Electron-Beam Injected Inductively Coupled Plasma Etching and Probe Measurements

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An inductively coupled plasma (ICP) was initiated under the electron-beam irradiation in a reaction chamber which was through an interface film made of polyester film of 1.5 μm thick. Tha plasma etching of the silicon wafer was performed by using aluminum mask of 0.2 μm patterned by focused ion beam (FIB), and the plasma was evaluated by probe measurements. In these experiments, the minimum RF power necessary for the discharge was observed to be lowered by injecting the electron-beam into the reaction chamber comparing with the discharge without electron injection. The 0.2 μm fine pattern could be fabricated successfully at a rate of 10.6 nm/min in CF_4 gas. From the probe measurements, it was found that the floating and plasma potentials were decreased and the electron temperature and density were increased by injecting electrons into the ICP.

Introduction

An electron-beam assisted plasma reactor is considered to be a candidate for the future processes. A new type of reactor has been proposed, which had a polymer interface between an electron-beam source and a reactor as an electron-beam transmission window. [1] The controllability of the processes will be improved by using the interface, because gas parameters in the reactor can be regulated independently from the electron source. But the problem is that the electron current is limited by the material and thickness of the interface. [2]

Recently, an inductively coupled plasma (ICP) is attracted for the etching process. In the ICP system, a current-flowing antenna is employed for the plasma generation at the outside or the inside of reactor, and fine pattern etching of Si or SiO_2 substrate with high aspect ratio at relatively high rates were reported. [3, 4, 5]

In this paper, the effect of electron-beam injection into the ICP was studied by a probe measurement to evaluate the reactor. And etching experiments for sub-quarter micron pattern were performed practically, where an evaporated aluminum film patterned by a focused ion beam (FIB) system as a resist mask.

Experimental

An apparatus developed for the process is shown in Fig. 1. The interface film was 1.5 μm thick polyester film coated by aluminum on one side and was supported by a copper mesh. The one-turn 30 mm diameter loop antenna was installed in the reaction chamber and located at a distance of 15 mm from the substrate, and rf power at a frequency of 13.56 MHz was supplied to the antenna. The loop antenna was made of 3 mmϕ copper wire covered with an insulating dielectric.

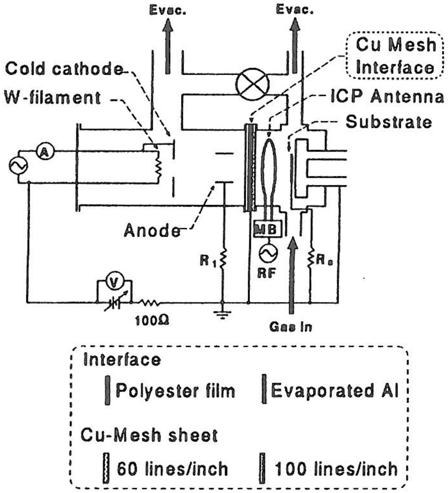

Fig. 1 : ICP reactor for etching process.

The mask material of the etching was an evaporated aluminum film of 0.1 μm thick on a silicon wafer and patterned by focused ion beam (FIB) milling. The fabrication was performed by JEOL JIBL-60 FIB apparatus using gallium ion beam accelerated at a voltage of 60 kV, an ion beam current of 25 pA (1.25×10^{-14} A·sec./pulse). The beam size was about 0.1μm. By using SEM (scanning electron microscope), it was confirmed that the aluminum film was etched off and etching of the silicon wafer (n-type As doped, (100) orientation) was negligible small by the ion beam. Thus, 0.2 μm aluminum line pattern was fabricated. The silicon wafer with the aluminum resist mask was placed perpendicularly to the electron-beam in CF$_4$ gas atmosphere. The ICP was gen-

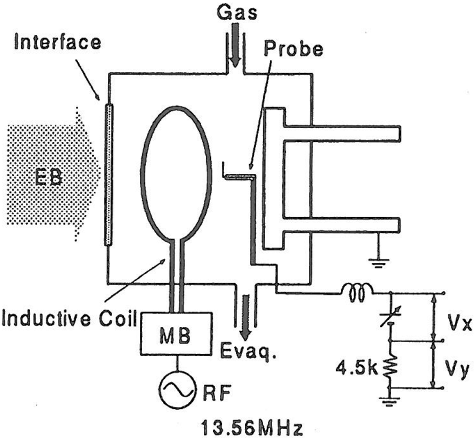

Fig. 2 : Langmuir probe and circuit of probe measurement.

erated under the electron-beam irradiation.

The probe measurements of the ICP under the injected electron-beam were performed by a Langmuir probe method. [6] The probe consists of a gold wire of 50 $\mu m\phi$ covered with a glass tube , the tip of 6 mm long was immersed in the plasma and located at the center of the loop antenna, as shown in Fig. 2.

Results and Discussion

It was observed that the minimum rf power necessary for the discharge was decreased by injecting the electron-beam in the CF_4 atmosphere at a pressure of 0.15 Torr. The current flowing into the substrate increased a little by the injected electron-beam.

The etching of silicon wafer was performed under the following conditions: a CF_4 pressure of 0.15 Torr, an rf power of 5 W, a tungsten filament current of 6.0 A, an electron-beam acceleration voltage of 8 kV, and an emitted electron current of 0.45 mA. In the experiment, the rf power was set at 5 W after the discharge was initiated at 20 W. And the 0.2 μm fine pattern was obtained successfully by the etching procedure at the condition of substrate current of 0.55 mA with the rate of 10.6 nm/min. Fig. 3 shows a SEM photograph of the etched pattern structure on silicon surface after removing the aluminum mask by a nitric acid solution. The value of the etch rate was one hundredth or one tenth smaller compared to Cl_2 electron-beam excited plasma (EBEP) etching of Hara et.al. [9]

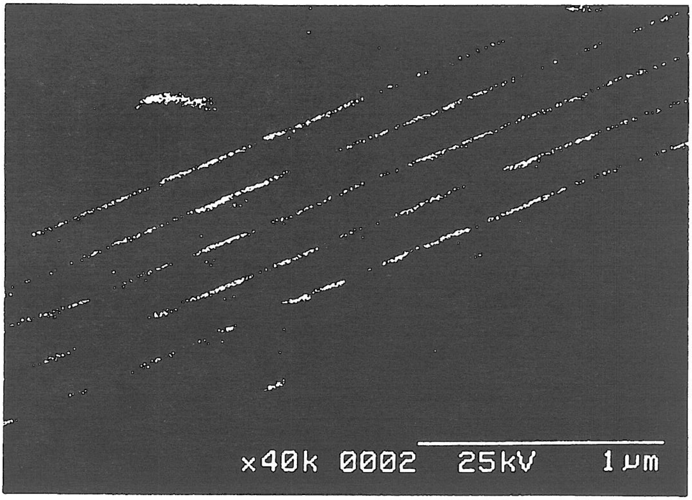

Fig. 3 : SEM photograph of the etched silicon surface with 0.2 μm pattern.

The probe measurements were performed at a discharge condition: a CF_4 pressure of 0.15 Torr, an rf power of 1 W, a tungsten filament current of 6.0 A, an electron-beam acceleration voltage of 8 kV, and an emitted electron current of 100 μA. The probe I-V characteristics were recorded by an X-Y plotter (X : probe voltage, Y : probe current), where the probe current was measured by the voltage drop of a resistor of 4.5 kΩ. Fig. 4 shows the I-V characteristics in the ICP without and with the electron-beam injection.

The plasma parameters from the I-V characteristics were tabulated in Table 1, which were evaluated by the conventional manners. [7] The electron temperature is derived from the slop of curve in the semi-log plot of the probe current and the probe voltage. The floating potential is derived by the voltage where the probe current is equivalent to zero, and the plasma potential is obtained from the voltage where the differential value of the probe current to the probe voltage becomes the maximum. The plasma density is calculated from the ion saturation current.

The plasma parameters from the I-V characteristics were tabulated in Table 1. The I-V curve was shifted toward the negative voltage by injecting the electron-beam to the ICP. The evaluated electron temperature and density were comparable to the other ICP [8] and EBEP. [9]

We notice that the floating and the plasma potentials are decreased by the electron-beam injection into the ICP, and the electron temperature and density are increased a little.

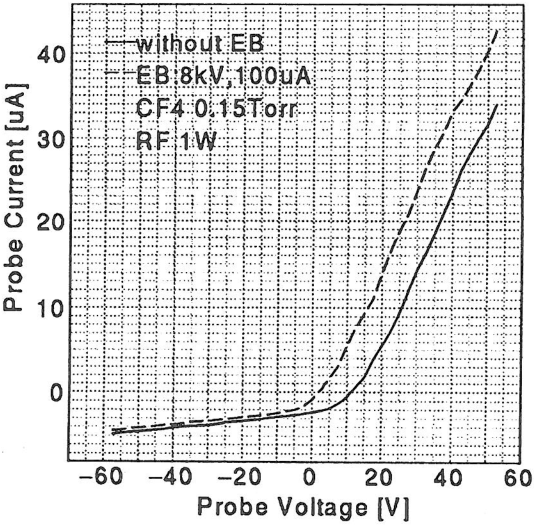

Fig. 4 : I-V characteristics of the ICP without and with electron-beam injection.

Table 2 shows the plasma palameters when the acceleration voltage of the injected electron-beam was changed, that is, the number of electrons emitted from the tungsten filament and transmitted through the interface into the reaction chamber were changed. The condition was in CF_4 gas at 0.11 Torr, the supplied rf power of 1 W and the interface was grounded. It was confirmed that the electron injected into the reaction chamber caused the increase of electron temperature and density.

However, the variation of plasma parameter of ICP by the electron-beam injection is not so large because the injected electron current was small. Even if the plasma parameters were not strongly affected, it is obvious that ICP can be controlled by the electron-beam injection.

Table 1 : Typical plasma palameters evaluated from the probe measurements.

	without EB	with EB
T_e [eV]	5.3	5.6
V_f [V]	12	2
V_p [V]	38	33
n_e [cm^{-3}]	2.21×10^{12}	2.68×10^{12}

T_e : electron temperature
V_f : floating potential
V_p : plasma potential
n_e : electron density

Table 2 : The variation of the plasma palameters by changing acceleration voltage of electron-beam.

EB accel. Voltage [V]	T_e [eV]	V_f [V]	V_p [V]	n_e [cm^{-3}]
0	2.5	11.4	25	1.68×10^{12}
4	2.9	9.1	23	1.70×10^{12}
6	3.3	7.2	22	1.71×10^{12}
8	3.5	7.4	23	1.74×10^{12}

Conclusion

It was found that the electron-beam injection into the ICP decreases the minimum rf power supplied to the loop antenna necessary for the initiation of discharge. This means that the ICP can be formed easily even if the gas pressure will be decreased.

A fine pattern of 0.2 μm was successfully fabricated by the ICP etching with the electron-beam injection using the resist mask of aluminum film fabricated by a fine gallium-FIB system.

From the probe measurements, the floating and plasma potentials were decreased and the electron temperature and density were increased by the electron-beam injection, compare to the ICP without the injection. This fact suggests that the ICP can be controlled by the injected electron-beam, and the electron density in ICP can be increased much more if electron current transmitted through the interface is increased.

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