Ion-beam lithography by use of highly charged Ar-ion beam

著者	Momota Sadao, Iwamitsu Shingo, Goto Shougo, Nojiri Yoichi, Taniguchi Jun, Miyamoto Iwao, Ohno Hirohisa, Morita Noboru, Kawasegi Noritaka
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Ion-beam lithography by use of highly charged Ar-ion beam

Sadao Momota, Shingo Iwamitsu, Shougo Goto, and Yoichi Nojiri
Kochi University of Technology, Miyano-kuchi, Tosayamada-cho, Kochi 782-8502, Japan

Jun Taniguchi, Iwao Miyamoto, and Hirohisa Ohno
Tokyo University of Science, Yamasaki, Noda, Chiba ■, Japan

Noboru Morita and Noritaka Kawasegi
Toyama University, Gofuku, Toyama, Japan

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In order to fabricate a nanoscale three-dimensional (3D) structure by using the ion-beam lithography (IBL), we tried to control the etching rate and the etching depth by means of the charge state, the beam energy, and the fluence of the ion beam. Ar-ion beams with $E=90$ keV and 80–400 keV were irradiated onto spin on glass (SOG) and Si, respectively. The Ar ions were prepared by a facility built at the Kochi University of Technology, which included an electron cyclotron resonance ion source (NANOGAN, 10 GHz). It was found that the irradiation of highly charged ions (HCIs) enhanced the etching rate of SOG. The etching rate and etching depth of Si were controlled by the beam energy and the fluence of Ar^{4+} ions. The present results show the effectiveness of IBL with HCIs to fabricate a nanoscale 3D structure. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2165269]

INTRODUCTION

Recently, nanoscale three-dimensional (3D) structures played important roles in various fields of industrial applications. Nevertheless, it is difficult to mass produce such structures. The nanoscale two-dimensional (2D) structures can be fabricated by the ion-beam lithography (IBL) with proton beams[1] and singly charged heavy-ion beams.[2] For a high throughput of fabrication, heavy-ion beams are suited compared with proton beams. However, a high-voltage terminal is required to fabricate a structure with a high aspect ratio by using singly charged heavy-ion beams. The development of an efficient fabrication process to produce nanoscale 3D structures has been eagerly required.

In order to develop a fabrication process, highly charged ions (HCIs) were applied to IBL, which can produce nanoscale structures. HCIs are expected to have two advantages to realize a fabrication process compared to singly charged ions: (1) HCIs can be accelerated to higher energy by means of a low-voltage terminal. HCIs would be suited to fabricate structures with a high aspect ratio. (2) HCIs can be applied to modify irradiated materials caused by its high reactivity;[3] the applicable fields are summarized in Ref. 4. Utilizing these advantages, it is expected that a 3D irradiation profile could be efficiently produced in materials by performing IBL with HCIs. The electron cyclotron resonance (ECR) ion source is suited to produce HCI beam with a sufficiently high beam intensity to perform IBL.

EXPERIMENT

Ar ions were irradiated onto the materials to be fabricated by using a facility that was built at the Kochi University of Technology.[5] The Ar ions were prepared by a 10 GHz NANOGAN,[6] which is an ECR ion source. Each charge state was identified and separated using a dipole magnet. At room temperature, $Ar^{1+,9+}$ ions with an energy of 90 keV and Ar^{4+} ions with energies of 80–400 keV were irradiated onto spin on glass (SOG) on a Si substrate and Si, respectively. In order to produce a pattern on irradiated materials, Ar ions were irradiated through a Cu stencil mask, which had square holes with 43 μm sides. The fluence rate was monitored during irradiation. In order to perform the precise measurements of the fluence rate, two electrodes and one collimator were designed and mounted, as shown in Fig. 1. The typical fluence rates for $Ar^{1+,4+,9+}$ ions were $0.1-1$ $\mu A/cm^2$. The irradiation of Ar ions onto SOG and Si was followed by etching using a solution of HF at room temperature. The etching time for SOG was 1 min, and that for Si was between 10 and 120 min. The surface profile of SOG and Si after the etching was examined using an Alpha-Step IQ surface profiler and an atomic force microscope (AFM), respectively.

RESULTS

A Cu stencil mask pattern was successfully transferred to SOG and Si by performing IBL with HCIs, and the irradiated region became hollow. The irradiation of Ar ions enhanced the etching rate of SOG and Si. Here, we define the etching depth to be the depth of the hollows from the surface induced by etching.

The etching depth of SOG is shown as a function of the Ar-ion fluence in Fig. 2. The figure shows that the etching depth of SOG in 1 min becomes constant, and no remarkable HCI effects are observed for the fluence of $20q-200q$ $\mu C/cm^2$, where q denotes the charge state of the irradiated Ar ions. For fluence values higher than $200q$ $\mu C/cm^2$, the etching depth of SOG for Ar^{9+} increased linearly with the fluence, and was about three times larger

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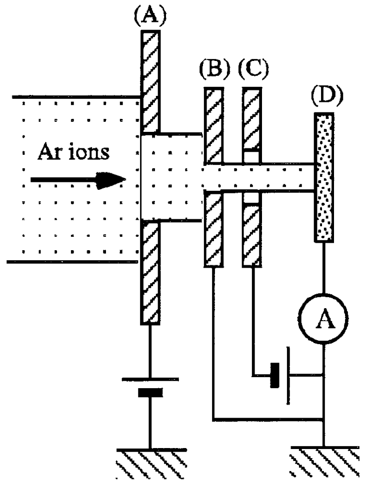

FIG. 1. Schematic picture of the measurement system of the irradiated beam current. During the irradiation of Ar ions, the fluence rate is monitored as a target current by using a current meter. An electrode (A) absorbs electrons coming from upstream. A collimator (B) defines the irradiation area of the ion beam. An electrode (C) suppresses any secondary electrons emitted from an irradiated sample (D).

than the depth obtained using Ar^{1+} ions at a fluence of $500q$ $\mu C/cm^2$. This phenomenon can be understood in terms of the HCI effect, which stimulates the creation of a damage, and would contribute to the etching of SOG. The etching depth of Si is shown as a function of the etching time in Figs. 3(a) and 3(b). In the figures, a delay of the etching process is found at the first stage. In principle, the etching depth increases with the etching time at the second stage and saturates at the final stage. Figure 3(a) shows that the delay of the etching process and the saturation value of the etching depth increase with the beam energy. The etching process (second stage) starts most quickly for the fluence of 800 $\mu C/cm^2$ and cannot be observed for larger fluence. The delay introduces the existence of a layer, in which the irradiation effect to promote the etching process is suppressed, at the surface.

In order to investigate the relation between the irradiation-induced damage and the etching depth, the depth distributions of damages are calculated based on the TRIM code.[7] The density distribution of the damage in SiO_2 induced by irradiation of Ar ions with 90 keV is shown in Fig. 4. The chemical composition of SiO_2 is similar to that of SOG. The maximum depth of the damage distribution

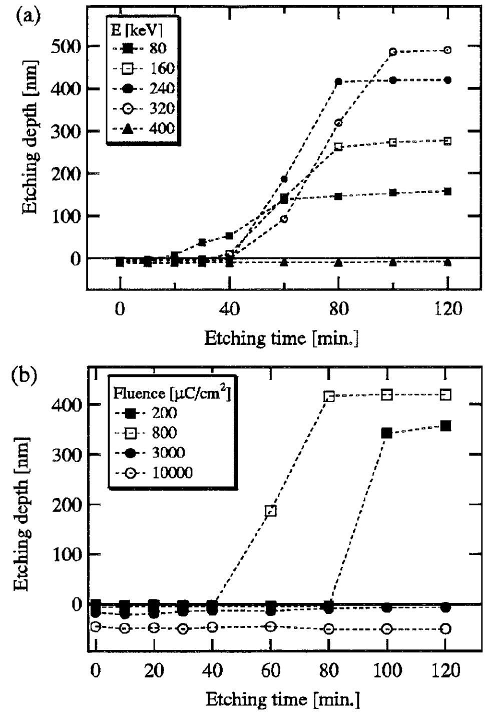

FIG. 3. Etching depth of Si as a function of the etching time. Ar^{4+} ions were irradiated onto Si. (a) The beam energy E was varied over the range of 80–400 keV. The fluence of Ar ions was 800 $\mu C/cm^2$. (b) The fluence of Ar ions was varied over the range of 200–10 000 $\mu C/cm^2$. The beam energy was 240 keV.

(~180 nm) is close to the observed maximum etching depth (208 nm) observed for Ar^{9+}-ion irradiation. In Fig. 5, the maximum depth of the damage distribution and the observed maximum etching depth for Si are shown as a function of the beam energy. The calculated maximum depth of damage well agrees with the observed etching depth. It is concluded from these results that the etching depth can be determined by the beam energy. Based on the above discussion, the etching rate would depend on the density and/or the type of damage. The layer, which would cause the delay of the etching process, can be explained by this idea.

DISCUSSION

In this study, HCIs of Ar were successfully applied to IBL, and the advantages of HCIs to fabricate nanoscale 3D

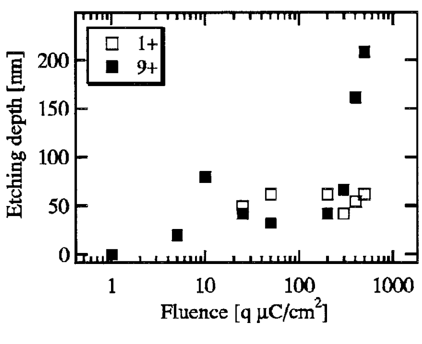

FIG. 2. Etching depth of SOG as a function of the Ar-ion fluence for the two charge states.

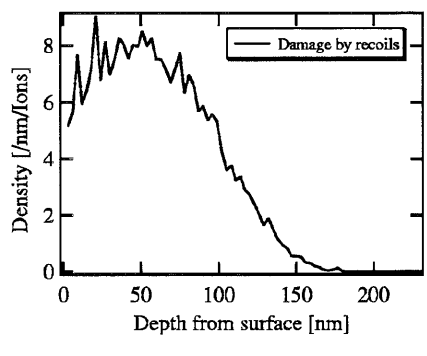

FIG. 4. Density distribution of vacancies in SiO_2 calculated by the TRIM code.

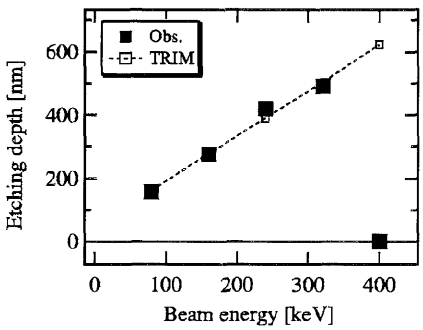

FIG. 5. Maximum etching depth of Si as a function of the beam energy.

structures were proved. An enhancement of the etching rate utilizing the high reactivity of HCIs would lead to a higher throughput of fabrication. The high aspect ratio of structures fabricated by HCIs is suited to fabricate 3D structures. Also, the depth of structures fabricated by IBL can be controlled by the charge state, the beam energy, and the fluence of ions. Furthermore, it has been proven that an ECR ion source can be applied to perform IBL with HCIs. In order to optimize the irradiation condition for practical applications, additional systematic research is required.

[1] K. Ansari *et al.*, Appl. Phys. Lett. **85**, 476 (2004).
[2] M. Koh *et al.*, Appl. Surf. Sci. **162–163**, 599 (2000).
[3] J.-P. Briand *et al.*, Rev. Sci. Instrum. **71**, 627 (2000).
[4] U. Kentsch *et al.*, Nucl. Instrum. Methods Phys. Res. B **216**, 196 (2004).
[5] S. Momota *et al.*, Rev. Sci. Instrum. **75**, 1497 (2004).
[6] C. Bieth *et al.*, *Proceedings of the 14th International Workshop on ECR Sources*, Geneva, 1999 (unpublished), p. 147.
[7] J. F. Ziegler *et al.*, *The Stopping and Ranges of Ions in Matter* (Pergamon, New York, 1985).