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Electron beam lithography for nano-fabrication

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This paper describes a newly developed electron beam(EB) lithography system for fabrication of devices with nano-meter scales and its applications. It is an 50 kV EB lithography system with a double chamber stage system, which enables EB exposure in an ultra high vacuum of 3.5×10^{-7} Pa and also compatible to EB induced direct process with introduction of reactive gases up to 1×10^{-3} Pa. The measured probe size was 2.8 nm with a probe current of 127 pA. Standard deviations of stitching and overlay accuracy were 14 nm and 18 nm, respectively. Patterning with nano-meter scales is demonstrated using SiO_2 as a high resolution resist. A Lift-off mask with a pattern width of 20 nm is fabricated by multi-layered inorganic resist process.

1. Introduction

Nano-fabrication technology becomes very important for research and development of electronic devices based on quantum effects or Coulomb blockade phenomenon as shrinkage of feature sizes may enhance quantum effects and raise operating temperature of such devices. Electron beam (EB) lithography with which 10-20nm wide patterns are delineated in organic resists[1], is thought to be one of the most promising tools for such nano-fabrication. In addition, it is possible to delineate patterns with higher resolution by using inorganic resists such as metal-oxides and -halides [2,3] of which the required doses are 3 to 4 orders higher than those of organic resists. Exposure of such materials should be carried out in an ultra high vacuum, otherwise contamination grown during EB exposure prevents self-development of sublimation of resist materials or reduces the resolution by scattering electrons. In addition, EB induced surface reaction such as direct etching of target materials and deposition of metals by introduction of appropriate gases[4,5] can be also realized if a vacuum of the process chamber is enough high. It is difficult that a conventional EB lithography system is adapted to those processes with keeping accuracy of EB exposure. Thus, we have constructed 'Nanobeam process system'[6,7] which is a fine-focused EB lithography system with an ultra high vacuum sample chamber by installing a double chamber stage system[8].

2. Electron beam lithography system

Figure 1 shows the schematic view of 'Nanobeam Process System' which is a 50 kV EB lithography system for nano-meter scale device fabrication using inorganic resist and EB induced surface reactions. A ZrO/W thermal field emitter and a triplet lens system with a zoom function were adapted. The gun lens is an electrostatic lens and the others are electromagnetic lenses. The total magnification and spherical and chromatic aberration coefficients are 0.024, 43.8 mm and 16.1 mm, respectively. The working distance and the optical path which were minimized as much as possible are 16 mm and

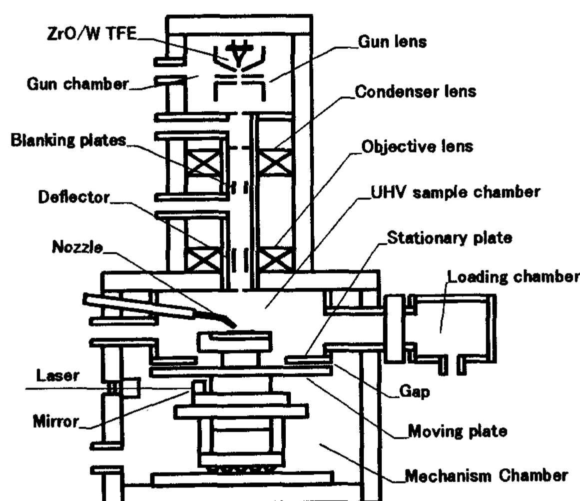


Fig.1. Schematic view of 'Nanobeam process system' with a double chamber stage system.

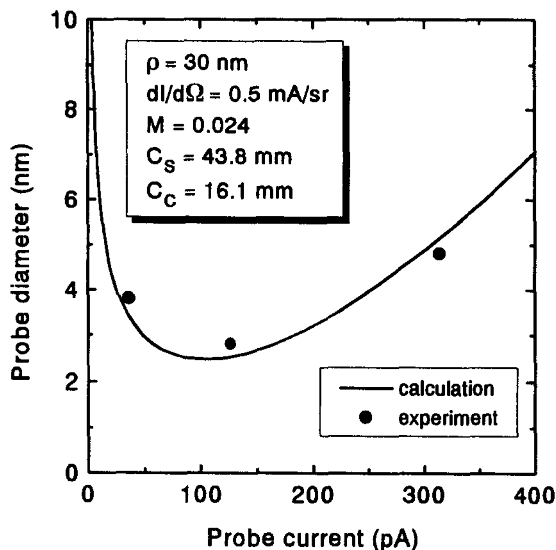


Fig.2. Probe diameter as a function of probe current.

381 mm, respectively. The optimum convergent half angle which gives the minimum probe diameter of 2.5 nm is 3.7 mrad. The probe diameter as a function of the probe current was calculated and is given in Fig. 2, where it is assumed that the source size, the energy spread of emitted electrons and the angular current density are 30 nm, 1 eV, and 0.5 mA/sr[9], respectively.

The developed double chamber stage system is illustrated in Fig.1. The mechanism chamber includes stage mechanism such as mirrors, stage guides, bearings and so on in order to reduce surface area of the sample chamber. The stage moves while maintaining the gap between the moving plate and the stationary plate at 0.3 mm. The gap of which the conductance corresponds to that of an orifice with a diameter of 0.25 mm and enables differential evacuation. A retractable gas injection nozzle is attached, which is adjusted a few tenths of a mm above the sample, in order to produce a high gas flux with a small gas flow for EB induced surface reaction. The gap prevents the process gases in the sample chamber from diffusing into the mechanism chamber in the case of EB induced surface reactions. By adapting a double chamber stage system, we can use reliable stage mechanisms without being concerned about reduction of the precision by baking or chemical protection.

Table 1. Principal specifications

Acceleration voltage	50 kV
Probe diameter	2.8 nm
Scanning increment	2.5 nm
Maximum scanning rate	6 MHz
Field size	80 μm
Laser resolution	5 nm
Stitching accuracy	14 nm(σ)
Overlay accuracy	18 nm(σ)
Substrate size	2 inch
Base pressure of sample chamber	3.5×10^{-7} Pa
Allowable gas flow	10^{-3} Pa

The optical column is also separated with orifices into several chambers which are evacuated by independent pumps. The sample chamber and the two neighboring chambers are evacuated with chemical proof turbo molecular pumps through vibration dampers.

Samples are exchanged through the loading chamber without breaking a vacuum of the sample chamber. Available sample sizes are a 2 inch wafer and a 10 mm square piece wafer. The maximum field size is 80 μm × 80 μm and the minimum scanning increment is 2.5 nm. The stage position is monitored with a laser measuring system with a resolution of 5 nm. The optical column and the most of control units are set in a clean room with a temperature stability of ± 0.1℃. The principal specifications are summarized in Table 1.

The probe diameter was measured by a knife edge method. A Au coated Ni mesh was used as a knife edge and a p-n junction detector was located underneath. A 50 kV EB with a diameter of 2.8 nm and the probe current of 127 pA was obtained for the optimum convergent half angle of 3.74 mrad. The measured probe diameters for 3 different convergent half angles are plotted in Fig. 2. The experimental results agree well with the calculation, thus it is concluded that the optical column operates as designed.

The sample chamber was baked at 245° C with built-in panel heaters, while the temperature of the stage top was raised less than 50° C. The pressure after baking was 3.5×10^{-7} Pa, which is two orders in magnitude smaller than that of a conventional EB lithography system. The changes in pressures of the gun chamber and the mechanism

chamber during gas introduction are shown in Fig.3. In this experiment, N_2 gas was introduced into the sample chamber by varying a pressure of the gas injection nozzle. When a pressure of the sample chamber became 1×10^{-3} Pa, that of the gun chamber was not varied at all and the variation of that of the mechanism chamber was 3×10^{-6} Pa. Thus, it is expected that the emitter and the stage mechanism will normally operate in case of EB induced surface reaction processes using reactive gases.

Stitching and overlay accuracy was measured by exposing a test pattern on 15 locations on a PMMA resist. The test pattern is a 320 μm × 320 μm chip composed of 4×4 fields where scales and verniers with a resolution step of 10 nm are arranged. The deviations at the same portion of different chips were evaluated by SEM inspection. The standard deviations of stitching and overlay were 14 nm and 18 nm, respectively. Relatively good results were obtained, however they are somewhat inferior to those of the original model (JEOL JBX-6000FS). As the sample is not in the plane of the laser beam paths in our EB lithography system (see Fig. 1), a pitch of the stage changes the sample position. The degradation of precision may be caused by such a phenomenon. However, it will not a serious problem for our purpose, because the exposure area of the key

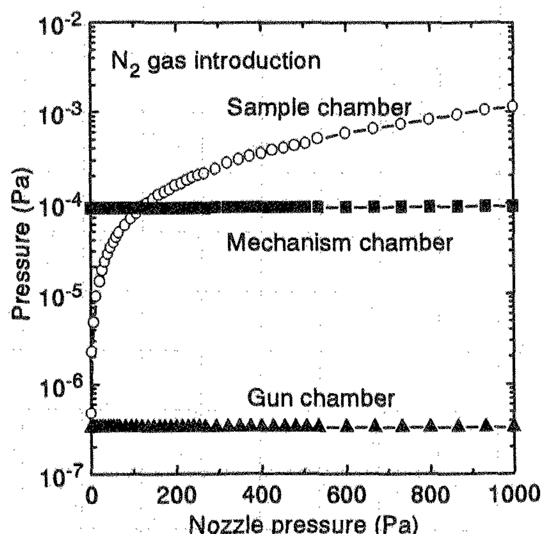


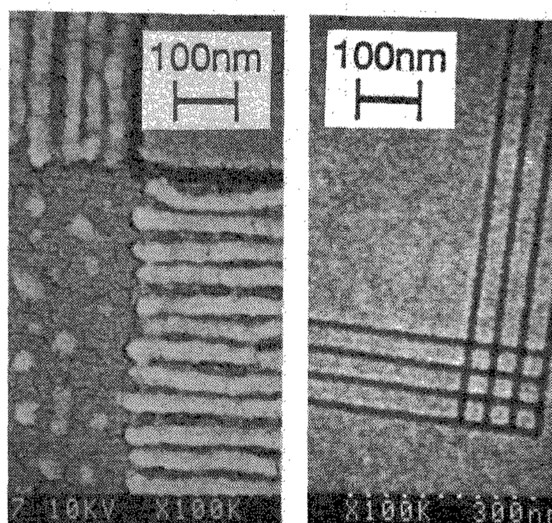
Fig. 3. Variation of pressures during gas introduction.

portion of nano-scale devices is probabl smaller than a field size in most cases. If pattern is so small that markers for overla are included in a field, overlay accuracy wa improved to 9 nm.

3. Inorganic resist process

Comparison between PMMA (pol methylmethacrylate) and SiO_2 is shown i Fig. 5. A 30 nm thick PMMA resist spun on Si wafer and a 20 nm thick SiO_2 were used where lines with a pitch of 40 nm ar delineated by the 50 kV EB with a prob current of about 100 pA. The PMMA wa developed using 1:3 MIBK:IPA at 22° C for 6 sec and coated with Au/Pd for SEM inspectio The SiO_2 was exposed in O_2 plasma an dipped in a buffered HF solution of which th concentrations of HF and NH_4F are 0.2 mol/ for 100 sec[10]. The width of developed line in PMMA are fluctuated and the residual between lines are broken as shown in Fig.4(a while smooth and fine lines were developed i SiO_2 as shown in Fig.4(b). Fine lines with width of about 5 nm and with a pitch of 15 nn have been fabricated in SiO_2 so far.

The sequence of multi-layered SiO2 resis process[12], which is developed for fabricatio



(a) PMMA linedose=0.61nC/cm (b) SiO2 linedose=2.0μC/cm

Fig.4. Comparison between (a)PMMA and (b) SiO_2.

of ultra small metal/insulator/metal(MIM) tunnel junction devices, is shown in Fig.5. The sample with a structure of 36 nm SiO_2/ 30 nm crystalline Si/ 116 nm SiO_2/ Si(100) substrate were prepared by oxidation of a SIMOX (Separation by IMplanted OXygen) wafer. The top SiO_2 layer was patterned by the 50 kV EB with a linedose of 2.8 μC/cm. After development of top SiO_2 in buffered HF, the intermediate crystalline Si is selectively etched in NMD-3 (Tokyo Ohka Co.,Ltd.) of which the main chemical component is TMAH (tetramethyl ammonium hydroxide). Finally, Al layers are deposited with different deposition angles and then MIM tunnel junction is fabricated[13].

Figure 6 shows a lift-off mask fabricated with using the above process. The darkest lines and the surrounding dark region thought to be the etch off part of the top SiO_2 and the etched area of intermediate crystalline Si, respectively. Lift-off mask patterns with a width of 20 nm can be fabricated by this multi-layered inorganic resist process.

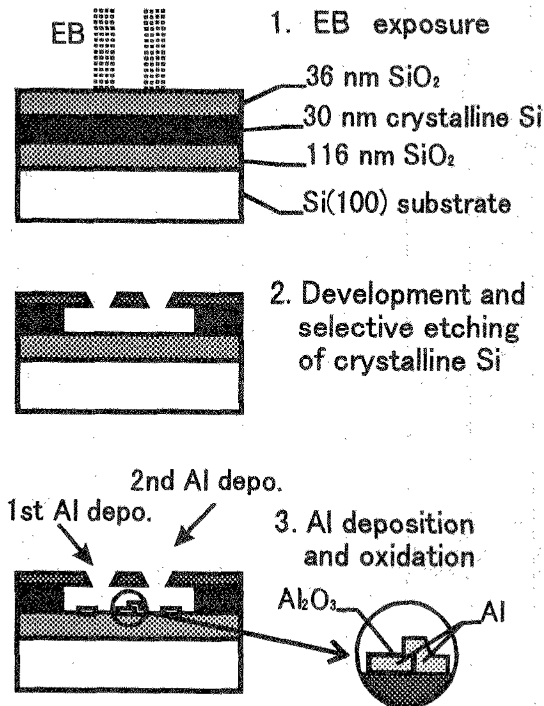


Fig.5. Multi-layered inorganic resist process.

4. Conclusion

We can conclude that the developed fine-focus UHV EB lithography system is helpful to nano-fabrication and SiO_2 is a promising material among high resolution inorganic resists from a point of view of fabrication of devices with nano-meter scales.

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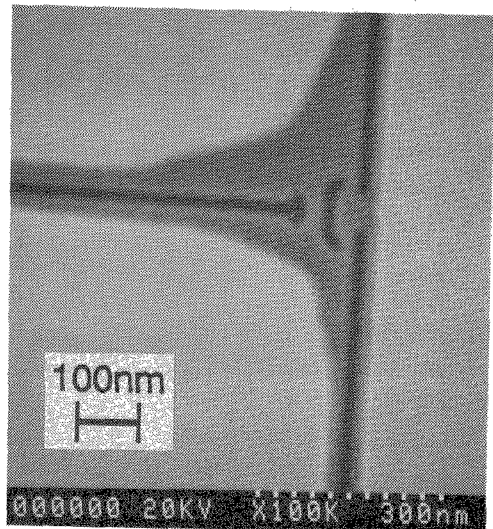

Fig. 6. Lift-off mask fabricated by multi-layered SiO_2 resist process.