# Recent Development in E-Beam Lithography techniques

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***Abstract:***

*In the fabrication of Integrated circuits, Lithography plays a major role in patterning the exact and specific shapes on the semiconductor substrates. As we know that the growing requirement in present trends of IC technology urges in the decrement of sizes and increment of complexity of the devices. Limits have been reached in the techniques of Mask making, optical projection, contact printing etc. To overcome these limitations, Electron Beam Lithography is one of the better options available for printing the patterns.*

*In E-beam lithography, custom pattern printing is carried out by the exposure of electrons using electron sensitive film on the substrate. This maskless lithography technique helps in achieving high resolution, low throughput and damage free patterns. Controlled and selective exposure on the required regions of the semiconductor substrate helps in gaining small feature sizes. E-beam has its wide application in areas of nano lithography.*

*This paper explains the recent developments and changes in the process of E-beam lithography and its impacts in the fabrication process.*

***Keywords:*** *Electron Beam Lithography, Photo Lithography, Pattern Printing, Integrated Circuits*

## I. Introduction

In the Modern World, the requirement of Integrated Circuits on a single chip increasing tremendously based on the Moore's law which was proposed by Gordon Moore in 1965. More transistor means more complex IC designs. Thus, patterning techniques have been reached to its limit's day by day. Likewise, Photolithography which was mostly used, has reached its end due to decreasing feature size.[1] This is also true for Mask Generations and patterning mask to the wafers. Decrease in the feature size and increase in the patterning areas started limiting the production of Masks. In Proximity printing, size again limits the procedure whereas Contact printing damages the wafer. One of the solutions for this problem is carrying out the pattern designs using electrons instead of Light. Here comes Electron beam lithography into light.

Electron beam lithography is a technique which emphasizes on creating patterns which are extremely small and smaller that they can't be visible to the naked eye. Simply this technique utilizes electron energy to pattern the desired designs. The electron beam is made to incident on an electron sensitive resist which produces the desired pattern. The main advantages of this technique are

a) Very High resolution.
b) Infinite patterns can be generated with an ease.
c) Can work with different materials

Being good with many advantages there are also few disadvantages in E beam, it is slow process compared to that of photolithography. It is very expensive as the tools itself might cost few million dollars and requires frequent maintenance for the tools [2].

## II. Resists

E-beam resists (aka Electron beam resists) are the ones used in Electron beam lithography. Small quantities that make thin layers are better suited for nano lithography processes. They are applied by spin coating at a rate of 1000 to 5000 rpm. A thin layer of thickness ranging below 30nm can be achieved with these resists.

**PMMA:** polymethyl methacrylate is a common polymer positive tone resist used in E beam lithography. It produces high resolution images and has less sensitivity to irradiation [3]. Even though it was discovered long back, it is mostly used now a days with converted scanning electron microscopes. It is used with direct write e-beam process [4].

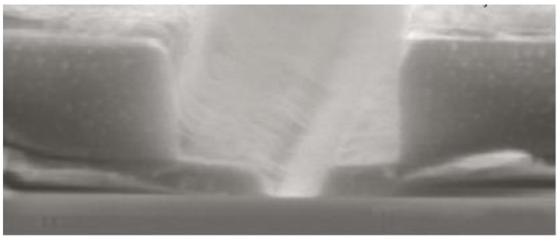

Figure 1: 100nm gate profile image with PMMA

**CSAR 62 (AR-P 6200):** These are made with styrene acrylates and are dissolved in anisole. These give high contrast and are highly sensitive compared to PMMA

**Novolac-based e-beam resists:** These are developed in aqueous alkaline. Novolac resists are available in both positive and negative tone resists. These resists are used because of their stability factor in plasma etching which is very high compared to both the above discussed resists.

## III. Conventional E-beam Tool

The following images shows the typical lithography tool and the blocks it has.

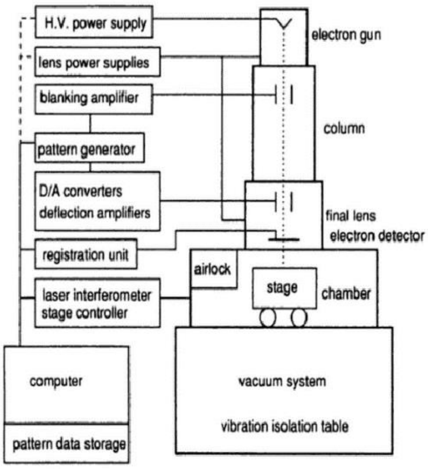


Figure 2: Block diagram of components in a e-beam tool

There will be a machine below which helps in loading and unloading the wafers. It loads the wafer that needs to be patterned and unloads when the process is done. The vacuum system which is very important chamber in the whole tool. It helps in maintaining the required vacuum until the process is done. The computer handles the data which has designs made using CAD (Computer aided design) and has a data storage unit. This data is used in making the e-beam to pattern the required designs. This computer and data also called as Datapath [3]. Computer also handles the loading and unloading machine.

The part which produces the Electron beam is known as Column. There are several parts present in the column such as an electron source, few lenses, tools for deflecting the beam, stigmator for corrections, electron detector and alignment tools etc. Column is the main part which tend to produce the desired patterns. A general e-beam is shown below,

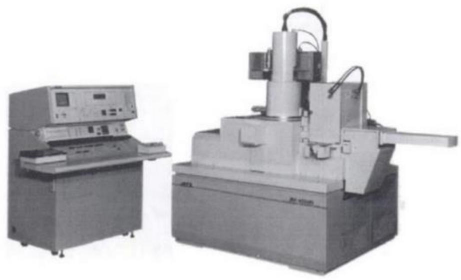

Figure 3: Commercial e-beam tool (Image from JOEL ltd.)

Next is the electron source, which is the main part which generates electrons required for the patterning. These electrons can be generated by two process namely thermionic emission or field emission. In thermionic emission, the electrons are generated through heat whereas in field emission electrons are generated through electric field. In field emission, the field is produces such that the potential barrier decreases providing the flow of electrons as a beam. Basically, these electron sources will have two to three electrodes which could generate the e-beam [3].

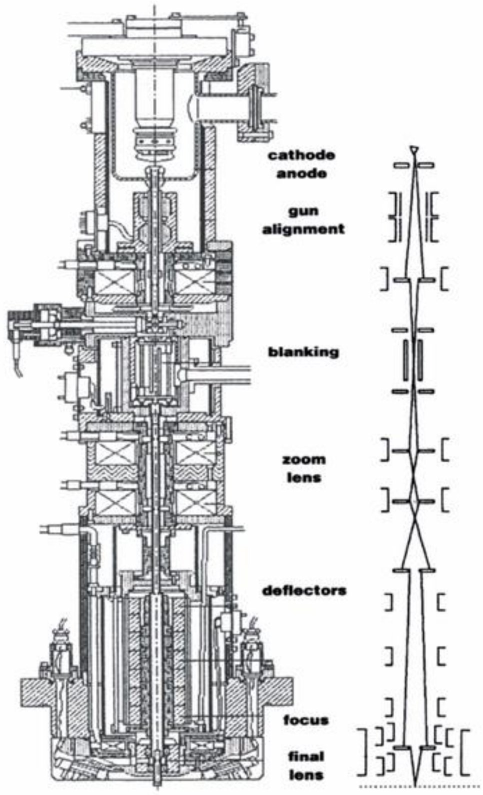


Figure 4: Cross-section of an Electron source

## IV. Applications

EBL has wide variety of applications in different areas. Some them are stated below:

**Mask Making:** Due to its high-resolution pattern designing and computer-generated design file capabilities (CAD Design file), electron beam lithography is used to make chrome on glass masks. These masks help in optical lithography. These masks are then used to make integrated circuits and also disk drive heads and display panels.

**Direct-writing E-beam Lithography:** As the name depicts, it simply means directly writing the pattern for devices without masks. In simple terms, it is maskless lithography [5]. A small spot of beam is incident over the resist to pattern the design.

**Projection Printing:** In projection printing, the beam which is relatively larger is passed through a mask and the conventional lens system to pattern the design.

**EBL in Research:** Having high resolution makes it a good tool for researching towards scaling factors in fabrication and also in the field of quantum physics [3]. For example, it is implemented in the study of Aharanov-Bohm effect, quantization levels in electrons and single electron transistor etc.

## V. Developments in Direct-Writing

It all started in 1960's when a group of researchers at Cambridge university, used the beam of electrons along with a mask and a photodiode in front of the beam achieved lines of 50-80 nm. In mid-1960's the general e-beam lithography tool discussed above came into light. In the year of 1967, a group at IBM used cathode ray tube for electron beam and made a transistor. The high-resolution electron sensitive resist PMMA came into uses the following year. Then "lift-off" process was discovered.

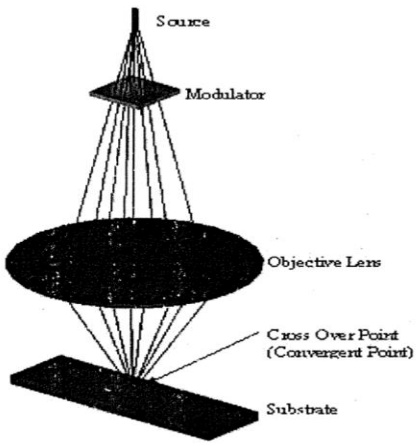


Figure 5: Schematics of Direct Printing

The year 1970 was when the converted scanning electron microscopes which can be used for e-beam lithography came into existence. They are widely used even now a days [5].

After few years Lanthanum Hexaboride became available which can be used in convertible scanning electron microscopes. That cathode can provide us with the brighter source of electrons [5].

The main limitation in the direct writing is pattern transfer time. It will take lot of time as the exposure is done in pixel by pixel flow. Single element by element is done which impacts in exposure speed and transfer time.

Recent developments include using Variable shaped beam. This could help in increasing the overall throughput. This technology work by parallelly writing the opposite sides of a pattern in one go. [7] Using just a single shot to pattern both sides could help by decreasing the exposure time and complex designs could be patterned. But this could possibly impact the resolution because pixel by pixel could be more accurate. So, a trade off should be done by choosing either resolution or the exposure time based on the applications and uses.

**Lift-off Process and recent developments:** Liftoff is the process which is highly used in e-beam lithography. It is an additive process.

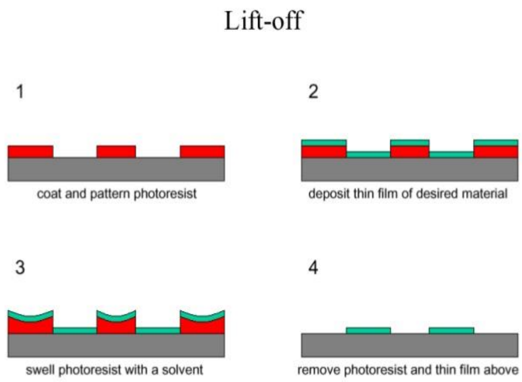


Figure 6: 1. Resist is coated and patterned 2. Metal deposition step 3. Solvent development 4. Developing the resist

This process is mostly done for metal deposition. The is done in a reverse manner compared to traditional etching. In this process, the substrate if firstly coated with the e-beam resist and is then patterned. Then the metal is deposited over the patterned resist. After that, the substrate is made to swell by developing in the solvent and later, the resist is removed giving us the metal deposition in required places. This process is mostly done using PMMA resist and be used in forming multiple metal level structures. Undercut profiles are preferred for liftoff process.

Recent developments have been made into liftoff process by IBM researches in successfully achieving the undercut profiles [9]. The undercuts were found in an experiment which uses ®AZ-type resists and ®AZ-Developer. Before developing the resist, the wafer underwent through a Chlorobenzene soak which helped in obtaining undercuts after the developer process is done. [9] Toluene can also be used instead of benzene in the soaking process but benzene helps in removing the residual solvent.

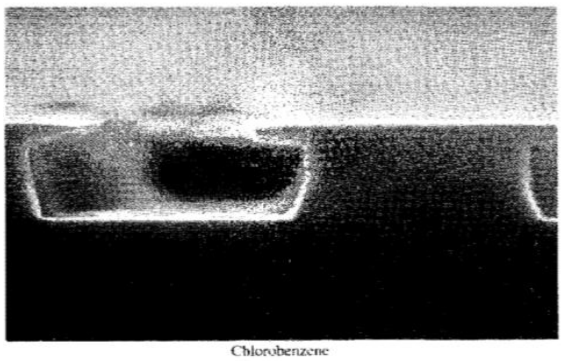


Figure 7: Profile achieved after chlorobenzene soak. (image obtained from ref [9])

The above seen profile can be obtained by following the procedure which can be ideally good for the liftoff process. Undercut simply provides a better separation of the metal.

## VI. Projection Printing

The projection printing is one of the schemes in electron beam lithography. The e-beam resist coated on the substrate is projected with a large beam of electrons which is passed through a precision lens system. The schematic of the projection printing is given below

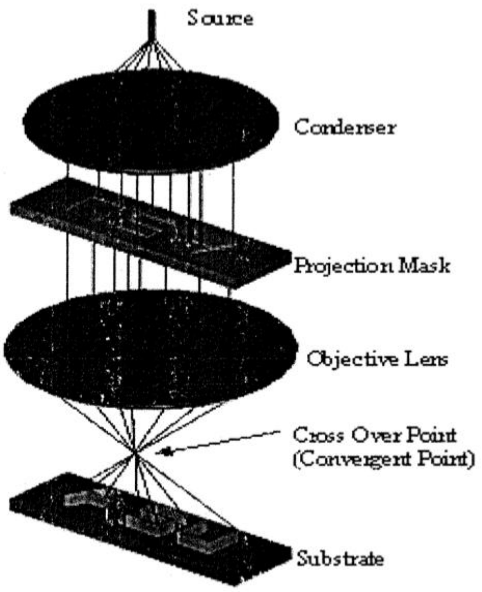


Figure 8: Schematics of Projection printing.

Projection printing is further taken forward with the two techniques.

1. SCALPEL System
2. PREVAIL technology

Bell laboratories are the once who invented the SCALPEL system which is Scattering with angular limitation in projection electron-beam lithography in 1989 [11]. SCALPEL uses a mask called “Scattering Mask”. This is especially designed to use it with Scalpel [6]. The pattern on the mask is then made on the wafer

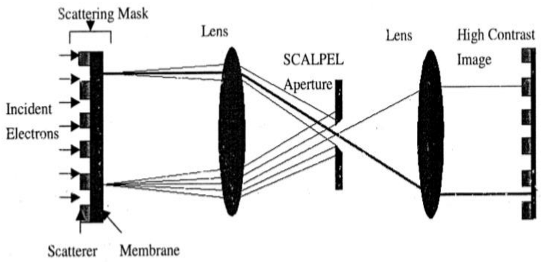


Figure 9: Working principle of Scalpel technique.

The main specialty of the SCALPEL process is the mask. It was specially designed with a low atomic number membrane, which has a pattern generated with a big atomic number element. This comes into advantage during the scattering. When the beam is passed through the mask, they scatter more at high valued angles when passed through higher atomic material. The aperture on the backside focal plane traps the highly scattering electrons. Some of the electrons which go via membrane undergoes very minute difference in their way and fly directly through the aperture. Consequently, the electrons which ever passes through the membrane will create a high contrast pattern on the surface of the substrate [7]. Thermal distortion is decreased by this method due to trapping of electrons at the aperture. To minimize the distortion the step needs to be taken is minimizing the beam’s field which makes a key problem to SCALPEL process. To get a full pattern the wafer needs to be exposed with that small beam at all the places on it. Mask need to be accurately positioned with the wafer to achieve this which could slow down the process and as a result low throughput is achieved. This process uses step and scan writing [7].

PREVAIL or Projection reduction exposure with variable axis immersion lenses was started by IBM in 1980’s. This process uses variable axis lens. This system works combinedly with e-beam scanning and mechanical scanning. The wafer is made to undergo both the scanning’s simultaneously. The variable axis lets the beam to vary around the area of predefined curvature. This is done along with the coordination of beam deflection by making it follow the accurate axis. This minimizes the off the axis distortions.

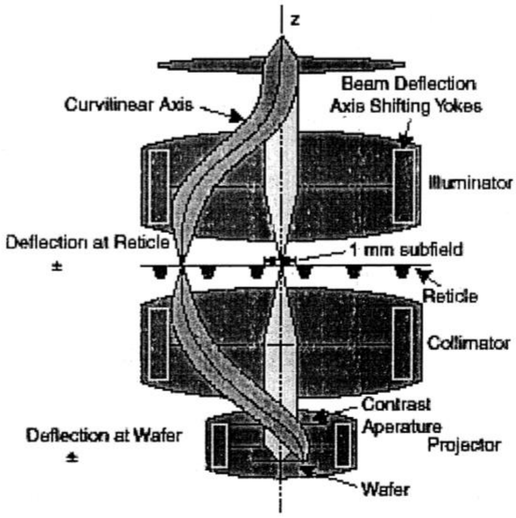


Figure 10: PREVAIL system work flow.

This whole process is made to work through a technique called superposition. Placing the magnetic deflection fields above each other and making them coincide with each other is what superposition mean. The figure above shows a typical PREVAIL system. The illuminator used in the process has lens induced with magnetic field, making a 1x1 beam to incident on the reticle for imaging the pattern. The Collimator forms a telecentric doublet with the projector which is known to create very small small distortions. It is found that PREVAIL method is able to print 10x10 which is quite good [7]. We need to have increased scan ranges for the coming future which is going to be a problem even for this method.

Some of the other ways using Projection is Multiple Beams in the process. The column discussed above are multiple in number in these processes. Using multiple beams can often generate high throughput. Increasing technology needs high density patterns. Higher the density means higher the time take for exposure. This increment in time for mask making in return increases the cost per mask. A new way is to overcome these problems was proposed by Hiroshi Yasuda [8].  It is by using Multi column cell. This technique is employed by using different beams controlled by deflectors which parallelly pattern from both the sides, thus increasing the throughput. Rather than using a single column, using multiple small beams could help overcome the increasing time of exposure.[8]

**Proximity Effect:**  Also called as Scattering effect. It tends to happen when electrons move or come out of the way where it was focused. When the electron beam is incident on the e-beam resist, due to its rigid nature some of the electrons might get scattered in low angles. Some electrons while penetrating from resist towards the substrate might strike back (called as Backscattering). Now those scattered electrons make it too the different parts of resist making more exposure in the unwanted regions. This is called proximity effect.

Recent studies have been conducted in this problem. This effect causes variations in the pattern. After studies conducted by the researchers the solutions found to minimize this effect is by using a very thin layer of e-beam resist which is less than the feature size. Another method is to try and put a very thin layer between resist and substate to stop the scattering electrons from substrate. [7]

## VII. Modified SEM’s

Modified or convertible scanning electron microscopes are used in reverse order for generating patterning. By reverse order means rather than using SEM for reading, it is used for writing patterns.

Although they are less complex, the disadvantages include miniature field view and less throughput. Now-a-days the commercial scanning electron microscopes comes with a pattern generator which can be used for e-beam lithography.

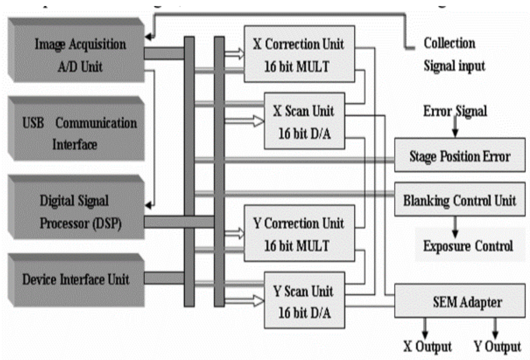


Figure 11: Block diagram of a typical pattern Generator.

Pattern generator comes with an analog to digital converter unit along with a signal processor and communication interface. When a computer-generated design is given, it can control the Sem accordingly to generate the desired pattern. Many commercial pattern generators are available in the market. Few of them are discussed below

**1.Nanometer Pattern Generator System (NPGS):** It was slod by Nabity lithography systems. It was included with 16-bit multifunction board which is used to control the X and Y axis of beam to generate the pattern. The deflecting beam draws the patterns that was given in the CAD file. The .npgs file is uploaded in the computer software provided by the company and then it controls the microscope to transfer the design to the substrate [6].

Figure 12: A typical NPGS system (Courtesy Nabity Lithography systems)

**2.Raith Pattern generators:** The conversion kit that shown in the figure 13 is the Raith Company’s tool. They have a low-end tool as well as a high end one. The low end is limited to mono writing mode and restricted to manual alignment. The high end has all the operations and also include laser correction stage [2].

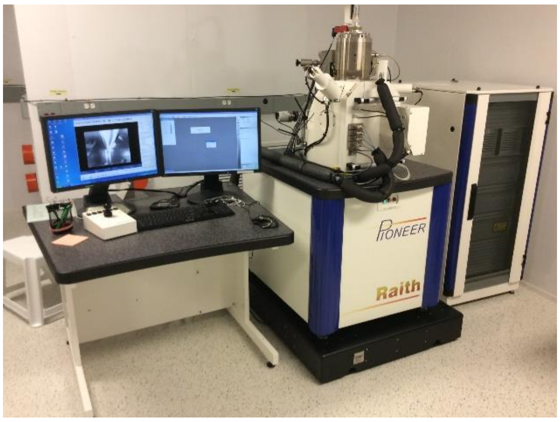


Figure 13: Raith PIONEER SEM and EBL tool. (Raith Company)

**3. Leica EBL Nano writer:** This is a combination of full electron beam lithography as well as a scanning electron microscope. It has both electron gun along with a pattern generator provided by Leica. The pattern generator also uses the Digital to analog converter which is of 16 bits.

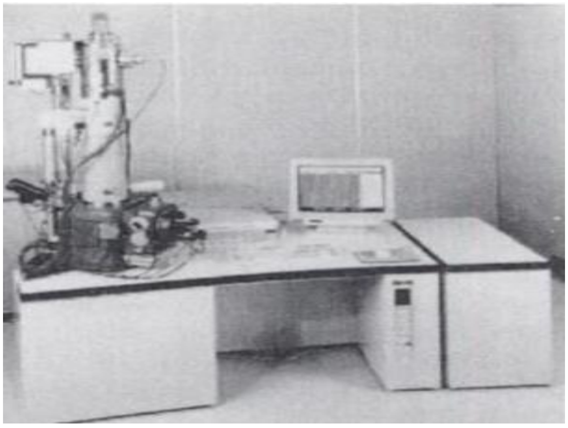

Figure 14: Leica EBL-100 (Courtesy of Leica Lithography Systems Ltd.)

## Other Recent Improvements in EBL:

**Evolving Electron Sources:** Electron sources are like the head of the e-beam lithography. It is the thing that creates electrons used for the process. So much evolution can also be seen in these sources. In the start, filaments made of tungsten is used as the electron source. It is heated at high temperatures to a point where electrons escape from the tungsten and are made to incident on the substrate. Tungsten is used due to its resistance at typically high temperature. Then after few years, Lanthanum hexaboride ($LaB_6$) is used in making the filaments. Using lanthanum hexaboride, we can simply work at low temperatures. LaB6 helped in decreasing the problem of spreading of electrons from the source.

Recent developments have come and LaB6 filaments are being swapped with field emitters made of tungsten which has a coating of Zirconium oxide. [5] These sources have improved brightness and minimized electron spread. The main advantage of these filaments is reduced current usage compared to that of lanthanum hexaboride which made them ideal to use as e-beam sources.

**Gap Contacts:** In the study of molecular of sciences, sometimes fabrication might need contacts placed very close to each other. Nanometer accuracy is need and known be achieved with Leica e-beam tool. The gap between those contacts needed to be less than 30nm. Project developed by Oak Ridge National Laboratories [5], electrodes of two different metals are needed by a little gap which is in nanometers. This is achieved by e-beam lithography.

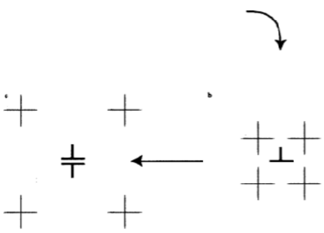

Figure 15: Two metals like the once shown above needs to be achieved.

It can be achieved by creating 2 alignment masks of 2 sets are made. First, the wafer is loaded and patterned with 1 set of 2 masks and liftoff metallization is done. Then the second set of masks is used to pattern the remaining metal and lift is done to achieve the final design,

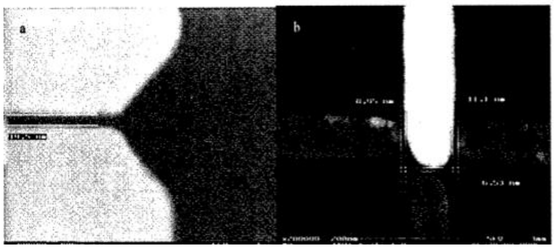

Figure 16: The nano gap created between two electrodes of different metals.

**Creating <10nm Structures Using organic Resist:**

E-beam lithography which works on less beam drift at nanoscale can be used when working with overly sensitive material resists. Recently works are being done on creating nano patterns on organic resists.

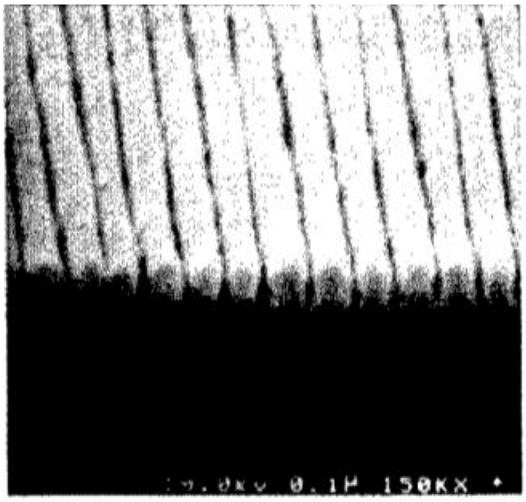

Figure 17: 10nm patterns on ZEP resists [5].

These patterns are created using Zep520 resist [5]. Due to its over sensitivity and less beam drift exposure, we can successfully create the nano patterns in this resist. Developer used for this resist is hexyl acetate.

CALIXARENE a negative tone extremely high-resolution resist is used for nanolithography. The sensitivity and durability of this resist is almost 20 times higher compared to Poly methyl metha crylate. Phenol derivative provides required firmness to Calixarene which is main component in Calixarene.

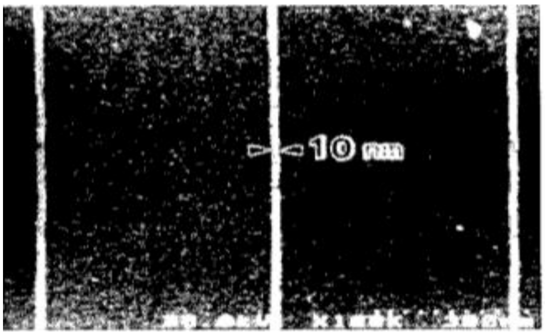


Figure 18: 10nm Calixarene Patterns

Above shown pattern can be created by prebaking, developing in Xylene and etching. Electron beam lithography is developing day by day.

**Shallow Junction in MOSFETS:** To find out how the MOSFETS work and to get know the features of the gate, very small nano patterns are generated using E-beam. An electrically variable shallow junction MOSFET is created with very shallow junctions. By this experiment, drain current and voltage characteristics are known.

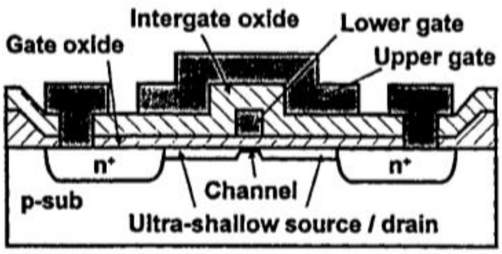


Figure 19: Cross-section of MOSFET (EJ)

Using the e-beam lithography and its high-resolution resists, creating nano patterns (<20nm) of junction to study about the transistor characteristics have become easy.

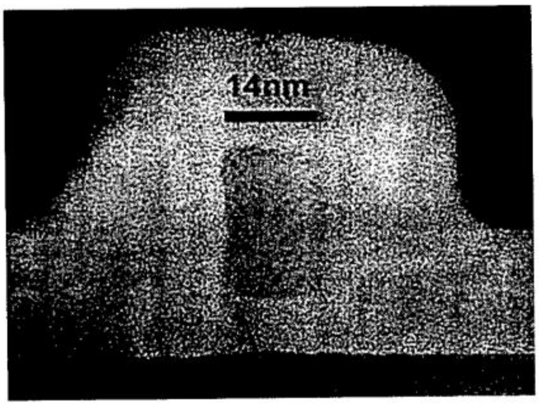


Figure 20: 14nm gate fabricated with E-beam

The gate shown in the above image is what have the control over the drain current [5].

**Chemically Amplified resists:** In the ever-evolving modern world, new developments are taking place in using chemically amplified resists. These resists can produce high resolution, better contrast, great resistance while etching which make them advantaged over typical e-beam resists.

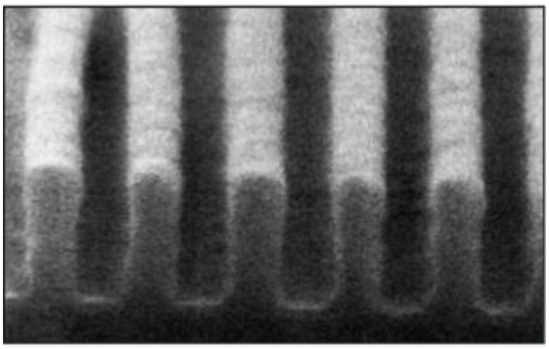

Figure 21: 55 nanometer equal lines and spaces [10]

The recent updates in fabrication field reports printing of 55nm equal lines along with spaces [10]. This was also created using e-beam lithography. Chemically amplified resists due to their advantages might replace conventional e-beam resists in the near future.

## Conclusion

This paper briefly explains the e-beam lithography's working, evolution and few of its recent developments. These developments in the areas of high-resolution pattern defining helps in studying more and more into the field of fabrication and will be useful in gaining more insights in working with electric circuits. E- beam lithography being one of the best tools for fabricating nano patterns plays an important role in the micro and nano fabrications. More developments being done in this area because modern technologies require a greater number of circuits to be placed on a conventional substrate. So, more developments will surely keep on arising in this area.

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