 27pU4 (1983), in Japanese
(9) V. J. Minkiewicz and B. N. Chapman, Appl. Phys. Lett., 34, 192 (1979)
(10) K. Asakawa and S. Sugata, Japanese J. of Appl. Phys., 23, L156 (1984)