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1993 Semicond. Sci. Technol. 8 1490

(http://iopscience.iop.org/0268-1242/8/7/049)

Semicond. Sci. Technol. 8 (1993) 1490–1492. Printed in the UK

LETTER TO THE EDITOR

Low-energy electron beam lithography with 30 nm resolution

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Received 5 April 1993, accepted for publication 26 April 1993

Abstract. Electron beam lithography (EBL) with a low accelerating voltage (~ 2 kV) was utilized for the fabrication of nanostructures. A resolution of 30 nm was achieved for both sparse and dense lines. The high resolution resulted from the low aberrations of the electron optics system of the field emission scanning electron microscope used as an EBL machine and from the preferred small-angle forward scattering characteristic of the low-energy exposing electrons. By comparison with 50 kV EBL, we show a large reduction in the proximity effect and demonstrate a 60 nm spacing between two large exposed areas. Moreover, it is shown that the critical dose at 2 kV is more than an order of magnitude less than that at 50 kV exposures.

Smaller devices allow higher speed and density of circuits. For device dimensions smaller than the electron mean free path (MFP) experimental research shows dominant quantum mechanical phenomena. Exploration of this quantum regime has increased the need for high-resolution lithography techniques. Among them, electron beam lithography (EBL), one of the highest resolution lithography methods, is used for direct writing on wafers and for fabrication of photolithography and x-ray masks.

Most commonly, high-energy electrons are used for exposure because they provide high resolution and weak sensitivity to electromagnetic interference and chromatic aberrations. However, EBL with a high accelerating voltage suffers from (*a*) low throughput due to the small amount of energy dissipated in the resist compared with the total energy of the primary electrons [1], and (*b*) proximity effects, resulting from the scattering of electrons at large angles in the resist, making the writing of dense patterns almost impossible without dose compensation (which requires expensive computer modelling). These drawbacks can be rectified by using low-energy EBL [2-7].

The use of low-energy electrons (of the order of 1.5-2 keV) for lithography has a number of advantages. (*a*) When the electrons' energy is low their MFP is small relative to the resist layer thickness [8]. This will result in electrons losing most of the energy in the resist layer (after a relatively small number of collisions), thus increasing the exposure efficiency (or the resist sensitivity). (*b*) At low energies electron–electron interactions are the dominant scattering events (not Rutherford scattering from screened nuclei). Thus the well known mechanism of beam broadening, which occurs for high-energy electrons, is not valid [9], and their narrow energy distribution in the resist [1, 2, 10] leads to a dramatic reduction in the proximity effect. (*c*) Only a small fraction of the total number of electrons will reach the substrate, thus decreasing the probability of causing damage to sensitive devices [3]. (*d*) Other advantages are the high dose tolerance [2, 3] and a reduced dependence on the substrate material [2].

In recent papers the high sensitivity and reduction in the proximity effect in low-energy EBL have been clearly demonstrated [2, 3, 4, 6, 11], but the best reported resolution was only some 90 nm [2], which is considerably worse than that for high-energy EBL and might not be sufficient for nanofabrication of quantum devices.

The purpose of the present work is to investigate the ultimate resolution of low-energy EBL and to study the different factors influencing the resolution and proximity effect. A comparison of exposures of 'standard proximity patterns' with electrons at 2 kV and 50 kV is presented and the advantages of low-kV EBL are clearly demonstrated.

A JEOL 6400F scanning electron microscope (SEM) was used as the electron beam writing machine by interfacing it with a computer using a custom-made low-noise 4 MHz vector scanning controller of 14 bit resolution and a fast, retractable, beam blanker. In this work we have used 80 μm scanning field. The beam blanker was designed with a variable blanking plate spacing in order to minimize electron beam distortions over a wide

0268-1242/93/071490 + 03 $07.50

range of accelerating voltages (1.5–30 kV). The resolution of the SEM for the low voltages (1.5–2 kV) was about 5 nm as measured on a standard gold–carbon sample, thus demonstrating the high focusing ability of the system. Additional measures were taken to minimize vibration levels and magnetic interference.

A conductive GaAs sample was used as the substrate in order to avoid charging problems (which could be clearly seen when a semi-insulating substrate was used). Two kinds of electron-sensitive resists were used: a single layer of 360K molecular weight PMMA, 45 nm thick, and a double layer 150K/360K resist, 70 nm thick. Typical exposure currents were a few pA. Exposures were done at a working distance of 7–8 mm. The exposures at 50 kV were made with a JEOL JBX-5FE EBL machine. After exposure the samples were developed in MIBK:IPA 1:3. For the fine patterns a 'lift-off' process of evaporated Ti/Au or Ni/Au was performed after the resist had been developed.

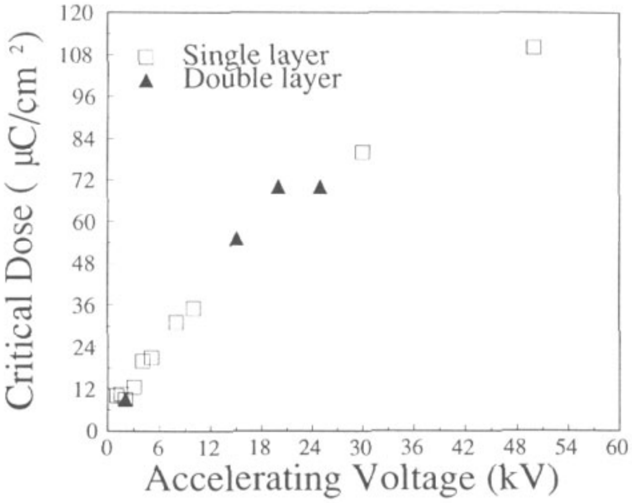


Figure 1. The critical dose as a function of beam accelerating voltage for single layer resist (squares) and double layer resist (triangles).

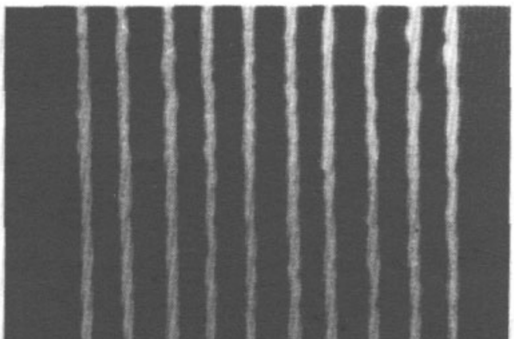


Figure 2. SEM micrograph of a series of metal lines, 30 nm wide separated by 80 nm centre to centre. The lines were exposed by a 2 kV electron beam on a single layer resist, 40 nm thick.

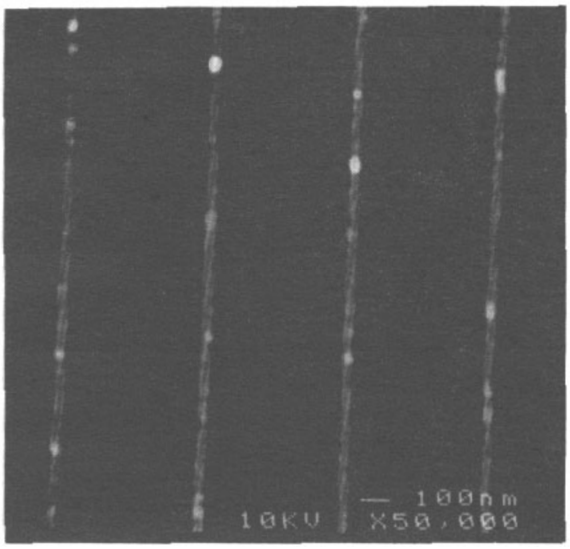


Figure 3. SEM micrograph of isolated lines 35 nm wide exposed by a 2 kV electron beam on a double layer resist, 70 nm thick.

The critical exposure dose was measured for accelerating voltages in the range 0.9–50 kV. This was done by exposing large resist areas with a wide range of doses at different accelerating voltages and plotting the thickness of the remaining resist after development as a function of the dose for each accelerating voltage. As can be seen in figure 1, the reduction in the critical dose, from 50 kV to 2 kV, is by more than an order of magnitude (110 μC cm^{-2} at 50 kV; 9 μC cm^{-2} at 2 kV).

To demonstrate the resolution of our process we patterned on a single layer resist, via lift-off, a series of

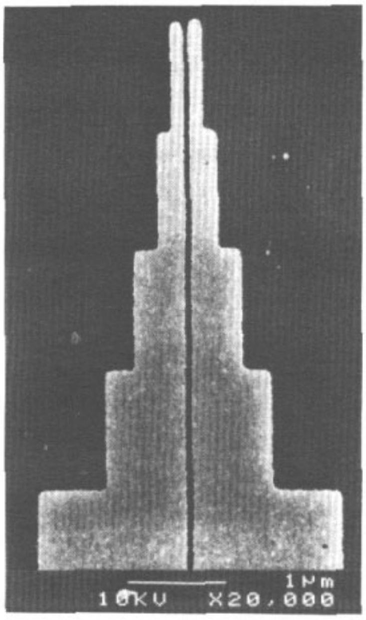
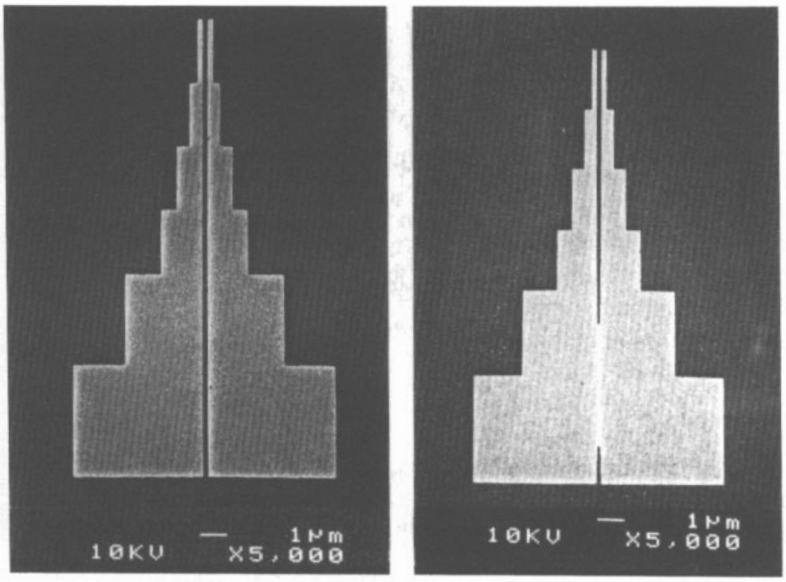


Figure 4. SEM micrograph of a 'standard proximity pattern' of two large exposed areas (shown via the lift-off pattern) separated by a nominal 60 nm spacer exposed by a 2 kV electron beam. The spacer is not affected by the size of the exposed areas.



(*a*) (*b*)

Figure 5. SEM micrographs of a 'standard proximity pattern' with a nominal 200 nm spacer exposed by (*a*) a 2 kV electron beam; (*b*) a 50 kV electron beam.

metal lines as seen in figure 2. The linewidth is as small as 30 nm and the periodicity is 80 nm (centre to centre). No difference between the width of an isolated line and a group of lines was observed. Isolated lines 35 nm wide were also obtained for the double layer resist (figure 3). The resolution we achieved is close to that achieved in exposures with 50 kV electrons. These results suggest that the poorer resolution reported previously [2, 4] had been caused, most probably, by technical reasons rather than by fundamental limitations of the low-voltage electron exposure. This is a clear demonstration that the scattering of low-energy electrons within the resist layer, probably via electron–electron interactions, leads to fast energy loss without meaningful change in the original electron direction.

The proximity effect was tested with a standard proximity pattern with a 60 nm spacer between two large areas exposed by 2 kV electrons. The results, shown in figure 4, show that the spacer width is not affected by the size of the exposed areas nearby. Since this spacer is too narrow for high-energy exposure, the same proximity pattern, but with a 200 nm wide spacer between the large areas, was exposed at 2 kV (figure 5(*a*)) and at 50 kV (figure 5(*b*)). As seen in figure 5(*b*), for exposures made at 50 kV the 200 nm nominal spacer is getting smaller as the size of the exposed areas increases. This shows that even at moderately high accelerating voltages, where the background exposure due to backscattered electrons is expected to spread across a very large area and hence be small, the proximity effect still poses a major problem. By comparison, the areas exposed by 2 kV electrons show no sign of the proximity effect.

To summarize, the method of low-kV EBL has been utilized for exposing nanostructures using a modified scanning electron microscope. The resolution achieved with low-energy electrons (2 kV) is found to be about 30 nm for both isolated and dense lines. The critical dose is shown to be more than an order of magnitude less at 2 kV than at 50 kV. The elimination of the proximity effect at these low energies is demonstrated by exposing two large areas separated by 60 nm. Features of that type cannot be written without special proximity corrections even at voltages as high as 50 kV. The ability to achieve such small features can be related to the high focusing ability and low noise of our experimental system and to the forward nature of the scattering mechanism of the exposing low-energy electrons in the resist mask.

We would like to thank D Levy for suggesting the experiment and for helpful discussions. The work was partly supported by a grant from the Ministry of Science, #5408.

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