Development Status of EPL Technology

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EPL (Electron Beam Projection Lithography) is expected especially for the application to contact hole and gate layers in the design rule below 65nm technology node. The reason is its excellent resolution and a good linewidth uniformity by adoption of high acceleration voltage of 100kV and a very small semi-angle of the electron beam. Nikon is developing an EPL exposure tool named as EB Stepper. The development status of an electron optical column and a vacuum compatible stage is introduced. The status of infrastructure is also introduced briefly. Current resist performance is overviewed. Generation process of secondary electron is reviewed and it implies shot noise issue is much moderated.

Keywords: Electron Projection Lithography (EPL), scattering contrast, image blur, stencil reticle, shot noise

1. Introduction

1.1 Development History

Electron Projection Lithography (EPL) is one of promising technologies below 65nm node, especially for layers of contacts and gates. The concept of an image formation in EPL is scattering contrast. This concept has been used in the area of transmission electron microscopy and was applied to the demagnified-image formation on an actinic film using a master stencil.[1] Later the basic study of EPL for micro device manufacture has been done under the name of SCALPEL® by AT&T [2] (Lucent Technologies, then Agere Systems) from the beginning of 1990's and the name of PREVAIL for an electron optical system by the joint work of IBM[3] and Nikon.[4] Now Nikon is developing EPL exposure tool as EB Stepper by adopting the PREVAIL technology for an electron optical system.[5,6]

1.2 Basic Parameters of the Electron Optics

An image blur can be used as a metric for resolution capability of EPL. The image blur is defined as the FWHM (full width of half maximum) of the point spread function of the point image which is correspond to the width of 12-88% edge slope height. This image blur consists of two components. One is a blur caused by geometrical aberrations and another is a blur caused by Coulomb interaction between electrons. The total blur can be expressed as the square root of the sum of the squares of these two contributions to the blur. The image blur by Coulomb interaction is given by

\[ B_c = \frac{k (I S L M^{0.5})}{(S F)^{0.5} V^{0.5}}, \]

where \( B_c \), \( I \), \( L \), \( M \), \( S \), \( F \), \( V \) are the image blur by Coulomb interaction, the total electrical current on wafer, the length between mask and wafer, magnification, the beam semi-angle on the wafer, sub-field size on the wafer and acceleration voltage, respectively.[4],[7] \( k \) is a coefficient and its value depends on the design of electron optics. Under the condition of the constant value of \( B_c \), larger acceleration voltage of electron gives larger electrical current, in other words higher throughput. Therefore the acceleration voltage of 100kV is adopted. Keeping the geometrical aberration within its tolerance, other parameters are set for EB Stepper as follows:

1) sub-field size of 0.25mm x 0.25mm on wafer,
2) magnification of projection lens of 1/4,
3) beam semi-angle of 6-8mrad on the wafer,
4) the maximum beam current of 100μA on mask (here after called as "reticle")

Deflection width of the electron beam is another important parameter and set to 5mm on wafer.
Combining the stage scanning control with the electron beam deflection control, higher throughput is expected.

In general it is not easy for the electron optics to realize a concave lens. Therefore the electron optics of EPL is a chromatic type and the energy dispersion of the electron beam should be small enough within its tolerance.

1.3 DOF and Resolution for Contacts

Wide DOF (depth of focus) and the resolution for contacts are characteristics of the imaging property of highly accelerated electron beam. The wide DOF enhances a process margin which gives a good linewidth uniformity.

Nikon developed the 100kV EPL experimental column by its own technology. Even though it does not have a large deflection function, it has been used for experiments of elemental technique developments.[8] Cross-sectional photographs of resist images of 100-60nm contacts exposed by this column are shown in Fig.1. Over 10µm DOF for 60nm contacts is obtained. It is cleared that DOF is over ten times wider than that of optical lithography and there is a large process margin for a good linewidth uniformity.

Fig.1; Focus series of 100-60nm contacts. The resist is EPLP-003-3 (TOK) (350nm thickness and 7μC/cm² dose) and exposed by Nikon’s 100kV EPL experimental column (the beam semi-angle is 1.5mrad). Defocus value of 0µm is around the best focus and the opposite defocus side is out of exposed defocus range.

Fig.2; Image formation of EPL by Scattering Contrast with a silicon stencil reticle.

2. Development status of EB Stepper

2.1 Scattering Contrast and Reticle Type

The charged particles scattered on the object plane are obstructed by an aperture plate on the pupil plane in the electron lens. Therefore if there are two kinds of areas on the object plane of which materials have a high scattering ability and a low scattering ability, a reticle as an plate of original patterns is realized.

Among candidates for such reticles, a silicon stencil type is the most promising one because the required membrane thickness is comparably thick, that is 1-2μm. As shown in Fig.2, almost all scattered electrons are stopped at the column inner wall and the contrast aperture plate in the projection optics and all of transmitted electron going through stencil apertures contribute on the image formation on the wafer plane. In the case that a half of aspect angle of the contrast aperture is 15mrad onto wafer, the ratio of scattered electrons to the wafer is only 0.1% for a silicon stencil reticle of 2μm and 1% for that of 1μm thickness.[5] Very high contrast of the aerial image is obtained. The demerit of the stencil type is the necessity of a division to a pair of complementary patterns. This causes throughput degradation and some amount of stitching errors at complementary boundaries.

A continuous membrane type is expected for the future reticle in order to avoid the above said demerit of the stencil reticle. In this case a very thin continuous membrane made of SiNx[9] or DLC(diamond-like-carbon)[10] works as an electron transmitter. In order to make a beam loss at the contrast aperture less than 50% and in order to make an induced energy spread small
enough for small chromatic aberration, the thickness less than 50nm is required.[6]

2.2 Reticle for EB Stepper
The illumination beam is shaped to 1mm square on a reticle. The reticle has many small membrane areas which are formed by etching a <200mm silicon wafer. The size of one membrane is 1mm square (sub-field) and patterns on the reticle are irradiated turning on and off the electron beam with sub-field by sub-field basis as shown in Fig.3. Minor struts between sub-fields have a role of a structure reinforcement.

Figure 4 represents a global structure of 200mm reticle. The membrane of 1mm square is small enough for controlling the intrinsic inner stress in order to make the image placement error small.[11] There are sub-field position measurement marks on the same side of reticle patterns below minor strut area. Each sub-field position error within the entire reticle is measured beforehand by a metrology tool such as Nikon Laser XY-6I or Leica LMS IPRO by means of detecting these marks. Those errors can be corrected by exposed position by deflection control of electron optics.[5,6,12]

2.3 Concept of Exposure Motion
It is assumed that device patterns are divided to those for each reticle sub-field without complementary division in order to make an explanation simple. Because the magnification of projection optics is 1/4, the size of the electron beam becomes 0.25mm square on wafer. Figure 5 shows a dynamic exposure motion of EB Stepper. The illumination beam is deflected and controlled by deflector along one direction of approx. 26mm. Reticle stage moves along a cross-beam-deflection direction with a constant velocity. Each reticle sub-field is irradiated by turns with the combination of the beam deflection and the stage motion. Simultaneously a wafer stage is controlled and scanned synchronously in the opposite direction of the reticle stage and patterns on the reticle are projected onto a wafer one after another. Minor struts are not projected onto a wafer by deflecting a beam to stitch adjacent sub-fields. A 5mm x 25mm area can be exposed on wafer by one stage scanning motion and from a <200mm reticle a 20mm x 25mm area can be exposed on wafer by a scan and stitch stage motion.

2.4 Error Correction Strategy
The projection optics has dynamic correctors for linear components of aberrations such as rotation, orthogonality, magnification, anisotropic magnification, x,y-translation, focus and astigmatism. These errors can be compensated with sub-field by sub-field basis.[13] The following factors are feedback to the correction control: those are errors of reticle and wafer stages, aberrations of electron optics at any sub-field
position within a main deflection field, space charge effect such as Coulomb refocus which is dependent on a pattern density of sub-field, reticle global deformation, mix-and-match with another exposure tool and programmable offsets (Fig. 6). The correction values related to space charge effect are calculated by plug-in software provided by Nikon in data post-processing software as mentioned later.[14].

\[ \text{Fig.6; Dynamic correction of focus, astigmatism, sub-field distortion and translation.} \]

2.5 Status of Electron optical column

Figure 7 shows the electron optical column which has been jointly developed by IBM and Nikon for EB Stepper.[15] Now all adjustments on Test Stand are completed and it is being integrated to EB Stepper's body.

\[ \text{Fig.7; Electron Optical Column for EB Stepper (on Test Stand).} \]

Resist image exposed by this column is shown in Fig. 8. 70nm nested line and isolated line are resolved. Cross-sectional photographs of resist images of 100-70nm contacts exposed by this column are shown in Fig. 9. At least DOF of several microns for 70nm contacts is obtained.

![Resist Image](image.png)

Because a different sub-field position has different linear components of aberration, it is required that sub-field distortion and resolution are simultaneously adjusted to the best performance at any position. Actual data of sub-field distortions near the center of the main deflection field and at the maximum deflection positions are shown in
Fig. 10. 20nm (3σ) is the worst case and there are residual distortions of slight trapezoidal shape. Those can be corrected by adjusting lens parameters more carefully after integrated to EB Stepper’s body because there is the limitation of the adjustment accuracy on Test Stand.

![Graph showing the distortion within the main deflection field and sub-field distortion data.](image)

The distortion within the main deflection field is composed from sub-field distortion and sub-field positioning accuracy. The current adjustment status of it is about 30nm (3σ). Future improvement is expected after improvement of sub-field distortions.

2.6 Vacuum compatible stage

EB Stepper can compensate position errors of reticle and wafer stages with higher response by correction lenses such as deflectors in the projection lens between a reticle and a wafer. However the constancy of velocity during stage scanning is required in order to make position errors as small as possible, therefore a linear motor with magnetic shields as an actuator and an air guide with differential pumping are adopted.[16] The scanning velocity of 200mm/s and the average acceleration of 2m/s² are achieved. Figure 11 shows pressure variation data of the prototype vacuum chamber during reticle stage scanning.

![Graph showing vacuum pressure during reticle stage scanning with turning on air guide.](image)

There is not a significant vacuum pressure degradation. The increase of vacuum pressure is within its tolerance in spite that the vacuum pressure value itself is relatively high because of imperfectness of the prototype vacuum chamber.

3. Status of infrastructure

3.1 Reticle for EB Stepper

Right now mask suppliers can supply only φ100mm silicon stencil reticle for EB Stepper, but it is expected that they will be able to supply φ200mm reticles in the latter half of 2002.

Research works for continuous membrane types are also being done in parallel.

3.2 Technologies related to EPL reticle

The proof-of-concept works for repair[17,18], cleaning[18,19] and inspection[12],[19] of a silicon stencil reticle have already been completed. Developments of tools for mass production are expected.

3.3 Data post processing software

The various functions are necessary for post processing from device design data to the writing data for a reticle of EB Stepper.[14] Those are sub-field division, complementary division, fuzzy boundary in order to make a division of a critical pattern at a sub-field boundary as less as possible, pattern edge deformation for divided patterns, pattern shape correction for proximity effect caused by backscattered electrons from a silicon wafer, etc. The output data of simulated imaging property dependent on patterns of each sub-field (space charge effect) is also required for the correction control of EB Stepper at exposure. Recently plural software suppliers announced their developments of such data post processing software for reticles of EB Stepper.[20] Figure 12 shows the function of such data conversion system. Fuzzy boundary and pattern edge

![Diagram showing the data conversion system for EB Stepper.](image)
deformation for divided patterns are countermeasures for stitching error in order to keep CD irregularity as small as possible.[5,6],[21] In the case of 100keV electron beam, proximity effect caused by backscattered electrons from silicon wafer are a dominant error factor and the forward scattering in resist is negligible. The backscattered radius is approximately 50µm, but its feature is continuous and gradual. Reticle pattern shape correction is adopted as a countermeasure.[5,6],[22] Plug-in software for SCE (space charge effect) calculation is provided from Nikon to each software supplier as mentioned in Section 2.4.

3.4 Resist
Resist has been developed for conventional electron beam direct write tools for a long time. Resist for 50kV electron beam can be used for EPL even though it is not optimized to 100kV.

Table 1 shows a part of requirements from ITRS Roadmap 2001.[23] Shrinking technology node, acceptable resist thickness becomes thinner. Regarding resist sensitivity, 5µC/cm² is Nikon’s minimum requirement for achieving specification of throughput.

Table 1: Required Resist Performance for EPL.

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement in ITRS Roadmap 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of production</td>
<td>2007</td>
</tr>
<tr>
<td>Technology node (DRAM 1/2 pitch)</td>
<td>65nm</td>
</tr>
<tr>
<td>MPU Gate length in resist</td>
<td>35nm</td>
</tr>
<tr>
<td>Contact size in resist</td>
<td>75nm</td>
</tr>
<tr>
<td>Resist thickness</td>
<td>140–220nm</td>
</tr>
<tr>
<td>Resist sensitivity @ 100kV</td>
<td>2–10µC/cm²</td>
</tr>
<tr>
<td>Line edge roughness (single side)</td>
<td>3nm (3σ)</td>
</tr>
</tbody>
</table>

Current resist performance for nested lines and contact holes are shown in Fig.13. Those data include the sample from the resist optimized to 100kV EPL. Both positive and negative types reach the requirements for 65nm technology node, but the improvement of sensitivity is required for negative type. For 45nm technology node, further improvements are required for both types. Regarding line edge roughness, sufficient study has not been yet. Required value is very small and it is not easy to distinguish resist and process factors from the actual data. In addition small outgas is also important requirement for EPL.

4. Discussion
4.1 Review of fundamental reaction
The ratio (β) of the velocity (v) of electron of energy (E) against light velocity (c) in vacuum is given by,

\[
\beta = \frac{v}{c} = \left(1 - \frac{1}{1 + E/m_e c^2}\right)^{1/2},
\]

here \(m_e\) is the rest mass of electron (512keV).
For the energy of 100keV, $\beta$ becomes 0.55. Then the kinetic energy ($T$) is given by,

$$T = m_i(\beta c)^2/2.$$  \hspace{1cm} (3)

For 100keV, $T$ becomes 77keV. As known well, ionization loss of electron ($-dE/dx$) is given by Bethe’s formula as follows:[24]

$$-dE/dx = (1/4 \pi \varepsilon_0)^{3/2} (\varepsilon e^4 N_e/T) \left[ \ln \left( TE/(1-\beta^2) \right) - \ln 2 \right.$$ \hspace{1cm}(4)

$$\left. \left( 1-\beta^2 \right)^{1/2} + \beta^2 \right]$$

here, $1/4 \pi \varepsilon_0 = 9.0E9$ (Nm$^2$/C$^2$) and $e=1.6E-19$(C). $I$ and $N_e$ represents ionization potential and the electron density, respectively. In order to make the estimation simple, it is assumed that resist is mainly made of carbon and its density is 1.5g/cm$^3$. Thus the electron density becomes $4.5E29(1/m^3)$. Ionization potential of carbon from neutral atom to first ion is approximately 10eV (Ionization potential of other kinds of atom such as hydrogen, oxygen, silicon, etc. is also from 8 to 15eV).[25] Substituting values to each parameters, $-dE/dx$ becomes 7.1E2(eV/µm). For the resist thickness of 200nm, 100keV electron loses only 140eV energy in the resist and injects a silicon wafer. Bethe’s formula given by Equ.(4) means energy loss of electron is continuous, but actual energy loss is discrete at every ionization. Lost energy of 140eV results in the generation of approximately fourteen secondary electrons along the trajectory of the incident electron.

By the way from Equ.(4), it is expected that $-dE/dx$ is approximately proportional to $1/T$ in other words $1/E$. This fact is useful when resist is exposed by electron beam of the different energy.

4.2 Shot noise influence on future finer contacts

Recently a concern about shot noise has been discussed for future finer contacts in photon lithography.[26] It is remarkable that in the case of photon lithography the absorption of the incident photon relates to resist image formation. Therefore the fluctuation of Poisson distribution (standard deviation of the event number is given by square root of event number) of the number of photons into the cell area directly influences on the dosage stability. On the other hand in the case of electron beam lithography, generation of secondary electron occurs statistically. Using the estimated number of secondary electron of fourteen, three or four secondary electrons is its fluctuation of Poisson distribution. At each secondary electron generation, statistics plays independently. As a result, the number of incident electron onto the cell area on resist does not directly influence on the dosage stability. Models including statistics, process and development have been proposed.[27,28] Further investigation is necessary to make clear the real limitation of resist sensitivity for future finer contacts. Table 2 shows the number of incident electrons for finer cells and different resist sensitivity. Even though the number of incident electrons into a finer cell is not large, the resist sensitivity of several µC/cm$^2$ is feasible to future finer contacts because each incident electron generates 10-20 secondary electrons along its trajectory. The distribution of secondary electron in resist is essential for the resist image formation. Further study and experiment are expected.

Table 2: Number of incident electrons into finer cells.

<table>
<thead>
<tr>
<th>Technology Node*</th>
<th>65nm</th>
<th>45nm</th>
<th>32nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of Production*</td>
<td>2007</td>
<td>2010</td>
<td>2013</td>
</tr>
<tr>
<td>Cell Size*</td>
<td>75nm</td>
<td>50nm</td>
<td>37nm</td>
</tr>
<tr>
<td>10µC/cm$^2$</td>
<td>3516</td>
<td>1563</td>
<td>856</td>
</tr>
<tr>
<td>5µC/cm$^2$</td>
<td>1758</td>
<td>781</td>
<td>428</td>
</tr>
<tr>
<td>2µC/cm$^2$</td>
<td>703</td>
<td>313</td>
<td>171</td>
</tr>
<tr>
<td>1µC/cm$^2$</td>
<td>352</td>
<td>156</td>
<td>86</td>
</tr>
</tbody>
</table>

* ITRS Roadmap 2001

5. Summary

EPL is looked forward to for the exposure of contact hole and gate layers at first. Nikon is developing an EPL exposure tool named as EB Stepper. At present the electron optical column and vacuum compatible stages are completed and those are being integrated to the main body of R&D tool. The basic performance will be evaluated by the end of 2002 and will be completed by the middle of 2003. In parallel EPL production tool will be developed and completed by the end of 2004.

The φ200mm silicon stencil reticle for EB Stepper has been developed by mask suppliers and will become available in 2002. Data post processing softwares for reticles of EB Stepper have already been available from software suppliers. Current resist performance reaches the requirement for 65nm technology node and further improvement is required for future node.
Fundamental reaction of 100keV electron with resist material is reviewed. Only 140eV energy is lost in resist of 200nm thickness and is used for secondary electron generations. The number of incident electrons to a finer cell is not large, but each incident electron generates 10-20 secondary electrons along its trajectory. The distribution of secondary electron in resist is essential for the resist image formation.

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References