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# Applications of Electron Beam Lithography (EBL) in Optoelectronics Device Fabrication

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**Abstract:** In this paper, we have investigated the capability of the Scanning Electron Microscope (SEM) JEOL JSM-6460LV with Raith-ELPHY Quantum, EBL-system for the fabrication of micro-scale Fresnel rings on silicon Si, substrate for optoelectronics devices application. The design of Fresnel rings was achieved by hierarchical structures in extended Graphic Database System GDSII Editor which is sub-software built in the Raith-ELPHY Quantum software. The Fresnel rings were fabricated by exposing electron beam on PMMA photoresist in the Fresnel zones' region on Silicon substrate. A Fresnel rings is made up of eleven concentric rings having the maximum diameter of the external rings as 52μm, and the minimum diameter of the internal ring as 5$\mu m$ was fabricated by this method.

**Keywords:** EBL, Optoelectronics, Fresnel Rings, Fresnel Zone, PMMA, SEM

## 1. Introduction

Lithography is the process of transferring patterns from one medium to another using the particle beams in semiconductor industry [1, 2]. The lithography can broadly be categorized in to two methods; radiation and non-radiation-based methods. In radiation based methods, a wafer of semiconductor material (usually silicon or quartz) is covered with a layer of radiation sensitive material called photoresist. Lithography by this methods are generally done using light (called: optical/photo-lithography), electrons beam (called: electron beam lithography), ions beam (called: ions beam lithography), or X-ray (called: X-ray lithography) [3].

The use of electron beam as a source has the advantages of producing an extremely high diffraction-limited resolution images and has been used for transferring patterns in nanometer scale sizes [4]. In addition to this, costly masks are not required for EBL patterning and the technique also provides the most realistic short-term possibilities for fabrication beyond the current limits of optical (photo-) lithography [5]. Historically, E-beams technique has been used for lithography purposes since the 1960s [6].

Electron beam lithographic EBL technique is the technique by which a tightly focused beam of electrons is being scans across the surface of a thin-film layer of resist in order to define the desire patterns on the resist [7]. Generally, a lithography system is added to modern scanning electron microscopes (SEM). A beam blanker is an added accessory for lithography purpose, in which the electron-beam can be controlled (i.e. on and off the beam) when writing from one pattern element to another without exposing the resist in between the patterns. For EBL system of pattern writings, the vector writing approach is adopted in which the beam moves in any direction and scans only areas to be exposed (pattern). The magnetic lenses in SEM are responsible for focusing the electron beam which is generated from thermionic emitters and thermal field emitters that have output voltages ranging between 1 keV and 200 keV [8]. The most commonly used voltages in EBL patterning process ranges between 50 keV and 100 keV [9]. The electron gun produces the electrons-beam and directed towards the target area (sample surface). Depending on the accelerating voltage (in unit of $KeV$), the beam is being accelerated by electrostatic field forces. The focusing of electrons-beam and the formation a focused electrons-beam spot on the target area are the main functions

of electromagnetic lenses and apertures. The sample stage, the electrons-beam scanning coils, the signal detector, and the processing system provide real-time observation and image recording of the surface of the given specimen area. Figure 1 shows the basics scanning electron microscope SEM set-up and its electron path.

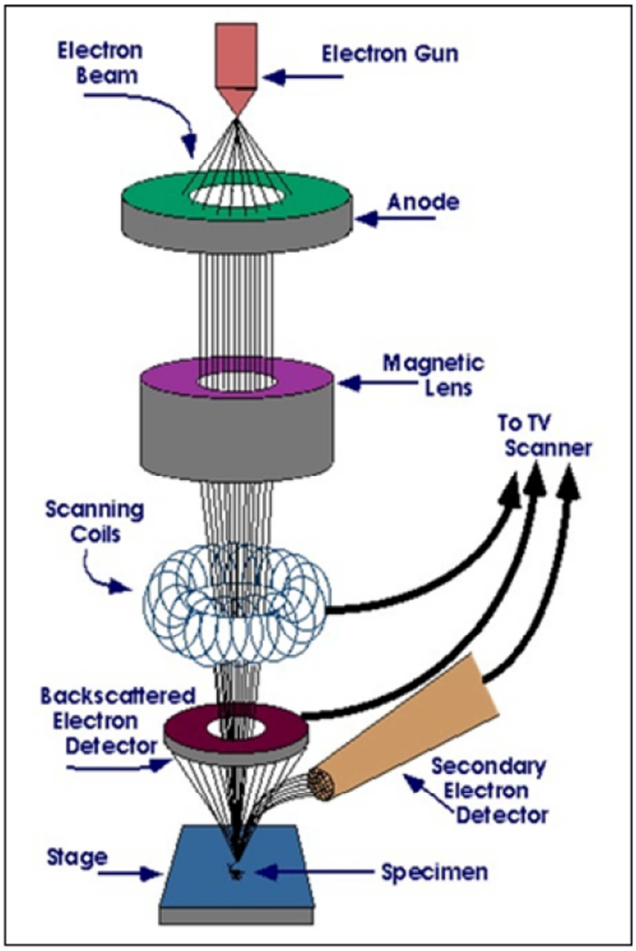


***Figure 1.*** *The basics scanning electron microscope SEM set-up and its electron path [10].*

In EBL pattern writing process, the production of the good and higher resolution images depends on the proximity correction and some important parameters which have to be set before the electrons-beam is to be exposed [11]. The proximity effects usually occurred as a result of the scattering of electron-beam in an unwanted area of the resist and substrate thereby exposing some resist outside the intended pattern area and it can be minimized by the proximity correction capability in the Raith software. On the other hand, other parameters are dependent up on the pattern design and resist requirements. The parameters are; (i) Write field size (ii) Working distance (iii) Aperture size (iv) Accelerating voltage (v) Beam current and (vi) Writing speed also called dosages.

a. *Write field (WF)*, is the area covered by the electrons-beam deflection and its size is determined by the magnification of the microscope. If a large area of fine features is desired, several fields can be positioned so that the field edges align with each other, normally known as stitching.
b. *Working distance (WD)*, is the distance from the underside of the objective lens (i.e. the lens focuses the electron probe on the specimen surface) to the focused point on the sample surface. WD influences the minimum spot size in such a way that, a shorter working distance improves the resolution of the microscope and decreases the susceptibility of the e-beam to external interference.
c. *Aperture size*, several apertures may be found in the electron column and their main functions are to reduce and exclude extraneous electrons in the lenses. The final lens aperture which is located below the scanning coils determines the diameter or spot size of the beam at the surface of the specimen in which the *spot size* on its part determines the resolution and depth of the field: in such a way that the smaller the *spot size* the deeper the field as well as the loss of brightness.
d. *Accelerating voltage* is the source of energy (usually measured in $KeV$) set to accelerates the electron beam and therefore, the penetration depth of electrons depends on the accelerating voltages; the high the accelerating voltages the deeper the electrons penetration and thus the lower the number of scattered electrons in the resist, resulting in fine e-beam line width.
e. *Beam current* is usually measured by using a Faraday cup which is determined by a combination of accelerating voltage and aperture size used.
f. *Electron-beam dosage* is the amount of electrons exposed in ($\mu C$) per unit length ($cm$) for a single pass line (SPL) or per unit area ($cm^{-2}$) for area exposure, or in more technical, it can be defined as the number of electrons per unit area required to achieve the desired chemical response in the resist. The *dosage* at which each exposure is run chiefly depends on the type of material used as a resist, its density and the dimension of pattern being written. In the process of writing a pattern, an *electron beam dwelling time* is highly affecting the *electron beam dosage* in such a way that, *electron beam dosage* increases with the increased *electron beam dwelling time* and thus causes the decreased in electron beam scanning/writing *speed* (in *cm/s*). Mathematically, electron beam dosage can expressed as

$$E_{beam\ dosage} = \frac{Probe\ Current\ (I_{probe}) \times Dwelltime\ (T_{dwell})}{(Step\ size)^2} \quad (1)$$

Scanning probe lithography SPL uses half a beam/spot size stepping ($^{d}/_{2}$) (as depicted in figure 1). In the process of exposing an area of the pattern, other important parameters have to be calculated carefully, these are; area step size, area-dose, SPL-dose and Dot-dose. As seen, the *step-size* is the distance between the spots of the focused electron-beam. In order to reduce the proximity effects, the *step-size* must be equal to the half of the spot-size. On the other hand, all dose related parameters are derived from the beam current $I_{beam}$

and dwell time $T_{dwell}$ with little differences between them. The following equation describes each of them:

$$Area - dose = \frac{I_{beam} \times T_{dwell}}{S^2} \left(\mu As/_{cm^2}\right) \quad (2)$$

$$SPL - dose = \frac{I_{beam} \times T_{dwell}}{S} \left(pAs/_{cm}\right) \quad (3)$$

$$Dot - dose = I_{beam} \times T_{dwell} \ (pAs) \quad (4)$$

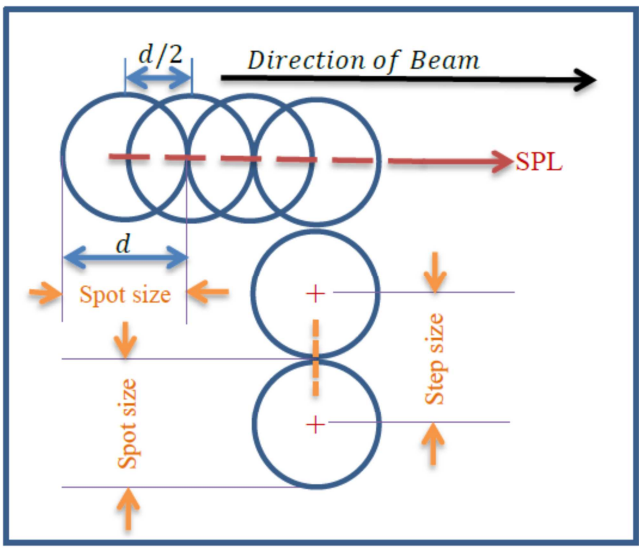


***Figure 2.*** *The schematic of e-beam configuration showing the different concepts of dose for area, lines, and dots.*

*Electrons-Solid Interactions:* Despite the fact that, EBL tools are capable of forming extremely fine electron-beam, the electrons are scattered as the beam crosses the boundary of the work piece. At that instant, some of the electrons undergoes scattering at a smaller angle (with reference to the angle of incident), while other undergoes at larger angles. When the electrons are impinging in to the substrate through the resist, the scattering of electrons at smaller angle are called "forward-scattering" while scattering at larger angle is known as "backward-scattering" [12]. On the other hand, other electrons moves slowly with low-voltage, the electrons in this respect are called *secondary electrons*. This section discusses more details on forward and backward scatterings as well as secondary electrons.

*Forward Scattering (FS):* The scattered electrons at smaller angle is known as forward scattered electrons and therefore, as forward scattering occurred, the primary beam diameter at the bottom of the resist will be broaden. The increase in the effective bean diameter $D_{forward,}$ (usually measured in $nano - meter$) depends on the thickness of the resist $R_{thickness}$, and the values of beam voltage $V_{beam}$, (measured in $KeV$) [13]. Mathematically $D_{forward,}$ can be expressed as:

$$D_{forward,} = \frac{9}{10}\left(\frac{R_{thickness}}{V_{beam}}\right)^{3}/_{2} \quad (5)$$

From equation (5) above, the degree of forward scattering can be minimized by reducing the thickness of the photo-resist at a high accelerating voltage.

*Backward Scattering (BS),* the electrons under going backward scattering are called backscattered electrons. The backscattered electrons attempting to return back through the resist at a certain distance from the primary dose site may cause extra resist exposure. The proximity effect explained earlier in this section resulted from the electrons scattering, and the major contributor to the proximity effects are the backscattered electrons [14].

The fraction $f_{b-e,}$ of backscattered electrons depends on the material used as substrate and the magnitude of primary electron dose in such a way that, materials with high atomic number experiences larger fraction and also, $f_{b-e}$ increases with the increase in primary electron dose [15]. Both forward and backward scatterings, shows the Gaussian distribution shape and therefore, the energy intensity distributions $E(x)$ of the overall exposure will be the sum of the individual Gaussian distributions. If the $e_f$ denote the forward scattering, $e_b$, backward scattering and $\sigma$ be the thickness of the substrate, then equation (6) holds;

$$E(x) = \frac{1}{1+f_{b-e}}\left(\frac{1}{\pi\sigma^2 e_f} e^{\left(-\frac{x^2}{\sigma^2 e_f}\right)} + \frac{f_{b-e}}{\pi\sigma^2 e_b} e^{\left(-\frac{x^2}{\sigma^2 e_b}\right)}\right) \quad (6)$$

*Secondary Electrons (SE):* During exposure, as the incident electrons-beam coming closer enough to the specimen atoms thereby giving some of their energy to the specimen electrons mainly in the inner electron shell (K-shell), resulting in the ionizing the specimen atoms and changing the electrons path. Thus, the ionized electrons that escaped from the specimen atoms during this process are called *Secondary electrons* [16]. The secondary electrons contribute only in the topographic analysis of the sample, this occurs after the ionization process when the SE moves towards the surface of the specimen they undergo both elastic and inelastic collisions on reaching the surface. But because of their low energy ($\sim 5eV$), only SE that are very close to the surface ($\sim 10nm$) are been escaped from the surface and are been detected for the topographic imaging analysis. Conversely, SEs increases the proximity effect and the combination of SEs with forward scattered electrons causes a broadening of the exposure region by roughly 10 $nm$ thereby limiting the resolution of EBL machines.

In this paper, the electron beam lithography (EBL) process was adopted for the fabrication of concentric circular rings in Fresnel configuration on Silicon wafer coated with PMMA photo-resist using the Scanning Electron Microscope (SEM) JEOL JSM-6460LV with Raith-ELPHY Quantum of the Nano-optoelectronics Research and Technology Laboratory (NOR-Lab) of the School of Physics, Universiti Sains Malaysia (USM), for optoelectronics device applications. The rings were designed using GDSII Editor contained in Raith-ELPHY Quantum software. The GDSII Editor is sub-software built in the Raith-ELPHY Quantum software, and it is used for designing many geometrical shapes such as rectangles, circles and curvatures, lines and dots as well as other polygons in separated layers for multilevel exposure [16].

## 2. Material and Methods

### 2.1. Fabrication process

A piece of $1cm^2$ P-type silicon of thickness $\approx 300\ \mu m$ with the orientation <100 > was cleaned using the RCA cleaning procedures to remove the ionic and metallic contaminants as well the native oxide and other associated organic contaminants. In RCA cleaning procedures, silicon wafer was immersed in to the mixture of ($H_2O$: $NH_4OH$: $H_2O_2$) in the ratio of 5:1:1 at the temperature range from 75°C to 80°C for a duration of 10 to 15 min, followed by immersing it into a mixture of (HF: $H_2O$) in the ratio of 1:50 for approximately 10 to 20 sec. The wafer was then immersed in to the mixture of (HCl: $H_2O_2$: $H_2O$) in the ratio of 1:1:6 at the temperature of 75°C for the duration 10 to 15 min. Finally, sample was rinsed with DI water and blown dried with ($N_2$). To obtain 200 nm thickness of PMMA resist layer on Si substrate, the wafer was spun coat at 4000 rpm rotational speeds for the duration of 90 sec using spin coater. Meanwhile, to ensure the total dryness and off-gassing, the sample was baked in an oven at temperature $180^oC$ for $60\ minutes$.

The EBL process was then used to define circular pattern of the rings in Fresnel configuration on the layer of PMMA. In EBL process, the exposure parameters used in this work are; $30\ KeV$ accelerating voltage with the beam current of $0.06\ nA$, while the area dose of $200\ \mu As/cm^2$ and the line dose of $500\ pAs/cm$ were used. Table 1 shows the EBL exposure parameters used in this work. However, $500\ nm$ was selected to be the e-beam diameter, which determines the thickness of the rings. The e-beam exposed layer of PMMA was developed in a mixture of Methyl Isobutyl Ketone MIBK, and Isopropyl Alcohol IPA, (MIBK: IPA) in the ratio of 1:3 at the temperature of $23^oC$ for the duration $35\ secs$. The wafer was then inserted in to the solution of IPA for the duration of $35\ sec$ as a stopper. The sample was then dried by blowing it with $N_2$.

***Table 1.*** *EBL parameters used.*

| S/N | EBL Parameter | Numerical Value | Unit of Measurement |
|---|---|---|---|
| 1 | Accelerating voltage ($V$) | 30.0000 | $KeV$ |
| 2 | Whitefield Size | 55.0000 | $\mu m$ |
| 3 | Minimum Step Size | - | $\mu m$ |
| 4 | Beam Current ($I_B$) | 0.0600 | $nA$ |
| 5 | Area step Size ($A_{SS}$) | 0.0504 | $\mu m$ |
| 6 | Area Dwell time ($A_{DT}$) | 0.0847 | $ms$ |
| 7 | Area Dose ($A_{Dose}$) | 200.0000 | $\mu As/cm^2$ |
| 8 | Area Beam Speed ($A_{BS}$) | 0.5950 | $mm/s$ |
| 9 | Line Step size ($L_{SS}$) | 0.0500 | $\mu m$ |
| 10 | Line Dwell time ($L_{DT}$) | 0.0420 | $ms$ |
| 11 | Line Dose ($L_{Dose}$) | 500.0000 | $pAs/cm$ |
| 12 | Line Beam Speed ($L_{BS}$) | 1.2000 | $nA$ |

### 2.2. Characterization Process

The developed structures (concentric circular rings in Fresnel configuration) were characterized using Field Emission Scanning Electron Microscope FESEM and EDS/EBSD detector system (model: FEI Nova NanoSEM 450) and the Atomic force Microscope AFM, (Dimension EDGE, BRUNKER; Shimadzu) system. Figure 3: Shows the FESEM image and the EDX spectrum of the developed structures, while Figure 4 shows the Atomic force Microscope AFM, analysis for the developed structures.

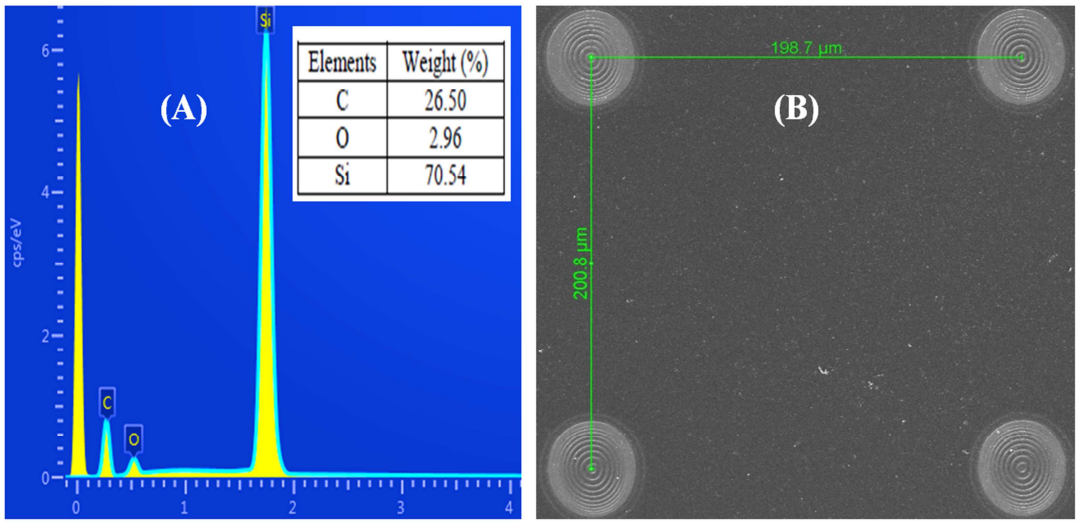


***Figure 3.*** *The EDX spectrum (A) EDX spectrum of PMMA/Si surface obtained from the EDX analysis and (B) FESEM image showing the developed structures of concentric circular rings in Fresnel configuration.*

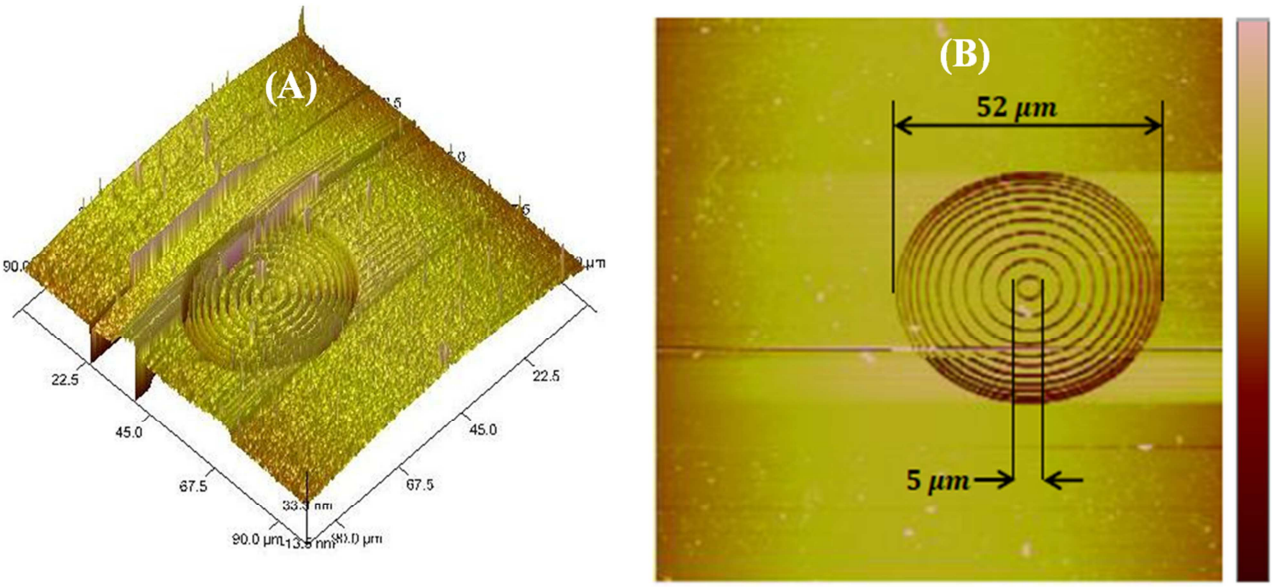


***Figure 4.*** *AFM Analysis on the developed structures (A) 2-D View (B) 3-D View.*

## 3. Results and Discussion

As depicted in Figure 3 (a): The Energy-dispersive X-ray spectroscopy (EDX) spectrum of the PMMA/Si spun coat shows the presence of silicon, oxygen and carbon at its surface. The presence of carbon and Oxygen confirmed the existence of PMMA and its decomposition products. However, the presence of hydrogen was analyzed on the EDX-spectra but it could not be reflected in the percentage weight ($weight\%$). This is because, in-terms of the weight, the hydrogen is the lightest element compared to other elements in the periodic table. On the other hand, Figure 3 (b) shows the FESEM images of developed structures (concentric circular patterns in Fresnel configuration). In Figure 3 (b), $2\ by\ 2$ array of Fresnel rings can be seen at the magnification of $1000X$, where each unit of Fresnel rings contains eleven concentric rings. The vertical distance between the centers of each Fresnel rings unit is $200.8\,\mu m$, while the horizontal distance is about 198.7µm. The diameter each ring can obtain by multiplying its radius by a factor of 2. The outermost ring has an approximate diameter of 52µm and the innermost ring has the diameter about 5µm. The separation between each ring decreases by a factor of $0.478\mu m$ starting from the innermost ring. This is consistent with Fresnel lens design technique.

## 4. Conclusion

In this paper, the capability of the SEM-JEOL JSM-6460LV with Raith-ELPHY Quantum, EBL-system in fabrication of micro-scale Fresnel rings on Si wafer have been demonstrated. These micro-scale Fresnel rings could be used in various optical systems such as data recording and retrieval systems, high speed detectors, as well as integrated micro-optical systems, and other electronics device applications, such as focused laser diode beam and Optical interconnection.

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