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Author(s)	Matsui, S.; Watanabe, H.
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S. Matsui and H. Watanabe

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Si and GaAs dry etching utilizing showered electron-beam assisted etching through Cl₂ gas

S. Matsui and H. Watanabe
Fundamental Research Laboratories, NEC Corporation, 34, Miyukigaoka Tsukuba, Ibaraki, Japan

Electron-beam (EB) dry etching for Si and GaAs has been studied by utilizing showered electron-beam assisted etching in the presence of Cl₂ gas. Anisotropic etching has been demonstrated for both Si and GaAs EB dry etching. Si and GaAs patterns with 0.6 and 0.3 μm linewidths have been obtained at a dose of 2×10^{-2} C/cm² and 1×10^{-3} C/cm². It was confirmed, through measuring photoluminescence, that damage induced by EB dry etching is nearly the same as that caused by gas etching and less than damage induced by reactive ion-beam etching and ion-beam etching.

Electron-beam induced selective etching and deposition (EBISED) technology is a new method for microfabrication.[1,2] This technique applies electron beam (EB) induced surface reaction at a gas-substrate interface to allow etching and deposition. To date, we have demonstrated nanofabrication using EBISED technology with a scanning transmission microscope (STEM) and a scanning tunneling microscope (STM) both using focused EB. A tugsten rod pattern with 15 nm diameter and carbon dot patterns with 10 nm diameters have been fabricated by STEM and STM-EBISED technology, respectively.[3,4] In this way, direct writing at nanometer size has already been achieved with EBISED technology using focused EB. On the other hand, not only direct writing but also pattern transfer can be achieved by dry etching with showered EB instead of focused EB. In dry etching with showered EB using EBISED technology, mask patterns are first printed on the substrate by conventional lithography methods. Then, the mask patterns are etched onto the substrate by showered EB assisted etching.

Dry etching is a very important technology to enable the transfer of patterns where mask patterns are transfered during device processes. Usually, ion beams are applied during the dry etching process. Ion bombardment enhances surface chemical reactions to produce volatile products. Ion-beam etching has a serious disadvantage in that ion-beam bombardment causes radiation damage in semiconductors such as point defects, dislocation, and amorphization. On the other hand, EB assisted etching has the possibility of overcoming problems due to damage. Less damage can be expected, with EB assisted etching than with ion-beam etching, because momentum transfer to the lattice using EB is much smaller than when ion beams are used. Also, only chemical reactions are introduced in EB assisted etching. Akita *et al.* reported that 10 keV focused EB assisted etching using Cl₂ gas causes less damage to a GaAs sample than when Ar plasma etching is used.[5] It is expected that dry etching using showered EB assisted etching is able to overcome this problem of damage in ion-beam dry etching. Dry etching is required in device fabrication to limit damage but also to produce stronger anisotropy and higher selectivity.

This letter describes the selectivity, anisotropy, and limited damage attainable by Si and GaAs dry etching with showered EB assisted etching using Cl₂ gas.

Figure 1 illustrates schematically the experimental apparatus. The system was evacuated with a turbo-molecular pump. The base vacuum was 1×10^{-7} Torr. The chamber contains a gas introduction system, an EB gun with a differential pumping system and an infrared (IR) heater to raise the substrate temperature. The reflection high-energy electron diffraction gun was used as a showered EB source in this experiment. The beam voltage, current density, and diameter for the sample were 10 kV, 1.4 μA/cm² and 40 mm, respectively. The calculated temperature increase on the sample surface is less than 10 °C for both Si and GaAs substrates.

The etching rate ratios (selectivity) of Si (100) substrates to SiO₂ and SAL601-ER7 resist (Shipley Co.) masks were measured. Table I shows the etching depth of Si, SiO₂, and the SAL-601ER7 resist in EB assisted etching using Cl₂ gas. EB dose, Cl₂ gas pressure, and substrate temperature were 1.3×10^{-2} C/cm², 1.0×10^{-4} Torr and 25 °C, respectively. The etching rate ratios of Si to SiO₂ and the SAL-601ER7 resist are 12.5 and 0.63. This indicates that SiO₂ is one of several excellent mask materials in Si EB dry etching. The calculated Si etching yield per elec-
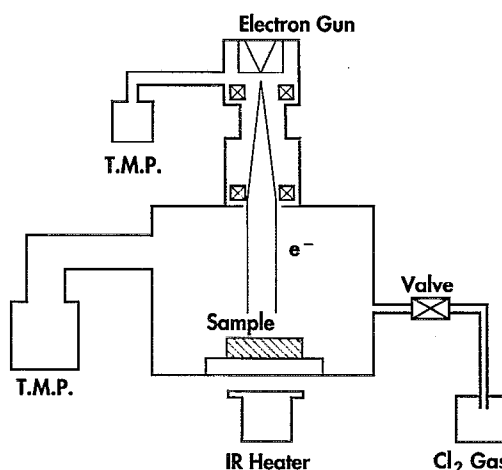

FIG. 1. Experimental arrangement for showered EB assisted etching apparatus.

TABLE I. Etched depth of Si (100), SiO_2, and SAL601-ER7 resist for showered EB assisted etching using Cl_2 gas.
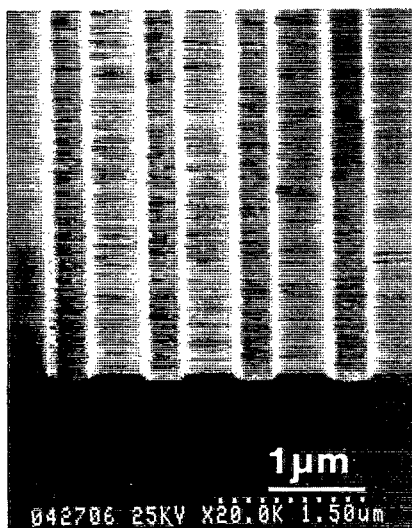
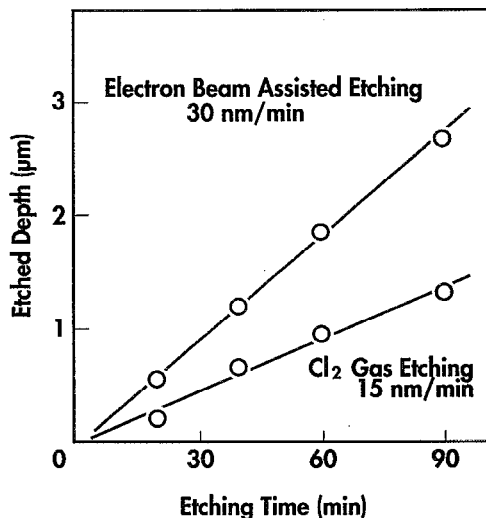|	Si	SiO_2	Resist SAL601-ER7
Etched depth	50 nm	4 nm	80 nm

FIG. 3. Relationship between etching time and etched depth for GaAs (100) by EB assisted etching and gas etching using Cl_2 gas.

tron is 3 atoms/electron. Previously, we reported that Si etching yield for EB assisted etching using XeF_2 is about 100.[6] Si substrate is etched by XeF_2 gas, even in the absence of EB irradiation, but is not etched by Cl_2 gas. Therefore, the large difference of EB stimulated etching yield between when using Cl_2 gas and XeF_2 gas is attributed to gas etching enhancement by EB irradiation.

Direct etching on the Si was achieved by using SAL-
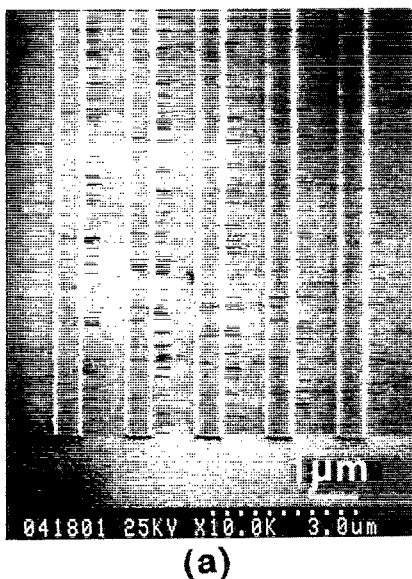
(a)

(b)

FIG. 2. SEM micrographs of Si etching patterns fabricated by showered EB assisted etching using Cl_2 gas. (a) Top view of 0.6 μm linewidth Si patterns. (b) Cross section of 0.6 μm linewidth Si patterns.

601ER7 resist mask patterns fabricated by focused ion-beam lithography.[7] Figures 2(a) and 2(b) show top and cross sectional views of 0.6 μm linewidth Si patterns with 70 nm etching depths fabricated by showered EB assisted etching at 1×10^{-4} Torr of Cl_2 gas and a dose of 2×10^{-2} C/cm^2. These scanning electron microscope (SEM) photographs indicate that submicron pattern transfer into the Si substrate can be achieved by showered EB assisted etching as well as ion-beam etching.

It is difficult to etch GaAs substrates at 25 °C, because a native oxide layer formed on the GaAs surface is not etched by Cl_2 gas at 25 °C. The oxide layer can be removed by heating the substrate, whereas GaAs substrates can only be etched with Cl_2 gas. Therefore, it is necessary to measure etch rates with and without EB irradiation through Cl_2 gas.

The relationships between etching time and etching depth for GaAs (100) are shown in Fig. 3. Cl_2 gas pressure and substrate temperature were 1.5×10^{-4} Torr and 75 °C, respectively. These results indicate that the etching rate of EB assisted etching is twice that of Cl_2 gas etching. The GaAs etching yield per electron due to EB assisted etching, calculated from these results, is 130 atoms/electron which is the same value as Si etching by EB assisted etching using XeF_2.[6] This high yield suggests that EB bombardment causes chemical reaction enhancement between Cl atoms dissociated from Cl_2 and GaAs surface atoms.

Figures 4(a) and 4(b) show SEM micrographs of the GaAs etching pattern fabricated at doses of 1.1×10^{-2} C/cm^2 and 1×10^{-3} C/cm^2. A deep etched profile with 4 μm depth is shown in Fig. 4(a), in which side etching due to Cl_2 gas etching is observed between sidewalls of the 0.6-μm-thick SAL601-ER7 resist pattern and the GaAs etched pattern. Also, sidewall roughness in the resist pattern is reflected onto the GaAs etched pattern. This demonstrates that anisotropic etching is achieved by EB dry etching. Figure 4(b) shows GaAs patterns with 0.3 μm linewidth and 0.35 μm depth achieved by EB assisted etch-

(a)
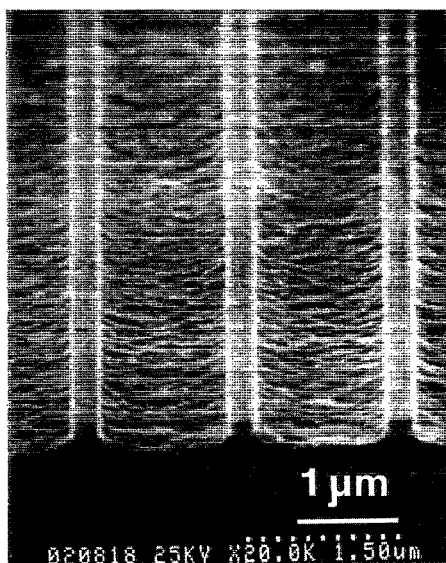
(b)

FIG. 4. SEM micrographs of GaAs etching patterns fabricated by showered EB assisted etching using Cl_2 gas. (a) Cross section of GaAs pattern with a 4 μm deep profile. (b) Cross section of 0.3 μm linewidth GaAs patterns.

ing using resist patterns with 0.4 μm linewidth. This indicates that high-precision pattern transfer onto a GaAs substrate can be achieved using this etching technique.

The damage induced by EB assisted etching was evaluated through photoluminescence (PL) measurements and compared with reactive ion-beam etching (RIBE) and ion-beam etching (IBE). The PL was measured at room temperature in air. These experiments were performed using HB Si doped n^+ GaAs wafers with a carrier concentration of 1×10^{18} cm^{-3}. Prior to etching, the wafers were etched by immersion in HCl for 1 min to remove a native oxide layer and then rinsed by dipping for 5 min in H_2O.

Figures 5(a)–5(e) show PL measurement spectra for samples of: reference, gas etching, EB etching, RIBE, and
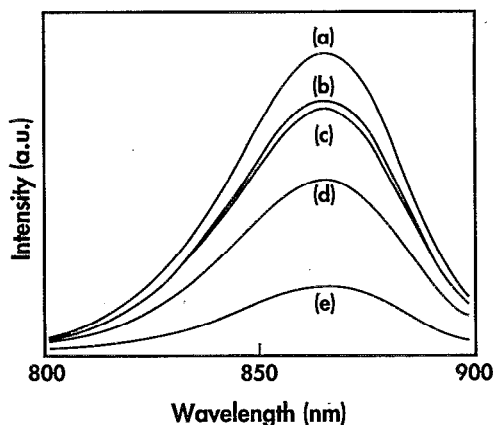

FIG. 5. PL spectra at the etched surface of GaAs. (a) Reference, (b) Cl_2 gas etching, (c) EB assisted etching with Cl_2 gas, (d) Cl_2 RIBE, (e) Ar IBE.

IBE, respectively. Gas etching was carried out at substrate temperature of 75 °C and 1.5×10^{-4} Torr Cl_2 gas pressure. The experimental conditions for EB etching were 10 kV, 1.4 μA/cm^2, 75 °C substrate temperature, and 1.5×10^{-4} Torr Cl_2 gas pressure. Both Cl_2 RIBE and Ar IBE were performed under etching conditions of 500 V and 1.5×10^{-4} Torr gas pressure at 75 °C of substrate temperature. The etching time was 30 min for gas etching, EB etching, RIBE, and IBE. The etched depths for gas etching, EB etching, RIBE, and IBE were 440, 670, 1000, and 430 nm, respectively. The PL intensity of gas etching in Fig. 5(b) is lower than that of the reference in Fig. 5(a), because surface roughness increases when gas etching is used. The PL intensity of EB etching is nearly the same as that for gas etching as shown in Figs. 5(b) and 5(c). On the other hand, PL intensities of RIBE and IBE are much smaller than that for EB etching, as shown by Figs. 5(d) and (e). These results indicate that showered EB assisted etching is a promising candidate to achieve damage-free dry etching rather than RIBE and IBE.

In summary, the EB dry etching of both Si and GaAs has been demonstrated using showered EB assisted etching through Cl_2 gas. Anisotropy etching was also observed with both Si and GaAs EB dry etching. Linewidth patterns of 0.6 and 0.3 μm for both Si and GaAs were obtained at a dose of 2×10^{-2} and 1×10^{-3} C/cm^2. Furthermore, it was confirmed, through measuring photoluminescence, that damage induced by EB dry etching is nearly the same as that for gas etching and less than that for RIBE and IBE.

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