Electron beam and scanning probe lithography: A comparison

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(Received 29 May 1998; accepted 16 September 1998)

Electron beam lithography (EBL) and scanning probe lithography (SPL) are electron exposure techniques capable of high resolution patterning of organic resists. This article compares the exposure properties of these two systems. We consider the resist sensitivity to EBL and SPL electrons, exposure tolerances, patterning linearity, and proximity effects. It is possible to print sub-50 nm features using both systems, but SPL has a wider exposure latitude at these small feature sizes. SPL requires a significantly higher incident electron dose for exposure than does EBL. In EBL, lithography control is most limited by proximity effects which arise from backscattered electrons whose range is considerably larger than the forward scattering range in the resist film. As a result, the exposed feature dimension depends strongly on the local feature density and size, leading to unacceptable linewidth variations across a wafer. These limitations are alleviated in the case of SPL exposures. We demonstrate improved linearity and reduced proximity effects with SPL. We have patterned 200 nm pitch grids with SPL where all individual features are resolved. The linewidth of features in these grids is the same as the width of an isolated line at the same dose. Finally, we suggest that the SPL exposure mechanism may be different than that for EBL. © 1998 American Vacuum Society. [S0734-211X(98)15306-4]

I. INTRODUCTION

As integrated circuit critical dimensions (CDs) shrink, more demands will be placed on lithography process control. According to the 1997 Semiconductor Industry Association (SIA) Roadmap for Semiconductors, 1 180 nm linewidths (1999) will require ±14 nm CD control, 100 nm linewidths (2006) will require ±7 nm CD control, and 50 nm linewidths (2012) will require ±4 nm CD control. This trend presents a number of challenges. First is the ability to print narrower and narrower features. Second is the ability to control the narrow feature dimensions to within strict tolerances in arbitrary pattern geometries.

Electron beam lithography (EBL) is a well-established high resolution patterning technique in which high-energy (10–100 keV) electrons are focused into a narrow beam and used to expose electron-sensitive resists. EBL linewidth control is hampered by proximity effects that cause the printed feature size to depend on the local pattern density.

An alternative electron exposure process known as scanning probe lithography (SPL) patterns resist with electrons emitted from a sharp probe tip in close proximity to a sample. These low-energy electrons may eliminate proximity effects and may provide other advantages over high-energy exposure. We have recently developed a mode of SPL that can reliably pattern uniform features with dimensions below 100 nm. The improved repeatability of this technique allows us to make reasonable comparisons between low-energy SPL and traditional high-energy EBL exposures.

II. EXPERIMENT

Organic polymer resists on silicon substrates were exposed with 30 keV electrons using the Hitachi HL-700F EBL machine. Identically prepared samples were also exposed with low-energy electrons emitted from a scanning probe. SPL was performed in air using the Park Scientific Instruments (PSI) Autoprobe M5 atomic force microscope (AFM) operating with the micromachined probe tip in contact with the resist surface. Tips used were oxidation sharpened doped silicon probes coated with 20 nm evaporated titanium. The tip–sample force was held constant at 10 nN. A voltage bias between the tip and sample generates the field emission of electrons from the tip. The emission current was monitored and held fixed during lithography by varying the tip–sample bias using custom circuitry. Since this system is composed of the key elements of the AFM and the scanning tunneling microscope (STM), it is referred to as the hybrid AFM/STM mode of SPL. 2

Starting samples were phosphorus-doped (100) silicon wafers. Prior to resist coating, the native oxide was removed in dilute hydrofluoric acid and the wafers were singed in a convection oven at 150 °C for 30 min. Resist used for SPL must be thin to allow reasonably small tip–sample voltages (<100 V) and to achieve high resolution. EBL also requires thin resists for ultrahigh resolution patterning, although standard EBL generally employs resists that are ≈400 nm thick. The resists were coated to a thickness of 50–70 nm using standard spin-coating techniques, which yielded pinhole-free, uniform coatings. Two organic resists were used: the positive resist polymethylmethacrylate (PMMA) and the negative resist Microposit SAL601 from Shipley Company. A solution of 1.25% PMMA by weight in chlorobenzene

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(C₆H₅Cl) was spun to a thickness of 50 nm, as measured by the NanoSpec optical film thickness measurement system. The wafers were baked for 2 h at 170 °C in a convection oven. After electron exposure, the PMMA was developed for 60 s in a solution primarily composed of methanol, methyl iso-butyl ketone (MIBK), 2-ethoxyethanol, and iso-propanol. (Other components are ethyl alcohol and methyl ethyl ketone.) This developer is designed to enhance the resist contrast and to provide appropriate resist sidewall profiles for lift-off. After development the samples were rinsed in isopropanol.

SAL601 is a novolac-based chemically amplified resist that has been known to exhibit good resolution and high contrast. Prior to SAL601 coating, the silicon wafers were vapor primed with hexamethyldisilazane (HMDS) adhesion promoter. SAL601 diluted in Microposit thinner type A was spin coated on the wafers to a thickness of 65 nm. These wafers were then baked (1 min at 80 °C on a hotplate, followed by 30 min at 90 °C in a convection oven). Because of this resist’s sensitivity to contamination, wafers were prepared with SAL601 just prior to EBL or SPL exposure. Immediately following exposure, the wafers were given the postexposure bake (PEB) for 1 min at 115 °C on a hotplate, developed in MF-322 for 10 min, and rinsed in de-ionized water.

Patterns consisting of lines of various widths and spacings were written over a wide range of exposure doses with both SPL and EBL. The developed resist patterns were transferred into the silicon substrate through direct etching or lift-off. Direct etching was performed in a LAM Research Systems TCP9400 reactive ion etcher. Wafers were hard baked at 110 °C for 30 min prior to etching. A high density plasma etch with NF₃ chemistry. This etch is highly anisotropic and selective against chrome.

III. RESULTS

A. Resolution and transfer capabilities of SPL

The current feedback system of the hybrid AFM/STM ensures that a constant dose of electrons is delivered to the resist. Setpoint currents were typically 10 pA–1 nA. The typical voltage bias was 40–60 V (tip negative with respect to sample), depending on the resist thickness and the writing speed. Figure 1 shows a grating with lines on a 500 nm pitch patterned with SPL lithography at different exposure doses. Patterns were written in SAL601 and etched into the silicon substrate. (a) Exposure line dose of 40 nC/cm yields linewidth of 52 nm. (b) Exposure line dose of 200 nC/cm yields linewidth of 123 nm.

![Fig. 1. Line gratings on 500 nm pitch patterned with SPL at different exposure doses. Patterns were written in SAL601 and etched into the silicon substrate. (a) Exposure line dose of 40 nC/cm yields linewidth of 52 nm. (b) Exposure line dose of 200 nC/cm yields linewidth of 123 nm.](image)

The patterns were imaged using the PSI AFM and the Hitachi S-800 scanning electron microscope (SEM) operating at 25 keV. Linewidth measurements were made from top-down SEM micrographs of the etched silicon features taken at ≥200 K magnification.

![Fig. 2. SPL patterned linewidth dependence on exposure line dose for SAL601 and PMMA resists.](image)
SAL601 exists for both: (1) a constant emission current of 50 pA and a variation of writing speed from 1 to 50 μm/s, and (2) a constant writing speed of 10 μm/s and a variation of emission current from 10 to 500 pA. In both cases the exposure dose was varied from 10 to 500 nC/cm. PMMA requires a factor of 20 higher incident dose than SAL601, indicating that it is less sensitive to the low-energy electrons.

At the appropriate doses we have printed lines below 50 nm in width in both resists. We are able to achieve smaller lines over a wider dose range using PMMA. The high selectivity and anisotropy of the reactive ion etches described in Sec. II allow us to transfer the narrow resist patterns deep into the silicon substrate to create high aspect ratio features. Figure 3 shows cross-sectional images of narrow features patterned by SPL. A 50-nm-wide line written in SAL601 and etched 300 nm into the silicon is shown in Fig. 3(a). This line has an aspect ratio of 6:1 and a reasonable etched profile. Figure 3(b) shows a 26-nm-wide feature (measured at the top of the line) after PMMA exposure, lift-off, and a silicon etch of 260 nm. This feature has an aspect ratio of 10:1 and an excellent sidewall profile.

**B. Sensitivity and exposure latitude of EBL and SPL**

In order to compare the resist’s sensitivity to 30 keV EBL electrons and to SPL’s low-energy electrons, we exposed features in SAL601 at various line doses with both lithography systems. The linewidth versus dose data is shown in Fig. 4. Here all features are lines written with a single pass of the electron beam or scanning probe. The EBL emission current was held constant at ~4 nA while the pixel rate was varied to alter the exposure dose. In order to print a 40-nm-wide feature in SAL601, EBL requires a line dose of 0.7 nC/cm, while SPL requires a dose of 20 nC/cm, almost a factor of 30 higher. The reduced sensitivity of SPL is consistent with the results of Perkins et al. PMMA also requires a significantly larger dose to expose with SPL than with EBL. PMMA is less sensitive to both 30 keV and to low-energy electrons than is SAL601.

![Fig. 3. Cross-sectional SEM images of etched silicon features patterned by SPL.](image)

(a) 50-nm-wide line written in SAL601 and etched 300 nm into the silicon (6:1 aspect ratio). (b) 26-nm-wide line written in PMMA and transferred through lift-off and anisotropic etching into the silicon substrate. The etch depth is 260 nm, giving the line an aspect ratio of 10:1.

![Fig. 4. Patterned linewidth dependence on exposure dose for EBL and SPL single-pass exposures of SAL601 resist.](image)

We have patterned and transferred continuous sub-50 nm features in SAL601 using both EBL and SPL. However, a more practical definition of resolution is the minimum feature size that can be achieved with an acceptable process latitude. From the slope of the curves in Fig. 4 we find that SPL has a higher dose latitude than EBL. We define dose latitude as the percent change in linewidth for a percent change in exposure dose. For example, when the EBL dose is increased by a factor of 10 from 0.7 to 7 nC/cm, the linewidth changes by a factor of 4.7 from 40 to 187 nm. Yet when the SPL dose is increased by a factor of 10 from 20 to 200 nC/cm, the linewidth increases by only a factor of 2.6 (from 40 to 105 nm). The improved exposure latitude means that SPL is less sensitive to dose fluctuations.

**C. Energy density distribution in the resist**

We would like to use the linewidth data in Fig. 4 to gain insight into the distribution of absorbed energy density in the resist. This is useful for understanding the behavior of densely spaced lines for the two different exposure modes. The incident electrons in EBL or SPL transfer some energy to the resist which causes chemical changes in the polymer (either directly or subsequently through a PEB step). In a simple threshold approximation, we assume that there is some critical absorbed energy density in the resist above which the resist is “exposed” and below which it is “unexposed.” For a negative resist such as SAL601, the “unexposed” regions dissolve away in the developer while the “exposed” areas are insoluble. At any height in the resist there will be some lateral distribution of absorbed energy density due to the finite beam diameter and to scattering. For a given incident electron energy, the shape of this distribution will remain fixed but the magnitude will vary with incident dose.

The linewidth versus dose data shown in Fig. 4 can be used to generate a plot of the absorbed energy density at the resist–substrate interface as a function of lateral position per-
pendicular to the exposed line. Figure 5(a) illustrates how we create the curve. The solid lines are representative distributions of the energy density for a line exposure at four different incident doses. The energy threshold is such that the lowest dose shown has a maximum absorbed energy density at the threshold. A line exposed at this low dose would not print (linewidth $\leq 50$). At two times this dose (the second solid curve), the patterned linewidth will be the width of the intersection of the distribution with the threshold. This width corresponds to the width at the 50% point of the bottom energy distribution curve, as shown with the dotted lines. Thus in general the linewidth at a given dose corresponds to the width of the distribution at $1/dose$. We use the data in Fig. 4 to plot the lateral distribution of absorbed energy density for EBL and SPL, normalizing each distribution independently to the threshold dose.

The absorbed energy density for EBL is shown in Fig. 5(b). The circles correspond to data points of measured linewidths from Fig. 4. There is an apparent tail to the distribution that we attribute to backscattered electrons. For 30 keV electrons on silicon, the backscattered range is known to be about 4 $\mu$m. We fit a double Gaussian to the data assuming this backscattered range. The solid line represents this fit. The half width of the narrow Gaussian is 48 nm. This includes the contribution of the beam diameter and forward scattering in the resist. This EBL data is machine specific, dependent on the electron energy and beam diameter used in the experiment. Nevertheless, the clear evidence of long-range exposure that gives rise to proximity effects is characteristic of EBL.

The same procedure is performed with the SPL linewidth versus dose data and the resulting energy density plot is shown in Fig. 5(c). The SPL energy distribution can be approximated by a single Gaussian with a half width of 33 nm. This Gaussian fit is an approximation and may not be physical since the electric field in the resist would tend to pull the electrons in parabolic trajectories toward the substrate. This would likely limit the range of scattering angles. Neverthe-
less, it is significant that the SPL data can be fit with a single Gaussian and that there is no indication of a backscattered tail.

D. Patterning linearity using a pixel writing scheme

The lithography patterns described thus far were single-pass exposures by EBL and SPL. An alternative writing scheme uses pixels exposed at a low dose to create arbitrarily sized features. This scheme is generally used for EBL patterning today and is more attractive for patterning features of various geometries. We patterned SAL601 resist with EBL and SPL using pixels spaced by 40 nm.

Figure 6 shows images of SPL patterns written in SAL601 at a line dose of 20 nC/cm with a 40 nm pixel spacing. The linewidth increases linearly from 37 nm (for a single-pixel-wide line) to 239 nm (for a six-pixel-wide line). The linewidth as a function of incident line dose for lines of various pixel widths is shown in Fig. 7. For both EBL and SPL the dose is varied by about a factor of 5 from the minimum dose to pattern a single-pixel-wide line. The SPL data [Fig. 7(b)] show that the linewidth increases linearly with increases in pixel width. Also, the curves have a small slope, showing again the wide exposure latitude of SPL even in the pixel writing scheme. These results are quite different for EBL [Fig. 7(a)]. The slope of the curves is much higher in the case of EBL. In addition, the slope of the linewidth versus dose curve for the six-pixel-wide features is greater than that for the one-pixel-wide feature, showing that the linearity worsens as the dose is increased.

Figure 8 plots the same data in a different form to illustrate the issue of patterning linearity. Here the printed linewidth is shown versus the “target” width (or pixel width), where a single-pixel-wide feature has a target width of 40 nm, a two-pixel-wide feature has a target width of 80 nm, and so on. The EBL data are shown in Fig. 8(a). At the lowest dose (0.4 nC/cm), the linewidth increases approximately linearly with dose, except that the single pass line does not print. If the dose is increased to provide the necessary exposure for the single pass feature to print, then the multiple pass lines become considerably wider and linearity worsens. Clearly in EBL the smallest features require a higher dose to pattern at the desired linewidth than do the larger features. This effect, known as the “intraproximity” effect in the case of EBL, is not apparent in SPL. Figure 8(b) shows the superior linearity achieved with SPL. For the large range of doses shown, incremental variations in linewidth are possible with SPL in the pixel writing scheme.

We can explain these results using our understanding of the distribution of energy density absorbed by the resist. In Fig. 9 we show the energy density absorbed as a function of position for a five-pixel-wide line with 40 nm pixel spacing. The circular points represent the data for a single pass line as plotted in Fig. 5. The dotted lines are the fits to the data (the double Gaussian for EBL and the single Gaussian for SPL) representing the five single line exposures separated by 40 nm. The solid line is the sum of the absorbed energy density contributed by these five pixels. The square data points represent linewidth measurements made on a five-pixel-wide line.

For EBL, the threshold to create a 40-nm-wide line in a single pass is ~0.85. At this threshold, a five-pixel-wide line has a width of 232 nm. It is possible to adjust the threshold or dose to create a 200-nm-wide line with five pixels, but at this dose (or threshold) no single pass lines would print. In the case of SPL, the energy distribution is narrower, minimizing the overlap between neighboring pixels. Figure 9(b) shows that at the threshold to create a 40-nm-wide line in a single pass (~0.7), the five-pixel-wide line is almost exactly 200 nm. The confined distribution of SPL energy density allows excellent linearity and superior linewidth control.

E. Proximity effects in EBL and SPL

The tail of the EBL energy density distribution also contributes to “interproximity” effects, or linewidth variations
due to the local feature density. Various proximity correction algorithms have been developed to achieve uniform resist exposure with EBL. These methods tend to be computer-intensive and time-consuming, compounding the problems of an already slow patterning technology. EBL patterns here were exposed without proximity correction for comparison with SPL. Figure 10 shows an example of the EBL proximity effect for a series of five single-pass lines spaced by 200 nm. The lines in Fig. 10(a) were written at a dose for which an isolated line has a width of 64 nm. The lines on the 200 nm pitch are resolved but the width of 140 nm is significantly larger than the isolated feature size. If the dose is increased such that the isolated feature size is 120 nm, the five lines on a 200 nm pitch can no longer be resolved [Fig. 10(b)]. This effect becomes more significant for larger arrays of lines, as features printed relatively far away contribute to the total absorbed energy density at each line.

This effect is illustrated by the absorbed energy density plots shown in Fig. 11. Here we have used the energy density plots shown in Fig. 11. Here we have used the energy density

![Figure 9](image9.png)

**Fig. 9.** Absorbed energy density of a five-pixel-wide feature with 40 nm pixel spacing for (a) EBL and (b) SPL. Contribution from each pixel is shown with dotted lines. Solid line represents the total energy density absorbed by the resist due to the five pixels. Data points indicate linewidth data measured for a single pass line and a five-pixel-wide line.

![Figure 10](image10.png)

**Fig. 10.** EBL proximity effects shown for lines spaced by 200 nm. (a) Lines written with EBL at a low dose. Isolated line at this dose has a width of 64 nm. Lines on the 200 nm pitch are resolved, but the linewidth is 140 nm, (b) At a higher incident EBL dose, the lines are not resolved even though the isolated linewidth at this dose is only 120 nm.
fits for single pass lines and spaced the lines by 200 nm. The individual features are shown with dotted lines. Data points show the actual linewidth measurements for the single line in the center. The solid line represents the sum of the absorbed energy density, including the contributions of all features. EBL patterning of five lines spaced by 200 nm is shown in Fig. 11(a). Here it is clear that there is some overlap of the density profiles and a large tail to the distribution. For a threshold above 0.23 (corresponding to an isolated linewidth of <120 nm), the lines will be resolved, while they cannot be
resolved for a lower threshold (i.e., larger isolated linewidth). This is consistent with our experimental observations. Figure 11(b) shows how the absorbed energy density distribution changes when the line grating is extended 2 μm in the positive and negative directions (21 lines total). Now the individual lines can only be resolved for a threshold above 0.79, corresponding to a dose at or below that required to print an isolated linewidth of 48 nm. Finally, we extend the line grating 5 μm in the positive and negative directions (52 lines total). The sum of the deposited energy density [Fig. 11(c)] indicates that it is impossible to resolve the individual lines with a dose at which an isolated line would print.

These proximity effect limitations are alleviated in the case of SPL. Figure 12 shows lines of various spacing written by SPL in SAL601 and etched into the silicon. The lines were all written at the same dose (50 nC/cm). Lines gratings are shown on a 500 nm pitch [Fig. 12(a)] and a 200 nm pitch [Fig. 12(b)]. Both gratings extend over a 10×10 μm area. Figure 12(c) shows a grid consisting of lines on a 200 nm pitch in both directions. Lines were written first in the vertical direction and next in the horizontal direction, therefore the intersections of the grid were doubly exposed. The printed linewidth is about 65 nm, independent of the line spacing. We have printed 200 nm pitch grids at doses from 20 to 80 nC/cm. All individual lines were resolved.

There is no evidence of long-range proximity effects in SPL. The Gaussian fit to the SPL absorbed energy density is used to show the effect of five lines on a 200 nm spacing [Fig. 11(d)]. The solid line sum follows the individual line profiles. The line grating is extended 5 μm in both directions [52 lines total, same as the printed 10×10 μm grating shown in Fig. 12(b)] and the result is shown in Fig. 11(e). The confined SPL energy density distribution minimizes the contribution of far away features on the width of individual lines. There is some overlap of the individual line profiles if the lines are spaced by 100 nm. Figure 11(f) shows the absorbed energy density distribution for nine lines on a 100 nm pitch. For a threshold above 0.20 (corresponding to an isolated linewidth below 84 nm) it should be possible to resolve individual lines written with SPL on a 100 nm pitch.

### IV. DISCUSSION

Various studies have been directed at decreasing the accelerating voltage for traditional EBL since the lower energy electrons have a more confined lateral scattering range that reduces the interaction volume in the resist. There are various challenges for creating a low-energy focused electron beam, including the beam’s high sensitivity to electromagnetic fields and its low brightness.\(^7\) Also, low-energy EBL requires thin resists because of the short penetration depth of the electrons in resist. For example, 2 keV electrons have a penetration depth of approximately 120 nm in organic resists and 1 keV electrons have a penetration depth of about 60 nm.\(^8\)

Several demonstrations of low-energy EBL on thin resists have shown that the sensitivity is improved over high-energy EBL. For example, Lee \textit{et al.} found that the dose to expose a 100 nm feature in PMMA was a factor of twelve smaller with 2 keV electrons than with 30 keV electrons.\(^7\) Low-energy EBL may be a more efficient process than traditional high-energy EBL since more of the low-energy electrons participate in the exposure process due to the short penetration depth in resist. In contrast, the sensitivity is much reduced in the case of SPL. This suggests that SPL exposure is not simply a low-energy EBL system. Lee \textit{et al.} also found that the dose tolerance increased as the accelerating voltage for EBL was reduced to 2 keV. We have also found an increased dose tolerance at the very low energies of SPL electrons.
In EBL, an electron gun emits a high-energy beam of electrons some large distance away from the sample. The electron beam is then focused down to a fine beam diameter under high vacuum. Electrons that reach the sample may lose their energy to the resist and/or substrate. Many high-energy electrons pass through the resist without much energy loss, since the resist films are thin with respect to the electron’s inelastic mean free path. For example, 30 keV electrons travel on average >14 µm in PMMA before they lose all of their energy.\(^9\) Nevertheless, the high-energy electron scattering events can be modeled by a “continuous slowing down” approximation in which it is assumed that an average electron is continuously retarded.

The continuous slowing down approximation is no longer valid for SPL since the electrons pass through the resist in a high electric field. The electrons are emitted from the tip with some small energy and then are accelerated by the field toward the substrate. They will undergo a number of inelastic scattering events in which they lose energy and then gain more from the field. This is a very different scenario than in the case of standard EBL exposures.

EBL exposure of SAL601 releases a photacid in the resist. Generally no other resist chemistry takes place until the PEB initiates the cross-linking reaction. In contrast, we have found that significant cross linking occurs during SPL exposure. We have repeated SPL single-pass exposures of SAL601 and developed them without a PEB. We find no measurable changes in linewidth from the data shown in Fig. 1. Therefore we suspect either local heating (essentially an \textit{in situ} PEB) or a fundamentally different exposure mechanism for the low-energy electrons.

It seems reasonable that some SPL electrons that scatter in the resist may not have enough energy to cause chemical changes. The multiple scattering events could heat the resist, providing the needed energy for the cross-linking reaction. It has been observed experimentally that at the same exposure dose, the temperature rise in the resist is higher for beams with lower acceleration voltage.\(^10\) Nevertheless, analysis by Perkins \textit{et al.} indicates that it is unlikely that significant heating occurs in the resist during SPL exposure.\(^3\) The insensitivity of the SPL pattern dimension to PEB time also suggests that local heating is not the cause of the cross linking during SPL exposure. Therefore, we propose that the low-energy electron exposure mechanism of SAL601 may be different than that of standard EBL whereby cross linking is performed directly by the incident low-energy electrons.

High-energy electrons from EBL can also directly cause a cross-linking reaction and thus induce differential solubility in SAL601. The incident high-energy electrons may form a cation radical in the novolac repeat unit (oxidizing the novolac), which can lead to cross linking. At small incident doses there may not be the required threshold of cross links to change the solubility. But at high incident electron doses, significant cross linking can occur. We patterned SAL601 with 30 keV EBL and developed it immediately after exposure (no PEB). We found that even at the highest incident exposure line dose used (20 nC/cm), the single pass exposures did not render the resist insoluble. But all features at least three pixels wide patterned at doses above 16 nC/cm. No patterns were evident after development (even for densely packed features) for doses below 5.6 nC/cm.

SPL electrons do not have enough energy to cause the above cationic reaction. They may, however, cause an anionic reaction by reducing the novolac (entering the lowest unoccupied molecular orbital of the novolac molecule). This can also lead to cross linking. The efficiency of this exposure process may be lower than the high-energy process, which could account for the reduced sensitivity of SAL601 to the SPL electrons. It may be possible to design resists optimized for low-energy SPL exposure.

\section*{V. CONCLUSIONS}

SPL is shown to have sub-50 nm resolution and the capability of creating 10:1 aspect ratio etched features. SPL has a wide exposure latitude, improved linearity in the pixel writing scheme, and reduced proximity effects; however it requires a higher dose of electrons for exposure than EBL. SPL absorbed energy density in the resist can be approximated with a single Gaussian, while EBL requires a double Gaussian fit to account for the large tail of the distribution due to the contribution of backscattered electrons. SPL’s confined energy density distribution allows densely packed features to be resolved. We have demonstrated this by patterning 200 nm pitch grids with SPL where all individual features are resolved. The linewidth of features in this grid was the same as the width of an isolated line at the same dose. We suggest that the SPL exposure mechanism may be different than that for EBL. If the throughput of SPL can be improved, then it may provide an attractive alternative for high resolution lithography because of its ability to maintain strict CD control.

\section*{ACKNOWLEDGMENTS}

The authors would like to acknowledge the valuable assistance of Dr. R. Fabian Pease and Dr. Mark McCord from Stanford University, and Professor Andy Neureuther and Nick Rau from U.C. Berkeley. Professor Jean Fréchet, David Tully, and Alex Trimble from U.C. Berkeley helped provide an understanding of the resist chemistry. Theresa Kramer from Stanford University recommended the PMMA development and lift-off process. One of the authors (K.W.) is pleased to acknowledge financial support from Advanced Micro Devices. This work was supported in part by DARPA under Contract No. MDA972-97-1-0010, by the SRC under Contract No. LC-460, and by DARPA/ONR under Contract No. N 00014-96-1-0771.

\footnote{\textit{National Technology Roadmap for Semiconductors} (Semiconductor Industry Association, San Jose, CA, 1997).}


\footnote{PMMA molecular weight 950 000 amu.}