A low cost high resolution pattern generator for electron-beam lithography

G. Pennelli^{a)} and F. D' Angelo

*Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa, 56126 Pisa, Italy*

M. Piatto

*Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni, Sezione di Pisa,
Consiglio Nazionale delle Ricerche, 56126 Pisa, Italy*

G. Barillaro

*Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa, 56126 Pisa, Italy*

B. Pellegrini

*Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa and Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni,
Sezione di Pisa, Consiglio Nazionale delle Ricerche, 56126 Pisa, Italy*

(Received 18 November 2002; accepted 21 April 2003)

A simple, very low cost pattern generator for electron-beam lithography is presented. When it is applied to a scanning electron microscope, the system allows a high precision positioning of the beam for lithography of very small structures. Patterns are generated by a suitable software implemented on a personal computer, by using very simple functions, allowing an easy development of new writing strategies for a great adaptability to different user necessities. Hardware solutions, as optocouplers and battery supply, have been implemented for reduction of noise and disturbs on the voltages controlling the positioning of the beam. © 2003 American Institute of Physics.

[DOI: 10.1063/1.1583861]

For several decades optical lithography (photolithography) has been the standard technique used for geometry definition of modern electronic devices. The main advantage of photolithography is the high throughput allowed by the simultaneous exposure of a great number of small features on a large area. Electron-beam lithography has been necessary for the semiconductor industry as the technique used for photomask definition. Low throughput applications have gone to e-beam lithography because of pattern generation versatility (no mask needed). But mainstream industry needs are far away from the ultimate resolution e-beam lithography can provide, and may never use it for high throughput applications such as memory and microprocessors. The high-resolution pattern definition attainable by electron-beam lithography is ideal for the realm of advanced devices with dimensions similar to the electron mean free path and nanotechnology applications.

Electron beam apparatus for industrial applications have been designed and perfected in the past years.¹ They show high features in terms of writing speed (anyway lower than photolithography) and resolution, and moreover they show a more and more increasing degree of automation. Even if an industrial apparatus is an excellent facility, it could represent a too big and unjustified investment for a research lab needing a small throughput. Moreover, an industrial apparatus is in general a “closed” system, not allowing an easy access for

modifications and innovations: this opportunity, on the contrary, is very important in particular for a laboratory interested not only in the fabrication and measurement of nanodevices, but also in the development of technologies for innovative devices, involving more and more complex and precise steps of nanolithography.

A possible solution is to adapt a scanning electron microscope (SEM) to electron-beam lithography using a pattern generator: with an high resolution SEM is possible to obtain a system with a good writing resolution. A SEM has in general a limited speed of the beam deflection, so it is possible to use this solution when writing speed and throughput are not important issues. Moreover a scanning microscope is optimized in the center of the field, because it is principally used for high resolution imaging, which means a small scanning field. In an industrial apparatus particular care is put into minimizing lens distortion on large areas and temperature control of the stage prevents distortions due to thermal drift of the optics in long exposure works.

In the past years innovative pattern generator hardware and software for SEMs have been reported.^{2,3} Some of them have become commercially available, such as Raith 150,⁴ but they are still too expensive for most small research laboratories. Nabity and Wybourne³ developed an excellent software for SEM control and pattern generation using a digital/analog board put on a PC, exploiting all the advantages of PC software environment; but the electrical disturbs, produced by the computer, could reduce precision in beam positioning. A pattern generator for writing geometries with polynomial borders had been designed by Straehle and

^{a)} Author to whom correspondence should be addressed; electronic mail: g.pennelli@iet.unipi.it

FIG. 1. Block diagram of the overall system applied to a scanning electron microscope.

co-workers,⁵ implementing a very good algorithm on programmable logic devices (FPGAs) and making use of a digital signal processor for system control. A very fast system (40 MHz) based on FPGAs had been developed by Anderson and co-workers.⁶

This article reports on a low cost, high precision, and versatile pattern generator. All the components and personal computers for the system can be bought for less than 3000 EURO and all the circuit boards can be realized even in a basic electronic laboratory. This does not penalize the high quality of the system and the precision in beam positioning. Another advantage of the pattern generator we are presenting is that patterns are generated by PCs, as in the Nabity's system, while the hardware we designed and developed performs only the final digital to analog (D/A) conversion. It is electrically isolated from electrical disturbs of the PC by optocouplers, and it is supplied by a battery pack with a separate ground, giving good stability and low noise. All the computational operations are done by PC software. In our case the software has been developed in C language but it can be easily reported in BASIC or in other high level, easy-to-use software languages commonly available on PCs. The only interface between computational part (software) and D/A converters is the digital data output, which can be easily implemented in any environment for software development.

Our system for electron beam pattern generation has been developed and applied to a JEOL6500F field emission gun SEM. The maximum acceleration voltage is 30 kV, and this has been used for lithography exposures.

The microscope has been equipped with a Deben electrostatic beam blanker with a fast beam deflection time of 50 ns. The beam blanker can be controlled both manually by console and electrically by a suitable TTL digital input, to be connected to one of the digital outputs of the pattern generator. The beam positioning of the microscope can be externally controlled by imposing suitable analog voltages on vertical and horizontal inputs, made available on a connector of the SEM electronics. Using a TTL digital signal, it is also possible to switch from the internal scanning control, nor-

mally used by the instrument imaging system, to the external, user-defined control.

The system is based on a software that starts by a high level definition of the features to be written, made by a computer aided design (CAD) with a GDSII output. The software produces numerical data that can be read by the hardware and converted in suitable X and Y beam positions. The hardware has been appositely designed to provide, through a digital to analog conversion, the voltages for the X (horizontal) and Y (vertical) position controls of the beam. The hardware provides also control signals for the beam blanker (on/off) and for switching from the internal SEM electronics to the external vectorial control of the beam. Figure 1 shows a complete functional sketch of our system.

The X (horizontal) and Y (vertical) voltage controls of the beam position are provided by two twin circuits, based on the analog devices AD7845 D/A converter integrated circuit. This converter shows a high precision ($\pm 1/2$ least significant bit) differential conversion, a low noise level ($50 \text{ nV}/\sqrt{\text{Hz}}$), and a conversion time of less than $6 \mu\text{s}$. The D/A converter needs a constant reference voltage of $\pm 5 \text{ V}$, which in our case is supplied by a Maxim (MAX6250) low-noise, precision voltage reference. This voltage reference also shows an excellent stability with respect to the temperature drift (less than 1 ppm per degree).

The output of the D/A converters can show disturbance for digital feed-through and glitches due to the not simultaneous commutation of the 16 digital input signals (digital data). For isolating the beam from this disturbance, we put a sample and hold (S/H) system between the D/A converters and the X or Y beam control. Before data are presented to the D/A converter, the S/H is put in the "hold" condition by a suitable digital signal and the last settled voltage is maintained at the output by the charge stored in a capacitor. In this way the beam is maintained in the last settled position. The S/H is put again in "sample" condition after a suitable time during which the conversion transient of the D/A is

completed and the voltage has been stabilized to the value imposed by the input digital data.

In order to minimize disturbance and electrical noise, the power supply of both of these circuits is provided by a stable, low noise battery pack, consisting of six batteries, each 6 V 10 Ah. One fully charged battery pack could supply the system for 20 h of continuous operation. The battery pack is recharged by a standard laboratory power supply (max current 3 A) in 2–3 h. A couple of battery packs allows for nonstop use of the system.

A PC provides the 16 digital data, plus eight control bits, through a digital output board. The D/A conversion circuitry is made electrically isolated by the PC by using fast optocoupler circuits (HA2630, rise time of 50 ns), in order to minimize disturbance coming from the computer. The 8 bit control bus provides digital signals for controlling the beam blaster, the external scan, and the sample and hold circuits.

The system is limited in frequency at 200 kHz by the digital throughput of the PC board. A fast D/A converter is not required as the speed limit is imposed by the digital output.

We estimated that the residual noise gives a beam deviation of less than 0.4 nm, using a beam step of 2.5 nm. This is smaller than the microscope's resolution limit, that is on the order of 1.5 nm.

The digital board is installed on a computer working in real time mode (DOS operating system) because control of the beam must be done with a suitable time accuracy for a good repeatability of the exposure time, which affects the charge dose on the resist during the exposure process.

The software has been developed in C language and consists of a few simple routines. Given a geometrical figure, each routine is capable of generating integer numbers between 0 and $2^{16}-1$ for describing this figure (line or rectangle). The routine then sends these data to the digital output board writing them as 16 bit words in suitable input/output locations and also controls the 8 bit control bus for the external scan, blanking conditions, and for the selection of the X and Y D/A channel and S/H. These routines are very simple and they could be easily written in Basic or Pascal, or some other developing language running on a PC.

Another computer, named the master computer, is used to design the structures to be written, and can run both under Windows or Linux operating systems. Through a high level CAD tool, the device can be designed and verified: a lot of free or GNU license software is available for this purpose (LASI, MAGIC, BOOLEAN), and also there are numerous commercially available software for microelectronics design, like L-EDIT or CADENCE. All these CAD programs are commonly used for device design and produce as output a file in GDSII format, which is an industry standard format. The software we developed reads GDSII files, composed by several designed layers. It can separate each level to be written into different files, again using the GDSII binary format. Then, for each layer saved in GDSII format, the master produces a file consisting of a set of primitive geometries (lines, rectangles, and polygons) whose coordinates are expressed by integer numbers between 0 and $2^{16}-1$. Each primitive geometry, with its position and dimensions, is saved in a file

FIG. 2. (a) A pattern designed by a GDSII CAD and prepared by our software, ready to be sent to the slave for a writing process. (b) A particular of the sample, after writing of the pattern reported in (a) development and metal deposition.

as ASCII format and automatically sent to the slave computer by means of a parallel (or serial) connection.

The slave computer decomposes each primitive in single points, generating the X and Y position of the beam, concerning the lithography criteria and strategies. At the moment in our system several basic writing strategies, all based on vectorial concepts, have been developed and successfully tested. It is possible to use the beam blaster for every point (full vectorial mode) or to do a raster fill in of every single geometry; serpentine and spiral fill in have also been implemented. It is very easy to implement new strategies and to adapt them to the most suitable configuration for the geometries that the user wishes to write. This involves only writing and modifying the very simple functions for the beam positioning. In this way, even very complex writing algorithms for the beam positioning, during geometry definition,

can be implemented and tested in a very short time. An alignment procedure, based on marker detection, has also been implemented.

For example, the master reads GDSII file and need to write a rectangle. It sends to the slave a "BOX" command and four coordinates X_1 , Y_1 , X_2 , Y_2 (the coordinates of the top right and of the bottom left corner). The slave evaluates all the X_i , Y_i coordinates for filling the rectangle and pilots the S/H, beam blanker, and D/A converters for moving the beam in the proper way. For example, using a full vectorial strategy, the slave sends each X_i , Y_i to the D/A converters and puts the beam on by using the beam blanker, for the T_{dwell} time required for the correct dose. The dose value is decided by the user and it should be suitable for the resist in use and the shape in writing. In this way, very complex shapes also can be written.

Figure 2(a) shows an example of a screenshot from our software depicting data to be sent to the pattern generator. The data are a set of line and rectangles designed in LASI CAD, saved in GDSII format, and later converted by our software to the format readable by the slave computer. The design width of the lines is 25 nm with a 150 nm pitch. The exposure field is 120 μm . Figure 2 also reports an experimental result of the exposure of this pattern. The substrate used is a chip of a standard silicon wafer (0.6 mm thick). The resist was poly(methylmethacrylate), molecular weight 350 K 3% solids in anisole, spun for 30 s at 5 krpm and baked in an oven at 160 $^{\circ}\text{C}$ for 30 min. The line dose is 13 nC/cm at 30 kV. The dose for the rectangle is 120 $\mu\text{C}/\text{cm}^2$. A single pass of the beam exposed the lines and the rectangles by

raster fill. After exposure the resist was developed for 30 s in a solution of methyl isobutyl ketone and isopropanol in a 3:1 ratio at 23 $^{\circ}\text{C}$. An aluminum layer of 20 nm was deposited by thermal evaporation.

The speed of the system is essentially limited by the data throughput of the digital board on the PC. Actually we are implementing a development of the system based on a fast (20 MHz) digital data output board (National Instruments 653). Data can be prepared by the slave computer employing the basic routines described above, and stored in the first in, first out memory of the board that provides the fast data output. By using faster digital to analog converters we can reach high writing speeds, with this technique, limited only by the microscope deflection system, maintaining the simplicity and adaptability of the system.

This work was supported by the National Research Council of Italy (Consiglio Nazionale delle Ricerche, CNR), within the Nanotechnology initiative, project "Lithographic Processes for Nanofabrication."

¹*Handbook of Microlithography, Micromachining and Microfabrication*, edited by P. Rai-Choudhury, Volume 1, Microlithography (1988), Chap. 2.

²J. G. Goodberlet, J. T. Hasting, and H. I. Smith, *J. Vac. Sci. Technol. B* **19**, 2499 (2001).

³J. C. Nabity and M. N. Wybourne, *Rev. Sci. Instrum.* **60**, 27 (1989).

⁴See web site of RAITH, Germany.

⁵S. Straehle, K. D. Schock, F. E. Prins, and D. P. Kern, *Microelectron. Eng.* **35**, 465 (1997).

⁶E. H. Anderson, V. Boegli, and L. P. Muray, *J. Vac. Sci. Technol. B* **13**, 2529 (1995).