Measurements of Developed Patterns by Direct Writing of Electron Beam on Different Materials underneath PMMA

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The developed patterns by direct writing of electron beam are measured by AFM, FESEM and optical profiler of WYKO NT3300. From different measurement methods, the measured linewidths of the patterns are shown a little bit wider than designed pattern size due to electrons scattering effect during direct writing of electron beam. The optimized conditions of these experiments are suggested and explained for the forming of structures below 0.1 μm dimension size. Because of electron scattering effects from the different under layers such as Si, Si_3N_4 and aluminum, the developed pattern size is also influenced by the accelerated energy of electrons, dose, resist and soft and hard bake conditions in PMMA. The distributions of electron beam and calculations of backscattering coefficient are demonstrated by Monte Carlo simulation. From the measured results, the developed linewidth of PMMA/Al /silicon is shown a little bit wider than that of PMMA/Si_3N_4/silicon structure due to the backscattering effects.

Keywords : Electron beam, AFM, FESEM, Optical profiler, Monte carlo simulation

1. INTRODUCTION

Optical projection lithography with light source such as KrF, ArF, and F_2 eximer laser is dominantly used in high integrated devices and circuits of semiconductor technology. But currently optical lithography can not be used below 0.1 μm structure. In this case, the stepper systems have to change for the fine lithography of optimal conditions. For this reason, NGL (next generation lithography) [1-4] is necessary to have SCALPEL (scattering with angular limitation in projection electron beam lithography), extreme ultra-violet (EUV), ion beam projection lithography (IPL), X-ray lithography and electron beam direct writing technology. NGL technology is targeting for patterning less than 100 nm. Specially electron beam can be directly focused and deflected through electromagnetic fields into the samples. Electron beam projection method can also used through the electron beam mask for the fabrication of high integrated circuits. Direct writing technology of electron beams on silicon wafers is applied to fabricate for nano-scale patterns [5,6] and single electron transistors in specified integrated circuits.

For the best resolution, PMMA is nowadays wide-spread as a positive resist for electron beam. In PMMA resist, long bridge molecules by electron beam irradiations are broken, and breaking fragments are soluble in proper developer. In electron beam lithography, electrons are generally accelerated with voltage in the range from 1 to 30 keV. The resolution of electron-lithography is not dependent upon electron beams, but is dependent upon accelerated energy and scattering effects of electron stopping mechanism in photo-resist or substrate material.

2. SIMULATION AND RESULTS

The distribution of electron beam through Monte Carlo simulation[7,8] is presented in Fig. 1. Backscattering coefficient from computer simulation is shown 0.165 in normal incident case of electron beam on the resist surface of PMMA (3000Å)/silicon as shown in Fig. 1.

Backscattering coefficient from computer simulation is shown 0.075 in normal incident case of electron beam on the resist surface of PMMA/ Si_3N_4/silicon as shown in Fig. 2.

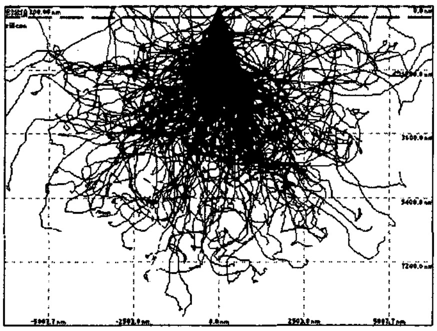


Fig. 1. Calculated trajectory and distribution of electron beams with Monte Carlo simulation in PMMA/Si (E= 30 keV, PMMA= 3000Å).

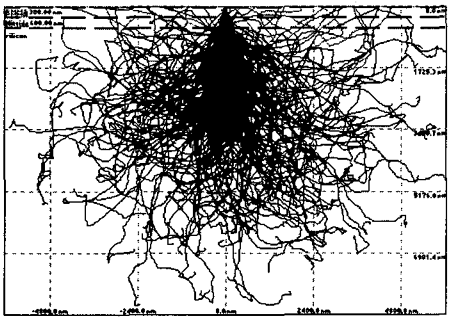


Fig. 2. Calculated trajectory and distribution of electron beams with Monte Carlo simulation in PMMA/Si_3N_4/Si (E=30 keV, PMMA= 3000Å, Si_3N_4=3000Å).

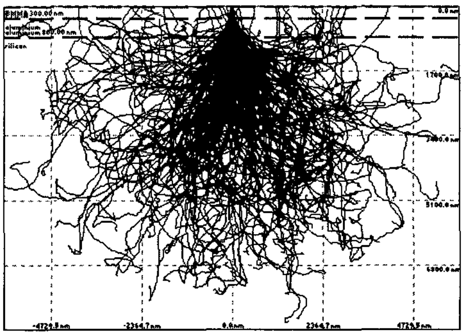


Fig. 3. Calculated trajectory and distribution of electron beams with Monte Carlo simulation in PMMA/Al/Si (E=30 keV, PMMA= 3000Å, Al=5000Å).

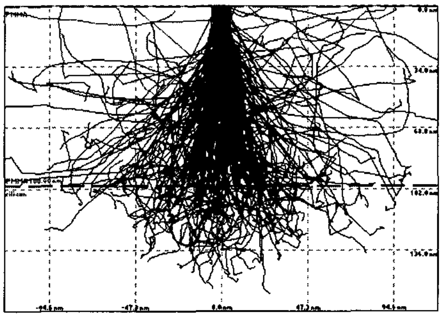


Fig. 4. Calculated trajectory and distribution of electron beams with Monte Carlo simulation in PMMA/Si (E=2.5 keV, PMMA= 1000Å).

In electron beam lithography, electrons are generally accelerated with voltage in the range from 1 to 30 keV. The arranged wavelength of electron beam has suitable relation as a following equation (1):

$$\lambda(nm) = \sqrt{\frac{1.5}{U/V}} \qquad (1)$$

where, U is accelerated voltage of electron beams.

Backscattering coefficient from computer simulation is shown 0.145 in normal incident case of electron beam on the resist surface of PMMA/Al/silicon as shown in Fig. 3. The lateral distribution of electron beam in PMMA/Al/silicon is a little bit broader than that of PMMA/Si_3N_4/Si.

To the depth of 340Å, electron beams are shown straight line type without backscattering effects as depicted in Fig. 4. But the backscattering coefficient from computer simulation is shown 0.085 due to backscattering effects in normal incident case of electron beam on the resist surface of PMMA/silicon as depicted in Fig. 4. In this case, the value of backscattering coefficient is the lowest in simulation results because of the thinnest layer of PMMA and the lowest accelerated energy of electron beam.

When the accelerated voltage of electron beam is higher, scattering effects of electrons due to backscattering have been shown dominantly. The pattern forms with electron beam exposure are affected by not only backscattering effects of electrons but also developing conditions. Forward scattering with small angles showed relative small size of pattern. On the other hand, electron beams at the two lateral sides can be caused broadly backward scattering effects from the substrate to photo resist layer. This effect plays very important role for the determination on resolution of line width in pattern. In these experiments, the patterns according to scattering effects by different underlying materials between PMMA/Si_3N_4/silicon and PMMA/Al/silicon structures are measured and compared each other. The fraction of electrons that are backscattered is roughly independent of beam energy, although it depends on the substrate material, with low atomic number materials giving less backscatter. Typical values of backscattering coefficient, η, range from 0.17 for silicon to 0.5 for tungsten and gold[4]. But the values of backscattering coefficients, η, from Casino simulation are 0.1-0.145 for PMMA/Al structure because the PMMA is lighter element than silicon with lower η.

3. MEASUREMENTS AND DISCUSSION

Silicon wafers with p type and 4 inch size are used for direct writing of electron beam with Gaussian shape. Cadence program is used for the layout of patterns in Unix workstation. In this case, the output file of electron beam is .gds format. Electron beam machine can only read .ebf format through the change of format. The experiment conditions by direct writing of electron beam on wafer are demonstrated in Table 1.

The linewidths of patterns using direct writing of electron beam on silicon wafers are measured by AFM, FESEM, and optical profiler of Veeco company.

3.1 Measurements of patterns by AFM

Eight patterns on silicon wafer are formed by direct writing of electron beam. Different fine line-widths are demonstrated in Fig. 5. The length of eight patterns is designed as 300µm and the uniform space of pattern is 1.5µm. Linewidths are designed as different scales as 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.5µm, respectively. The three dimensional measurements of patterns after direct electron beam irradiation on silicon wafer and stripping of photo resist are shown by AFM.

Table 1. Conditions of electron beam lithography.

Process items	Experiment conditions
E-beam machine	EBMF 10.0 Vectorscan-machine
Thickness of resist	3000Å
Soft bake	160 ℃, 4 min.
Hard bake	120℃, 4min.
Development	MIBK:IPA=1: 3, 150 sec.
Rinse	IPA 2min.
Probe current	5 nA
Electron beam energy	30 keV

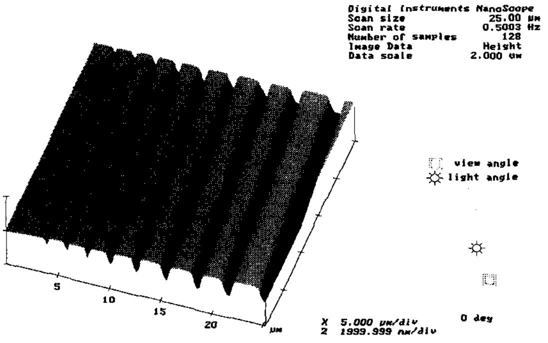


Fig. 5. Measurement of three dimensional pattern form by AFM.

The measured data by AFM are compared with original designed size of linewidth from the Fig. 6 and are presented in Table 2. The designed uniform space of pattern is 1.5 µm, and the measured space is about 1.536 µm, respectively.

Surface roughness on silicon is also measured by AFM. The measured average value of roughness is 0.09173 µm and value of RMS(root mean square) is 0.1179 µm, respectively. Two dimensional measurements of different nine linewidths by AFM are shown as depicted in Fig. 6.

3.2 Measurements of patterns by FESEM

Measurements of patterns on Si_3N_4/Si and $Al/SiO_2/Si$ by FESEM(field emission scanning electron microscophy) are presented in Fig. 7 and Fig. 8, respectively.

Table 2. Comparision between measured data on PMMA/Si by AFM and the designed size of linewidth.

Designed Size (µm)	Measured Data (µm)
0.3	0.367
0.4	0.469
0.5	0.573
0.6	0.682
0.7	0.787
0.8	0.891
0.9	1.039
1.0	1.367
1.5	1.875

Fig. 6. Measuremets of nine different line widths of patterns by AFM.

The pattern forms on Al/Si are distorted due to scattering effects of electron beams. Energy of electron beam is selected as 5 keV. When the energy during the measurements is high, the layer of photoresist is bent because of power heating effects despite of gold coating of 30 Å on photoresist layer.

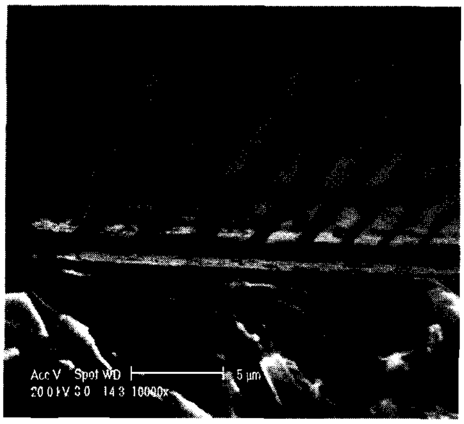


Fig. 7. Measured patterns of PMMA by FESEM on Si_3N_4/Si structure (PMMA = 3000 Å, Si_3N_4 = 3000 Å).

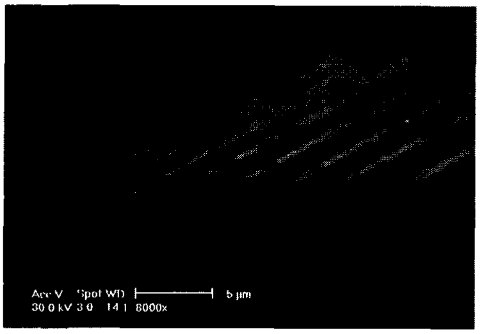


Fig. 8. Measured patterns of PMMA by FESEM on $Al/SiO_2/Si$ structure (PMMA = 3000 Å, Al = 5000 Å, SiO_2 = 3000 Å).

Table 3. Comparision between the measured data of FESEM on Si_3N_4/Si and the designed size of linewidth.

Designed Size (µm)	Measured Data (µm)
0.3	0.32
0.4	0.429
0.5	0.588
0.6	0.612
0.7	0.717
0.8	0.898
0.9	0.975
1.0	1.01
1.5	1.69

3.3 Measurements of patterns by optical profiler

The developed patterns as two and three dimensional structure by electron beam are measured by optical

Table 4. Comparision between the measured data of FESEM on $Al/SiO_2/Si$ and the designed size of linewidth.

Designed Size (µm)	Measured Data (µm)
0.3	0.374
0.4	0.452
0.5	0.548
0.6	0.615
0.7	0.717
0.8	0.91
0.9	1.02
1.0	1.12
1.5	1.837

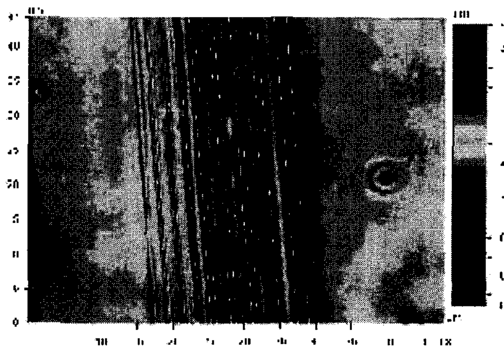


Fig. 9. Measured patterns as two dimensional by optical profiler on $PMMA/Si_3N_4/Si$ structure.

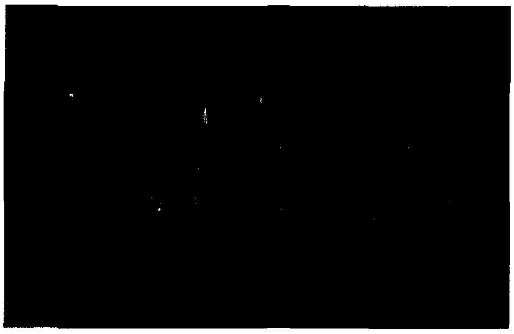
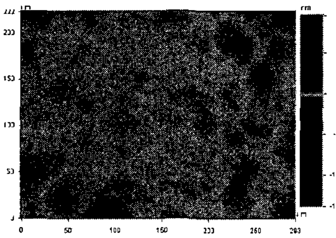
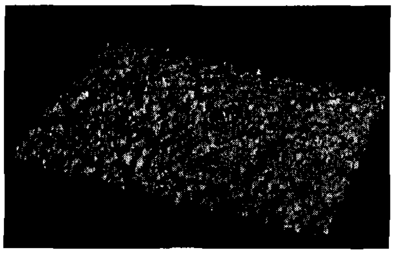


Fig. 10. Measured patterns as three dimensional structure by optical profiler on $PMMA/Si_3N_4$ /Si structure.

profiler of WYKO NT3300 in Fig. 9 and Fig. 10, respectively. PMMA layer as a photoresist is coated on Si_3N_4/silicon structure using spin coater. From left to right side, linewidth is gradually varied in size. A figure of a water drop is designated pin hole as deposited Si_3N_4 layer by PECVD(plasma enhanced chemical vapor deposition). This effect of pin hole causes bad surface conditions as a mask layer in anisotropic etching process. The experiment conditions of PECVD are carried out at 300 °C and 580 mTorr in furnace temperature and pressure. The thicknesses of Si_3N_4 and SiO_2 layer are same as 0.3 μm. The thickness of PMMA is also 0.3 μm.



(a) Surface morphology in frontside of wafer



(b) Surface morphology in backside of wafer

Fig. 11. Measured patterns as three dimensional structure by optical profiler on $Si_3N_4/Si/Si_3N_4$ structure.

Table 5. Comparision between the measured data of optical profiler on $Si_3N_4/SiO_2/Si$ and the designed size of linewidth.

Designed Size (μm)	Measured Data (μm)
0.3	0.67
0.4	0.78
0.5	0.89
0.6	1.01
0.7	1.12
0.8	1.23
0.9	1.35
1.0	1.68
1.5	2.13

Three dimensional $PMMA/Si_3N_4/Si$ structure of the developed patterns is demonstrated in Fig. 11. A Si_3N_4 layer on silicon substrate is deposited by PECVD and measured as three dimensional structure by optical profiler in Fig. 11. The average and RMS value of surface roughness in frontside of wafer are shown 0.26 nm and 0.35 nm as depicted Fig. 11(a), respectively. In other side, the averge and RMS value of surface roughness in backside are shown 0.9 nm and 1.18 nm as depicted in Fig.11(b), respectively.

Table 6. Comparision between the measured data of optical profiler on $Si_3N_4/SiO_2/Si$ and the designed size of linewidth.

Designed Size (μm)	Measured Data (μm)
0.3	0.7
0.4	0.8
0.5	0.9
0.6	1.1
0.7	1.2
0.8	1.3
0.9	1.5
1.0	1.8
1.5	2.3

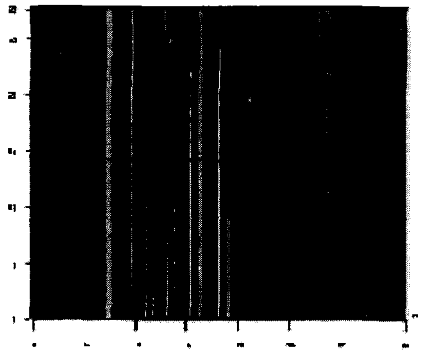


Fig. 12. Measured patterns as two dimensional structure by optical profiler on PMMA/Al/ SiO_2/Si structure.

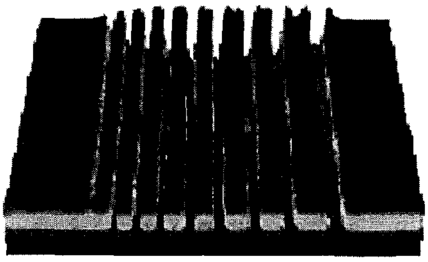
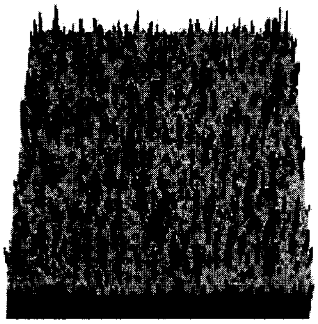


Fig. 13. Measured patterns as three dimensional structure by optical profiler on PMMA/Al/ SiO_2/Si structure.



(a) Surface of frontside in Al/SiO_2/Si structure

(b) Surface of backside in Al/SiO_2/Si/Al structure

Fig. 14. Measured patterns as three dimensional structure by optical profiler on Al/SiO_2/Si structure.

Table 7. Conditions of electron beam lithography.

Process items	Experiment conditions
E-beam machine	Leica Lion LV1
Thickness of resist	100 Å
Soft bake	160 ℃, 4 min.
Development	MIBK:IPA=1: 3, 100 sec.
Probe current	10.5 pA
Electron beam energy	2.5 keV

The measured patterns as two and three dimensional structure by optical profiler on PMMA/Al/ SiO_2/Si structure are shown in Fig. 12 and Fig. 13, respectively. As the electrons penetrate the resist, some fraction of them will undergo small angle scattering events, which can result in a significantly broader beam profile at the bottom of the resist than at the top. Because the backscattering effects from the large angle scattering events are affected the developed pattern form. The fraction of electrons that are backscattered is roughly independent of beam energy. In the other side, it relatively depends on the background substrate material. Accordingly, the measured data of linewidth in the structure of PMMA/Al/ SiO_2/Si show a little bit larger than these in PMMA/Si_3N_4/Si. The average and RMS value of surface roughness in frontside are shown 4.95 nm and 7.53 nm as depicted in Fig. 14 (a), respectively. In other side, the averge and RMS value of surface roughness in backside are shown 5.1 nm and 7.61 nm in as depicted Fig. 14 (b), respectively.

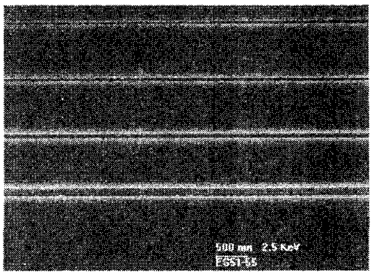


Fig. 15. Measurements of linewidth of PMMA/Si structure by SEM.

3.4 Measurements of nanoscale patterns by SEM

The linewidth of pattern by direct writing of electron beam on silicon wafer is measured by SEM. The measured size of linewidths from 0.04㎛ to 0.14㎛ is shown as depicted in Fig. 15. In this case, electron beam lithography is followed conditions in Table 7.

4. CONCLUSION

The developed linewidths of patterns by direct writing of electron beam are measured by AFM, FESEM, and optical profiler. The measured data of linewidths are remarkably affected by backscattering effects of material in under-layer. As the electrons penetrate through the photoresist, two mechanisms of slowing down of electron beam are forward scattering with small angle and backscattering with relative large angle in substrate beneath photoresist. Forward scattering of electron beam is minimized by the thinnest possible resist and the lowest available accelerating voltage. The resolution of developed pattern depends significantly on backscattering effects due to the material of substrate. From the backscattering effects, the measured linewidths in Si_3N_4/Si structure are a little bit narrower than these in Al/Si structure. Finally, high resolution of the developed pattern by direct writing of electron beam is necessary to reduce the energy of accelerated electron and thickness of resist as optimal conditions. At the same time, the material underneath resist has to be properly selected for the minimization of backscattering effects. Nanoscale structures of patterns are fabricated with the experiments of conditions as explained in Table. 7 and demonstrated by SEM as depicted in Fig. 15. But the measurement of sidewall in pattern is very difficult with conventional tools. In the future, nanoscale structure of pattern is necessary to find out new tools and analytic methods for exact aspect ratio measurement of sidewall and linewidth.

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