

Flexible Nanofabrication Equipment: E-beam Lithography System Based on SEM

Shuhua Wei*, Lan Dai, Jing Zhang

Department of Microelectronics, College of Information Engineering, North China University of Technology, No.5 Jingyuanzhuang Road, Shijingshan District, Beijing, China

*Corresponding author, e-mail: jslwsh@hotmail.com

Abstract

Electron beam lithography (EBL) is widely used in nanoscale device fabrication and research due to high resolution and excellent flexibility. In this paper, nanometer EBL system based on scanning electron microscope (SEM) is introduced. Its main components include a modified SEM, a laser interferometer controlled stage, a versatile high speed pattern generator, and a fully functional and easy-operational software system. In order to explain this EBL system design principle, realization method, this paper mainly introduces each component's design basis, main structures and functions. Stitching experiments overlay experiments and arbitrary shape patterns exposure experiments have been done on this EBL system based on JSM-35CF SEM. The lithography results demonstrate that the resolution of electron beam lithography system can approach nanometer domain. This kind of EBL system based on SEM can meet the need of micro-nanofabrication research and design activities at flexibility and low price.

Keywords: nanofabrication, electron beam lithography system, pattern generator

Copyright © 2014 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

Electron beam lithography (EBL) is widely used in nanoscale device fabrication and research such as nanoelectronics, nanophotonics, and nanoelectromechanical systems (NEMS) due to nanoscale resolution and excellent flexibility [1, 2]. Given that the de Broglie wavelength of an electron accelerated to 25 keV is around 0.008nm, the practical results of EBL technique are not influenced by diffraction effects and ultra high resolution patterns can be generated [3]. Hence the EBL plays an irreplaceable role in nanolithography especially in applications where fast prototyping and nanometer resolution is required [4, 5].

The resolution and throughput of EBL depend largely on the performance of the electron beam lithography equipment. Since the first electron beam machine was developed in the late 1960s, various electron beam lithography systems have already been developed and perfected in the past years [6]. These include commercial beam writing systems, custom built electron-optics and control systems, tunneling microscopes, and electron microscopes that have been modified to allow the scanning coils to be controlled by an external source [7]. The performance of commercial systems in terms of resolution, stability, writing speed and automation is excellent [8]. However, commercial systems are considerably more expensive for research laboratories which are just interested in the development of technologies for innovative devices. So a high performance, low cost and flexible operation EBL system is a good solution. Reference [9] proposed a simple and general-purpose EBL system based on scanning electron microscopy (SEM). And there are some commercial SEM based nanolithography systems [10]. In this paper, a new EBL system is introduced, which is composed of a modified SEM to allow external signals to control beam position, a laser interferometer controlled stage, a versatile high speed pattern generator, and a fully functional and easy-operational software system [11-13]. This EBL system based on SEM is flexible and low cost. It has a great potential to be used in the nanoelectronics, nanooptics and most other nanofabrication fields.

2. Exposure Mechanism of EBL

Lithography is the process of transferring patterns from one medium to another. The EBL process is a chemical reaction on a resist surface guided by electron beam scanning and

etching. It uses a finely focused beam of electrons to expose a radiation sensitive polymer on a wafer surface by accurate deflection of the beam over the wafer surface, and selectively removes either exposed or non-exposed regions of the resist to create very small structures in the resist that can subsequently be transferred to the substrate material. Resists suitable for EBL are various such as PMMA, HSQ and ZEP-520. These electron beam resists have different performance to be chosen in different applications. For example, PMMA resist can be used with a 3nm 100keV electron beam to fabricate 20nm resolution unexposed gaps between exposed lines [14]. HSQ is a negative resist that is capable of forming sub-30 nm lines in very thin layers, but is itself similar to porous, hydrogenated SiO₂. It may be used to etch silicon but not silicon dioxide or other similar dielectrics. ZEP-520 is a popular electron beam resist, and can fabricate a pitch resolution limit of 60nm structure independent of thickness and beam energy [15]. Electrons are focused using electrostatic or magnetostatic lenses. The electrons are accelerated at voltages as high as 100 keV. For this reason, the electron beam diameter is not diffraction limited since the wavelength of the electrons which are accelerated at voltages of 30–100 keV is on the order of fractions of an angstrom [16]. It can be seen that the work principle of EBL technique is familiar with the Scanning electron microscope (SEM). So we can extend the SEM function to lithography while keeping the SEM's original scanning function intact to form the EBL system.

3. Main Components of EBL System

A typical schematic of this EBL system based on SEM is shown in figure 1. System elements consist of the electron source or cathode to generate electron beam; the beam blunker to keep the electron beam away from the sample surface when the stage is moving; the apertures to further confine the beam; the magnetic deflector to deflect the beam along a predetermined path on the wafer surface; the mark detection to detect secondary electrons and backscattered electrons; the embedded precision stage to realize scanning field stitching; the nanometer pattern generator to transfer patterns and control beam blunker; and the EBL control software. This kind of EBL system based on SEM is inexpensive, easy to operate, and has a good prospect in micro-nanofabrication application. As follow, some important components which are essential for this kind EBL system will be introduced.

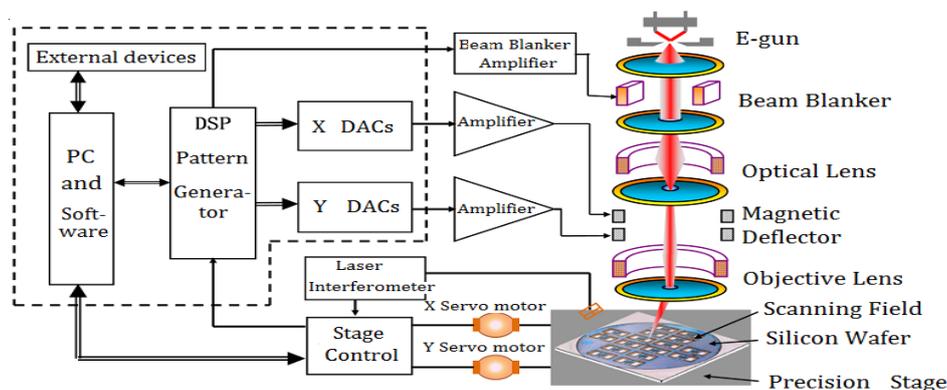


Figure 1. The Schematic of EBL System Based on SEM

3.1. Thermal Field Emission SEM

The SEM is employed in electron beam focusing, astigmatic correction and setting lithography field size. The electron-optical performance has a direct effect on the resolution and stability of the EBL system, so the suitable SEM must be chosen. Lower resolution systems can use thermionic sources, which are usually formed from LaB₆. However, systems with higher resolution requirements need to use field electron emission sources, such as heated W/ZrO₂ for lower energy spread and enhanced brightness [13]. After analysis and comparison, we found that the thermal field emission SEMs were preferred over cold field emission sources for

stabilizing total electron beam current, maximizing probe current and reducing electron beam noise, as well as in sensitivity to the environment. The main function of SEM is to produce electron beam, focus on electron beam and control electron beam on and off to realize electron beam scanning.

3.2. Laser Interferometer Controlled Stage

The positioning accuracy of SEM stage is usually in range of 1-5 μm , and mobile range is limited. However, writing the entire wafer requires a large number of the stage translations that includes acceleration, deceleration, settling operations. So it can't meet the requirements of EBL scanning field stitching [17]. In order to achieve high accuracy of field stitching, the precision laser interferometer controlled stage is needed. It is composed of work stage machinery structure, laser interferometer measurement system, XY positioning control system, CCD alignment system and automatic transmission tablet control system. The laser interferometer measurement system and XY positioning control system constitute a closed loop measurement control system, which can locate the stage in the target location. CCD alignment system is used to make the silicon wafer in the depth of focus of electronic optical system, to get the best exposure effect. Positioning is controlled by a DMC-1842 motion control card. Special control commands are downloaded to flash memory to improve the stage positioning performance in dealing with acceleration and deceleration. The stage is designed compactly to fit in the small chamber of the SEM.

3.3. Nanometer Pattern Generator

The pattern generator is the key component of making use of SEM to assemble the EBL system. The main functions of pattern generator are to interpret data produced by a software package and control beam deflection and beam blanking coils of SEM for high resolution lithography. Figure 2 shows a block diagram of the hardware structure of the pattern generator. It consists of operation control unit, digital-to-analog converter (DAC) unit, image acquisition unit, blanking control unit, and some others [11].

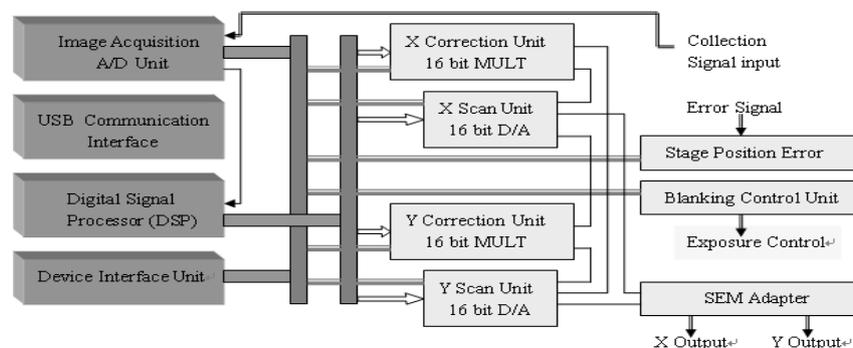


Figure 2. Block Diagram of the Pattern Generator Hardware Structure

3.3.1. Operation Control Unit

The patterns to be exposed are broken down into a series of exposure points by operation control unit. A growing number of important applications, such as opto-electronic and diffractive optical devices, require smooth curved shapes. The pattern generator requires high speed and high accuracy in the translation of pattern data to shot data. So the digital signal processor (DSP) is employed in the operation control unit. In this system, the TMS320C6713 200-MHz DSP is employed to interpret circles, rings and other complex curved shapes. This DSP has powerful computing capability, which can complete 32 float of multiplication and division operations during 80 clock cycles. Figure 3 shows the configuration of operation control unit. It also consists of complex programmable logic device (CPLD) to implement external circuit, FLASH memory to store procedures, synchronous dynamic random access memory (SDRAM) to store data, universal serial bus (USB) interface, power supply and other elements.

The USB2.0 interface is used to resolve data transfer bottlenecks, whose speed of transfer data to computer can be up to 20 Mbps. Therefore, circles, rings and other complex curved shapes can be interpreted with a very high speed.

3.3.2. Scanning Unit

The core component of scanning unit is digital-to-analog converter (DACs). The pattern generator sends a stream of coordinates to the DACs, which converts pattern digital information to voltage to drive the deflection coils and cause the beam to trace a shape. Meanwhile, in order to implement pattern overlay and fields stitching, the gain, offset, rotation errors of scanning field, and workstage position errors need to be corrected. The scanning unit is controlled by two set of 16-bit DACs. Either set of DACs includes one main DAC and three multiplicative DACs. The main DAC receives pattern coordinates, and three multiplicative DACs receive the gain, offset, rotation and stage position corrections. The scanning unit can also generate blanking signals to control beam blanking coils. The main DAC used in the pattern generator is AD669, which is high resolution 16-bit analog-to-digital converter (A/D) and has 65,536 binary codes. In this system 64,000 binary codes from 0x2FF to 0xFCFF are used. The saturated mode of main DAC can be avoided through this method. Furthermore, the step size can be minimized to 1.25nm, and higher pattern accuracy can be achieved. The work state of main DAC is voltage mode, whose input is 16-bit shift binary codes and output is $\pm 5v$. When output voltage is changed during full scale, the establishment time of main DAC is 6 μ s, and the frequency can reach 1MHz. This can sufficiently meet SEM operating frequency, and exposure rate can achieve the maximum.

3.3.3. Image Acquisition Unit

In order to correct scanning field distortion, standard image must firstly be acquired. The function of image acquisition unit is to scan marks and standard chess graphics to acquire image information. The main component is DAC. In this system we choose AD9220 D/A converter. Acquired data appears on the data bus after four trigger clock, so the initially four times data acquisition has no significance and do not need to be saved. From the fifth trigger clock, acquired data represent the real image information. These data are converted from analog signal of image information collected by sensor to data signal by D/A converter. They are transferred to computer by USB2.0 interface and displayed on the screen.

3.4. Software System

The EBL system is so complicated and sophisticated, which needs a fully functional and easy-operational software system to ensure it run correctly. The main functions of the software system include initializing the system, generating exposure data, detecting the status of system components, correcting the scanning field, transferring exposure data and parameters, and controlling the exposure process. According to these functional requirements, the software system has been designed three modules: exposure layout processing functional module, alignment control functional module, and exposure control functional module. The software system is developed based on Visual C++6.0 development environment [12].

3.4.1. Exposure Layout Processing Module

The main purpose of exposure layout processing module is to generate exposure data format (EDF) files. The EDF file is one of our custom file formats which is easily recognized and received. It stores enough information for the exposure of one complete shape. It contains scanning field information, a control word which specifies the geometric class of primitive shape, geometry information of primitive shapes (such as vertex coordinates height and width, center coordinates and radius), exposure dose of primitive shapes [18]. EDF files can be accomplished by two processes, one of which is exposure layout design, and another is format conversion. Various layouts including line, polyline, rectangle, circle, ellipse, ring, sector and polygon can be designed directly by drawing and editing figures. Another way of creating exposure layout is to import common industrial layout such as Caltech Intermediate Format (CIF) and Graphic Design System II (GDSII) format file, which can be edited conveniently. The file format is parsed by recursive descent parsing method on basis of BNF (Backus-Naur Form) rule. This method is comprehensive and precise so any complex layout can be imported and displayed correctly

(see Figure 3). Both layouts designed directly and common industrial layouts imported can be transferred to EDF file.

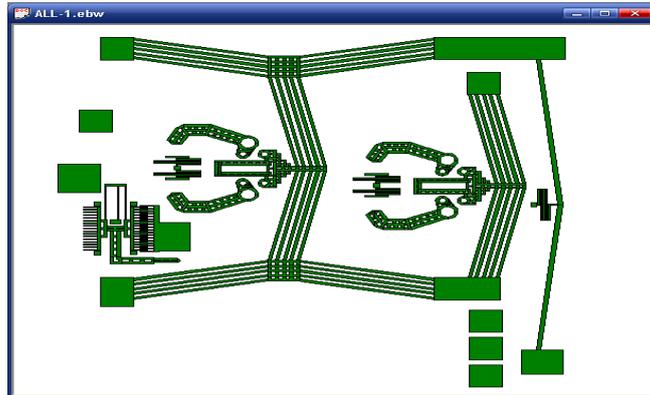


Figure 3. CIF Format Exposure Layouts Imported by the Software System

3.4.2. Alignment Control Module

The alignment control module is to implement scanning field alignment and coordinates alignment. This can be implemented by scanning and acquiring standard chessboard image, adjusting marks positions, calculating correction parameters and then transmitting them to pattern generator. Then pattern generator controls beam deflection according to these correction parameters scanning again to accomplish scanning field and coordinates alignment. Image processing technologies such as noise reduction and border recognition have been used to implement automatically write-field alignment. The coordinate's alignment is to detect alignment marks of the substrate in accordance with a predetermined sequence to ensure the best overlay accuracy.

3.4.3. Exposure Control Module

The exposure control module is to control the whole process of exposure, which is the final procedure and also integrated operation of many processed. The exposure parameters are important to determine the dose of exposure, which is the description of resist absorbing the electronic energy when expose layouts. Various graphics have different exposure dose [12]. The EDF file acquired from the exposure layout processing module and these exposure parameters can be transferred to pattern generator, which will control beam deflection according to layouts information stored in EDF file to exposure layouts.

4. Exposure Experiments

Exposure experiments have been done on the electron beam lithography system based on JSM-35CF SEM. Exposure experiments include stitching experiments, overlay experiments and patterns exposure. Stitching and overlay accuracy is an important evaluation indicator of EBL equipment performance.

4.1. Exposure Stitching Experiments

In order to ensure stitching accuracy, it is necessary to calibrate the scanning field. The calibration can be realized by use of coordinate system linear transformation, and its mathematical expression is as follows:

$$\begin{aligned} dx &= A + Bx + Cy \\ dy &= E + Fx + Gy \end{aligned} \quad (1)$$

Where, dx and dy are deviation of the actual position and the ideal position; x and y are the sample stage position of the mark; A , E represent shift parameters; B , F represent gain parameters; C , G represent rotation parameters. For solving the six coefficients, three marks in

a scanning field are needed as shown in Figure 4(a). The pattern generator controls the SEM to scan the three marks and gain the actual position coordinates. The actual calibration process can be carried out by use of chessboard image as shown in Figure 4(b).

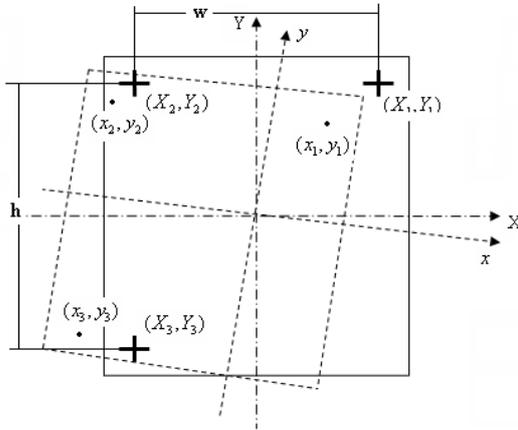


Figure 4(a). Principle diagram of scanning position

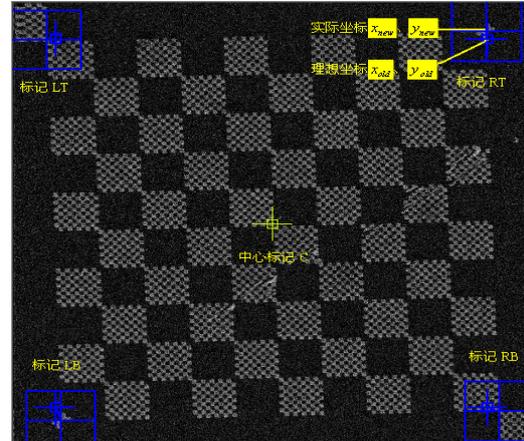


Figure 4(b). The chessboard image and mark field calibration

According to the formula of correction algorithm (4), the implementation formula is as follows:

$$S_x = \frac{(\frac{LTx_{new} + RTx_{new} + LBx_{new} + RBx_{new}}{4} - Cx) \cdot F_s}{R_M}$$

$$S_y = \frac{(\frac{LTy_{new} + RTy_{new} + LBy_{new} + RBy_{new}}{4} - Cy) \cdot F_s}{R_M} \tag{2}$$

$$G_x = \frac{\frac{RTx_{new} - LTx_{new}}{RTx_{old} - LTx_{old}} + \frac{RBx_{new} - LBx_{new}}{RBx_{old} - LBx_{old}}}{2}$$

$$G_y = \frac{\frac{LBy_{new} - LTy_{new}}{LBy_{old} - LTy_{old}} + \frac{RBy_{new} - RTy_{new}}{RBy_{old} - RTy_{old}}}{2} \tag{3}$$

$$R_x = \frac{\tan^{-1}(\frac{RTy_{new} - LTy_{new}}{RTx_{new} - LTx_{new}}) + \tan^{-1}(\frac{RBy_{new} - LBy_{new}}{RBx_{new} - LBx_{new}})}{2}$$

$$R_y = \frac{\tan^{-1}(\frac{LBx_{new} - LTx_{new}}{LBy_{new} - LTy_{new}}) + \tan^{-1}(\frac{RBx_{new} - RTx_{new}}{RBy_{new} - RTy_{new}})}{2} \tag{4}$$

Where, S_x , S_y , G_x , G_y , R_x , R_y represent shift parameters, gain parameters and rotation parameters. The software system acquires these coordinates and calculates the six equations to get calibration coefficients, then send these parameters to pattern generator. The scanning unit of pattern generator control beam deflection coils according to these parameters. This process will be executed several times until the precise scanning field can be obtained.

The stitching test pattern is designed directly by the software. It is a 6×6 array of 100 μm size vernier cursor fields. According to the error calculation formula:

$$\sigma_n = \sqrt{\frac{\sum_{i=1}^n (\bar{x} - x_i)^2}{n}} \quad (5)$$

Where, n is sample size, \bar{x} is sample average and σ_n is sample mean-square deviation. Statistical results show that this exposure test error σ_x is 31.19 nm and σ_y is 26.53 nm .

4.2. Exposure Overlay Experiments

Multilayer lithography is needed for some MEMS structure and semiconductor fabrication. In this process, each layer pattern is exposed and then removed out to do post-treatment. When this silicon chip is back into the work stage, its relative position of the work stage is changed. So in order to guarantee overlay accuracy, it is needed to alignment marks of chip, determine the position and azimuth of chip.

Experiment operation steps are as follows: a. Put the sample with marks into the stage, and implement the coordinate system correction to make the stage coordinate and silicon wafer coordinate consistently. b. Control the stage to exposure area, and implement the scanning field calibration, then the EDF file of main verniers is exposure. c. After the first layer exposure, take the silicon wafer out. d. Put the silicon wafer into the stage again, and then implement the coordinate system correction once again. e. Control the stage to exposure area, and implement the scanning field calibration, then the EDF file of deputy verniers is exposure. The error calculation formula is the same with the stitching experiments. Statistical results show that this exposure test error σ_x is 31.95 nm and σ_y is 33.38 nm .

4.3. Exposure Patterns Experiments

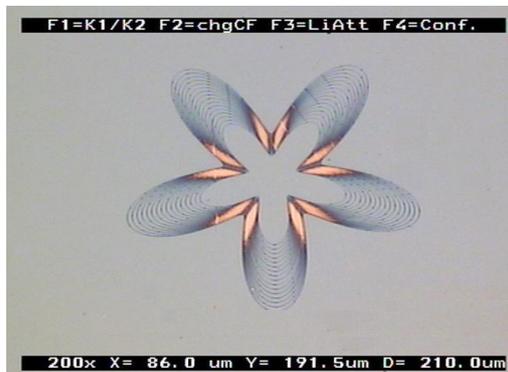


Figure 5(a). SEM micrograph of flower pattern exposed in PMMA at 30kV

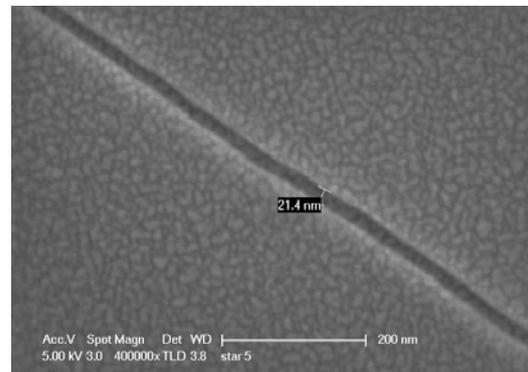


Figure 5(b). SEM micrograph of line exposed in PMMA at 5kV

Arbitrary shape patterns exposure experiments have been done to verify the resolution and accuracy of this EBL system. Figure 5(a) shows the SEM micrograph of flower pattern exposed at the acceleration voltage of 30 kV. The resist is monolayer PMMA, and the beam current is 5pA. The curve of rings exposed appears to be smooth, which demonstrates the strong divisional power of the pattern generator. The minimization of line width achieved by this electron beam lithography system is 21.4nm. Figure 5(b) shows the SEM micrograph of this experimental result. The exposure was made at the beam energy of 5kV in PMMA resist. This result demonstrates that the resolution of electron beam lithography system can approach

nanometer domain.

5. Conclusion

The above experiments testify the feasibility of this EBL system based on a modified SEM. It is equipped with a laser interferometer stage which facilitates precise multilevel lithography with automatic mark recognition and patterns to be stitched together. This EBL system can be used for large-scale micro-nanofabrication and functional MEMS or micro electrical parts. This EBL fabrication system can meet most lithography applications in university laboratories with its powerful functions, friendly manipulation and low cost. It has made very important contributions in quantum effect devices, integrated optical device manufacturing and nanostructure manufacturing.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (No.61001052) and Beijing Natural Science Foundation (4123096).

References

- [1] Pain L, Tedesco S, Constancias C. Direct write lithography: the global solution for R&D and manufacturing. *Comptes Rendus Physique*. 2006; 7(8): 910-923.
- [2] Peter H, Olaf F. '50 years of electron beam lithography: Contributions from Jena. *Microelectronic Engineering*. 2009; 86(4-6): 438-441.
- [3] Zárate JJ, Pastoriza H. *Correction Algorithm for the Proximity Effect in e-beam Lithography*. Proceedings of the Argentine School of Micro-Nanoelectronics *Technology and Applications*. 2008; 38-42.
- [4] Vieu C, Carcenac F, Pepin A, et al. Electron beam lithography: resolution limits and applications. *Applied Surface Science*. 2000; 164(1-4): 111-117.
- [5] Tseng AA, Chen K, et al. Electron Beam Lithography in Nanoscale Fabrication: Recent Development. *IEEE on Electronics Packaging Manufacturing*. 2003; 26: 141-149.
- [6] Rai-Choudhury P. Handbook of Microlithography, Micromachining and Microfabrication. *Microlithography*. 1997; 1.
- [7] Nabyty JC, Wybourne MN. A versatile pattern generator for high-resolution electron-beam lithography. *Review of Scientific Instruments*. 1989; 60(1): 27-32.
- [8] Pennelli G, Angelo FD, Piotta M, et al. A low cost high resolution pattern generator for electron-beam lithography. *Review of Scientific Instruments*. 2003; 74(7): 3579-3582.
- [9] Mølhave K, Madsen DN, Bøggil P. A simple electron-beam lithography system. *Ultramicroscopy*. 2005; 102(3): 215-219.
- [10] Tennant DM, Bleier AR. Handbook of Nanofabrication, 1st ed., edited by Gary P. Wiederrecht, Chap. 2010; 4: 121-148.
- [11] Wei SH, Liu W, Han L. *A new versatile high speed pattern generator for nanolithography*. Proceedings of the IEEE INEC. 2008; 824-828.
- [12] Wei SH, Zhang JZ, Han L. *Design and Implementation of Software System of E-beam Lithography Based on SEM*. Proceedings of the IEEE NEMS. 2009; 547-550.
- [13] Yin BH, Fang GR, Liu JB, et al. Miniature Electron Beam Lithography System for Micro /Nanometer Pattern Fabrication. *Nanotechnology and Precision Engineering*. 2010; 4: 290-294.
- [14] Cumming DRS, Thoms S, Beaumont SP, et al. Fabrication of 3 nm wires using 100 keV electron beam lithography and poly (methyl methacrylate) resist. *Applied Physics Letters*. 1996; 68(3): 322-324.
- [15] Yang H, Fan L, Aizi J, et al. *Low-energy Electron-beam Lithography of ZEP-520 Positive Resist*. Proceedings of the IEEE NEMS. 2006; 391-394.
- [16] Fontana RE, Katine J, Rooks M, et al. E-Beam Writing: A Next-Generation Lithography Approach for Thin-Film Head Critical Features. *IEEE Transactions on Magnetics*. 2002; 38(1): 95-100.
- [17] Lv SL, Song ZT, Feng SL. Fabrication of arrays of line with nanoscale width and large length by electron beam lithography with high-precision stage. *Microelectronics Journal*. 2008; 39(9): 1126-1129.
- [18] Wei SH, Liu W, Li X, et al. Design and Implementation of Exposure Data Format for E-beam Lithography', *Microfabrication Technology*. 2006; 6(6): 6-10.