Sub-10 nm structures written in ultra-thin HSQ resist layers, using Electron Beam Lithography

Anda E. Grigorescu^a, Marco C. van der Krogt^b, Cees W. Hagen^a

^a Delft University of Technology, Charged Particle Optics Group, Delft, 2628 CJ, The Netherlands
phone: +31-(0)15-2781022 e-mail: A.E.Grigorescu@tudelft.nl

^b Delft University of Technology, Kavli Institute of Nanoscience, Nanofacility, The Netherlands

Key words: high resolution, electron beam resist, HSQ, electron beam nano-lithography, development process

Abstract

Isolated dots and lines with 6 nm width were written in 20 nm thick Hydrogen silsesquioxane (HSQ) layers on silicon substrates, using 100 keV electron beam lithography. The main factors that might limit the resolution, i.e. beam size, writing strategy, resist material, electron dose, development process, are discussed. We demonstrate that, by adjusting the development process, a very high resolution can be obtained. We report the achievement of 7 nm lines at a 20 nm pitch written in a 10 nm thick HSQ layer, using a KOH-based developer instead of a classical TMAH developer. This is the smallest pitch achieved to date using HSQ resist. We think that the resolution can be improved further, and is presently limited by either the beam diameter (which was not measured separately) or by the not fully optimized development process.

1. Introduction

When writing nanostructures with Electron Beam Lithography (EBL), at least three main elements are needed. First, a tool must be available that is capable of providing a writing beam smaller in diameter than the minimum feature dimensions desired. EBL is a promising technique, since an e-beam can easily be focused to a spot of 4 nm or less [1]. The writing strategy and the applied area dose have also an important effect on the ultimate resolution that can be achieved with EBL. The second element in nanostructures fabrication is the so-called resist, the medium onto which the desired pattern is written by the electron beam. This electron-sensitive resist must be altered by the beam in such a way that, after development the portion exposed to the beam is removed (positive resist) or remains on the substrate after the unexposed portion is removed (negative resist). Resist materials are in general polymeric solutions that are applied onto the surface of the substrate by spinning techniques and are dried to form a thin uniform layer of thickness depending on the application and the resolution (minimum feature size) required. The properties of the resist material used in the lithographic process are an important factor governing the resolution. In e-beam lithography, the resolution is not limited by the probe size but rather by electron scattering, both in the resist and in the substrate. The forward scattering in the resist can be minimized by the use of thin resists and high energy electron beams [2]. However, the effects of the scattered electrons from the substrate are more difficult to minimize. For many applications, the substrate cannot be thinned to membrane dimensions. In general, the substrate has a higher atomic number than the resist material and therefore produces more electron scattering and larger scattering angles. There are two solutions in order to reduce the effects of scattering from the substrate. One method is to use low energy electrons, which do not scatter over large distances [3]. Another method is to use very high energy electrons which penetrate deep into the substrate and only a small fraction of them will have enough energy to go back to the resist, to expose it. This method combined with the dose correction works well for isolated features [4] but becomes more complicated when dense features with a size below 10-20 nm is needed. For nanolithography, where higher acceleration voltages and thinner resists are used, secondary-electron generation close to the incident electron beam is probably the resolution limiting factor, rather than the secondary electrons generated by the backscattered electrons. During e-beam irradiation either the polymeric structure is cross linked (negative tone), forming insoluble material or the polymer molecules are broken (positive tone), leading to smaller soluble molecular fragments. In both situations, the smallest definable pattern is at least as large as the molecular area of the polymer molecule on the substrate (several nm for most polymeric resists). It is therefore desirable

that the area of the resist molecules on the surface is as small as possible. Furthermore, the resist must have a high sensitivity, good resistance to chemical etching and a good adhesion to the substrate. In order to find an ideal resist, several materials have been investigated, including low molecular weight organic molecules [5], inorganic materials such as metal fluorides [6], fullerenes [7], and fullerene derivatives [8]. In the last decade, hydrogen silsesquioxane (HSQ, Flowable Oxide, FOx-12 from Dow Corning) became a serious candidate as high-resolution electron beam resist because of its small line edge roughness, high etching resistance and small molecular size [9]. HSQ is also an excellent resist for testing e-beam machine resolution limits because HSQ lines on silicon can be imaged directly in a SEM without the need of gold evaporation for conduction or "lift-off" techniques. In a previous work [10] we reported the achievement of 8 nm linewidth at a pitch of 30 nm written in a 10 nm thick HSQ layer. The sample was developed for 30 s using a KOH-based developer (AZ 400K from Clariant) instead of the conventional tetra methyl ammonium hydroxide (TMAH). We were also able to achieve 10 nm lines and spaces on a 10 nm thick HSQ layer. The lines were relatively smooth which is a major attribute of HSQ as a resist. It was noted that by better optimization of the development process the resolution could probably be improved further.

The development process is the third important element. A lot of experiments have been done by many workers, which proves the importance of the development time and developer concentration [11,12] on the resolution. However, in order to reach sub-10 nm resolution, a variety of extra process steps [13, 14], before, during or after electron beam irradiation, have often been necessary.

This current work is focused on experiments with ultra thin (10 nm, 20 nm) resist layers. All the experiments reported in the HSQ literature were made using 50-100 nm resist layers and by using the standard TMAH based developer. We believe that thinner resist layers and a better optimization of the development process may improve the resolution that can be achieved with HSQ as a high resolution electron beam resist. It is the objective of this paper to investigate the important factors which may limit the ultimate resolution that can be achieved with HSQ by writing small dots and lines and spaces.

2. Experiment

Silicon wafers were diced and cleaned with ultrasonic agitation in 100% fuming nitric acid, demineralized water and isopropanol for 2 min and finally blown dry with nitrogen gas. Next, the samples were baked at 200 °C for 2 min to remove residual moisture. For high resolution patterning, the silicon wafers were spin coated with a solution of 1:5 FOx-12: Methyl Isobutyl Ketone (MIBK) or 1:10 FOx-12: MIBK at different rotation speeds varying from 1000 rpm to 5000 rpm for 60 s. In order to get the thinnest possible resist layers, two different spinners were used. On a Karl Suss spinner two spinning sessions were made: one with the lid closed (in order to decrease the rate of evaporation of the solvent) and one with the lid open. From Figure 1 we can see that an approximately 20 nm thick HSQ layer is obtained, when a solution of 1:5 FOx-12: MIBK is spun at 3000 rpm for 60 s, using the Karl Suss spinner with closed lid. When the lid is open, almost a double thickness (40 nm) is obtained. For comparison, the same experiment was done on a Convac spinner and the result was a 32 nm thick HSQ resist layer. By using a higher dilution rate 1:10 FOx-12: MIBK, a 10 nm thick HSQ layer was obtained at 3000 rpm for 60 s, on the Karl Suss spinner with the lid closed. The HSQ spin coating was performed directly on the silicon wafer without using a primer. After spinning, the HSQ layer was prebaked on a hotplate for 40 min at 90 °C in order to get a high contrast and a good reproducibility [15]. The thickness of the resulting HSQ, ranging from 10 nm to 20 nm, was measured with a Gaertner ellipsometer. The wafers were exposed in a Vistec Electron Beam Pattern Generator (EBPG 5000+) at 100 kV with an aperture of 300 μ m (201 pA beam current, 2 nm estimated spot size). The test pattern consists of five sets of 4 μ m long lines. Within each set all lines are designed with a fixed width and pitch but between the sets the linewidth and pitch varies. Chosen widths are 1.25 nm, 2.5 nm, 5 nm, 7.5 nm and 10 nm at a pitch of 50 nm, 75 nm, 100 nm, 120 nm and 150 nm, respectively. The structures were all written with a fixed beam step size (BSS, the distance between two adjacent exposures) of 1.25 nm. Depending on the designed linewidth, an exposure is performed by scanning the beam once (single pass) over either one line (single exel or 1-exel) or n adjacent lines (n-exel line). A schematic representation of the writing strategy is illustrated in Figure 2. In principle, the smaller the beam diameter that is used, the thinner the resulting line can become (see Figure 1a). However, if the beam diameter is for example equal to half the BSS, the line obtained after developing is not continuous. In Figure 2b), an example of a line for which the designed width is two times the BSS, is shown. The beam diameter is two times the BSS. When the same line is written at higher dose, the linewidth is broadened because of the proximity exposure (the outer circles). However, in order to write the thinnest lines possible, single exel lines can be written, where the linewidth is equal to the beam size. Of course the linewidth also depends on the exposure dose. By doing a dose test, an optimum dose can be determined for which the linewidth after exposure and development is equal to the designed linewidth. For

simplicity, and because the beam size is not accurately known, we define the designed linewidth as the number of exels times the BSS. The line dose is calculated by multiplying the area dose with the designed linewidth. The design mentioned above was written in an array of 10*10 cells, each cell containing five sets of lines. Each cell was exposed with a different electron dose. The starting dose was 3000 $\mu\text{C}/\text{cm}^2$ (unless otherwise stated) and the dose of each next cell is found by multiplication with a factor of 1.048, leading to an end dose of 283247 $\mu\text{C}/\text{cm}^2$. We also exposed dots by writing a design with an array of the smallest possible pattern: squares measuring 1.25 nm * 1.25 nm (1*1 BSS), each representing a single, isolated exposure. The pitch was 125 nm in the x direction and 100 nm in the y direction. A dose test was performed by writing this design in an array of 10*10 cells, each cell exposed with a different area dose. The starting dose was 5000 $\mu\text{C}/\text{cm}^2$ (unless otherwise stated) and the dose of each next cell is found by multiplication with a factor of 1.055, leading to an end dose of 1 C/cm². The samples were developed by manual immersion at 20°C in TMAH based developer (MF-322 from Rohm and Haas) for 60 s, unless otherwise stated. Exposed substrates were then rinsed in 1:9 developer: demineralized water for 10 s, rinsed in demineralized water for another 10 s and blown dry with nitrogen. Following the development process, the resist linewidth was imaged and measured using an FEI Nova Nano 200 Scanning Electron Microscope.

3. Results and discussions

3.1 Isolated features: dots

First, we describe the resolution obtained for nanostructures that we call “isolated”, meaning that the pitch between adjacent features is much larger than the size of the designed features. Experiments on resolution limits were conducted on single layers of HSQ of 10 and 20 nm thick by exposure of test patterns consisting of dots and lines with different widths and pitches written with various exposure doses. Dots were realized by writing a design with the smallest possible pattern: squares measuring 1.25 nm * 1.25 nm (1*1 BSS), each representing a single, isolated exposure. Using 100 keV electron beam lithography, we report the achievement of 6 nm dots (see Figure 3) with a pitch of 125 nm in the x direction and 100 nm in the y direction in a 20 nm HSQ layer on silicon substrates. Although the pitch is relatively large, this result is important because these are the smallest dots ever written in HSQ. The sample was developed for 60 s using MF-322 developer. Figure 4 shows the results of dot size as function of the area dose. The starting dose was 5000 $\mu\text{C}/\text{cm}^2$ and the dose of each next cell is found by multiplication with a factor of 1.055, leading to a final dose of 1 C/cm². It is seen that the dot size increases with the area dose. From the SEM inspection, we observed that the first cell where a regular array of dots appears is found at a very high dose, i.e. 527150 $\mu\text{C}/\text{cm}^2$. The first dots are visible at a dose of 212150 $\mu\text{C}/\text{cm}^2$ but the array is not complete. Below this dose, the structures are not visible at all. We expected the regular array of dots to be visible at a lower dose. The fact that the written structures start to be visible only at doses higher than 212150 $\mu\text{C}/\text{cm}^2$ may be simply due to the fact that the electron dose range was chosen to start at too small values, but it could also be that the development time was too long for these thin layers, such that the structures were washed away. It is noted here that most of the experiments reported in the HSQ literature using TMAH based developer and development times of 60 s using were done on much thicker resist layers of typically 50-400 nm thick. For our relatively thin layers a shorter development time might be sufficient and also a smaller feature size is to be expected. Of course, it can not be ruled out that the beam size is still limiting the resolution, as it was not measured separately.

To quantify the influence of the development process on the feature size one can either change the development time or the strength (normality) of the developer. We performed experiments in which the whole process was identical, except for the development process. In the first set of experiments, we changed the development time from 60 s to 45 s and 30 s respectively. The results of these experiments don't show a significant improvement of the resolution. Although it is possible that even shorter development times do improve the resolution we decided to change the strength of the developer instead.

In this second set of experiments, we kept the development time constant (60 s) but we varied the strength of the developer. In Figure 5, the dot size as a function of the area dose is indicated for two different concentrations of TMAH developer. MF-322 was used undiluted (N=0.268 eq/l) and diluted with demineralized water in a ratio 1:3 (N=0.067 eq/l). For diluted developer, the regular arrays of dots appear at a lower electron dose than when the developer is undiluted. Since all samples are exposed with the same dose range, this is a clear indication that the structures that turn out to be well developed with the diluted developer are washed away in the undiluted case. Still, no better resolution than 6 nm was obtained.

In a third set of experiments, we changed the developer type, by using a potassium hydroxide (KOH) aqueous solution instead of TMAH. Namatsu [14] suggested that this novel developer can be used, when high resolution is required. One

sample was developed with TMAH ($N=0.268$ eq/l) for 60 s and the other one was developed for 10 s with a KOH aqueous solution ($N=1.39$ eq/l). Although in terms of ultimate resolution we obtained the same results (almost 8 nm dots, for both samples), an interesting effect occurs when the sample is developed with AZ 400K from Clariant. Even for a six times shorter development time, the features are washed away when a stronger developer (higher normality) is used. The first visible regular array of dots needs a three times higher dose, when the sample is developed with AZ 400K compared to MF-322.

In terms of ultimate resolution, we obtained a minimum dot size of approximately 6 nm with a pitch of 125 nm in the x direction and 100 nm in the y direction. This resolution may be limited by the beam diameter, which was not measured separately, or by a still not well optimized development process.

3.2 Isolated features: isolated lines

We also wrote lines with different widths and pitches at various exposure doses. The lines were all written with a fixed BSS of 1.25 nm. Depending on the designed linewidth, an exposure is performed by scanning the beam once (single pass) over either one (single exel or 1-exel) or n adjacent lines (n -exel line). The sample was developed for 60 s, using MF-322. The line dose is calculated by multiplying the area dose with the designed linewidth. When the SEM inspection is performed, the lines that are visible first (at the lowest dose) are the 8-exel lines (10 nm designed linewidth). This is to be expected since the line dose is the highest for these lines (proximity exposure). The same general behavior is observed as for the dots: if the dose increases, the lines become wider (Figure 7). For doses of $6976 \mu\text{C}/\text{cm}^2$ and $25926 \mu\text{C}/\text{cm}^2$ the measured linewidth (after development) is smaller than the designed linewidth, 5.5 nm, 8.7 nm respectively (see Figure 7a, 7b). This may be due to the fact that the dose was too low and the structures were not completely exposed. At a dose of $32775 \mu\text{C}/\text{cm}^2$ we measured 10.5 nm linewidth and this can be called the optimum dose because the measured linewidth after development is equal to the designed linewidth (Figure 7c). For higher doses, i.e. $296843 \mu\text{C}/\text{cm}^2$ 20 nm lines are obtained (Figure 7d). In this case, the structure is clearly overexposed. The next lines that appear are the 6- and 4-exel lines (7.5 nm and 5 nm designed linewidth) (Figure 8), with a measured linewidth of 5.7 nm at a dose of $16223 \mu\text{C}/\text{cm}^2$ (for 6-exel, see Figure 8a) and 5.5 nm at a dose of $17002 \mu\text{C}/\text{cm}^2$ (for 4-exel, see Figure 8b). Again we found a dose that is insufficient for the complete exposure of the 7.5 nm designed structures and an optimum dose for 5 nm designed structures. We also observe that the 4-exel single pass exposure appears at a higher dose than the 6-exel single pass exposure. The 2- and 1-exel (2.5 nm and 1.25 nm designed linewidth), appear at an even higher dose, $17818 \mu\text{C}/\text{cm}^2$, and $27171 \mu\text{C}/\text{cm}^2$, respectively (Figure 8c, 8d). This can be explained by a too long development time, such that the structures written at lower doses were washed away. The measured linewidth is almost six (for 1-exel) and four times (for 2-exel) larger than the designed linewidth. Because the lines were single exel, and double exel, single pass exposures, we suspect that the structures were overexposed.

3.3 Dense features

The real resolution test in lithography is, of course, the fabrication of dense lines and spaces. In a previous paper [10] we reported the achievement of 8 nm linewidth at a pitch of 30 nm written in a 10 nm thick HSQ layer. The sample was developed for 30 s using KOH-based developer instead of the conventional TMAH. Next we were able to achieve 10 nm lines and spaces on a 10 nm thick HSQ layer. The lines were relatively smooth, which, is a major attribute of HSQ as a resist.

In order to see whether the resolution can be further improved, a new experiment was conducted on a 10 nm thick HSQ layer with the same design as described in [10] (lines with 20 nm pitch). Again, this design was written in an array of 10×10 cells, each of them exposed with a different electron dose. The starting dose was $750 \mu\text{C}/\text{cm}^2$ and the dose of each next cell is found by multiplication with a factor of 1.048, leading to an end dose of $77773 \mu\text{C}/\text{cm}^2$. These doses are four times smaller than used for the isolated lines, described above, because we wanted to diminish the proximity effect that can occur when dense arrays of structures are written. The sample was developed for 15 s using AZ 400K. The reason for choosing this relatively short development time was to prevent the structures from being washed away, since this KOH based developer is almost 5 times stronger than MF-322. The smallest lines obtained in a 10 nm thick HSQ layer are shown in Figure 9. In Figure 9a) a 7 nm wide line is shown resulting from a 2-exel (i.e. 2.5 nm designed width) single pass exposure with an area dose of $70812 \mu\text{C}/\text{cm}^2$. This is a clear improvement of the result obtained before [10]. In Figure 9b) a 4-exel (i.e. 5 nm designed width) single pass line with area dose of $36732 \mu\text{C}/\text{cm}^2$ is shown which has a measured width of 7.5 nm. Looking at the dose we see that the 2.5 nm designed linewidth needs almost a double dose in

order to be completely developed, in comparison with the 5 nm designed linewidth. This may be caused by the proximity effect, which contributes to the final linewidth.

4. Conclusions

We have shown that ultra thin layers (10 nm to 20 nm) of HSQ can be obtained when a spinner is used which has a small volume between lid and spinning chuck (Karl Suss spinner with lid closed compared to Convac spinner). In terms of ultimate resolution, we obtained 6 nm isolated dots. The dot size increases approximately from 6 to 10 nm when increasing the area dose from 0.5 to 1 C/cm². The dot size was not influenced much by decreasing the development time from 60 s to 30 s. However, by diluting the developer, while keeping the exposure dose constant, the dot size increases. Furthermore, the lowest dose that results in well-developed dots shifts to lower values. This suggests that small features exposed at small doses are washed away when too strong developers are used. The same behaviour was observed when we compared a KOH-based developer (strong) and TMAH (weaker).

The fact that, when using dilute developer solutions, the dots at low exposure doses are not significantly smaller than the smallest dots developed in strong developers suggests that the dot size is probably limited by the electron probe size. Using TMAH as a developer 5.5 nm wide isolated lines were obtained in a 20 nm thick HSQ layer with a 4-exel, single pass, exposure at 17000 $\mu\text{C}/\text{cm}^2$.

By refining the development process (shorter development time, a novel developer) 7 nm lines at a 20 nm pitch were written in a 10 nm thick HSQ layer, using 100 keV, 2-exel single pass, e-beam exposure at a dose of 70812 $\mu\text{C}/\text{cm}^2$. This represents the smallest pitch achieved to date using HSQ as electron beam resist.

The experiments revealed that, when writing sub-10 nm structures, the resolution is influenced by multiple factors such as beam size, writing strategy, area dose, resist thickness, and the development process. By varying these parameters we demonstrated that resolution improvements could still be achieved. Further work is needed in order to quantify all these parameters and to find the ideal recipe for the ultimate resolution that can be achieved with HSQ electron beam resist. At present we can not conclude yet whether the resolution is limited either by the beam size (which was not measured separately) or by the development process. We plan to write dense lines and spaces in a scanning transmission electron microscope (STEM), which has a very small probe size of 0.3 nm. When the probe size is still limiting the resolution this will clearly lead to better results.

References

- [1] K. Yamazaki, H. Namatsu, Jpn. J. Appl. Phys. 43, 3767 (2004)
- [2] R. Heidenreich, J. Appl. Phys. 48, 1418 (1977)
- [3] E. A. Dobisz, C. R. K. Marrian, Appl. Phys. Lett. 58, 2526 (1991)
- [4] Y. Lee, R. Browning, N. I. Maluf, R. F. W. Pease, Proc. SPIE 1671, 155 (1992)
- [5] J. Fujita, Y. Ochiai, S. Matsui, Appl. Phys. Lett. 68, 1297 (1996)
- [6] J. Fujita, H. Watanabe, Y. Ochiai, S. Manako, J. S. Tsai, S. Matsui, Appl. Phys. Lett. 66, 3064 (1995)
- [7] T. Tada, T. Kanayama, Jpn. J. Appl. Phys. 35, L63 (1996)
- [8] A. P. G. Robinson, R. E. Palmer, T. Tada, T. Kanayama, J. A. Preece, Appl. Phys. Lett. 72, 1302 (1998)
- [9] H. Namatsu, Y. Takahashi, K. Yamazaki, M. Nagase, K. Kurihara, J. Vac. Sci. Technol. B 16, 69 (1998)
- [10] A. E. Grigorescu, M. C. van der Krogt, C. W. Hagen, P. Kruit, accepted for publication in Microelectron. Eng. (2007)
- [11] W. Henschel, Y. M. Georgiev, H. Kurz, J. Vac. Sci. Technol. B 21, 2018 (2003)
- [12] D. Lauvernier, J. P. Vilcot, M. Francois, D. Decoster, Microelectron. Eng. 75, 177 (2004)
- [13] M. J. Lercel, H. G. Craighead, A. N. Parikh, K. Seshadri, D. L. Allara, Appl. Phys. Lett. 68, 1504 (1996)
- [14] H. Namatsu, K. Kurihara, M. Nagase, T. Makino, Appl. Phys. Lett. 70, 619 (1997)
- [15] W. Henschel, Y.M. Georgiev, H. Kurz, J. Vac. Sci. Technol. B 21 2018 (2003)

Figure 1 Spin curve for HSQ at different dilution rates and at different rotation speeds, when using Karl Suss spinner (with the lid closed or open) and a Convac spinner

Figure 2 Schematic representation of the writing strategy

- a) single exel, single pass: designed linewidth=BSS
- b) n exel, single pass: designed linewidth=n*BSS, n=2 in the case shown

Figure 3 SEM image of 6.3 nm dots (with 125 pitch in the x direction and 100 nm pitch in the y direction) written in a 20 nm HSQ layer at 100 keV; the area dose was 556143 $\mu\text{C}/\text{cm}^2$

Figure 4 Dot size as function of the area dose written in 20 nm thick HSQ

Figure 5 Dot size as a function of the area dose written in 20 nm thick HSQ, when two different concentrations for TMAH are used: N=0.067 (triangles) and N=0.268 (squares)

Figure 6 Dot size as function of the area dose written in 20 nm thick HSQ, when two different developers are used: TMAH, 60 s; AZ 400K, 10 s

Figure 7 Sequence of SEM micrographs, showing 10 nm designed lines (8-exel, single pass exposure) exposed at 100 keV, with 4 different doses at a pitch of 150 nm; the sample was developed for 60 s with TMAH;

- a) area dose of $6976 \mu\text{C}/\text{cm}^2$ (line dose: $6.98 \text{ nC}/\text{cm}$); measured linewidth is 5.4 nm
- b) area dose of $25926 \mu\text{C}/\text{cm}^2$ (line dose: $25.93 \text{ nC}/\text{cm}$); measured linewidth is 8.7 nm
- c) area dose of $32775 \mu\text{C}/\text{cm}^2$ (line dose: $32.78 \text{ nC}/\text{cm}$); measured linewidth is 10.5 nm
- d) area dose of $296843 \mu\text{C}/\text{cm}^2$ (line dose: $296.8 \text{ nC}/\text{cm}$); measured linewidth is 40 nm

Figure 8 SEM micrographs of n-exel, single pass exposures (1.25 nm beam step size, 100 keV beam energy) written in a 20 nm thick HSQ layer at four different area doses

- a) 6-exel, single pass exposure with an area dose of $16223 \mu\text{C}/\text{cm}^2$ (line dose: 12.2 nC/cm); measured linewidth is 5.7 nm and the pitch is 120 nm;
- b) 4-exel, single pass exposure with an area dose of $17002 \mu\text{C}/\text{cm}^2$ (line dose: 8.5 nC/cm); measured linewidth is 5.5 nm and the pitch is 100 nm;
- c) 2-exel, single pass exposure with an area dose of $17818 \mu\text{C}/\text{cm}^2$ (line dose: 4.45 nC/cm); measured linewidth is 10.4 nm and the pitch is 75 nm;
- d) 1-exel, single pass exposure with an area dose of $27171 \mu\text{C}/\text{cm}^2$ (line dose: 3.39 nC/cm); measured linewidth is 7.8 nm and the pitch is 50 nm;

Figure 9 SEM micrographs of n-exel, single pass exposures (1.25 nm beam step size, 100 keV beam energy) written in a 10 nm HSQ layer at two different area doses. The pitch is 20 nm

- a) 2-exel, single pass exposure with an area dose of 70812 $\mu\text{C}/\text{cm}^2$ (line dose: 17.7 nC/cm); measured linewidth is 7 nm
- b) 4-exel, single pass exposure with an area dose of 36732 $\mu\text{C}/\text{cm}^2$ (line dose: 18.4 nC/cm); measured linewidth is 7.5 nm