Chapter 4

ENERGY DISSIPATION PROFILE

4.1 INTRODUCTION

It is generally acknowledged that electron beam lithography will play an important role in the future development of microelectronic devices. This is due primarily to the fact that electron beam lithography can readily create submicron resolution patterns in radiation-sensitive polymer films, and these patterns in turn can be used to define doping patterns, relief structures, and metal film structures. Electron beam lithography is also attractive because the scanning and control of the beam can be fully automated.

In this Chapter we focus on electron beam energy deposition in the resist and the substrate. We performed our simulation in both two and three dimensions. We include both the scattering of the incident electrons as they penetrate the resist and electrons backscattered from within the resist and from the substrate. The calculations yield contours of equal absorbed energy density, and these are interpreted as the contours which bound the resist after development. The absorbed energy density is found as the sum, for all electrons, of the product of the energy absorbed per unit length of trajectory. In order to predict the behaviour of electron resists under various exposure conditions, an analytical understanding of the exposure process is required. Two factors are involved. The first one is the chemistry of the electron resist which includes the relationship of the absorbed energy to the change in the molecular weight of the resist and the influence of the developer solution. The second factor is the pattern of energy absorption produced by the electrons. In this chapter we will present a simple model for computing the absorbed energy in the resist and the substrate. We study the influence of beam energy, type of substrate and resist thickness. We divided the energy loss into component parts: (1) the contribution from the forward scattered primary electrons and (2) the contribution from the electrons backscattered from the thin film and the substrate.

The use of electrons, however, introduces certain problems. One example is the dissipation of energy at points remote from the original point of entry, due to scattering both in the polymer film (PMMA) and the substrates. An understanding of the role of electron scattering in the exposure of polymer films on substrates, therefore, is very
important to the implementation of electron beam lithography. Electron beam lithography is usually carried out by first coating a substrate with a thin (~0.1- to 1-μm) film of a radiation-sensitive polymer (often called an electron resist). The polymer is then exposed by scanning a 10- to 100-keV electron beam over it in accordance with the desired pattern.

![Fig. 4.1. Schematic diagram illustrating the undercut contours typically obtained in a PMMA film of thickness \( T \) on top of a substrate after exposure by a scanned electron beam and developing.]

The experimental procedures is illustrated in Fig. 4.1. When PMMA is exposed in a line by a scanned electron beam, developed in a solvent to remove the exposed regions, and viewed in cross section, undercut contours are observed whose dimensions depend on the line charge density. Similarly, if the beam is held at a fixed position and turned on for a time interval, \( T \), a radially symmetric contour is obtained that we term a dot exposure. These contours have been identified as surfaces of equal energy dissipation per unit volume. From this assumption, we can immediately write an expression for the contours of a dot exposure:

\[
(qir)I(r, z) = D \text{ (ergs/cm}^3\text{)},
\]

where \( D \) is the energy dissipated per unit volume required to expose the polymer adequately for development. The radially symmetric function \( I(r, z) \) is the energy dissipated per unit volume per electron (ergs/cm\(^3\) electron). The factor proceeding \( I(r, z) \) is the number of electrons incident — that is, \( q \) is the number of electrons per coulomb and \( i \) is the beam current in amperes. The present work is concerned with the calculation of \( I(r, z) \). \( I(r, z) \) is of fundamental significance since it allows one to calculate the energy dissipated per unit volume at any point in the polymer film for any given exposure pattern.
Chapter 4: Energy Dissipation Profile

The following section describes the Monte Carlo calculation of the spatial distribution of energy dissipated in a range of (1000-10000) Å thick film of PMMA on a number of substrates due to a normally incident electron beam of finite beam diameter and energy in the 10- to 100-keV range.

4.2 Monte Carlo Model:

In the present calculation, we focused on the energy dissipation profile in layer structures using Monte Carlo Simulation. The main purpose is to get fine patterns on the spatial resolution of the resist film when irradiated by an electron beam. We consider the electron source as the electron beam with initial energy E. The electron beam is considered incident normal to a target composed of a substrate coated with a thin layer of electron sensitive resist, PMMA. In our theoretical simulations we considered a few substrates: Silicon, GaAs, and SiC. The thickness of the resist film, PMMA is fixed at 1 μm. However its thickness can be varied to any depth. Electron beam energies starts from 20 keV to 100 keV. Our calculation is based on a single scattering model. An electron trajectory is divided into many small steps, length of which is taken equal to the mean free path of elastic scattering. We used the screened Rutherford formula (equation 2.12 - 2.15) for finding total cross section and mean free path for elastic scattering cross section. The scattering and azimuthal angles are calculated with equation 2.16 -2.18. The energy loss is calculated by Bethe's continuous slowing down approximation (CSDA) explained in equation 2.23-2.24. The present calculation is performed up to 70,000 trajectories for a particular simulation.

The energy dissipated in the thin polymer film PMMA and in the semiconductor substrates are calculated up to 2 μm. As is illustrated in Fig. 4.2, the energy dissipated in the annulus was calculated and normalized by dividing by $2\pi r \Delta r \Delta z N$, to obtain the average value of $I(r, z)$, where $N$ is the number of trajectories computed. In our calculation we set $\Delta z$ and $\Delta r$ equal to 400 Å each (but it can be varied to any length). The number of electron trajectories calculated was at least 30000 in all cases. We calculated separately the contribution from electrons scattered within the polymer prior to entering the substrate and the contribution from electrons that were backscattered from the substrate, as well as the total of the two.
To get the energy density counter in Fig 4.3 we consider planes at different depths. Each plane is divided into a number of small cells. We obtained the equi-energy density contours on the surface by connecting the cells with the equal absorbed energy density at each layer. We performed in two ways (a) Two dimensional Model and (b) Three dimensional Model.

![Energy Distribution profile for PMMA & GaAs Substrate at different Depths](image)

**Fig. 4.3** - Energy Distribution profile for PMMA & GaAs Substrates at different Depths. Electron Beam Energy = 30KeV, Thickness of the PMMA resist = 1 micron, Number of particles used for this simulation is 30000.
A. 3-Dimensional Model:

We consider a plane at any depth of the material i.e. at Resist or at Substrate or at the interface. Due to co-axial symmetry around the z-axis as shown in Fig. 4.2 for a normal incidence the polymer film or the substrate (for testing) is divided into concentric donut-shaped volumes with inner radius $R$, outer radius $R + \Delta r$, with thickness $\Delta z$ at depth $Z$.

![Fig. 4.4 All possible paths of the particles inside the plane](image)

Fig. 4.4 shows the possible paths of the particles inside the plane considered. Some of the electrons may pass to a single cell or more than one cell. In all cases we find out the distance to each cell for every electrons. After knowing the distances inside the cells we find out the energy loss of all electrons in terms of volumes and stored as a histogram of $\Delta E$ (total) versus $R$ and $Z$.

In our simulation we also focus to the all possibilities of the electron paths inside the given volume element including forward and backward scatterings. The energy density (eV/cm$^3$) per electron in every cell is then calculated and plotted as a smooth curve through the midpoints of the histogram.

The absorbed energy $Q_s$ per unit volume in $s^{th}$ ring is given by the formula [9],

$$Q(s) = -\frac{1}{2\pi R(s)(dR)^2} \sum_i \sum_j l_i(j) \cdot f(E),$$  \hspace{1cm} (4.2)
where \( R(s) \) is the radius of the \( s \)-th ring, \( l_s(i) \) the length for which an electron passes through the \( s \)-th ring in the scattering process and \( f(E) \), the stopping power at that event. \( l_s(i) f(E) \) means the absorbed energy when an electron passes through the ring. The first summation is taken over the absorbed energy in the ring along an electron trajectory till the electron energy becomes 500eV. The second summation is over the total contribution from all sample electrons (\( N = 70000 \)).

The Average energy \( \bar{E} \) given by an electron is represented as [9]:

\[
\bar{E} = \frac{1}{N} \sum_{n} 2\pi (dR)^2 R(s) Q(s)
\]

(4.3)

B. 2-Dimensional Model:

In the Three-dimensional approach we consider \( x, y, z \) in terms of \( r = \sqrt{x^2 + y^2} \) and theta whereas we consider \( x \) and \( z \) only in Two-dimensional approach. In both cases we considered for different planes at different depths from 0.1\( \mu \)m-2\( \mu \)m. All methods are same as three-dimensional, the difference is we don't use the value of \( y \) and we calculated the energy loss in terms of area instead of volume element. Here the profiles of the energy dissipation are obtained by integrating the energy dissipation for infinitesimal spot size cell along \( X \)-axis. To make these profiles we considered different planes at different depths and divided the inside of resist and substrate into many square nodes as we did in three-dimensional approach. All possibilities of the paths of the electrons, for incident electrons and backscattered electrons, inside the plane thickness are shown in the Fig.4.4. These possibilities are taken care by our program.