LIMITS TO NANOPATTERNING BASED ON E-BEAM LITHOGRAPHY

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1. Introduction

Nowadays, various lithographic techniques ranging from conventional methods (e.g. photolithography, immersion ArF lithography extensions, x-rays, Extreme UV, charge particle lithography) to unconventional ones (e.g. nanoimprint lithography, self-assembled monolayers) are used to create small features. Among all these, resist-based electron beam lithography (EBL) is one of the a fundamental technique of nanofabrication that allow us to create patterns at the nanoscale. It is allowing not only the direct writing of structures down to sub-10 nm dimensions, but also enabling high volume nanoscale patterning technologies such as (DUV and EUV) optical lithography and nanoimprint lithography through the formation of masks and templates.

The boundaries of EBL, the workhorse of current nanofabrication processes, is constantly being pushed further down into the single nanometer range by researchers' efforts to overcome the various limitations of EBL resolution - spot size, electron scattering, secondary-electron range, resist development, and mechanical stability of the resist.

In this paper, experiments with variable shaped e-beam system and Gaussian spot beam system were performed with high resolution PMMA and HSQ e-beam resists. Limitations of e-beam lithography nanopatterning are discussed.

2. Equipment

Mask writer tools that use electron beams are of key importance in patterning surfaces for semiconductor manufacture. Currently, the most commonly used tools are variable shaped beam (VSB) mask writers. These enable alteration in the shape of the 20 - 100 keV beam during writing, achieving considerably higher throughput than Gaussian spot beam tools, which are used for ultra-high-resolution work.

An overview of current e-beam lithography configurations is given in [1]. The realization of a proof-of-concept of a multibeam mask writer for nodes of 11 nm or less which employ thousands of e-beams to write complex mask patterns in parallel is described in [2].

3. Resolution in e-beam lithography

EBL is a very sensitive process determined by various factors, starting with the choice of resist material and ending with the development process.

The ultimate resolution of electron beam lithography is not set by the resolution of electron optical systems, which can approach 0.1 nm, but by the resolution of the resist and by the subsequent fabrication process [3] The contribution by electron scattering was explained by Chang who pointed out that there were two major types of scattering, forward scattering and backscattering, and that these could be treated separately and modeled by Gaussian distributions [4]. When high throughput is important, however, the resolution with electrons also becomes limited by the optics.

There is a large number of parameters affecting the EBL process in a complex, interacting fashion. The objective of manipulating these parameters is to achieve a high resolution, high quality, high throughput result with large process windows to maximize yield and reproducibility. Summary of those key factors are shown in [5, 6].

As requirements for lithography have progressed toward the sub-20 nm regime, novel EBL processes that would extend capabilities of the technology significantly into the deep nanoscale regime entail new approaches to resist design, exposure strategies, and development techniques [7-13]. To achieve this will require thorough, systematic understanding of the limiting factors [14] involved in both the electron-resist interaction and in the polymer dissolution (development), as well as the corresponding intricate interplay of the numerous process control parameters including the accelerating voltage, exposure dose, and development conditions.

The direct writing of structures down to sub-10 nm dimensions was demonstrated in some publications, e.g. [15, 16, 17]. The highest resolution patterns ever achieved using EBL with common resists was reported in [18]. The minimum feature size of 2 nm and 10 nm periodic dense structures was patterned using an aberration-corrected scanning transmission electron microscope (STEM) as the exposure tool. The STEM provides high-energy electrons 200 keV with the spot size available 0.15 nm. HSQ negative resist was used as it is the resist with the highest reported resolution available.

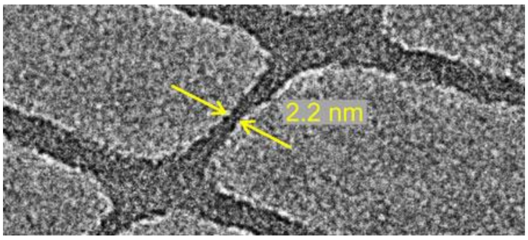


Fig. 4: *The minimum feature size of 2 nm and 10 nm periodic dense structures [19].*

4. Materials

Sub-10 nm features are possible in principle employing polymer resists such as PMMA but they are limited with the size of the molecules. Commonly used e-beam resist in sub-20 nm patterning is PMMA. Examples of optimized, PMMA-based ultra-high resolution lithographic device fabrication are demonstrated in a number publications, e.g. silicon carbon nitride (SiCN) bridge resonator fabrication technology [19, 20] employing a low-voltage, cold development EBL process [21].

In the last decade, there has been significant interest in the usage of an alternative inorganic EBL resist hydrogen silsesquioxane (HSQ), which has shown considerable potential at the 10-nm scale [22 - review paper]. HSQ (*Dow Corning*) is a negative tone resist which cross-links to form an insoluble silica-like structure, although at significantly higher doses than required to process positive tone PMMA.

5. Experiment

Limitations of e-beam lithography have been investigated on various line and spot gratings. Some results with VSB are demonstrated in Figs. 1 and 2. E-beam lithography system ZBA23 (*Vistec*) with minimal spot size of 50 nm was used for exposures (at UI SAV, Bratislava, Slovakia). Line gratings were exposed in 200 nm thin positive resist PMMA at 40 keV electron energy and transfered into silicon substrate with RIE plasma. Designed Line/Space (L/S) was changed from 50/350 nm to 50/650. Linewidth in resist after exposure was depending on the exposure dose and the relation Line/Space due to the electron scattering. The minimal linewidth of 150 nm was achieved in case of the space 550 nm (Fig. 1a) and the minimal space of 110 nm was in case of the linewidth 920 nm (Fig. 1c). Linewidth equal to Space can be achieved at appropriate dose. The patterning of 200 nm lines with 15 nm precision is demonstrated in Fig 1b where Line/Space is 185/215 nm.

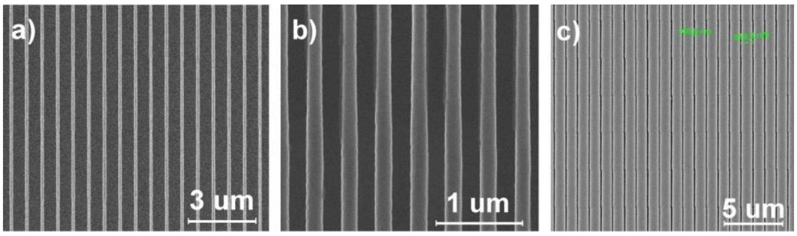
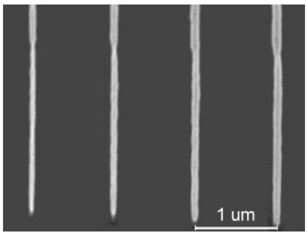
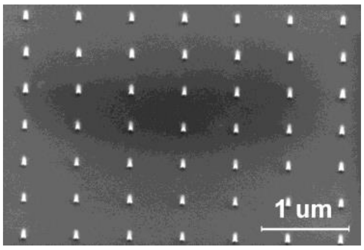


Fig. 1: *Line grating with various Line/Space exposed at 40 keV electron energy in 200 nm thin PMMA positive resist and transfered into Silicon substrate with RIE plasma: (a) Line/Space 150/550 nm. (b) Line/Space 185/215 nm. (c) Line/Space 920/110 nm.*



Lines exposed in 150 nm thin HSQ negative resist on silicon substrate exposed using VSB with rectangular e-beam spot 50 x 3000 nm at 40 keV are shown in Fig. 2. The minimal linewidth 75 nm was measured after silicon etching in RIE plasma. The linewidth was controled with exposure dose variation, measured 75, 85, 95, 110 nm (from the left to the right).

Fig. 2: *Lines in 150 nm thin HSQ resist on Silicon substrate exposed using VSB with rectangular e-beam spot 50 x 3000 nm at 40 keV.*



An example demonstrated a high voltage exposure convenience is shown in Fig. 1b. Pillars with diameter 50 nm in 150 nm thin HSQ XR1541 on silicon subtsrate have been achieved at 100 keV electron energy. E-beam lithography system Vistec EBPG 5000+ with Gaussian beam was used for exposures (at IMEL Demokritos, Athens, Greece). The standard development was done in 2,38% solution TMAH at room temperature 21^{o}C.

Fig. 3: *Pillars in 150 nm thin HSQ XR1541 negative resist on silicon substrate with 50 nm diameter exposed at 100 keV electron energy using Gaussian spot beam.*

6. Conclusions

Limitations of e-beam lithography nanopatterning were discussed. Measurements of minimal size of structures achieved with high voltage e-beam exposure were performed. The size of structures in resist after exposure is depending on the exposure dose and the relation Line/Space due to electron scattering. Comparison of values achieved with variable shaped e-beam system and Gaussian spot beam system was performed for high resolution PMMA and HSQ e-beam resists. Minimal linewidth 150 nm was achieved in case of variable shaped e-beam system at 40 keV electron energy and dots with diameter 50 nm in case of Gaussian spot beam at 100 keV.

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