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Invited

Novel Applications of Focused Ion Beam Technology

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Focused ion beams (FIBs) have potentiality for a local modification of materials which results in applications to microfabrication and change in film properties. The paper is intended to review novel applications with the FIBs. The first topic is concerning on the FIB assisted etching in Cl_2 gas ambient, in which basic properties and simulation is discussed to make clear the optimum condition for rapid engraving. In the second, we describe FIB induced lateral solid phase epitaxy of amorphous Si on insulator to realize longest recrystallized layer from the seed.

1. INTRODUCTION

Since the advent of 50-nm ion probe in 1979[1], a number of people have been making tremendous efforts to advance the focused ion beam (FIB) technology. Nowadays the FIB has been an indispensable tool for restructuring lithography masks and microcircuits[2,3], where the FIB is used to remove unnecessary layers with physical sputter etching and also to attach new layers such as electrical conductive films. The latter is accompanied with exposure to appropriate gases and called FIB assisted process[4], including FIB enhanced etching in reactive gases. These procedures have been also expected as a in-situ processing combined with other facilities such as molecular beam epitaxy. The first topic described here is on basic properties and simulation of the FIB assisted etching of Si and GaAs in Cl_2[5,6].

In addition to microfabrication technologies, the FIB has also a unique capability to modify thin film properties. It is well-known that ion irradiation enhances vertical epitaxial growth of amorphous Si[7]. In the second topic, we introduce recrystallization of amorphous Si film on insulator(SOI) induced by FIB irradiation (Lateral Solid Phase Epitaxy, LSPE). The optimum growth condition to obtain longest recrystallized layer is discussed[8,9].

2. FIB ASSISTED ETCHING

In order to examine basic characteristics, an etch yield (the number of substrate atoms removed per ion) was measured in case of showered Ga ion irradiation. The Cl_2 gas flux dependence of etch yield for Si is shown in Fig.1. Similar features were also observed for the GaAs/Cl_2 system. On the assumption that the reaction is mainly governed by the surface density of physisorbed Cl_2, the etch yield EY was expressed as[5]

$$EY = s\,g\,F/(g\,F+(x/2)\,s\,I+N_0/\tau)\ , \qquad (1)$$

where g refers to the sticking probability, F the gas molecule flux, s the averaged number of substrate atoms excited with ion bombardment, I the ion flux, N_0 the surface atom density, and τ the mean residential time of adsorbed Cl_2. The value of x is determined by assuming that the major etchant product is emitted as a MCl_x where M means elements of the substrates. The experimental data after

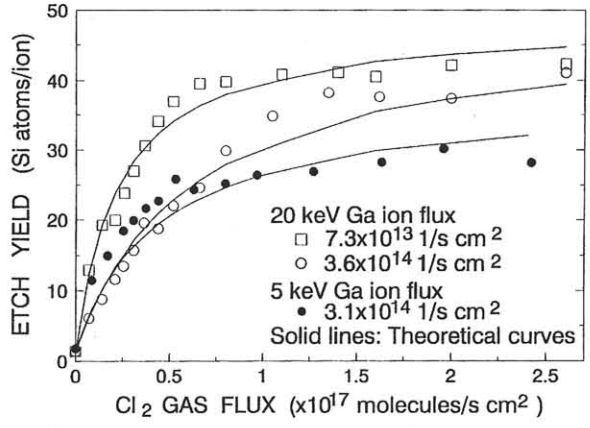

Fig. 1 Variation of etch yield for the Si/Cl_2 system at a room temperature as a function of Cl_2 flux, where showered Ga^+ ion with 5 and 20 keV energy were irradiated. Solid lines show curves calculated from eq. (1) by using parameters tabulated in Table I.

Incident ion	Substrate (Temperature)	Parameters in EY g	τ (sec)	s (Atoms/ion)	Accumulated energy (eV/nm) Lattice	Electronic
20keV Ga	Si(20 ℃)	0.68	0.15	47	800	400
5keV Ga	Si(20 ℃)	0.68	0.15	36	600	200
20keV Ga	Si(110 ℃)	0.68	0.002	47	800	400
20keV Ga	GaAs(20℃)	0.87	0.15	101	1090	370
20keV Ga	GaAs(110℃)	0.87	0.15	430	1090	370

Table I Empirically determined parameters for etch yield expressed by eq. (1), where x=4 for Si ($SiCl_4$) and x=3 for GaAs ($GaCl_3$ and $AsCl_3$).

subtracting a physical sputter yield were fitted to eq. (1) as indicated by solid lines in Fig. 1. The best fit parameters used are summarized in Table I together with the results for the GaAs/Cl_2. It should be noted that the value of s is nearly proportional to the lattice energy transferred from the incident ion.

The etch yield for the Si/Cl_2 decreases with the substrate temperature because of reduction of mean residential time τ which activation energy is determined to be 0.37 eV. On the contrary, the etch yield for the GaAs/Cl_2 increases with the temperature, while it still has a saturated trend. We believe that the reason might be that chlorination at higher temperature is enhanced over several layers for GaAs[10] so that the chlorides on the top of the surface would have rather weaker binding energy.

By using the three parameters in Table I, the etch yield in cases of Ga^+ FIB raster-scanning were computed as a function of scanning time based on the time-dependent rate equation for the density of adsorbed Cl_2. The results for the GaAs/Cl_2 are shown in Fig. 2, where we can see a good agreement between the theory and the experiment. Thus it is concluded that to lengthen a recovery time for Cl_2 adsorption is the most important factor for rapid engraving.

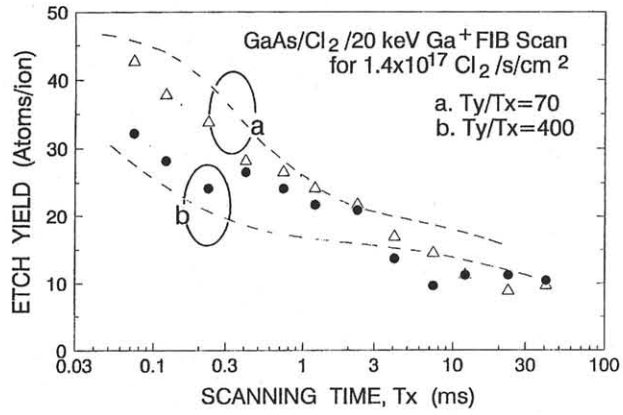

Fig. 2 Etch yield for the FIB raster scanning over a 36x36 μm^2 at a room temperature as a function of scanning time T_x, where the FIB with a diameter of around 1.2 μm and a current density of about 0.2 A/cm^2 was used. T_y/T_x means the number of scans per one frame and broken lines show calculated curves.

Figure 3 shows a micrograph of field-electron emitter array in GaAs fabricated by the present etching procedure. Various microfabrication will be demonstrated.

3. LATERAL SOLID PHASE EPITAXY

In this experiment, amorphous Si films with about 0.2 μm thickness were deposited on partially oxidized (100) Si wafer and then the substrates were annealed at 600 ℃ so as to complete a seed crystalline region through a vertical SPE. The FIB of Si^{2+} with about 0.3 μm diameter was irradiated to induce the LSPE. The formed SOIs were observed with a scanning electron microscope after etching in phosphoric acid at 195℃, which removes the amorphous regions selectively.[10]

First, we examined the case of uniform irradiation as shown in Fig. 4a), where the FIBs were rapidly scanned over an area involving both the seed and the SOI. The LSPE layer elongated up to about 2 μm from the seed, while polycrystallization was enhanced in the SOI region irradiated distantly from the seed. In other words, these poly-grains hinders elongation of the LSPE at higher dose. Figure 5 shows the dose rate dependence of the LSPE length per dose and the LSPE rate. It is considered that the higher dose rate produces a number of complex defects which severely inhibits the LSPE

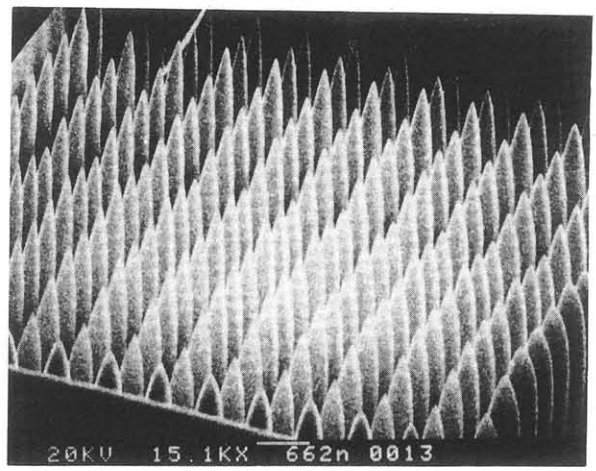

Fig. 3 A micrographs of field-electron emitter array in GaAs fabricated by the FIB assisted etching.

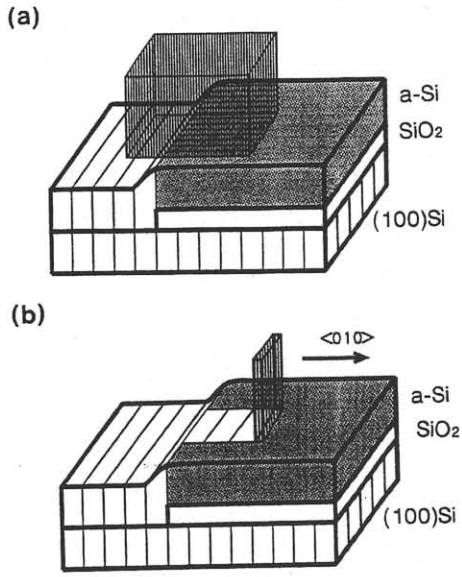

Fig. 4 Diagram of lateral solid-phase epitaxy process using ion beams of two different shapes: (a) square-shaped beam and (b) pseudo-linear beam.

growth[7]. This is the reason why the LSPE rate exhibits probably a maximum of 30 nm/s which is about two orders of magnitude larger than that of thermally induced LSPE at 600℃.

To elongate the LSPE layer, the rapidly scanned FIB was slowly swept from the seed as shown in Fig.4b). The results are summarized in Fig.6. When we notice the data at a fixed current density (the data shown by (A) and (B)), the fastest sweep-velocity required to complete the regrowth over the swept region becomes larger with the current density. This is similar to the result in Fig.5. The LSPE length at 550℃ indicated that longer LSPE could not be obtained since the growth was hindered by poly-grains. This is probably because the higher temperature creates significantly a large number of nuclei for polycrystallization before ion irradiation. Thus the present investigation shows that the

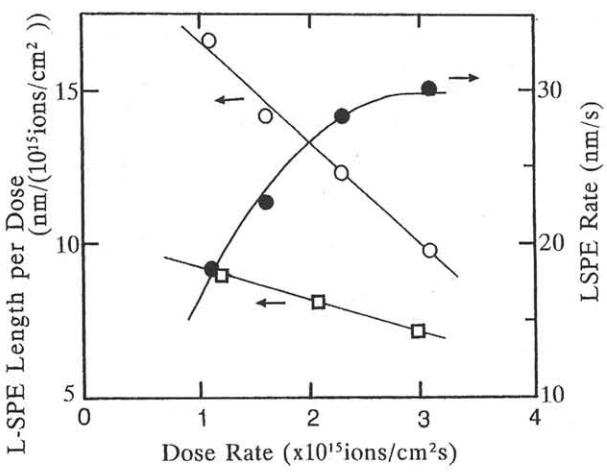

Fig. 5 Dose rate dependence of the LSPE length per dose and LSPE rates in Fig. 4a), where open and sold circles are for the substrate temperature of 500℃ and squares for 470℃.

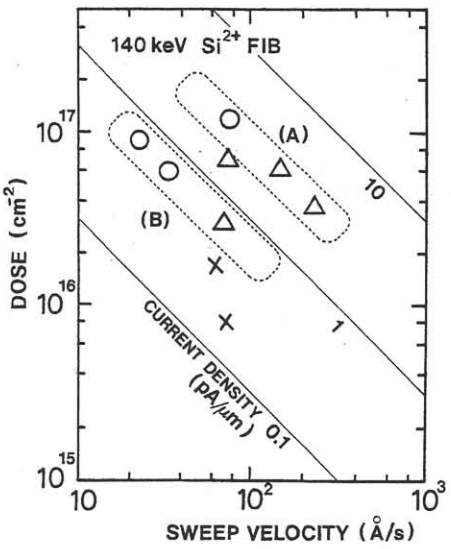

Fig. 6 Dependence of the LSPE length on dose and sweep velocity. ○ :grown to the edge of the swept area, △ :grown halfway, and × :ungrown.

temperature of 500℃ is optimal to accomplish the highest growth rate and longer LSPE layer.

4. SUMMARY

Characteristics of ion beam assisted etching and beam induced lateral solid phase epitaxy were described. The former may be rather applicable to the field of micromachining since a lot of ion beam induced damages are still remained in the substrates[4]. On the other hand, film qualities have to be investigated in the latter experiment to ensure feasibility of device formation in this films.

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