Optimization of e-beam landing energy for EBDW

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ABSTRACT

As critical dimensions in Logic chips continue to shrink, EBDW (E-Beam Direct Write) will play a growing role. EBDW is capable of patterning 2D shapes at extremely high resolution. EBDW will pattern low-density critical wafer-layers, complementing optical lithography in high volume manufacturing.

E-beam landing energies ranging from 5 keV to 100 keV are used in EBDW today. The choice of e-beam energy effects resolution, throughput and overlay errors due to thermal effects.

We present an analysis of the tradeoffs of various e-beam landing energies. We examine 5 keV, 7.5 keV, 10 keV, 20 keV and 50 keV. We use a simple column design and SIMION 8 simulation software. SIMION 8 (from Scientific Instrument Services, Inc.) is used for electrostatic lens analysis and charged particle trajectory modeling

We examine:

1. Resolution (beam dose profile in resist)
2. Overlay errors due to thermal effects (beam power)

Low energy EBDW has advantages in resist sensitivity and thermal control. Its disadvantages include lower beam current and a requirement for very thin resist.

High energy EBDW has advantages in beam current and resolution. Its disadvantages include wafer heating and low resist sensitivity.

With set requirements for resolution and thermal expansion, we report findings of beam profile and beam dose at various beam energies.

Keywords: E-Beam, Lithography, Maskless, EBDW, ML2, EBL, NGL, Resolution

1. INTRODUCTION

EBDW, also known as Electron Beam Lithography (EBL) has been used in the production of ICs since the l970s. However, today's EBDW systems are too slow for high volume manufacturing (HVM) in wafer fabs. Recently, a new generation of EBDW equipment has been proposed with much higher throughput for high volume manufacturing at the 20nm half pitch and beyond.

Like any other lithography, the largest challenges in EBDW are throughput, resolution, overlay accuracy, defect density, and cost of ownership. In this paper, we discuss beam energy optimization for EBDW and impact on resolution, and throughput to meet requirements for the 22 nm, 16 nm and 11 nm technology nodes.

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2. RESOLUTION OF E-BEAM LITHOGRAPHY

The resolution of state-of-the-art Scanning Electron Microscopes is a few nano-meters. However, the high throughput desired for e-beam lithography means that a high current is required. This high current limits the beam spot size to a minimum of 5 to 10 nm. We examine multiple factors and tradeoffs to select the best beam energy in a column design for EBDW in HVM.

First, we discuss the beam spot size of any electron beam tool, which is estimated from the following equation:

$$Final\ beam\ spot\ size = \sqrt{(DL)^2+(IS)^2+(SA)^2+(CA)^2+(OA)^2+(EE)^2} \quad \text{(Equation \#1)}$$

DL = Diffraction limit
IS = Image size of virtual source
SA = Spherical aberration
CA = Chromatic aberration
OA = Other higher order aberrations
EE = Beam broadening due to electron-electron repulsion

2.1 Diffraction limit

In e-beam lithography, the energy of the electron beam is in the range of 1 keV to 50 keV, where the electron wavelength is in the range of 5 to 50 pico-meters. The half angle of a typical electron beam column design is in the range of 1 to 10 mR (mili-Radian), which means that the diffraction limit of the electron beam column design in the worst case is approximately 2.4 nm (assuming 1 keV beam energy and 10 mR half angle). This diffraction limited resolution value is small compared with other components in equation 1.

2.2 Image size of virtual source

For the purposes of e-beam lithography, the best electron source is a Schottky Field Emitter, which has long life, stable beam current, and a “virtual source size” in the range of 20 nm in diameter. We can assume the virtual source follows a Gaussian distribution and 95% of the beam is within the 20 nm diameter of the virtual source. This means that the sigma value of the source intensity profile is about 5 nm. Depending on the column design, the ratio of the image to the source size can be reduced to 1/2 or smaller. For the purposes of this paper, we assume an all-electrostatic lens with a ratio of the source image size to the virtual source of 2:3. Given this 2:3 condition, the contribution of the image size of the virtual source to the beam spot on wafer is about 7.8 nm (FWHM)[i]. Therefore, the image of the virtual source is a major factor in determining the minimum resolution (minimum patterned feature size) of an e-beam lithography system.

2.3 Spherical and chromatic aberrations

Spherical and chromatic aberrations are simulated using software packages, such as SIMION[ii]. An example of a SIMION simulation result is shown in Figure 1. In this example, we use a point source to emphasize the effect of spherical and chromatic aberrations. The simulation shows that spherical and chromatic aberrations contribute approximately 3-10 nm to the beam spot size, depending on the column design, and beam energy.

We simulate chromatic aberration by varying e-beam energy +/- 0.6 eV in a Gaussian distribution, typical for a Schottky Field Emitter. Chromatic aberration is not critical at beam energies above 10 keV, but it becomes a key factor at beam energies of 5 keV or below.

Both spherical and chromatic aberrations are functions of the half angle of the column design. This means that we can reduce these aberrations by using smaller apertures in the column. However, reducing the half angle will also limit the beam current, reducing potential throughput.

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[i] FWHM (Full Width Half Maximum of beam profile) is $= 2*\sigma*\sqrt{2*ln(2)} = 2.35*\sigma$

[ii] SIMION was developed by David A. Dahl, at Idaho National Laboratory. SIMION can be obtained from Scientific Instrument Services, Inc.

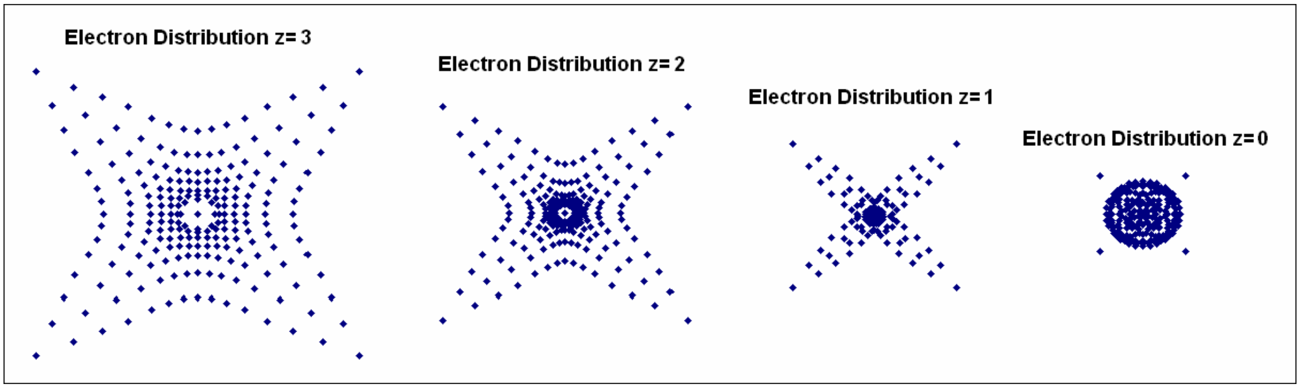

Figure 1. SIMION simulations showing the effects of spherical and chromatic aberrations.

2.4 Beam broadening due to electron-electron repulsion

Here, we discuss beam broadening ("beam blur") due to electron-electron repulsion in a high current electron beam column. When beam current is high and beam energy is low, this has a major impact on resolution.

To achieve high throughput in e-beam lithography, we use high beam current to reduce exposure time. E-beam current of greater than 1 µA (or > 10 nA per column in a multi-column system with 100 columns) is required to achieve 5 wph throughput for low-density critical wafer-layers. Unless otherwise specified, we assume beam current is 20 nA per column throughout this paper.

Crewe[1] suggested that the beam spot increase due to electron-electron repulsion is approximated by the following equation:

$$\Delta r = \frac{\alpha * L * I}{(half\,angle)*(KE)^{1.5}} \qquad \text{(Equation \#2)}$$

Δr = beam broadening, (Full Width at Half Maximum) of the beam profile
$\alpha = 1.072*10^{13}$
L = Length of the e-beam column (we assume L = 100 mm)
I = Beam current
half angle = half angle of the e-beam optics system
KE = Beam energy

Beam current is related to the half angle in the column design (equation #3, below):

$$I = \frac{Source\,Brightness}{Solid\,Angle} * \pi * (half\ angle)^2 \qquad \text{(Equation \#3)}$$

I = Beam current
(Source Brightness)/(Solid Angle) = $2*10^5$ nA/Sr (iii)(2)
half angle = half angle of the e-beam optics system

Figure 2 depicts beam broadening (beam spread) versus beam current at various beam energies. At lower beam energies, beam broadening due to e-e repulsion is greater. Thus, at 5 keV beam energy and 20 nA beam current, beam broadening due to e-e repulsion is greater than 11 nm. If the beam energy is increased, beam broadening due to e-e repulsion is reduced. For example, increasing the beam energy to 10 keV reduces beam broadening to ~ 4 nm.

[iii] Sr (Steradian) is the SI unit of solid angle

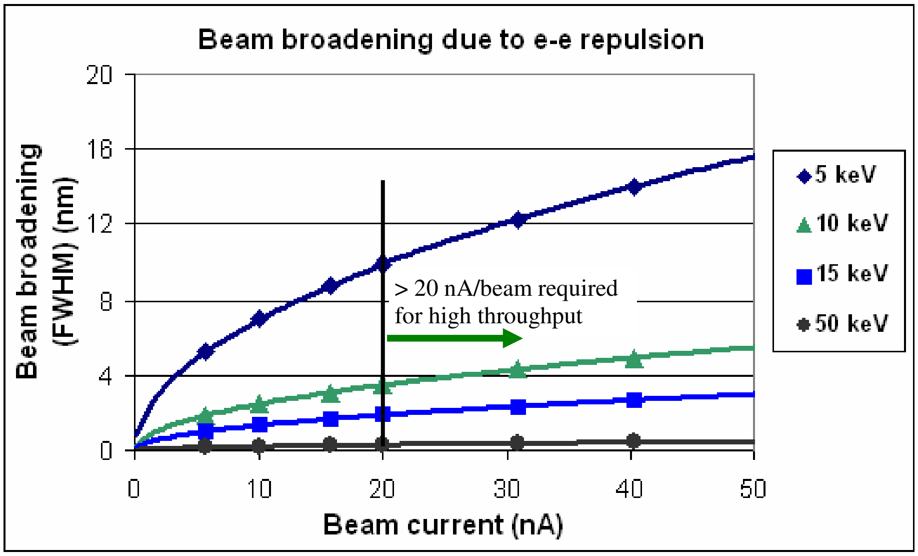

Figure 2. Beam broadening due to electron-electron repulsion. Assume 100 mm column length.

2.5 Beam Profile Broadening due to electron-resist interactions

In this section, we discuss the beam dose profile broadening effect of electron resist interactions.

The energy deposited in the resist layer is estimated from the incoming beam spot size combined with the beam dose profile broadening due to electron-resist interactions. A simple model uses an assumption of Gaussian distribution for both the incoming e-beam and the forward scattering distribution.

Electron-resist interactions are sometimes modeled as two Gaussian functions, one for forward scattering, and the other for back-scattering. Backscattered electrons create a broad background dose contributing to the proximity effect (with a range of ~1 µm), but backscattered electrons have almost no effect on resolution[3].

We start by considering the forward scattering of a "point source" of incoming electrons. In literature, this has been described as a "point spread function" (PSF), a Gaussian curve with a forward scattering range $\sigma_f = \sigma * \sqrt{2}$. Recently, Dr. Cord wrote, *"calculations show that, past a certain point, improved contrast will not result in improved resolution, and that the minimum achievable feature size will ultimately be limited by the point-spread function (PSF) of the exposing radiation, rather than the contrast of the development process."*[4]

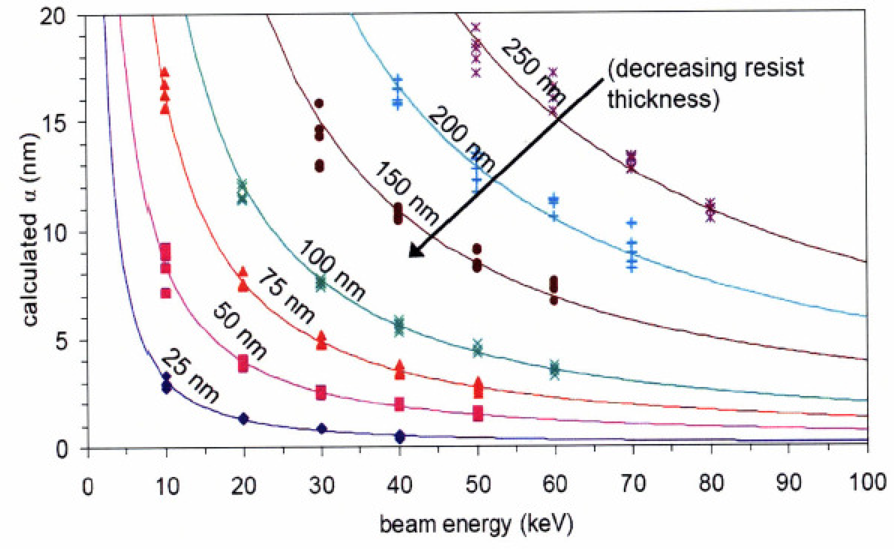

Figure 3. Figure 3 is copied from Cord[5] "Forward scattering coefficients (α is the standard deviation of the final beam distribution) as a function of beam energy for various thicknesses of PMMA, calculated using CASINO, a free Monte Carlo modeling program. For simplicity, the initial beam profile was assumed to be a delta function (zero width) in this simulation. The scattering width decreases dramatically as the beam energy is increased, but using thicker resist results in more scattering." [6]

From Cord's work, it becomes clear that a very thin resist will enhance the resolution of e-beam lithography. In Figure 3, we see substantial beam spread at 5 keV energy, even with very thin resist.

Sidorkin confirmed the effect of resist thickness on e-beam resolution, and demonstrated that "thickness of resist layer was found to have a substantial influence on sensitivity, contrast and surface morphology of HSQ resist"[7].

A recent paper published by MAPPER in the Journal of Vacuum Science and Technology used similar Monte Carlo models and concluded "Resist processes do not have any new limitation on resolution at 5 kV for thin resist layers (sub-50-nm). For thicker resist films, forward scattering has to be evaluated. We carried out simulations with CASINO[iv] software to evaluate forward scattering … A 50 nm thickness leads to no forward scattering at 5 keV."[8]

After reviewing the literature, we performed Monte Carlo simulations (e.g. Figures 4 and 5). Our analysis is focused on low-density patterns only, such as those seen in Complementary E-Beam Lithography (CEBL)[9]. For dense patterns, we would need to consider the migration of low energy secondary electrons, diffusion within the resist, and resist-developer interactions.

[iv] CASINO was programmed by the research team of Raynald Gauvin (Ph.D., Full professor at Université de Sherbrooke, Québec, Canada). It was initially programmed by Pierre Hovongton, Ph.D. and Dominique Drouin, Ph.D. in 1996 and it was updated by Paula Horny, M.Sc.A. student and by Hendrix Demers, undergraduate student in 1999. All programming was performed under the supervision of Professor Raynald Gauvin.

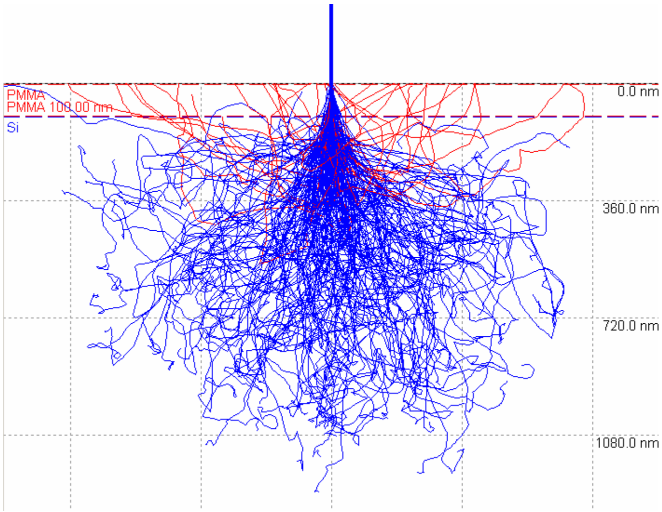

Figure 4. Monte Carlo simulation of beam with 10 keV energy in 100nm PMMA on Silicon.

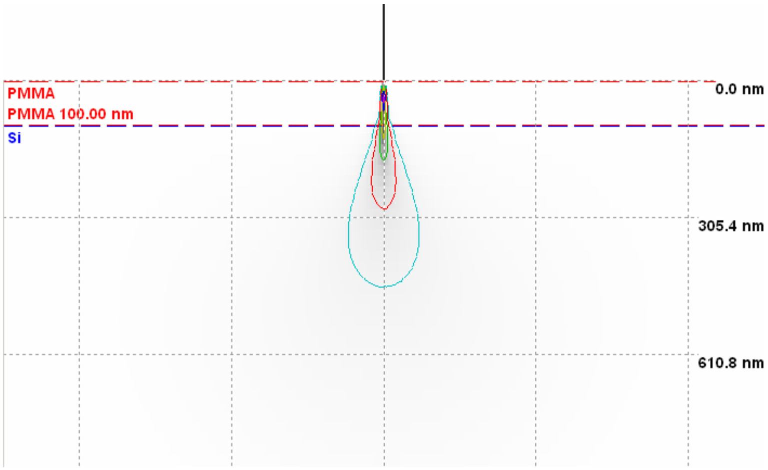

Figure 5. Monte Carlo simulation of beam with 10 keV energy in 100nm PMMA on Silicon.

After multiple Monte Carlo simulations, we are able to reach a few broad conclusions:

a) With 5 keV e-beams patterning 100 nm thick HSQ, minimum point source spread is > 20 nm.

b) With 5 keV e-beams patterning 50 nm thick HSQ, minimum point source spread is > 10 nm.

c) With >10 keV e-beams patterning 50 nm thick HSQ, minimum point source spread is < 10 nm.

Thin resists are required to achieve the best resolution in e-beam lithography, especially at low beam energy. This is true at any beam current.

Unfortunately, it is not possible to use an arbitrarily thin resist. There are three factors to take into consideration: resist defect density, resist thickness uniformity, and the need for a conductive coating to minimize charging. These factors limit our ability to use thinner resists.

Resist thickness of 5 nm has been demonstrated in R&D on flat substrates[10]. If the wafer has step height (topography) variations in the range of 25 nm, a resist thickness of 50 nm or greater may be recommended.

3. COMBINED BEAM PROFILE AND RESOLUTION

With e-beam lithography, the resolution (minimum patterned feature size) is determined by two key factors: a) the size of the incoming electron beam, b) the forward scattering caused by electron-resist interactions. We assume that the patterned feature size is roughly the same as the beam dose profile in resist (FWHM), approximated in equation #4:

$$BR = \sqrt{(Final\ beam\ spot\ size)^2 + (Beam\ dose\ profile\ broadening\ in\ resist)^2} \qquad \text{(Equation \#4)}$$

BR = Beam dose profile in resist (FWHM), an approximation for resolution

We assume 20 nA beam current, 50 nm resist thickness, 100 mm column height, 5.6 mR half angle, and 9 nm beam spot size (FWHM) excluding e-e interactions.

Table 1. Resolution is approximated by the beam dose profile in resist (FWHM). Beam size, electron-electron repulsion and beam broadening in resist all contribute to minimum resolution. In this example, we assume column length of 100 mm, beam size (FWHM) of 9 nm, current of 20 nA and resist thickness of 50 nm. The resolution is approximated by the beam profile in resist (FWHM).

Beam Energy (keV)	Beam size (FWHM) (nm)	Broadening from e-e repulsion (FWHM) (nm)	Beam Broadening in Resist (FWHM) (nm)	Beam Dose Profile in Resist (FWHM) (nm)
5	9	9.9	10.4	**16.9**
7.5	9	5.4	7.6	**12.9**
10	9	3.5	6.2	**11.5**
15	9	1.9	4.5	**10.2**
20	9	1.2	3.3	**9.7**
50	9	0.3	1.8	**9.2**

From Table 1 we expect that the minimum patterned feature size (resolution) is approximately 17 nm at 5 keV, 12 nm at 10 keV, and 10 nm at 15 keV (assuming 20 nA per column, 100 mm column length and 50 nm resist thickness). We could improve the resolution by reducing beam current, but only by sacrificing throughput.

High-energy beams have multiple benefits in resolution. High energy beams have less energy spread (less chromatic aberration), travel faster (less e-e repulsion), and result in less broadening of the beam dose profile due to resist interactions. From Table 1, we see that beam energy above 10 keV is necessary to achieve high resolution (e.g. <12 nm).

4. OVERLAY ERROR DUE TO THERMAL EFFECT OF E-BEAM ENERGY

Resolution is only one of the factors we consider when determining the best beam energy for e-beam lithography in HVM. Another major concern is thermal expansion, resulting from the high beam current required for high throughput.

We make several assumptions in a first estimate of wafer thermal expansion due to e-beam energy. We assume that 80% of the energy from incoming electrons is converted to thermal energy within the Silicon wafer (the remaining 20% is converted to chemical energy in the resist, or drained off in outgoing electrons). We also assume that most of the thermal energy transfers out of the wafer (into the wafer stage) over the course of patterning (99% heat transfer over 5 minutes).

The temperature change of the Si wafer is calculated with the following equation:

$$\Delta T = \frac{(BE)*(Dose)*(HE)*(1-(HT))}{WHC}$$ (Equation #5)

ΔT = Change in temperature of wafer
BE = Beam energy
Dose = Total dose
HE = Percent beam energy converted to heat energy (assume 80%)
HT = Heat transfer our of wafer (assume 99% over five minutes)
WHC = Heat capacity of 300 mm silicon wafer

Table 2 shows thermal expansion of a 300 mm wafer, based on beam dose, pattern density, and heat transfer efficiency. Please note that beam dose, which is dependent on resist sensitivity, is a function of beam energy. Here, we use beam dose of 30 µC/cm^2 at 5 keV, and 60 µC/cm^2 at 10 keV.

Table 2. Thermal expansion of 300mm wafer due to incoming e-beam energy, calculated with Equation #5.

Beam energy (keV)	**5**	**7.5**	**10**	**15**	**20**
Beam dose (C/cm^2)	3.0E-05	4.5E-05	6.0E-05	9.0E-05	1.2E-04
Wafer area (cm^2)	688	688	688	688	688
Pattern density	5%	5%	5%	5%	5%
Total e-beam energy (J)	5.2	11.6	20.6	46.4	82.6
Thermal energy, *assuming 80% of beam energy is converted to heat* (J)	4.1	9.3	16.5	37.2	66.1
Thermal energy remaining in wafer, *assuming 99% heat transfer* (J)	0.041	0.093	0.16	0.37	0.66
300mm wafer heat capacity (J/ºC/wafer)	37.4	37.4	37.4	37.4	37.4
Delta Temperature (ºC)	0.001	0.002	0.004	0.010	0.018
Thermal expansion over 300mm (nm)	**0.9**	**1.9**	**3.4**	**7.8**	**13.8**

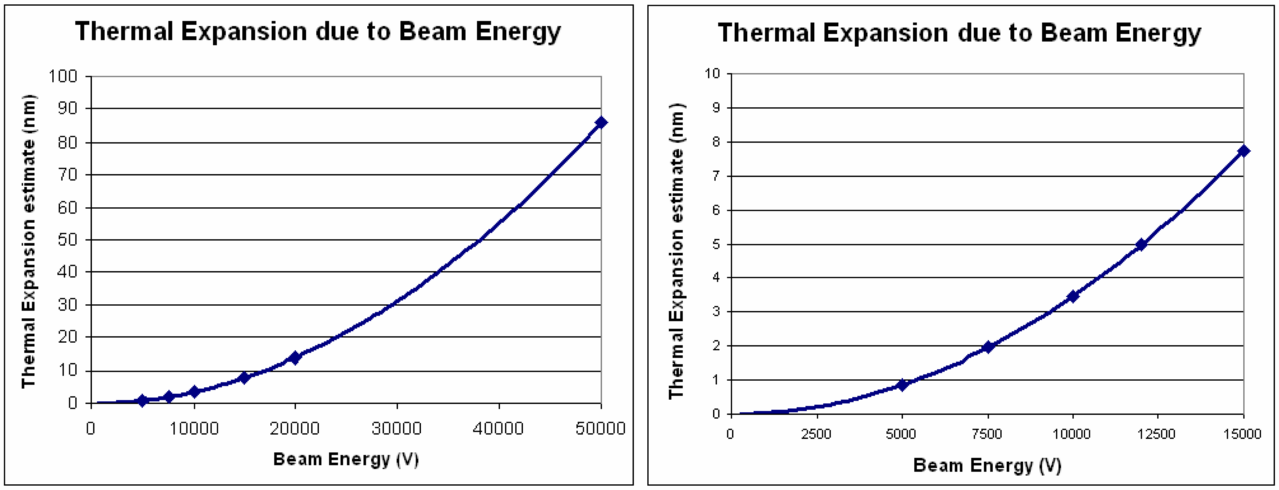

Figure 6. Thermal expansion of 300mm wafer due to e-beam energy, calculated with Equation #5.

Table 2 and Figure 6 show we can limit thermal expansion (and overlay error) by using lower beam energy. For the purposes of this paper, we set a limit for thermal expansion to 5 nm. With Equation #5, we calculate that maximum beam energy of 12 keV meets the goal of no more than 5 nm wafer expansion during patterning. If beam energy is > 12 keV, wafer expansion will necessitate frequent re-registration during wafer patterning.

5. CONCLUSIONS

What is the optimal beam energy for e-beam lithography in HVM? The answer depends on resolution requirements. To achieve the highest resolution while maintaining high beam current, beam energy above 10 keV is required. At the same time, beam energy below 15 keV improves overlay accuracy by reducing thermal expansion.

Advantages of high beam energy (above 10 keV):

1. Higher resolution with high beam currents
2. Less beam position drift due to external electro-magnetic fields or charging effects

Advantages of low beam energy (below 15 keV):

1. Less beam dose (better resist sensitivity) allows higher throughput
2. Less thermal expansion

Table 3 summarizes our estimate of thermal effects and resolution capability at various beam energies.

Table 3. Summary of thermal expansion and resolution capability at various beam energies, based on the assumptions detailed in this paper. We assume a beam spot size, excluding e-e repulsion of 9 nm. Green means "no technical issues", yellow means "potential difficulty" and red means "highly challenging, or no known solution".

Beam Energy (keV)	Beam Current (nA)	Resist Thickness (nm)	Min. Beam Size in Resist (FWHM) (nm)	Thermal Expansion, estimate (nm)	Min. Feature Size		
					22 nm	16 nm	11 nm
5	20	25	14.5	0.9	🟩	🟨	🟥
		50	16.9	0.9	🟩	🟥	🟥
7.5	20	25	11.2	1.9	🟩	🟩	🟥
		50	12.9	1.9	🟩	🟩	🟥
10	20	25	10.2	3.4	🟩	🟩	🟨
		50	11.5	3.4	🟩	🟩	🟥
15	20	25	9.5	7.8	🟩	🟩	🟩
		50	10.2	7.8	🟩	🟩	🟨
20	20	25	9.3	13.8	🟩	🟩	🟩
		50	9.7	13.8	🟩	🟩	🟩

5.1 Summary of overlay accuracy due to thermal effects of high energy beams

For thermal budget calculations, we assume 5% pattern density, 30 μC/cm^2 resist sensitivity at 5 keV, and 99% heat transfer efficiency. We set the thermal budget requirement at < 5 nm thermal expansion across a 300mm wafer. Beam energy at 12 keV or below is required to meet the thermal budget. At beam energies above 12 keV, wafer thermal expansion will necessitate frequent re-calibration of beam position.

5.2 Summary of resolution limitations due to low energy beams

To achieve high throughput in a multiple-column system (e.g. 100 columns), the beam current per column should be around 20 nA. At low beam energy, the effects of electron-electron repulsion become especially pronounced, causing beam broadening. Additionally, at low beam energy the forward scattering (Point Spread Function) of incoming electrons in the resist layer necessitates the use of very thin resist structures. From Table 4, we conclude that beam energy of > 10 keV is required for 11 nm resolution.

It should be emphasized that at low beam energy (e.g. 5 keV), the point spread function defines resolution in resist, making it impossible to pattern very small geometries, even if we assume a point source with minimal beam current.

5.3 First estimate of optimal beam energy

Based on the assumptions in this paper, maximum beam energy of 12 keV meets the thermal budget requirement. At 12 keV beam energy, 20 nA beam current and 50 nm resist thickness: a beam spot size of 9 nm is needed to achieve 11 nm patterned feature size. This is achievable with Multibeam's column design.

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