Electron beam lithography

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September 22, 2008

Important Notice

This manuscript is based on the **Handbook of Microlithography, Micromachining and Microfabrication**, Editor P.R. Choudhury, SPIE Press Monograph PM 39
(Chapter 2 *Electron Beam Lithogaphy, M.A. McCord, Stanford University and M.J. Rocks, Cornell University*)
Nevertheless significant modifications were done with respect to the instrumentation used in the Lab Course for Biomolecular Engineering and Biophyics at Technical University Dresden.Literature citations of the original are presently not assigned.

Contents

1 Introduction

1.1 Definition and historical perspective

Electron beam lithography (EBL) is a specialized technique for creating the extremely fine patterns (much smaller than can be seen by the naked eye) required by the modern electronics industry for integrated circuits. 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 process of forming the beam of electrons and scanning it across a surface is very similar to what happens inside the everyday television or CRT display, but EBL typically has three orders of magnitude better resolution. The main attributes of the technology are

1. it is capable of very high resolution, almost to the atomic level;
2. it is a flexible technique that can work with a variety of materials and an almost infinite number of patterns;
3. it is slow, being one or more orders of magnitude slower than optical lithography;
4. it is expensive and complicated - electron beam lithography tools can cost many millions of dollars and require frequent service to stay properly maintained.

The first electron beam lithography machines, based on the scanning electron microscope (SEM), were developed in the late 1960s. Shortly thereafter came the discovery that the common polymer PMMA (polymethyl methacrylate) made an excellent electron beam resist (1). It is remarkable that even today, despite sweeping technological advances, extensive development of commercial EBL, and a myriad of positive and negative tone resists, much work continues to be done with PMMA resist on converted SEMs. Fig.1 shows a block diagram of a typical electron beam lithography tool. The column is responsible for forming and controlling the electron beam.

Underneath the column is a chamber containing a stage for moving the sample around and facilities for loading and unloading it. Associated with the chamber is a vacuum system needed to maintain an appropriate vacuum level throughout the machine and also during the load and unload cycles. A set of control electronics supplies power and signals to the various parts of the machine. Finally, the system is controlled by a computer, which may be anything from a personal computer to a mainframe. The computer handles such diverse functions as setting up

an exposure job, loading and unloading the sample, aligning and focusing the electron beam, and sending pattern data to the pattern generator. The part of the computer and electronics used to handle pattern data is sometimes referred to as the datapath.
Fig. shows a picture of a typical commercial SEM (Zeiss Gemini DSM 982) system including the column, chamber, and control electronics. The column is modified by a set of plates (Blanking amplifier) which are used to deflect the electron beam according to the pattern generated by an external pattern generator (Elphy plus , Raith Company)

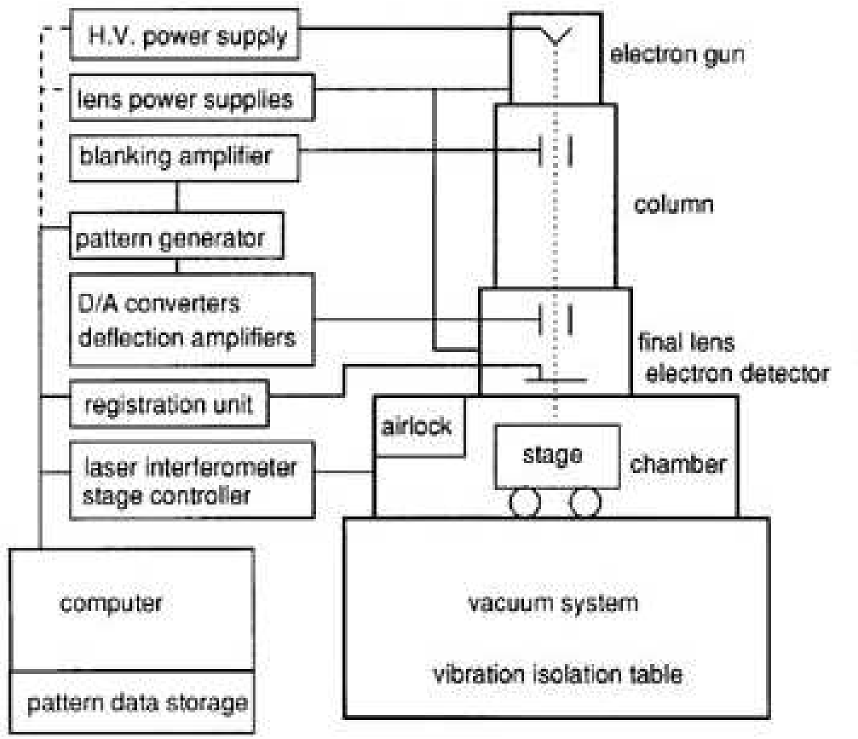

Figure 1: Block diagram showing the major components of a typical electron beam lithography system

1.2 Applications

Currently, electron beam lithography is used principally in support of the integrated circuit industry, where it has three niche markets. The first is in maskmaking, typically the chrome-on-glass masks used by optical lithography tools. It is the preferred technique for masks because of its flexibility in providing rapid turnaround of a finished part described only by a computer

Figure 2: Low Voltage Scanning Electron Microscope Zeiss Gemini DSM 982 with beam blanking attachement

CAD file. The ability to meet stringent linewidth control and pattern placement specifications, on the order of 50 nm each, is a remarkable achievement.
Because optical steppers usually reduce the mask dimensions by 4 or 5, resolution is not critical, with minimum mask dimensions currently in the one to two μm range. The masks that are produced are used mainly for the fabrication of integrated circuits, although other applications such as disk drive heads and flat panel displays also make use of such masks.

An emerging market in the mask industry is 1 masks for x-ray lithography. These masks typically have features ranging from 0.25 μm to less than 0.1 μm and will require placement accuracy and linewidth control of 20 nm or better. Should x-ray technology ever become a mainstream manufacturing technique, it will have an explosive effect on EBL tool development since the combination of resolution, throughput, and accuracy required, while technologically achievable, are far beyond what any single tool today is capable of providing.

The second application is direct write for advanced prototyping of integrated circuits (2) and manufacture of small volume specialty products, such as gallium arsenide integrated circuits and optical waveguides. Here both the flexibility and the resolution of electron beam lithography are used to make devices that are perhaps one or two generations ahead of mainstream optical lithography techniques.

Finally, EBL is used for research into the scaling limits of integrated circuits (3) and studies of quantum effects and other novel physics phenomena at very small dimensions. Here the resolution of EBL makes it the tool of choice. A typical application is the study of the Aharanov-Bohm effect, (4-6) where electrons traveling along two different paths about a micrometer in length can interfere constructively or destructively, depending on the strength of an applied magnetic field. Other applications include devices to study ballistic electron effects, quantization of electron energy levels in very small structures, (7,8) and single electron transistors. To see these effects typically requires minimum feature sizes of 100 nm or less as well as operation at cryogenic temperatures.

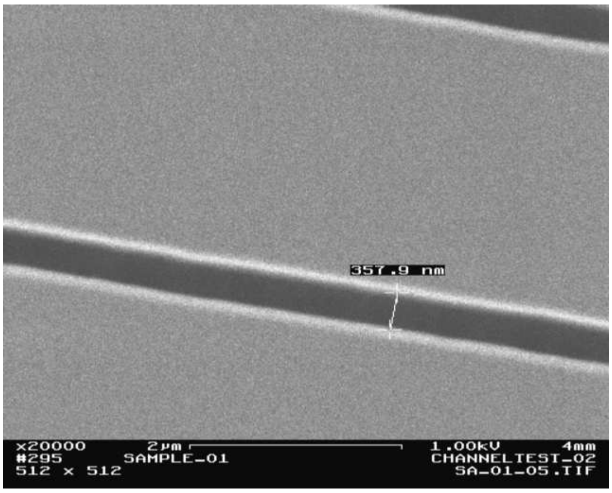

Figure 3: Micrograph of a portion of a microchannel structure prepared in PMMA

During the last years the preparation of submicrometer sized systems which are used in nanofluidic devices to control the diffusibility and shape of biomacromolecules especially DNA becomes increasingly important. A typical part of a microchannel structure prepared by ebeam lithography in PMMA is shown in 3.

2 Elements of electron optics

2.1 Introduction

The part of the EBL system that forms the electron beam is normally referred to as the column. An EBL column (Fig. 4) typically consists of an electron source, two or more lenses, a mechanism for deflecting the beam, a blanker for turning the beam on and off, a stigmator for correcting any astigmatism in the beam, apertures for helping to define the beam, alignment systems for centering the beam in the column, and finally, an electron detector for assisting with focusing and locating marks on the sample. The optical axis (Z) is parallel to the electron beam, while X and Y are parallel to the plane of the sample.

Electron optics are a very close analog of light optics, and most of the principles of an electron beam column (except for the rotation of the image) can be understood by thinking of the electrons as rays of light and the electron optical components as simply their optical counterparts. In order to operate an EBL machine, generally it is not necessary to understand the underlying math and physics, so they will not be discussed here although several excellent texts are available should the reader desire more information. (13,14) In addition, computer programs are available that allow easy and accurate design and simulation of optical components and columns. (15)

In 1994 the Zeiss company pioneered an electron optical setup which allows the use of low energy electrons both for imaging and lithographical purpose. The electron optics in the Zeiss Gemini column handles electrons down to energies of only 100 eV. The advantage of Low energy electrons can be two-fold:

- In imaging non-conductive material surfaces such as polymers, glass or ceramics the electrical charging of the surface can be avoided with electrons less than 1 KeV energy. Around this energy the number of incoming primary electrons and the outgoing secondary electrons nearly equilibrates resulting in a zero net charge of the surface.

- The low penetration depth of low energy electrons (approximately 50 nm / 1 KeV in organic materials) favors superior imaging conditions for ultrathin organic layers. Under low voltage imaging conditions even self-assembled monolayers can be imaged with sufficient contrast.

The electron optical setup of the Gemini lens systems is illustrated in Fig.5

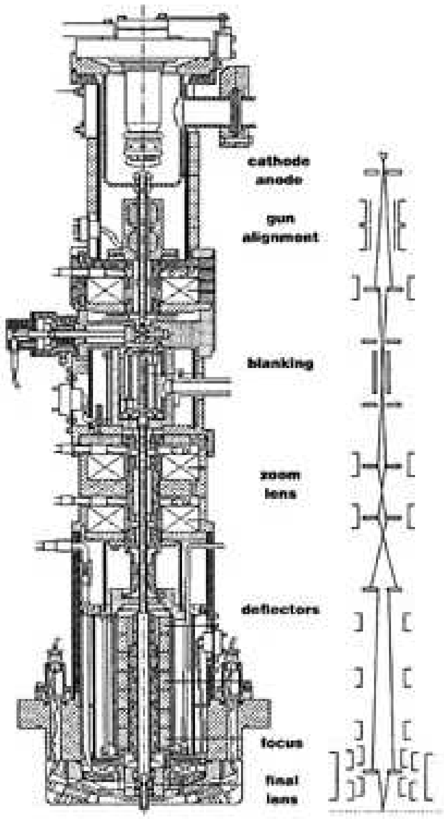

Figure 4: Cross section drawing of a typical electron beam column along with a raytrace of the electrons as they pass through the various electron optical components (Courtesy of Leica Lithography Systems Ltd.

The electrons pass the column with an energy of more than 8 KeV in order to become less sensitive towards external electromagnetic stray fields. Their energy is reduced to the low voltage with an electric field applied to the final lens of the objective which is an electrostatic lens.

2.2 Electron sources

Electrons may be emitted from a conducting material either by heating it to the point where the electrons have sufficient energy to overcome the work function barrier of the conductor (thermionic sources) or by applying an electric field sufficiently strong that they tunnel through the barrier (field emission sources). Three key parameters of the source are the virtual source size, its brightness (expressed in amperes per square centimeter per steradian), and the energy

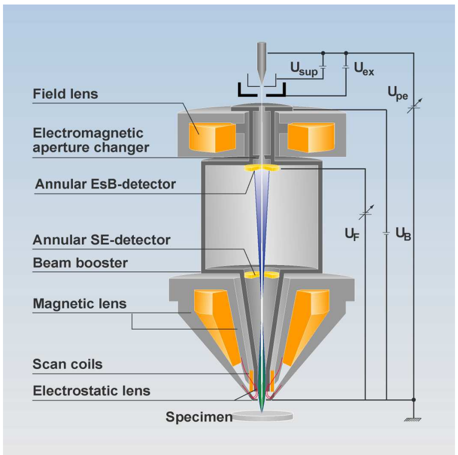

Figure 5: Electron optical setup of the Zeiss Gemini column optimized for low energy elctrons.

spread of the emitted electrons (measured in electron volts).

The size of the source is important since this determines the amount of demagnification the lenses must provide in order to form a small spot at the target. Brightness can be compared to intensity in light optics, so the brighter the electron source, the higher the current in the electron beam. A beam with a wide energy spread (which is undesirable, as will be shown in the section on lenses) is similar to white light, while a beam with a narrow energy spread would be comparable to monochromatic light. Although the energy spread of the source is important, space charge interactions between electrons further increase the energy spread of the beam as it moves down the column (Boersch effect). (16) An electron source is usually combined with two or more electrodes to control the emission properties, as shown in Fig. 6(17)

source type	brightness (A/cm^2/rad	source size	energy spread (eV)
tungsten thermionic	10^5	25 μm	2-3
Lab_6	10^6	10 μm	2-3
thermal field emitter	10^8	20 nm	0.9
cold field emitter	10^9	5 nm	0.22

The table summarizes the properties of common sources. For many years the standard thermionic electron source for lithography optics was a loop of tungsten wire heated white hot by passing a current it. Tungsten was chosen for its ability to withstand high temperatures without melting or evaporating. Unfortunately, this source was not very bright and also had a large energy spread caused by the very high operating temperature (2700 K). More recently, lanthanum

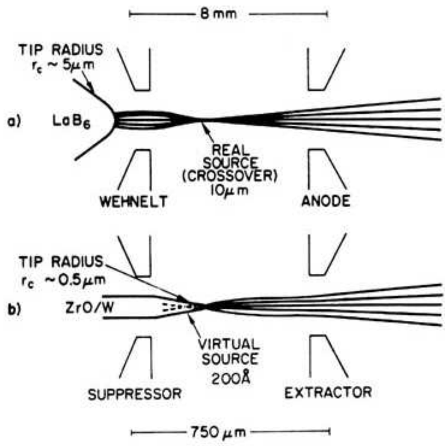

Figure 6: Electrode structure and relevant dimensions for a) LaB_6 gun and b) thermal field emission gun. The electrodes are circular symmetric about the optical axes. The Wehnelt and suppressor are biased negative with respect to the cathode, while the anode and extractor are positively biased.

hexaboride has become the cathode of choice; due to a very low work function, a high brightness is obtained at an operating temperature of around 1800 K. The beam current delivered by thermionic sources depends on the temperature of the cathode. Higher temperatures can deliver greater beam current, but the tradeoff is an exponentially decreasing lifetime due to thermal evaporation of the cathode material.

Field emission sources typically consist of a tungsten needle sharpened to a point, with a radius less than 1 μ. The sharp tip helps provide the extremely high electric fields needed to pull electrons out of the metal. Although cold field emission sources have become common in electron microscopes, they have seen little use in EBL due to their instability with regard to short term noise as well as long term drift, which is a much more serious problem for lithography than microscopy. The noise is caused by atoms that adsorb onto the surface of the tip, affecting its work function and thus causing large changes in the emission current. Heating the tip momentarily (flashing) can clean it, but new atoms and molecules quickly readsorb even in the best of vacuums. In addition, atoms may be ionized by the electron beam and subsequently accelerated back into the tip, causing physical sputtering of the tip itself. To minimize the current fluctuations, the electron source must be operated in an extreme ultra high vacuum environment, 10^{-10} Torr or better.

A technology that is now available to EBL (as well as in many electron microscopes) is the thermal field emission source. It combines the sharp tungsten needle of the field emission source and the heating of the thermal source. Because the tip operates at a temperature of about 1800

K, it is less sensitive to gases in the environment and can achieve stable operation for months at a time. Although thermal field emitter is the common name, it is more properly called a Schottky emitter since the electrons escape over the work function barrier by thermal excitation. It features a brightness almost as high as the cold field emission sources, a very small virtual source size, and a moderate energy spread. The tungsten is usually coated with a layer of zirconium oxide to reduce the work function barrier. A heated reservoir of zirconium oxide in the electron gun continuously replenishes material evaporated from the tip. It requires a vacuum in the range of 10^{-9} Torr, which, although much better than required for the thermionic sources, is readily achievable with modern vacuum technology. (A light bakeout might be required to remove water vapor after the system has been vented.) LaB6 sources are still preferred for shaped beam systems since the total current provided by the thermal field emission source is inadequate for this application.

2.3 Electron Lenses

Electrons can be focused either by electrostatic forces or magnetic forces. Although electron lenses in principle behave the same as optical lenses, there are differences. Except in some special cases, electron lenses can be made only to converge, not diverge. Also, the quality of electron lenses is not nearly as good as optical lenses in terms of aberrations. The relatively poor quality of electron lenses restricts the field size and convergence angle (or numerical aperture) that can be used. The two types of aberrations critical to EBL are spherical aberrations, where the outer zones of the lens focus more strongly than the inner zones, and chromatic aberrations, where electrons of slightly different energies get focused at different image planes. Both types of aberrations can be minimized by reducing the convergence angle of the system so that electrons are confined to the center of the lenses, at the cost of greatly reduced beam current.

A magnetic lens is formed from two circularly symmetric iron (or some other high permeability material) polepieces with a copper winding in-between. Fig.7 shows a cross-section through a typical magnetic lens, along with some magnetic flux lines.

The divergence of the magnetic flux along the optical axis imparts a force on electrons back towards the optical (Z) axis, resulting in focusing action. The magnetic field also causes a rotation of the electrons (and the image) about the Z axis in a corkscrew fashion. Although this does not affect the performance of the lens, it does impact the design, alignment, and operation of the system. For instance, the deflection system must be rotated physically with respect to the stage coordinates. Also, when aligning a column, X and Y displacement in the upper regions of the

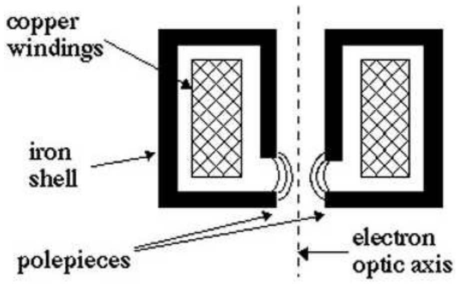

Figure 7: Cross-section through a magnetic lens with lines showing the magntic field distribution

column will not correspond to the same X and Y displacement at the target. Finally, changes in focus or changes in the height of the sample can cause a slight rotation in the deflection coordinates. This must be properly corrected or stitching and overlay errors will result. Magnetic lenses, particularly the final lens, may be liquid-cooled to maintain a controlled temperature, which is critical for stable operation of a system.
Electrostatic lenses have worse aberrations than magnetic lenses, so they are not as commonly used. They are most often found in the gun region as a condenser lens since they can be combined with the extractor or anode used to pull electrons out of the cathode, and they are easily made for ultrahigh vacuum use and are bakeout compatible. Also, aberrations in the condenser lens tend to be less important; system performance is usually dominated by the aberrations of the final lens. A simple electrostatic lens, as shown in Fig.8 consists of three consecutive elements like apertures, the outer two being at ground potential and the inner at some other (variable) potential that controls the lens strength. The electric potentials set up by such a lens tend to pull an electron that is traveling away from the optical axis back towards the axis, resulting in the focusing action.

2.4 Other optical elements

Other optical elements include apertures, deflection systems, alignment coils, blanking plates, and stigmators.

2.4.1 Apertures

Apertures are small holes through which the beam passes on its way down the column. There are several types of apertures. A spray aperture may be used to stop any stray electrons without

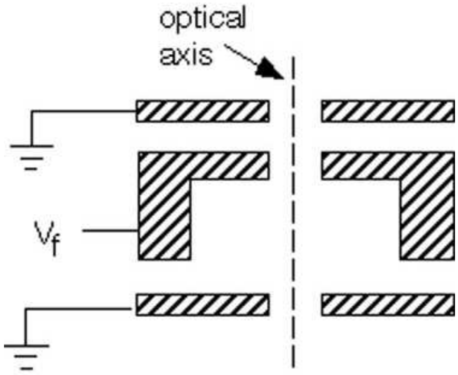

Figure 8: Cross section through an electrostatic Einzel lens. The focus of the lens is controlled by voltage applied to the center electrode

materially affecting the beam itself. A blanking aperture is used to turn the beam on and off; by deflecting the beam away from the aperture hole, the aperture intercepts the beam when not writing. A beam limiting aperture has two effects: it sets the beam convergence angle [[alpha]] (measured as the half-angle of the beam at the target) through which electrons can pass through the system, controlling the effect of lens aberrations and thus resolution, and also sets the beam current. A beam limiting aperture is normally set in an X-Y stage to allow it to be centered, or aligned, with respect to the optical axis. It is best to have a beam limiting aperture as close to the gun as possible to limit the effects of space charge caused by electron - electron repulsion.

Apertures may be heated to help prevent the formation of contamination deposits, which can degrade the resolution of the system. If not heated, the apertures typically need to be cleaned or replaced every few months. With platinum apertures, cleaning is easily accomplished by heating the aperture orange hot in a clean-burning flame. Shaped beam systems also have one or more shaping apertures, which can be square or have more complicated shapes to allow the formation of a variety of beam shapes, such as triangles, etc.

2.4.2 Electron beam deflection

Deflection of the electron beam is used to scan the beam across the surface of the sample. As with lenses, it can be done either magnetically or electrostatically. The coils or plates are arranged so that the fields are perpendicular to the optical axis, as shown in Fig.9(a). Deflecting the beam off axis introduces additional aberrations that cause the beam diameter to deteriorate, and deviations from linearity in X and Y increase as the amount of deflection increases. These effects limit the maximum field or deflection size that can be used. As with lenses, magnetic deflection introduces fewer distortions than electrostatic deflection. Double magnetic deflection using a pair of matched coils is sometimes used to further reduce deflection aberrations. However, electrostatic deflection can achieve much higher speeds since the inductance of the magnetic deflection coils limits their frequency response, and eddy currents introduced by the magnetic fields may further limit the speed of magnetic deflection. Since deflection systems are frequently placed inside the final lens, care must be taken to prevent the fields from interacting with conducting metal parts. Usually the final lens will be shielded with ferrite to minimize eddy currents. Some tools use multiple deflection systems, where high speed, short range deflection is done electrostatically while long range deflection is magnetic. In either case, the field size of the tool is limited by aberrations of the deflection system; some tools introduce dynamic corrections to the deflection, focus, and stigmators in order to increase the maximum field size, at the cost of additional complexity.

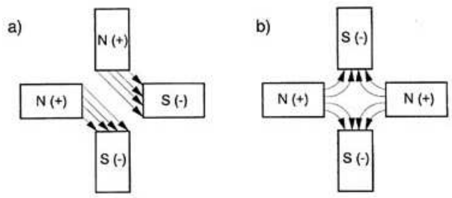

Figure 9: Schematic showing the magnetic (electrostatic) field distribution for a) simple beam deflector or alignment device energized for diagonal deflection and b) a stigmator. The optical axes is perpendicular to the plane of the page

2.4.3 Beam blanking

Blanking, or turning the beam on and off, is usually accomplished with a pair of plates set up as a simple electrostatic deflector. One or both of the plates are connected to a blanking amplifier with a fast response time. To turn the beam off, a voltage is applied across the plates which sweeps the beam off axis until it is intercepted by a downstream aperture. If possible, the blanking is arranged to be conjugate so that, to first order, the beam at the target does not move while the blanking plates are activated. Otherwise, the beam would leave streaks in the resist as it was blanked. The simplest way to ensure conjugate blanking is to arrange the column so that the blanking plates are centered at an intermediate focal point, or crossover. In very high speed systems, more elaborate blanking systems involving multiple sets of plates and delay lines may be required to prevent beam motion during the blanking and unblanking processes. (14)

2.4.4 Stigmators

A stigmator is a special type of lens used to compensate for imperfections in the construction and alignment of the EBL column. These imperfections can result in astigmatism, where the beam focuses in different directions at different lens settings; the shape of a nominally round beam becomes oblong, with the direction of the principal axis dependent on the focus setting, resulting in smeared images in the resist. The stigmator cancels out the effect of astigmatism, forcing the beam back into its optimum shape. Stigmators may be either electrostatic or magnetic and consist of four or more poles (eight is typical) arranged around the optical axis. They can be made by changing the connections to a deflector, as shown in Fig. 2.8(b). With proper mixing of the electrical signals, a single deflector may sometimes perform multiple functions, including beam deflection, stigmation, alignment, and blanking.

2.4.5 Other column elements

A number of other components may be found in the column, which although not important to the electron optics are nonetheless critical to the operation of the system. A Faraday cage located below the final beam limiting aperture is used to measure the beam current in order to ensure the correct dose for resist exposure. It can be either incorporated directly on the stage or a separate movable assembly in the column. The column will also typically have an isolation valve that allows the chamber to be vented for maintenance while the gun is still under vacuum and operational. All parts of an electron beam column exposed to the beam must be conductive or charging will cause unwanted displacements of the beam. Often a conductive liner tube will be placed in parts of the column to shield the beam from insulating components.

Finally, the system needs a method of detecting the electrons for focusing, deflection calibration, and alignment mark detection. Usually this is a silicon solid state detector similar to a solar cell, mounted on the end of the objective lens just above the sample. Channel plate detectors and scintillators with photomultiplier tubes may also be used. Unlike scanning electron microscopes, which image with low voltage secondary electrons, EBL systems normally detect high energy backscattered electrons since these electrons can more easily penetrate the resist film. The signal from low energy secondary electrons may be obscured by the resist.

2.4.6 Resolution

There are several factors that determine the resolution of an electron beam system. First is the virtual source size dv divided by the demagnification of the column, M^{-1}, resulting in a beam diameter of $d_g = d_v/M^{-1}$. In systems with a zoom condenser lens arrangement, the demagnification of the source can be varied, but increasing the demagnification also reduces the available beam current. If the optics of the column were otherwise ideal, this simple geometry would determine the beam diameter. Unfortunately, lenses are far from perfect. Spherical aberrations result from the tendency of the outer zones of the lenses to focus more strongly than the center of the lens. The resultant diameter is $d_s = 1/2C_s a^3$, where C_s is the spherical aberration coefficient of the final lens and a is the convergence half-angle of the beam at the target. Using an aperture to limit the convergence angle thus reduces this effect, at the expense of reduced beam current. Chromatic aberrations result from lower energy electrons being focused more strongly than higher energy electrons. For a chromatically limited beam, the diameter is $d_c = C_c a DV/V_b$, where C_c is the chromatic aberration coefficient, DV is the energy spread of the electrons, and V_b is the beam voltage.

Finally, quantum mechanics gives the electron a wavelength $L = 1.2/(V_b)^{1/2}$ nm; although much smaller than the wavelength of light (0.008 nm at 25 kV), this wavelength can still limit the beam diameter by classical diffraction effects in very high resolution systems. For a diffraction limited beam, the diameter is given by $d_d = 0.6L/a$. To determine the theoretical beam size of a system, the contributions from various sources can be added in quadrature: $d = (d_g^2 + d_s^2 + d_c^2 + d_d^2)^{1/2}$.

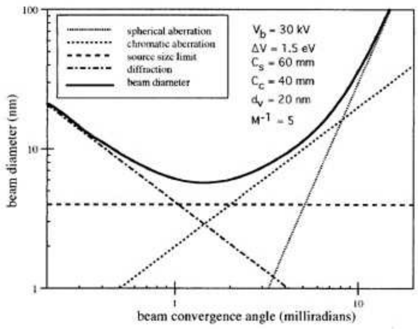

Figure 10: A plot showing resolution as a function of beam convergence angle for an electron beam column at 30 KeV. The plot assumes an energy spread of 1.5 eV, a source diameter of 20 nm and a fixed demagnification of 5

The diagram in Fig. 10 shows how these sources contribute in a typical column. In systems with thermionic sources, spherical aberrations tend to be the limiting factor for beam diameter, while chromatic aberrations dominate in field emission systems. For a given beam current, there will be an optimum combination of convergence angle and system demagnification. Resolution can generally be improved in most systems by using a smaller beam limiting aperture, at the expense of reduced beam current and throughput. In systems where the demagnification can be varied, increasing the demagnification will also improve resolution, at the expense of reduced beam current.

3 Electron-solid interactions

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, they occasionally undergo large angle scattering events (backscattering). The backscattered electrons cause the proximity effect, (18) 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 voltage electrons called secondary electrons.

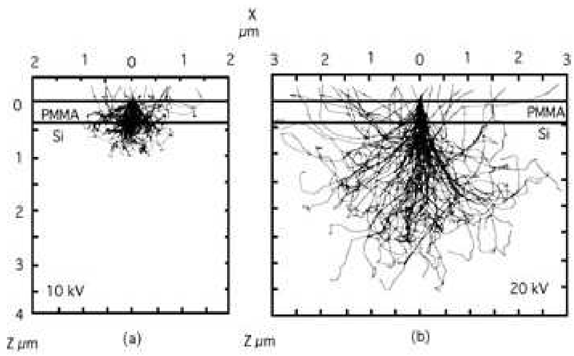

Figure 11: Monte Carlo simulation of electron scattering in resist on a silicon substrate at a) 10 KeV and b) 20 KeV(From Kyser and Viswanathan (19)

Abbildung
Figure 11 shows some computer simulations of electron scattering in typical samples. (19) The combination of forward and backscattered electrons results in an energy deposition profile in the resist that is typically modeled as a sum of two Gaussian distributions, where a is the width of the forward scattering distribution, b is the width of the backscattering distribution, and ee is the intensity of the backscattered energy relative to the forward scattered energy. Fig.12 shows an example of a simulated energy profile.

3.1 Forward scattering

As the electrons penetrate the resist, some fraction of them will undergo small angle scattering events, which can result in a significantly broader beam profile at the bottom of the resist than at the fxtop. The increase in effective beam diameter in nanometers due to forward scatter-

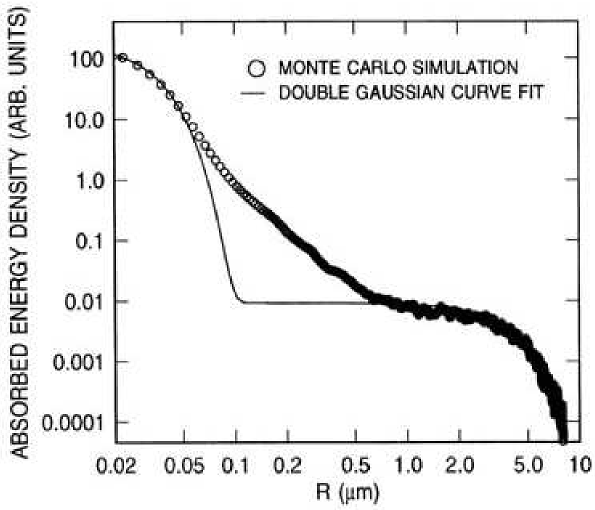

Figure 12: Simulated profile of the energy absorbed from an electron beam exposure

ing is given empirically by the formula $d_f = 0.9(R_t/V_b)^{1.5}$, where R_t is the resist thickness in nanometers and V_b is the beam voltage in kilovolts. Forward scattering is minimized by using the thinnest possible resist and the highest available accelerating voltage. Although it is generally best to avoid forward scattering effects when possible, in some instances they may be used to advantage. For example, it may be possible to tailor the resist sidewall angle in thick resist by adjusting the development time. (20) As the time increases, the resist sidewall profile will go from a positive slope, to vertical, and eventually to a negative, or retrograde, profile, which is especially desirable for pattern transfer by liftoff.

3.2 Backscattering

As the electrons continue to penetrate through the resist into the substrate, many of them will experience large angle scattering events. These electrons may return back through the resist at a significant distance from the incident beam, causing additional resist exposure. This is called the electron beam proximity effect. The range of the electrons (defined here as the distance a typical electron travels in the bulk material before losing all its energy) depends on both the energy of the primary electrons and the type of substrate. Fig.13 shows a plot of electron range as a function of energy for three common materials. (21) The fraction of electrons that are backscattered, e, is roughly independent of beam energy, although it does depend on the substrate material, with low atomic number materials giving less backscatter. Typical values

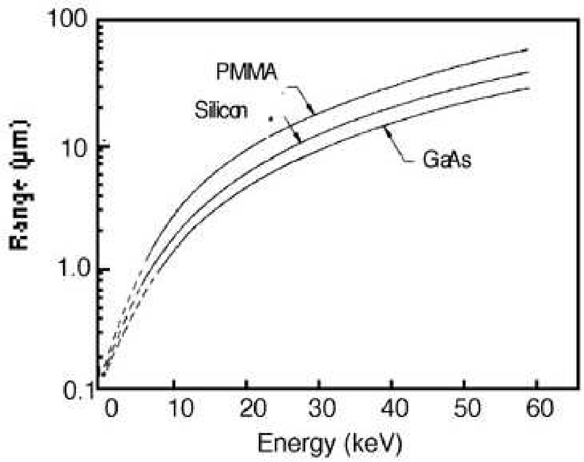

Figure 13: Electron range as a function of beam energy for PMMA resist, silicon, and gallium arsenide (From Brewer ,1980)

of e range from 0.17 for silicon to 0.50 for tungsten and gold. Experimentally, e is only loosely related to e_e, the backscatter energy deposited in the resist as modeled by a double Gaussian. Values for e_e tend to be about twice e.

3.3 Secondary electrons

As the primary electrons slow down, much of their energy is dissipated in the form of 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 10 nm. This largely accounts for the minimum practical resolution of 20 nm observed in the highest resolution electron beam systems and contributes (along with forward scattering) to the bias that is seen in positive resist systems, where the exposed features develop larger than the size they were nominally written.
A small fraction of secondary electrons may have significant energies, on the order of 1 keV. These so-called fast secondaries can contribute to the proximity effect in the range of a few tenths of a micron. Experimentally and theoretically, the distribution of these electrons can be fit well by a third Gaussian with a range intermediate between the forward scattering distribution and the backscattering distribution.

3.4 Modelling

Electron scattering in resists and substrates can be modeled with reasonable accuracy by assuming that the electrons continuously slow, down as described by the Bethe equation, (22) while undergoing elastic scattering, as described by the screened Rutherford formula. (23) Since the different materials and geometries make analytic solutions difficult, Monte Carlo techniques, where a large number of random electrons are simulated, are commonly used. The input to the program contains such parameters as the electron energy, beam diameter, and film thicknesses and densities, while the output is a plot of energy deposited in the resist as a function of the distance from the center of the beam.

Curve fitting with Gaussians and other functions to the simulated energy distribution may also be employed. In order to get good statistics, the energy deposition for a large number (10,000 to 100,000) of electrons must be simulated, which can take a few minutes to an hour or so on a personal computer. Software for Monte Carlo simulation of electron irradiation is available from several sources. (24-27) Such simulations are often used to generate input parameters for proximity effect correction programs (see next section). Alternatively, experimental data can be obtained by measuring the diameter of exposed resist from a point exposure of the beam at various doses (28) or by measuring the linewidths of various types of test patterns such as the tower pattern. (29).

4 Proximity effects

4.1 Introduction

The net result of the electron scattering discussed in the previous section is that the dose delivered by the electron beam tool is not confined to the shapes that the tool writes, resulting in pattern specific linewidth variations known as the proximity effect. For example, a narrow line between two large exposed areas may receive so many scattered electrons that it can actually develop away (in positive resist) while a small isolated feature may lose so much of its dose due to scattering that it develops incompletely. Fig.14 shows an example of what happens to a test pattern when proximity effects are not corrected. (30)

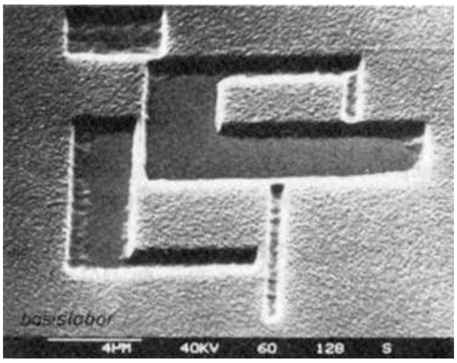

Figure 14: SEM micrograph of a positive resist pattern on silicon exposed with a 20 KeV electron beam demonstrates the proximity effect , where small isolated exposed areas receive less dose relative to larger or more densely exposed areas (From Kratschmer (30), 1981

4.2 Proximity effect avoidance

Many different schemes have been devised to minimize the proximity effect. If a pattern has fairly uniform density and linewidth, all that may be required is to adjust the overall dose until the patterns come out the proper size. This method typically works well for isolated transistor gate structures. Using higher contrast resists can help minimize the linewidth variations. Multilevel resists, in which a thin top layer is sensitive to electrons and the pattern developed in it is transferred by dry etching into a thicker underlying layer, reduce the forward scattering effect, at the cost of an increase in process complexity.
Higher beam voltages, from 50 kV to 100 kV or more, also minimize forward scattering, although in some cases this can increase the backscattering. When writing on very thin mem-

branes such as used for x-ray masks, higher voltages reduce the backscatter contribution as well since the majority of electrons pass completely through the membrane.(31)
Conversely, by going to very low beam energies, where the electron range is smaller than the minimum feature size, the proximity effect can be eliminated. (32) The penalty is that the thickness of a single layer resist must also be less than the minimum feature size so that the electrons can expose the entire film thickness. The electron-optical design is much harder for low voltage systems since the electrons are more difficult to focus into a small spot and are more sensitive to stray electrostatic and magnetic fields. However, this is the current approach in optical maskmaking, where a 10 kV beam is used to expose 0.3 μ thick resist with 1 μ minimum features on a 5 mask. In more advanced studies, a 1.5 kV beam has been used to expose 70 nm thick resist with 0.15 μ minimum features. (33) A technique that can be used in conjunction with this approach in order to increase the usable range of electron energy is to place a layer with a high atomic number, such as tungsten, underneath the resist. This has the effect of further limiting the range of the backscattered electrons.
Abbildung

4.3 Proximity effect correction

4.3.1 Dose modulation

The most common technique of proximity correction is dose modulation, where each individual shape in the pattern is assigned a dose such that (in theory) the shape prints at its correct size. The calculations needed to solve the shape-to-shape interactions are computationally very time consuming. Although the actual effect of electron scattering is to increase the dose received by large areas, for practical reasons proximity correction is normally thought of in terms of the large areas receiving a base dose of unity, with the smaller and/or isolated features receiving a larger dose to compensate.

Several different algorithms have been used. In the self-consistent technique, the effect of each shape on all other shapes within the scattering range of the electrons is calculated. The solution can be found by solving a large number of simultaneous equations; (34) unfortunately, this approach becomes unwieldy as the number of shapes increases and their size decreases. An alternative is to define a grid and compute the interaction of the pattern shapes with the grid and vice versa; (35) however, the accuracy and flexibility of this technique may be limited. An optimal solution may also be arrived at by an iterative approach. (36) Finally, neural network techniques have been applied to the problem of proximity correction; (37) while not an attractive technique when implemented on a digital computer, it might be advantageous if specialized neural network processors become a commercial reality. Many of the algorithms in use assume that the energy distribution has a double Gaussian distribution as discussed in Sec. 2.3.

4.3.2 Pattern biasing

A computationally similar approach to dose modulation is pattern biasing. (38-39) In this approach, the extra dose that dense patterns receive is compensated for by slightly reducing their size. This technique has the advantage that it can be implemented on EBL systems that are not capable of dose modulation. However, the technique does not have the dynamic range that dose modulation has; patterns that contain both very isolated features and very dense features will have reduced process latitude compared to when dose modulation is used, since the isolated features will be under-dosed while the dense features will be overdosed. Pattern biasing cannot be applied to features with dimensions close to the scale of the pixel spacing of the e-beam system.

4.3.3 GHOST

A third technique for proximity correction, GHOST,(40) has the advantage of not requiring any computation at all. The inverse tone of the pattern is written with a defocused beam designed to mimic the shape of the backscatter distribution (Fig.15). The dose of the GHOST pattern, $e_e/(1 + e_e)$, is also set to match the large area backscatter dose. After the defocussed inverse image is written, the pattern will have a roughly uniform background dose. GHOST is perhaps an underutilized technique; under ideal conditions it can give superb linewidth control. (41) Its disadvantages are the extra data preparation and writing time, a slight to moderate loss of contrast in the resist image, and a slight loss in minimum resolution compared to dose modulation due to the fact that GHOST does not properly correct for forward scattering.

4.3.4 Software

A number of companies for some time have had proprietary software for proximity correction. (25) (42-43) Just recently, commercial proximity packages have become available, or are about to become available. (44-45) At present, these are limited in their accuracy, speed, and

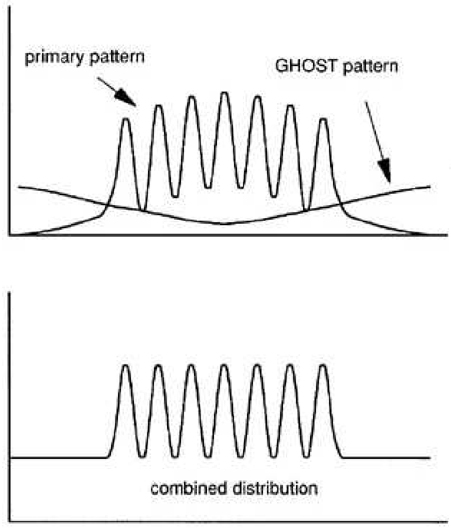

Figure 15: A plot showing resolution as a function of beam convergence angle for an electron beam column at 30 KeV. The plot assumes an energy spread of 1.5 eV, a source diameter of 20 nm and a fixed demagnification of 5

data volume capability; while excellent for correcting small research patterns, they may have difficulties with complex chips. Finally, several packages have been developed at university and government laboratories, some of which might be available to an adventurous user with excessive amounts of free time. (38) (46).

5 Systems

5.1 Environement

For best results, systems should be installed in a clean, quiet environment. 60 Hz noise is pervasive in most systems. To minimize this, careful consideration must be paid to the grounding of the system components to prevent ground loops. Also, analog and digital grounds should be kept separate as much as possible to minimize high frequency noise components. One useful method for tracking noise problems is to place the beam on the edge of a mark and monitor the electron detector output with a spectrum analyzer while disconnecting various suspect noise sources.

Acoustical noise can be a significant problem, especially in systems with field-emission electron sources. In such systems the demagnification of the field emission source, and thus the demagnification of vibrations, is much less than that of LaB6 systems. Stray magnetic fields are also a common problem. Mechanical pumps, transformers, and fluorescent lights should be moved at least 10 ft from the column if possible. The system should be well isolated from mechanical vibrations with a pneumatic table; ideally, it should also be located on the ground floor. Finally, the temperature should be well controlled, ideally to within a tenth of a degree. This is particularly important if good placement accuracy is required.

This section begins with a description of the smallest e-beam systems - namely, SEM conversions - and proceeds to the largest commercial mask production tools. We conclude the section with a listing of e-beam fabrication services.

5.2 SEM and STEM conversions

Any tool for microscopy - optical, electron, or scanning probe - may be adapted to work in reverse; that is, for writing instead of reading. Converted electron microscopes suffer the same limitations as light microscopes used for photolithography, namely, a small field of view and low throughput. Nevertheless, for a subset of research and R and D applications, converted SEMs offer a relatively inexpensive solution.

Of the many custom designed SEM conversions, most use a single set of digital-to-analog converters (DACs), from 12 to 16 bits wide, to drive the scan coils of the microscope. The beam is modulated with an electrostatic or magnetic beam blanker, which is usually located near a crossover of the beam. Alternatively, the beam can be blanked magnetically by biasing the gun alignment coils or not blanked at all. In the later case, the beam must be dumped to unused sections of the pattern. Figure 2.15 illustrates the "vector scan" method, in which shapes are filled with a raster pattern and the beam jumps from one shape to the next via a direct vector. By taking over the scan coils and beam blanking, a SEM can be used as a simple but high resolution lithography tool.

SEM conversions have evolved greatly in the past twenty years, primarily due to improvements in small computers and commercially available DAC boards. Early designs used relatively slow computers that sent primitive shapes (rectangles, trapezoids, and lines) to custom hardware. The custom pattern generator filled in the shapes by calculating coordinates inside the shapes and feeding these numbers to the DACs. While this approach is still the best way to avoid data transmission bottlenecks (and is used in commercial systems), inexpensive SEM conversions can now rely on the CPU to generate the shape filling data. A typical configuration uses an Intel CPU based PC, with a DAC card plugged into an ISA bus. In this case, the CPU can generate data much faster than it can be transmitted over an ISA bus.

The bus limits the deflection speed to around 100 kHz, that is, to a dwell time per point of 10 μs. What dwell time is required? With a 16-bit DAC and a SEM viewing field of 100 μ, the size of a pixel (the smallest logically addressable element of an exposure field) is 100 μm $/2^{16}$=1.5 nm , and its area A is the square of this. The charge delivered to this pixel in a time t is It, where I is the beam current. This must equal the dose times the pixel area. Given a beam current I on the order of 50 pA and a required dose D around 200 $\mu C/cm^2$ (typical for PMMA), we have a pixel dwell time

$$t = DA/I = 910^{-8}s \qquad (1)$$

or a deflection speed of 11 MHz. This being impossible with an ISA bus, we must either space out the exposure points, apply a short strobe to the beam blanker, or use a combination of the two. When the exposure points are spaced every n pixels (that is, when the 2^{16} available exposure points are reduced by a factor of n) then the "pixel area" and thus the dwell time is increased by a factor of n^2. Note that the placement of features can still be specified to a precision of 2^{16} within the writing field, while the shapes are filled in with a more coarse grid.

In the above example, we can set n to 11 so that the dwell time is increased to 1.1 10^{-5} s (91 kHz), increasing the pitch of exposure points to 16.5 nm. This spacing is a good match to the resolution of PMMA, and allows fine lines to be defined without any bumps due to pixelization. However, when we require 100 times the current (5000 pA in this example), the exposure point spacing must be increased by a factor of 10, possibly leading to rough edges. Some pattern

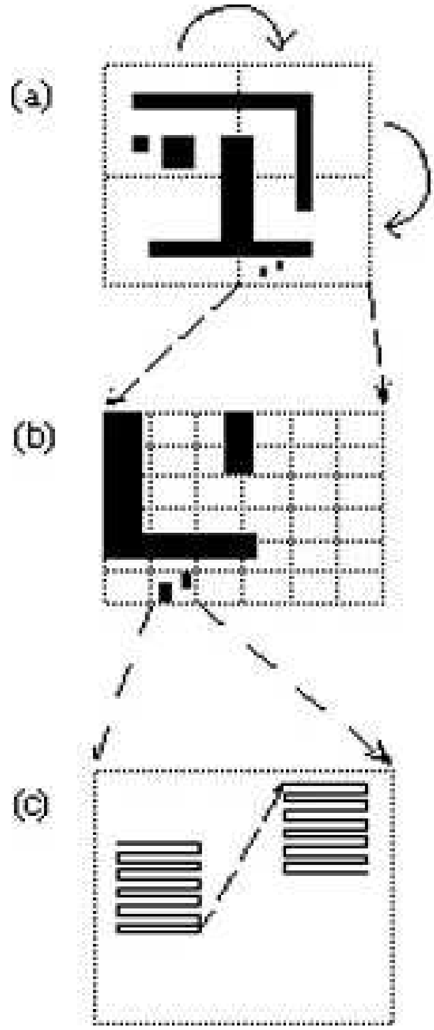

Figure 16: The vector scan writing strategy

generators (see Sect. 2.5.3.1) avoid this problem by allowing different exposure point spacings in the X and Y (or in the r and theta) directions, thereby allowing a larger exposure point spacing in the less critical dimension.

To use a SEM without a beam blanker, one must consider the large exposure point spacing required for common resists. Lack of a beam blanker leads to the additional problem of artifacts from the settling of scan coils and exposure at beam dump sites. Many SEM manufacturers offer factory-installed beam blankers. Retrofitted blankers are also sold by Raith GmbH. (47)

The scan coils of a SEM are designed for imaging in a raster pattern and so are not commonly optimized for the random placements of a vector scan pattern generator. Settling times are typically around 10 us for a JEOL 840 to as long as 1 ms for the Hitachi S800, where the bandwidth of the scan coils has been purposely limited to reduce noise in the imaging system. Thus, it is important to consider the bandwidth of the deflection system when purchasing a SEM for beamwriting.

The other major limitation of a SEM is its stage. Being designed for flexible imaging applications, SEM stages are not flat, and even when equipped with stepper motor control are no more accurate than ca. 1 to 5 μ. Periodic alignment marks can be used to stitch fields accurately, but this requires extra processing as well as the use of photolithography for printing alignment marks. The mark mask would presumably be fabricated on a commercial system with a laser-controlled stage. Fortunately, alignment with a converted SEM can be quite accurate, especially when using Moire patterns for manual alignment. Automated alignment in the center of a SEM writing field is at least as good as in large commercial systems. Alignment at the edges of a SEM field will be compromised by distortions, which are typically much larger than in dedicated e-beam systems. Laser-controlled stages can be purchased for SEMs, but these are usually beyond the budgets of small research groups.

Electron beam lithography requires a flat sample close to the objective lens, making secondary electron imaging difficult with an ordinary Everhart-Thornley detector (a scintillator-photomultiplier in the chamber). A few high end SEMs are equipped with a detector above the objective lens or can be equipped with a microchannel plate on the pole-piece. These types of detectors are a great advantage for lithography since they allow the operator to decrease the working distance, and thus the spot size, while keeping the sample flat and in focus.

With patterning speed limited by beam settling and bus speed, it is clear that inexpensive SEM conversions cannot match the high speed writing of dedicated e-beam systems. However, a SEM based lithography system can provide adequate results for a wide variety of applications, at a small fraction of the cost of a dedicated system. The number of applications is limited by stitching, alignment, and automation. Practical applications include small numbers of quantum devices (metal lines, junctions, SQUIDs, split gates), small numbers of transistors, small area gratings, small masks, tests of resists, and direct deposition. The main limitations with SEM lithography are observed with writing over large areas, or when deflection speed and throughput are critical. Specifically, difficulties with stitching and/or distortions due to the electron optics of the microscope can become significant. SEMs are not practical for most mask making, integration of many devices over many fields, large area gratings, multifield optical devices, or any application requiring a large substrate.

5.3 Commercial SEM conversion systems

subsubsectionNanometer Pattern Generation System The SEM conversion kit sold by J.C. Nabity Lithography Systems (48) is built around a Windows-based PC-compatible with an ISA bus. A 16 bit multifunction board from Data Translation (49) is used to generate the X and Y beam deflections and to program a second board which provides the signals for blanking control. The beam is deflected from shape to shape in a writing field (vector scan mode), with the unique feature that the raster for filling arbitrary polygons can be defined by the user. Arbitrary polygons can be designed with up to 200 vertices and the user can specify the raster to be parallel to any side of the polygon. A unique feature of the NPGS is that the user has control over the exposure spot spacing in X and Y, allowing the critical dimension (e.g. perpendicular to grating lines) to be filled with greater accuracy (see Sect. 2.5.2). Circles and circular arcs are swept using a polar coordinate approach, with user control of the exposure spot spacing in r and . As with any ISA system, the data throughput is limited to around 100 kHz; and like most pattern generators, exposure points filling the features can be spaced by multiples of the DAC resolution (216) while still allowing full resolution for feature placement.

To provide for lower doses at reasonable currents, the Nabity system strobes the blanker at each exposure point. (50) For systems without a beam blanker, the Nabity Pattern Generation System (NPGS) can be programmed to dump the beam at user-defined locations within the writing field; however, this imposes significant limitations on the exposure spot spacing or on the lowest deliverable dose for a given beam current (refer to discussion above).

Mark alignment on the NPGS is performed by calculating the correlation between the measured mark image and the user-defined mark pattern. Signal processing such as averaging and edge enhancement can be executed before the alignment correlation, allowing the use of low contrast or rough marks. If the user supplies precisely defined marks (usually printed with a mask made on a commercial maskmaking tool) then NPGS can be used to correct for global rotation, scaling, and nonorthogonality. NPGS can control motorized stages, providing fully automated sample movement and pattern alignment. However, SEM stages are typically orders of magnitude slower than those of dedicated e-beam tools, and do not provide feedback to the deflection system (see Sect. 2.5.4).

Angled lines, polygons, and arbitrarily shaped features are all supported, and data can be imported in common e-beam formats: GDSII (Stream), CIF, and a subset of DXF (AutoCAD.)

subsubsectionRaith Pattern Generator The Proxy-Writer SEM conversion kit is Raith's low end PC-based pattern generator. Like the Nabity system, the Proxy-Writer is a vector-scan system.

Unlike the Nabity NPGS, the Proxy-Writer has only manual alignment, and patterns are limited to single writing fields. Corrections for rotation, shift, and orthogonality are applied to single fields (with single patterns); these corrections are not applied globally to correct the workpiece rotation and stage nonorthogonality. The unusual feature of this simple system is its support for exposure simulation and semiautomatic proximity effect correction. Pattern data can be generated with the simple CAD program included or imported from a DXF (AutoCAD) file.

The higher end Raith system, known as **Elphy-Plus**, supports the full range of e-beam operations, including control of a laser-controlled stage and corrections for workpiece rotation, gain, and orthogonality. The laser stage, also manufactured by Raith, allows field stitching to better than 0.1 m. While the primary control is still a PC-compatible computer, the limitations of the ISA bus are circumvented by using a separate computer and integrated DAC as the pattern generator. In this way, the PC transmits only the coordinates of the corners of a shape, and the patterning hardware generates all of the internal points for exposure. Data throughput is thereby increased to 2.6 MHz (0.4 s/point minimum); however, many SEM deflection systems will be limited to less than 1 MHz due to the inductance of the coils and low pass filters in the imaging system. The Elphy-Plus system supports fully automated mark detection and field stitching. All standard e-beam data formats are supported.

Useful features of the Raith Elphy-Plus system include support of data representation in polar coordinates (greatly reducing the data required to represent circles), bit-mapped pattern exposure, and a path writing mode. In the path writing mode, the beam is steered in a circular pattern (defining the width of a line) while the stage is moved over the length of the line or curve. This is a relatively slow way of writing a long line but avoids spatially localized stitching errors. Instead, the placement and drift errors are averaged over the length of the feature. The Raith Elphy-Plus is not only available for SEM conversions but is also used as the pattern generator for Leica's LION-LV1 e-beam system (see below.)

Even the most expensive SEM conversion kit will be limited by the SEM's slow magnetic deflection, large distortion, and small stage. Next, we look at fully integrated commercial systems.
Abbildung

5.4 Gaussian vector scan systems

Like the converted SEMs, Gaussian vector scan systems use the writing strategy of stopping in each field, deflecting the beam from shape to shape, and filling in the shapes with a raster pattern. Large commercial systems, however, break the deflection into two (or more) sections, usually making use of a 16-bit DAC for "subfield" placement, and a faster 12-bit DAC for deflection inside the subfield (see Fig. 2.15). This is the scheme used in systems from JEOL, and some of the systems from Leica. Leica's EBPG series, and the Vector Scan (VS) tools built by IBM use an alternative technique: the slower DACs are used for placing the origin of each primitive shape and the faster DACs are used for filling in the shape. In addition to deflecting the beam with separate DACs, systems from Hitachi and Leica use these separate DACs to drive physically separate deflectors (magnetic or electrostatic). JEOL systems, in contrast, use a single stage electrostatic deflector. Single stage deflectors have fewer problems with matching deflections of the "fast" and "slow" electronics, but sacrifice some speed.

The largest distinction of these commercial Gaussian spot systems (and in fact all commercial e-beam systems) is the use of high precision laser-controlled stages. Stage controllers from Hewlett-Packard or Zygo use the Zeeman effect to split the line of a He-Ne laser. The split-frequency laser beam is reflected off a mirror attached to the stage, and the beat frequency from the two lines is measured by high speed electronics. When the stage moves, the beat frequency shifts according to the Doppler effect, and the stage position is calculated by integrating the beat counts. While often referred to as "interferometers," these stages actually have more in common with radar speed guns.

Analysis of multiple points on the stage mirror allows the measurement of X, Y, and rotation about Z (yaw). Stage precision is often given in terms of a fraction of the laser's wavelength; a precision of /128 = 5 nm is commonly used in commercial systems, and the best stages now use /1024 = 0.6 nm. Even though the controller reports the stage location to this precision, the accuracy of the stage is limited by unmeasured rotations about the X and Y axes, and by bow in the mirrors. These nonlinearities, called "runout", limit the absolute placement accuracy to the order of 0.1 μ over 5 cm of stage travel.

The high precision in reading the stage position means that the stage motors and drive do not have to be highly refined. In fact, simple capstan motors and push rods have been used at IBM. (52-53)] The stage controller receives a target location from a computer, drives the motors to a point close to this location, then sends an interrupt back to the computer and corrects the field position by applying an electronic shift. This shift is applied continuously, in real time, to compensate also for stage drift and low frequency vibration. In comparison, the laser stage built by Raith for SEM conversions applies corrections to relatively slow piezoelectric translators on the stage itself. By moving and measuring an alignment mark at various locations in the writing field, laser stages are used to calibrate the deflection gain, deflection linearity, and field distortion; that is, the stage is used as an absolute reference, and the deflection amplifiers are calibrated using the stage controller.

Other common features of commercial systems include a flat stage, a fixed working distance (contrasting with a SEM), and automated substrate handling. A flat stage keeps the sample in focus but requires the use of a detector either on or above the objective pole-piece. Most commonly, a microchannel plate or a set of silicon diodes is mounted on the pole-piece.

The market niche for commercial Gaussian spot high resolution e-beam tools has been primarily in research, and to a lesser extent for small-scale production of MMICs, high-speed T-gate transistors, and integrated optics.

Table 2.1. Characteristics of SEM-based lithography systems. In all cases the resolution is high, depending (for Nabity and Raith) on the chosen SEM. All of these systems have relatively small stage motion, ca 2 in. The Nabity and Raith devices are add-on products, while the Leica Nanowriter is an integrated system.

6 Data Preparation

6.1 Pattern structure

Preparation of pattern data for electron beam lithography may begin with a high level symbolic or mathematical description of a circuit, with the algorithmic description of a pattern (e.g. a Fresnel lens), or with a simple geometric layout. A computer aided design (CAD) program is usually used to lay out or at least inspect the pattern and to generate output in a standard exchange format. A separate program is then used to convert the intermediate format to machine-specific form. This last step can be quite involved since in most cases all hierarchy must by removed ("flattened"), polygons must be reduced to primitive shapes (e.g., trapezoids or triangles and rectangles), and the pattern must be fractured into fields, subfields, and even sub-subfields.

For shaped beam machines, or if the data is to be proximity corrected, medium and large sized shapes should be sleeved, so that the edges of shapes are exposed separately from the interiors. For shaped beam machines this allows the edges to be exposed with a small shaped size that has better resolution; for proximity corrected patterns, this allows finer control over the dose delivered to the shapes. Frequently, a bias (also known as sizing) may be applied to the pattern shapes to account for resist characteristics or process steps that affect the final device linewidth.

For Gaussian beam machines, a reasonable pixel size must be selected. A good compromise is usually to use a pixel size of about half the beam diameter. Larger pixel sizes may speed up throughput, while smaller pixel sizes will reduce line edge roughness and improve feature size control. The machine field size is usually a fixed multiple of the pixel size. Field sizes may range from less than 100 μ for high resolution, high accuracy work to more than 1 mm for high speed, low resolution lithography.

When designing a device such as a transistor, you would organize the fabrication in a set of steps; e.g., mesa, ohmics, gate, etc. Each step is assigned to a "layer" in the CAD tool, and multiple layers are displayed as overlapping patterns (usually in different colors). Much later on, the layers will be split apart into separate pattern files. Some of these layers may be patterned with photolithography, some with e-beam. For example, you may design the geometry of each layer and place all of this information in the transistor "cell". Now you can put this cell at a number of other locations to create, say, a NAND logic gate. If you have not simply copied the transistor but rather have created instances of the cell (somewhat like a function called in a program) then any modifications in the transistor cell will be instantiated all over the NAND gate. The NAND gate is now a higher level cell, which can be used as part of, say, a half-adder. The hierarchy of an entire circuit is continued in this way. Of course, when building circuits from a standard technology such as CMOS, all of the basic component cells are usually purchased as part of the CAD program (a library of cells), and may even be placed and connected automatically as part of a symbolic CAD package.

6.2 Avoiding Trouble Spots

An e-beam lithographer would be unlikely to use any high level design tools. Rather, the lithographer must deal with data at the lower, geometrical level. If the scale of critical dimensions is far larger than the e-beam tool's placement errors, then the designer is free to place features anywhere. For instance, a set of 5 reticles with 5 μ design rules and 0.5 μ overlay error budget will demand little (except stability) of a commercial e-beam system. However, when the design requires a direct-write e-beam layer with 0.05 μ alignment, the placement of alignment marks becomes critical, and e-beam stitching errors can significantly affect device performance and yield. It is important for the designer to consider the limitations of the e-beam system before laying out any pattern.

Consider the case of a pattern targeted for a high resolution Gaussian beam system, such as the Leica EBPG or the JEOL-JBX series. For high resolution work the writing field may be as small as 80 μ. Larger patterns are formed by moving the sample and stitching fields together. Field stitching errors will be around 20 nm, so any fine lines in the pattern (e.g., a narrow gate) should not be placed at a field boundary.

6.3 Alignement Marks

Electron-beam lithography may be used to pattern optical masks and their corresponding alignment marks; steppers and contact aligners have specific design requirements for these marks. However, we will discuss here only the marks used for direct-write e-beam layers. There are two phases of alignment: (1) correction for the placement and rotation of the wafer (or piece) and (2) correction for the placement of individual chips on the wafer. The e-beam tool aligns each pattern file (in its final fractured form) to a mark before writing the pattern.

If your alignment tolerance is greater than ca. 0.5 μ, then the individual chip alignment will not be necessary. Global alignment – that is, correction for the placement and rotation of the workpiece – can use marks which are separate and larger than those used for chip alignment.

Large global alignment marks are useful for the exposure of full wafers since the machine can be programmed to search for the first mark. Typical marks used for global alignment are large crosses of width 2 to 6 μ and length ca. 100 to 200 μ, placed at the top, bottom, left, and right sides of the wafer, as illustrated in Fig.17. Alternatively, a few of the marks used for chip alignment could also be used for global alignment; this would allow global alignment on small pieces of a wafer. Alignment to chip marks is especially useful as a diagnostic of the maskmaking tool, allowing the measurement of displacements as a function of chip location.

For large patterns that take a long time to write, it may improve registration and placement accuracy if the machine stops periodically (every 5 to 10 minutes is typical) to reregister to the alignment marks. This corrects for thermal or other drifts that can occur during the writing process. For single level processes or maskmaking, reregistering to a single mark is sufficient to correct for drift. The size of a chip may be on the order of centimeters, and in photolithography

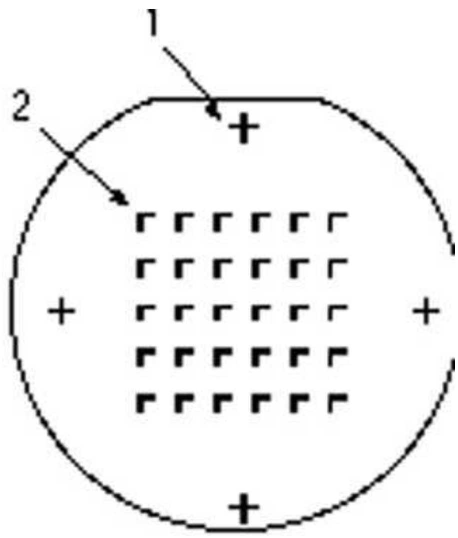

Figure 17: Alignement marks used for electron beam lithography

the chips or entire wafers are aligned at once. While e-beam systems can align to global marks alone, the best tolerance (<0.1 m) will be achieved when the alignment marks are within several hundred micrometers of the critical region. The designer may therefore wish to split the e-beam layer into smaller sections so that critical regions can be aligned individually. If these critical regions (e.g., gates) are arranged in a regular pattern, then arranging the sequence of e-beam writing will be simple. If the critical regions are placed randomly in the chip, the designer will have a time-consuming job of arranging the e-beam sequence and avoiding field boundaries.

Alignment marks must be patterned in previous steps of the device fabrication. A "zero level" is sometimes used for the sole purpose of placing robust alignment marks on the sample before any actual device data are written. Typically the designer includes a photolithography step simply for patterning alignment marks as trenches to be etched into the substrate. The best alignment of layer 2 to layer 1 will be achieved when layer 1 contains the marks used for aligning layer 2 and when the marks are as close as possible to critical areas. If the material of layer 1 is unacceptable for alignment (e.g., a 20 nm thick metal layer) then both layers will have to be aligned to a third reference pattern (the zero level). Alignment to a third layer adds a factor of ca.1.4 to the overlay error.

Well designed marks are commonly destroyed by processing. For example, ohmic metalizations become very rough when annealed. The rough marks are fine for optical alignment, but the lumps may cause the e-beam alignment hardware to trigger at the wrong locations. A good solution to this problem is to fabricate alignment marks as deep etched trenches (deeper than 1 m). Plasma-etched or wet-etched trenches may be used. Such pits will not change after high temperature processing (unless material is deposited in them), and (unlike Au) are compatible with MOS processing. Other examples of effective alignment marks are W on Ti, Pt on Ti, and Au on Cr. Au is compatible with GaAs processing, but to maintain a smooth film, the alignment marks must be patterned after the annealing steps. In each of these cases the Ti or Cr provides improved adhesion to the substrate. A 200 nm thick layer of Pt or Au provides a good alignment signal, and 10 to 20 nm of Ti or Cr under the high-Z material provides improved substrate adhesion. Metal films can be patterned with very smooth edges by a liftoff process using a bilayer of PMMA and P(MMA/MAA) (see Sect. 2.7.4.2). In all cases, the designer must consider the thickness, roughness, and process compatibility of the material used for e-beam alignment marks, as well as the mark shape required for specific e-beam tools.

6.4 CAD Programms

CAD programs range from the very expensive schematic capture tools for VLSI to simple and inexpensive polygon editors. At the high end are widely used circuit capture, simulation, and layout tool sets from Cadence [101] and Mentor Graphics. [102] Other high-end packages are sold by Silvar Lisco, [103] Integrated Silicon Systems, [104] and a number of other vendors. [105] These tools run almost exclusively on UNIX workstations, and generate the standard intermediate format GDSII (also known as "Calma Stream" format) as well as the machine-specific MEBES format. Software tools in these sets include analog and digital simulators, silicon compilers, schematic capture, wire routers, design-rule checkers, and extensive cell libraries for CMOS, BiCMOS, and bipolar technologies.

In the mid-range of expense are the programs from Design Workshop [106] (DW2000) and Tanner Research [107] (L-Edit). Design Workshop implements a fully-functional graphical editor with the unusual feature of providing not only GDSII format, but also output in machine-specific formats for MEBES, JEOL, and Leica systems. DW2000 includes an integrated command language for algorithmic pattern definition. Design Workshop runs under the Macintosh OS, UNIX, and Windows NT. The Tanner Research tools run on PC compatibles, Macintoshes, and several UNIX workstations; output is in CIF or GDSII. Both Design Workshop and Tanner Research have implemented a less extensive set of companion tools (rule checkers, routers, simulators, etc.) and concentrate on the core graphical editors.

Inexpensive graphical editors include AutoCAD and other general-purpose CAD tools for PC compatibles and the Macintosh. AutoCAD and other similar programs generate DXF format, which must be converted to GDSII with a separate program. (108) AutoCAD has the disadvantage that it was not designed for lithography and so can generate patterns (such as 3D structures) that cannot be rendered by e-beam systems. Also, DXF format does not support datatype tags, which are used to specify individual dose values for geometrical shapes. Datatype tags are important when compensating (manually or automatically) for the proximity effect (see Sect. 2.4).

At the very low end are the free programs from UC Berkeley: Magic and OCT/VEM, which run on UNIX workstations. Magic is a widely used program geared for MOSIS-compatible CMOS processing. Magic is restricted to rectangles at right angles (Manhattan geometry) and has no support for polygons. The VEM polygon editor in conjunction with the OCT database manager provides support for polygons. A number of companion simulation and routing tools also work with the OCT database but are distributed "as is," and without support. While these programs are distributed for only a shipping fee, (109) the real cost is the time and expertise required for installation and for working around bugs. Magic and VEM generate patterns in CIF format, which is supported by some mask vendors or may be translated to GDSII.

6.5 GDSII

GDSII, also known as Calma Stream General Electric. Rights to the Calma products have changed hands several times, and are now owned by Cadence Design Systems. GDSII is by far the most stable, comprehensive, and widely used format for lithography. GDSII is a binary format that supports a hierarchical library of structures (called cells). Cells may contain a number of objects, including:

- Boundary, which may be used to represent polygons or rectangles,
- Box, which may be used to represent rotated rectangles,
- Path, which may be used to represent wires,
- Text, for annotation either on the CAD screen or the device,
- Sref, to include an instance of one structure (cell) inside another, and
- Aref, similar to Sref but providing an array instance of a cell.

There are 64 available Layers, numbered 0 to 63. Each primitive object (Boundary, etc.) lies on one of these layers. Each layer number typically represents one mask or electron-beam exposure step in a process. A specification of GDSII format appears in the appendix to this chapter, portions of which are reprinted by permission of Cadence Design Systems.

6.6 DXF

DXF format is produced by the program AutoCAD as well as by a number of other inexpensive CAD programs for Windows/DOS and the Macintosh. These programs were not designed for lithography and so contain structures (e.g. three-dimensional figures) that have no meaning in this area. Also, the common jargon (e.g., cell) has been replaced with less familiar terminology (e.g. block). Like CIF, this format does not support datatype numbers. DXF is useful only after it has been translated into GDSII by a program such as that sold by Artwork Conversion Software (108) or those of various mask vendors.

In DXF there can be considerable confusion over such issues as whether an enclosed line represents a polygon or an actual line. Translation programs support different subsets of DXF and translate the structures into GDSII using various sets of rules. Users of DXF are advised to submit sample patterns for conversion before investing a lot of time in CAD work, and to bear in mind that the DXF file used for one vendor may not work at all for a different vendor. Therefore, the cost of data conversion should be considered when choosing an apparently inexpensive CAD tool.

7 Resists

Electron beam resists are the recording and transfer media for e-beam lithography. This section is not intended as a review of research in resists or as a guide to resist chemistry; for this, the reader is referred to Chap. 4 and to several review papers (118-122). Instead, we present here a few standard resist systems and some useful recipes for processing and pattern transfer. The commercially available resists described here are summarized in Table 2.5.

The usual resists are polymers dissolved in a liquid solvent. Liquid resist is dropped onto the substrate, which is then spun at 1000 to 6000 rpm to form a coating (123). Further details on resist application can be found in Chapter 4. After baking out the casting solvent, electron exposure modifies the resist, leaving it either more soluble (positive) or less soluble (negative) in developer. This pattern is transferred to the substrate either through an etching process (plasma or wet chemical) or by liftoff of material. In the liftoff process a material is evaporated from a small source onto the substrate and resist, as shown in Fig.18. The resist is washed away in a solvent such as acetone or NMP (photoresist stripper). An undercut resist profile (as shown) aids in the liftoff process by providing a clean separation of the material.

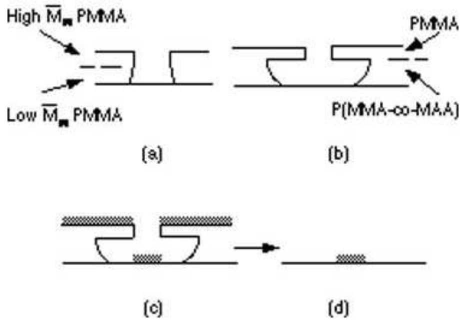

Figure 18: Undercut PMMA

If we expose a positive resist to a range of doses and then develop the pattern and plot the average film thickness versus dose, we have a graph as shown in Fig. 2.29. The sensitivity of the resist is defined as the point at which all of the film is removed. Ideally, the film thickness would drop abruptly to zero at the critical dose. In practice, the thickness line drops with a finite slope. If D1 is the largest dose at which no film is lost [actually, the extrapolation of the linear portion of Fig. 2.29(a) to 100

$$C = log_{10}(D_2/D_1)^{-1} \tag{2}$$

The same expression defines the contrast of a negative resist (the film is retained where irradiated), when D_1 and D_2 are the points shown in Fig.19(b). A higher contrast resist will usually

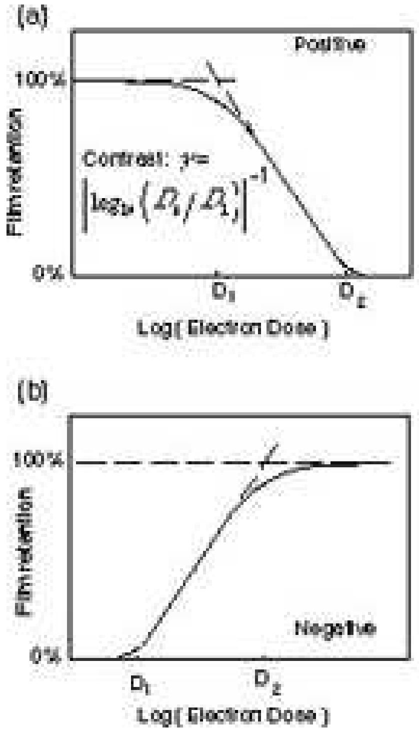

Figure 19: Film thickness versus exposure dose for (a) positive and (b) negative resist. Contrast is defined as the slope of the linear portion of the falling (or rising) section of the curve

have a wider process latitude as well as more vertical sidewall profiles. In order to help minimize bias and proximity effects, positive resists should usually be exposed and/or developed as lightly as possible while still adequately clearing the resist down to the substrate for all features. In electron beam lithography, especially at beam voltages of 50 kV or more, it is possible to make resist structures with very high aspect ratios. Unfortunately, when the aspect ratio exceeds roughly 5:1, most resists undergo mechanical failure (features will fall over) during development, due primarily to surface tension in the rinse portion of the development sequence. (124) Recently, commercial software for simulating electron-beam exposure of polymer resists has become available. (125)
Abbildung
The primary goals of e-beam lithography are high resolution and high speed (high sensitivity). Unfortunately, the highest resolution resists are usually the least sensitive. We can see a reason for this trend when we consider the limit of resist sensitivity. If a very sensitive resist has a

critical dose of 0.1 $\mu C/cm^2$, and a pixel is 0.1 μ on a side, then only 62 electrons are needed to expose the pixel. (126) At this sensitivity, even small changes in the number of electrons will cause variations in the dose delivered to each pixel. If the sensitivity is increased further, then the number of electrons in each pixel becomes too small to allow an even exposure of the pattern. To look at it another way, if we wish to decrease the pixel size, then the resist will have to be made less sensitive to avoid statistical variations in the exposure. Although there is room for improving the sensitivity of both high and low resolution resists, the statistics of resist exposure will eventually limit the resist sensitivity and exposure rate.
In the following we describe some common resists, categorized as either positive (removed where exposed), or negative (retained where exposed), single layer or multilayer, and organic or inorganic.

7.1 Charge Dissipation

A common problem is the exposure of resist on insulating substrates. Substrate charging causes considerable distortion when patterning insulators and may contribute significantly to overlay errors even on semiconductors. (56) A simple solution for exposure at higher energies (>10 kV) is to evaporate a thin (10nm) layer of gold, gold-palladium alloy, chrome, or aluminum on top of the resist. Electrons travel through the metal with minimal scatter, exposing the resist. The film is removed before developing the resist. When using Au or Au/Pd, the metal film is removed from the top of the resist with an aqueous KI/I solution. (127) A chrome overlayer would be removed with chrome etch. (128) Aluminum can be removed from the resist with an aqueous base photoresist developer. Acid mixtures or photoresist developer for removing aluminum will sometimes react with exposed e-beam resist; therefore, aluminum is not the best choice for charge dissipation. When evaporating any metal, it is important not to use an electron gun evaporator since x-rays and electrons in the evaporator will expose the resist.

Another approach to charge dissipation is the use of a conducting polymer, either as a planarizing layer under the resist or as a coating over the resist. The commercial polymers TQV (Nitto Chemical Industry) and ESPACER100 (Showa Denko) have been used for this purpose. (129-130) Both are coated at a thickness of about 55 nm and have a sheet resistance around 20 M/. TQV uses cyclohexanone as the casting solvent, which swells and dissolves novolac resins (present in most photoresists and SAL), and so a water-soluble PVA (polyvinyl alcohol) layer is needed to separate the resist from the TQV. ESPACER100 has the advantage that it is soluble in water and so can be coated directly onto many resists. TQV is removed with methyl isobutyl ketone/isopropanol (MIBK/IPA), the developer used for PMMA. ESPACER is removed in water. Other water soluble conducting polymers can be prepared from polyaniline doped with onium or triflate salts. (131-132)

7.2 Positive Resists

In the simplest positive resists, electron irradiation breaks polymer backbone bonds, leaving fragments of lower molecular weight. A solvent developer selectively washes away the lower molecular weight fragments, thus forming a positive tone pattern in the resist film (Fig.20.

7.2.1 PMMA

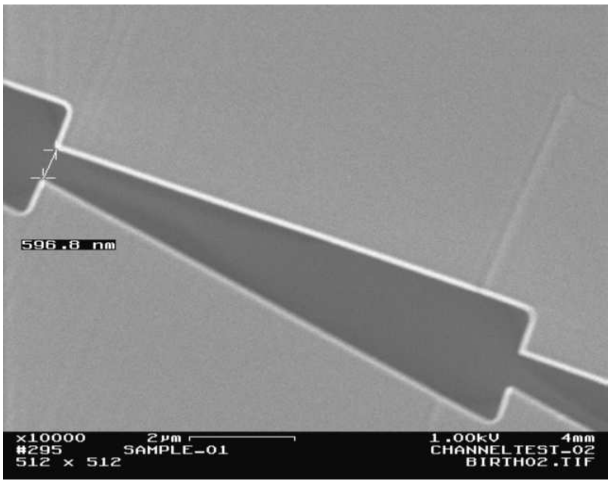

Figure 20: PMMA as example for positive resists

Polymethyl methacrylate (PMMA) was one of the first materials developed for e-beam lithography. [133-134] It is the standard positive e-beam resist and remains one of the highest resolution resists available. PMMA is usually purchased (135) in two high molecular weight forms (496 K or 950 K) in a casting solvent such as chlorobenzene or anisole. PMMA is spun onto the substrate and baked at 170C to 200C for 1 to 2 hours. Electron beam exposure breaks the polymer into fragments that are dissolved preferentially by a developer such as MIBK. MIBK alone is too strong a developer and removes some of the unexposed resist. Therefore, the developer is usually diluted by mixing in a weaker developer such as IPA. A mixture of 1 part MIBK to 3 parts IPA produces very high contrast (136) but low sensitivity. By making the developer stronger, say, 1:1 MIBK:IPA, the sensitivity is improved significantly with only a small loss of contrast.

The sensitivity of PMMA also scales roughly with electron acceleration voltage, with the critical dose at 50 kV being roughly twice that of exposures at 25 kV. Fortunately, electron guns are proportionally brighter at higher energies, providing twice the current in the same spot size at 50 kV. When using 50 kV electrons and 1:3 MIBK:IPA developer, the critical dose is around 350 $\mu C/cm^2$. Most positive resists will show a bias of 20 to 150 nm (i.e. a hole in the resist will be larger than the electron beam size), depending on the resist type, thickness, and contrast and development conditions and beam voltage.

When exposed to more than 10 times the optimal positive dose, PMMA will crosslink, forming a negative resist. It is simple to see this effect after having exposed one spot for an extended time (for instance, when focusing on a mark). The center of the spot will be crosslinked, leaving resist on the substrate, while the surrounding area is exposed positively and is washed away. In its positive mode, PMMA has an intrinsic resolution of less than 10 nm. (137) In negative mode, the resolution is at least 50 nm. By exposing PMMA (or any resist) on a thin membrane, the exposure due to secondary electrons can be greatly reduced and the process latitude thereby increased. PMMA has poor resistance to plasma etching, compared to novolac-based photoresists. Nevertheless, it has been used successfully as a mask for the etching of silicon nitride (138) and silicon dioxide, (139) with 1:1 etch selectivity. PMMA also makes a very effective mask for chemically assisted ion beam etching of GaAs and AlGaAs.(140)

- Start with 496K PMMA, 4 per cent solids in chlorobenzene. Pour resist onto a Si wafer and spin at 2500 rpm for 40 to 60 seconds.
- Bake in an oven or on a hotplate at 180 C for 1 h. Thickness after baking: 300 nm.
- Expose in e-beam system at 50 kV, with doses between 300 and 500 uC/cm2. (Other accelerating voltages may be used. The dose scales roughly with the voltage.)
- Develop for 1 min in 1:3 MIBK:IPA. Rinse in IPA. Blow dry with nitrogen.
- Optional descum in a barrel etcher: 150W, 0.6 Torr O2.
- Mount in evaporator and pump down to 210-6 Torr.
- Evaporate 10 nm Cr, then 100 nm Au.
- Remove from evaporator, soak sample in methelyne chloride for ca. 10 min.

Agitate substrate and methylene chloride with an ultrasonic cleaner for ca. 1 min to complete the liftoff. Rinse in IPA. Blow dry.

7.3 Neagtive Resists

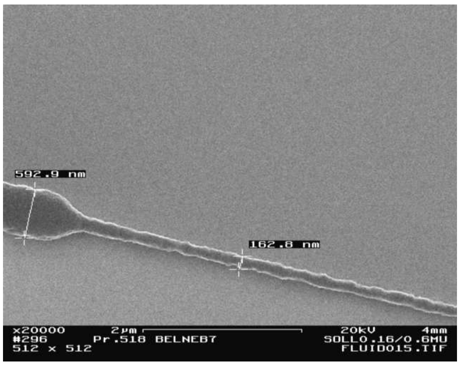

Figure 21: A chemical amplified negative resist

7.4 Some practical pitfalls with resist system

A typical problem with negativ resist is the structure collaps of free standing motives with a high apsect ration. The collapse usually appears due to capillary interaction of solvents used during development procedures.

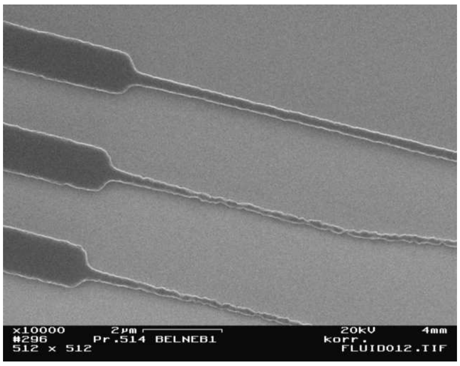

Figure 22: Distortion of a negative resist system due to surface delamination

8 Experiments in the lab course

The lab course includes the following experimental work related to electron beam and soft-lithography:

1. Preparation of PMMA resist by spin-coating 8.1
2. Design of a structure to be prepared by ebeam lithography, Ebeam lithography with the Raith Elphy Plus system, development of resist and inspection of structure by light- and scanning electron microscopy 8.2
3. Preparation of metal electrode by thermal evaporation and linewidth determination by SEM 8.3
4. Preparation of PDMS replica and surface patterning by micro-contact printing 8.4

Questions for preparation of the experimental work
Section 8.1:

1. How do you modify the silicon chip a) to become hydrophobic or b) hydrophillic ?
2. What are the key problems if the surface chemistry of the substrate and the resist are not adopted ?
3. Explain at least 3 parameters that are favorable to change the resist layer thickness.

Section 8.2:

1. What are the key parameters you need to know for correct exposure time calculation and how do you measure the Ebeam current experimentally ?
2. Estimate the total exposure time that you need to irradiate a 100 μ sized square with an ebem current of 150 pA using a standard PMMA resist with a sensitivity of 150 μC $/cm^2$ and a ebeam step size of ... nm?
3. What do you understand by proximity effect and how can this effect be influenced ?

Section 8.3:

1. Why are the vaccum conditions important in a metal evaporation process ?

2. What is the measurement principal for thickness measurement of the evaporated metal layer and what are the materials parameter that you have to change for the measurament if you measure the layer thickness of different metals (such as chromium and gold)? item Why do we need a chromium coating before gold coating of a glass substrate ?
3. Make a suggestion for the preparation of individual nm sized Au clusters on a glass surface and how you characterize a optically a glas surface coated with a monolayer of nm sized gold clusters (tip: colour of metal layers, particles)?

Section 8.4:

1. If you replicatie a structure with PDMS from a silicon master, what surface treatement is important to avoid grafting of the PDMS to the master and therefore irreversible destruction of the master ?
2. How can you improve the adhesion between PDMS and glass in order to prepare a pressure resistant sealing between the two components ?

Time (minutes)	Experimental procedure	Instrument	Referenz
30	spin-caoting	-	A
60	Introduction SEM-Litho	SEM	B
30	Development Litho-LIMI	-	C
30	SEM Inspection, Exp.	SEM	D
60	Strcuture Design	Elphy Computer	E
30	Structure Litho	SEM	F
30	Au Evaporation	Univex	G
30	Au Ev. Resist Strip, LIMI	-	H
30	Electrode SEM	SEM	I
30	PDMS Hardening	-	K
30	Au Evaporation	Univex	L
30	Printing - Condensation	-	M

8.1 Spin-coating

PMMA resist layers are prepared from a PMMA solution (Mol. Weight 950 KDalton) in chlorobenzene. The handling of the PMMA solution is done in the hood. A silicon wafer (15 mm x 15 mm) is placed on the chuck inside the spin-coating unit (23. The vacuum pump is switched on and the vacuum line connected with the spin-coater. The nitrogenegas line is opened. The wafer surface is covered with the PMMA solution using a pipette. The spin-coater is closed and the coating process is started with the start button. started.

During the coating process the speed rotation speed is defined by the programmable controller. The parameters used for the coating process are :

After finishing the coating process the sample is removed from the chuck and kept in a glass cover.

8.2 Ebeam Lithography

The ebeam exposure process is done within a so called writefield which is equal to the scanning field that is imaged at a given microscope magnification. The higher the magnification, the smaller is the scanning field. In the instrumentation used in the labcourse the simple rela-

Figure 23: Spin-coater for preparation of thin resist layers

tionship given in eq.3 is valid.

$$80000 = Magnificationxscanfield(\mu m) \tag{3}$$

The structural design in the course should be done within a 400 μm writefield.
If more than one writefields (structure) are exposed the sample needs to be moved by the microscope stage. In order to achieve a parallel arrangement of all writefields written after the other the coordinate system valid for stage movement and that given by the sample (rectangular wafer slice of 25 mm x 25 mm) both coordiante systems need to be adjusted (with the help of a calibration sample - Chessy).
Thereafter the structure to be irradiated by with the ebeam needs to be designed with the design programm of the lithographic system. Based on the maximum writefield size of 400 μ you

should design either

1. an interdigitating electrode system (minimum electrode width 2 μm) - supply electrodes 10 μ or

2. a microfluidic system which realizes a microchannel system in which a systematic variation of the concentration of 2 liquid components feed into the channels .

Next the electron beam current has to be measured with a Faraday cup and a picoampermeter. The measured beam current, the writefield size, the dose sensitivity of the PMMA resist (120 μAs / cm^2) (15 KV) allows you to set up a good approximation for the first irradiation process. For the fine calibration of the correct dose (the dose that realizes the predefined structure size in the development resist) typically a simple motif is repeatedly exposed within the sam writefield but with a systematic variation of the relative dose. The relative dose should be varied in between 0.5 and 2 of the calculated dose.
After the exposure the resist film is to be developed (in the ChemLab - use a hood) according to the following recipe:

- Develope the resist in a mixture of MIBK (Methylisobutylketone) and Isopropanol of 1:3. With gentle shaking the development time should be 150 sec at room temperature.

- Take the sample with a tweezer and wash it by shaking in isopropanol

- Dry the sample in a gentle stream of nitrogene

Now the sample can be inspected optically in a reflective light microscope. This should be documented with the camera. After optical insection the sample should be placed on the microscope stage, readjusted and the irradiated structures should be measured in line width with the SEM. From the systematic variation of the irradiation conditions within the different motifs exposed in the writefield you should determine the relative dose that gives the best fit between the predefined and the measured motif size. With this relative dose you should exposure your structure of interest (electrode system or microfluid system). Prior to exposure the ebeam should be well focused using the exposure test structure. After exposure the development is done in the same way as previously described.

8.3 Metal evaporation unit

The preparation of thin metal layers of defined thickness is done in a thermal evaporation units (Fig. 24) which is equipped with 2 heat sources. The adhesion of gold layers on glass is poor and therefore a chromium adhesion layer (3 nm thickness) has to be prepared prior to the gold evaporation. One group should prepare a 3 nm cr and 400 nm gold layer on glas slide for microcontact printing. The other group preparing the electrode system should coat the resist bearing the developed microelectrode design with a 3 nm cr and 40 nm gold layer.
After evaporation the samples are removed from the evaporation system. The glass gold system should be kept in a dust protected environment and the elctrode system should be transfered into a dish with acetone. The acetone dissolves the PMMA. The sample should be kept in the acetone solution for 15 minutes and than be treated in an ultasonic bath. Finally the polymer and the metal layers on top of the polymer should be mpletely removed and only the structure evaporated onto the glass surface should remain. The electrode should be inspected and documented in the reflective light microscope and afterwards in the SEM. Measure the size of the electrode structure and compare it with the predefined structure size.

Figure 24: Metal evaporation unit

The thickness measurement for active control of the metal deposition rate and for the final layer thickness is measured by a quartz oscillator. The measurement depends on the frequency change during mass change of the quartz crystal.

8.4 Softlithography

For replication of the PMMA microfluidic system into a PDMS structure the PMMA structure is completely covered with a mixture of the Sylgard 184 and the corresponding Pt catalyst in a ratio of 10:1. When all bubbles are removed the sample is cure thermally on a heating plate at 80 degrees for 45 minutes. Hereafter the elastomeric film is carefully separated from the PMMA master and the structures are inspected by reflective light microscopy. For microcontact printing a stamp prepared in the same way from a silicon master (which is available) will be contacted with an ethanolic solution of the 12 mercaptoundecanoic acid. The liquid is blown from the stamp in a gentle nitrogene stream and the stamp carefully placed on the gold coated glas samples. The contact time is approximately 30 seconds. After removal of the stamp the sample will be kept for 15 minutes in a ethanolic solution of Hexadecylmercaptane in order to introduce hydrophobic hydrocarbons. After this the sample will be cooled on a peltier element below the dew point and the condensation patterns of water should be documented.