Electron-beam lithography (EBL)

1. Introduction

Electron Beam Lithography (EBL) is a specialized technique for creating extremely fine patterns down to sub 10nm. It can also produce high volume and high density nanoscale patterning like Deep UV optical lithography and Nanoimprint lithography through the formation of master masks and templates for these techniques.

To convert a standard Scanning Electron Microscope (SEM) into a basic electron beam lithography writer, only one modification is absolutely necessary, that is to change the signal feed to the SEM scanning coils (which guide the beam over the sample surface) so that instead of “drawing a square” (like a Cathode Ray Tube) the coils will guide the beam to draw an arbitrary pattern. Unlike optical lithography, the direct write systems have the advantage of extremely high resolution and ability to create any orbitrary patterns without a mask. Their disadvantage is the long time taken to write large complex patterns.

In some cases an outlet is already provided on the operation and display module. The outlet usually has several pins, one for guiding one coil (X) one for guiding the other (Y) one for grounding and one for switching between the built in pattern generator (CRT) and our arbitrary pattern generator.

The main attributes of the technology are:

1) It is capable of very high resolution down to sub 10nm
2) It is a flexible technique that can work with a variety of materials
3) It is slow, being one or more orders of magnitude slower than optical lithography
4) It is expensive and complicated – electron beam lithography tools can cost many millions of dollars and require frequent service to stay properly maintained.

2. Working of EBL

The basic idea behind electron beam lithography is identical to optical or any other lithographies. The substrate is coated with a thin layer of electron sensitive resist (in analogy with photoresist we use the word e- resist), which is chemically changed under exposure to the electron beam (Fig 2.2), so that the exposed (non-exposed) areas can be dissolved in a specific solvent positive (negative) lithography. This process is called development in analogy with development of photographic films (Fig 2.3) and at this step we obtained nanotemplate in e-resist thin film

After the removal of the exposed resist a thin metallic layer is deposited on the e-resist nano template deposited on a substrate. On the areas exposed to the electron beam the deposited metal sticks to the substrate, while on the unexposed areas the metal sticks to the resist surface (Fig. 2.4).

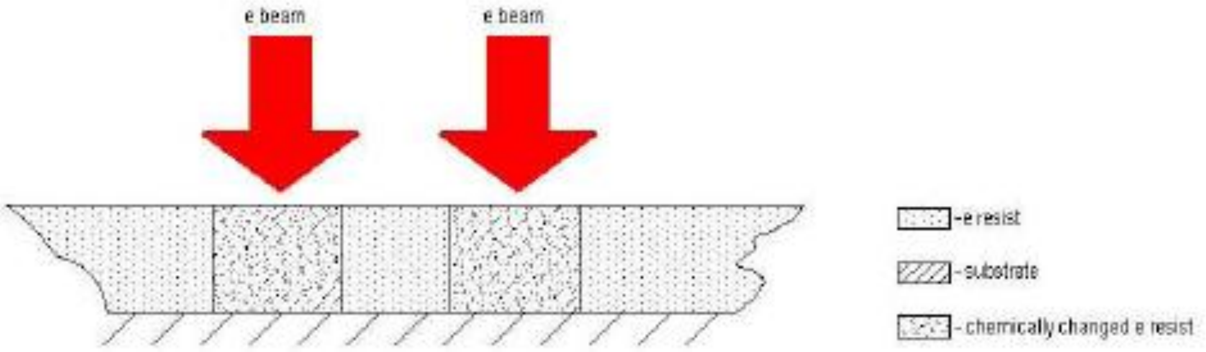

Fig. 2.2. E-resist crossection: The electron beam causes chemical change in the exposed areas.

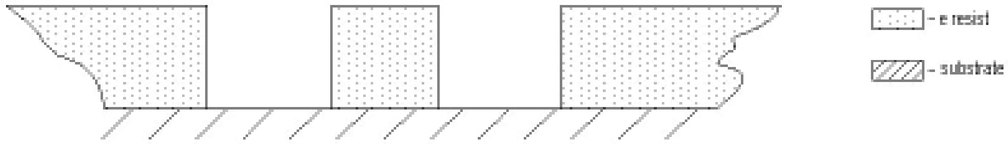

Fig. 2.3. E-resist crossection: Only the chemically changed e-resist can be dissolved in the specific solvent (positive lithography)

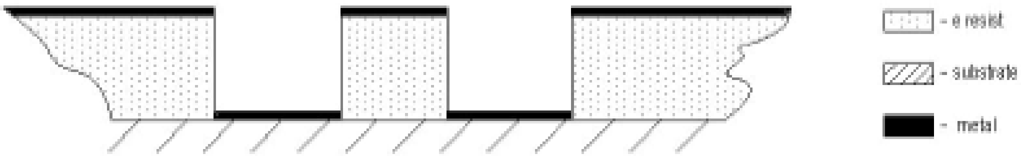

Fig. 2.4 E-resist crossection after metal deposition

After metal deposition the remaining (unexposed) e resist is dissolved in an aggressive solvent (lift off). The metal sticking to the resist looses “footing” and so only the metal sticking to the substrate remains giving us required nanostructures pattern (Fig.2.5).

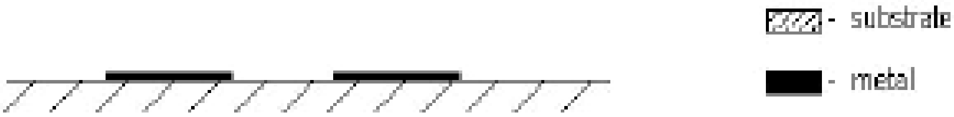

Fig. 2.5: Circuit crossection: Final result

3. Substrate selection for EBL

A substrate for electron beam lithography must satisfy different (contradictory) conditions: it should be relatively conductive (if insulator, the wafer would build up an electric charge, which would deflect the electron beam and thus distort the drawn pattern), on the other hand the base for electronic circuits should obviously be insulating (otherwise the entire circuit would be short circuited). Apparently a compromise must be made in substrate selection: the substrate should be as close to insulating as possible without distorting the drawn pattern. The most widely used substrate is (semiconducting) silicon with a thin insulating layer of silicon dioxide on top. Other possible substrates that can be used are glass plates coated with metal (ITO, chrome on glass (widely used in mask production), in which case the metal layer should be grounded before drawing.

4. Resist for EBL

To perform electron beam lithography we need a resist, which can be chemically changed under exposure to the electron beam. There is quite a large amount of different resists with different properties, which require different chemicals for development and lift-off. One of the first materials developed for e-beam lithography was polymethyl methacrilate (PMMA). It is the standard positive e-beam resist and remains one of the highest resolution resists available. PMMA can be purchased in one of several molecular weight. PMMA is spun on the substrate and baked at 170 to 200 °C. Electron beam exposure breaks the polymer into fragments that can be dissolved in methyl isobutyl ketone (MIBK), while both the exposed and the unexposed PMMA can be dissolved in pirolidone or acetone. MIBK alone is too strong as developer and removes some of the unexposed resist, that is the reason a mixture of 1 part MIBK to 3 parts isopropanol is used. When exposed to more than 10 times the optimal positive dose, PMMA will crosslink, forming a negative resist.

5. Beam broadening & Proximity effects

Although electron beam lithography tools are capable of forming extremely fine probes, things become more complex when the electrons hit the resist or substrate. **As the electrons penetrate the resist, they experience many small angle scattering events (forward scattering),** which will slightly deflect the electron beam and tend to broaden the initial beam diameter. The beam broadening will increase with thickness of resist and and this effect is more pronounced at low electron energies (Fig. 2.6).

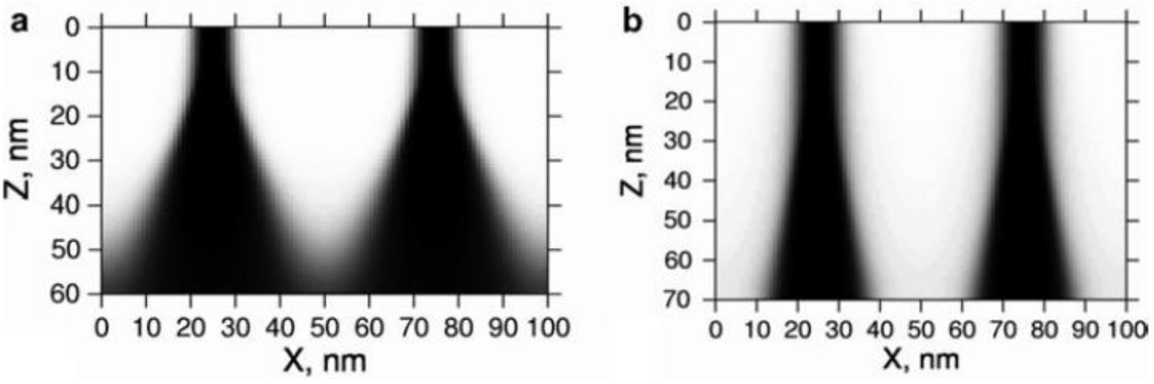

Fig. 2.6 Electron beam broadening due to forward scattering in the resist at (a) 3 KeV (b) 10KeV of incident energy. Shown is a predicted crossection of resist exposure for two parallel e-beams.

In addition to forward scattering there is also back scattering of electrons to consider. As the electrons penetrate through the resist into the substrate, most of them penetrate deep into substrate but some fraction of them will experience enough large angle scattering events (backscattering) to re-emerge from substrate into resist at some distance to the point where they left it (Fig. 2.7). At higher energies these backscatter electrons may cause exposure microns away from where the beam entered. This leads to so called **proximity effect**, where the dose that a pattern feature receives is affected by electrons back scattering from other features nearby causing pattern distortion or overexposure (Fig. 2.7).

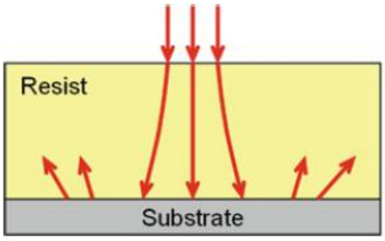

Fig. 2.7 Forward and backscattering of electrons in resist and substrate leading to beam broadening and proximity effects

Another electron transport is secondary electrons. These are low energy electrons produced by ionizations due to inelastic collisions by primary incident electrons with energies from 2 to 50 eV. They are responsible for the most of the actual resist exposure process. Since their range in resist is only a few nanometers, they contribute little to the proximity effect. Instead the net result can be considered to be an effective widening of the beam diameter by roughly 10nm. This largely accounts for the minimum practical resolution of 20 nm observed in the highest resolution electron beam systems.

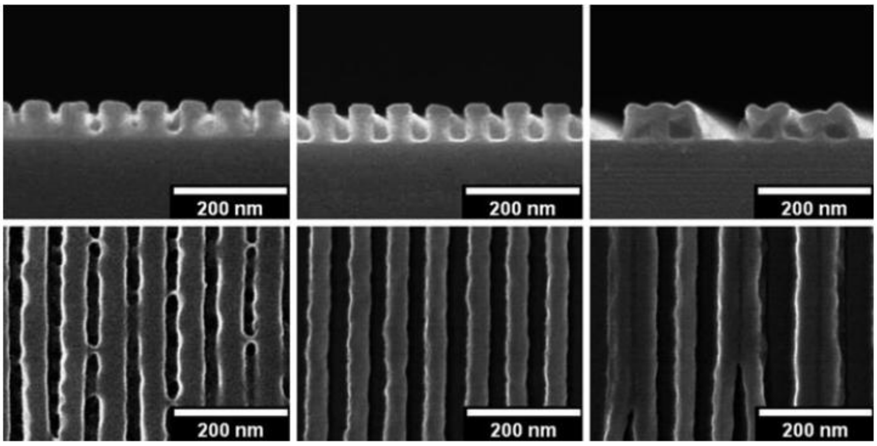

Fig 2.8 PMMA grating structures in cross-section (top) and plain view (bottom). Shown are low quality or under exposed/under-developed (left), Better quality or properly exposed/properly developed structures (middle) and over exposed/over developed collapsed pattern (right).

In basic SEM conversion systems the proximity effect caused by the backscattered electrons limits the resolution, to some 100 nm. This resolution level can be increased using some sort of dose correction method.

Nanofabrication from a thin film deposited on a substrate

E-beam lithography

This method differs from previous in the sense that, now we have already thin film deposited on substrate whose nanostructures are to be fabricated. All the steps are same like previous e-beam lithography method until development. After development unlike in previous method, instead of depositing metal or any material whose nanostructure are required we deposit metallic resist, mostly titanium (Ti) on the e-beam resist template, we obtained after development.

Then we do lift-off by putting sample in acetone like in previous method. After lift off process, we obtain nanostructures pattern made of titanium metallic resist on thin film whose nanostructures are required. Now, to obtain required nanostructure which are below titanium nanostructures, sputtering (dry etching) is done to remove titanium above nanostructures and extra thin film material in between nanostructures to get isolated nanodots or nanopattern made of required material (Fig. 2.9).

The titanium resist thickness should be such that titanium and extra thin film material beside nanostructures should be sputter at the same time.

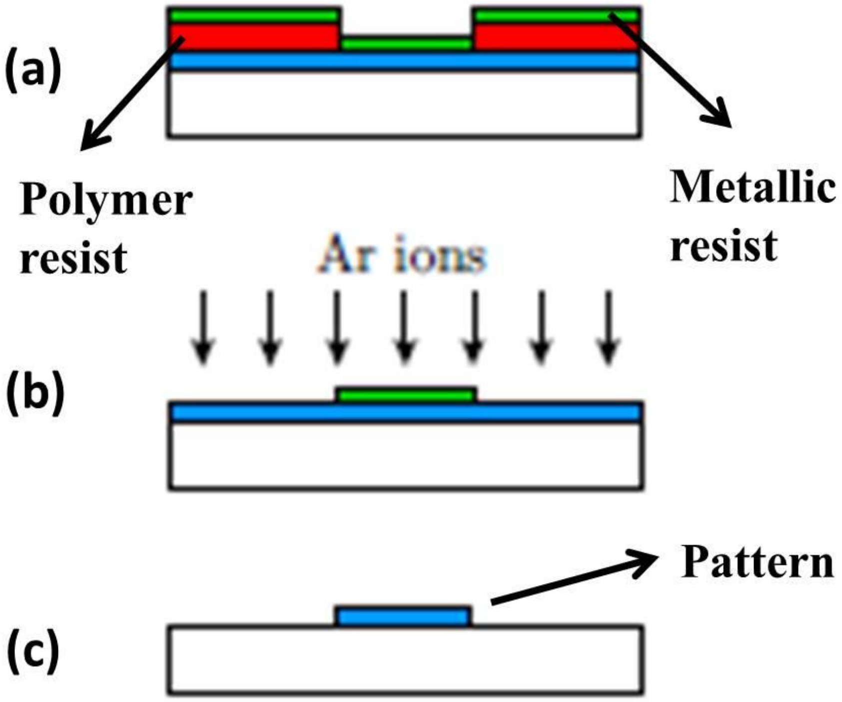

Fig 2.9. Schematics e-beam lithography

Similarly, optical lithography can be used to make nanostructures with this method as described above.