

Introduction to Electron Beam Lithography

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1. Introduction

Electron Beam Lithography is a specialized technique for creating extremely fine patterns (~ 50 nm). Derived from the early scanning electron microscopes, the technique in brief consists of scanning a beam of electrons across a surface covered with a resist film sensitive to those electrons, thus depositing energy in the desired pattern in the resist film. The main attributes of the technology are: 1) it is capable of very high resolution; 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 and 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. The basic idea of electron beam lithography

The basic idea behind electron beam lithography is identical to optical or any other lithographies. The substrate is coated with a thin layer of resist (in analogy with photoresist we use the word e resist), which is chemically changed under exposure to the electron beam (Fig 2.1), 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 2.2).

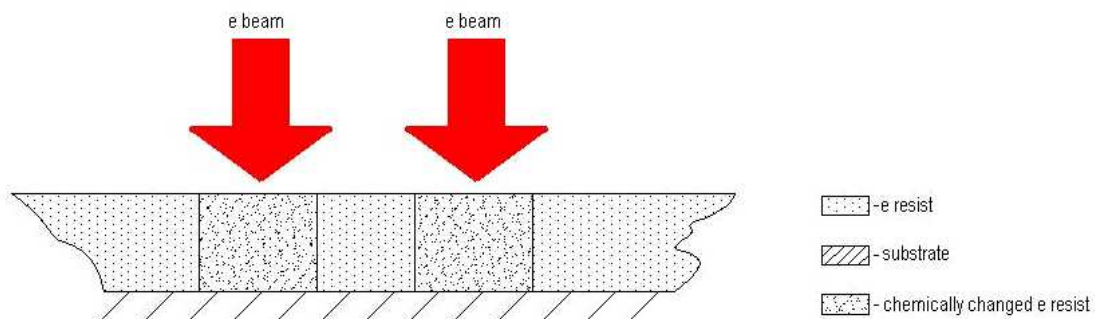


Figure 2.1 E resist crosssection: The electron beam causes chemical changes in the exposed areas

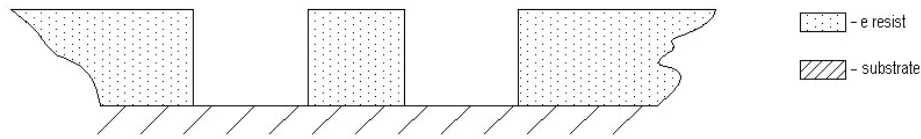


Figure 2.2 E resist crosssection: Only the chemically changed e resist can be dissolved in a specific solvent (positive lithography)

After the removal of the exposed resist a thin metallic layer is deposited on the 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. 2.3).

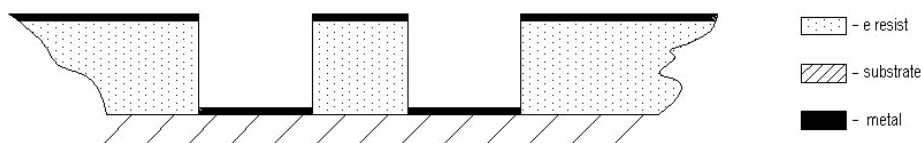


Figure 2.3 E resist crosssection after metal deposition

After metal deposition the remaining (unexposed) e resist is dissolved in an aggressive solvent (lift off). The metal sticking to the resist loses “footing” and so only the metal sticking to the substrate remains.



Figure 2.4 Circuit crosssection: Final result

3. Scanning Electron Microscopy (SEM) basics

The image is formed in a SEM microscope by scanning an electron beam across a sample and collecting some signal from the beam-sample interaction, which is used to control the intensity of the spot on a television monitor that is scanning in synchronization with the beam on the sample.

A typical SEM microscope is composed (Fig. 3.1) of 1) a column, which is the most important part of the microscope. It contains an electron gun (thermionic or field emission), magnetic lenses, which focus and guide the beam, and a specimen chamber. 2) vacuum system which keeps the column and the specimen chamber at high vacuum (10^{-4} Pa) and 3) the operation and display system which analyses the signals and supplies the electronic signals that guide the electron optics and the vacuum system.

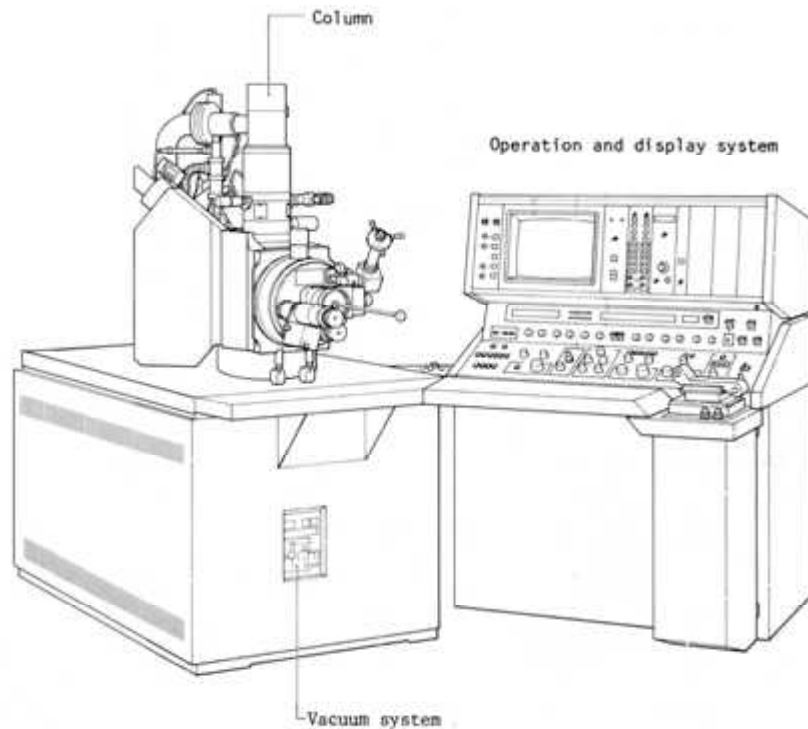


Figure 3.1: SEM composition

Let us take a more detailed look in the composition of the column (Fig. 3.2). The source of the beam is the electron gun, which is positioned at the top of the column. There are two basic types of electron guns: thermionic and field emission sources. A thermionic source is basically a heated wire from which electrons are given enough thermal energy to overcome the work function of the source, combined with an electric potential to give the newly free electrons direction and velocity. A field emission gun consists of a sharply pointed tungsten tip held at several kilovolts negative potential relative to a nearby electrode, so that there is a very high potential gradient at the surface of the tungsten tip. The result of this is that the electrons can escape from the metal by tunneling. Thermal field emitters enhance the pure field emission effect by giving some thermal energy to the electrons in the metal, so that the required tunneling distance is shorter for successful escape from the surface.

The electron beam is then focused with several magnetic lenses and finally the beam hits the sample. The beam-sample interaction can produce several different phenomena:

- 1) Secondary electrons: low energy electrons emitted from the sample due to passage of beam electrons. Typical energies of these electrons are of the order of a few eV. These electrons can be detected by an Everhart-Thornley detector (A scintillator in a Faraday cage at a positive potential attracts electrons. The signal from the scintillator is amplified by a photomultiplier.)
- 2) Backscattered electrons: Back Scattered Electrons are primary beam electrons that have undergone one or more collisions within the sample and eventually have bounced around enough to re-emerge from the surface they came in. Their energy is distributed between 0 and beam energy E_0 with a peak somewhere between $0.4E_0$

and $0.95E_0$. These electrons can be detected with a detector similar to the Everhart-Thornley detector without the positive collection potential.

- 3) X-rays
- 4) Cathodoluminescence

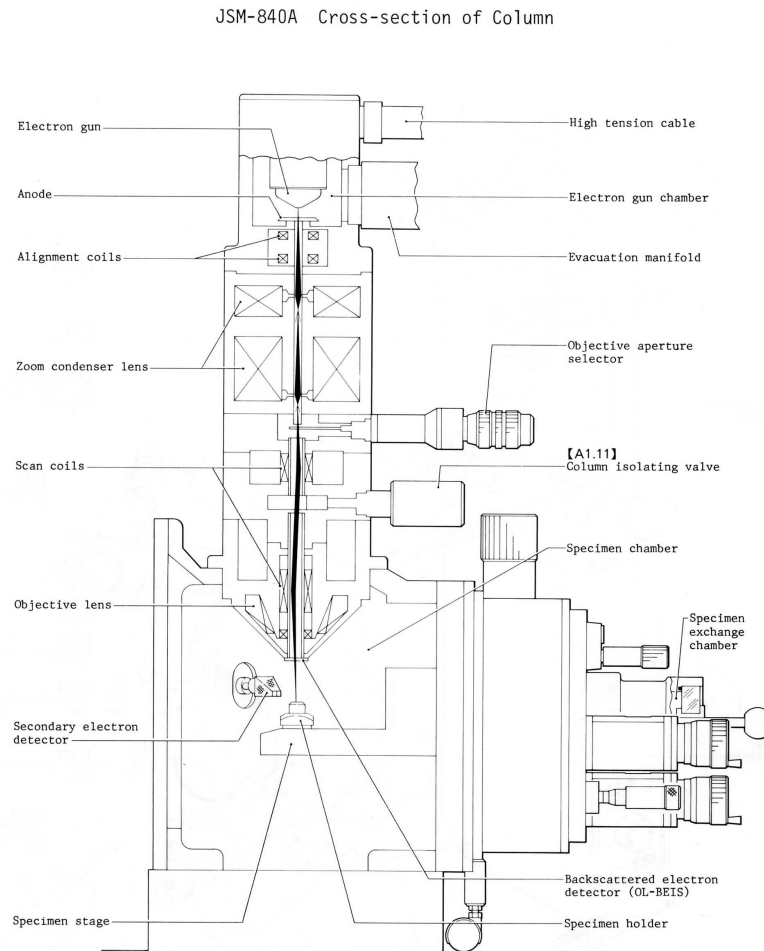


Figure 3.2 Column crosssection

To convert a standard SEM microscope into a basic electron beam lithography writer, only one modification is absolutely necessary, that is to change the signal feed to the scanning coils (which guide the beam over the sample surface) so that instead of “drawing” a square (like a CRT) the coils will guide the beam to draw an arbitrary pattern.

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.

4. Substrate selection

A substrate for electron beam lithography must satisfy different (contradictory) conditions: it should be relatively conductive (in the opposite case 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.

5. Electron beam resist

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 liftoff. One of the first materials developed for e-beam lithography was polymethyl methacrylate (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 forms (50 K – 950 K), usually dissolved in chlorobenzene.

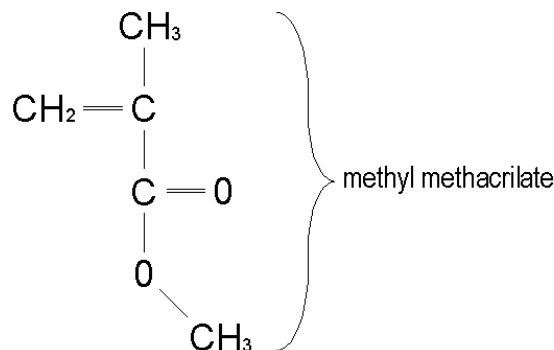


Figure 5.1: Chemical structure of methyl acrilate (monomer of PMMA)

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 a 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. PMMA has poor resistance to plasma etching, but it is very effective as a mask for chemically assisted ion beam etching.

It is possible to form a bilayer system where a high molecular weight PMMA is spun on top of a low molecular weight PMMA. The low weight PMMA is more sensitive than the top layer, so the resist develops with an enhanced undercut (Fig 5.2), which enables easier lift off.

A larger undercut resist profile is often needed for lifting off thicker metal layers. This can be achieved by spinning PMMA on top of a P(MMA-MAA) copolymer.

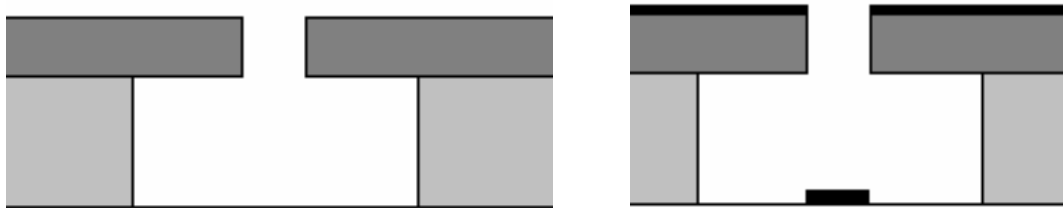


Figure 5.2: Undercut enables easier liftoff

6. Drawing

Although electron beam lithography tools are capable of forming extremely fine probes, things become more complex when the electrons hit the workpiece. As the electrons penetrate the resist, they experience many small angle scattering events (forward scattering), which tend to broaden the initial beam diameter. As the electrons penetrate through the resist into the substrate, many of them will experience large angle scattering events (backscattering). The backscattered electrons cause the proximity effect, where the dose that a pattern feature receives is affected by electrons scattering from other features nearby. During this process the electrons are continuously slowing down, producing a cascade of low energy electrons called secondary electrons with energies from 2 to 50 eV. They are responsible for the bulk 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. 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. The main effect of proximity effect is that small features are exposed less than the larger features, which causes significant distortion in very small features (that is also the reason why the exposition rate may depend on pattern geometry and size). The simplest dose correction method is simply the use of double layer e-resist, but this only works for quite large features ($\sim 1\mu$). The other dose correction methods usually consist of

calculating the cumulative exposition rate that a feature receives directly from the beam and also from other features, and then compensating for the excess dose by adapting the beam current (from feature to feature), the speed with which the beam scans over the sample, or the shape of the drawn features.

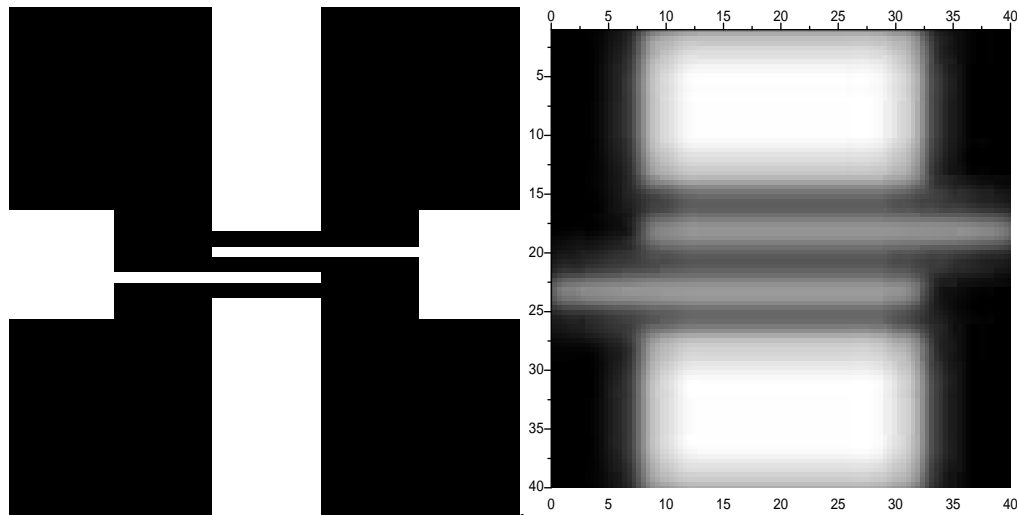


Figure 6.1: A numerical simulation of proximity effect. The left image represents the desired pattern, while the right one represents a 40x40 micron inset of the central part. Exposition rate is depicted by brightness.

7. Recipes

The following recipes describes the procedure of making narrow channels using e-beam lithography. This recipes were tested on a test pattern (Fig 7.1 - 7.3) and the exposition rate for small features depends quite considerably on the pattern geometry and size (this can be overcome by using some sort of dose correction method or bi-layer resist, which we are using (only works well for relatively large features $>1\mu\text{m}$)).

A recipe for achieving high resolution:

- Spin a 4 % mixture of 50 K PMMA and ethylacetate on a silicon wafer. Spin at 4000 rpm for one minute, than place the wafer on a hotplate at 160 – 180 °C for 10 minutes, for a thickness of 50 nm.
- Spin a 2 % mixture of 950 K PMMA and chlorbenzene on a silicon wafer. Spin at, 4000 rpm for one minute, than place the wafer on a hotplate at 160 – 180 °C for 10 minutes, for a thickness of 50 nm.
- Expose the desired areas with a 40 kV electron beam at 500 $\mu\text{C}/\text{cm}^2$ (exposition depends on pattern geometry and size).
- Develop the pattern for 1 minute in 1:3 mixture of MIBK (methyl-isobuthyl-ketone) and isopropanol.

- Sputter the desired thickness (10-40 nm) of metal on the wafer (some metals like gold don't stick to the SiO₂ layer very well, that is why an intermediate level of Titanium or Nickel is required).
- Soak the wafer in pirrolidone or acetone for a couple of hours to dissolve the remaining resist, mild ultrasonic agitation is advised to remove metal around small features. Rinse with isopropanol.

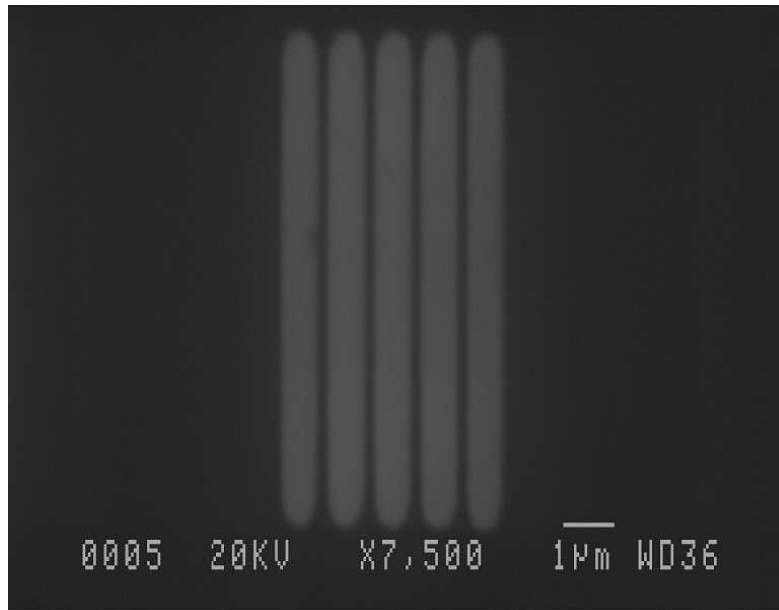


Figure 7.1: Overexposed pattern

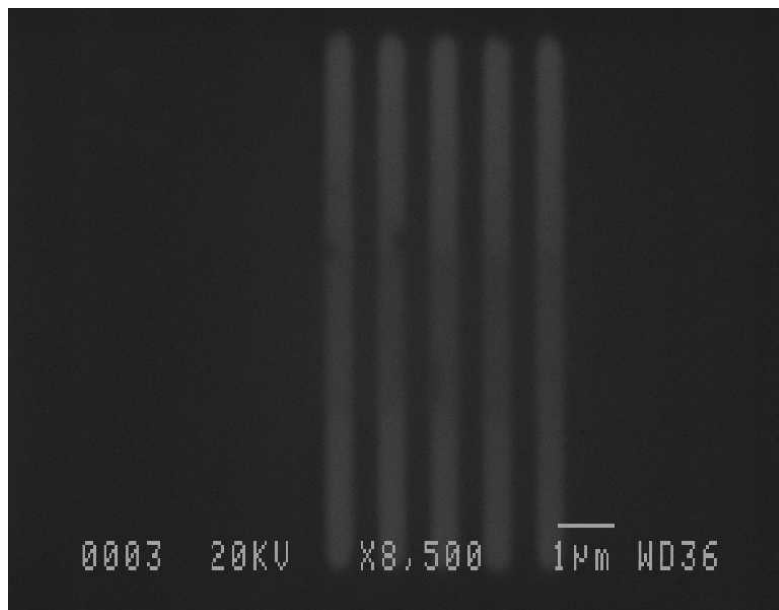


Figure 7.2: Ideal exposure (identical channel and finger width)

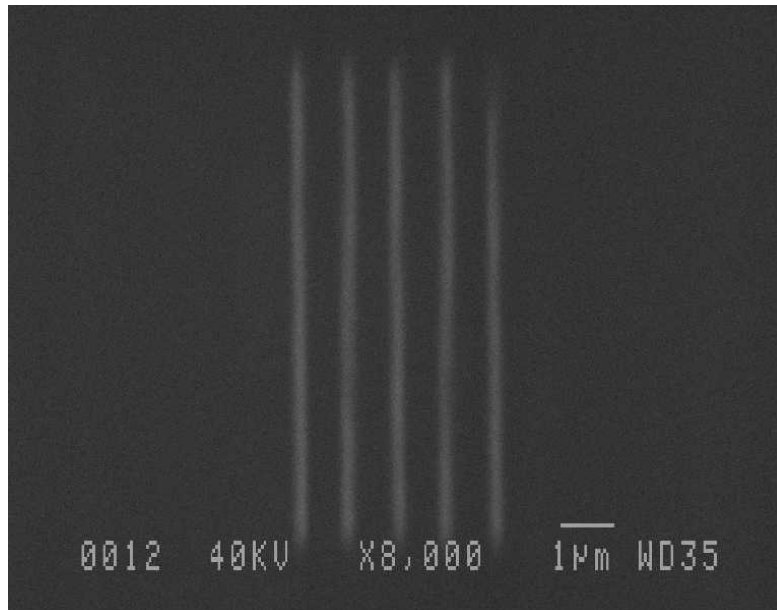


Figure 7.3: Underexposed pattern

A recipe with a high resolution and improved liftoff:

- Spin a 3 % mixture of 33% PMMA/MAA on a silicon wafer. Spin at 2000 rpm for one minute, than place the wafer on a hotplate at 200 °C for 10 minutes, for a thickness of 130 nm.
- Spin a 2 % mixture of 950 K PMMA and chlorbenzene on a silicon wafer. Spin at, 6000 rpm for one minute, than place the wafer on a hotplate at 160 °C for 10 minutes, for a thickness of 90 nm.
- Expose the desired areas with a 20 kV electron beam and exposition rate 170 $\mu\text{C}/\text{cm}^2$ (exposition depends on pattern geometry and size).
- Develop the pattern for 1 minute in 1:3 mixture of MIBK (methyl-isobuthyl-ketone) and isopropanol.
- Sputter the desired thickness (10-40 nm) of metal on the wafer (some metals like gold don't stick to the SiO_2 layer very well, that is why an intermediate level of Titanium or Nickel is required).
- Soak the wafer in pirolidone or acetone for a couple of hours to dissolve the remaining resist, mild ultrasonic agitation is advised to remove metal around small features. Rinse with isopropanol.

A recipe with enhanced liftoff, with minor reduction in resolution:

- Spin a 6 % mixture of 33% PMMA/MAA on a silicon wafer. Spin at 4000 rpm for one minute, than place the wafer on a hotplate at 200 °C for 10 minutes, for a thickness of 290 nm.

- Spin a 2 % mixture of 950 K PMMA and chlorobenzene on a silicon wafer. Spin at, 6000 rpm for one minute, than place the wafer on a hotplate at 160 °C for 10 minutes, for a thickness of 90 nm.
- Expose the desired areas with a 20 kV electron beam and exposition rate 125 $\mu\text{C}/\text{cm}^2$ (exposition depends on pattern geometry and size).
- Develop the pattern for 1 minute in 1:3 mixture of MIBK (methyl-isobutyl-ketone) and isopropanol.
- Sputter the desired thickness (10-70 nm) of metal on the wafer (some metals like gold don't stick to the SiO_2 layer very well, that is why an intermediate level of Titanium or Nickel is required).
- Soak the wafer in pirolidone or acetone for a couple of hours to dissolve the remaining resist, mild ultrasonic agitation is advised to remove metal around small features. Rinse with isopropanol.

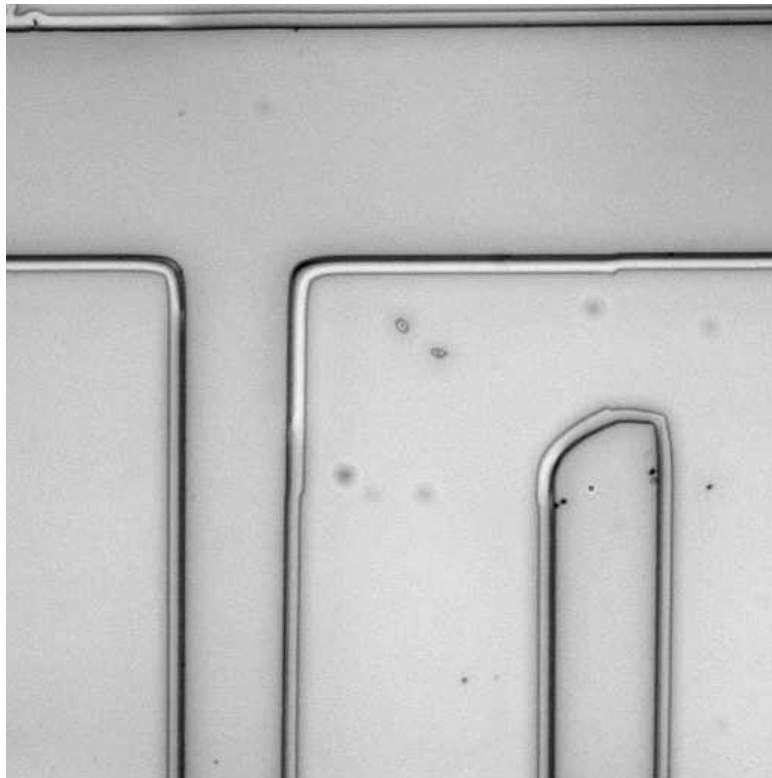


Figure 7.1: Enhanced undercut

8. References

- P. Rai-Choudry: Handbook of Microlithography, Micromachining and Microfabrication, Volume 1: Microlithography, SPIE, 1997
- JEOL JXA-840A Electron probe microanalyzer Instructions