High-Speed Nano-Processing with Reactive Cluster Ion Beams

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Abstract

Cluster ion beam processes can produce high rate sputtering with low damage in comparison with monomer ion beam processes. Especially, it is expected that extreme high rate sputtering can be obtained using reactive cluster ion beams. Reactive cluster ion beams, such as SF₆, CF₄, CHF₃, CH₂F₂, Cl₂, and O₂ were generated and their cluster size distributions were measured using Time-of-Flight (TOF) method. Si substrates were irradiated with the reactive cluster ions at the acceleration energy of 5-80 keV. Each sputtering yield was increased with acceleration energy and was about 1000 times higher than that of Ar monomer ions. The sputtering yield of SF₆ cluster ions was about 3300 atoms/ion at 80 keV. With this beam, 12 inches wafers can be etched 0.3 µm per minute at 1 mA of beam current. Although the sputtering yield with SF₆ cluster is very high, a SF₆ cluster irradiated Si surface was smoothed. This high-speed processing with reactive cluster ion beam can be applied to fabricate nano-devices.

Introduction

The gas cluster ion beam process has become a candidate technique for advanced nano-fabrication, where both throughput and precise functionality are required. A cluster is an aggregate of a few to several thousands atoms. When the many atoms constituting a cluster ion bombard a particular area, high-density energy deposition and multiple-collision processes occur simultaneously. Because of the unique interactions between cluster ions and surface atoms, new surface modification processes could be developed, and surface smoothing [1–4], shallow implantation [5,6], high rate sputtering [7] and low damage surface processing [8], have been demonstrated using this technique.

Recently, the energy and size of cluster have become well controllable and many kinds of gaseous materials become available as cluster source gas. Especially, a gaseous material with chemical reactivity towards the target material has often been applied as a cluster source. It is demonstrated that extreme high-speed and precise nano-processing can be realized with reactive cluster ion beams. For example, etching a photonic crystal with cluster ion beams could smooth both the bottom surface and the sidewall of Si pillars [9]. Sidewall smoothing is essential for ultra-low-loss photonic crystals. To date, this technique has been applied to photonic, magnetic [10], electronic [11], and biological materials [12].
Gas Cluster Ion Beam Generation

Figure 1 depicts a schematic diagram of the cluster ion beam irradiation system. The formation of gas cluster beams utilizes the adiabatic expansion of high-pressure gas through a nozzle [13]. The cluster beam enters into high vacuum through a skimmer and the neutral clusters are ionized by electron bombardment. The ionized clusters are accelerated and transported towards targets. For high-speed surface processing with gas cluster ion beams, a high-current and high-energy cluster ion beam is needed, and in order to achieve this goal, the cluster generator, ionizer and ion extraction have been studied [14,15]. A neutral cluster beam with high intensity was generated by the development of large metal nozzles and efficient ionization and extraction were realized by structural improvements of the ionizer. Figure 2 presents the year-to-year development of the neutral cluster beam intensity and beam current of Ar cluster. Both the neutral cluster beam intensity and the beam current have increased by a factor of 10 in the last several years. A beam current of more than 1 mA was achieved in 2004 [15]. With this beam current, 12-inch wafers can be treated with a dose of $2 \times 10^{15}$ ions/cm$^2$ in about 4 min. This process speed is sufficiently high for the cluster beam to be adopted for next generation processes.

On the other hand, etching yields by cluster ion beams are expected to increase with acceleration energy [16]. A high-energy gas cluster ion beam irradiation system was developed, in which high-energy beams of Ar, SF$_6$, Cl$_2$, CHF$_3$, and O$_2$ clusters were
generated [17]. The gas clusters of SF$_6$, Cl$_2$, CHF$_3$, and O$_2$ are reactive and are expected to etch specific target materials with extremely high speed. SF$_6$, CHF$_3$, and O$_2$ cluster ion beams can be generated with high intensity by using a high-pressure gas mixed with He. The mean size of Ar, SF$_6$, Cl$_2$, CHF$_3$, and O$_2$ clusters, measured with a Time-of-Flight (TOF) system at the source gas pressure and ionization conditions shown in Table 1 was about 1850 atoms, and 650, 1500, 1750 and 2900 molecules, respectively (Fig.3).

### High-Speed Etching

The sputtering yield of Si calculated using TRIM [18] does not increase with the acceleration energy for Ar monomer, but it increased for Ar cluster (Fig. 4(a)). With Ar cluster the sputtering yield of Si reached about 230 atoms/ion at 80 keV, and this value is about 180 times that obtained with Ar monomer ions, whereas the sputtering
yields of Si with reactive gas clusters were several times those obtained with Ar cluster ions. In particular, the sputtering yield of Si with SF$_6$ cluster reached about 3300 atoms/ion at 80 keV, i.e. about 2600 times the value obtained with Ar monomer ions (also Fig. 4(a)). With this beam, 12-inch wafers can be etched at a rate of 0.3 µm per min at a beam current of 1 mA. The sputtering yield of CVD diamond with O$_2$ cluster was about 5 times that obtained with Ar cluster ions (Fig. 4(b)). We found that reactive sputtering occurred with irradiation with cluster ions of SF$_6$, Cl$_2$, CHF$_3$, and O$_2$. Overall, these results show that extremely high-speed etching can be realized with high-energy reactive cluster ion irradiation.

Figure 5 shows the effect of acceleration energy on the etching ratio of Si/Ni and Si/SiO$_2$ after SF$_6$ or Cl$_2$ cluster irradiation. For SF$_6$ cluster irradiation, the etching ratio of Si/SiO$_2$ was high at low acceleration energy, but was low (below 2) at high acceleration energy. On the other hand, the etching ratio of Si/Ni was very high (above 25) at acceleration energy of 20 keV. The etching ratio of Si/Ni decreased with acceleration energy, but was still high (above 8) at 80 keV. For a material to be used as a mask for Si etching, its selectivity should be high. Because the sputtering yield of Si is high at high acceleration energy, high-speed fabrication could be realized using SF$_6$ cluster ion beams, if the selectivity is also high in this energy range. The etching ratio of Si/Au was constantly high (above 6) at acceleration energies in the range 5–45 keV [19]. It is expected that metals can maintain the high etching ratio at high-energy. In fact, at high-energy there is a slow-down in the reduction of the Si/Ni etching ratio. Therefore, Ni is suitable as mask material in high-speed fabrication using high-energy SF$_6$ cluster ion beams. In the case of Cl$_2$ cluster irradiation, the etching ratio of Si/SiO$_2$ was above 10 at acceleration energies in the range 10–50 keV. Thus, SiO$_2$ can be used as a mask for irradiation with Cl$_2$ cluster ion beam, which is an advantage for semiconductor processing.

**Surface Smoothing**

The smoothing effect by cluster ion irradiation is derived from the horizontal movement of many surface atoms by cluster impacts [20–22]. On the other hand, on an atomically flat surface, a cluster impact forms a crater [23,24]. A rough surface can be
smoothed until it reaches the roughness caused by the crater formation [25]. Figure 6 shows the average roughness of Si surfaces after irradiation by Ar cluster at a dose of $5 \times 10^{15}$ ions/cm$^2$ and by SF$_6$ cluster at a dose of $10^{15}$ ions/cm$^2$ as a function of acceleration energy. The results are compared with those of SF$_6$ monomer ion irradiation at a dose of $8 \times 10^{16}$ ions/cm$^2$. The roughness increased with the acceleration energy of the bombarding cluster. Because the initial Si surface was atomically flat, the increase in surface roughness is caused by the dominance of the surface cratering over the smoothing mechanism. The average roughness with SF$_6$ cluster irradiation was a little higher than that with Ar cluster, but both were less than 3 nm at acceleration energies in the range 20–80 keV. In comparison, when the Si surface was irradiated with SF$_6$ monomer ion beam (acceleration energy of 20 keV, dose of $8 \times 10^{16}$ ions/cm$^2$), the average roughness was about 4.4 nm. The sputtering yield of Si with SF$_6$ monomers was about 6, and thus the etching depth by SF$_6$ monomers with this ion dose was less than that by SF$_6$ cluster with ion dose of $10^{15}$ ions/cm$^2$. These results show that surfaces etched by high-energy reactive clusters are smooth compared with etching by monomer ions.

Figure 7 shows AFM images of Si surfaces irradiated with clusters of Ar, SF$_6$, and Cl$_2$ at the same acceleration energy (20 keV) and ion dose ($10^{15}$ ions/cm$^2$). The average roughness of the initial Si surface was 5.4 nm. Irradiation with a monomer ion beam would normally rough the surface. However, with cluster irradiation the Si surfaces were smoothed...
regardless of the species. Particularly, although the sputtering yield with SF$_6$ cluster was very high, the surface irradiated with SF$_6$ cluster was smoothed. This result indicates that using reactive cluster ion beams high-speed and smooth processing of materials can be realized.

**Summary**

High energy and high current cluster ion beams have been generated, and many kinds of reactive gas cluster ion beams have become available for materials processing. It was demonstrated that extremely high-speed and smooth surface processing can be realized with using reactive cluster ion beams. The cluster ion beam is a strong tool for advanced nano-fabrication.

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**References**