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Nanoscale evaluation of width deviation of resist pattern using atomic force microscopy

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The nanoscale width deviation of a resist pattern fabricated by electron beam lithography was evaluated using dynamic force mode atomic force microscopy (AFM). A scaling analysis based on the fractals was applied to the AFM images to obtain a quantitative evaluation. The standard deviation of a ZEP resist pattern width was 2.8 nm and the correlation length was 68 nm. The scale dependence of the surface roughness of a resist film lightly exposed to an electron beam was confirmed to be almost the same as that of the width deviation of the pattern. Granular textures with a feature size of 30-50 nm were observed on the resist surface.

1. INTRODUCTION

A fabrication technique based on nano-lithography combined with a Si-LSI process has recently been used to realize such Si-nano-devices as single-electron transistors (SET) [1-3]. Since the main component of a Si-SET is a sub-10-nm Si structure or Si island, size fluctuations are a serious problem. In fact, the electrical properties of the SETs were different even though they were designed in the same way because of the size fluctuations of the Si island [3]. To integrate the devices, it is necessary to minimize the fluctuations.

In Si-SET fabrication, a 1-dimensional Si wire is converted to an island by means of 'pattern dependent oxidation'. The height, length and width of the wire defines the size of this Si island. The length is the largest of the three dimensions and the deviation of height, which corresponds to Si layer thickness, is relatively small [3]. The fluctuations in the Si island originate mainly with the width. The width is firstly defined by a resist pattern generated by EB lithography. However, it is difficult to observe the nanoscale width deviation of a resist pattern with conventional tools, such as a scanning electron microscope (SEM).

This paper describes the quantitative evaluation of resist pattern fluctuations using AFM.

2. EXPERIMENTAL

A high-contrast positive resist, ZEP-520, with a thickness of 50 nm was exposed with an electron beam (EB) and developed with hexyl acetate. This combination of resist and developer is effective for improving resolution and reducing pattern fluctuations [4,5]. A modified HL-700F system with a beam about 10 nm in diameter was used for the pattern generation.

AFM observations were carried out using the dynamic force (cyclic-contact) mode of an SPI3700/ SPA350,SPA300 system (Seiko Instruments Inc.). This mode is suitable for observing in-process wafer surfaces and soft materials such as resist because it causes little damage and the friction force is negligible. A Si tip with a top portion radius of about 10 nm was used as a dynamic force sensor.

In order to evaluate nanoscale fluctuations the noise of the microscope must be sufficiently small. Figure 1 shows the width deviation of the Si wire measured using both AFM and SEM. The average width of the rectangular-shape wire [6] was about 40 nm. The width in the AFM results was measured at a constant height which was 5 nm below the top of the wire. The half height algorithm [7] was used for the SEM width measurement. The width deviation can be seen in detail in the AFM results. However, the noise level in the SEM results is very high. Since the noise

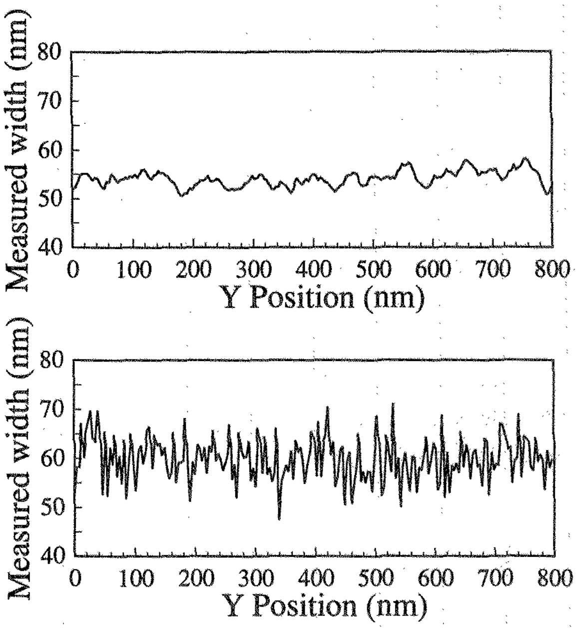

Fig. 1 Width deviation of a Si wire with a rectangular cross-section [6] measured by (a) AFM and (b) SEM. The average width of the wire is about 40 nm. The width in the AFM results was measured at a constant height which was 5 nm below the top of the wire. The half height algorithm [7] was used for the SEM width measurement.

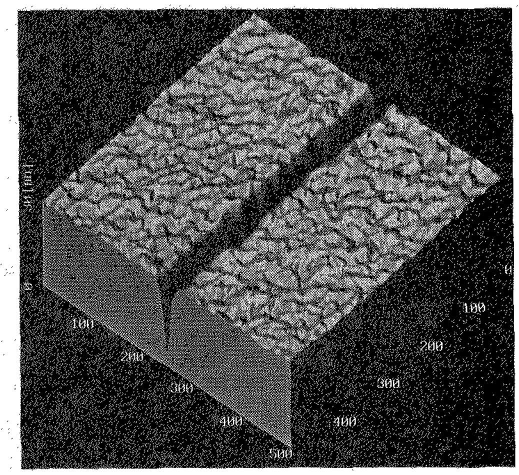

Fig. 2 A cyclic contact mode AFM image of a ZEP resist pattern with a width of about 30 nm.

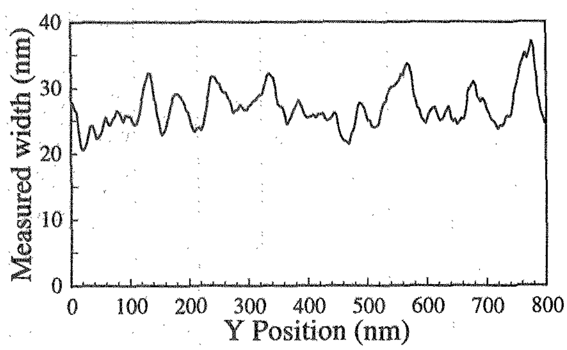

Fig. 3 Width deviation of the ZEP resist pattern. The width was measured at a constant height which was 5 nm below the surface of an unexposed region.

level in the AFM measurements is less than 1 nm in the standard deviation, AFM is clearly the more suitable method for nanoscale inspection.

3. RESULTS AND DISCUSSION

3.1. Evaluation of width deviation of resist pattern

Figures 2 and 3 show an AFM image of a ZEP resist pattern about 30 nm wide and the width deviation of the resist pattern measured at the height 5 nm below the surface of an unexposed region, respectively. The nano-scale fluctuation of the resist pattern can be clearly observed.

We evaluated the width deviation quantitatively by a roughness scaling analysis based on fractals. This method is commonly used to analyze surface roughness [8].

The dependence of the standard deviation (SD) of the pattern-width on the sampling length (scale) is shown in Fig. 4. Two distinct regions with different scaling behaviors are clearly seen. In the longer scale region, the SD is constant of 2.8 nm. In the shorter region, the deviation varies as a power of the scale. The correlation length at the border of the two regions is 68 nm.

The size fluctuations of the longer scale influence the reproducibility of mesoscopic devices, because the correlation length is longer than the size of the device. In fact, the standard deviation value of the fluctuations is almost the same as that of fluctuations estimated from the electrical properties of Si-SET devices [3].

Short range roughness, on the other hand, also affects the properties of the SET. Small fluctuations in the scale of the device (Si island) are important in terms of ensuring the formation of a single Si island in the device. If the fluctuations are relatively large in the device width, multi-islands will appear due to undesirable constrictions.

The scaling analysis of width fluctuations provides us with quantitative parameters related to the characteristics of mesoscopic devices.

3.2. Cause of the width deviation

The sidewall surface of the resist pattern was lightly irradiated with an electron beam. To simulate this situation, we exposed resist film to several rather low EB doses.

Figure 5 shows scale dependence of the surface roughness of the exposed resist. The roughness increases with the dose. Notably, the SD of the pattern-width shown in Fig. 4 agrees with the roughness of the resist exposed to 24 μC/cm^2. This value is about 30% of D_0 (sensitivity) and is almost the same as the simulated dose where the resist pattern edge was exposed to the tail of the electron beam. This result indicates that observation of the exposed resist surface provides the same information as the resist pattern fluctuations. Therefore, this is a strong indication that the resist pattern width fluctuation has the same origin as the surface roughness of the lightly dosed resist.

Figure 6 (a) shows the surface morphology of the resist exposed to 24 μC/cm^2. Granular structures can be seen. The typical diameter of these structures after eliminating the effect of the AFM probe shape is estimated to be 30-50 nm. These structures are the main cause of the pattern fluctuation, because the mean distance between them is almost the same as the correlation length discussed earlier.

The mean molecular weight of the ZEP resist measured by gel permeation chromatography is 54463, and the maximum weight is about 300000. The typical and maximum diameters of a resist molecule are

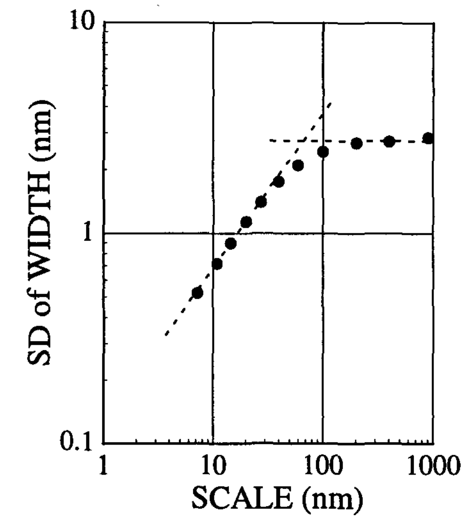

Fig. 4 Dependence of the resist pattern-width deviation on sampling length (scale) was calculated from the results in Fig. 3. The scale dependence is divided into two distinct regions with different scaling behaviors at 68 nm in the scale. This length is the correlation length of the fluctuations. The deviation value in the scale above the correlation length is 2.8 nm.

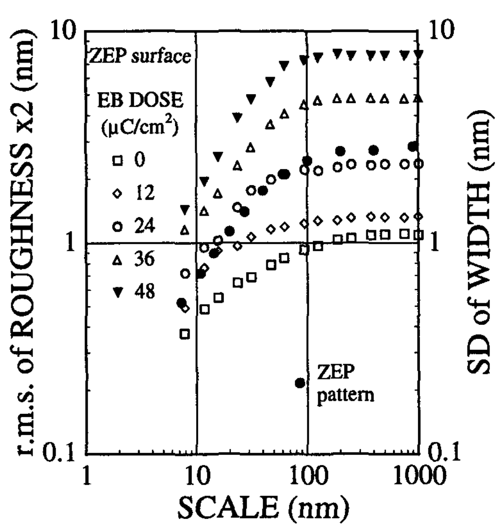

Fig. 5 Scale dependence of resist surface roughness exposed to several doses of electron beam irradiation. D_0 of the ZEP resist in this case is about 70 μC/cm^2. Twice the roughness value corresponds to the width deviation. The roughness dependence of 24-μC/cm^2-dosed surfaces is almost the same as the width deviation dependence shown in Fig. 4.

estimated to be about 5 nm and 9 nm respectively, on the assumption of a resist density of 1.2 g/cm^3. Therefore, the surface structure on the EB-exposed resist corresponds to a large group of resist molecules.

The surface morphology of PMMA resist subjected to EB exposure with about 30% of D_0 is shown in Fig. 6(b). Granular structures, slightly larger than those of the ZEP resist, were also observed. This result suggests that granular structures larger than molecular size are the usual structures in organic-resist films and are the cause of the fluctuations.

In this paper, we have demonstrated the utility of AFM in evaluating resist pattern fluctuations as a first step to improving nano-fabrication. Further detailed experiments should be undertaken on the resist film structure and the development process in order to reduce the fluctuations.

(a)

(b)

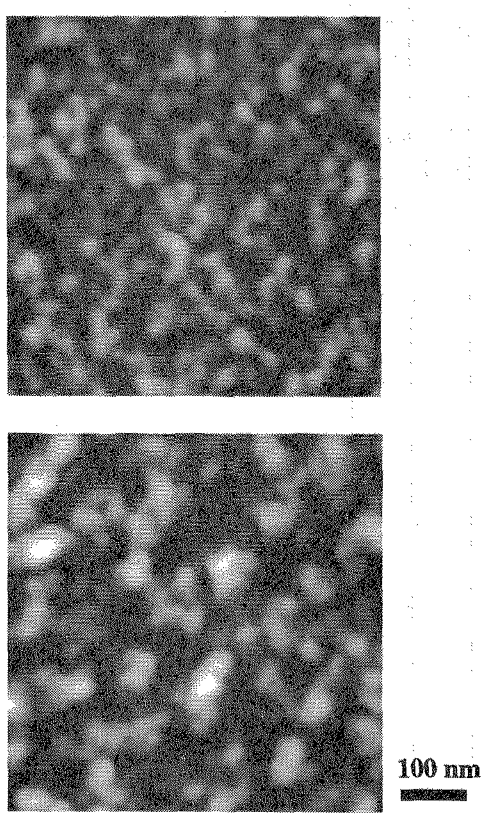

Fig. 6 Surface morphologies of resist exposed to EB irradiation with a dose of 30 % of D_0. (a) ZEP. (b) PMMA. The granular structures larger than the molecular size are observed in the films of both ZEP and PMMA resist.

4. CONCLUSION

We evaluated the resist pattern fluctuation on a nanometer scale by using dynamic force mode AFM. The standard deviation of the width fluctuations in ZEP resist patterns was 2.8 nm (r.m.s.). This value is not small enough for mesoscopic devices. We used a lightly exposed resist surface to represent the pattern sidewall. Granular structures larger than molecular size were the dominant factor in pattern fluctuation.

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