ELECTRON BEAM ENERGY DEPOSITION AND RESIST PROFILE MODELING DURING ELECTRON BEAM LITHOGRAPHY PROCESS

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Abstract: *Electron beam lithography (EBL) is a key technology for the fabrication of new generation integral circuits and devices of electronics, photonics and nano-engineering. The computer simulation of the processes of electron exposure and development of the resist profiles in EBL is important for the optimization of this expensive technology process, due to the expensive equipment used in microelectronic fabrication, the use of sophisticated materials and the long chain of sequential steps required to obtain the desired micro- and nano-structure. In this work investigation of the exposure and the development of Poly-methyl methacrylate resist (PMMA) with 100 nm thickness on Si substrate is presented. Different simulation techniques are implemented for the estimation of the distribution of the absorbed energy in the sample during electron beam exposure and for the development of the resist profile. Results from Monte Carlo simulation softwares CASINO, TREM, SELID are presented.*

KEYWORDS: ELECTRON BEAM LITHOGRAPHY, RESIST EXPOSURE, PROFILE DEVELOPMENT, PMMA RESIST PROFILES

1. Introduction

The first results from the use of the process electron beam lithography were obtained in the 1960s with a modified electron microscope. In large companies, electron beam lithography has been made since 1965, in Westinghouse and in IBM since 1969. In Bulgaria the first experiments were performed in the Bulgarian Academy of Sciences (BAS) in 1972 and in 1974 in the Institute of Electronics (IE) - BAS started the work on a modified transmission electron microscope, working as a lithograph with an acceleration voltage of up to 100 keV [1].

Modern microelectronics builds its success based on the lithographic process. Modern computers, for example, are faster, more compact, with more memory thanks to modern semiconductor technology.

Electron beam lithography is a major technology in micro-construction. In this process, as a first step, recording (exposure) is made by irradiation with electron beam in a sensitive thin layer, called a resist (because during the subsequent transfer of the image into the underlying material it will protect parts of the surface of the etched pattern). The second step of the process is to develop the latent image by dissolving the irradiated or non-irradiated regions of the resist (the recorded micrographs), which transforms the latent image into a relief image of the structure in the resist.

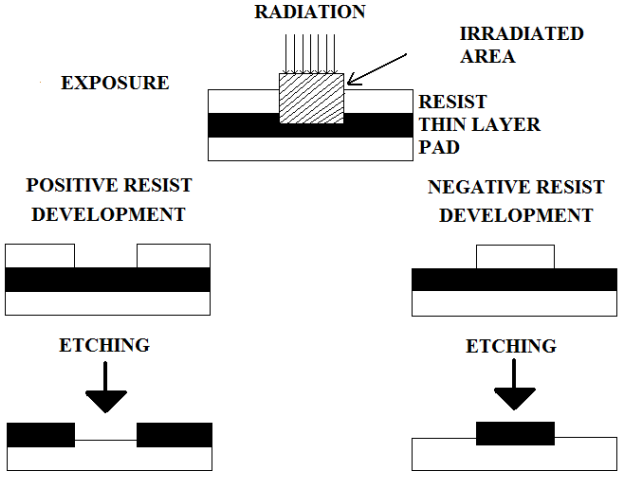

Fig. 1 *Schematic representation of electron beam lithography.*

Figure 1 represents a schematic representation of the lithographic process. "CASINO" is software for simulating the electron movement trajectories and the distribution of the backscattered and the absorbed in the sample energies during electron beam exposure. The software uses a single-scattering algorithm for modeling low-energy beam interactions in bulk and thin foil samples [2]. Developed in C ++, giving it the advantage of working with a PC, it is widely used by people involved in such processes. At the beginning, when the program was developed in the 1990s, the simulation was a slow process, sometimes took more than a few hours, but as the speed of modern computers accelerated, the time for obtaining the simulation results accelerated considerably.

The program offers a user-friendly graphical user interface that can easily set specific conditions for the simulation of the exposure process during electron beam lithography. The software is a good way to run simulation experiments in a computer environment to find the optimum process parameter values and in such way to prepare for real experiments. This option gives a number of advantages, the greatest of which is the ability to reduce the number of real time expensive experiments.

In this article exposure and development study of Poly-methyl methacrylate resist with 100 nm thickness on Si substrate is presented. The acceleration voltage of the electron gun is 20 keV. The absorbed energy is simulated using the CASINO software product and our simulation tool TREM [3]. The process of resist development was performed on the SELID program. Results concerning estimated dissolution rate, based on obtained experimental data are also presented.

2. Electron beam exposure

An electron beam lithography experiment was made on Poly-methyl methacrylate (PMMA) resist with structural formula $(C_5H_8O_2)_n$ and 100 nm thickness. PMMA is one of the first materials used in electron beam lithography as a resist. It is a standard positive resist and it has one of the highest resolutions. The acceleration voltage of the electron gun is 20 keV. Electron beam with Gaussian distribution and a diameter of 20 nm is applied. Silicon (Si) was chosen for substrate.

The CASINO program applies the Monte Carlo method, which simulates the electron trajectories by generating incident numbers (the use of random numbers to determine the atom of the specimen with which each stroke is performed, to select the azimuthal angle of scattering, to estimate the specific value of the free stroke

between the impact, etc.). When calculating, it is assumed that the diffusing atom is represented by Rutherford's shielded potential, and the deviation of the trajectory of the penetrating electron at impact is obtained from the differential section of the elastic scattering. The energy losses experienced by the penetrating electron along its entire trajectory until it is stopped or left out of the sample is calculated on the BETt's score for inelastic losses from the penetrating electron strikes with the electrons of the sample.

The electron trajectories are calculated using the following formulas [2]:

$$X_0 = \frac{d\sqrt{\log(R_1)}}{2\ x\ 1.65}\ x\ \cos(2\pi R_2) \quad (1)$$

$$Y_0 = \frac{d\sqrt{\log(R_1)}}{2\ x\ 1.65}\ x\ \cos(2\pi R_3) \quad (2)$$

R_x are random numbers uniformly distributed between 0 and 1, d is the electron beam diameter. The distance L [nm] between two successive collisions is [2]:

$$L = -\lambda_{el}\ log(R_4) \quad (3)$$

$$\frac{1}{\lambda_{el}} = \rho N_0 \sum_{i=1}^{n} \frac{C_i\ \sigma_{el}^i}{A_i} \quad (4)$$

C_i, A_i are the weight fraction and atomic weight of element i, respectively, ρ is the density of the region (g/cm^3) and N_0 is the Avogadro's constant.

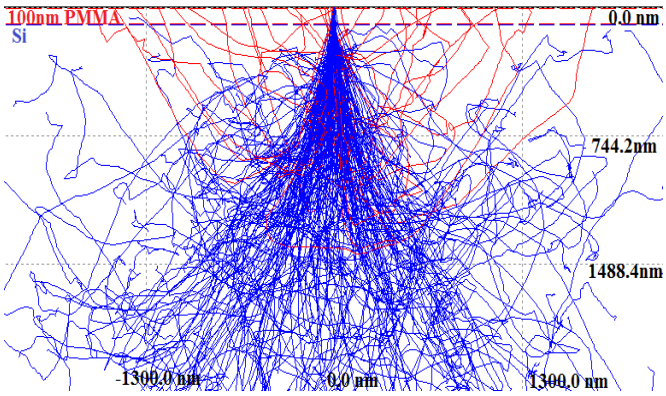

Fig. 2 *Simulated electron trajectories.*

A simulation with 20 000 electron trajectories was performed. The simulation took 2.31 minutes, which is a negligible interval of time. After the simulation, the software provides a series of graphs showing different process data.

In the Fig. 2, 200 of the simulated by CASINO electrons trajectories are given: in blue color are the transmitted electrons, and with red one are shown the backscattered electrons.

Fig. 3 presents the distribution of the absorbed energy in the sample: electron beam energy 20 keV a) on x and z axes, b) top-down view on the x and y axes of the absorbed energy in PMMA resist. The number of electron trajectories simulated is 20 000. In Fig. 4 is presented the maximum penetration depth in the sample of the electrons, as hits, normalized by the number of primary simulated electrons.

Fig. 5 shows graphically the dependence of the absorbed electron energy on the radial distance (from the direction of the initial movement of the electrons beam) at the resist/substrate interface for 100 nm PMMA on Si at 20 keV energy, obtained using TREM simulation Monte Carlo tool, developed in the IE-BAS [3].

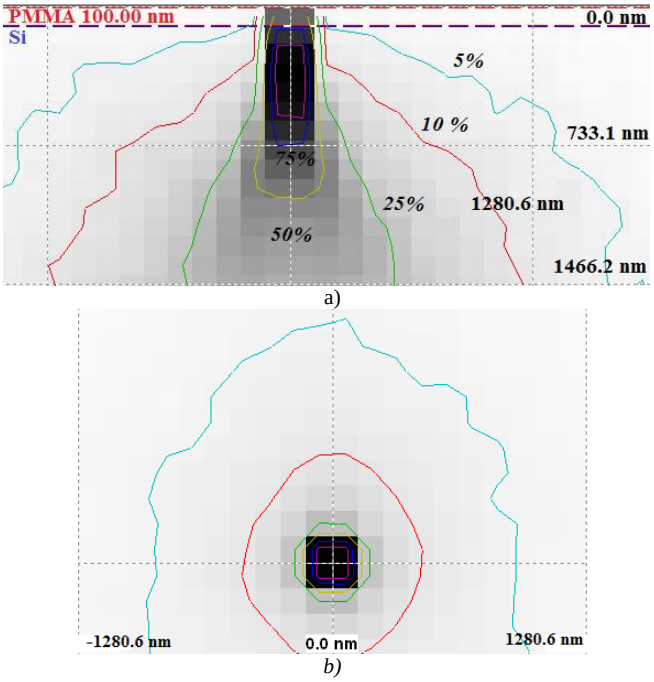

Fig. 3 *Distribution of the absorbed energy in the sample: a) on x and z axes, b) top-down view on the x and y axes in PMMA resist at electron beam energy 20 keV. Number of electron trajectories simulated is 20 000.*

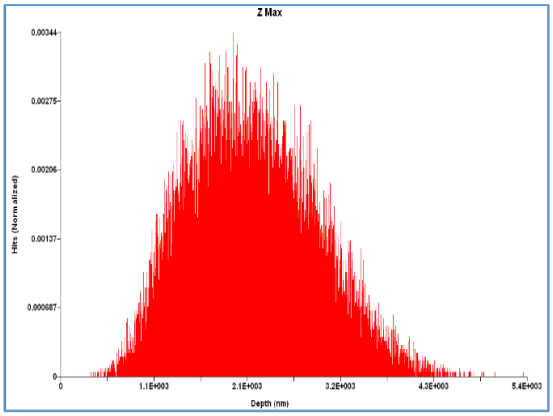

Fig. 4 *Maximum penetration depth in the sample of the electron trajectories.*

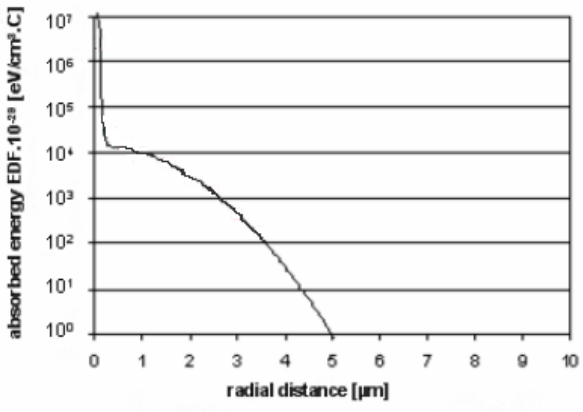

Fig. 5 *Absorbed electron energy vs. the radial distance (from the direction of the initial movement of the electrons beam).*

In Fig. 6 – Fig. 8 are shown simulated data by CASINO software connected with the backscattered electrons. Fig. 6 presents the maximum penetration depth in the sample of electron trajectories that will escape the sample surface, Fig. 7 presents the energy of backscattered electrons when escaping the surface of the sample and Fig. 8 gives the radial position of backscattered electrons, calculated from the landing point of the primary beam on the sample.

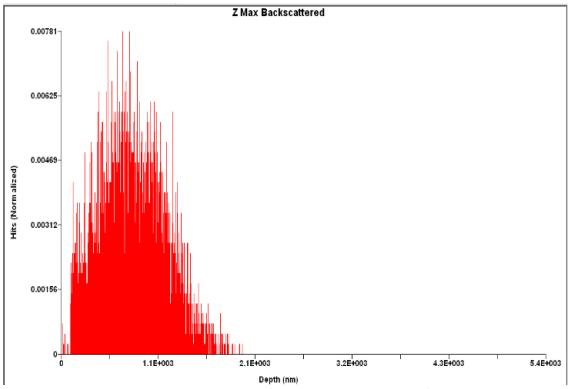

Fig. 6 *Maximum penetration depth in the sample of electron trajectories that will escape the sample surface.*

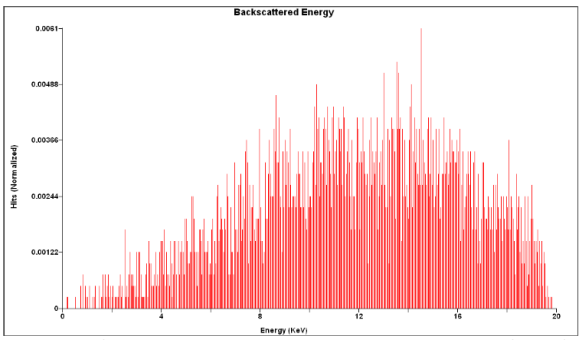

Fig. 7 *Energy of backscattered electrons when escaping the surface of the sample.*

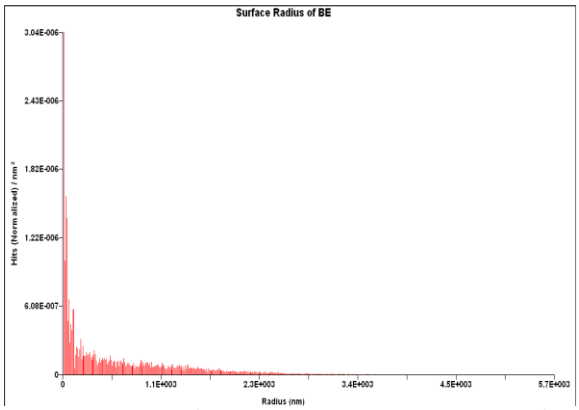

Fig. 8 *Radial position of backscattered electrons, calculated from the landing point of the primary beam on the sample.*

3. Resist profile development

The development of PMMA is realized by selectively dissolving the irradiated and truncated polymer chains. The rate of dissolution depends on the exposure dose and the chemical characteristics of the developer. In this case developer MIBK:IPA 1:3 is considered.

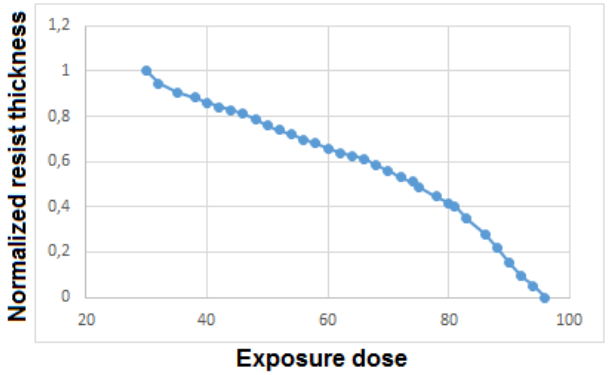

Fig. 9 *Contrast curve - normalized resist thickness vs. the exposure dose [μC/cm²] for 100 nm PMMA at 20 keV and developer MIBK:IPA 1:3.*

Fig. 9 and Fig. 10 are presented correspondingly the experimentally measured a contrast curve and the estimated dissolution rate for 100 nm PMMA at beam energy 20 keV and used developer MIBK:IPA 1:3.

The dissolution rate of the resist depends on the exposure dose, the beam diameter and the acceleration voltage of the electrons. For one-component polymer resists it can be calculated by the empirical formula [1,3]:

$$S = R_0 + B / \overline{M_f^A} \quad (5)$$

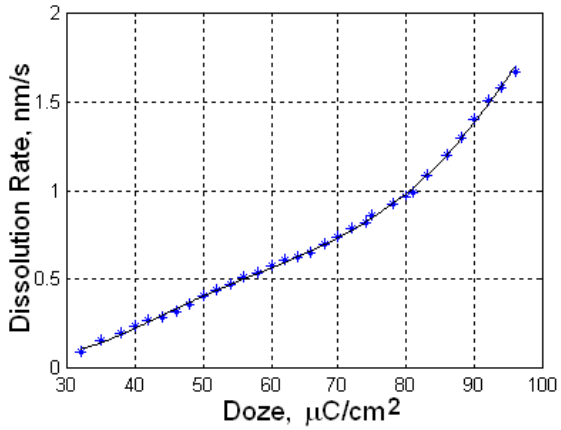

Fig. 10 *Dissolution rate dependence estimated for 100 nm PMMA at 20 keV and developer MIBK:IPA 1:3.*

There $\overline{M_f}$ is the average molecular weight after irradiation, R_0, B and A are constants for a selected pair resist-developer.

SELID (Simulation of Electron Beam Lithography in 2 and 3 Dimensions) provides a comprehensive simulation tool covering most aspects of today's advanced electron beam lithography, such as process optimization and parameter determination for the electron beam proximity effect correction. SELID consists of 4 major parts: the simulation of the exposure step, the post-exposure bake, the resist development and analysis. On the output it displays many different views of the geometry of the exposed images, as well as 2D resist profiles and resist structures in full 3D rendering.

First, the exposure dose (dose to clear) needed for the irradiation of 100 nm PMMA resist that will lead to full removal of the resist reaching the Si substrate after development is estimated. It depends on the beam energy – 20 keV, the resist thickness – 100 nm, on the type of the developer - MIBK:IPA 1:3 and the development time (Table 1). Fig. 11 presents the 2D and 3D views of the developed resist profiles, for development time 120 s and exposure dose (dose to clear) 223.14 μC/cm².

Table 1: *Dose to clear for different development times.*

Development time, s	**Dose to clear,** μC/cm^2
60	**457.19**
90	**298.06**
120	**223.14**

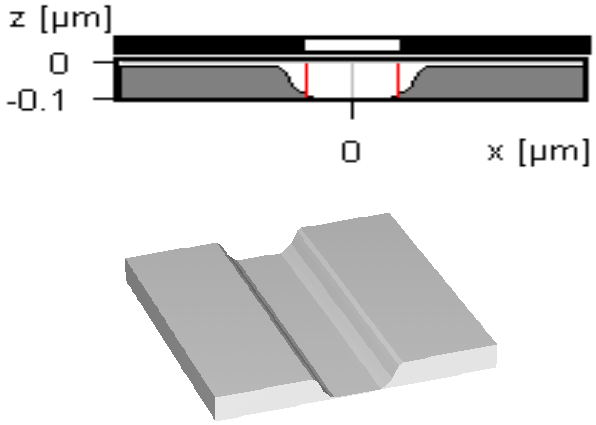

Fig. 11 *The 2D and 3D views of the developed resist profiles.*

4. Conclusions

The electron beam lithography process is essential for the construction of small-scale electronic components. Real-time experiments take a long time and resources, they are conducted only in specialized laboratories, require highly skilled staff and optimization of process parameters in real conditions is an extremely difficult and labor-intensive task. Software products such as SELID and CASINO provide a virtual environment for learning the process and conducting experiments even by less knowledgeable professionals, they provide a good opportunity to explore the impact of parameters such as accelerating voltage, number of electrons, exposure dose, thickness and structure of resist, developer and others. Apart from the mentioned advantages, the programs do not require specialized hardware, which means that they can be started on almost all modern computers or laptops, which in turn enables anyone who wants to know the process or wants to perform a simulation in order to select good parameters to conduct a real experiment to do this at home, office or anywhere on your computer. Another very important advantage is the access to tutorials and user-friendly graphical software, which is light and user-friendly.

Acknowledgements

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