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ELECTRON BEAM LITHOGRAPHY FOR LARGE AREA PATTERNING 3: DATA CONVERSION AND ELECTRON BEAM DEFLECTION CONTROL

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Abstract

Electron beam direct writing technologies, specifically for the large area patterning of electronic devices such as printed wiring boards, are studied in this paper. The vector scanning method with two kinds of beam deflection, main-deflection and sub-deflection, has been adopted for the fabrication of circuit patterns of various line widths. The sub-deflection of high frequency oscillation is superimposed on the main-deflection, which allows for controlling each line width with ease. A data conversion and a deflection control system with several strategies have been developed to reduce the conversion time and the volume of output data. It is revealed that circuit patterns of widths from 70 μm to 250 μm can be fabricated effectively with these new technologies.

Key Words: Electron beam lithography, electron beam direct writing, printed wiring board, large field scanning, electron beam main-deflection, electron beam sub-deflection, data conversion, large area patterning, line width, electrodeposited thick resist.

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Introduction

A novel electron beam (EB) system has been designed and prototyped for the large area patterning of electronic devices such as printed wiring boards (Hoshinouchi *et al.*, 1990a). The electron gun has assured a long service life and high brightness under high emission current, and the optics column has given fast and accurate deflection over a large field. Long term operations have confirmed that it provides a stable beam spot, 35 μm in diameter (full width at half maximum, FWHM) with current intensity of 50 μA at 60 kV. The column designed with magnetic deflection covers a 52 mm square field. It is confirmed that the system can provide accurate deflection within a $\pm$ 20 μm tolerance, together with high speeds, for the quite large field of 52 mm x 52 mm.

Also, the exposure characteristics of an electrodeposited negative resist have been examined as a candidate of the resist for EB lithography of large area electronic devices (Hoshinouchi *et al.*, 1990b). The experimental results have confirmed the excellent performance of the resist, which shows a sensitivity of 2.0 x 10^{-7} C/cm^2, without any charging problems. Furthermore, Monte Carlo simulations were carried out to confirm experimental data. The results have indicated that the pattern profile is characterized by a critical energy density of 1.5 x 10^{19} eV/cm^3 and the line width can be predicted with considerable accuracy by using this value.

One of the most serious problems is the efficient writing of lines of various widths. A variable-shaped EB lithography system has been applied to the development of large-scale integrated circuits (LSI) which have a large number of dense patterns with submicron dimensions (Gonzales, 1989). However, this system cannot be applied to the circuits of printed wiring boards, which have long lines of various widths, because of substantially low throughput.

The aim of this paper is to describe the development of high throughput EB direct writing technologies for fabricating electronic devices with far larger areas than LSI devices. Two key technologies for the development: **(a)** a computer aided design (CAD) data conversion system, and **(b)** a high-performance EB deflection system for controlling line widths, will be presented.

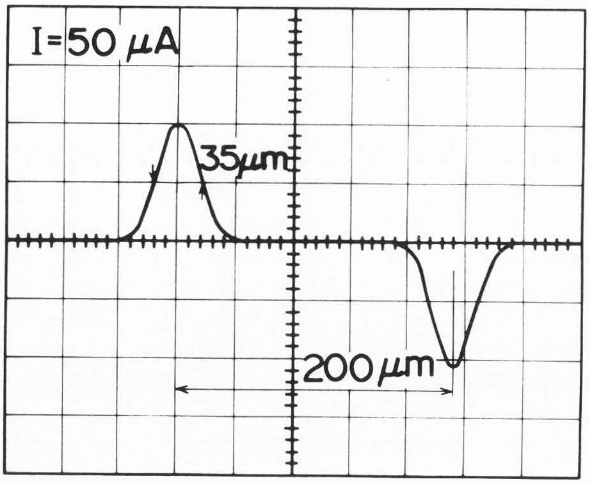


Figure 1. A measured beam profile at a beam current of 50 μA.

Process-Flow Overview

For the evaluation of circuits patterns, 20 μm thick resists were prepared on Cu clad laminates. An electrodeposition process was adopted to meet the following demands: **(a)** a thick resist with strong adhesion to the substrate was required to etch the thick Cu layer, and **(b)** a preparation process needed to provide uniform coating at the edges and the wall surfaces of many small holes used to fabricate the three dimensional wiring. The main components that contributed to the chain cross-linking were unsaturated acrylic resins (Hoshinouchi *et al.*, 1990b).

The EB exposure was done on the large field deflection EB lithography system (Hoshinouchi *et al.*, 1990a) at 60 kV and with the current density of 4 A/cm^2. The sensitivity of the electrodeposited resist was 2.0 x 10^{-7} C/cm^2. Since the basic performance of the system has been described in detail elsewhere, only the beam focusing properties are briefly described in this section. The beam intensity profile was obtained by measuring the time transient profile of the reflected electron current from a marker. Figure 1 shows an example of the results. The beam profile was quite similar to a Gaussian distribution with FWHM of 35 μm. The diameter was almost independent of both the beam current and the deflection angle. The distribution of beam diameter in the scan area of 52 mm x 52 mm was also measured to confirm the high stability of the beam diameter within a fluctuation of less than $\pm$ 2 μm.

After being exposed, the resist was developed in a solution of 1 wt% sodium carbonate in water.

System Description

System overview

A photograph of the prototyped EB lithography system is shown in Figure 2.

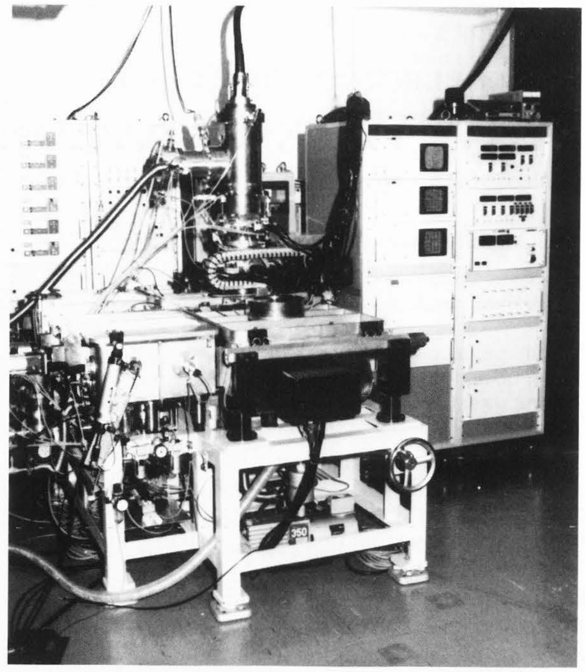


Figure 2. A photograph of the prototyped electron beam lithography system.

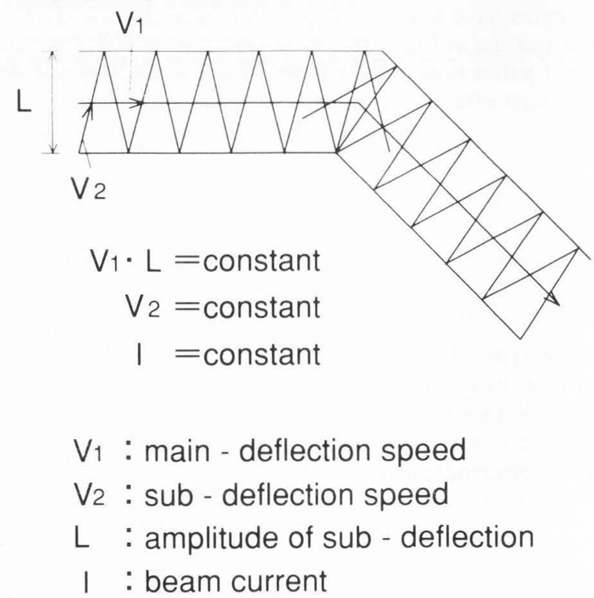


Figure 3. The concept of direct writing in the vector mode.

The system utilizes the vector scanning method for the main-deflection of the electron beam to obtain high throughput. One of the most serious problems is the efficient writing of lines of various widths. The line widths in the pattern depend upon the requirements of the design and take discrete values such as 100, 150 and 250 μm. The concept of direct writing in the vector mode is shown in Figure 3. One of the features of this

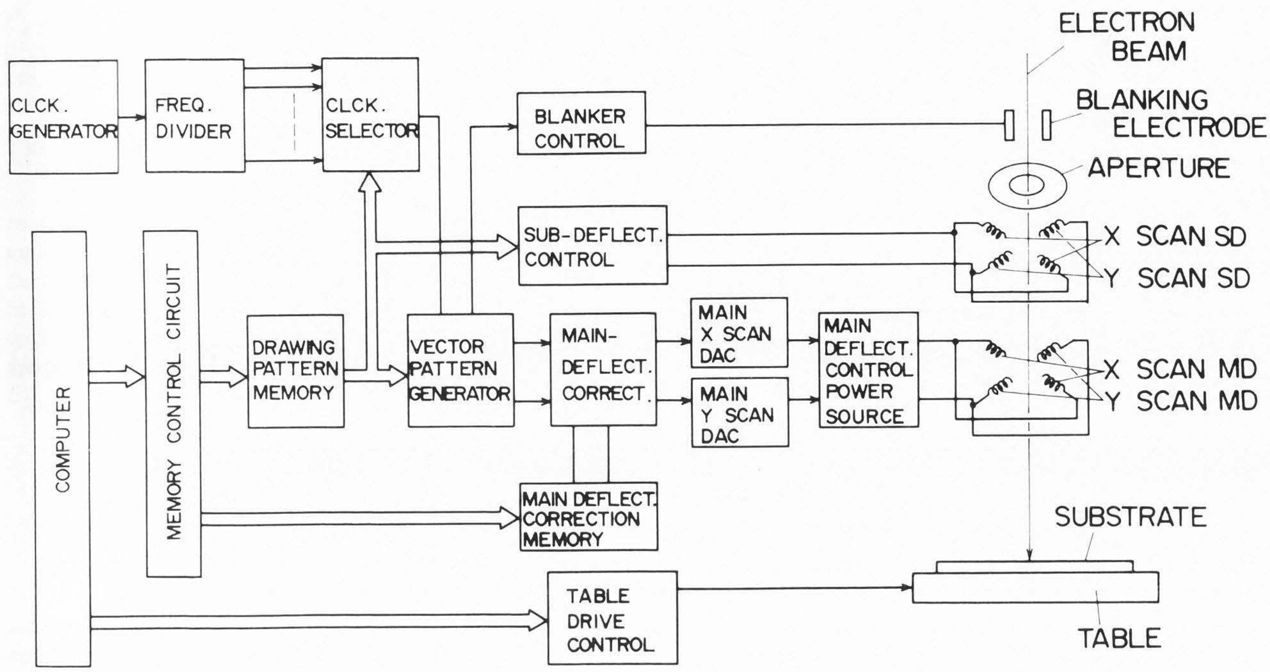


Figure 4. A functional block diagram of the system.

system is the sub-deflection by high frequency oscillations superimposed perpendicular to the direction of main-deflection, thus allowing the line width to be controlled with ease.

Figure 4 shows a functional block diagram of the system. The system is mainly composed of a deflection data generation section, a main-deflection (MD) control section, a sub-deflection (SD) control section and an optics column.

Resists of several tens of micrometers in thickness are generally used in the fabrication of printed wiring boards. From experiments and simulations on incident electrons in such thick resists (Hoshinouchi *et al.*, 1990b), we have chosen 60 keV as the maximum primary beam voltage.

The optics column is composed of an electron gun, a blanking electrode, an aperture, a sub-deflector and a main-deflector. Both the sub-deflector and the main-deflector use deflection coils for scanning electrons in X and Y directions. Magnetic deflection is utilized in order to obtain a combination of large, accurate spot deflection together with high speeds. The main-deflector covers a field of 52 mm x 52 mm by writing pixels in the vector scan.

The deflection data generation section is composed of a computer, a memory control circuit and a pattern memory.

The main-deflection (MD) control section is composed of a MD correcting memory, a vector pattern generator, a MD correcting circuit, digital/analog convertors (DACs) for the main-deflection in X and Y direction and a MD control power source. The MD correcting memory which is connected to the output of the memory control circuit stores data to correct for various distortions of deflection. The vector pattern generator provides deflection data with the pattern data from the pattern memory. The deflection correcting circuit generates corrected deflection data by referring to the distortion correcting data stored in the MD correcting memory.

The sub-deflection (SD) control section includes three circuits, one for generating periodic rectangular waves, one for selecting phase signals and the other for generating gains in X and Y scans.

Data conversion

The CAD data for printed circuit boards are described generally in Gerber format by the following codes:

a) a code corresponding to the line width of a pattern;

b) a code assigning a starting point coordinate (X_s, Y_s) and an end point coordinate (X_e, Y_e) of each line segment; and

c) a code indicating whether the line segment is to be exposed.

The patterns described in these codes cover a large area of the printed wiring board.

The first step in data conversion is referred to as a field division, where the pattern data in Gerber format throughout the board are divided into fields of 52 mm x 52 mm each by the computer.

In the second step, the data for each field are converted into the following vector format suitable for the use of the system:

a) coordinate (X,Y) of the starting point of line segment;

b) length of line segment; and

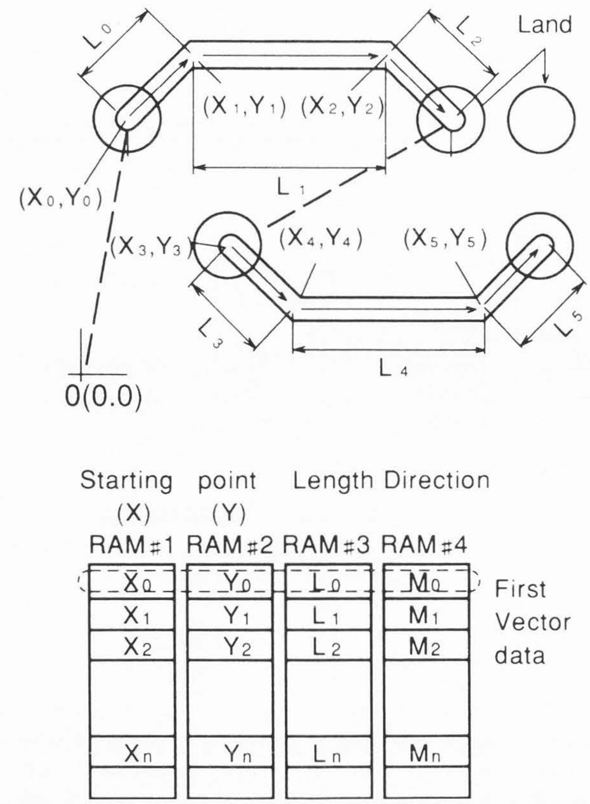


Figure 5. The vector format for a typical pattern.

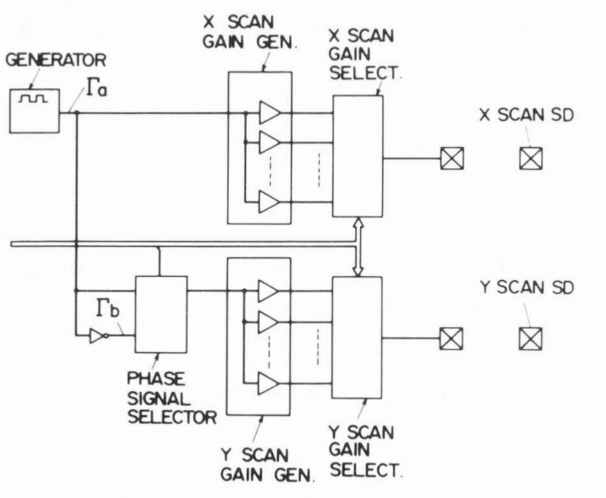


Figure 6. A detail of the sub-deflection control section.

c) orientation and gain of sub-deflection for each line segment.

The vector format for typical patterns is shown in Figure 5. The circles at the start and the end of each line segment, which are called "lands", are exposed by drawing swirls.

Prior to the commencement of the writing operation, the pattern information and the data for correcting the distortion are supplied to the pattern memory and to the MD correcting memory. At the start of the direct writing, data concerning the start point coordinate (X,Y), length and orientation for one line segment are read out from the pattern memory and are supplied to the vector pattern generating circuit. The latter circuit, which is composed of electric logic circuits such as counter, provides X and Y scan data in digital form as the control signals for the main deflector in response to the data mentioned above. These scan data are supplied to the MD correction memory. An operation of correcting the deflection distortion is performed in real time according to the correction data stored in the MD correction memory. When the correction is completed, these data are converted into analog signals by the DACs and are supplied to the power source to drive the main-deflection.

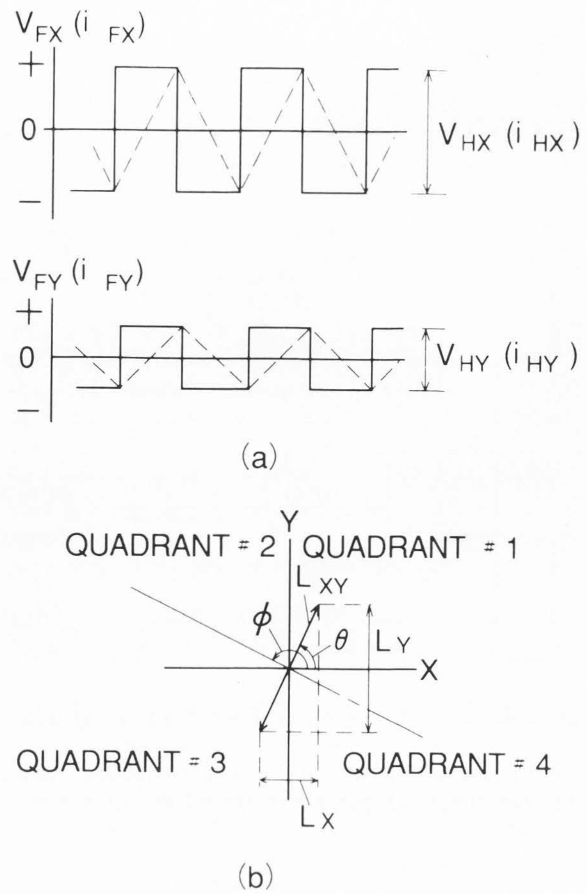


Figure 7. The periodic rectangular in-phase signals (**a**; top) and a movement of electron beam (**b**; bottom).

On the basis of these strategies, the output data volume was reduced to 1/10 of that previously required.

Control of line width

Figure 6 shows a detail of the SD control section. A signal generator supplies an output signal Γ_a of periodic rectangular waves to the X scan gain generator and to the phase signal selector. The signal Γ_b, which is inverted from the signal Γ_a, is also supplied to the phase signal selector. The selector supplies either the signal

Γ_a or Γ_b to the Y scan gain generator according to the digital input value. The X and Y scan gain generators are composed of the same number of amplifiers. The amplification factor of a pair of X and Y scan amplifiers is set initially so that the SD scanning of a predetermined width can be performed on the substrate.

When the SD coils for X and Y scan receive such rectangular in-phase voltages V_{FX} and V_{FY} with the amplitudes V_{HX} and V_{HY} shown in Fig. 7(a), the electric currents i_X and i_Y with the amplitudes i_{HX} and i_{HY} flow in the SD coils. The currents are shown in Fig. 7(a) with dotted lines. In this case, the following relations are established between the direction, Θ, and the width, L_{XY}, of the sub-deflection on the substrate:

$$\Theta = \tan^{-1}(V_{HY}/V_{HX}) = \tan^{-1}(i_{HY}/i_{HX}) \quad (1)$$

$$L_X = L_{XY}\cos\Theta = K \cdot V_{HX} = K' i_{HX} \quad (2)$$

$$L_Y = L_{XY}\sin\Theta = K \cdot V_{HY} = K' i_{HY} \quad (3)$$

where K and K' are constant and L_X and L_Y are X and Y components of the deflection width L_{XY} respectively.

Figure 7(b) shows the movement of the electron beam on the substrate. Since the rectangular voltages V_{FX} and V_{FY} are in-phase, the electron beam moves in the first and the third quadrants. When the phases of these voltages are shifted 180 degrees as shown in Fig. 8(a), the electron beam moves in the second and the fourth quadrants as shown in Fig. 8(b). The chain lines in Fig. 7(b) and Fig. 8(b) show the scanning direction of the main-deflection.

The system includes the control circuit to optimize the electron dose automatically as shown in Fig. 4. This design comprises three elementary circuits: (**a**) a clock circuit for generating a rectangular clock signal with a constant frequency f; (**b**) a frequency divider for producing rectangular signals with frequencies f_i on the signal lines; and (**c**) a clock selection circuit for selecting one of the frequencies among f_i as a MD control clock f_M so as to keep the exposing dose constant even if the pattern width to be written varies. The frequency selected by the clock selection circuit is supplied to the vector pattern generator.

A scan area S(m^2) in a time t_M which is necessary to scan a length equivalent to one bit of digital data by the main-deflection is expressed by equation (4):

$$S = d \cdot L_{XY} \quad (4)$$

where d is a beam diameter in meters.

The exposure dosage per unit area D(C/m^2) can be expressed as:

$$D = (I \cdot t_M)/S \quad (5)$$

where I is the electron beam current in amperes.

Therefore, combining equations (4) and (5), the following relation is obtained:

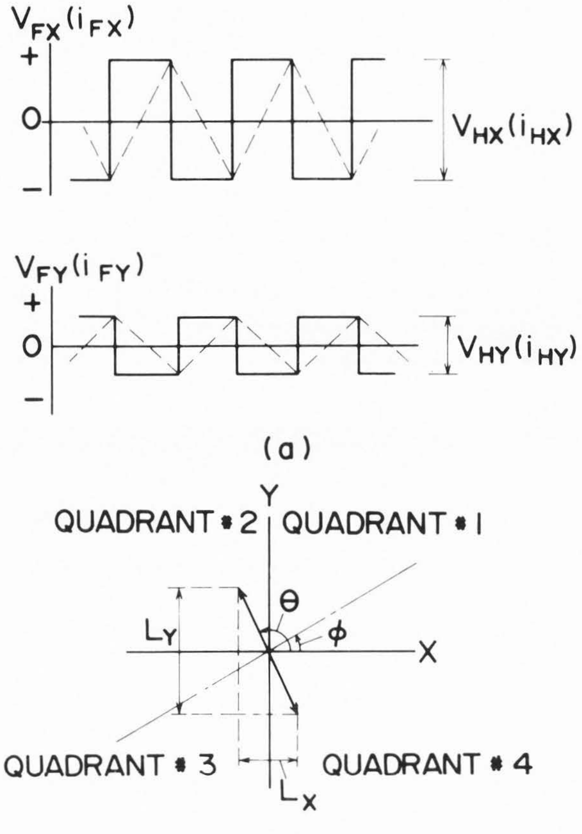


Figure 8. The signals which are out of phase 180 degrees (**a**; top) and a movement of electron beam (**b**; bottom).

$$t_M = (d \cdot D) \cdot L_{XY}/I \quad (6)$$

Since $t_M = 1/f_M$, the equation (6) can be transformed into the following equation:

$$f_M = \{1/(d \cdot D)\} \cdot (I/L_{XY}) \quad (7)$$

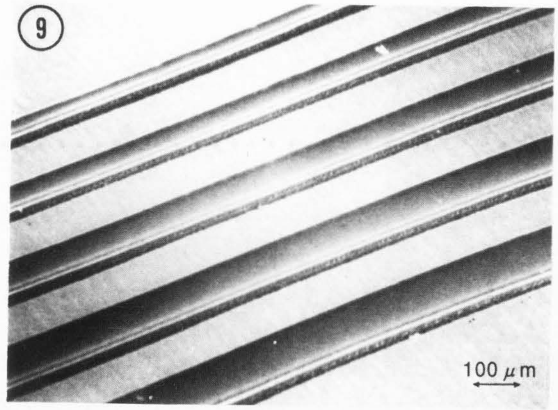
From the equation (7), it becomes possible to obtain an optimum exposure for each pattern width by selecting optimum frequency according to the data being written.

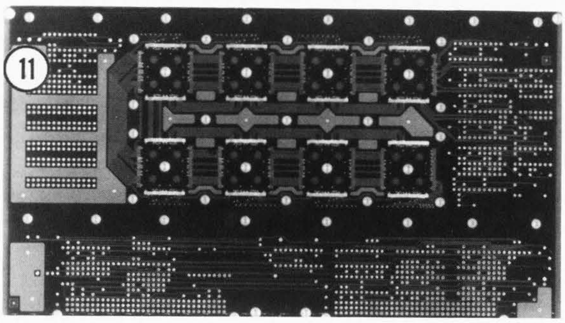
System Performance

The novel lithography system developed for the fabrication of large area electronic devices was evaluated with regard to the stability of line width and the throughput.

Stability of line width

Figure 9 shows a scanning electron micrograph of the resist pattern obtained by this experiment. The widths of the resist patterns in the figure (from top left





Size		340mm x 400mm
Data Volume (Gerber Data)		430 k byte
Lines	Direction	Horizontal Vertical 45°
	Width	100 ~ 200μm
Lands	Diameter	0.5 ~ 3.0μm
	Number	4900

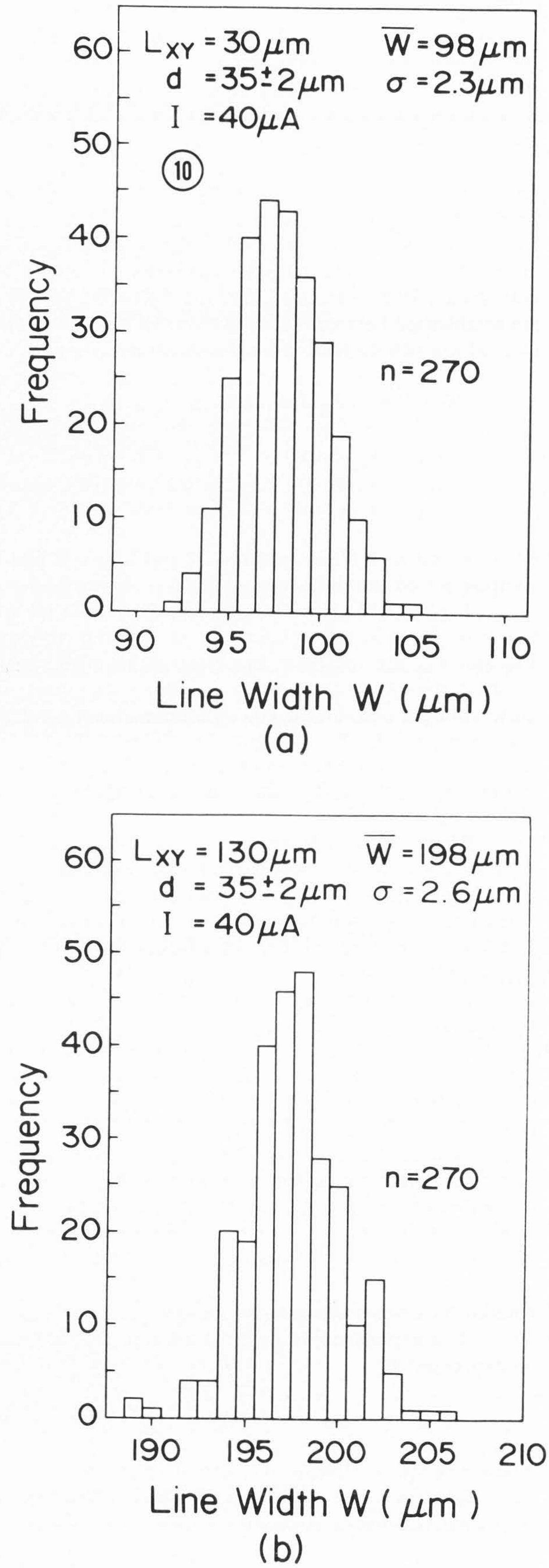


Figure 9 (above, top). A scanning electron micrograph of the resist pattern. Bar = 100 μm.

Figure 10 (at right). The distribution of line width in the field of 52 mm x 52 mm prepared under L_{XY} = 30 μm (**a**, top) and L_{XY} = 130 μm (**b**, bottom).

Figure 11 (above, bottom). An outerview and a specification of the sample board.

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to bottom right) are 70, 100, 150, 200 and 250 μm respectively. Figure 10 shows the distributions of line widths in the field of 52 mm x 52 mm prepared under L_{XY} = 30 μm and L_{XY} = 130 μm. The distributions can be expressed by Gaussian distributions with a standard deviation (σ) of 2.3 μm and 2.6 μm. The distribution of line width prepared without the sub-deflection was also evaluated (Hoshinouchi *et al.*, 1990b). The standard deviation for the lines written without the sub-deflection was 2 μm. These data led to the conclusion that the present control system is able to write the lines of various widths with considerable accuracy, well suited for the fabrication to printed wiring boards.

Throughput

The basic throughput of the system was evaluated using a sample board. Figure 11 shows an outerview and a specification of the sample board. A minicomputer with the capability of 7 million instructions per second (MIPS) was used. It is revealed that the basic throughput is one board per minute for a printed wiring board of 340 mm x 400 mm and the data conversion speed is about 430 byte/s.

Conclusions

A novel EB lithography system has been designed and prototyped with several strategies to improve the throughput and to control the line widths for large area patterning. The circuit patterns of various line widths can be fabricated effectively with high accuracy by adopting the vector scanning method with two kinds of beam deflection. The data conversion time and the volume of output data has been reduced considerably.

In conclusion, the present prototyped lithography system has proven to be a very powerful instrument for the development and manufacture of large area electronic devices.

Acknowledgement

The authors are greatly indebted to Mr. Ehichi Tsuda, Dr. Takio Okuda, Mr. Seiji Yasunaga and Mr. Katsunori Hara of Mitsubishi Electric Corporation for their encouragement during this study and Mr. Shigeru Yamaji, Mr. Masashi Kamio, Mr. Akira Miura and Mr. Yoh Noguchi of Mitsubishi Electric Corporation for their technical assistance in the construction of the system.

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Discussion with Reviewers

M.G.R. Thomson: Is there any evidence of roughness in the line edges caused by the use of a "sawtooth" scan? What range of waveform periodicities (in the direction of the line) is commonly used?
Authors: The edge roughness is not enlarged by the use of the sub-deflection. The frequency of the sub-deflection is 5 MHz.

M.G.R. Thomson: Can errors in beam position be seen as a line crosses from one 52-mm field to another?
Authors: Errors can be seen as much as $\pm$ 16 μm (3σ), due to mainly the positioning error of the mechanical stage.

K. Murata: The resist line edge definition looks good in Fig. 9. Could you comment on how careful you must be for the factors which determine the quality of the line edge, such as the quality of the pulse shape and the experimental conditions for sub-deflection, etc.?
Authors: The waveform periodicities is the most important factor. We used the frequency of 5 MHz.

K. Murata: Please comment on the factors which cause the fluctuations of line width in Fig. 10.
Authors: The measured electron probe size has a fluctuation of $\pm$ 2 μm in the scan area of 52 mm x 52 mm. Therefore, we think that the greater part of the fluctuations of the widths occurs from the fluctuations of the electron probe size.

S. Okazaki: Please specify the edge roughness of the pattern using SD.
Authors: The edge roughness is very small and less than 1 μm. The data in Fig. 10 contains the specific edge roughness.

S. Okazaki: Are there any correlations between line width variation and field size?
Authors: The line width increases slightly as the field size increases. This originates from the aberrations caused by the magnetic deflection.

S. Okazaki: Please specify the contribution of SD to the improvement of throughput.
Authors: The SD contributes mainly to the control of the line width with ease. The SD also contributes to the improvement of throughput through the increase of the data conversion speed.