# Electron-Beam Lithography: From Past to Present

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# 1    Introduction

Lithography is the technique which enables patterns to be transfered to a material. In the simplest electrical engineering application, it is used to create Printed Circuit Boards (PCBs). These large-scale PCBs can even be made using a pattern printed from a laser printer on white paper, and some sort of Ultra-Violet (UV) light source. Over the years lithographic technology has become more and more advanced, allowing finer resolution and these advances have been part of what has allowed the semiconductor market to grow into the industry that it is today. Without lithography, the creation of circuits in semiconductors like Silicon (Si) and the interconnection of those circuits with each other and the outside world would not be possible.

Current optical (visible, UV) photolithography is reaching its limits in terms of modern Ultra Large Scale Integration (ULSI) fabrication. Many applications in microelectronics need even higher levels of performance (higher speed and lower power) and higher functional density [1]. They also require high reliability and lower cost as well. As we approach the 100 $nm$ feature-size mark and go beyond, other lithographic techniques will need to be used. These possible future techniques include Extreme Ultra-violet (EUV) lithography, X-Ray lithography, and Electron Beam Lithography (EBL). On the surface, it seems that EBL is one of the most promising technologies, as electrons can achieve a theoretical wavelength of up to $3 \times 10^{-13}$ $m$, which is much smaller than the wavelength of X-Ray or UV light. Currently, however, EBL is limited to about $10 - 20$ $nm$ under ideal conditions. The use of electrons can also mean the elimination of masks, as direct-writing of patterns is possible. It does have some disadvantages, however, because compared to the sizes of wafers ($> 300mm$), electron beams are small, so the electron beams must be scanned across a wafer. This means that electron beam lithography can be much slower. Today, as microelectronics approaches sub-micron feature sizes, researchers are focusing on ways to improve the throughput of EBL system. Electron beam lithography has already undergone much development and in the next ten years, it will be surely be an integral part of the semiconductor manufacturing process, and continue to be used to manufacture exotic nano-devices. Even if EBL is not the method of choice for patterning materials for devices, it will continue to be used to create masks for optical and/or X-Ray lithography.

## 1.1    History and Trends in Lithography for Microelectronics

Photolithography enables the transfer of a pattern onto a material so that the material can be etched in a way that is determined by the pattern. This is done through the use of a light source, and a photosensitive material, photoresist. Mercury (Hg) sources were used

for the 435 $nm$ peak (g-line), and then a 365 $nm$ peak (I-line) was used later. Excimer lasers were then used, which provide light in the Deep Ultra-Violet (DUV) range. KrF excimer lasers produce light at a wavelength of 248 $nm$ and are used to produce devices with minimum feature sizes of 0.25 $\mu m$. Conventionally, it is not possible to define features with a size smaller than the wavelength of the light being used. Using Resolution Enhancement Technology (RET) techniques, however, it is possible to use 248 $nm$ light to produce devices with features as small as 160 $nm$ [2]. See Figure 1 which shows the trend in ULSI in the past 20 years, as well as the predicted trend until 2010. Figure 1 shows that the miniaturization
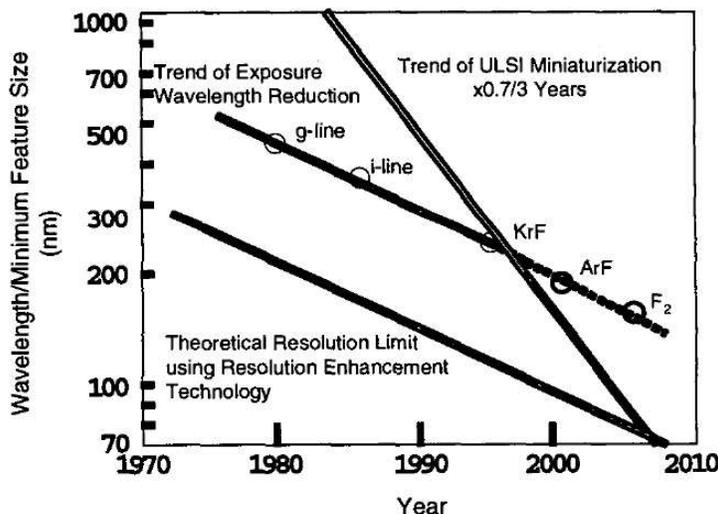


Figure 1: Wavelength in optical lithography and miniaturization trend in ULSI. From [2].

trend is moving faster than the wavelength reduction in optical excimer sources. So either newer excimer sources like ArF or $F_2$ need to be available sooner than predicted, or RET will be necessary, in order to continue the miniaturization rate of progress towards the 70 $nm$ feature-size mark. Beyond the 70 $nm$ node, EBL or some other lithographic technology will surely be necessary.

## 1.2   Basic Photolithography

The basic traditional optical lithography process begins with the deposition of the photoresist. A few drops of liquid photoresist solution are applied to the wafer, and then the wafer is "spun" in a centrifuge. The centrifugal force spreads the photoresist across the wafer, and a desired thickness of photoresist can be achieved by selecting an appropriate spin speed. The photoresist is then "pre-baked" on a hot-plate or in a furnace. This hardens the photoresist layer. The photoresist now needs to be patterned. This is done by with the help of a mask, which is normally made of Chromium (Cr) deposited on glass to define a

pattern. The mask is placed in front of the wafer, and then the mask is carefully aligned with the previous patterns on the wafer. UV light is then shone through the mask using a stepper. This exposes the photoresist in the areas which were not beneath the Cr part of the mask. If positive photoresist is used, then the exposed areas will be susceptible to certain chemicals (the developer), and if negative photoresist is used, the unexposed areas will be susceptible to the developer. When the wafer is placed into a developer solution, the now sensitive areas will be dissolved, and only a pattern will remain, which will look like the pattern on the mask (for positive resist), or the inverse of that pattern (for negative resist). The wafer is then "post-baked" which will harden the photoresist layer further, and make the pattern more resistant to peeling. There is now a mask directly on the surface of the wafer. The material under the photoresist mask may now be etched, doped, or treated in whatever way the device engineer would like. Or, a new layer can now be deposited and the lift-off technique can be used. The photolithography process is complex, however, it does have the following advantages:

1. It is fast, because UV light can illuminate the entire area of the wafer at one time.

2. Large area wafers can be used.

3. No complex light focussing systems are required.

4. Well-developed technology.

The main disadvantage of photolithography is that devices are now being fabricated with device features on the same scale as the wavelength of the light. This means that light diffraction through the mask becomes a problem. RET techniques can be used to double the resolution. Beyond that, optical lithography simply cannot function below one-half of the wavelength of the light without some serious reliability issues. Photolithography already has one of the lowest yields in the process sequence for semiconductor devices.

## 1.3   Current State of the Art

Current lithography techniques, use ArF 193 $nm$ light for exposure, which allows minimum feature sizes of around 100 $nm$ using RET. This is sufficient for the 1.3 $\mu m$ node and the 100 $nm$ node. Intel has invested lots of money into EUV, however, which uses 157 $nm$ UV light and is capable of patterning device features below 70 $nm$. Thus EUV will most likely be used into the 100 $nm$ and 70 $nm$ nodes. Beyond that, semiconductor fabrication will need to rely on newer techniques such as x-ray lithography, EBL, or other advanced methods. Nanotechnology devices are already relying on EBL especially for devices which rely on quantum effects, which require feature sizes well below 100 $nm$.

Electron Beam Lithography (EBL) has been used for many years. They have progressed from Gaussian-beam system to shaped-beam system and now to electron beam projection systems (see Figure 2). More recently projection EBL has achieved even higher levels of
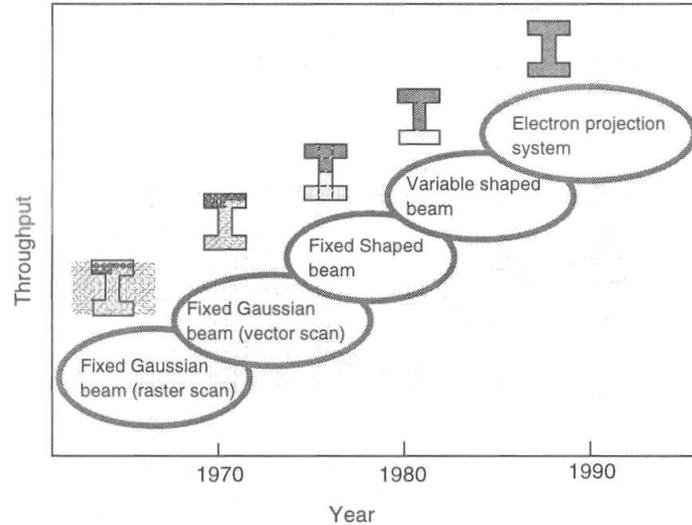


Figure 2: Improvement in throughput by changing beam shape and shot number. From [3].

throughput has become viable for the mass-production semiconductor industry with system such as SCALPEL from Bell Labs/Lucent and PREVAIL from IBM. There is also much research into the fabrication of massively parallel electron beams and optics fabricated by MEMS technology. EBL may be ready for the 70 $nm$ feature node and beyond, and it will allow for new higher-speed lower-power devices to be fabricated.

# 2   Electron Optics

## 2.1   Basic Electron Physics

In 1924 Louis de Broglie wrote his Ph.D thesis which attempted to show that electrons could show wave-like properties under certain conditions. The ideas in his thesis were fully confirmed with the observation of electron diffraction in crystals in 1929. In his thesis, De Broglie's gave a simple formula for the wavelength of an electron and it is as follows:

$$\lambda = \frac{h}{p} = \frac{h}{m \cdot v} \tag{1}$$

where $h$ is Planck's constant $(6.626 \times 10^{-34} J/s)$, $p$ is the momentum, $m$ is the mass of the electron $(9.11 \times 10^{-31})$, and $v$ is it's speed. This neglects special relativity effects, because it is assumed that the electrons are travelling sufficiently below the speed of light. If the electron were travelling at the speed of light, $c$ $(2.9979 \times 10^9 m/s)$ which is it's maximum theoretical speed, it would have a wavelength of $0.24\ pm$.

An electron's velocity can be determined from it's kinetic energy, by the formula

$$E_{kin} = \frac{1}{2}mv^2. \tag{2}$$

Thus,

$$v = \sqrt{\frac{2E_{kin}}{m}}, \tag{3}$$

and deBroglie's formula becomes,

$$\lambda = \frac{h}{\sqrt{2Em}}. \tag{4}$$

If $E$ is expressed in Electron Volts $(eV)$, and given the constants above, the formula reduces to:

$$\lambda = \frac{1.23}{\sqrt{E}}\ [nm] \tag{5}$$

where $E$ is expressed in $eV$. So if an electron were accelerated to an energy of $100\ keV$ , then it would have $\lambda = 12.3\ pm$. This clearly shows that if lithography could be done with electrons it would have a huge advantage over current optical lithography systems which are limited by their wavelength which is as low as $100\ nm$. This is just a theoretical limit, however. EBL system use projection, as opposed to traditional contact masks, and with most forms of EBL, no mask is used at all. So except in high-resolution systems (with very low throughput) where electron diffraction can come into play, the resolution of the system is limited by the beam column rather than the wavelength of the electrons. Figure 3 shows

the effects of various beam column effects on the minimum achievable beam width at the resist. The resist, however, also places limitations on the resolution of the beam which can
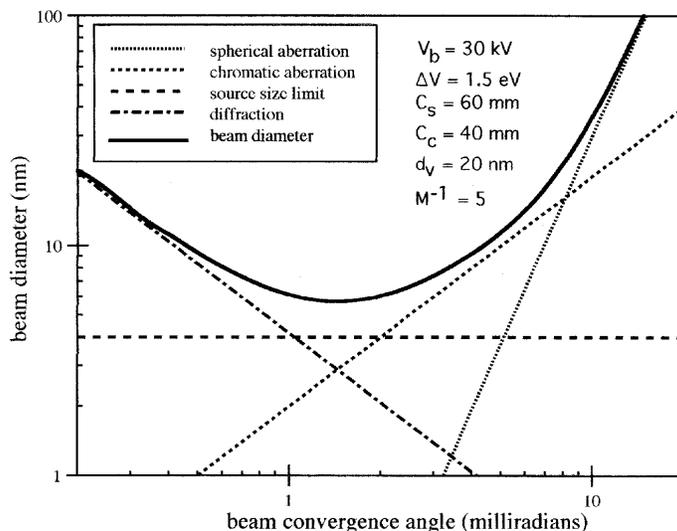


Figure 3: Beam diameter vs. beam convergence angle due to various beam column effects such as abberations and source size, and diffraction. From [4].

be greater than those effects shown in Figure 3, and in most cases scattering in the resist places the limiting factor for the resolution.

## 2.2  Electron Column

The electron column is the most critical part of the Electron Beam Lithography system. It consists of the electron source/gun, an alignment system for centering the beam in the EBL column, a mechanism for shuttering or blanking the beam, several lenses, a stigmator (used for correcting astigmatism in the beam), and a beam deflector. A typical electron beam column is shown in Figure 4. EBL columns vary greatly however, depending on the shape of the beam that is desired in the end. Figure 5 shows four different configurations of EBL columns for different final beam shapes.

## 2.3  Electron Sources

The electron source is where it all begins. This is where the electrons are generated, which will end up reaching the resist on the sample. There are three main criteria for an electron source, which are somewhat analogous for light sources:

Figure 4: Cut-away view of a typical EBL column. From [5].



Figure 5: Four different types of EBL columns showing their electron-optical components. From [6].

1. Virtual source size: Determines the amount of demagnification required in the column. Smaller is better here, as it will allow a the electron beam to be focused into a smaller spot size on the sample, with fewer lenses. This makes the column less complicated, and allows a higher resolution to be achieved.

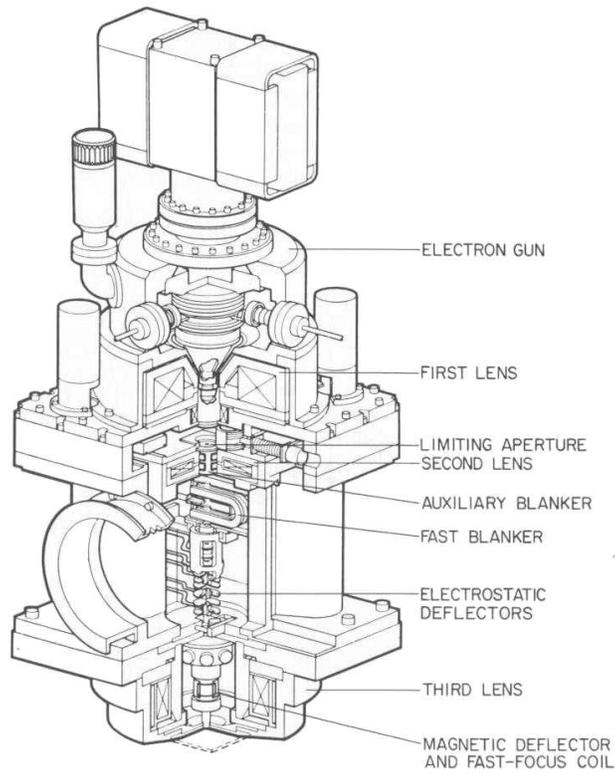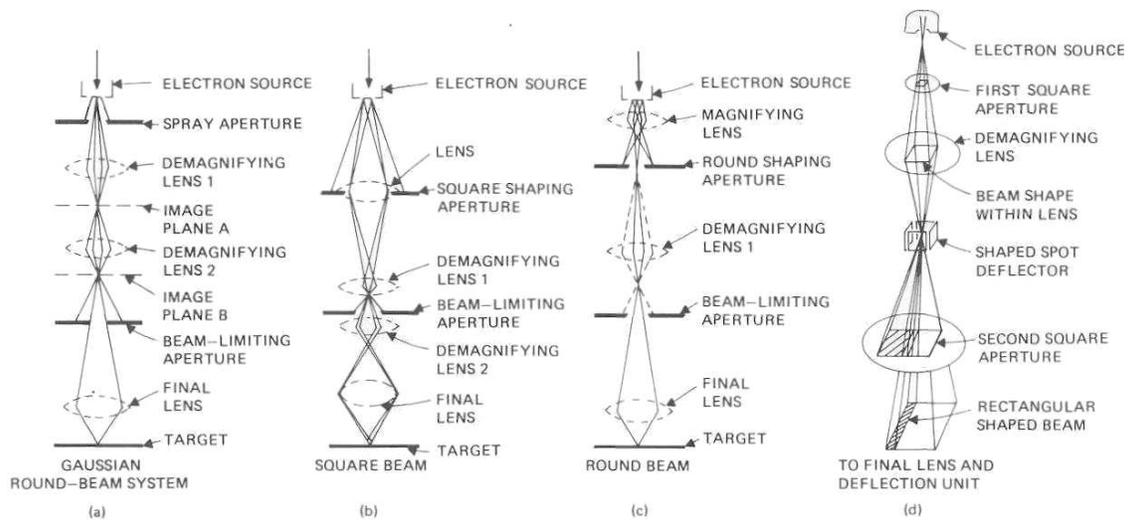2. Brightness: Similar to the intensity in conventional light optics. Brightness is measured in $A/cm^2/steradians$. To a first order, higher brightness is better, as it allows increases the rate of reaction with the resist. However, if a high resolution is required, a lower brightness is necessary.

3. Energy spread: Measured in Electron Volt ($eV$), this describes the spread of the energy distribution of the emitted electrons. An electron beam with a wide energy spread is comparable to white light, while an energy beam with a narrow spectrum is comparable to a laser source. A narrow electron energy spread is desired as it reduces chromatic aberrations.

Traditionally tungsten sources were used as electron sources. The tungsten filament is heated by passing current through it and electrons are emitted thermionically from a sharp tip. The disadvantage of tungsten sources include a low brightness, and a high energy spread due to the high operating temperature (2700 $K$) [4]. Lanthanum Hexaboride (LaB$_6$) is a newer thermionic source which can achieve very good brightness at a lower temperature of 1800 $K$. It has a slightly smaller source size than tungsten, however, it requires a better vacuum of $10^{-8}$ $Torr$ which is easily attainable in present systems.

Thermionic field emission sources are the best available electron sources. Cold field-emission sources are rarely used in EBL mainly because of high short term noise which is due to atoms adsorbing onto the tip. This causes fluctuations in the electron current in the short term and as well as in the long term. Thermal field emission sources combine the best of both field and thermionic emission sources. A tungsten needle (with approximately 1 $\mu m$ tip) is used at only 1800 $K$, thus increasing the lifetime of the source. The barrier to field emission of electrons is lowered because the needle is heated. It's brightness, source size and energy spread are all better than the standard thermionic sources. An example of an electron source and the electrodes is shown in Figure 6. Two anodes are normally used, as shown in Figure 7. The first anode (Wehnelt), is the extraction electrode, and is used to extract the electrons from the cathode tip, and the second is used to accelerate the electrons to their full potential [5]. The shield electrode is used to prevent thermally generated electrons from entering the beam. Thus electrons are only emitted from the tungsten tip. The electron source in Figure 6 has the Wehnelt cathode acting as the cathode and the shield.
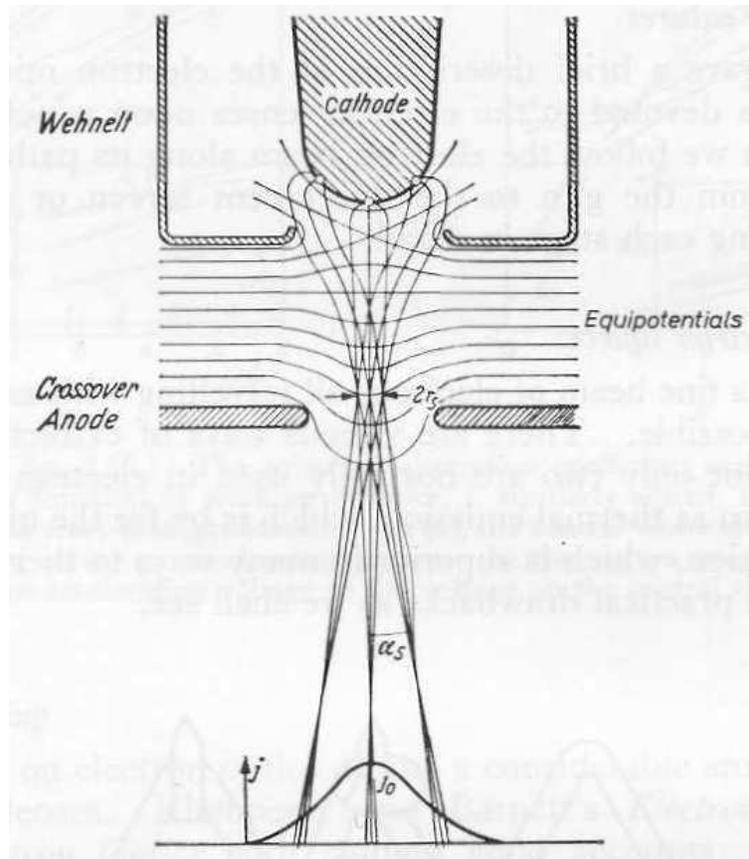
Figure 6: An electron tip showing the electron emission paths along the electric field lines. From [7].
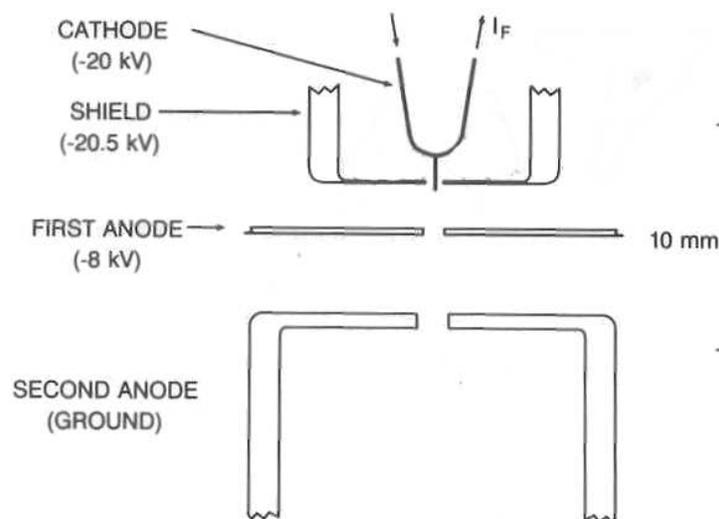


Figure 7: Electron source showing 2 anodes and shield electrode. From [5].

## 2.4   Electron Lenses

Although electrons may have wave-like properties under certain conditions, they are still not electromagnetic waves, like light. In electron optics, electrons can be focused and manipulated in much the same way that light is treated in bulk geometrical optics. However, they behave like classical charged particles, as opposed to waves.

Electrons are manipulated in two basic ways, through an external electric field, or a magnetic field. From Coulomb's law, we know an electric field will exert a force on a charged particle. An electron will experience a force of $\boldsymbol{F}_E = -e\boldsymbol{E}$, where $e$ is the elementary charge of an electron, and $\boldsymbol{E}$ is the electric field. According to Lorentz's Law, an electron will experience a force when travelling perpendicular to a magnetic field. This force will be perpendicular to the magnetic field and the electron's velocity, and is given by $\boldsymbol{F}_B = -e\boldsymbol{v} \times \boldsymbol{B}$. The contributions could be summed together, however, normally in EBL systems, both magnetic and electric fields are not used simultaneously. Most of the basics in electron optics come from the above two equations combined with Newton's second Law, $\boldsymbol{F} = m \cdot \ddot{\boldsymbol{r}}$, where $\ddot{\boldsymbol{r}}$ is a position vector in three dimensions, and the double-dot notation indicated the second derivative with respect to time [7].

Magnetic lenses are used primarily because the aberrations produced by magnetic lenses are less severe than those produced by electrostatic lenses. A cross-section of a magnetic lens is shown in Figure 8. The radial magnetic fields cause the electrons experience rotation
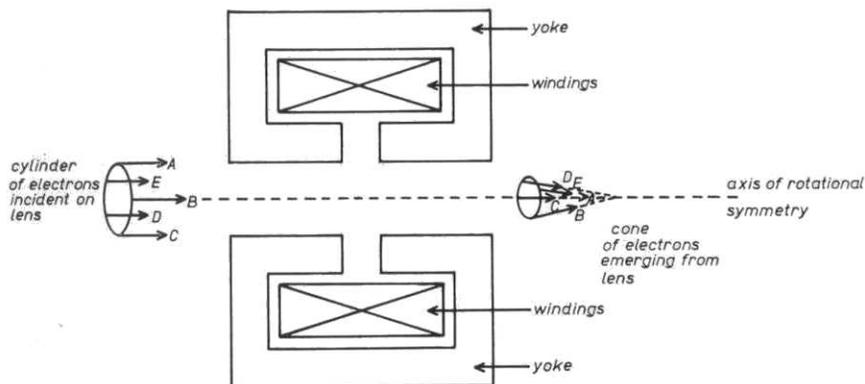


Figure 8: Three-dimensional cut-away view of a magnetic electron lens. From [7].

about the optical axis upon entering the lens. The electrons now have a velocity component in the tangential direction about the optical axis. This component now interacts with the axial magnetic field, imparting a force on the electrons towards the optical axis, bringing them close to the axis. A three-dimensional cut-away view shown in Figure 9 illustrates this more clearly.
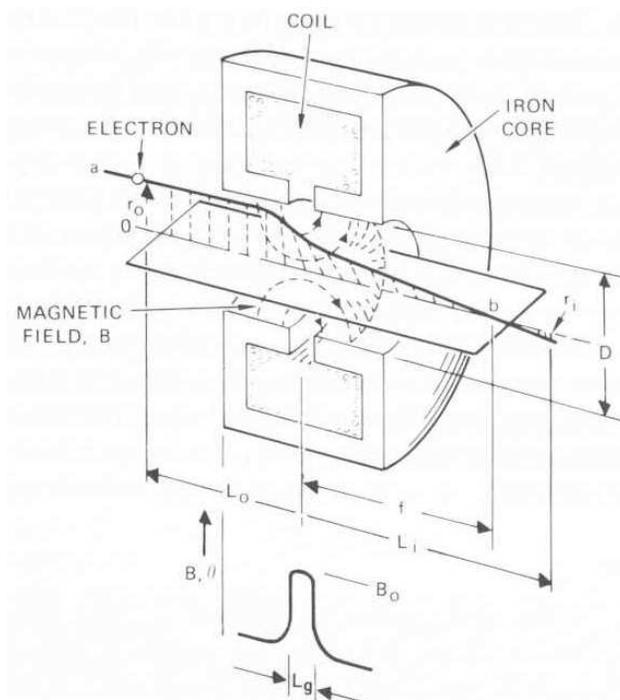
Figure 9: Cross-section of a magnetic electron lens. From [6].

In absence of aberrations (not realistic), the electrons are focused to a focal point a distance $f$ beyond the centre of the lens. If $f$ is large relative to axial magnetic field region, $L_g$, then to a good approximation,

$$f \cong \frac{8V_0}{L_g B_0^2 \eta},$$  (6)

where $V_0$ is the voltage representing the electron's velocity, $\eta = e/m$, and $B_0$ is the approximately uniform axial magnetic field on the axis of the lens across the gap $L_g$.

The same focusing action can be achieved with an electrostatic lens. They are most often used near the electron source as a condenser lens, since the large abberations produced by such a lens will not affect the quality too much in this area of the column. Aberrations caused be the final lens are more detrimental to performance than in the first few lenses. Electrostatic lenses are made up of three plates with an aperture on the optical axis, the two outer plates held at ground and the inner plate held at some voltage. The electric fields act so as to pull the electrons closer to the optical axis.

There are two main types of aberrations in electron beams: chromatic aberrations and spherical aberrations. Chromatic aberrations are caused by the fact that the electron source emits electrons with different energies. The electrons will therefore not be focused to the same spot. Spherical aberrations occur when the outer part of the beam is focused more than the inner part of the beam.

Figure 10: An electrostatic lens. From [7].

## 2.5   Other Electron Optics Components

There are also some other components in the electron beam column which are important, these include apertures, stigmators and beam deflectors.
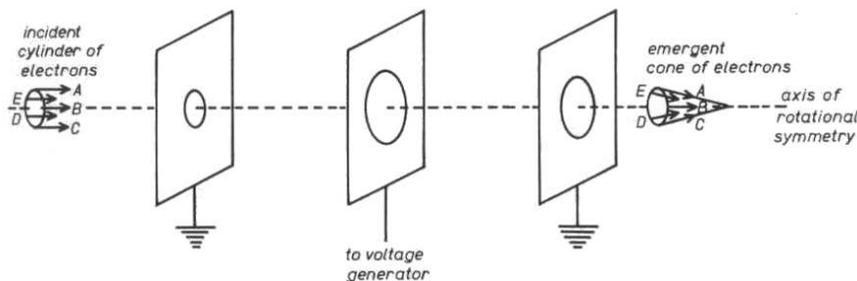
### 2.5.1   Apertures

There are a few different types of apertures, blanking apertures and beam-limiting apertures. Blanking apertures be deflect the beam by deflecting the beam away from the aperture hole. Beam-limiting apertures set the beam convergence angle, $\alpha$ (the angle between the beam trajectory and the normal line to the target) which controls the effect of lens aberrations and resolution but also limits the beam current [4].

### 2.5.2   Beam Blanker

Beam blankers are used to turn off or "blank" the beam. This is necessary when doing vector scanning and the beam needs to be moved from one part of the wafer to another. The beam must be blanked in a time which is very small compared to the time it takes to illuminate one pixel on the array, and the beam cannot move along the substrate while it is being blanked. A common blanker is shown in Figure 11 and it works by applying a voltage to the upper plate which deflects the electron beam away from the centre of the column. A more detailed explanation of the operation of this blanker is given in [5].

### 2.5.3   Stigmators

Astigmatism is a common problem in light optics as well as electron optics. Astigmatism is a type of abberation where the electron beam focuses differently depending on the lens setting. This is due to imperfections in the beam column, due to its construction or poor alignment. Sometimes a beam which is supposed to be circular can end up being elliptical, and rotated differently depending on the amount of focusing. A stigmator can correct for this and other

ELECTRON BEAM

BLANKING
SIGNAL

KNIFE EDGE

50-Ω TERMINATION
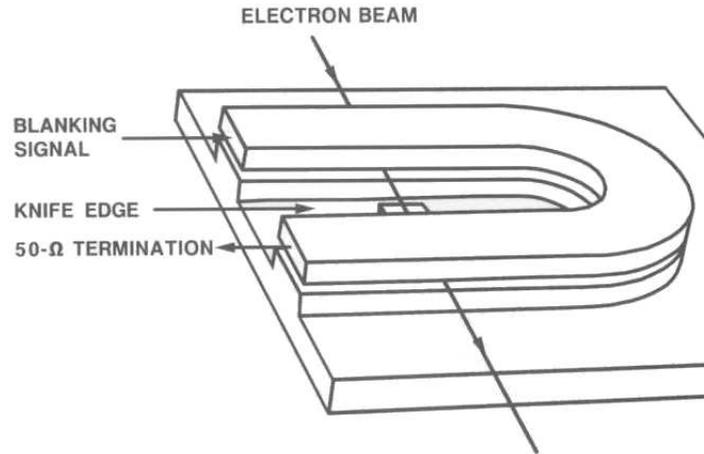
Figure 11: A typical beam blanker. From [5].

kinds of astigmatism imperfections. Stigmators are normally made with $4 - 8$ magnetic
or electrostatic poles positioned around the optical axis. These poles can be configured to
correct for beam imperfections.

### 2.5.4   Beam Deflectors

Beam deflectors are used to scan the electron beam over the target, across an area called
the scan field. The must be done very linearly, with minimal degradation to the electron
beam spot size. In other words you want predictable deflection, constant beam size, and
no hysteresis. Like in electron lenses, deflection can be done by an electric field or by
a magnetic field. Electrostatic beam deflection results in more distortions in the beam,
so magnetic deflection is normally used. Beam deflectors are one of the most important
components, however, any non-linearities or problems with beam deflectors can easily be
fixed in the software which drives them.

# 3   Electron Interactions

One of the problems which limits the resolution of EBL greatly is the electron interactions which occur when they enter the resist and penetrate further into the substrate. There are two main types of interactions which can occur: forward scattering and backscattering. The effects of forward scattering and backward scattering are summarized in Figure 12. The
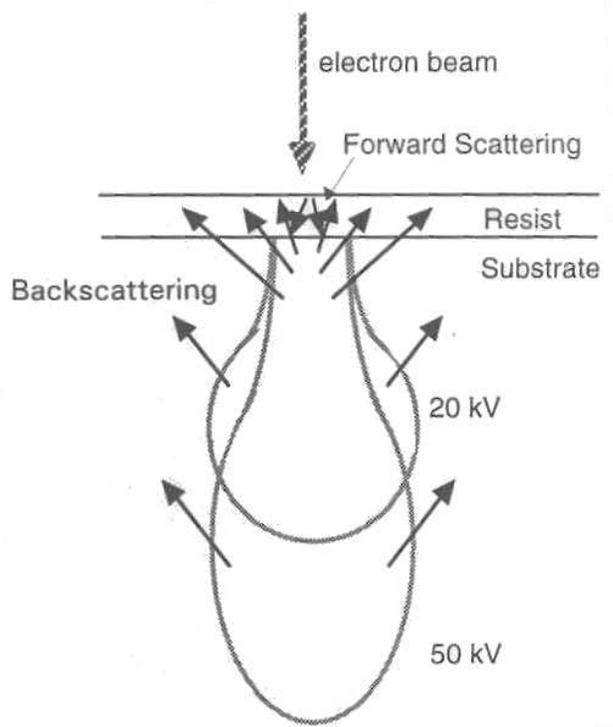


Figure 12: Effects of forward and backward scattering, which cause the actual effective beam size in the resist to widen substantially. From [3].

severity of these interactions clearly will depend on the energy of the electrons involved, as seen in Figure 13. The figure shows the paths of electrons in resist after impinging on the substrate at a single point, as generated by computer simulations. These simulations model the continual slowing of the electrons using the Bethe equation, and model scattering using the screened Rutherford formula. Monte Carlo techniques are often used in order to make the simulations less computationally intensive.

## 3.1   Forward Scattering

Forward scattering is when electrons are deflected by small angle scattering events. This can cause a measurable increase in the effective beam diameter as seen by the resist, which

Figure 13: Computer simulation showing trajectories of electrons in resist. From [3].

depends on the energy of the electrons as well as the resist thickness. And empirical formula which describes the increase in beam diameter is given by,

$$\Delta d = 0.9 \left( \frac{t_R}{V_b} \right)^{1.5}, \tag{7}$$

where $\Delta d$ is the change in beam diameter after entering the resist, $t_R$ is the resist thickness and $V_b$ is the accelerating voltage of the electron beam. Forward scattering is detrimental if very high reso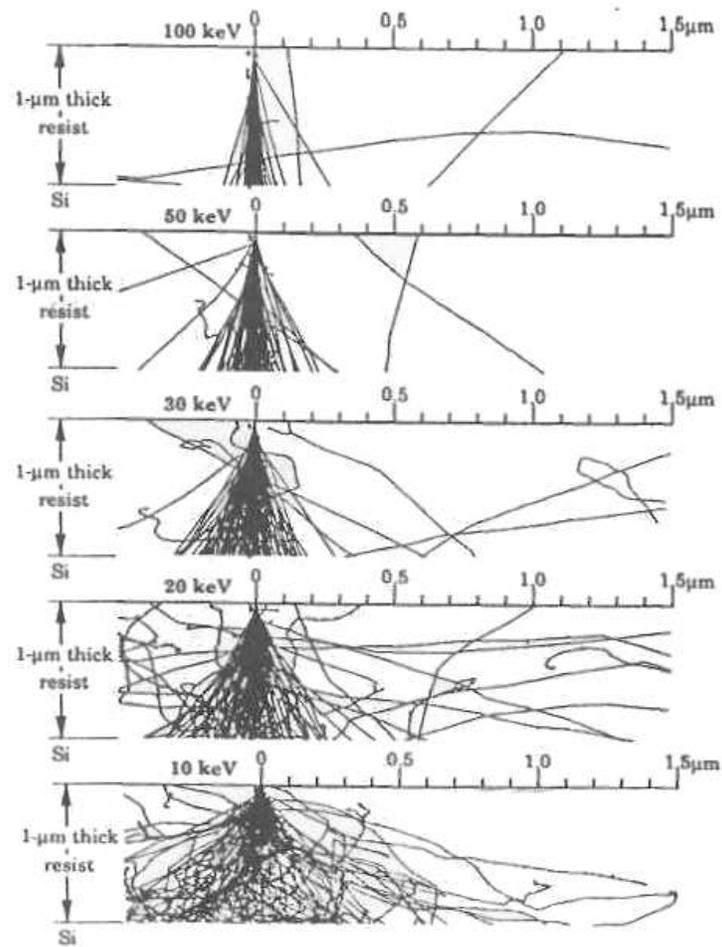lution is required, and can be reduced by increasing the accelerating voltage. Forward scattering does have one advantage, however; it can be used to create a negative sidewall angle in the developed resist. This is advantageous when doing liftoff process with positive resist, because a slight negative sidewall angle is required (see Figure 14). This
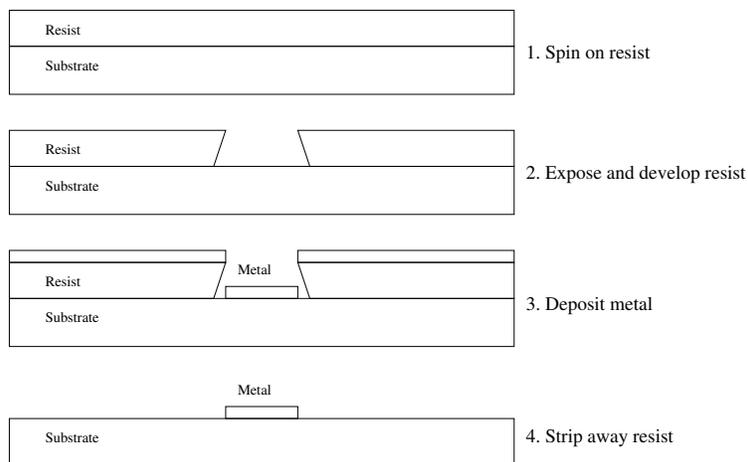
Figure 14: An example of a lift-off process for depositing a metal, using the natural negative sidewall angle as produced by forward scattering.

eliminates the need for using two layers of different resists and simplifies the processing.

## 3.2   Secondary Electrons

When the electrons in the electron beam enter the resist they begin to slow down, and much of this energy is released in the form of secondary electrons, which have energies in the 2 to 50 $eV$ range. This electrons are the most responsible for the actual exposure of the resist. The secondary electrons also cause an effective beam width widening of 10 $nm$. This is what fundamentally reduces the resolution in EBL systems to about 20 $nm$. Secondary electrons, as well as forward scattering cause the bias where exposed features develop larger than the size that they were written, which of course can be compensated for.

## 3.3   Backscattering and the Proximity Effect

Backscattering is a process whereby electrons are scattered in the substrate at large angles and return into the resist sometimes at very large distances from the point where they first entered the resist. This effect is known as the "electron beam proximity effect". For a silicon substrate, approximately 17% of the electrons are backscattered and for a gold substrate, 50% of the electrons are backscattered [4].

The proximity effect is due to backscattered electrons as described above, and is the most serious problem experienced in EBL system. If it is not corrected for, it can cause serious problems in the developed patterns. In essence, the proximity effect is when backscattered electrons expose areas of the resist outside the desired area. In a positive resist system, there are two examples in which the proximity effect can severely affect the pattern. If there is a narrow line between two large exposed areas, the narrow line region may receive such a large dose from scattered electrons, can it can end up being completely developed. Or, a small feature may lose much of its dose due to scattering that it will not develop completely. These two effects can both be seen in Figure 15. The proximity effect also leads to a general
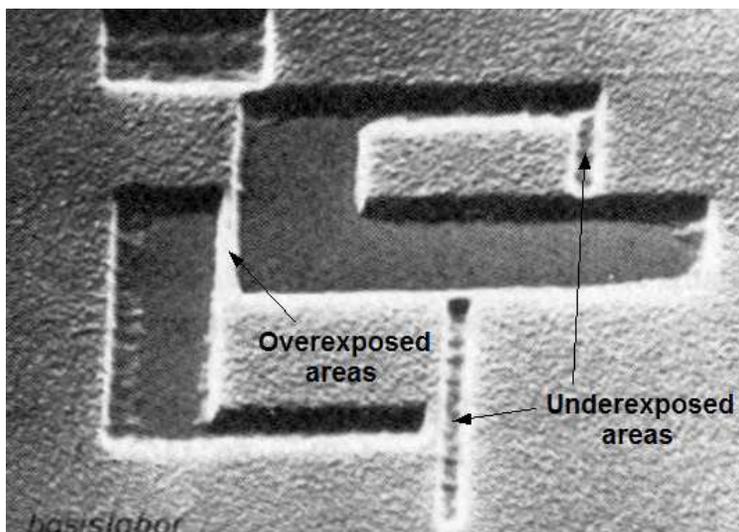


Figure 15: Positive resist pattern affected by the proximity effect. From [4].

increase in linewidth, similar to forward scattering and secondary electrons.

If the pattern has fairly uniform linewidths across the entire sample, it may be possible to simply adjust the electron beam dose until the desired pattern is obtained. Some resists also have higher contrast than others, and this can help prevent the proximity effect as well. Using very low electron beam voltages can greatly reduce the proximity effect, however, one problem with doing so is that the resist must be made thinner to ensure that the entire resist thickness is exposed to the electrons. Another possibility it to put a layer of dense

material (such as gold or tungsten) beneath the resist, to absorb electrons, and reduce the number of backscattered electrons. This can be very effective, as seen in Figure 16, however, it complicates the fabrication process slightly. Similarly, if the material beneath the resist is
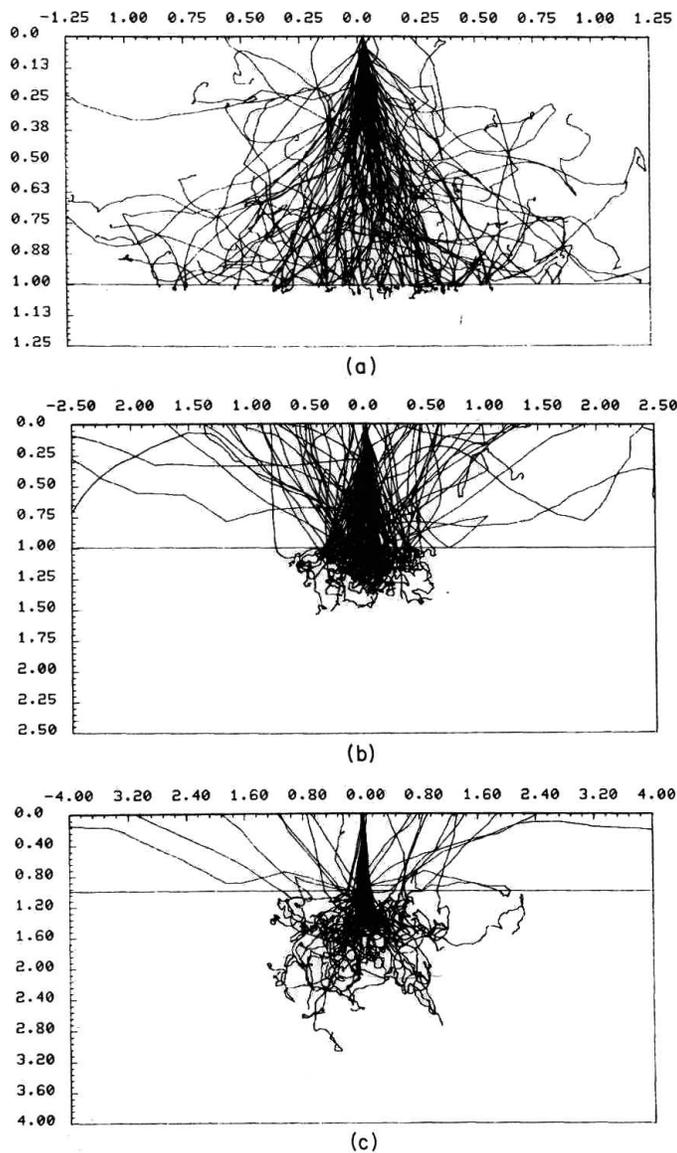


Figure 16: Electron trajectories at (a) 10, (b) 25, and (c) 50 $keV$ incident energy respectively on a gold substrate situated at 1 $\mu m$ beneath the surfrace. From [8].

a thin membrane, then this reduces the backscattering and increases resolution significantly.

There are some other more complicated methods to decrease the proximity effect, without altering the actual materials used, the resists, or the actual process steps. It is possible to reduce the proximity effect by changing only the EBL exposure process. One method is to assign a different amount of exposure to each feature on the pattern. Thus large exposed

features, will receive a smaller dose, and small features will receive a large dose. There are many different software approaches which are being used to calculate the doses for each feature [9, 10, 11]. Similarly it is possible to alter the sizes of all the features to be printed, in order to compensate for the proximity effects. Figure 17 shows an original pattern and a pattern which has been corrected for the proximity effect.
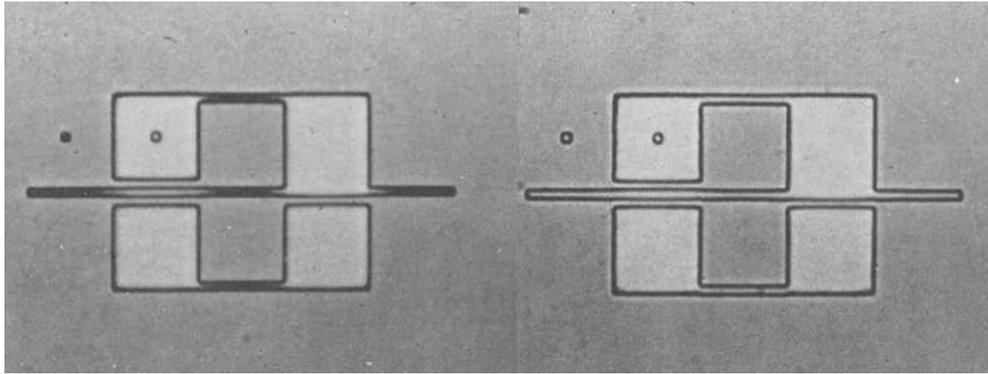


Figure 17: The pattern shown on the left is uncorrected, and the pattern on the right has been corrected for the proximity effect. From [9].

An even more advanced technique which does not require any extra processing is the "GHOST" technique. The inverse of the pattern is written onto the wafer, but through a defocused beam which is designed to match the intensity of the backscattered electrons. This technique causes the non-patterned areas to have a uniform dose, and leads to excellent line width control [4]. Figure 18 shows example of the GHOST technique being used for a pattern of lines. This technique has some drawbacks, however, which include the extra writing time, and some loss of contrast in the resist pattern.

Figure 18: The figure on the top shows a pattern of lines, and the GHOST pattern super-imposed. The figure on the bottom shows the summed contribution of the GHOST pattern and the line pattern. From [4].

# 4   Resists for Electron Beam Lithography

When electrons strike a resist, there are two main physical reactions which take place. One is excitation, where an impinging electron's energy is absorbed by an atom, thus putting the atom in an excited state. A second is ionization, where an incoming electron provides enough energy to cause an electron to be r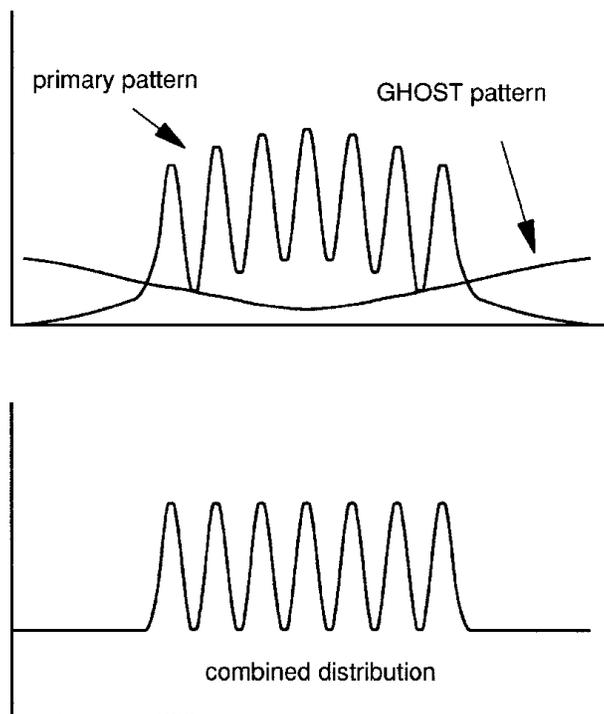emoved from an atom. In polymers, these lead to many different chemical reactions, which can be broadly classified as either chain-scission or crosslinking reactions. Chain-scission is where a polymer chain is broken up into much smaller pieces. This reduces the molecular weight of the resist, which makes it more soluble in a organic solvent (developer). The exposed area is thus dissolved away, leaving behind unexposed areas of resist which form the desired pattern. Thus chain-scission polymers can be used as positive resist. Crosslinking polymers form three-dimensional structures when exposed to an electron beam, thus makes the exposed areas insoluble in a solvent. Thus crosslinking polymers can be used as a negative resist. Figure 19 below shows the scission and cross-linking reactions schematically.
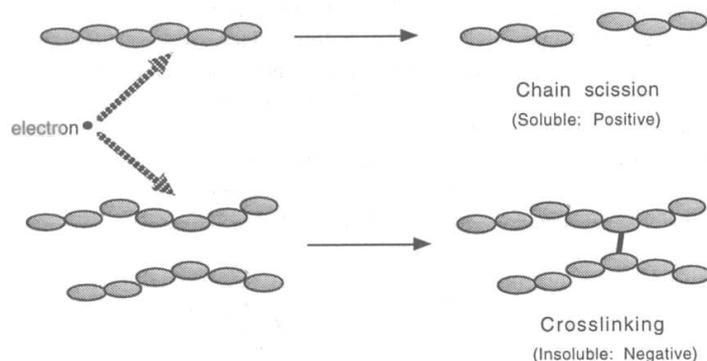


Figure 19: Scission and cross-linking reactions in polymer resists. From [3].

## 4.1   Positive EBL Resists

Polymethylmethacrylate (PMMA) was one of the first resists developed for EBL in 1968 [12] and it remains to this date, one of the highest resolution resists available (about 10 $nm$). PMMA is a chain-scission type resist which allows for high resolution because of its high contrast and non-swelling type dissolution in a developer [3]. The main chain-scission reaction is shown in Figure 20. One of the major disadvantages of PMMA is low sensitivity. PMMA also has poor resistance to dry-etching, which is not so important for mask fabrication by EBL, but very important for pattering layers on silicon wafers. PMMA is available in low-molecular weight form and high-molecular weight form, of which the former is more sensitive

Figure 20: Chemistry of PMMA reaction. From [3].

than the latter. Thus if two layers of PMMA are used, with the low-molecular weight form on the bottom, this will cause the resist to develop with an undercut, thus making it suitable for a lift-off process.

A positive resist which has high sensitivity as well as high dry etch resistance is New Positive electron Resist (NPR), which is made up of poly(2-methylpentene-1-sulfone) (PMPS) and a novolak resin. PMPS is a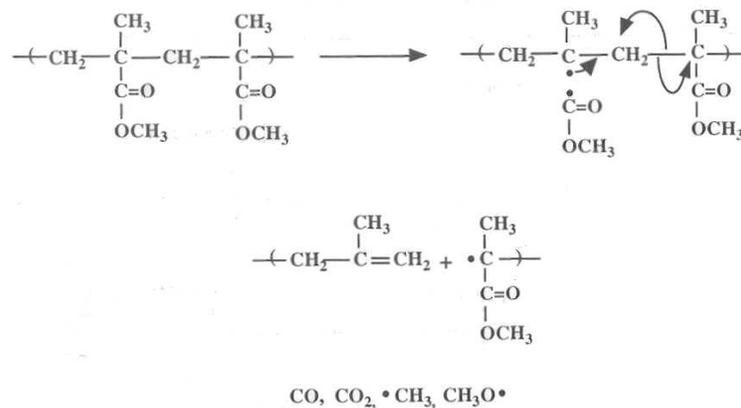 chain-scission polymer and the exposed areas will become soluble in an aqueous base. It also shows self-development, in that the film will actually evaporate somewhat after being exposed to an electron beam. The novolak resin helps the dry-etch resistance of the resist.

A new resist called ZEP has an order of magnitude improvement in sensitivity versus PMMA and it has 2.5 times better etch resistance compared to PMMA although it is still not as resistant as novolak-based resists. ZEP has about the same resolution as PMMA of about 10 $nm$ and it has demonstrated an ability to produce lines of width 10 $nm$ with a pitch of 50 $nm$.

## 4.2   Negative EBL Resists

Negative resists work by cross-linking, as described in section 4 above, however, in general the patterns they produce are not as perfect as those produced with positive resists. Some of the problems include, swelling during development, and bridging between features. They do have much less bias than positive resists do.

If PMMA is exposed to ten times the normal critical dose, chain-linking will occur and it will behave like a negative resist, however, it's resolution will be degraded to about 50 $nm$. One useful resist is SAL-606, which has a resolution of 100 $nm$ and a sensitivity comparable to that of ZEP, which makes it suitable for writing masks for 0.13 $\mu m$ or 0.1 $\mu m$ technology.

# 5    Electron Beam Lithography Systems

EBL have some additional technical hurdles compared to optical systems. Electrical and magnetic noise can both cause problems with the electron beam, and both must be tightly controlled. This means computer monitors, transformers, and pumps must all be kept at a distance from the beam column or some shielding is required. Mechanical vibrations are also a problem, however these are also present in optical systems. EBL systems do provide much higher resolution than optical systems, so mechanical vibrations can be even more disastrous to the performance.

There are many different types of EBL systems on the market, from SEM and STEM coversion kits, to mask-writers, shaped-spot systems, and modern electron-beam projection machines. Some general types of machines will be discussed and various methods which are used in all machines to achieve the desired performance.

## 5.1    Converted SEM Machines

Scanning Electron Microscope (SEM) and Scanning Transmission Electron Microscope (STEM) systems can easily be converted into EBL systems. These systems suffer, however, from a small field of view, and low throughput. They can however be a good option for research in universities where throughput is not an issue and low cost is important. SEMs normally have some lenses to focus the beam on the specimen, a beam-blanking mechanisms, and some magnetic deflection coils used to scan the beam across the sample. With access to these parts of the column, an SEM can be used as an EBL machine. A PC can be fitted with a 16-bit Digital to Analog Converter (DAC) card in the PCI bus, and this can be connected to the beam deflection system of the SEM. Unfortunately, the scan coils of SEM machines are normally optimized for imaging in raster format, as opposed to vector format. The raster and vector methods are show in Figure 21 below. Clearly, raster scanning is
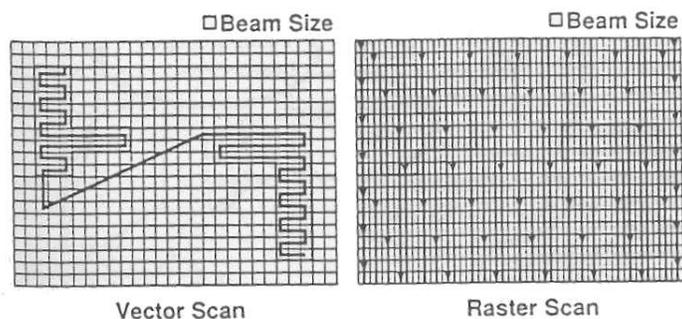


Figure 21: Comparison between raster-scan method and vector-scan method. From [3].

much slower than vector scanning, although the slowdown due to raster scanning depends on the time needed to deflect the beam to each new beam position, compared to the time to scan from to each device feature in vector scanning. At worst is only a factor of 2-3 times slower than vector scanning. Regardless, although SEM machines cannot compete against dedicated EBL systems as far as writing area and speed, they can be useful for applications such as small quantum devices (metal lines, junctions, SQUIDs), a few transistors, small gratings, and other small devices.

## 5.2   Gaussian Vector Scan Method

Vector scanning in one form or another is much more common than raster scanning, as the increase in complexity is not too big, and the increase in speed can be significant. Most systems use two sets of DACs, the first DAC drives a deflector which directs the beam onto the corner of some primitive shape on the target wafer. The second DAC drives the same deflector or a different deflector in a raster pattern to fill in the shape. A moveable x-y substrate stage is often used, and is normally controlled using a laser interferometer to give accuracy down to the wavelength of the laser being used. An example of this type of vector-scanning is shown in Figure 22.

## 5.3   Shaped Beam and Cell Projection Systems

Shaped spot system are an attempt to improve on the throughput even more compared to vector scanning. In shaped spot system, the beam is passed through a shaped aperture, most often a square or a rectangle. It is more common however, to have a second aperture, so that the beam shape can be varied dynamically during the lithography process. This is illustrated schematically in Figure 23. The shaping deflector shown in the the figure, directs the already-square beam onto a corner of the square aperture to form a rectangle of almost any dimension. If the second aperture can be rotated, then it is also possible to form triangles of any shape as well. This has a considerable increase in throughput over conventionally vector and raster scan systems.

Cell projection system use a "stencil" mask which has all the desired shapes for the pattern which needs to be created. This can be especially useful if the pattern that needs to be generated only has a few basic shapes, such as RAM or other arrays. Cell projection has an advantage over shaped beam systems in that complex shapes can be created on a stencil mask beyond rectangles and triangles, at a modest increase in throughput. An example of a cell projection system is shown in Figure 24 below.
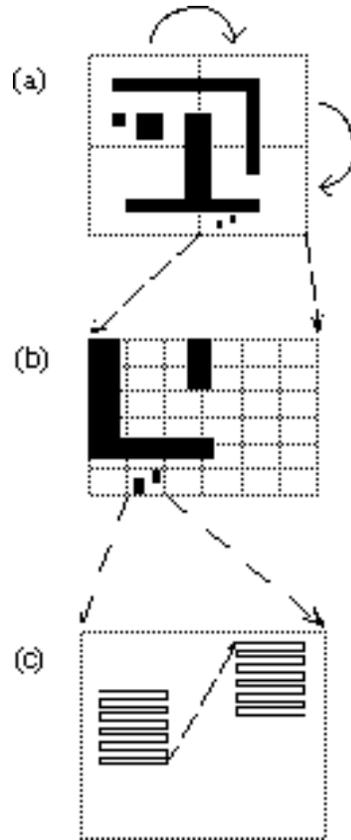
Figure 22: An example of vector scanning: (a) A moveable stage can move the wafer between fields. (b) The device feature can be selected using a "coarse" DAC. (c) The rastering of individual features can be done using a "fine" DAC. From [4].
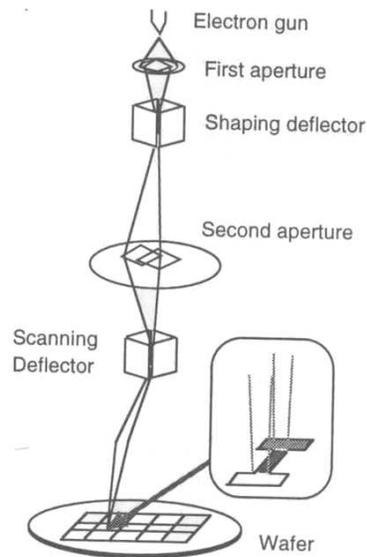


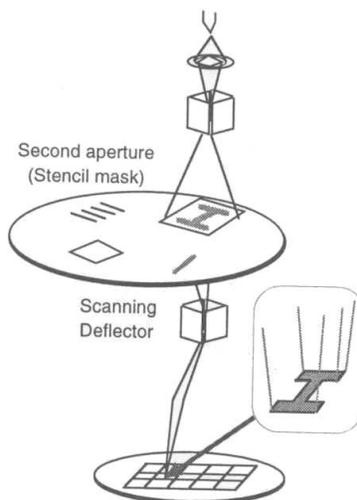Figure 23: Example of a shaped beam system. From [3].

Figure 24: Cell projection EBL system. From [3].

## 5.4   Mask Projection Systems

The projection systems discussed here are very similar to the cell projection system discussed in section 5.3, however, they are different enough that they deserve their own catergory. One of the problems with cell projection is that 20 $\mu m$ of Si is required to stop 50 $keV$ electrons from penetrating and exposing the resist in unwanted areas. The wafer containing these patterns cannot have too high of an aspect ratio for these holes, so the holes in the wafer must be at least 2 $\mu m$ wide. Electron optics can then be used to demagnify the cell pattern by 20 in order to produce features on the order of 0.1 $\mu m$. This means that a large mask will be required to pattern a very small area. Another disadvantage of cell projection is that the electrons which are absorbed in the mask will cause the mask to be heated which can cause significant changes in the sizes of features.

Some projection systems have been designed to alleviate these problems associated with EBL projection systems. The projection system most likely to be used in mass-production EBL is SCaterring with Angular Limitation Projection Electron-beam Lithography (SCALPEL) [2]. The key feature of the SCALPEL system is the use of a scattering mask as opposed to a mask which absorbs the electrons. The mask consists of a thin layer of Silicon nitride (SiN) (150 $nm$) covered with a 50 $nm$ pattern of Gold (Au) or Tunsten. High energy 100 $keV$ electrons are used, and the electrons which pass through the SiN are most likely to be focused and to pass through the back focal plane aperture, and those which pass through the heavy-metal pattern will be scattered, and will not pass through the aperture. This concept is illustrated in Figure 25. The advantage of this system is that the scatterer can be made very thin (50 $nm$) which allows very fine patterns to be delineated in the mask wafer. The
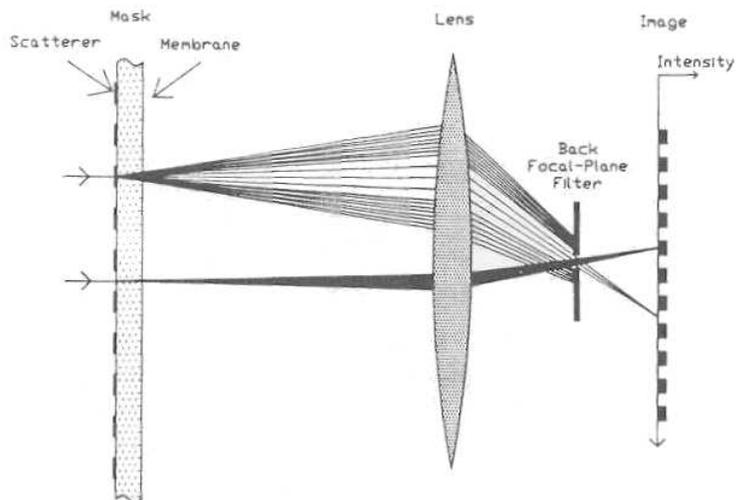
Figure 25: Basic principle in SCALPEL. From [3].

SCALPEL system produces contrast as high as 95% in the resist, as very few of the scattered electrons reach the resist. This system also has a huge advantage over traditional cell projection in that contrast generation and energy absorption are separated between the mask and the aperture [2]. The electrons' energy is not absorbed in the mask, only scattered, thus there is no thermal instability in the mask.

The SCALPEL system uses a large 1 $mm$ × 1 $mm$ parallel beam of 100 $keV$ electrons and scans the beam continuously across the mask by moving the mask itself. After passing through the mask, the beam is demagnified by a factor of four using two sets of lenses. Thus the target wafer must be moved in the opposite direction but only one-quarter the distance. The thin projection mask is supported by vertical struts which help keep the mask flat. The area between the struts is the same width as the electron beam, so after one scan of the beam across a column of the mask, the beam must be "stepped" to the next row. This technique is illustrated in Figure 26. Beam deflectors placed close to the wafer (seen in Figure 26) are used to "stitch" the pattern back together since each strip of the pattern on the mask is separated by a strut. There is some slight overlap (several $\mu m$) in the patterns of each row. This is to compensate for the slight Gaussian nature of the beam.

According to its designers at Lucent/AT&T Bell Labs, the SCALPEL has many advantages besides the simply optical design. The area over which the beam may be scanned is not limited by the electron optics (ie. the deflectors or lenses), but only the size of the mask and the mask stage travel. Also, because the beam is continuously scanned across a column on the mask, the final image in the resist is made up of many overlapping images along this column, eliminated any problems with stitching in this direction.

The SCALPEL shows a typical tradeoff between resolution and throughput. This is due
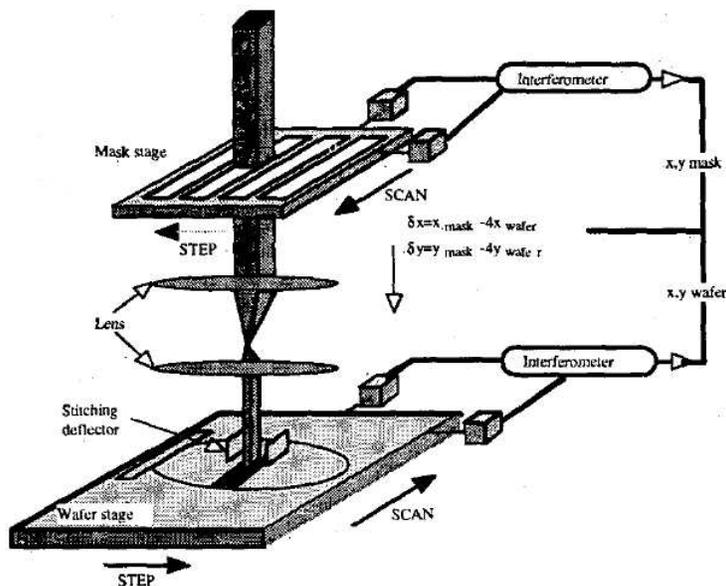
Figure 26: Illustration showing the SCALPEL step-and-scan technique. From [2].

to the fact that if the beam current is increased, faster exposure takes place, however, at the expense of blurring due to increased electron repulsion in the beam (also known as space charge effects). Throughput on the SCALPEL system as been predicted to be approximately 45 wafers per hour. This is ten times higher than raster-scan EBL systems, and only 50% slower than optical lithography machines. It is estimated by SCALPEL's designers that SCALPEL will be cheaper than optical lithography systems which use RET and hence, could be used for the sub-100 $nm$ ULSI nodes.

IBM has a prototype of a system which uses many of the ideas from SCALPEL. Their system is called Projection Reduction Exposure with Variable Axis Immersion Lenses (PRE-VAIL) [13], and it uses a scattering mask similar to that used in SCALPEL (see Figure 27). The PREVAIL system achieves higher throughput by shifting the main optical axis of the electron beam through the use of a variable-axis lens designed at IBM. This variable axis lens is shown in Figure 28. Deflections within each sub-field can be superimposed onto the magnetic and electric fields used in the variable axis lens. This variable axis system allows the beam to be moved quicker from cell to cell on the mask, and reduces the dependence on slower mechanical components. This system is still in a prototype stage, however, it will surely be a contender in next-generation lithography tools along with SCALPEL.
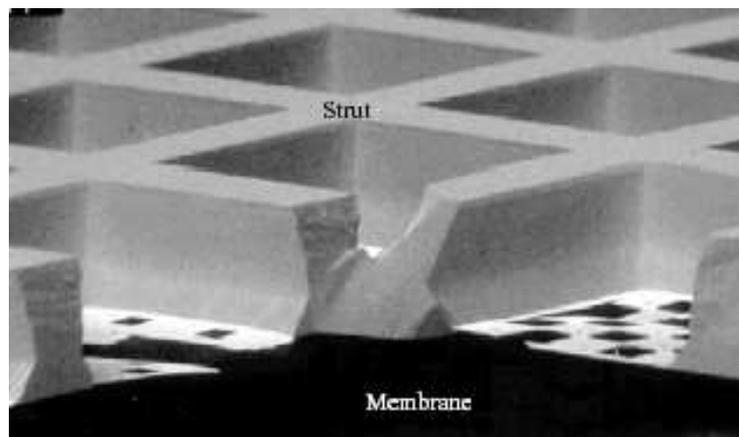
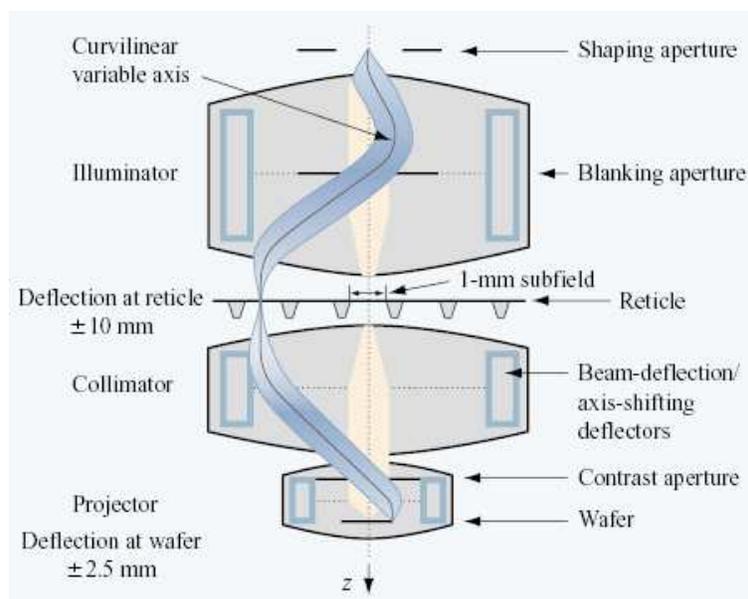Figure 27: A cutaway view of a mask used in the PREVAIL system. From [13].



Figure 28: A schematic of PREVAIL's variable axis lens. From [13].

## 5.5  Massively-Parallel Beam Systems

The system described in the above sections still cannot rival or surpass the throughput of modern optical lithography systems. There are much ongoing research into improving the throughput of EBL systems.

### 5.5.1  MEMS Array of Electron Sources

One method to increase the throughput of EBL system is to construct many tiny electron guns using a micromachining process. Researchers at Ithica university have done just that, with their Micromachined Electron Gun (MEG) device [14, 15]. A MEG device consists of a field-emitter tip made from low resistivity n-type bulk silicon. A tip is grown by a series of conformal depositions of dielectrics and Reactive Ion Etching (RIE) etching of the silicon around the tip, as shown in Figure 29. The tip is made smaller by a wet oxidization
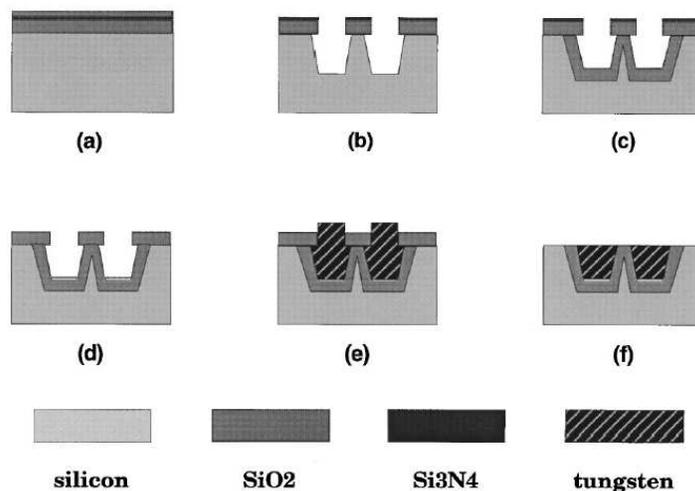
Figure 29: Formation of the silicon tip emitters with self-aligned tungsten electrodes. From [15].

process. A silicon implant is made into the wells, which gives selective depotion of Tunsten. Mechanical micropolishing is then used to ensure the gate electrode is planar. The emitters have an aperture of about 0.5 $\mu m$ and in an array the pitch is 5 $\mu m$. Two tungsten electrodes can be fabricated above the emitter which can act as lenses. The process is shown in Figure 30. It is accomplished by successive oxide depositions, a deep anisotropic etch, followed by a silicon implant, a selective growth of Tunsten, and a mechanical micropolishing. Some simulations have been performed on these lenses, and are shown in Figure 31. The electrode on the far left is the extraction electrode at 80 $V$, the centre electrode is at 24.32 $V$ and the electrode on the far-right is at 200 $V$. This yields a spot size of 8.7 $nm$ at a working distance
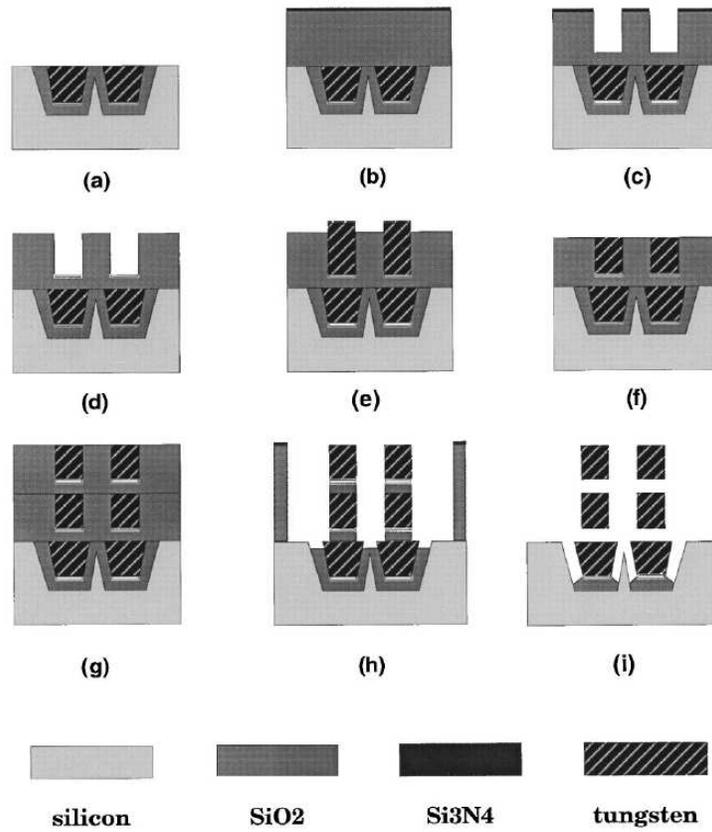
Figure 30: Process sequence for the fabrication of electron lenses on top of the electron guns. From [15].
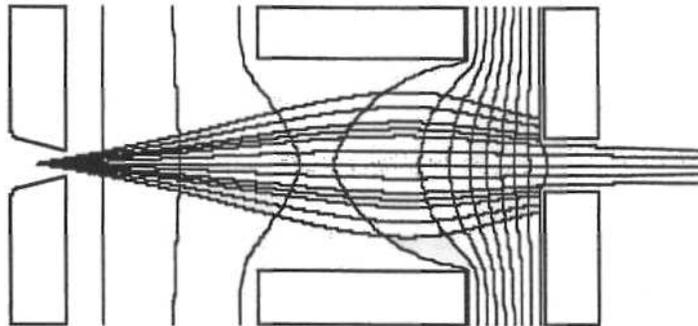


Figure 31: Simulation of a three-electrode electrostatic microlens. From [14].

of 20 $\mu m$. Not only have lenses been integrated with the emitters, but feedback resistors and heaters have been integrated as well [14]. The lower voltage operation of these emitters mean that the electrons will have negligible backscatter and no proximity-effect corrections will be needed, however, exposure times may be longer due to the low narrow/low-current beam.

Arrays of these MEG devices have been constructed, however, process reliability and process complexity are possible concerns with this system. This system also cannot support large beam currents at each pixel, and currently with no beam deflection system, the pitch is limited to 5 $\mu m$ (the spacing of the pixels due to processing constraints). Clearly the sample will need to be mounted to some sort of stage and the beams will have to be turned on and off as the stage moves by 5 $\mu m$ in the x and y directions. It is unclear exactly what kind of throughput could be achieved with a device such as this, because this kind of system is still very much in the prototype stage. One clear advantage of this system is that it does not require a mask, as in the SCALPEL system.

### 5.5.2    Single Beam Multipath system

An alternative to the above method is to use one very large electron beam, and then use miniature MEMS lens and apertures to divide the beam into smaller beams which will focus onto the target wafer. Shimazu has proposed such a structure [16], although it does not seem that any working prototype has been constructed to date. A proposed configuration is shown in Figure 32. This system has a $32 \times 32$ array of sub-electron beams which cover a total of 3.6 $mm \times 3.6$ $mm$ area. It would require arrays of small lenses, blanking deflectors, blanking apertures, and beam deflectors, all implemented in a silicon substrate. The deflectors only need to deflect the beam in one direction, and a stage can move the sample in the other direction.

### 5.5.3    STM Aligned Field Emission (SAFE) Microcolumn Arrays

The SAFE is not much different from the MEG system, although in the SAFE proposal [17] they do not specify how the miniature electron beam columns are to be constructed. The proposed system is shown in Figures 33 and 34.   It is safe to assume that a system like this would have to be constructed using silicon Micro Electro Mechanical Systems (MEMS) technology. Chang provides some estimates about the throughput and resolution of such a system. A resolution of below 100 $nm$ (up to 25 $nm$) is easily achievable, and at 100 $nm$ resolution, it may be possible to attain a throughput of 60 200 $mm$ wafers per hour [17]. This is approaching the throughput of optical lithography which is at least 90-100 wafers
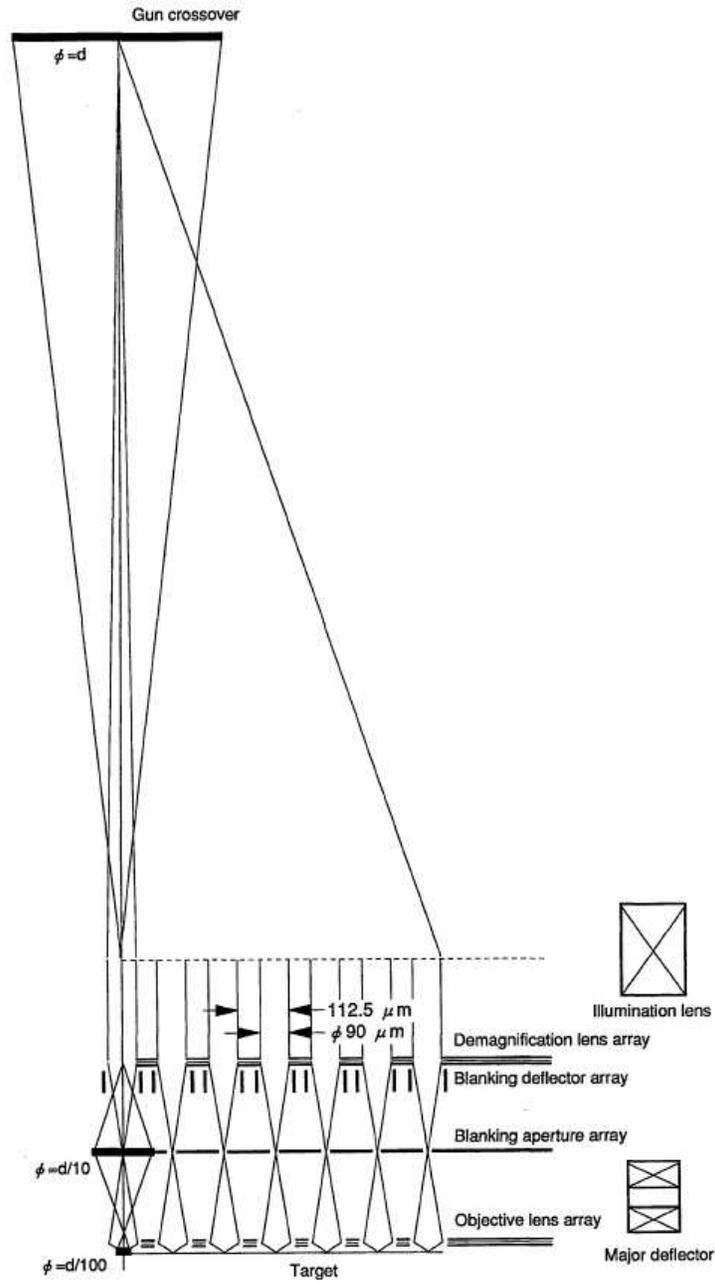
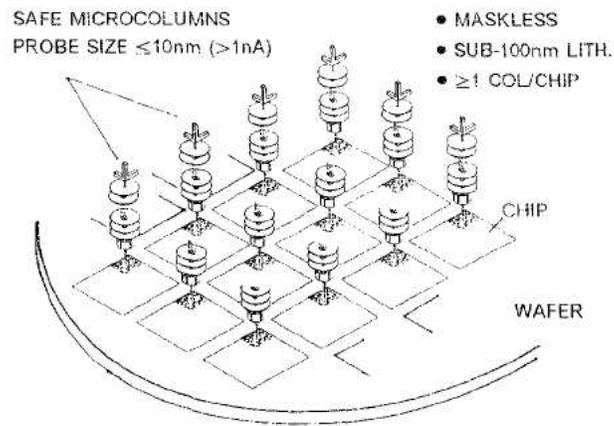Figure 32: Proposed electron optical system for single gun and multiple paths. From [16].

Figure 33: Arrayed microcolumns lithography. From [17].
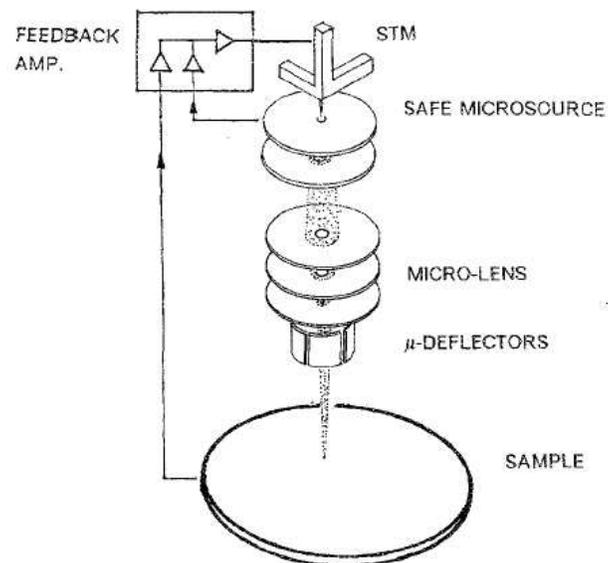


Figure 34: Possible microcolumn structure. From [17].

per hour. Given that this paper was written in 1992, it is possible that Chang's estimates have improved since then.

# 6 Conclusion

There are currently many unknowns when it comes to Electron Beam Lithography. It is still yet to be determined whether or not EBL becomes the tool of choice for lithography beyond the 100 $nm$ feature-size node. Some companies are aggressively pursuing EUV sources and applying Resolution Enhancement Technology (RET) which will enable optical photolithography down to the sub-100 $nm$ regime. There are some competitors for this regime besides EBL, such as X-Ray lithography. Even within the EBL it is unclear which technology which be suitable for production in the microelectronics industry. The SCALPEL and PREVAIL definitely seem like strong candidates, however, it will ultimately be cost and throughput (which is related to cost) which determines which EBL technologies will be the future lithographic tool for the sub-100 $nm$ processes.

# Glossary

**Al** Aluminium - Aluminium is a silvery, ductile metal with atomic number 13, commonly used in electronics as a conductor.

**Au** Gold - Gold is soft yellow metal with an atomic number of 79. It is an excellent conductor of electricity and it's high atomic weight makes it useful in many other scientific applications.

**Cr** Chromium - Chromium is a steel-grey, hard metal with atomic number 24 and is sometimes used for Thin-Film Transistors (TFTs).

**DAC** Digital to Analog Converter - A DAC converts discrete digital signals made up of a certain number of bits into a single analog value.

**DUV** Deep Ultra-Violet - Deep Ultra Violet is a loose term to describe UV light with a wavelength between 200 $nm$ and 300 $nm$.

**EBL** Electron Beam Lithography - Electron Beam Lithography is a means of defining patterns on devices using an electron beam.

**EUV** Extreme Ultra-violet - A term used to describe UV light with a wavelength between approximately 10 $nm$ and 200 $nm$.

*eV* Electron Volt - An Electron Volt is a unit of energy. It is the amount of work required to move an electron through a potential of 1 $V$.s

**Hg** Mercury - Mercury is a heavy silvery metal with atomic number 80, and is the only metal which is liquid at room temperature.

**MEG** Micromachined Electron Gun

**MEMS** Micro Electro Mechanical Systems

**NPR** New Positive electron Resist - Composed of PMPS and a novolak resin.

**PCB** Printed Circuit Board - A PCB interconnects electronic components without discrete wires. Alternative names are printed wiring board or PWB.

**PMMA** Polymethylmethacrylate - A typical chain scission polymer used as a positive resist for EBL.

**PMPS** poly(2-methylpentene-1-sulfone)

**PREVAIL** Projection Reduction Exposure with Variable Axis Immersion Lenses

**RET** Resolution Enhancement Technology - Resolution enhancement technologies are special techniques used to increase the resolution of UV lithography.

**RIE** Reactive Ion Etching - RIE is an etching process which uses a plasma to create reactive chemical radicals and accelerates ions for etching enhancement.

**SAFE** STM Aligned Field Emission

**SCALPEL** SCaterring with Angular Limitation Projection Electron-beam Lithography

**SEM** Scanning Electron Microscope - This microscope operates by scanning an electron beam across a specimen and observing the secondary electrons which emerge.

**SiN** Silicon nitride - Stoichiometric silicon nitride has the chemical formula $Si_3N_4$, however amorphous $Si_xN_y$ can also be grown by various methods.

**STEM** Scanning Transmission Electron Microscope

**Si** Silicon - Silicon is a metalloid with an atomic number of 14. It is the most abundant material in the earth's crust, and is the principle material used in semiconductors.

**SiO$_2$** Silicon dioxide - Silicon dioxide is an insulating material most commonly used as a gate dielectric/insulator in semiconductor manufacturing.

**TFT** Thin-Film Transistor - A TFT is a transistor constructed from thin-films deposited on a substrate, unlike transistors constructed from wafers of single-crystal silicon.

**ULSI** Ultra Large Scale Integration - The integration of millions of transistors a single chip. ULSI supersedes VLSI (Very Large Scale Integration), which means thousands of transistors on a single chip.

**UV** Ultra-Violet - A term used to describe light in the electromagnetic spectrum with a wavelength between approximately 10 $nm$ and 380 $nm$.

**W** Tunsten - Tungsten is a very hard heavy metal with atomic number 74. It has many electrical applications, mainly in filaments.

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