

Comparison of atomic scale etching of poly-Si in inductively coupled Ar and He plasmas

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Abstract—Atomic scale etching (ASE) of poly-Si, which can give etching with atomic scale accuracy, was investigated in inductively coupled Ar and He plasmas. ASE used a cyclic operation of gas adsorption and ion beam irradiation, which is the same concept as atomic layer etching of single crystal substrates. The etch rate gradually increased, reached the saturated region, and then rapidly increased with increasing bias voltage (or ion energy) in both Ar and He plasmas. This saturation region offered a process window for the realization of ASE. At the bias voltage within the process window for ASE, the etch rate was self-limited with respect to the duration of ion beam irradiation for both Ar and He plasmas, confirming that ASE of poly-Si was successfully achieved in both Ar and He plasmas. The range of the process window for ASE using He plasmas was about 10 times wider than that using Ar plasmas. This is because heavier Ar ions impart a greater fraction of ion energy to the surface atoms compared to lighter He ions.

Key words: Atomic Scale Etching, Plasma, Cyclic Operation, Process Window, Ion Energy

INTRODUCTION

As device dimensions keep shrinking, the control of dimensions down to the atomic level is increasingly required for the fabrication of abrupt heterostructure interfaces and extremely thin layers for many devices [1]. This has led to the evolution of atomic layer processing, which can offer atomic layer control over deposition and etching for a variety of materials.

A reactive ion etching (RIE) technique is currently used for defining fine features [2,3], but energetic reactive ions generated in a plasma are known to cause serious radiation damages [4]. Lowering ion energy, in order to reduce radiation damages, results in isotropic chemical reactions caused by neutrals, and the corresponding deterioration of the pattern definition. To eliminate a wide variety of damages and achieve high-resolution features, a new concept of directional etching with minimum reaction energy is needed. For this purpose, atomic scale etching (ASE), which is a layer-by-layer removal of materials with self-limited characteristics, is one of the attractive candidates.

ASE, which is a cyclic process consisting of four steps, has the same concept as the so-called atomic layer etching (ALET) of single crystal substrates [5-8], in that pulsed operation of etchant gas adsorption and energetic beam irradiation are repeated. Fig. 1 demonstrates the concept of an ALET process. During step 1, a clean substrate surface is exposed to an etchant gas, and the etchant gas adsorbs (chemisorbs) onto the surface to form a monolayer. In this step, the etchant gas should not spontaneously etch the substrate

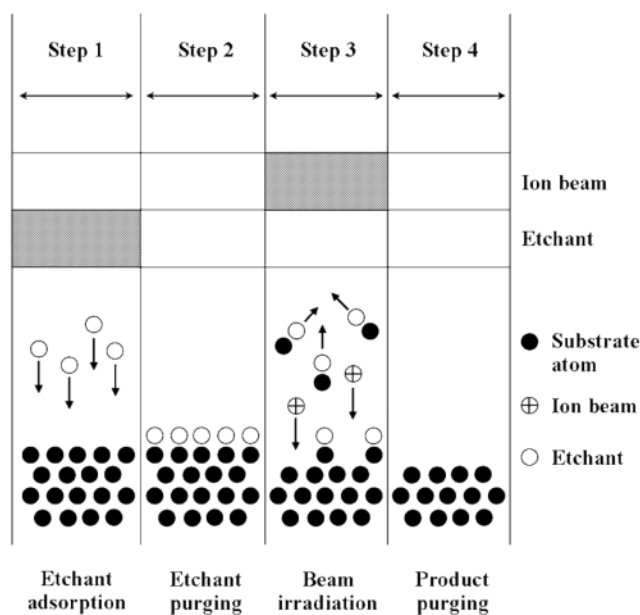


Fig. 1. Schematic of ALET of a single crystal substrate.

atoms. The residual etchant gas that does not adsorb on the substrate is pumped out in step 2, so that only the adsorbed layer will react. During step 3, the substrate surface is exposed to an energetic beam (such as ion beam) to induce chemical reactions between the adsorbed gas and the underlying substrate atoms so that etching takes place. In this step, the ion beam itself should not sputter any substrate atoms. Otherwise, etching with atomic layer accuracy will be lost. Etch products are evacuated from a reaction chamber in step 4 since the remaining products may affect the adsorption of etchant gas in step 1 of a new ASE cycle. In this way, an ideal ASE pro-

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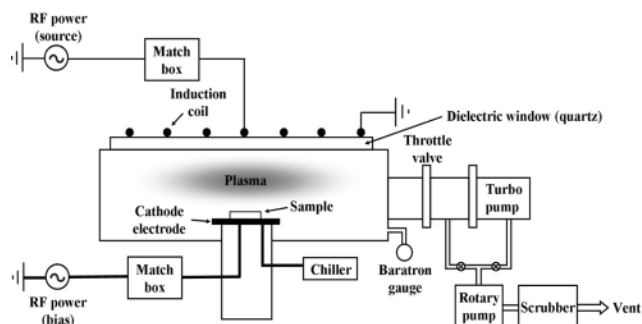


Fig. 2. Schematic of the inductively coupled plasma system for ASE experiments.

cess would etch exactly one monolayer of the substrate surface during one ASE cycle. To realize this, the etch rate should be self-limited with respect to the exposure of both etchant gas (in step 1) and energetic beam (in step 3).

In this work, an experimental system and a methodology were developed to perform ASE of poly-Si in inductively coupled Ar and He plasmas. Other studies on etching with monolayer accuracy have focused on single crystal surface (such as Si and Ge), and ASE of polycrystalline film has not been reported.

EXPERIMENTAL

ASE was performed in an inductively coupled plasma system, which is shown in Fig. 2. Separate 13.56 MHz rf power generators were used to ignite a plasma and to bias a substrate holder. The plasma was ignited in a reaction chamber 200 mm in inner diameter and 90 mm in height by applying the rf power to a five-turn coil through a matching network. The bias power was applied via a stainless steel cathode 120 mm in diameter. In order to perform a cyclic process of ASE, a computer-controlled system was used to control on/off switching and timing of the source and bias powers and etchant gas flow.

Chlorine was used as an etchant in this study. Chlorine is a suitable etchant for ASE of poly-Si because chlorine does not spontaneously etch poly-Si at room temperature. As an ion beam source for step 3 in ASE, inductively coupled Ar and He plasmas were used.

The source power was 250 W, and the bias power was varied to get a bias voltage up to -100 V. Ar and He flows were continuously maintained at 40 sccm, respectively, and 2 sccm of chlorine was introduced to the chamber during step 1. The chamber pressure was fixed at 80 mTorr throughout the experiment with a throttle valve. This pressure, a bit higher than pressures used in other atomic layer etching processes, was selected because a stable He plasma was hardly obtained at low pressures. The duration of each step was 20 s, 30 s, and 30 s for steps 1, 2, and 4, respectively. The duration of step 3 was varied to check self-limited characteristic of the etch rate with respect to ion beam dose.

Samples were undoped blanket poly-Si substrates, cut into a $1\text{ cm} \times 1\text{ cm}$ square and placed on the cathode. Before experiments, the samples were cleaned in a buffered HF solution to remove native oxide. The etch rates were determined by measuring changes in poly-Si thickness before and after ASE by using a thickness meter (Spectra Thick 2000-Deluxe, K-mac).

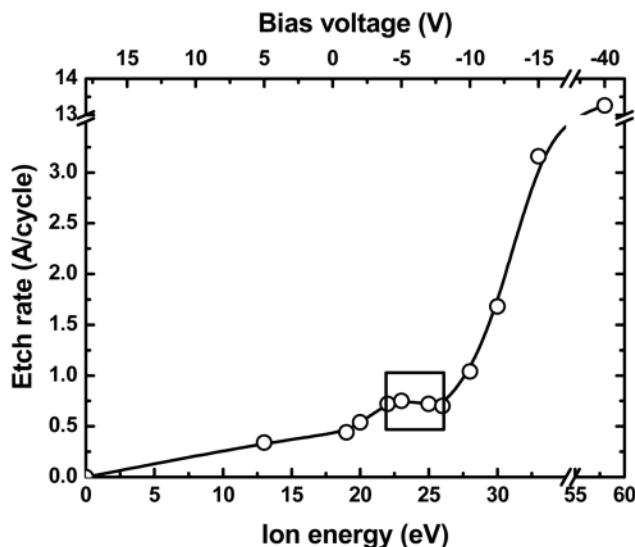


Fig. 3. Etch rate of poly-Si in ASE using an Ar plasma as a function of bias voltage. The rectangle represents a process window for the realization of ASE. The duration of steps 1, 2, 3, and 4 was 20 s, 30 s, 30 s, and 30 s, respectively.

RESULTS AND DISCUSSION

As mentioned earlier, the etch rate should be self-limited with respect to ion beam dose in step 3 in order to achieve ASE. The role of an ion beam in ASE is to only induce chemical reactions between the adsorbed etchant atoms and the underlying substrate atoms. In other words, the ion beam itself should not sputter any substrate atoms. Therefore, the energy of ions generated in a plasma is one of the important parameters to achieve ASE. Since inductively coupled plasmas were used as a source of ion beam in this study, the ion energy could be independently controlled by varying the bias voltage.

Fig. 3 shows the etch rate of poly-Si in ASE using an Ar plasma as a function of bias voltage. We made Langmuir probe measurements, and a plasma potential of 18 V was obtained in the Ar plasma. So, the X-axis was also designated as ion energy, accounting for the plasma potential. The duration of steps 1, 2, 3, and 4 was 20 s, 30 s, 30 s, and 30 s, respectively. The etch rate gradually increases with bias voltage of up to -4 V, and it is saturated at the bias voltages between -4 and -8 V. With further increase in the bias voltage, the etch rates increase rapidly.

This behavior of the etch rate implies that ASE of poly-Si in an Ar plasma was obtained at the bias voltages between -4 and -8 V or at the ion energies between 22 and 26 eV. At this range of the bias voltage (or ion energy), Ar ions contributed to fully induce chemical reactions between the adsorbed chlorine atoms and the underlying poly-Si atoms, resulting in ion-induced chemical etching. Therefore, the variation of the bias voltage (or ion energy) in this range does not affect the etch rate. It can be said that this range is a process window for the realization of ASE of poly-Si. The etch rate at the bias voltages higher than this range, however, are strongly dependent on the bias voltage, because Ar ions with high ion energy will sputter poly-Si atoms rather than induce chemical etching. Sputtering with Ar ions led to the loss of etching with atomic scale ac-

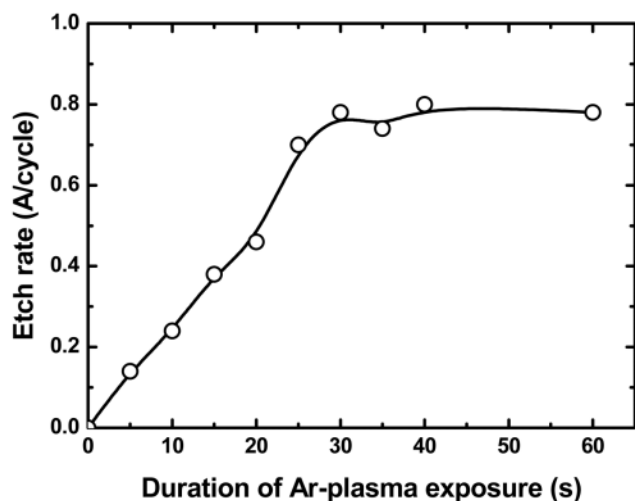


Fig. 4. Etch rate of poly-Si in ASE using an Ar plasma as a function of duration of step 3 (Ar-plasma exposure). The bias voltage was -5 V, which was within the process window for ASE.

curacy.

At the bias voltage of -5 V (within the process window for ASE), it can be seen from Fig. 4 that the etch rate increases and reaches a saturation value as the duration of step 3 (Ar-plasma exposure) is increased. This indicates that self-limited etching is achieved with respect to ion dose, confirming that ASE of poly-Si was obtained at this condition. The self-limited etching was possible at this bias voltage because the Ar ions within the process window do not sputter poly-Si atoms but induce chemical etching. Therefore, once a saturated etch rate was obtained, further increase in Ar-ion irradiation did not lead to an increase in the etch rate.

One can see that the process window for ASE is very narrow, which is only 4 V of bias voltage. This tough condition may make

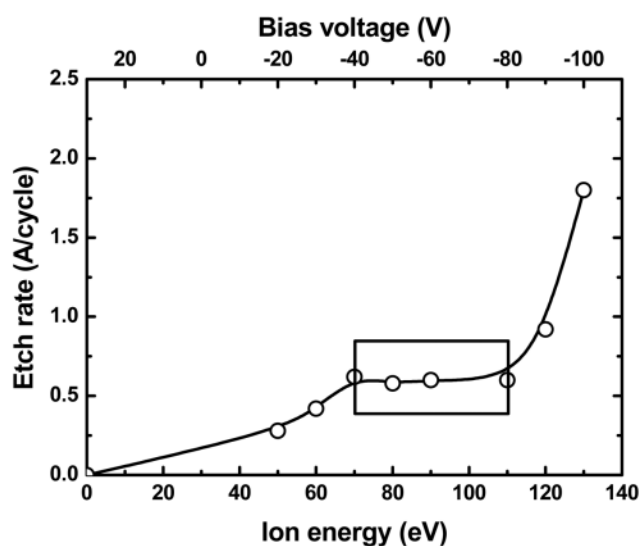


Fig. 5. Etch rate of poly-Si in ASE using a He plasma as a function of bias voltage. The rectangle represents a process window for the realization of ASE. The durations of steps 1, 2, 3, and 4 were 20 s, 30 s, 30 s, and 30 s, respectively.

ASE very difficult for practical usage. In order to have mild conditions for the realization of ASE, we have tried to use He plasmas instead of Ar plasmas as an ion beam source in step 3.

Fig. 5 shows the etch rate of poly-Si in ASE by using a He plasma as a function of bias voltage. Langmuir probe measurements were also conducted and a plasma potential of -30 V was obtained in the He plasma. The durations of each step are the same as those using an Ar plasma: 20 s, 30 s, 30 s, and 30 s for steps 1, 2, 3, and 4, respectively. It can be seen that the behavior of the etch rate using He plasmas with varying the bias voltage is the same as that using Ar plasmas. That is, the etch rate gradually increases with bias voltage of up to -40 V, reaches a saturated region at the bias voltages between -40 and -80 V, and then increases rapidly with further increase in the bias voltage. This suggests the existence of a process window for the realization of ASE of poly-Si using a He plasma as in the case of an Ar plasma. However, the range of the bias voltage for etch rate saturation, which is a process window for ASE, is 40 V in He plasmas, 10 times wider than compared to Ar plasmas. This may result from the difference in mass between Ar and He ions. The total distance that a heavier Ar ion travels in solid substrates before coming to rest is less than that for a lighter He ion [9,10]. Therefore, a greater fraction of the ion energy will be imparted to the surface atoms for the case of Ar ions. This resulted in very narrow process window for ASE using Ar plasmas while much wider process window was obtained using He plasmas.

Fig. 6 shows that the etch rate of poly-Si in ASE using a He plasma at the bias voltage of -50 V as a function of duration of step 3. This bias voltage is within the process window for ASE. The etch rate is self-limited with respect to the duration of He-plasma exposure, confirming that ASE of poly-Si in He plasma was also achieved. Therefore, it can be said that the use of a He plasma gives favorable process conditions to realize ASE of poly-Si compared to an Ar plasma.

CONCLUSIONS

ASE of poly-Si was investigated by using a cyclic process of gas

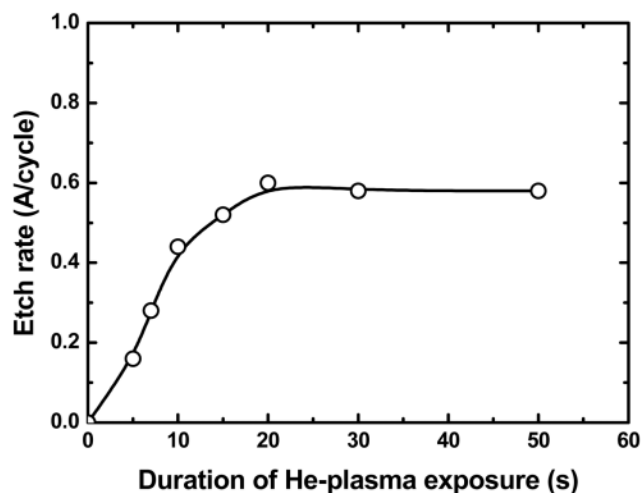


Fig. 6. Etch rate of poly-Si in ASE using a He plasma as a function of duration of step 3 (He-plasma exposure). The bias voltage was -50 V, which was within the process window for ASE.

adsorption and ion beam irradiation. The etch rate gradually increased, reached the saturated region, and then rapidly increased with increasing the bias voltage in both Ar and He plasmas. The saturation region offered a process window for the realization of ASE because the variation of the bias voltage (or ion energy) in this range did not affect the etch rate. Comparison of Ar and He plasmas as a source of ion beam in ASE showed that the process window for ASE using He plasmas was about 10 times wider than that using Ar plasmas, implying that the use of a He plasma can offer better conditions to realize ASE of poly-Si compared to an Ar plasma. This was thought to result from the difference in mass between Ar and He ions. At the bias voltage within the process window for ASE, the etch rate was self-limited with respect to the duration of ion beam irradiation during step 3 for both Ar and He plasmas. The self-limited characteristic of the etch rate confirmed that ASE of poly-Si was successfully achieved in both Ar and He plasmas.

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