Lab 1. Resolution and Throughput of Ion Beam Lithography

(SRIM 2008/2013 computer simulation)

Objective
The objective of this laboratory work is to evaluate the exposure depth, resolution, and throughput of focused ion beam (FIB) processing of lithographic resist using SRIM simulation software. This objective is achieved by performing simulation of the process of ion irradiation of positive photoresist and determination of the size of ion beam exposed area.

Principles
Exposure of lithographic resist to ion irradiation results in its chemical modification. In case of positive resist, the ion-irradiated area of the resist becomes more soluble and can be removed in a solvent. Energetic ions propagating through target material collide with atoms of the target losing their energy. If the collisions are strong enough and the energy transferred to the target atoms exceeds a certain threshold energy $E_d$ (displacement energy), these atoms leave their regular positions producing vacant atomic sites (vacancies). The knocked-out atoms and vacancies are the defects responsible for the changes of the properties of the ion-irradiated resist.

A common software used for simulation of ion irradiation and the irradiation-induced defect production is SRIM [http://www.srim.org]. Below, Fig. 1 shows an example of simulation of propagation of one Ga ion of initial energy 100 keV in a solid carbon target of density 1.2 g/cm$^3$. 

![Depth vs. Y-Axis](image-url)
Fig. 1. SRIM2008 simulation of defect production in solid carbon of density 1.2 g/cm³ by one Ga ion of initial energy 100 keV. Red trace shows trajectory of Ga ion. Green lines and dots show trajectories of knocked-out carbon atoms of the target and the created vacancies.

Because of the collisions with the atoms of target, the ion does not propagate along straight line. It experiences multiple collisions (scatterings). Some target atoms are knocked out of their regular sites violently and may move over long distances sometimes penetrating deeper than the initial ion. Since the energy loss of the ion and knock-outs is random process, every ion has its unique pathway and unique pattern of the created defects.

The result of simulation of ion irradiation with many ions is shown in Fig. 2. Fig. 2a shows trajectories of the primary (implanted) ions. Fig. 2b shows pathways of the knock-out atoms of the target and the created defects.

Fig. 2. SRIM2008 simulation of irradiation of solid carbon target of density of 1.2 g/cm³ by 200 Ga ions of initial energy 100 keV. (a) Trajectories of ions are shown by red traces. Final positions of the ions are shown by black dots. (b) Trajectories of knock-out carbon atoms and distribution of created defects are shown by green lines and dots respectively.

The distribution of the implanted ions through the depth has approximately gaussian shape the two main parameters of which are the depth of the maximum density $R_p$ (projected range of ions, or ion range) and the width of the gaussian $2\Delta R_p$. $\Delta R_p$ is the longitudinal straggling, or average scattering of ions through the depth (Fig. 3a).
Depth distribution of the defects is shown in Fig. 3b. A considerable defect production starts from the very surface of the irradiated resist. The defect distribution curve does not have a gaussian shape. However, its tale towards greater depths can be approximated by gaussian distribution.

Comparing distributions of the implanted ions and the created defects one can see that average penetration of the ions in deeper than that of the defects. The depth of the maximum density of the implanted ions is about 110 nm (1100 Å), whereas the maximum density of defects is at a depth of 70 nm (700 Å).

**Exposure Depth**

Since the radiation defects are the primary reason for the change of solubility of resist, the defect distribution through the depth determines the depth of the exposure and hence the thickness of the resist layer which can be processed with given ion species of given energy and given exposure dose. From the graph on Fig. 3b one can conclude that the maximum penetration depth of defects is about 200 nm. However, the density of defects at depths greater than 130 nm drops down rapidly. Thus, the effective depth of penetration of defects $R_d$ is only about 130 nm. A simple estimation of the magnitude of $R_d$ can be done calculating sum of the depth of the maximum concentration of implanted ions $R_p$ (projected range of ions, or ion range) and the longitudinal stragglng $\Delta R_p$:

$$R_d = R_p + \Delta R_p$$

The results of the simulation shown in Fig. 3 yields in $R_p = 114.7$ nm and $\Delta R_p = 28.1$ nm. Correspondingly $R_d = 142.8$ nm. Thus, the thickness of the resist layer which can be used for this ion irradiation is about 140 nm.

More precise calculation takes into account the dose of the ion irradiation and the critical concentration of defects corresponding to clearance dose $D_c$. With the increase in the ion dose, the
layer in which the concentration of defects exceeds $D_c$ expands in depth and ultimately can be as deep as 200 nm. In order to calculate the ion dose required for the exposure of resist of a given depth $d$, the efficiency of defect production $n_d$ at this depth is determined from Fig. 3b. For instance, at a depth of 160 nm $n_d = 0.1$ vacancy/ion*Å = $10^7$ vac/ion*cm. Then, the ion dose needed to achieve the critical defect concentration $N_c$ at depth $d$ is $D_c = N_c/n_d$. A common critical defect concentration (clearing defect concentration) corresponding to the clearing dose $D_c$ of polymeric resist is about $N_c = 10^{19}$ cm$^{-3}$. Thus, $D_c = 10^{12}$ cm$^{-2}$ at depth 150 nm. For a resist layer of thickness 100 nm, $n_d = 1.25$ vacancy/ion*Å = $1.25 \times 10^8$ vac/ion*cm. Then the corresponding $D_c = 8 \times 10^{10}$ cm$^{-2}$.

Resolution

Fig. 2 shows that even when the ions enter target in one and the same point, they do not propagate along one and the same straight line because of lateral (side) scattering. The lateral scattering broadens the damaged area and this broadening is especially pronounced for ion beams of small diameter. The lateral scattering of ions is described by lateral range $R_l$ and lateral straggling $\Delta R_l$. The lateral deviation of ions from straight propagation shown in Fig. 2a is about 30 nm, whereas it is about 70 nm for defects (Fig. 2b). The lateral distribution of defects can be described in the same way as we did it for the depth distribution. Thus, we assume that the effective depth of the lateral propagation of defects equals the sum of the lateral range and the lateral straggling:

$$R_{dl} = R_l + \Delta R_l$$

The simulation of lateral scattering is shown in Fig. 4. It is seen that the lateral scattering increases with depth. For simple modeling, average values of lateral range and lateral straggle can be taken: $R_l = 15.7$ nm and $\Delta R_l = 19.9$ nm. Correspondingly, $R_{dl} = 35.6$ nm.
Lateral scattering causes broadening of the area exposed to ion irradiation and consequently deteriorates resolution of ion lithography. The effective resolution of lithography $R$ utilizing exposure with ion beam focused to diameter $D$ can be estimated as:

$$R = D + 2R_{sl}.$$

In case of our simulation example, an ion beam of diameter 20 nm can provide resolution of 90 nm in 140 nm thick resist.

**Clearing dose**

An important parameter of any lithography method including ion beam lithography is the clearing dose $D_c$. $D_c$ correspond to the number of particles per unit area sufficient for chemical modification of the resist in the irradiated area through the whole resist depth. Clearing dose can be also presented as the density of energy losses deposited by ions.

Energy losses of energetic ions propagating through target material have to components: energy losses in elastic collisions with the target atoms (nuclear stopping) and energy losses in inelastic interaction with the target electrons (electronic stopping). The main result of nuclear stopping is the production of defects and heating the target (generation of phonons). Depth distribution of energy losses in our simulation example is shown in Fig. 5.
Fig. 5. SRIM2008 simulation of electronic (a) and nuclear (b) energy losses of 100 keV Ga ions in solid carbon of density 1.2 g/cm$^3$. Red traces show direct losses by Ga ions. Blue areas show losses by carbon recoils.

Comparing Figs. 3, 4 and 5 one can conclude that effective deposition of energy and generation of defects occur in a layer of thickness $R_d$.

The value of the clearing dose is specific for every combination ion specie and type of resist. It is established experimentally. Let us assume that $D_c$ of 100 keV Ga ion beam lithography is $10^{12}$ cm$^2$. Then, for a 140 nm thick resist, average density of energy losses $E_{\text{average}}$ is:

$$E_{\text{average}} = \frac{(D_c E_{\text{ion}})}{R_d} = \frac{(10^{12} \text{cm}^2 \times 10^5 \text{eV} \times 1.6 \times 10^{-19} \text{J/eV})}{140 \times 10^{-7} \text{cm}} = 1.14 \times 10^3 \text{J/cm}^3.$$

Area density of the deposited energy, or the clearing dose is: $D_c = E_{\text{average}} \times R_d = 16 \text{mJ/cm}^2$.

**Throughput**

Throughput of lithographical procedure $T$ is the speed of exposure of resist at the clearing dose:

$$T = \frac{A}{t} = \frac{I}{(eD_c)}$$

where $A$ is the irradiated area and $t$ is the time required for this irradiation, $e$ is the electron charge and $I$ is the ion beam current. For ion beam $I = 10$ pA, $T = 100 \mu$m$^2$/s. If an ion beam of diameter 20 nm is used for making a pattern of straight lines, this pattern can be produced with a speed of 5 cm/s.

**Tasks of the lab work**

1. Compare parameters of two lithography techniques which utilize Ga and He ion beams. In both cases a carbon-based resist of density 1.4 g/cm$^3$ and clearance dose 100 J/cm$^3$ is used. Displacement energy if carbon atoms in resist is 15 eV.
**Input parameters of Ga ion beam lithography:** Ion energy - 50 keV. Ion beam current is 20 pA. Nominal diameter of the ion beam is 10 nm. Sensitivity of resist $N_c = 2 \times 10^{19}$ cm$^{-3}$.

**Input parameters of He ion beam lithography:** Ion energy - 30 keV. Ion beam current is 10 pA. Nominal diameter of the ion beam is 5 nm. Sensitivity of resist $N_c = 3 \times 10^{19}$ cm$^{-3}$.

2. Calculate thickness of the resist layer corresponding to the given clearing dose $2 \times 10^{12}$ cm$^{-2}$.

3. Calculate maximum thickness of the resist layer for the irradiation dose $5 \times 10^{13}$ cm$^{-2}$.

**Parameters to be found and compared:**

1. Parameters of distribution of ions.
2. Parameters of distribution of damage.
3. Lithography resolution.
4. Clearing dose in units [ion/cm$^2$] and [J/cm$^2$].
5. Throughput for areal exposure and line exposure.

**Questions**

1. Which parameters of ion beam exposure are to be changed in order to process a thicker resist layer?
2. What are the advantages and disadvantages of using heavy ions for ion beam lithography?
3. What are the advantages and disadvantages of using light ions for ion beam lithography?
4. Lateral scattering makes resolution of ion beam lithography greater than ion beam diameter. Is it possible for ion beam lithography to achieve resolution less than ion beam diameter?