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A simple electron-beam lithography system

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Abstract

A large number of applications of electron-beam lithography (EBL) systems in nanotechnology have been demonstrated in recent years. In this paper we present a simple and general-purpose EBL system constructed by insertion of an electrostatic deflector plate system at the electron-beam exit of the column of a scanning electron microscope (SEM). The system can easily be mounted on most standard SEM systems. The tested setup allows an area of up to about 50 × 50 μm to be scanned, if the upper limit for acceptable reduction of the SEM resolution is set to 10 nm. We demonstrate how the EBL system can be used to write three-dimensional nanostructures by electron-beam deposition.

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Keywords: e-Beam lithography; Electron optics; SEM; Electron-beam deposition; Electron-beam-induced deposition

1. Introduction

In recent years electron-beam lithography (EBL) has become a commonly used technique for defining nanostructures, often combined with traditional photolithography for patterning of larger surrounding structures. EBL-defined contacts to both carbon nanotubes [1,2] and semiconducting nanowires [3,4] have enabled a systematic investigation of the electrical properties and creation of high-performance field-effect transistors. Furthermore, resist-based EBL techniques have been employed in the fabrication of nanomechanical structures, such as the carbon nanotube-based rotational actuator demonstrated by Fennimore et al. [5]. In addition to the resist-based EBL technique, electron beams can be used for constructive lithography, such as electron-beam deposition (EBD). Here, organic or organometallic vapors added to the specimen chamber are decomposed by the electron beam, leading to the formation of three-dimensional nanostructures, which in some cases can be conductive. The EBD metal deposition technique has been employed for fabrication of three-dimensional devices made

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entirely of electron-beam-deposited material [6,7], and for soldering of carbon nanotubes using nanoscale deposits with a high gold content [8,9].

Commercial EBL tools are either complete systems or additional options to an SEM. However, even an add-on system can be a significant expense in an experimental budget, which would be out of proportion if the needs are occasional, basic experimental applications.

In this paper we present a simple low-cost EBL system that meets the requirements for range and precision needed to write nanoscale contacts or interconnects between microelectrodes defined by standard lithography. The system is an electrostatic deflection system inserted into the specimen chamber above the sample. This solution is particularly convenient when the electron microscopes do not have direct external connections for beam control in the column, as is often the case. Electrostatic control of charged particle beams has proven to have several advantages over magnetic beam control in some systems [10]. Complex all-electrostatic systems have been built, such as storage rings for charged particles [11] and miniature electron microscopes [12]. Electrostatic beam deflection is also used in some EBL systems [13,14].

To obtain the highest possible resolution, defocusing and astigmatism introduced by the EBL system should be minimized. For instance, the EBL system JBX-9300FS from JEOL uses a combination of electrostatic quadrupole and octopole beam deflectors. A highly harmonic potential can be achieved by choosing an electrode geometry similar to the design of a quadrupole mass spectrometer (or linear Paul trap) [15]. This also allows a simple and short deflector design, providing a short working distance that is essential for high image quality in an SEM.

2. Theory

The SEM-based EBL system presented here is based on an electrostatic deflector plate system consisting of four electrodes placed inside the SEM specimen chamber, around the beam where it exits the column. With the SEM in "spot" mode, the deflector plate system will fully control the beam position.

An illustration of the design is shown in Fig. 1. Calculations by Denison [16] show that if the rod diameter d_e and diagonal inter-rod distance d_d are chosen to be $d_e/d_d = 1.147$, the leading term of the deviation from the harmonic potential will be of the order of $(r/d_d)^{12}$, where r is the distance from the center of the deflector plates.

If a voltage $\pm\frac{1}{2}U$ is applied to two diagonally opposed rods, while the other two are kept at ground potential, the electrical field, $E = U/d_d$, will be constant and the electron beam will be deflected a distance D from the center given by

$$D = \alpha \frac{L\left(\frac{1}{2}L + L_{\mathrm{free}}\right)}{2d_d}\frac{U}{V} = C\frac{U}{V}, \tag{1}$$

where L is the rod electrode length, L_{free} is the length from the end of the rods to the sample, V is the electron-beam acceleration voltage, and α is a coefficient accounting for edge effects due to the finite length of the rods. The deflection distance D is seen to be proportional to U/V with C denoting the proportionality constant. The coefficient α is expected to be about 1. If needed, α and higher-order corrections can be found by simulations of

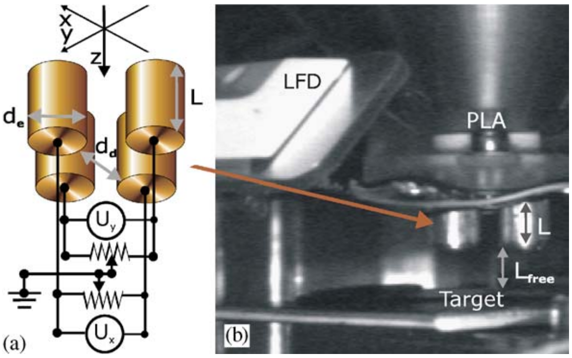

Fig. 1. The EBL setup. (a) Diagram of the four rod electrodes with the electron beam oriented along the rods. Voltages for scan in the x and y directions are applied to the electrodes through potentiometers for minimization of astigmatism. (b) Image of the deflector setup mounted in an ESEM. The system is here mounted onto the pressure limiting aperture (PLA), where the e-beam exits the column. The rod length L and distance L_{free} from the end of the rods to the target, are marked in the figure. To the left, a LFD is visible.

the electrical field in the device. Using the values $U = 10\,\mathrm{V}$, $V = 10\,\mathrm{kV}$, $d_\mathrm{e} = 5\,\mathrm{mm}$, $d_\mathrm{d} = 4.3\,\mathrm{mm}$, $L = L_\mathrm{free} = 5\,\mathrm{mm}$, and $\alpha \approx 1$, we find $D \approx 3\,\mu\mathrm{m}$ corresponding to a $6 \times 6\,\mu\mathrm{m}$ scan area. Since standard photolithography typically has a resolution of $1\,\mu\mathrm{m}$, this scan range is sufficient for fabricating nanostructures that interface microelectrode structures, and for refining microstructures as needed in many research applications [17].

The maximum obtainable scan range is limited by the deflection voltages that can be applied to the electrodes without inducing serious astigmatism and defocusing effects. A straightforward method for verifying that such effects are not present is to observe the image resolution while applying deflection voltages. Depending on the specific setup and the detector type, there will also be different upper limits to the deflection voltages that can be applied without degradation of the image contrast, since the charged electrodes will tend to deflect the low-energy electrons away from the detection system. In preliminary tests, a standard Everhart–Thornley detector in a Leo 1550 SEM showed no significant effects on the image quality with deflection voltages up to 75 V, while the large field detector (LFD) in a Phillips XL-30 FEG Environmental SEM (ESEM) sets an upper limit for the deflection voltage of about 25 V.

3. SEM experiments

The deflector plate system shown in Fig. 1a was built using brass rod electrodes with $L = 6\,\mathrm{mm}$, $d_\mathrm{e} = 5\,\mathrm{mm}$, and $d_\mathrm{d} = 4.3\,\mathrm{mm}$, mounted on a polycarbonate plate. The dimensions of the system were machined to about 0.1 mm precision. The deflector system was mounted on a small rod above the sample on the stage in a LEO 1550 SEM.

The stage was used to center the deflection system around the beam. With an applied deflection voltage on the EBL system, no noticeable dependence of the image quality on the position of the system relative to the beam was observed within about 10% of d_d from the center of the system. With the deflector system centered, and the electrodes grounded in one direction, the maximum voltage that would allow proper imaging was applied in the other direction. The astigmatism was then minimized by adjusting one of the potentiometers shown in Fig. 1a, thereby compensating for slight misplacements and other imperfections in the setup. Then the same procedure was followed for the other potentiometer. The test showed a resolution of about 20 nm at $U = 0\,\mathrm{V}$. After potentiometer optimization at $U = \pm 75\,\mathrm{V}$, which gave rise to a displacement $D = \pm 90\,\mu\mathrm{m}$ (at $V = 10\,\mathrm{kV}$ and $L_\mathrm{free} = 13\,\mathrm{mm}$), the resolution was about 40 nm. From the displacement the correction factor α in Eq. (1) can be estimated to $\alpha \approx 1.1$.

To compare our system with commercial EBL systems, one should consider both the resolution requirements and the achievable scan range. In resist-based EBL the resolution is often limited to roughly 10 nm. The resolution of our EBL system is limited by the inherent resolution of the SEM electron-beam, as well as by the loss of resolution of the beam due to the deflection system. The latter appeared to be roughly proportional to the deflection voltage and thereby the scan range. Based on the preliminary test, a scan range of about $90\,\mu\mathrm{m}$ ($\pm 45\,\mu\mathrm{m}$ deflection) can thus be obtained with less than 10 nm reduction of the SEM resolution.

The lithography system can be controlled via a standard DAQ card. For electron-beam exposure of resist, the dwell time precision can be as low as 10 ns per pixel in raster scans. This requires the DAQ card to sustain sampling rates up to 100 MS/s. EBD demands much higher doses and dwell times, requiring less than 100 S/s. The DAQ-card resolution must be of the order of 10 mV/bit on two channels to support 10 nm precision of the beam position in two dimensions. If a beam blanker is available in the SEM, one could use an extra DAQ-card channel to control it. We use a National Instruments 1200 DAQ card in a laptop PC. Direct driving of the system with the DAQ card limits the applicable voltage to 10 V, which is compatible with the contrast requirement of the ESEM detection system in our setup. The 16-bit resolution gives a 0.15 mV/bit corresponding to a resolution of 0.15 nm, which is much smaller than the resolution of the ESEM.

4. ESEM results and discussion

For the EBD experiment, the deflector system was mounted onto the pressure-limiting aperture of a Philips XL-30 FEG ESEM, as shown in Fig. 1B. Despite the relatively coarse manual alignment no influence on deflection and induced astigmatism was observed when the system had been removed and reinserted between the experiments. This is in accordance with our observations in the preliminary test.

The deflection as a function of voltage for the EBL system was calibrated by EBD using a source containing dimethylacetylacetonate gold(III) inserted into the specimen chamber of the XL-30 ESEM. First, a reference marker was deposited with all electrodes at ground potential. Next, a marker was deposited with an applied deflection voltage from a power supply. Such sets of markers were deposited at a series of deflection voltages, and for each set the deflected distance was measured. Fig. 2a presents the obtained deflection distance versus deflection voltage for electron-beam acceleration voltages of 5, 10 and 20 kV. A linear dependence was seen for all tested acceleration voltages. Linear fits give the proportionality factors 0.52, 0.30 and 0.16 μm/V, respectively. In Fig. 2b the proportionality factors from Fig. 2a are shown versus inverse acceleration voltage. A linear fit gives the parameter $C = 2.7(1)$ mm in accordance with the theory if $\alpha = 0.73$.

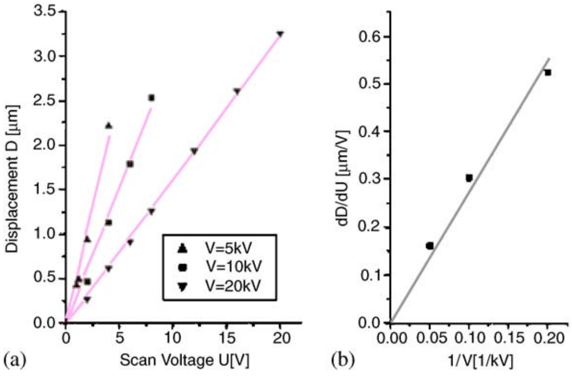

Fig. 2. Calibration of the EBL system. (a) Beam deflection versus applied voltage for electron-beam acceleration voltages of 5, 10 and 20 kV. Linear fits give the proportionality factors 0.52, 0.30 and 0.161 μm/V, respectively. (b) Proportionality factors from Fig. 2a versus reciprocal acceleration voltage, indicating a linear dependence as expected from theory.

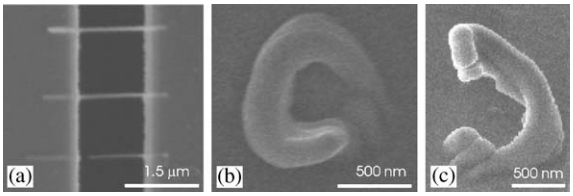

Fig. 3. (a) ESEM image showing EBD lines deposited as bridges between microcantilevers using the lithography system. (b) SEM image showing a top view and (c) side view of an electron-beam-deposited spiral structure obtained with the computer controlled x–y scan.

Several three-dimensional test structures were deposited using the system, as shown in Fig. 3. Conducting interconnects making horizontal bridges between microcantilevers [18] were deposited at scan speeds of up to 30 nm/s. The line width was measured to be 60–200 nm, decreasing with scan speed, and comparable to the line width obtained for deposits fabricated without the EBL system [9]. The conductivity of the deposited material has been measured to be 1–2 orders of magnitude lower than pure bulk gold.

The spiral-like structure in Fig. 3b and c was deposited using a circular scan at a low scan speed of 10 nm/s. The structure is not perfectly circular since carbon contamination accompanying EBD in an ESEM deforms the already deposited parts of the structure, when exposed to electron radiation. A more detailed study of the environmental EBD process in three dimensions can be found in Ref. [18].

5. Conclusion

A simple EBL system can be made by inserting a small electrostatic quadrupole deflection system into a standard SEM. The reduction of the SEM resolution caused by the EBL system increases with the applied deflection voltage, and is of the order of 10 nm within a 50 μm scan range in the tested system. Although the scan range of commercial EBL systems are typically an order of magnitude larger, this combination of scan range and resolution is adequate for many research applications, and few standard SEM-based EBL systems offer minimum precision below 50 nm. For electron-beam nanolithography, dwell times in the sub-microsecond range are often required, demanding very rapid movement of the beam. Due to the lack of inductance in the system, the deflection speeds should primarily be limited by the bandwidth of the DA converters. However, exposure of nanoscale patterns in a resist film is yet to be demonstrated.

We point out that the EBL system presented here is straightforward to construct and install, and that results competing with results from far more complex and expensive setups can be obtained. If required, the tested system could be improved considerably both in terms of shielding against electrical noise, prevention of charging of the plastic parts, and tighter tolerances on the mechanical parts.

The presented system is ideal for EBD experiments, when using LabView-controlled DAQ cards without amplification electronics for pattern generation and beam control. The setup gives a high degree of flexibility to make customized solutions for experiments where full-beam control is advantageous, besides providing a straightforward path to resist-based EBL. We expect this post-column deflection system to be valuable for both scientists and students in making full-control EBL available to a wider range of laboratories.

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