Module-8_Unit-5: NSNT

Electron Beam Lithography (EBL)

1. Introduction

Electron beam lithography or e-beam lithography, is a technique used to draw patterns over a substrate by used focused electron beam. The surface of the substrate is covered with an electron-sensitive film, also termed as resist. It does not deposit the material onto the surface, rather it changes the solubility of the resist, already present on the surface. On exposure to the electron beam, the solubility of the resist changes such that the resist can be selectively removed, wherein, either the exposed part becomes more soluble or the unexposed part becomes more soluble depending on the type of resist. The resist can be simply removed by immersing it in a solvent, often termed as 'developing'. Similar to photolithography, small features are created in the resist and then subsequently transferred to a substrate via etching.

The most important advantage of e-beam technique over standard photolithography is that it can draw patterns with nanometer resolutions. E-beam is a maskless technique having high resolution and low throughput. As a result, its use is limited to fabricating photomasks, producing semiconductor devices in low volumes, and research and development activities.

1.1 E-beam Lithography Systems

E-beam lithographic systems employed for commercial applications are dedicated electron beam writing systems are very costly (greater than USD One Million). For research purposes, an electron microscope is usually converted into e-beam lithography system by attaching additional accessories which are relatively inexpensive (~ USD 100 K). Although, these converted systems do not achieve the resolution inherent to e-beam lithography systems, they still manage to get ~10nm linewidths.

The classification of e-beam lithography systems in based on the beam shape as well as the system used for beam deflection. Earlier system were based on Gaussian shaped beams and raster scanned the surface. Modern systems have shaped beams which can be vector scanned, i.e., deflecting the beam to multiple positions in the writing field.

1.2 Electron Sources

Systems having low resolutions use thermionic source made of lanthanum hexaboride. To achieve high resolutions, field emission sources, e.g., heated W/ZrO_2 for low energy spread and enhanced brightness. There are two types of field emission sources: thermal and cold emission sources. The beam size is bigger in thermal emission sources in comparison to the cold ones. However, owing to their better stability for prolonged writing times, thermal field emission sources are usually preferred.

1.3 Lenses

Electrostatic as well as magnetic lenses may be used. But, due to more aberration, electrostatic lenses are not suitable for fine focusing. Since chromatic electron beams are not produced currently, very fine focusing is achieved by using extremely narrow dispersion of electron beam energy.

1.4 Stage, Stitching and Alignment

Electrostatic lenses may be used for very small beam deflections, whereas electromagnetic lenses are required for large beam deflections. Due to the inaccuracy and finite number of steps in exposure grid, the writing field is around 100 microns to 1 millimetre. Stage needs to be adjusted for drawing large patterns. Accurate stage positioning is critical for stitching (tiling writing fields exactly against each other) and pattern overlay (aligning a pattern to the previously drawn pattern).

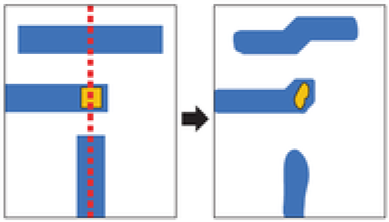

Figure 1 Schematics of field stitching. It is a major concern for critical features crossing a field boundary (red dotted line).

1.5 Electron Beam Write Time

Minimum time required to expose a given area can be expressed as:

$$D.A = T.I$$

where, the object needs to be exposed for a time T (and can be further divided into exposure time per unit step size), I represents the beam current, D is the dose and A is the exposed area.

As an example, consider an area of 1 cm^2 is exposed to a dose of 10^{-3} C/cm^2 at a beam current of 10 nanoamperes, the time required to write as calculated from above equation is 10^6 s or ~12 days. Additional time is needed for stage adjustment, time required to blank the beam (blocking during deflection), etc. Similarly, to cover 700 cm^2 of a 300 mm silicon wafer, writing times is around 22 years. Thus throughput is a serious concern of e-beam lithography, and it is worse for creating dense patterns over larger areas. This, seriously precludes any commercials scale production using this technique.

A small field of electron beam used to write the pattern, makes this technique very slow in comparison to the standard photolithography. Due to the small size of the electron filed, more exposure fields are needed to scan for creating a pattern. For comparison, the field size is less than one mm^2 in e-beam, whereas it is greater than 40 mm^2 in optical mask projection scanner. Further, the stage also moves in between field scans. Due to this small size, raster scan is required to create patterns (e.g., for a 26 mm x 33 mm pattern) in e-beam, whereas in photolithography, only one-dimensional scan is required for this purpose. Presently, for a given resolution, optical massless lithographic tool is much faster than e-beam tool in patterning a photomask.

1.6 Shot Noise

With a reduction in feature size, there is a corresponding decrease in the number of incident electrons for a fixed dose. When the number of electrons approaches 10000, shot noise starts dominating, resulting in significant variations in the dose within a large feature population. The feature are decrease by half with each successive process node, thus, for keeping the noise level at its previous value, dose must be doubled. This results in decreasing the throughput by half with each successive process node.

Shot noise needs to be considered for mask formation as well. For instance, commercial mask electron beam resists such as FEP-171 uses doses below 10 µC/cm^2, this results in substantial noise for a target CD even of the order of 200 nm on the mask.

1.7 Defects in Electron-beam Lithography

Even though e-beam lithography is a high resolution technique, defects can be generated during the process. These defects are of two types: data related defects and physical defects.

There are still two types of data related defects: (a) Blanking of deflection, and (b) shaping errors. Blanking errors are related to the improper defection of the electron beam, whereas, if the projecting shape is not correct, shaping error occurs. Data errors may be caused by either electron optical control hardware or input data which taped out. These errors are more dominant in large data files.

There are several types of physical defects, such as charging of the sample (both positive or negative), backscattering calculation errors, dose errors, outgassing, fogging (long range deflection of backscattered electrons), errors due to contaminants, drift in beam, etc. Because e-beam takes a very long time for creating patterns, random errors are more frequent. This possibility is more for large data files.

Majority of the photomask defects occur while e-beam lithographic processing employed to define pattern.

2. Electron Energy Deposition

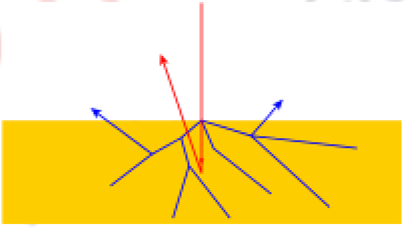

Figure 2 Possible trajectories of electrons in a resist. An incident electron (red) creates secondary electrons (blue). The incident electron may also get backscattered, thereby leaving the resist.

The incident electrons may undergo inelastic scatterings and collisions with the electrons present in the target material. In this way, the incident electron loses its energy. During collisions, incident electron transfers its momentum to the electron present in an atomic orbital of the material. The transferred momentum is given by:

$$dp = 2e^2/bv$$

here, b is the distance of the closest approach between the electrons, v is the velocity of the incident electrons. The energy transferred via collision is:

$$T = (dp)^2/2m = e^4/Eb^2$$

m is the mass of electron and E in the energy of the incident electron ($E = 1/2mv^2$). An integration over T between binding energy (E_0) as the lowest limit and the incident energy as the highest limit, demonstrates the inverse relation between the total cross-section for collision and the incident energy, i.e., collision cross-section is proportional to ($1/E_0 - 1/E$). Usually, binding energy is much smaller than the incident energy, and therefore can be neglected.

The integration over T from $2E_0$ to E demonstrates that half of the inelastic collisions of incident electrons generate electrons having kinetic energies more than E_0. These are called secondary electrons are can break the bonds (since the binding energy is only E_0) near the collision location. In addition to this, they can also produce some electrons with lower energies, producing a cascade of electrons. The secondary electrons are significant in spreading the energy deposition.

Generally, for a molecule 'AB', we have:

$e^- + AB \rightarrow AB^- \rightarrow A + B^-$

The relation is called the 'electron attachment' or the 'dissociative electron attachment'. It usually occurs when electrons slows down to a halt, as it can be readily trapped in this situation. The cross-section of attaching the electrons scales inversely with the electron energy at higher energies, and approaches the maximum value at zero energy. The electron mean free path at low energy (of the order of few eV, the regime of dissociative attachment) is usually more than 10 nanometers, thereby obstructing consistent resolution.

2.1 Resolution Capability

Aberration as well as space charge limit the electron beamwidths, which are of the order of few nanometers. But the feature resolution is not affect by beam size, rather it depends on the forward scattering (effective beam broadening) in the resist. In addition, the pitch resolution depends upon propagation of secondary electrons in the resist. This was demonstrated in 2007, where e-beam was used for double patterning to fabricate 15 nm half-pitch zone plates. In this study, the 15 nm feature could be easily resolved, whereas a 30 nm pitch could not be achieved. This was caused by the scattering of secondary electrons from the adjacent feature. Due to the use of double pattering, the spacing between the features could be increased so as to reduce the scattering of secondary electrons. The use of high energy electrons and thin resist can reduce the forward scattering, however, secondary electron occur inevitably. Low energy electrons have been found to travel large distances (several nanometers) in insulating materials (e.g., PMMA). This mainly occurs because below ionisation potentials, energy can only be lost via phonons and polarons. Even though polarons are ionic lattice effects, they can exhibit long range hopping, that is, upto 20 nanometers. The distance covered by a secondary electron is not physically calculated value, but is usually estimated experimentally or Monte Carlo simulations below 1 eV (energy distribution in secondary electrons peaks much below 10 eV). Thus, the resolution limit is not cited as a fixed number like an optical diffraction limited system. Resist development and intermolecular forces are important to the image formation.

2.2 Scattering

Apart from creating secondary electrons, the incident or primary electrons (having enough energy to penetrate the resist) can also may undergo multiple scatterings from the underlying film or substrates, over large distances. This may expose the areas which are far from the required exposed area. In thicker resists, when incident electrons move forward, they are increasingly scattered in lateral direction to the beam defined location. This is referred to as the 'forward scattering'. However, in some cases, the incident electrons may get scattered at angles exceeding 90º, in these cases, they do not propagate further in the resist. These are termed as backscattered electrons and produce similar effect as the long range flare in optical projection systems. If the backscattered electrons are more, they may expose the resist over a very large area than that defined by the beam spot.

2.3 Proximity Effect

Proximity effect results when the electrons from a nearby exposed region reach the current pattern (to be created) and cause enlargement of the new feature. It also decreases the contrast of the new feature to be created. Usually the e-beam lithography is employed for created isolated features, since the cascaded features exaggerate the proximity effects. Thus, the feature resolution in case of nested/cascaded features becomes hard to control. For most resists, it is difficult to go below 25 nm lines and spaces.

Proximity effect gets manifested when the secondary electrons leave the top surface of resist and come back at some distance (of the order of 10nm). Scattering induced proximity effects can be addressed by solving the inverse problem to calculate the exposure function E(x,y) which results in a dose distribution to the closest desired dose D(x,y) when convolved with scattering distribution point spread function PSF(x,y). Noticeably, any error in the dose (which may be due to shot noise), will lead to failures in correcting the proximity effects.

3. Charging

Being charged particles, electrons can negatively charge the substrate if they remain there. Thus, it is necessary to offer a quick path to the electrons to ground. A silicon wafer virtually stops all the electrons from a high energy beam, and they follow the path to ground. In the case of quartz substrates (e.g., photomasks), these electrons take longer time to reach the electrical ground. A secondary electron emission in vacuum can be used to provide counter (positive) charge to avoid negative charge accumulation on a substrate. The use of thin conducting layers above or below the resist cannot solve the charging problem completely as the high energy electrons may penetrate through these layers to reach the substrate. The charge dissipation layer can only be used upto 10 keV, because due to the thinness of resist, the majority of electrons stop either at the resist or near the conductive layer. The large resistance of these conducting layers may significantly obstruct the path of electrons towards the ground, thus, these layers are of limited use.

Low-energy secondary electrons (which is the largest portion of the free electron population in the resist-substrate system) contributing towards charging, do not have a fixed range, and usually vary between 0 and 50 nm. This leads to inconsistent resist-substrate charging, making it difficult to compensate. The accumulation of negative charges causes deflection of the electron beam away from the charged area whereas positive charge accumulation attracts the electron beam.

4. Electron-beam Resist Performance

Since the scission efficiency is usually an order of magnitude higher then that of crosslinking, majority of the polymers used for positive-tone e-beam lithography will crosslink (and become negative-tone) at a dose an order of magnitude higher than the dose required for positive-tone exposure. Such large dose increases may be needed to preclude the impact of shot noise.

It has been reported that low energy electrons can damage PMMA films of upto 30 nm thickness. The damage was in the form of material loss. Other observations may be summarised as follows:

- for ZEP-520, the frequently used resist, the pitch resolution limit was achieved at 60 nm (30 nm lines and spaces), and this value did not depend on thickness of the film and energy of the beam.
- the resolution was increased to 20 nm by using a 3 nm 100 keV e-beam and PMMA resist. 20 nm unexposed gaps between exposed lines showed inadvertent exposure by secondary electrons.
- hydrogen silsesquioxane (HSQ), negative-tone resist, can produce isolated 2 nm wide lines and 10 nm periodic dot arrays (10 nm pitch) in very thin layers. HSQ is like porous hydrogenated SiO_2, and can be employed to etch Si but not and SiO_2 like dielectrics.

5. New Frontiers in E-beam Lithography

To avoid the creation of secondary electrons, low-energy electrons may be used to irradiate the resist. The energy of these electrons should not exceed a few eV for exposing the resist without creating secondary electrons. Thus, these electrons will not have enough energy to generate secondary electrons. This has been successfully done with a STM (scanning tunnelling microscope) as the beam source. Observations have shown that electrons having energy around 12 eV penetrate a 50 nm thick layer of polymer resist. However, low energy electrons spread in the resist. Furthermore, the use of low energy electrons seriously limits the resolution. Additionally, low energy electrons also suffer the most due to Coulombic repulsions from other electrons.

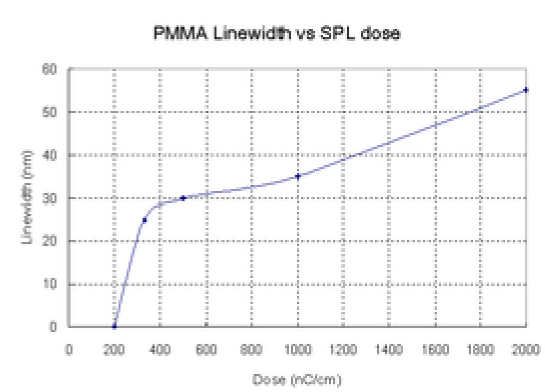

Figure 3 Scanning probe lithography can be used in low-energy e-beam lithography. The resolutions reached via this technique are of the order of 100 nm, and are influenced by the dose of low energy electrons.

Alternatively, very high energy electrons (greater than 100 KeV) can be used to effectively ‘drill’ or sputter the material. It is commonly seen in TEM. Nonetheless, it is inefficient process because the momentum cannot be transferred effectively from the incident electrons to the material. Consequently, the process is very slow and requires prolonged exposure duration in comparison to the conventional e-beam lithography. Besides, the substrate may get damaged due to the high energy electrons being irradiated onto it.

Arrays with nanoscale periods can also be patterned using e-beam interference lithography. The main benefit of electrons over photons in interferometry is the short wavelengths of electrons for a fixed energy.

Regardless of the above mentioned complexities involved in e-beam lithography, it still is a widely used technique to concentrate maximum energy into a smallest area. There have been continuous efforts towards increasing the throughput of this technique. Another concern is the high cost of the equipment.

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