Electron beam lithography for advanced LSI fabrication

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INTRODUCTION

The current technology used in IC (Integrated Circuit) and LSI (Large Scale Integration) fabrication is based on optical lithography or the art of photocopying. The light wave length sets an ultimate and absolute limit on the resolution of the optical method at about one micron (\( \mu \text{m} = 10^{-6} \text{ meter} \)) and the current LSI technology has almost reached this limit.

In microscopy, a drastic improvement of resolution was achieved in the 1930’s by switching from glass (light) optics to electron optics. The similar is taking place in lithography for LSI fabrication. X-ray lithography and electron beam lithography are the two promising methods for improving the resolution by at least one order of magnitude over optical lithography. The characteristic features of these three lithographic methods are summarized in Table I.

In Table I, “Mask in Contact” means that a mask, with a master pattern inscribed on it, is placed in close proximity to the target (silicon wafer covered with photo-resist) so as to selectively expose the target to the incident beam. The finite and rather short life of the masks in contact is the major disadvantage of this scheme.

In Table I, “Mask Projection” means that an image forming projection system (actually a lens) is placed between the mask and the target so that the mask does not have to be in contact with the target. Since there is no material suitable for making an X-ray projection lens, this scheme is not applicable to X-ray.

In Table I, “Direct Pattern Generation” means a feature in which the incident beam is maneuvered so as to generate the pattern directly on the target without using a mask. While this feature can be implemented by suitably deflecting an electron beam at high speed without any fundamental difficulties, this is not the case for light and X-rays. Note that the sub-micron pattern generation feature is also needed for making the masks themselves. Therefore, “electron beam pattern generation” is the key and the very heart of advanced LSI technology which requires sub-optical or sub-micron resolutions.

Moreover, because of flexibility and many other practical reasons, electron beam pattern generation is considered advantageous for making masks to be used with optical lithography in many cases.

The development of practical electron beam pattern generation schemes is reviewed in a later section. The recent developments in electron optics, i.e., the theoretical foundation of the image-forming processes of electron beams, are reviewed and their implications to the practical systems are discussed. Fly’s eye optics which may find some use in the future is also discussed.

ELECTRON BEAM PATTERN GENERATION SCHEMES

Figure 1 shows three practical electron beam pattern generation schemes, and their developments are summarized in Table II.

In Figure 1, “Spot Scanning” means that an electron beam, with a small circular cross-section (spot), typically of 0.1 micron in diameter, is deflected electrically (by applying magnetic deflection field or electrostatic deflection field or both) and the pattern is generated by scanning the beam across the area to be exposed to the beam. In other words, the pattern is generated similarly to the pictures on a television screen, except for much increased resolution. So far as scanning and the resolution are concerned, this scheme is similar to SEM (Scanning Electron Microscope). Actually, SEM’s with slight modifications were used in the early models of pattern-generating machines. For example, the first Japanese pattern-generating machine JBX-2A was developed concurrently with the first SEM, JSM-1. Using this spot scanning machine (JBX-2A), Tarui and his collaborators successfully made MOS transistors purely with electron
TABLE I.—A Comparison of Lithographic Methods

<table>
<thead>
<tr>
<th>Mask in Contact</th>
<th>Mask Projection</th>
<th>Direct Pattern Generation</th>
<th>Ultimate Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>0</td>
<td>x</td>
<td>≥ 1 μm</td>
</tr>
<tr>
<td>X-Ray</td>
<td>0</td>
<td>x</td>
<td>≤0.1 μm</td>
</tr>
<tr>
<td>Electron Beam</td>
<td>0</td>
<td>0</td>
<td>≤0.1 μm</td>
</tr>
</tbody>
</table>

0—Practicable. x—Impracticable.

beam pattern generation without using any masks at all in 1968 [L1].

EBES2 and VL-1 (entries 3 and 4, Table II) are also "spot scanning" machines. In EBES2 the electron beam is deflected electrically only in one direction (deflection width 0.128–0.256 mm) and the target is scanned mechanically in the other direction so as to scan and generate two dimensional patterns. In VL-1 the electron beam is deflected two dimensionally within a square scanning area of 5 mm by 5 mm.

Referring to Figure 1, "Fixed Shaped Beam" means that the cross-section of the electron beam at the target has a fixed shape, typically a square of 2.5 μm by 2.5 μm. This is achieved by projecting the image of a mask with a square hole on to the target. The pattern is generated by scanning and/or patching the area to be exposed to the beam. EL-1 is a "fixed shaped beam" machine.

In Figure 1, "Variable Shaped Beam" means that the shape of the cross-section of the beam at the target is variable, typically a rectangle x by y μm with x and y being varied from 0.1 to 25 μm. This is achieved, for example, by using two masks each having a square hole. The image of the first mask is projected on the second mask and the image of the second mask is further projected on the target. The combined action of the two masks is varied by the beam-shaping deflector placed between the two masks, and the shaped beam is directed to a selected position on the target. The "variable shaped beam" concept was first reported at the May 1977 EIPBT (Electron, Ion and Photon Beam Technology) Symposium by four independent groups (entries 6, 7, 8, and 9, Table II).

Figure 2 is a photograph of one of the first test patterns generated by JBX-6A, the variable shaped beam machine of the Japanese group. Entry 10 in Table II shows the result of the design and feasibility studies made by the authors' group on the variable shaped beam scheme.

Before making comparison and evaluation of the various pattern generation schemes we shall review the recent advances in electron optics.

ADVANCES IN ELECTRON OPTICS

The studies on the image-forming processes of electron beams are called electron optics. Similar to glass (light) optics, the deviations in the actual image from the ideal image are called geometrical aberrations.

The term "geometrical" means that the wave nature of the beam is being neglected. Since the wave nature or quantum mechanical effects can be neglected in the schemes shown in Table II, we shall drop the term "geometrical" hereinafter for simplicity. The aberration theory of the pure (deflection-less) image-forming process of electron beam is well established and we can learn the results from definitive text books on the subject, such as those authored by Glaser [E1] and El-Kareh [E2].
TABLE II.—Electron Beam Pattern Generators

<table>
<thead>
<tr>
<th>Model</th>
<th>Beam Shape (μm)</th>
<th>Resolution (μm)</th>
<th>Total Beam Curr. (A)</th>
<th>Year Developed</th>
<th>Reported at/by</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 JSM-1</td>
<td>0.1 φ</td>
<td>0.1</td>
<td>10 μA</td>
<td>1966</td>
<td>JEOL</td>
<td>[1]</td>
</tr>
<tr>
<td>2 JBX-2A</td>
<td>0.35 φ</td>
<td>0.35</td>
<td>0.01 μA</td>
<td>1968</td>
<td>JEOL&amp;ETL</td>
<td>[L1]</td>
</tr>
<tr>
<td>3 EBES2</td>
<td>0.25-0.5 φ</td>
<td>0.25-0.5</td>
<td>0.1 μA</td>
<td>1975</td>
<td>BTL</td>
<td>[L4]</td>
</tr>
<tr>
<td>4 VS-1</td>
<td>0.05 φ</td>
<td>0.05</td>
<td>1 μA</td>
<td>1975</td>
<td>IBM</td>
<td>[L5]</td>
</tr>
<tr>
<td>5 EL-1</td>
<td>2.5</td>
<td>4</td>
<td>3 μA</td>
<td>1976</td>
<td>IBM</td>
<td>[L7]</td>
</tr>
<tr>
<td>6 JBX-6A</td>
<td>0.5-2.5 φ</td>
<td>0.5</td>
<td>1 μA</td>
<td>1977</td>
<td>IPCR&amp;JEOL</td>
<td>[L9]</td>
</tr>
<tr>
<td>7 —</td>
<td>0.6-2 φ</td>
<td>0.6</td>
<td>2 μA</td>
<td>1977</td>
<td>IBM</td>
<td>[L10]</td>
</tr>
<tr>
<td>8 —</td>
<td>0.5 φ</td>
<td>0.5</td>
<td>1-0.4 μA</td>
<td>1977</td>
<td>BTL</td>
<td>[L11]</td>
</tr>
<tr>
<td>9 —</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1977</td>
<td>Thomson</td>
<td>[L12]</td>
</tr>
<tr>
<td>10 —</td>
<td>0.1-25 φ</td>
<td>0.1</td>
<td>≥1 μA</td>
<td>1978</td>
<td>IPCR</td>
<td>[1]</td>
</tr>
</tbody>
</table>

Remarks:
1. SEM (Scanning Electron Microscope), Japan Electron Optics Laboratory Co., Ltd.
2. Spot scanning, Electrotechnical Laboratory, Japan.
3. Spot scanning, Bell Telephone Laboratories Inc., U.S.A.
5. Fixed shaped beam.
6. The Institute of Physical and Chemical Research, Japan. 6,7,8,9,10: Variable shaped beam.

However, when electrical deflection of the beam enters, the theories developed up to the 1960’s are all incomplete in that the focusing field and the deflection field are spacially separated. A unified treatment of spacially superimposed focusing and deflecting fields are needed for the full development of the aberration theory and this has been accomplished only very recently.

Electron optics is a rather specialized art full of jargon of lengthy mathematical formulas and odd terminologies for non-specialists. The authors would try their best to review the advance without entering the jargon. Nevertheless, we shall need the definitions of, at least, some quantities for the sake of clarity.

Figure 3 shows the definitions of three (optical) parameters α, β and γ. We assume that there is a final electron lens (the objective lens) which projects the beam on the target. The shape of the beam on the target is called the image. The distance (specifically called the working distance in pattern-generating machines) from the objective lens to the target is denoted by L.

The parameter α = F/2 = a/L, with a being the aperture radius of the lens, is the half aperture angle at the image. The brightness of an optical lens (say of a camera) is usually measured by using an index F called the F-number. Hence, α = F/2 means that α is the index representing the brightness of the electron lens.

The parameter β = b/L, with b being the size of the image, is an index representing the size of the electronic image relative to the (working) distance L.

The parameter γ = c/L, with c being the amount (or the length) of deflection on the target, is an index representing the amount of deflection relative to L.

The ratio ΔV/V, with V being the acceleration voltage of the electron, represents the relative spread in electron energy, which may be caused by thermal effects on the cathode, variations in the accelerating voltage itself as well as by the Boersch effect to be discussed later.

The aberration theory has to do with expressing the quantity δw = δ(x + iy), the deviation of the actual beam point...
incident on the target from the ideal point, as a function of \( \alpha, \beta, \gamma \) and \( \Delta V/V \), where \( x+iy \) is the two dimensional cartesian coordinate in the target plane in complex form. Namely, we have a function \( f \) such that \( \delta w = f(\alpha, \beta, \gamma, \Delta V/V) \).

This function is usually expanded into a Taylor series, and each term in the series is given a specific name. For example, the terms including the energy spread index are called chromatic aberrations.

The recent advances in the aberration theory and results in the design of electron optical systems with reduced aberrations are summarized in Table III.

First, note that the deflection-less \( (\gamma=0) \) pure image-forming case has to do with the special case \( \delta w = f(\alpha, \beta, 0, \Delta V/V) \), and that for "spot scanning" the point image \( (\beta=0) \) function \( f(\alpha, 0, \gamma, \Delta V/V) \) would be sufficient but the full function \( f(\alpha, \beta, \gamma, \Delta V/V) \) would be needed for "fixed- and variable-shaped" beam schemes.

Ohiwa, Goto and Ono (\#1 in Table III) introduced a MOL (Moving Objective Lens) concept and showed that there exists \( (3f) \) a system for point image \( (\beta=0) \) free of all deflection-induced aberrations, i.e., \( f(\alpha, 0, 0, \gamma) = g(\alpha) \). Chromatic aberrations, however, were not included (assuming \( \Delta V/V=0 \)).

Munro (\#3) derived the formula for point image case \( (\beta=0) \) with chromatic aberrations.

Goto and Soma (\#6) derived the formula for the finite image case \( (\beta \neq 0) \) and also theoretically proved the existence of systems free of all deflection-induced aberrations by making use of the MOL concept.

Soma (\#8) derived the most general formula valid for any combination of magnetic and electro-static fields and for electrons running at relativistic speeds. The formula is some 80 pages long and the computerized formula manipulation system Reduce 2 [E12] was utilized for the derivation. It is extremely difficult to handle such a long formula without such manipulation systems.

The other entries in Table III with "min" (for minimization) gave practical results in reducing various aberrations (there are some 20 aberrations.)

We want to emphasize that, in all the aberration reduction calculations made by the authors' group (entries 1, 6, 7 and 9 in Table II), we also required the beam to land vertically on the target. As a result of these studies, all aberrations except for two have been found to be either eliminable or negligibly small in practice. The two are the spherical aberration \( \delta w_s \) and the axial chromatic aberration \( \delta w_{a} \), which have the following forms:

\[
\delta w_s = S a^2, \quad \delta w_{a} = A a \Delta V/V
\]

where \( S \) and \( A \) are the aberration constants. Note that these aberrations exist even in the deflection-less point image case \( (\beta=\gamma=0) \), i.e., \( f(\alpha, 0, 0, \Delta V/V) = S a^2 + A a \Delta V/V \). In spite of a great number of efforts trying to eliminate the spherical aberration, no practical scheme has been found yet. [E3]

These two aberrations are explained pictorially in Figure 4. The spherical aberration means that electrons having larger aperture angle \( \alpha \) are bent stronger by the lens, and the axial chromatic aberration means that slower electrons (\( \Delta V/V<0 \)) are bent stronger by the lens.

**LIMITS ON CURRENT DENSITY AND EXPOSURE SPEED**

Besides geometrical aberrations there is another factor, not having its counterpart in light optics, which causes...
broadening in the shape of electron beams. That is the electron-electron interaction. When the intensity of an electron beam is increased beyond a certain limit the electrons would start to repel each other and collide with others thereby broadening the shape of the beam. The theory of such broadening is not in a fully satisfactory form [B2] at present.

Among others the Boersch effect, named after the first observer of the effect, [B1], is a controversial issue. Some experimentalists have even questioned the very existence of the effect itself. [B5, B6] Boersch and some others [B6] observed broadening in electron energy \(\Delta V/V\) which is much larger than the thermal fluctuations to be expected from the cathode temperature, when electrons are passed through a spatial region of high electron density. Boersch effect would imply an increase of chromatic aberrations. In addition to the Boersch effect, the space charge causes the displacement of electron trajectories. By regarding the electron beam as a continuous and charged fluid, the displacement caused by the average (averaged over all electron trajectories) space charge effect can be easily derived, yielding the following to be called the space charge broadening formula:

\[
\delta w_{sc} = K IL/(Vv\alpha),\) (in CGS units),
\]

where \(\alpha\) is the half aperture angle, \(V\) is the accelerating voltage and \(L\) is the path length of the electron as defined in the previous section. Further, \(I\) is the total beam current (not the current per unit area), \(v\) is the electron speed \(v = \sqrt{2eV/m}\), and \(K\) is a number of the order of unity, which does not depend critically upon the image size \(\beta\) nor on other detailed structures of the system. Thus, we may well use \(K=1\) as the rule of thumb.

The experiments performed on JBX-6A (Table II, #6) indicate that axial chromatic aberration and chromatic aberration due to the Boersch effect could hardly affect the projected 0.1 micron resolution and that the observed broadening of the image agrees reasonably well with the space charge aberration \(\delta w_{sc}\). Thus, the spherical aberration \(\delta w_s\) and the space charge aberration \(\delta w_{sc}\) are concluded to be the major limitations imposed on the resolution and on the beam current.

The space charge aberration \(\delta w_{sc} = K IL/(Vv\alpha)\) would be reduced by increasing \(\alpha\), the brightness of the objective lens, but this would increase the spherical aberration \(\delta w_s = S a^2\). Hence, there is an optimum value of \(\alpha\) as a result of compromise. The lithographic process requires the acceleration voltage \(V\) to be around 20 K volt. Using the design figures of \(L=S=10\) cm, we arrived at the conclusion that "more than 1 micro ampere beam current would be feasible at 0.1 micron meter resolution" as indicated in Table II, #10.

The following are the implications of 1 \(\mu\)A beam current.

1. The lithographic sensitivity of the advanced electron resist material is better than \(10^{-4}\) coulomb/cm\(^2\). Hence, exposure speed of 1 cm\(^2\)/sec would be achieved (20 sec exposure time for 2 inch wafer).

2. If "spot scanning" with 1 \(\mu\)A beam current in a 0.1 \(\mu\)m spot were used, scanning speed of \(10^9\) spots/sec (10 Giga-Hz) would be needed, which would be extremely difficult to engineer. For this reason alone, one would have to use "shaped beam" schemes in order to increase the scanning speed.

3. Moreover, 1 \(\mu\)A in a 0.1 \(\mu\)m spot implies \(10^4\) A/cm\(^2\) in current density. A very bright cathode (e.g., field emission type) would be needed to realize such high current densities, but this would reduce the engineering freedom in the cathode design. The current density would be greatly reduced in "shaped beam" schemes.

4. From these considerations just given, "shaped beam" schemes are believed to be quite advantageous and even a necessity for attaining high exposure speed. On the other hand, "spot scanning" may be advantageous for lower speed devices because of its structural simplicity.

### FLY'S EYE OPTICS FOR PURE ELECTRICAL LARGE AREA SCANNING

In all the electron beam pattern generation schemes described earlier (cf. Table II), the electrically scanned areas (typically \(5\times5\) mm\(^2\)) are too small to cover the entire target area of silicon wafers, typically two to five inches in diameter. Hence, the target is placed on a mechanically scannable stage so as to back up the electrical scanning. The widening of the electrically scanned area is difficult because it would imply an increase in the working distance \(L\) resulting in an adverse effect on the space charge aberration \(\delta w_{sc} = K IL/(Vv\alpha)\).

Fly's eye optics may provide a method for scanning a large area purely electrically. Figure 5 shows two fly's eye schemes. The "post deflection" type was invented by Newberry [F1] and the "double deflection" type, by one of the present authors. [EG] [F2, F3, F6]. In Figure 5, FEL (Fly's Eye Lens) is illustrated by a matrix of lenses. In both types, the electron beam is selectively passed through a specific...
lens in the FEL by the action of the main deflector MD. The beam is further deflected by sub-deflector(s) SD(s), so as to scan a small area. The difference between the two schemes consists in that while a number of small sub-deflectors are placed after the FEL in the "post deflection" scheme, a single sub-deflector placed before the FEL is sufficient in the "double deflection" scheme. Lenses L1 and L2 are inserted in the "double deflection" scheme for the explanatory purpose but they may be removed.

The "post deflection" scheme and its modifications are used in electron beam memory schemes, with sub-micron memory cells. [F4, F5, F7]. The "double deflection" scheme is used in very high precision cathode ray tubes. [F2, F3, F6].

CONCLUSION

Electron beam pattern generators with 0.1 micron resolution running at a speed greater than 1 cm/sec are believed to be technologically feasible, based on electron optical studies. The "variable shaped beam" scheme will be used in faster machines and the "spot scanning" scheme, in slower machines.

The impacts of such pattern generators on LSI fabrication are rather difficult to foresee precisely because of the conglomeration nature of the LSI technology. We, as specialists in electron optics, firmly believe that the electron beam can never be the bottleneck in the development of advanced LSI's with sub-micron and sub-optical patterns.

We would like to acknowledge Messrs. S. Miyauchi, K. Tanaka and T. Someya of JEOL for stimulating discussions and for providing us with the photograph of the test pattern (Figure 2).

REFERENCES

Lithography by electron beam


Electron optics


Beam broadening


