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E-beam lithography for micro-/nanofabrication

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Electron beam lithography (EBL) is one of the tools of choice for writing micro- and nanostructures on a wide variety of materials. This is largely due to the fact that modern EBL machines are capable of writing nanometer-sized structures on areas up to mm^2. The aim of this contribution is to give technical and practical backgrounds in this extremely flexible nanofabrication technique. © *2010 American Institute of Physics.* [doi:10.1063/1.3437589]

I. INTRODUCTION

Electron beam lithography (EBL) is one of the key fabrication techniques that allow us to create patterns at the nanoscale. The development of EBL tools started in the late 1960s (Ref. 1) by modifying the design of scanning electron microscopes (SEMs). The EBL working principle is relatively simple and very similar to photolithography: A focused beam of electron is scanned across a substrate covered by an electron-sensitive material (resist) that changes its solubility properties according to the energy deposited by the electron beam. Areas exposed, or not exposed according to the tone of the resist, are removed by developing. Since the discovery of polymethylmethacrylate (*PMMA*) as an electron resist by Hatzakis[2] in 1969, EBL has been used for fabricating a wide variety devices, ranging from integrated circuit production,[3–5] to photonic crystals,[6–9] to channels for nanofluidics experiments.[10,11] In order to give the reader a basic understanding, this contribution is organized in three parts. In Sec. II, a brief description of a typical EBL system is presented, while Sec. III explains the jargon and outlines the steps involved in obtaining a pattern. Section IV will present a simplified worked example on the basis of what has been discussed throughout the paper. It is assumed that the reader has a basic knowledge of standard photolithographic processes (for a review, see, for example, Chapter 1 of Ref. 12).

II. EBL SYSTEMS

It is possible to identify two main categories of EBL systems, according to how the electron beam is scanned, as schematically shown in Fig. 1. A third category, involving at the moment mostly experimental systems, has the electron beam projected to the substrate through different types of stencils.[13] The discussion in this paper will be limited to Gaussian beam tools, for several reasons; in particular, they are overwhelmingly the most common in academic nanofabrication environment, they are arguably the most flexible for research purposes, and they provide with the highest spatial resolution, below 5 nm.[14]

A typical EBL system closely resembles a SEM. The main difference between a SEM and an EBL is that in an EBL the beam is scanned onto the sample according to the instructions coming from the pattern generator, while in a SEM the beam is raster scanned over the sample in order to collect secondary electrons to form an image. As shown in Fig. 2, an EBL schematically consists of a chamber, an electron gun, and a column. Column and chamber are maintained in high vacuum by a suitable set of pumps. The column contains all the electron optical elements needed to create

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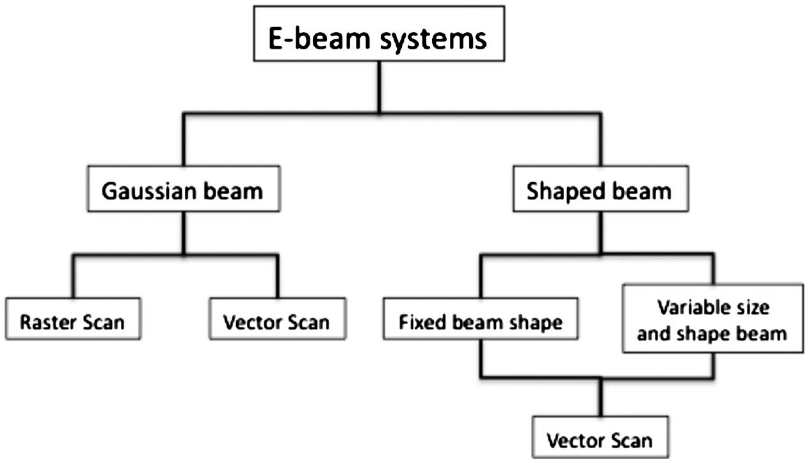

FIG. 1. Classification of EBL systems according to beam shape.

a beam of electrons, to accelerate it to the working voltage, to turn it on and off, to focus, and to deflect it as required by the pattern to be written. The samples are normally loaded via a loadlock into the main chamber and are typically placed on an interferometric stage for accurate positioning of the working piece. Figure 2 does not show the computing system, the pattern generator, the operator interface, and all the electronics needed to control and operate the machine. Due to the close similarity between a SEM and an EBL, SEM columns are routinely converted into lithographic systems.[15,16] Some suppliers of EBL tools are those in Refs. 17–19.

The maximum acceleration voltage is one of the major difference between converted SEMs and EBLs. While the first typically can work up to 30 kV, the latter operate at up to 100 kV. Typically, the price difference existing between an EBL and a converted SEM is about a factor of 2: An EBL costs above \$2 000 000 while a converted SEM can be purchased around the \$1 000 000 mark. The price difference is justified by several technical solutions that render ma-

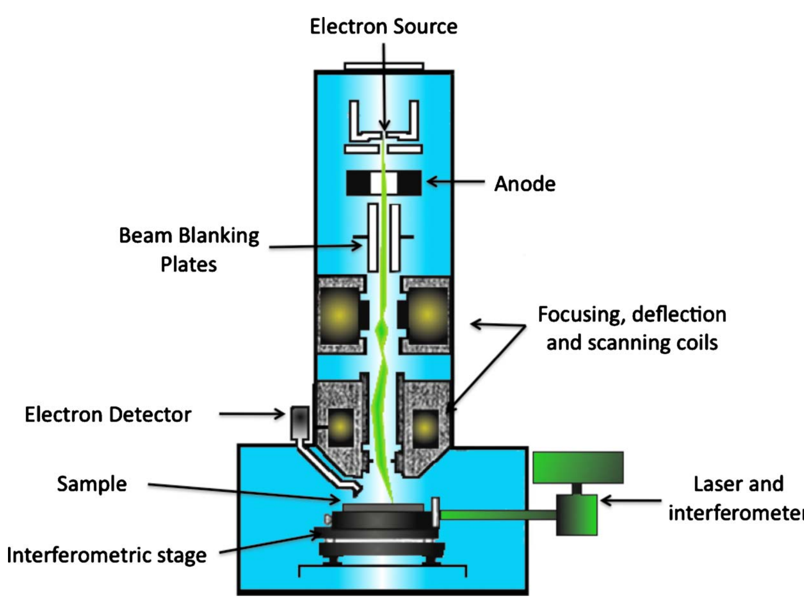

FIG. 2. A typical EBL system, consisting of a chamber, an electron gun, a column containing all the electron optics needed to focus, scan, and turn on or turn off the electron beam.

chines specifically designed for lithography far superior, in terms of lithographic performances, to converted SEMs. Nonetheless, converted SEMs are a cost-effective solution for having access to such a patterning tool.

III. TERMINOLOGY AND CONCEPTUAL WORKFLOW

Before having a closer look to each of the steps practically involved in EBL, and in order to avoid confusion, it is necessary to introduce some of the terminology used in the field.

Writing field: It is the largest area exposed without the stage moving, with typical dimensions ranging from few tens of microns to few millimeters. Field size is typically decided by the operator and its choice is a trade off between minimizing stage movements and obtaining the required resolution from the system.

Exposure element: Each writing field is subdivided in a fixed number of exposure elements (*EXELs*), determined by the specific main Digital to analog converter (DAC) mounted on each tool; therefore smaller fields allow for better definition of finer features. For example, a 15 bit DAC subdivides each field into a writing grid of 32 768 EXELs *per side*, meaning that for a 327.68 μm field, the EXEL dimension is 10 nm.

Stitching: If the pattern dimensions are such that the exposure needs more than one writing field, the fields are *stitched* together via stage movements. The accuracy of stitching depends on the quality of the stage, with interferometrically controlled stages giving a generally better result than mechanical ones, on the stability of the system and its environment (i.e., temperature, humidity and acoustic noise control), and also on the specific software implemented, which can compensate different types of drifts.

Exposure dosage: It is the amount of energy deposited per unit area. Since the acceleration voltage and the electron beam current are fixed during a single exposure, the dosage is actually measured in terms of current deposited per unit area, μC cm^{-2}. The dosage at which each exposure is run depends chiefly on the resist used, and the density and dimension of the pattern being written.

System clock: It is also called writing speed. It is the inverse of the time the beam dwells on an EXEL, for example, 47.832 MHz or 500 kHz. The higher the clock number, the faster the exposure. Each tool is characterized by its maximum writing speed, which depends on the hardware mounted on the machine itself. Top speed for commercial systems range from 1 to 50 MHz. For example, the beam on a machine running at 10 MHz (10^7 s^{-1}) with an EXEL of 1 nm (10^{-9} m) moves at 10 mm/s.

Proximity effect: Due to the fact that electrons undergo multiple elastic and inelastic scattering events once in the substrate, a finite amount of energy is deposited microns away from the desired area.[20] This gives rise to unwanted features/geometries revealed upon development. Proximity effects can be corrected by using specifically developed software. Higher acceleration voltages help in reducing proximity effects.

Beam current: It defines how many electrons are impinging on the sample each second. Its value affects the maximum obtainable resolution; as due to space charge density issues, a high current electron beam tends to be physically larger than a small current one. Typically, high resolution work is done with currents ranging from 0.05 to 0.5 pA.

The logical and practical steps needed for obtaining an EBL patterned sample depend on the specific system used for patterning, particularly in regard to data conversion, as this might be done *on the fly* and automatically right before the exposure. In general, the process flow is outlined in the following.

A. Conceptual design

Before starting any work in the laboratory, the final device must be designed. As a general rule, it is important to define precisely the final geometry and to establish clearly the critical and overall dimensions of the final device. This information translates into what writing field and what beam current are needed. It is important to consider the EBL step in the context of the full processing needed for fabricating the final device, as this may affect the choice of resist type and tone, dosages, sacrificial layers deposition, and so on. At the end of this phase, the full set of parameters for the whole device fabrication should be clear.

B. CAD design

The pattern to be exposed is designed via a suitable CAD package. The industry-accepted format of such a design is a GDSII file[21] and most of the available CAD packages are able to produce files in GDSII format, even if the software might not handle GDSII files internally. There are several options available, both free and for sale—see, for example, Refs. 22–25.

C. Conversion and proximity correction

A process called *fracturing* is necessary before exposure. During this process, a proprietary software converter translates the GDSII data into a machine-exposable file, which contains all the instructions needed by the pattern generator to direct and scan the beam as required by the pattern data file. In order to correct for proximity effect, a software is run over the data file, correcting the exposure dosages according to a physical model implemented into it. Proximity correction is not always required for EBL exposures, as operator experience can sometimes compensate for proximity effect. Also, the very nature of the pattern might render the correction unnecessary. Once the data file has been converted and processed for proximity effect (if needed), it is transferred into the memory of the pattern generator.

D. Sample preparation

Preparing a sample for EBL requires attention, as the desired features are below 100 nm in dimension. This requires working in a clean environment, International Standard Organization (ISO) class 5 or better, and careful handling of the specimen in all the preparation and subsequent phases. Due to the limited depth of focus of the electron beam (few microns), substrates for EBL must have a flat surface, which in turn must be perfectly perpendicular to the incoming beam. This is achieved by using carefully machined sample holders, where the sample is retained by kinematic mountings. Some systems allow for sample's surface height correction (measured via a laser beam) but this applies in a range of about $\pm 50\ \mu m$. A typical sample preparation procedure is outlined below:

(1) cleaning in warm acetone (45–50 °C for 5 min);
(2) rinse in cold acetone quickly followed by rinse in isopropyl alcohol (*IPA*);
(3) blow dry under nitrogen;
(4) resist deposition and baking.

The resist should have been chosen in the conceptual design phase so as to comply with the requirements of the subsequent fabrication steps. Since during e-beam lithography samples are heavily irradiated by a finely focused beam of energetic electrons, they require electrical grounding in order to avoid charging effects that would result in loss of patterning accuracy. Insulating substrates can be successfully exposed by depositing a thin metal layer, typically Al or Au, 10–30 nm thick, either between the substrate and the resist layer or on top of the resist. Once the sample is ready, it is mounted on the sample holder, which in turn is transferred into the vacuum chamber, ready for exposure.

E. Machine calibration

In order to successfully perform the desired exposures, the tool must be carefully calibrated. A calibration sequence involves checking gun and column alignment, calibrating the writing field, setting up the beam current, and adjusting beam focus and astigmatism. Some tools perform all the calibrations automatically, following either commands from the operator or sequences specified in batch files, while others need input, i.e., the beam has to be adjusted manually, and confirmation and/or correction of measurements have to be made by the operator. It is critical that every machine parameter is checked and in the optimal range for the exposure to be successful.

F. Exposure

The exposure is then launched. The EBL software can normally take care of separating the pattern in different writing fields, if so required, and automatically moving the stage in the required positions. Many modern EBL machines allow for exposures to be programed in so-called job files. This automation allows writing for prolonged periods of time, up to the order of days, without direct operator intervention into the process, in order to expose, for example, a full 5 in. diameter quartz mask.

G. Development

The development process is critical for controlling the fine features that are printable via e-beam. It is of paramount importance to carefully control the developing solution temperature, as repeatability is strictly related to how tight the control on the development temperature is. Ultrasound agitation sometimes proves useful during development,[26] but this has to be carefully considered against all the other process parameters.[27]

It is important to note that some of the concepts just explained might vary slightly according to the specific brand of tool. Nonetheless the reader should have now an idea about EBL jargon and the that is accurate enough to start working with.

IV. EXAMPLE

A series of 1000 nanochannels, each 80 nm wide and 300 nm deep, spaced by 1 μm and 1 mm long and made in resist, has to be EBL written for nanofluidics purposes on a silicon wafer. The total dimensions of the pattern are therefore $1000 \times 1000\ \mu m^2$. The EBL system available has a main DAC with a 16 bit capacity, runs at 100 kV, and is equipped with an interferometric stage. Given the DAC capacity, the main writing field is divided into $2^{16}=65\,536$ EXELs per side. In order to have a reasonable definition of the channels, at least ten EXELs are needed. Thus, the maximum acceptable EXEL size is 8 nm, meaning that the writing field is $8\ \text{nm} \times 2^{16} = 524.288\ \mu m$, which in turn means that four writing fields have to be stitched together. The pattern is thus designed using the L-Edit (Ref. 24) CAD software, using the matrix copy function, in a $500 \times 500\ \mu m^2$ area, and converted into the EBL-specific format by the proprietary converter. Proximity correction is deemed not necessary so it is not carried out, and the pattern file is transferred into the main EBL computer. Since doped silicon is conductive enough to avoid charging effects, the samples are not metal coated. The substrate is cleaned in hot acetone for 5 min, rinsed in cold acetone and IPA, and blown dry under nitrogen flux. A 300 nm thick PMMA layer is deposited by spin coating and the sample is baked on hot plate for 5 min at 170 °C. In order to establish the optimal processing conditions, a *dose matrix* (also called *dose array*) is first written. The pattern is exposed in a 4×4 geometrical array, with a single 524.288 μm field, each point with a different dosage, ranging from 200 up to 1400 $\mu C\ cm^2$. The sample is then developed for 1 min at 21 °C in a solution of methylisobutylketone and IPA (1:3 in volume), then rinsed in IPA and carefully blown dry under nitrogen. SEM analysis reveals that the optimal dosage is 920 $\mu C\ cm^2$. At this dosage, all the channels are completely developed, sidewalls are vertical and smooth, and there are no resist residues at the bottom of the channel. Another sample is then prepared in exactly the same conditions as described above. The job is set up to expose 4524.288 μm fields, moving the stage 500 μm in X or Y, in order to get a $1 \times 1\ mm^2$ total written area, at 920 $\mu C\ cm^2$. Once the exposure is finished, the sample is developed as described above and inspected for quality under SEM

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