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Sub-micrometer-sized Patterning of Photoresist by Electron Beam Projection Lithography Using Tabletop Scanning Electron Microscopy System and Stencil Masks

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We demonstrated a lithography technique using stencil masks and a tabletop scanning electron microscopy (SEM) system by applying electron beam projection lithography (EPL) technology. Si and Pt were used as stencil mask materials. Si has excellent fabrication workability, and Pt has excellent electron shielding. The lithography was performed at an incident electron energy of 5 to 10 kV, which is typically used in the tabletop SEM system. This technique achieves high throughput and can expose large areas at once. Sub-micrometer- and micrometer-sized patterns can be formed simultaneously.

1. Introduction

Lithography technology is an essential element in the fabrication of MEMS devices. Although electron beam lithography (EBL) can be used to fabricate finer patterns than photolithography, EBL generally has low throughput because the electron beam is irradiated in a scanning mode. Electron beam projection lithography (EPL) systems, such as EB steppers, have been developed to solve this issue.[1] EPL, a type of EBL, is a technology that transfers a mask image onto a wafer and exposes the wafer and is used to achieve high throughput while maintaining high resolution.[2–6] In low-energy EPL (LEEPL), a type of EPL technology, a stencil mask is placed close to a wafer coated with a resist and irradiated with an electron beam. Si is used as the stencil mask material in EB steppers, whereas a polycrystalline diamond thin film is used as the stencil mask in LEEPL. In particular, it would be desirable to fabricate stencil masks with common materials instead of diamond thin films. LEEPL is operated using specialized equipment with 2 kV electron beam exposure.[7–9]

Therefore, to achieve EPL without these specific equipment and diamond stencil masks, we propose EPL with a tabletop SEM system for observation. We realized LEEPL with a simple method using a tabletop SEM system. This technique is easy because patterning can be

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performed with a tabletop SEM system by preparing a stencil mask. Furthermore, EBL enables the fabrication of sub-micrometer-sized patterns, which is difficult to achieve with contact exposure using mercury vapor lamps, which are widely used in research. We believe that the EPL technique using a tabletop SEM system is expected to expand its application to the fabrication of biochips containing sub-micrometer-sized patterns.[10–12] The important point of this technique is to fabricate stencil masks with common materials instead of diamond. In addition, using a tabletop SEM system, which is compact and easy to use, allows biologists to use this EPL technique with their own observation equipment. Biologists will benefit from having devices that are needed in large quantities, especially disposable ones, to be more easily available. Such devices are, for example, cell separators with sub-micrometer-order pillar-gap structures[13] and plasmonic crystal sensors.[14] These devices used in research and development will be fabricated using a tabletop SEM system.

In this study, stencil masks were fabricated using Si for micrometer-order lithography and Pt for sub-micrometer-order lithography. These materials were selected because Si has excellent fabrication workability and Pt has a large atomic number and an excellent electron shielding property. In particular, a thin Pt film can shield against electron beams, which enables the narrowing of the aperture pattern of the stencil mask. In this study, the EPL technique using a tabletop SEM system and a Si or Pt stencil mask was demonstrated. A photoresist was used to demonstrate the fabrication of sub-micrometer-sized resist patterns using the tabletop SEM system.

2. Experimental Methods

2.1 Lithography

Figure 1 shows a schematic of this experiment. The stencil mask was placed in contact with the wafer coated with a resist and exposed in the observation mode of the tabletop SEM system. A Hitachi High-Tech FlexSEM1000II was used as the tabletop SEM system for EPL. The magnification of the SEM image was 50 × in EPL, and the exposure area was 2.5×2 mm^2. The focal point of the SEM system was set 1 mm above the resist surface. The dose was estimated to be 50 μc/cm^2. This dose was reached after 10 min of exposure in the observation mode when using this SEM system. The acceleration voltage was from 5 to 10 kV. The higher the acceleration voltage, the higher the resolution, because a low acceleration voltage enhances the scattering of electrons inside the resist. The acceleration voltages generally used in tabletop SEM systems in the observation mode are from 5 to 15 kV, and 20 kV at the highest. In this study, the EPL technique was intended to be realized with a tabletop SEM system and was performed at an acceleration voltage from 5 to 10 kV.

Figure 2 shows the electron depth range in Pt and Si. This range is the maximum at which accelerated electrons penetrate a material. The range was calculated using the Kanaya–Okayama equation.[15] The electron depth in Si was 1.5 μm at an incident electron energy of 10 kV. Therefore, the thickness of the stencil mask should be larger than 1.5 μm. The resist was exposed

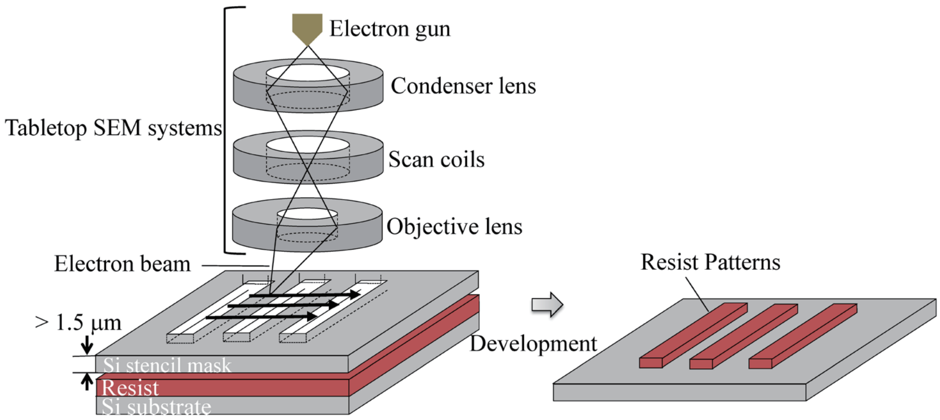

Fig. 1. (Color online) Schematic of this experiment.

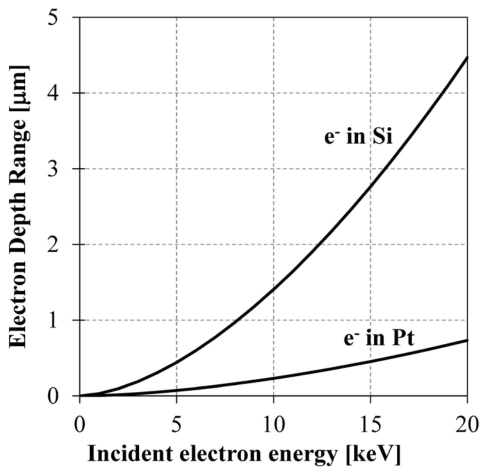

Fig. 2. Relationship between electron depth range and incident electron energy in Si and Pt.

to or shielded from the electron beam using the stencil mask. Si is suitable as a stencil mask material for micrometer-sized lithography because of its high stiffness.

On the other hand, the electron depth ranges in Pt were 0.24 µm at an incident electron energy of 10 kV and 0.07 µm at an incident electron energy of 5 kV. The Pt film with a smaller thickness than the Si film shielded the resist from the electron beam. Therefore, stencil masks with the Pt film were fabricated for sub-micrometer-sized lithography. Forming sub-micrometer-sized resist patterns requires the fabrication of Si stencil masks with a high aspect ratio, which is difficult to achieve considering the electron depth range. The smaller the thickness required for the stencil mask, the smaller the aspect ratio of the stencil mask, and it becomes easier to fabricate the mask. Therefore, we consider that the application of this technique to thin-film structures is possible by utilizing the difference in the electron depth range of materials.

AZ5214E (Merck) was used as the resist. The resist was diluted and spin-coated on the Si substrate. The thickness was 150 nm. The specimen was developed after electron beam exposure followed by reversal bake and flood exposure because it was used as a negative resist in a reversal exposure.[16,17] 2.3% Tetramethyl ammonium hydroxide (TMAH) was used as the developer. The cross-sectional profile of the fabricated resist patterns was measured with a stylus surface profilometer (Veeco Dektak 150).

2.2 Fabrication method of Si stencil masks for micrometer-sized lithography

The Si stencil mask was fabricated in this experiment by wet etching, as shown in Fig. 3(a). Wet etching enables the simultaneous etching of both sides of the substrate, thereby reducing the number of process steps compared with fabrication by dry etching.

The amorphized layer used as a mask for KOH etching was formed on the Si(110) substrate surface by ion irradiation with an electron cyclotron resonance (ECR) ion shower system (Elionix EIS-200ER).[18–20] The amorphized layer of 15 nm thickness can be formed on the Si(110) substrate surface by N^+ irradiation at 1 keV, and the etching rate ratio to Si is over 10000. The amorphized layer does not have SiO_2 or SiN films; therefore, charging does not occur in principle during electron beam exposure.

In this experiment, the thickness of the Si(110) substrate was about 300 µm and the thickness of the electron beam shielding area of the stencil mask was about 100 µm. A vertical profile of Si is fabricated by anisotropic etching as shown in Fig. 3(b).[21–23] Wet etching is typically isotropic, whereas Si(100) etching with alkaline solution is anisotropic owing to the difference in the etching rate with crystal orientation. Therefore, it is possible to fabricate vertical profiles, and such profiles were applied to the fabrication of stencil masks.

2.3 Fabrication method for Pt stencil masks for sub-micrometer-sized lithography

Figure 4 shows the fabrication of stencil masks. Pt was deposited on a Si substrate, and the Pt film was fabricated by etching the Si substrate from its back side using a deep-reactive-ion

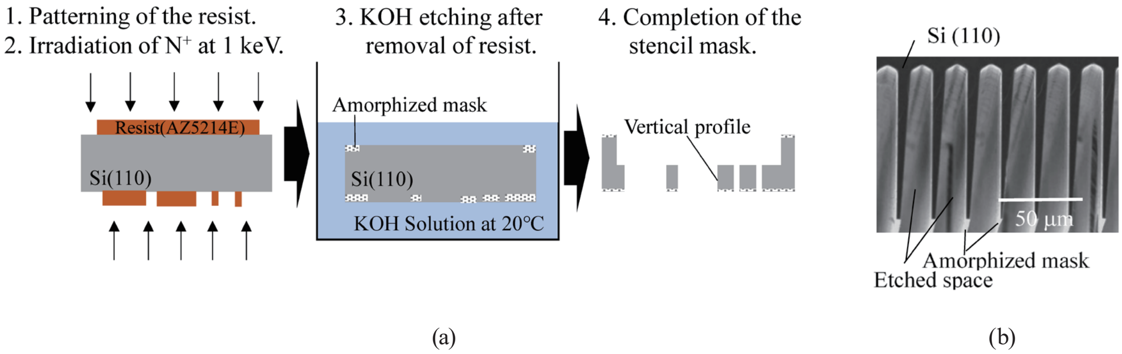

Fig. 3. (Color online) (a) Process of stencil mask fabrication. (b) Cross section of Si (110) etched with KOH.

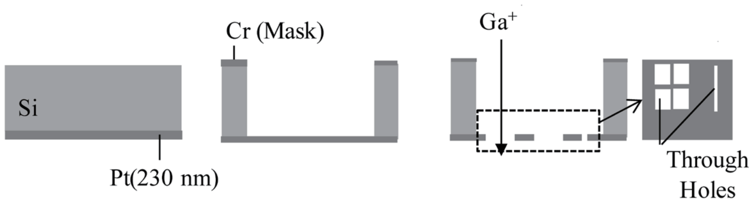

Fig. 4. (Color online) Fabrication of stencil masks with a Pt film structure.

etching system. The thickness of the Pt film was 230 nm. The stencil pattern was fabricated in the film using a focused ion beam system.

3. Results and Discussion

3.1 EPL using Si stencil mask

Figure 5(a) shows an SEM image of the fabricated micrometer-sized stencil mask and Fig. 5(b) shows an optical microscopy image of the resist pattern after exposure and development and the cross-sectional profile. The incident electron energy in the SEM system was 10 kV. Resist patterns of 10 μm size can be formed. The cross-sectional profile also shows that the pattern was formed without resist residues. The proposed technique for fabricating patterns using the tabletop SEM system was demonstrated.

3.2 EPL using Pt membrane structure as a stencil mask

Figure 6 shows (a) the fabricated stencil mask and (b) the resist pattern formed by EPL using the tabletop SEM system. The incident electron energy was 5 kV in EPL. EPL using a tabletop SEM system can be applied to forming resist patterns of micrometer and sub-micrometer sizes, which can be formed simultaneously. However, the resist pattern was larger than the stencil mask. This was particularly clear in sub-micrometer-sized resist patterns with line shapes. Figure 7 shows the relationship between the width of the stencil mask and the width of the fabricated resist patterns. Lithography was carried out several times with the same mask. As a result, the expanded size of the fabricated resist pattern was 0.3 μm independent of the stencil mask size. The size variation (coefficient of variation) of the fabricated resist patterns was approximately 2% on average and 3% at the maximum. This is considered to be due to the distance between the stencil mask and the resist, the effect of forward scattered electrons generated upon exposure at a low incident electron energy, and the angle of incidence of the electrons caused by the low magnification.

In this experiment, the stencil mask was placed in contact with the top of the resist, but the deformation by stress may have caused a gap between the mask and the resist. The through-hole width of the stencil mask was 130 nm, which was sufficiently larger than the de Broglie wavelength of 0.02 nm at 5 kV electron beams. The incident electron beam is considered to pass

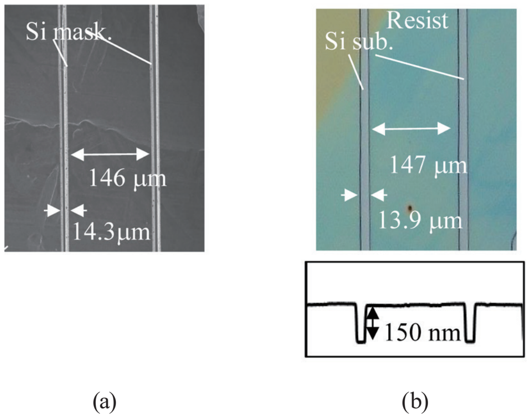

Fig. 5. (Color online) (a) SEM image of fabricated micrometer-sized stencil mask. (b) Optical microscopy image of resist pattern after exposure and development and cross-sectional profile.

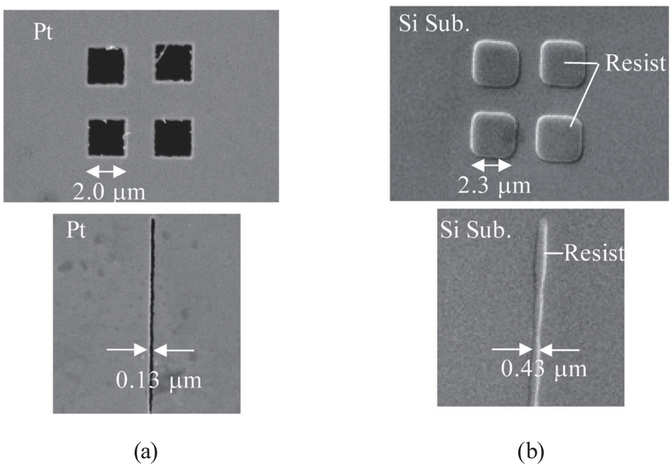

Fig. 6. (Color online) SEM images of (a) fabricated stencil mask and (b) resist pattern formed by EPL using a tabletop SEM system.

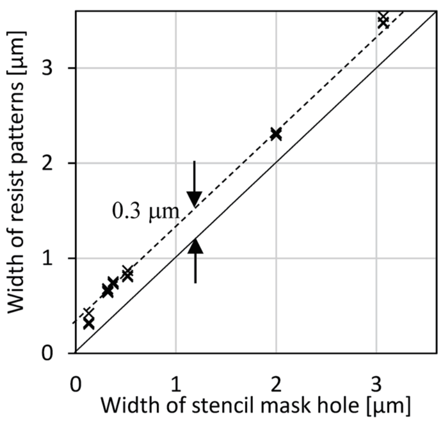

Fig. 7. Relationship between the width of the stencil mask and the width of the fabricated resist patterns

straight through the stencil mask. However, it is considered that the pattern was expanded because of the broadening of the electron beam and the angle dependence of the incident electron beam.

Figure 8(a) shows a schematic of the EPL experiment shown in Fig. 6, including the deformation of the stencil mask. To determine the deformation Δ of the stencil mask, an experiment with a spacer was performed. Figure 8(b) shows a schematic of the path of the electron beam through the stencil mask aperture in the experiment with spacers. When spacers (12 μm) were inserted between the stencil mask used in this experiment and the Si substrate coated with a resist and exposed to the beam, the width of the exposed resist was 0.54 μm. When 24 μm spacers were used, the width of the exposed resist was 0.66 μm. As the distance between the stencil mask and the Si coated with the resist increased, the width of the fabricated resist increased. The electron beam spread angle θ can be calculated from the width of the pattern and the distance of the spacer. θ is the angle between the straight line from the 0.13 μm aperture edge to the resist edge and the vertical line to the resist surface. The beam spread angle θ in the exposed pattern was estimated to be 0.57° from these experimental results. The distance between the stencil mask aperture and the Si coated with the resist can be calculated from this angle and the width of the resist in Fig. 6. As a result, we estimated the stencil mask deformation Δ to be 15 μm using this beam spread angle.

The problem of the resist pattern being larger than the stencil mask can be overcome by decreasing the stencil mask pattern size according to the distance between the mask and the Si substrate. It is also important to optimize the thickness of the resist. Figure 9 shows the relationship between the thickness of the resist and the width of the fabricated resist pattern. EPL was performed using Pt stencil masks with aperture widths of 2 μm or 0.1 μm, respectively. The thinner the resist, the smaller the fabricated resist patterns. This is considered to be a result of pattern widening due to electron scattering in the resist when the film thickness is thick at low acceleration voltages. The tabletop SEM system has a limited acceleration voltage, which limits the pattern size. Although there is a limit to the pattern size, it is possible to fabricate resist patterns similar to the stencil mask by reducing the thickness of the resist. This technique can be applied to sub-micrometer-order pattern fabrication.

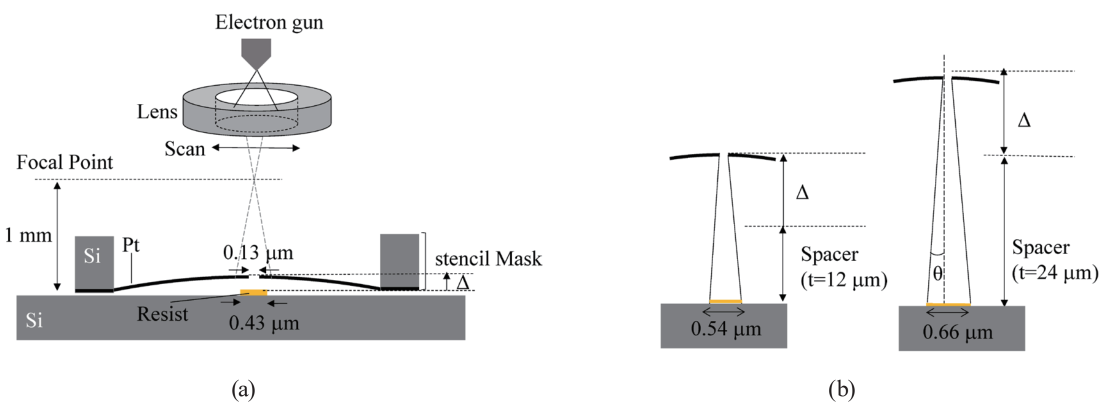

Fig. 8. (Color online) (a) Schematic of EPL experiment shown in Fig. 6. (b) Schematic of path of electron beam through the stencil mask aperture in the experiment with spacers.

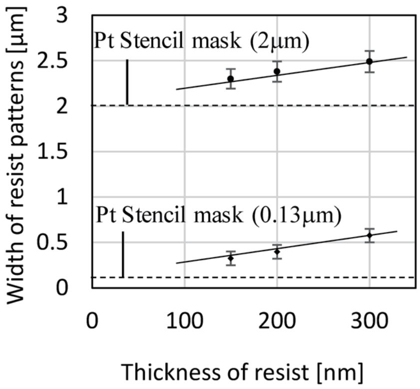

Fig. 9. Relationship between the thickness of the resist and the width of the fabricated resist patterns.

4. Conclusions

We demonstrated that the EPL technique using the stencil mask and tabletop SEM system can be applied to forming sub-micrometer-sized patterns. Furthermore, we demonstrated that the EPL technique using the Pt stencil mask with excellent electron shielding performance and tabletop SEM system can be applied to the simultaneous formation of the micrometer- and sub-micrometer-sized patterns. This technique is considered to be more insensitive to vibration than EB direct writing because the mask is placed in contact with the resist. The lithography of sub-micrometer-sized patterning with high throughput using a tabletop SEM system is expected to be achieved by optimizing the stencil mask material and exposure conditions. As a future research prospect, it is necessary to optimize the stencil mask design, material, and film stress. For example, the use of Au or Bi, which have a higher atomic number than Pt, or the use of a honeycomb structure to support the membrane of the stencil mask and reduce the amount of deformation can be considered.

It is difficult to fabricate a floating structure pattern with a doughnut shape in a stencil mask, and it is also difficult to fabricate multiple circular patterns with stencil masks. However, they are considered possible when using a mask with a freestanding Pt pattern with low electron penetration on a support membrane with high electron penetration.

Conventional electron beam lithography systems for research and development are used for patterning below the wavelength of a mercury vapor lamp and have issues with throughput. With conventional electron beam lithography systems using the same W-SEM, an area of 2.5×2 mm^2 with the same dose and raster scan would take nearly 5 h at an acceleration voltage of 30 kV. However, this technique enabled the exposure of the same area in 10 min. Compared with conventional electron beam lithography systems, this system has a larger exposure area and enables patterning below the wavelength of light at a higher throughput by increasing the irradiation current value. It is considered suitable for fabricating devices for repetitive experiments including sub-micrometer-order-sized patterns.

The EPL technique using a tabletop SEM system is expected to be applicable to the fabrication of microfluidic filters, biochip array structures, and optical devices.

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