COMPARISON OF ULTIMATE RESOLUTION ACHIEVED BY E-BEAM WRITERS WITH SHAPED BEAM AND WITH GAUSSIAN BEAM

Stanislav KRÁTKÝa, Vladimír KOLÁŘÍKA, Milan MATĚJKAa, Michal URBÁNEKA, Miroslav HORAČEKa, Jana CHLUMSKÁa

aInstitute of Science Instruments of the ASCR, v.v.i., Královopolská 147, 612 64 Brno, Czech Republic, kratky@isibrno.cz

Abstract:
This contribution deals with the comparison of two different e-beam writer systems. E-beam writer with rectangular shaped beam BS600 is the first system. This system works with electron energy of 15 keV. Vistec EBPG5000+ HR is the second system. That system uses the Gaussian beam for pattern generation and it can work with two different electrons energies of values 50 keV and 100 keV. The ultimate resolution of both systems is the main aspect of comparison. The achievable resolution was tested on patterns consisted of single lines, single dots (rectangles for e-beam writer with shaped beam) and small areas of periodic gratings. Silicon wafer was used as a substrate for resist deposition. Testing was carried out with two resists, PMMA as a standard resist for electron beam lithography, and HSQ resist as a material for ultimate resolution achievement. Process of pattern generation (exposition) is affected by the same undesirable effect (backscattering and forward scattering of electrons, proximity effect etc.). However, these effects contribute to final pattern (resolution) by various dispositions. These variations caused the different results for similar conditions (the same resist, dose, chemical developer etc.). Created patterns were measured and evaluated by using of atomic force microscope and scanning electron microscope.

Key words:
Electron beam lithography, e-beam writers with shaped and Gaussian beam, PMMA, HSQ.

INTRODUCTION
Although electron beam lithography is not a new technique, it is still one of the most usable techniques in micro and nanofabrication. It is mainly used in microelectronics industry to creating photolithography masks. E-beam lithography is still developing. One of the major goals of the development is the higher resolution of prepared structures. To achieve this, more sophisticated and precise e-beam writers are needed.

This work deals with comparison of maximum resolution of two different e-beam writers. The first one, BS600, works with electron energy of 15 keV and it has rectangle shaped beam [1]. The theoretical maximum resolution of this system is 17 nm. The second system is the system with Gaussian beam with electron energy of 100 keV, Vistec EBPG5000+ HR. Maximum resolution of this system should be 2 nm.

1. THEORETICAL RESOLUTION IN E-BEAM LITHOGRAPHY
However, maximum resolution is not just a result of theoretical resolution of the system. Electron resist used for lithography has great influence on final resolution. The interactions of electrons with solid matter (resist) cause several undesirable scattering effects that affect the final resolution. These scattering effects depend on [2]:
- Electron energy,
- Resist material,
- Penetration depth.

These effects will be discussed further.
1.1 Forward electrons scattering

Forward electrons scattering is described by energy absorption $E_a$ in a material as a function of penetration depth $z$. Energy absorption is defined as follows [2]:

$$E_a = \frac{Q \cdot E_0}{e \cdot R_g} \lambda(I),$$  \hspace{1cm} (1)

where $E_a$ – energy absorption (eV·cm\(^{-3}\)), $Q$ – exposure dose (C·cm\(^{-2}\)), $E_0$ – primary electron energy (keV), $e$ – elementary charge (C), $R_g$ – electron range in a material (cm), $\lambda(I) = 0.74 + 4.7(z/R_g) - 8.9(z/R_g)^2 + 3.5(z/R_g)^3$, $z$ – penetration depth. On Fig. 1 is the dependency of energy absorption on penetration depth.

Fig. 1 The dependency of energy absorption on penetration depth in PMMA for three different primary electron energies and exposure dose of 10 $\mu$C·cm\(^{-2}\).

1.2 Lateral electrons scattering

Lateral electrons scattering is the next effect which has influence on final resolution in e-beam lithography. It can be described as the effective radius of electron beam in a penetration depth for a material. This is the empiric formula for PMMA [3]:

$$\sigma = 0.9 \cdot (z/E_0)^{1.5},$$  \hspace{1cm} (2)

where $\sigma$ – lateral scattering (nm), $z$ – penetration depth (nm), $E_0$ – primary electron energy (keV). On Fig. 2 is the dependency of lateral scattering on penetration depth for various primary electron energies.

Fig. 2 The dependency of lateral scattering on penetration depth in PMMA for three different primary electron energies.
1.3 Proximity effect

Besides mentioned scattering effects, there are a lot of other parameters that have an influence on final resolution, for example: substrate material, resist type (positive, negative), chemical developer and so on. The influence of most of these effects on final resolution is called proximity effect (for particular resist of defined thickness and substrate material). It is described by so called modulation transfer function (MTF) [4]:

\[
M = \frac{1}{1 + \eta} \left[ \exp\left( -\frac{\pi^2 \alpha^2}{\rho^2} \right) + \eta \cdot \exp\left( -\frac{\pi^2 \beta^2}{\rho^2} \right) \right],
\]

where \( \alpha \) – coefficient characterizing lateral electrons scattering at their forward scattering, \( \beta \) – coefficient characterizing backscattered electrons range, \( \eta \) – coefficient characterizing ratio of backscattered electrons energy to primary electrons energy, \( \rho \) – space period of close exposures (lines period). On Fig. 3 is MTF in dependency of lines period for two primary electron energies (15 keV and 100 keV) for resist (PMMA) thickness of 50 nm (resist layer used in experiment). Necessary coefficients were obtained by Monte Carlo simulations.

![MTF as a function of lines period for 50 nm PMMA layer on silicon substrate for two different primary electron energies.](image)

According to described scattering effects, better resolution is expected of the Vistec e-beam writer because it is the system working with electrons with energy of 100 keV.

2. EXPERIMENTS

It was prepared similar testing pattern for maximum resolution testing for both system. The testing pattern consisted of single lines (widths of 17 – 500 nm for BS600, 5 – 200 nm for Vistec), single dots (diameters of 50 – 500 nm for BS600, 5 – 200 nm for Vistec) and periodical gratings (periods of 100 – 1000 nm for BS600, 10 – 400 nm for Vistec). Exposure data were prepared with several ways of record order. It means that the various sizes of single shot was used as well as a different exposure direction and proximity effect correction was applied for a part of the testing pattern.

2.1 Sample preparation

PMMA resist was used for testing on both systems and HSQ resist was used only for testing on Vistec system. Both resist were spin-coated onto the silicon wafers. The thickness of PMMA was about 50 nm and thickness of HSQ was about 20 nm.

2.2 Exposure

Exposures on both systems were carried out for various exposure doses to obtaining wider technological window during the developing process. The doses of 10, 20, 50, 80 and 100 \( \mu \)C.cm\(^{-2} \) were used for exposure
on BS600 e-beam writer. The doses for Vistec e-beam writer were 200, 300, 350, 400, 450, 500 µC·cm⁻². The doses of several thousands of µC·cm⁻² were used for testing of HSQ resist because it is much less sensitive than the PMMA.

2.3 Developing process
Wet solution of isopropyl alcohol and water was used for the developing of PMMA. This developer was chosen due to its high contrast and low sensitivity, ideal combination of parameters for gaining of maximal resolution. The temperature of developer was the same as the room temperature – 21.1°C. The developing time was determined according to sensitive curve for middle exposure dose (60 s for both systems). Standard developer was used for developing HSQ resist (in bath with temperature of 50°C). After the developing, wafers were dried up by nitrogen gas.

3. RESULTS
Since the created structures were under the resolution of optical microscope, only the scanning electron microscope (SEM) and atomic force microscope (AFM) can be used for evaluation of maximum resolution of both systems. Thin metal layer has to be sputtered onto the resist because of SEM observation. This thin metal layer (~5 nm of chromium) has to be counted in determination of maximum resolution.

3.1 Maximum resolution of BS600
The smallest single line which could be considered as a successful exposure was the one with designed width of 83 nm (Fig. 4). The actual average measured width of this line was 64 nm. The result of single dots exposure was very similar. The smallest exposed dot (Fig. 5) was 52 nm wide (design was 100 nm). However, it is necessary to count with metal sputtering. The largest difference can be plus 10 nm (if we consider that the edges of the lines were completely covered with chromium) – 5 nm for each side). It should be mentioned that lines and dots with smaller width/diameter were also visible but their shape cannot be considered as a successful exposure. It might help to increase the exposure dose.

The smallest grating which was not destroyed by influence of proximity effect was the one with designed period of 240 nm (Fig. 6). Measured period was 236 nm. The ratio between exposed and non-exposed areas was approximately 2.3:1 (intended was 1:1). On Fig. 7 is of the gratings with smaller period. It is clear that lines in grating were overexposed. The adjustment of design and exposure doses could improve the result of smaller gratings.

![Fig. 4 Designed 83 nm line exposed on BS600.](image)

![Fig. 5 Designed 100 nm dot exposed on BS600.](image)
3.2 Maximum resolution of Vistec

As expected, higher resolution was achieved on Vistec system. The smallest single line which was successfully exposed was 10 nm wide (Fig. 8). The actual width of the line was hard to determine because such a small structure is strongly affected by metal sputtering (we can even see single chromium clusters). Nevertheless, measured width was 6 nm. The smallest single dot exposed on Vistec was 15 nm (Fig. 9). The determination of actual width (12 nm) was similar like in a case with single line. However, the smallest designed dots and lines were also visible it is hard to decision if it was successful exposure or if it was completely covered by chromium.

The smallest grating which still had the shape of grating was the one with period of 40 nm (Fig. 10). Measured period was approximately 43 nm. The ratio between exposed and non-exposed areas is impossible to determine due to the metal sputtering. The same problem does not allow to recognize if gratings with smaller period was successfully exposed or not. The test for HSQ resist consisted only of single lines with designed width of 8 nm (Fig. 11). The actual width was 7.6 nm. The advantage of HSQ observation in SEM is the non-destructive impact of electron beam on the resist. Because of that, created structures are not affected by metal sputtering.
3.3 Comparison of achieved resolution

Unfortunately it was not possible to observe created structures (the smallest ones according to the SEM measurement) with AFM because of the depth of the structures (~50 nm) and the shape of the AFM tip probe. The comparison between e-beam writers BS600 and Vistec EBPG5000+ HR is in Table 1.

<table>
<thead>
<tr>
<th>Exposed motive</th>
<th>Single line (nm)</th>
<th>Single dot (nm)</th>
<th>Grating (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS600</td>
<td>83/64 *+10</td>
<td>100/52 *+10</td>
<td>240/236 *+10</td>
</tr>
<tr>
<td>Vistec</td>
<td>10/6 *+10</td>
<td>15/12 *+10</td>
<td>40/43 *+10</td>
</tr>
</tbody>
</table>

Note: designed/measured *maximum difference caused by chromium sputtering

4. CONCLUSION
We successfully made the exposure on two different e-beam writers; BS600 and Vistec EBPG5000+ HR; to determine their ultimate resolution in resist PMMA (and HSQ for Vistec system). Created structures were evaluated by scanning electron microscope. As expected, better resolution was achieved on Vistec system.

ACKNOWLEDGEMENT

This work was partially supported by the EC and MEYS CR (project No. CZ.1.05/2.1.00/01.0017 ALISI, project No. CZ.1.07/2.3.00/20.0103 OPVK), the TACR project No. TE 0102033 and by the institutional support RVO: 68081731.

REFERENCES