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Sub-5 keV electron-beam lithography in hydrogen silsesquioxane resist

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ABSTRACT

We fabricated 9–30 nm half-pitch nested Ls and 13–15 nm half-pitch dot arrays, using 2 keV electron-beam lithography with hydrogen silsesquioxane (HSQ) as the resist. All structures with 15 nm half-pitch and above were fully resolved. We observed that the 9 and 10-nm half-pitch nested Ls and the 13-nm-half-pitch dot array contained some resist residues. We obtained good agreement between experimental and Monte-Carlo-simulated point-spread functions at energies of 1.5, 2, and 3 keV. The long-range proximity effect was minimal, as indicated by simulated and patterned 30 nm holes in negative-tone resist.

1. Introduction

Electron-beam lithography (EBL) at energies 30 keV and above is a well established method of fabricating sub-20-nm-pitch structures [1–4]. However, EBL at these high energies suffers from long-range proximity effects. Low-energy (sub-5 keV) EBL exhibits five key advantages over EBL at higher energies: (1) reduced dwell-time required for exposure (due to a higher resist sensitivity with only slightly reduced beam current) [5–7]; (2) lower system cost and a smaller footprint [7–9]; (3) significant reduction in long-range proximity effects [5,7,10]; (4) lower probability of sample damage and substrate heating [9]; and (5) more efficient delivery of energy into ultra-thin resists and self-assembled monolayers [11].

Previously, the finest pitch reported of adjacent lines fabricated at beam energies below 5 keV was 50 nm using calixarene [12], 60 nm using ZEP-7000 [12], 50 nm using poly-methyl-methacrylate (PMMA) [13], and 60 nm using hydrogen silsesquioxane (HSQ) [9,14]. This range of resolution is not sufficient for applications that require high throughput and high pattern resolution, such as photomask fabrication and multiple-electron-beam lithography for integrated circuits [7,9]. The key challenges to achieve high resolution at low electron energies are the reduced electron range, the increased broadening of the incident beam (forward-scattering), and larger minimum spot size. To overcome these limitations, our experiments were conducted with ultra-thin (~15-nm-thick) HSQ in conjunction with high-contrast development (contrast value, $\gamma = 10$) [15]. Monte-Carlo models of electron scattering at sub-5 keV [16,17] have never been tested at sub-20 nm length scales. The validity of low-energy exposure models are thus an important question in the field.

Here we report fabricating 9–30-nm-half-pitch nested Ls structures, and 13 and 15-nm-half-pitch dot arrays at electron energy of 2 keV. The dots at the corners of the 4 μm × 4 μm arrays showed minimal deviation in diameter, indicating minimal long-range proximity effect. Monte-Carlo simulations of the point-spread function (PSF) at low electron energies are in agreement with experimental results. To demonstrate the expected reduced long-range proximity effect, we exposed a 2 μm × 2 μm area in HSQ, leaving a small central region unexposed. This type of structure would be extremely difficult to realize (even with proximity-effect correction) at higher energies.

2. Resolution limit and dose requirements

The resolution of low-energy EBL is expected to be lower than that of high-energy EBL (e.g. 30–100 keV) due to increased electron scattering and generally larger spot size. In addition, the dose required to expose HSQ at low energies should also be much lower due to more efficient energy-transfer between the incoming electrons and the resist [6].

To experimentally determine the resolution limit of low-energy EBL, all samples were prepared by spin-coating HSQ (1% solids XR-1541, Dow Corning) on silicon wafers with native silicon dioxide at a spin-speed of 6.5 krpm. The resulting thickness was determined to be 15 nm using an ellipsometer. To avoid thermally-induced cross-linking of HSQ, which might lead to a loss in resolution, no pre-exposure bake was performed [15]. Unless stated otherwise,

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all exposures were carried out at an electron energy of 2 keV on a Raith 150 EBL system with a thermal-field-emitter source operating at 1800 K (~0.5 eV energy spread), a 20 μm aperture, 50 μm field size, a working distance of 6 mm and a beam current of 64 pA. After exposure, samples were immersed in salty developer [15] for 4 min at 24 °C, rinsed under deionized water for 2 min, and blown dry with nitrogen gas. The typical total processing period from spin coating to development was about 2–3 days. The fabricated structures were imaged by scanning-electron microscope (SEM) at 10 keV with ~6 mm working distance, and their dimensions were measured by image processing software (ImageJ).

Two designs of nested-L test structures, consisting of either five or seven single-pixel L-shaped-lines, were patterned in 15-nm-thick HSQ at half-pitches from 9 to 30 nm. Fig. 1 shows nested Ls at half-pitches of 9, 10, 15, 20, and 30 nm (the 15-nm-half-pitch structure was fabricated in a separate experiment). Although the 9- and 10-nm-half-pitch structures could be resolved, residual HSQ was present between the lines, and the single isolated lines washed away. On the other hand, structures patterned at 15, 20 and 30 nm half-pitches appeared to be fully developed.

As previously suggested [10], by using the ultra-thin resist we reduced the impact of forward scattered electrons, leading to higher resolution than seen previously [9,14]. In addition, the use of HSQ with high contrast development aided in achieving higher resolution. The minimum half-pitch observed (9 nm) coincided with the electron beam spot size (9 nm), which was measured previously in [4].

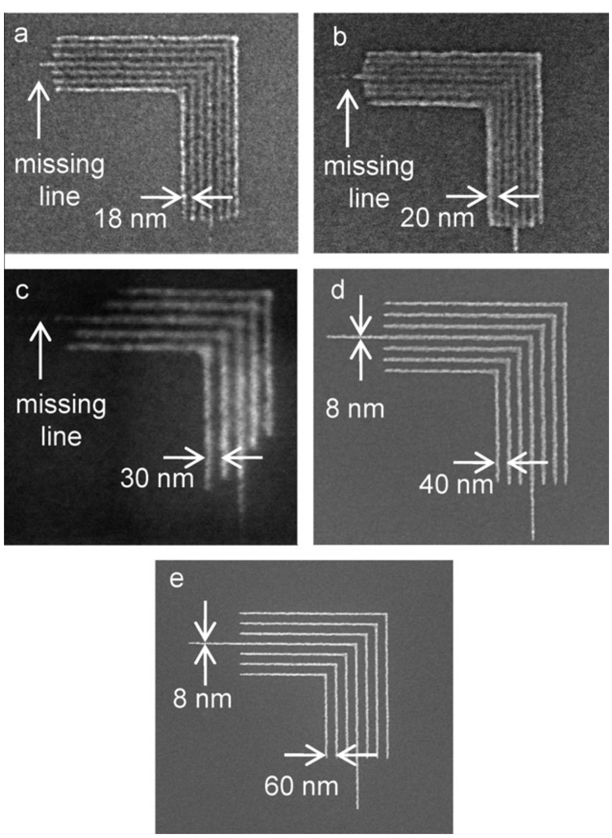

Fig. 1. Scanning-electron micrographs of nested Ls in 15-nm-thick HSQ exposed at 2 keV. (a) 9 nm half-pitch with a dose of 0.4 nC/cm (250 electrons/nm); (b) 10 nm half-pitch with a dose of 0.6 nC/cm (370 electrons/nm); (c) 15 nm half-pitch showing a clearly developed structure with a dose of 0.6 nC/cm (560 electrons/nm) (this experiment used cascading nested Ls); (d) 20 nm half-pitch with a dose of 0.9 nC/cm (560 electrons/nm); and (e) 30 nm half-pitch with a dose of 1 nC/cm (620 electrons/nm).

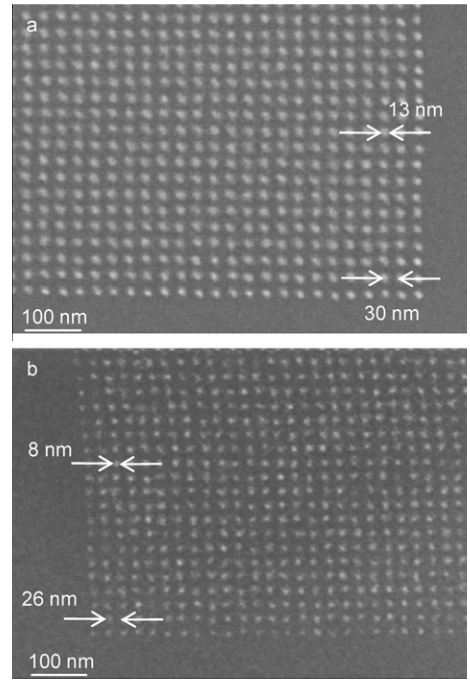

Fig. 2. Scanning-electron micrographs of a corner of a 4 μm × 4 μm dot array in 15-nm-thick HSQ, exposed at 2 keV. (a) 15 nm half-pitch with a dose of 2 fC/dot (12,000 electrons/dot) and (b) 13 nm half-pitch with a dose of 1.5 fC/dot (9300 electrons/dot). The small deviation (~12%) in dot diameter between the center and the corner of the array indicated minimal proximity effect.

To evaluate if we could maintain high resolution over large areas, we exposed 4 μm × 4 μm dot arrays on 15-nm-thick HSQ at 2 keV, with half-pitches of 15 and 13 nm (~1 Teradot/in.^{2} or ~0.15 Teradot/cm^2), as shown in Fig. 2a and b, respectively. A small amount of residual HSQ was present between the 13-nm-half-pitch dots, and the dots had considerable variation in diameter. In contrast, the dots in the 15-nm-half-pitch array were uniform and without apparent residual HSQ between the dots. The dots at the corner of the array showed only minimal size deviation (~12%), demonstrating that the long-range proximity effect was minimal, as expected.

Patterning the same structures as shown in Fig. 1 at 30 keV required 6.4 (4000 electrons/nm) to 16 nC/cm (9900 electrons/nm), which is roughly 16 times higher than what was required at 2 keV. Similarly, the dot array with 26-nm-pitch in Fig. 2b required 1.5 fC/dot (9300 electrons/dot) at 2 keV and 18 fC/dot (110,000 electrons/dot) at 30 keV; about 12 times higher.[1] The increased resist sensitivity at low energies may pose problems for more sensitive resists such as PMMA by causing shot noise and increased line-edge roughness [18].

3. Proximity effect

In high-energy (e.g., 30–100 keV) EBL, a large background dose extends over several micrometers, due to back-scattered electrons. This long-range proximity effect is expected to be much less severe at low-energies due to the shorter electron range. However, this expectation has never been verified at length scales smaller than 50 nm, which is of ever-increasing importance in direct-write lithography.

[1] The dose comparisons made here, at 2 and 30 keV, are regarding single-pixel lines and single-dot exposures. This type of single-pixel exposures would require more dose than aerial exposures, due to the concentrated electron distribution at the center of these structures.