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Susumu Hoshinouchi
Mitsubishi Electric Corporation

Akio Yoshida
Mitsubishi Electric Corporation

Hidenobu Murakami
Mitsubishi Electric Corporation

Utah State University
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ELECTRON BEAM LITHOGRAPHY FOR LARGE AREA PATTERNING 4: EXPOSURE OF RESIST ON INTERNAL SURFACE OF A THROUGH-HOLE

Susumu Hoshinouchi*, Akio Yoshida and Hidenobu Murakami

Manufacturing Development Laboratory, Mitsubishi Electric Corporation, Amagasaki, Hyogo, 661 Japan

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 exposure characteristics of the resist on the internal surface of a through-hole are examined. A thick film resist which is composed mainly of unsaturated acrylic resins is prepared on the internal surface of the hole by an electrodeposition process.

It is proven that a 20 μm thick resist on the internal surface can be exposed efficiently by a 60 keV electron beam. This phenomenon becomes even stronger by placing a gold plated metal plate on the back of the substrate.

The comparison between the experiments and the Monte Carlo calculations for electron trajectory leads to a conclusion that the exposure characteristics of the resist on the internal surface of the through-hole can be explained mainly by the behavior of backscattered electron in the hole.

*Address for correspondence:
Susumu Hoshinouchi
Manufacturing Development Laboratory
Mitsubishi Electric Corporation
1-1, Tsukaguchi-Honmachi 8-Chome
Amagasaki,
Hyogo, 661 Japan

Telephone No.: (06)497-7310
Fax No.: (06)497-7601

Introduction

In the fabrication of such large area electronic devices as printed wiring boards, advanced technologies are required to meet the demands for finer circuitry, more diversified production lots and shorter turnarounds. Until now, these devices have been fabricated mainly by photolithography with photo-tools and ultraviolet light. However, it is becoming more and more difficult to satisfy the more stringent requirements mentioned above by this process, due to the problems inherent in the processing and handling of photo-tools.

The direct writing technology represented by electron beam lithography is one of the most promising solutions for these requirements. A novel electron beam (EB) system has been designed and prototyped (Hoshinouchi et al., 1990a). Long term operations of the developed electron gun have confirmed that it provides a stable beam spot, 35 μm in diameter (full width at half maximum, FWHM) with a current intensity of 50 μA at 60 keV. The column designed with magnetic deflection covers a 52 mm square field. It has been confirmed that the system can provide accurate deflection within a $\pm$ 20 μm tolerance, together with high speeds, for the relatively large field.

A thick film composed of unsaturated acrylic resins and prepared by an electrodeposition process has been proposed as the most suitable resist for EB lithography of large area electronic devices (Hoshinouchi et al., 1990b). The examination for the exposure characteristics confirmed the excellent performance of the resist, which showed a sensitivity of 2.0 x 10^{-7} C/cm^2, without any charging problems.

The vector scanning method with two kinds of beam deflection, main-deflection and sub-deflection, was proposed for the efficient writing of lines of various widths (Hoshinouchi et al., 1993). The data conversion and the deflection control systems with several strategies have been developed to reduce the conversion time and the volume of output data. The examination revealed that circuit patterns of line widths from 70 to 250 μm could be fabricated effectively.

To apply this electron beam lithography to printed wiring boards, it is necessary to develop the novel
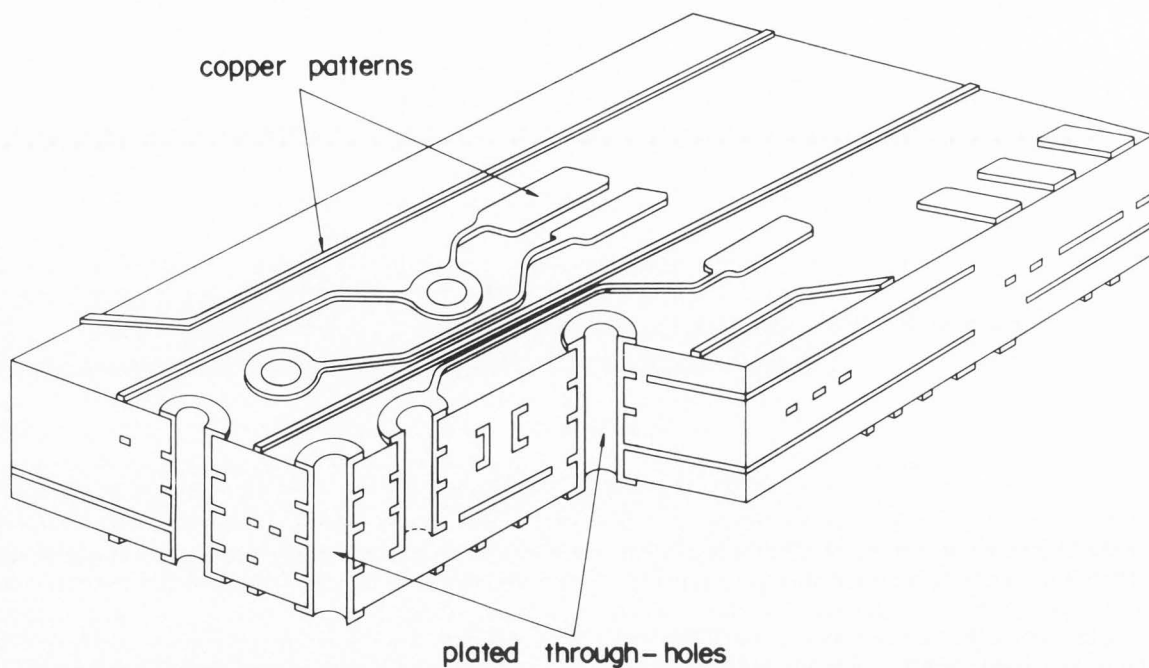
copper patterns

plated through-holes

Figure 1. The configuration of the multi-layer printed wiring board.

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technology for this problem which is unique in the fabrication of those devices. The circuit patterns of printed wiring boards comprise multi-layers of Cu patterns and through-holes plated with Cu for three dimensional wiring as shown in Fig. 1. Figure 2 shows a typical process for making the patterns and plated through-holes. One of the most serious problems is how to expose the resists on the internal wall surfaces of the plated through-holes.

The aim of this paper is to describe the exposure characteristics in the plated through-hole and to propose a method to insure the exposure to the electron beam.

Materials and Experimental Procedure

Figure 3 illustrates the samples used in the experiments. The substrate is 1.6 mm thick copper clad laminate, which is composed of glass-reinforced epoxy resin and 50 μm thick copper. The slit of 0.8 mm width in Fig. 3a and the through-holes of 0.8 mm and 0.4 mm diameter were machined and plated with about 30 μm thick copper. The through-holes of 0.8 mm and 0.4 mm diameter are commonly used in the fabrication of high density printed wiring boards. The samples with 0.8 mm wide slits were prepared for simplifying and facilitating the analyses of the exposure phenomena.

For the evaluation of exposure characteristics in the hole, 20 μm thick negative resist was prepared on the whole surface of the substrate. An electrodeposition process was adopted. Since the deposition process and the characteristics of the resist have been described in detail elsewhere (Hoshinouchi *et al.*, 1990b), only the composition and the sensitivity to the electron exposure

are briefly explained in this section.

The main components that contribute to the chain cross-linking are unsaturated acrylic resins. Figure 4 shows the monomer and polymer formula of the main components. Figure 5 shows the sensitivity of 20 μm thick electrodeposited negative resist for 60 keV electrons. The beam current, I, was varied from 1 to 10 μA and the scanning speed, S, from 4 to 254 m/s. The resist shows a high contrast with the threshold dosage of 2.0×10^{-7} C/cm^2 as shown in Fig. 5. This is the lowest exposure at which no thickness loss was observed after resist development.

The EB exposure was done on the large field deflection EB lithography system (Hoshinouchi *et al.*, 1990a) at 60 keV. 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, α. The column designed with magnetic deflection covers a 52 mm square field and can deflect the beam angle, α, from 0 to $\pm$ 7.5 degrees.

The slits and the through-holes were arranged at each position corresponding to the deflection angle α of 0, 1.8, 3.6, 5.3, and 7.1 degrees. as shown in Fig. 6a. The electron beam was scanned at an adequate pitch to deposit the electrical charge uniformly. After being exposed, the resist was developed in a solution of 1 wt% sodium carbonate in water. The distributions of the remaining resist thickness of the internal surfaces were measured by observing the profiles of the cross-sections. The exposure characteristics in the slits were evaluated in terms of the height of the exposed area, h, as shown in Fig. 6b. Also, those in the through-holes were evaluated in terms of the ratio of the exposed area, A_e, to the whole area of the internal surface of the through-hole, A_0.
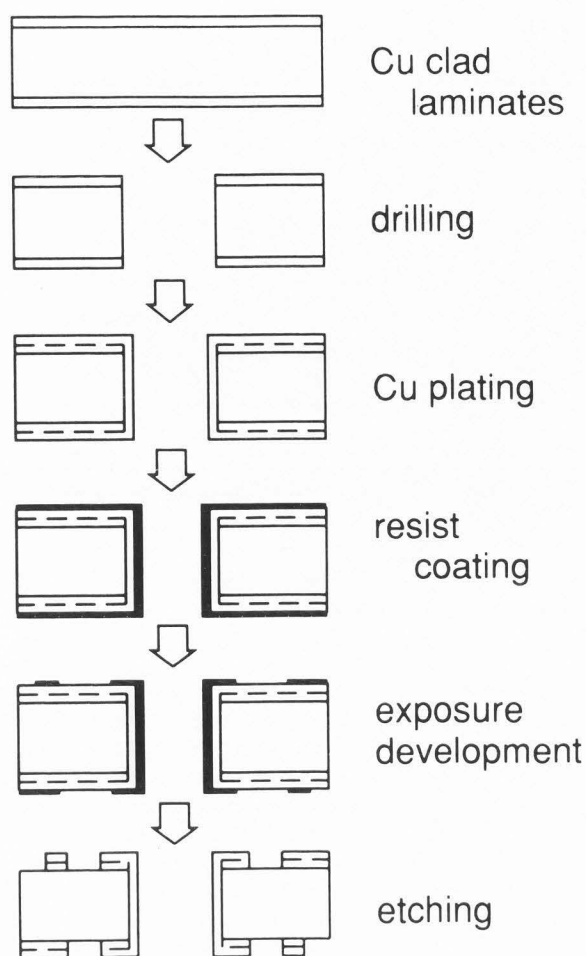
Figure 2. The typical process to fabricate the printed wiring board.

Cu clad laminates

drilling

Cu plating

resist coating

exposure development

etching

$$CH_2=CH \longrightarrow \left(CH_2=CH \right)_n$$
$$\quad | \qquad\qquad\qquad | $$
$$COOR \qquad\qquad\quad COOR$$
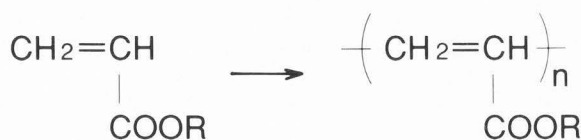
Figure 4. The monomer and the polymer formula of the main component of the electrodeposited resist.
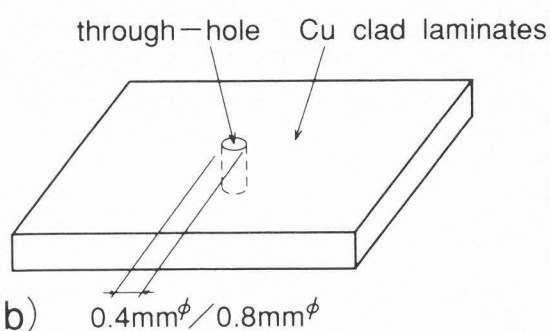

Experimental Results and Discussions

The remaining height of exposed area, h, in the slit was evaluated in terms of electrical charge per unit area on the top surface, D_s. The measured height of the exposed area was normalized by the thickness of the substrate. The evaluations were carried out on both the wall a and the wall b of the slit shown in Fig. 6b arranged at the position of $\alpha = 0$ and $\alpha = 7.1$ degrees.

Any sufficient exposure (defined as the one at which no thickness loss occurred after the development),

Slit   Cu clad laminates

1.6mm

(a)   0.8mm

through−hole   Cu clad laminates

(b)   0.4mm$^\phi$/0.8mm$^\phi$
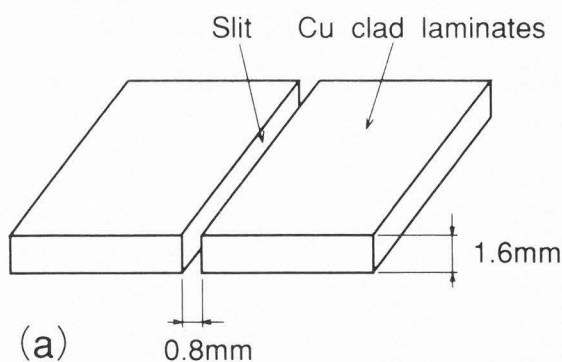
Figure 3. The illustrations of the samples used in the experiments.

E : 60keV

$\gamma = 1.7$

I μA	S (m/s)	symbol
1	4	○
1	8	△
1	16	□
1	32	▽
1	64	●
1	127	▲
1	254	◻
5	254	▼
10	254	◇

Normalized Remaining Thickness

Electrical Charge Per Unit Area D (C/cm²)
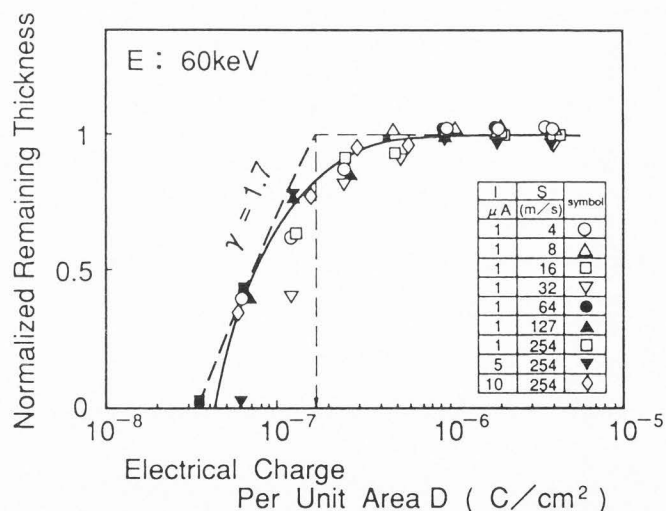
Figure 5. The resist sensitivity to the electron beam exposure.

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could not be observed on the wall a or b of the slit arranged at the position of $\alpha = 0$ degree. Figure 7 shows the exposure characteristics in the slit arranged at the position of $\alpha = 7.1$ degrees. The resist on the wall b showed the clear threshold dosage, $D_{th(wb)}$, of 4×10^{-6} C/cm². This value is 20 times larger than the threshold dosage for the same resist on the top surface, D_{th}.
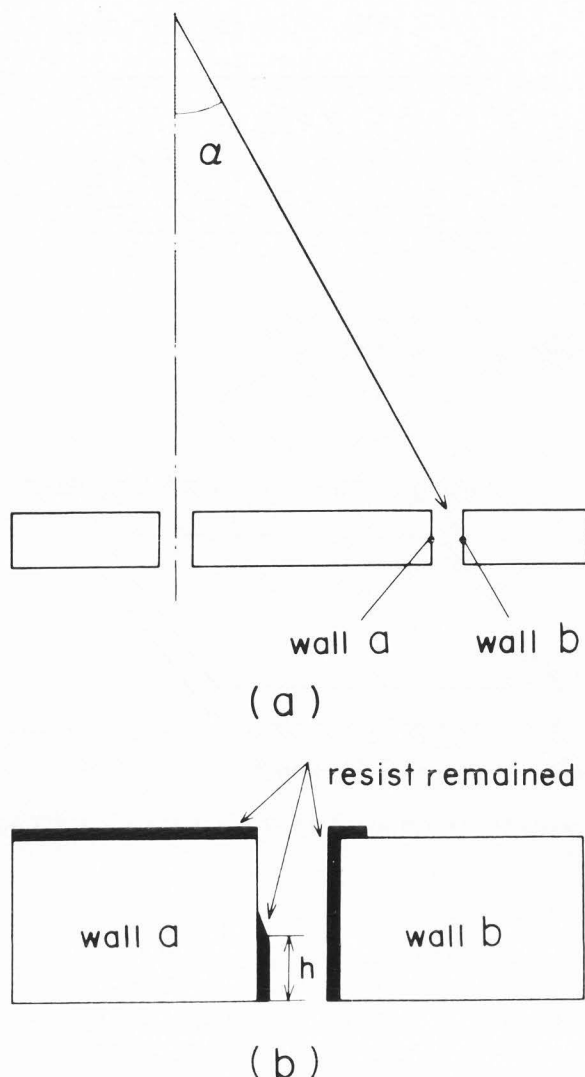
59

Figure 6. The arrangement of the slits and the through-holes to the beam axis (a) and the method to evaluate the exposure characteristics in the hole (b).

Table 1. The values for the mean energy of ionization.

Atom	Z	J/Z (eV)
H	1	18.7
C	6	13.0
O	8	11.1
Cu	29	10.8
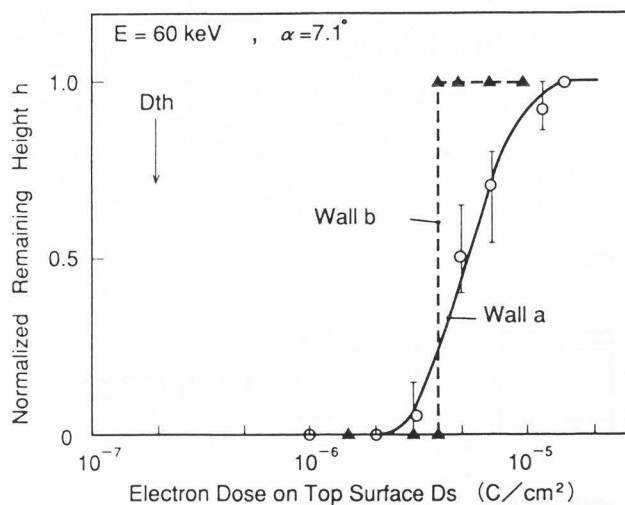
Figure 7. The exposure characteristics in the slit arranged at $\alpha = 7.1$ degrees.

The remaining height of the resist on the wall *a* depends on D_s. The threshold dosage to obtain full remaining height, $D_{th(wa)}$, is 1.5×10^{-5} C/cm². This value is 75 times larger than D_{th}. It is very interesting that the resist on the wall *a* can be exposed to the electron beam even though the resist is arranged in the shade of the accelerated electrons.

The Monte Carlo calculations for the scattering were carried out to provide an understanding of the exposure phenomena in the slit. The method of Monte Carlo calculations has already been described elsewhere (Hoshinouchi *et al.*, 1990b). The continuous slowing down approximation (Kyser, 1982) and the Rutherford formula for differential cross-section for elastic scattering were also adopted in the calculation. The density of the electrodeposited negative resist is 1.10 g/cm³. The values for the mean energy of ionization used in the present calculations are listed in Table 1. For these calculations, 1,000 electron trajectories were simulated.

Figure 8 shows the Monte Carlo results of the angular distribution and energy distribution of backscattered electrons in the slit arranged at the position of $\alpha = 7.1$ degrees. The numbers in this figure indicate the number of the backscattered electrons. The following facts from this calculation are worth noting: (a) 40% of the impinged electrons dissipate their energy in the resist; (b) 60% of the impinged electrons are emitted from the resist as backscattered electrons; and (c) most of the backscattered electrons keep enough energy to expose the 20 μm thick resist.
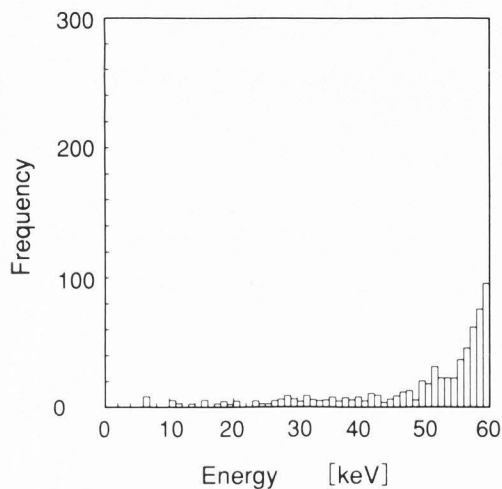
Figure 9 shows the result for electrons impinged vertically to the resist surface. In this case, only 10% of the electrons are emitted from the resist as backscattered electrons.

From these simulations, $D_{th(wb)}$ is estimated roughly by equation 1:
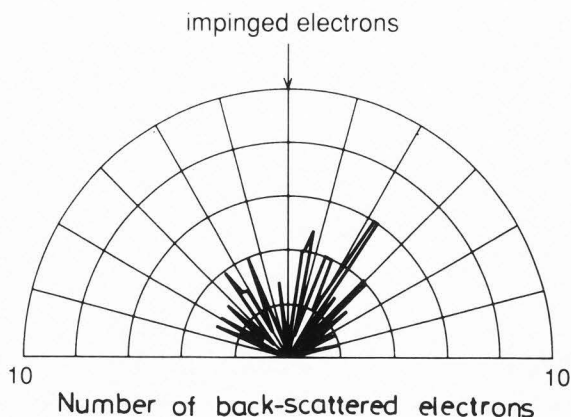
Number of back-scattered electrons
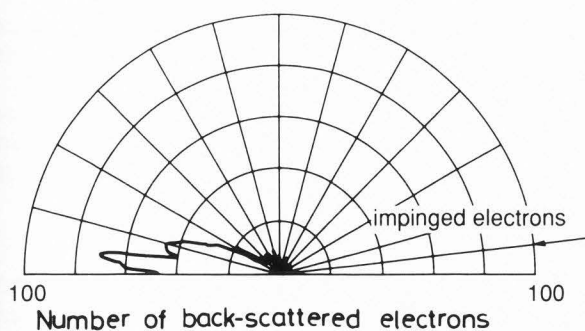
(a)

(b)

Figure 8. Monte Carlo results of the angular distribu-·tion of the backscattered electrons (a) and the energy distribution of the backscattered electrons (b) in the slit arranged at $\alpha = 7.1$ degrees.

$D_{th(wb)}$
$= D_{th}$ x $(1/\tan 7.1)$ x $\{(N_i - N_{r0})/N_i\}/\{(N_i - N_r)/N_i\}$
$= 18$ x D_{th} (1)

where N_i: the number of impinged electrons, N_r: the number of backscattered electrons emitted from the wall b in the slit arranged at the position of $\alpha = 7.1$ degrees, N_{r0}: the number of backscattered electrons in the case of vertical impingement. The experimental result shown in Fig. 7 agrees approximately with this estimation.

Supposing that the exposure of the resist on the wall a originates from the backscattered electrons emitted from the resist on the wall b, the number of backscattered electrons irradiated into the resist on the wall a was estimated. Figure 10 shows the model and the result. The surface of the wall b was divided into 100 finite elements in the direction of thickness. The number of backscattered electrons irradiated at the position h on the wall a was calculated by equation 2:

$$N_a(h) = \Sigma \, N_{rj} \qquad (2)$$

Number of back-scattered electrons

(a)
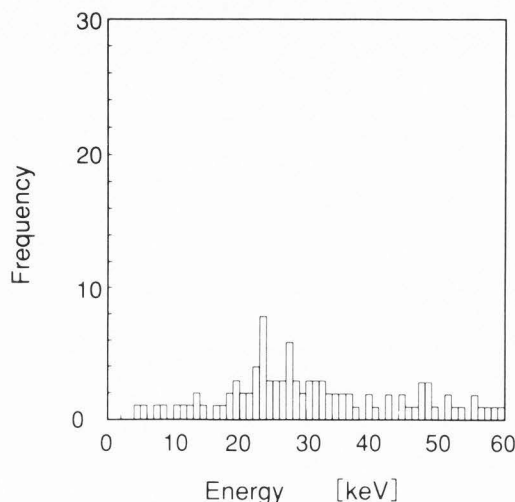
(b)

Figure 9. The angular distribution of the backscattered electrons (a) and the energy distribution of the backscattered electrons (b) in the case of vertically impinged electrons to the resist.

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where N_{rj}: the number of backscattered electrons from the finite elements j on the wall b.

The estimated results shown in Fig. 10b indicates that a considerable dosage, more than 50 times of D_{th}, is needed to expose the whole surface of the wall a. This finding agrees approximately with the experimental result.

These analyses lead us to conclude that the exposure of the resist on the wall a in the slit originates mainly from the backscattered electrons. On the basis of this consideration, a metal plate was installed on the back of the substrate to insure the generation of backscattered electrons. The metal plate was composed of iron and coated with 5 μm thick gold. This coating material was selected because of the high reflectivity of gold to impinging electrons. The experimental results are shown in Fig. 11. It was revealed that the sufficient exposure occurred on the resist on the wall a even in the
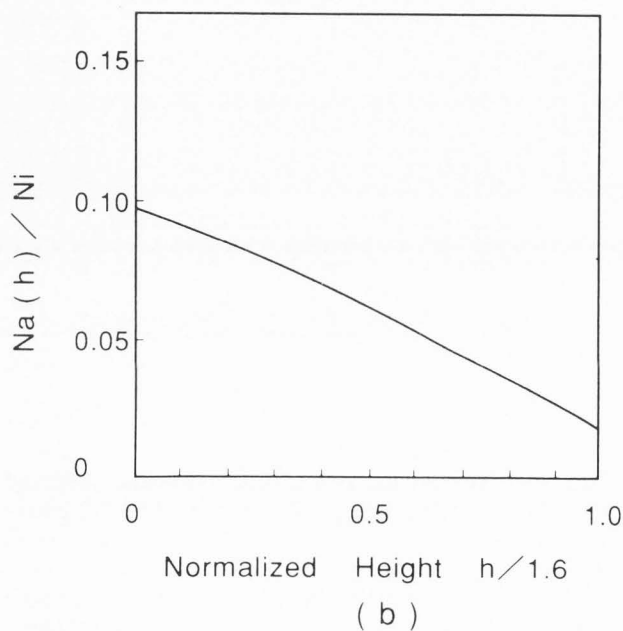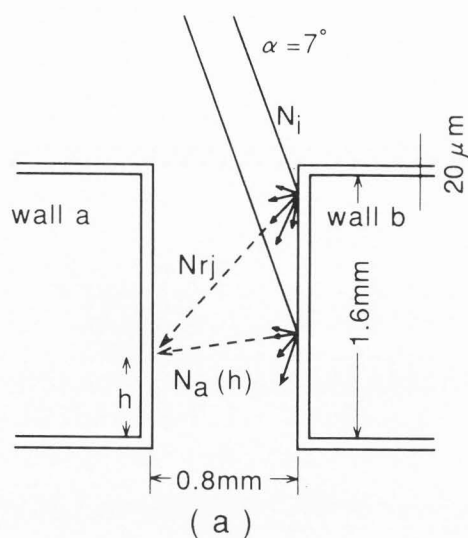
(a)

(b)

Figure 10. The model to estimate the number of the backscattered electrons (**a**) and the result (**b**).

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slit arranged at the position of $\alpha = 0$ degree. Although the influence of X-rays emitted from the metal plate was expected to add to the effect of backscattered electrons, these effects could not be analyzed separately.

Finally, the exposure characteristics in the real through-hole was evaluated. Figure 12 shows the results of the plated through-hole of 0.8 mm diameter. In these evaluations, the gold-coated back-plate was utilized. It was confirmed that each through-hole arranged at the position of $\alpha = 0$, 1.8, 3.6, 5.3, and 7.1 degrees could be exposed with certainty under the electron dosage of 4×10^{-6} C/cm^2. Figure 13 shows a scanning electron micrograph of the resist pattern in the circumference of

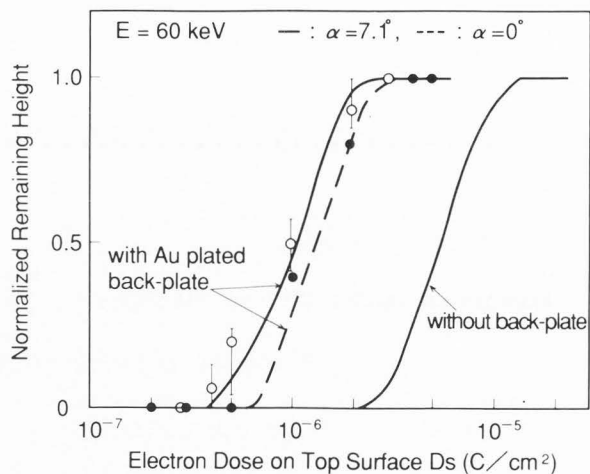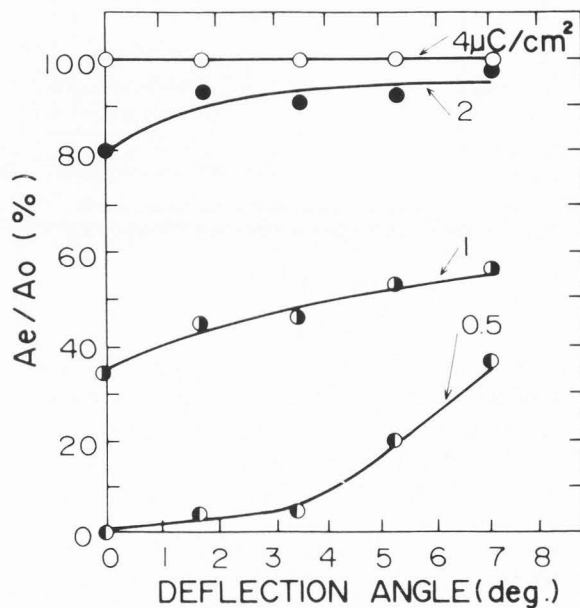**Figure 11**. The influence of the back-plate on the exposure characteristics in the slit.

Figure 12. The exposure characteristics in the through-hole of 0.8 mm diameter.

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the plated through-hole. Similar results were confirmed for the through-hole of 0.4 mm diameter.

Conclusions

The exposure characteristics of a thick resist on the internal surfaces of the through-holes were examined. The results confirmed that the internal surface could be exposed efficiently to the scanning electron beam. This effect becomes even stronger by installing a metal plate on the back of the substrate. The recommended material for the back-plate is gold coated iron.

The Monte Carlo calculations for the scattering of electrons were compared with experimental data. The results indicated that the backscattered electrons with

considerably higher energy contributed to the exposure of the resist in the through-hole.

It is concluded that the developed electron beam lithography system is of practical use for large area patterning and three dimensional wiring in the fabrication of printed wiring boards.

Acknowledgements

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Discussion with Reviewers

M.G.R. Thomson: Would it not be advantageous to use a deflection system in which the beam always lands vertically, with $\alpha = 0$?
Authors: It is considered that the accuracy of the resist pattern will be improved by the use of such a deflection method. However, there is not enough necessary basic data to introduce such a method into the large field deflection system.

M.G.R. Thomson: Is the dose for all line widths the same? Or is the dose used to control the line widths?
Authors: The dose is the same for all line widths below 250 μm. The dose for through-holes is increased by drawing swirls.

J.C. Wiesner: Could you comment on why you have such a sharp rise-up characteristics for the wall *b* in Fig. 7?

Authors: The ordinates indicate the normalized remaining height. It is considered that the normalized remaining height shows a sharp rise-up under the conditions of critical dose.
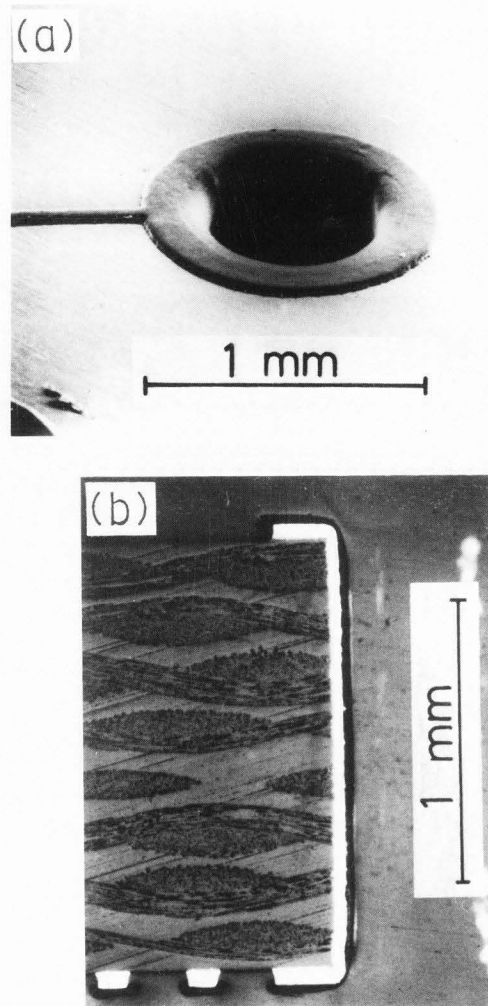

Figure 13. Scanning electron micrograph (**a**) and cross-sectional view (**b**) of the resist pattern in the circumference of the through-hole. Bar = 1 mm.

J.C. Wiesner: Did you check how much the dose required for successful resist remaining is decreased with a gold back plate in both cases of $\alpha = 0$ and 7.1 degrees in Fig. 11, based on Monte Carlo simulation?
Authors: We have not fully studied this point yet.

J.C. Wiesner: Did you include a relativistic effect in your Monte Carlo simulation of electron scattering?
Authors: We did not include a relativistic effect in our simulation.

S. Okazaki: In Eq.(1), a number "18" is used. This number seems to be a fitting parameter. How does this number come out?
Authors: We used the following values which are calculated by the Monte Carlo simulation for the angular distribution and the energy distribution of backscattered electrons:

$$N_{r0} = 0.1 \times N_i$$
$$N_r = 0.6 \times N_i.$$