Real-time spatial-phase locking for vector-scan electron beam lithography

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Spatial-phase locked electron beam lithography (SPLEBL) provides feedback control of electron beam position by monitoring the signal from a fiducial grid on the substrate. Continuous, or “real-time,” spatial-phase locking has been investigated for raster-scan Gaussian beam and for shaped-beam systems. Discontinuous feedback, or “look-then-write,” techniques have been implemented for vector-scan systems. However, it would be advantageous to provide real-time spatial-phase locking for vector-scan systems because of their wide adoption for research, prototyping, and specialty device production. Here, the authors present a phase locking algorithm, performance simulations, and initial experimental results for real-time, vector-scan SPLEBL. The authors demonstrate that real-time, vector-scan SPLEBL can provide subnanometer precision phase locking for different feature filling strategies, exposure parameters, and pattern geometries using reasonable data lengths and practical grid signal-to-noise ratios. © 2007 American Vacuum Society. [DOI: 10.1116/1.2781518]

I. INTRODUCTION

Currently, scanning-electron beam lithography (SEBL) is the only technology for generating arbitrary patterns with nanoscale features while maintaining reasonable throughputs. As a result, SEBL is a standard approach for high resolution mask fabrication as well as imprint template fabrication, device prototyping, and low-volume production. However, SEBL exhibits pattern placement accuracy that remains poor compared to its resolution. The primary contributor to this problem is the open-loop nature of SEBL systems. Although the stage supporting the substrate or wafer can be positioned precisely, conventional systems have no way to determine the actual beam position on the substrate during patterning. To combat the resulting placement errors, state-of-the-art tools require precision electron optics, sample-positioning stages, and environmental controls, as well as time-consuming stabilization, calibration, alignment, and exposure procedures. Despite these extensive efforts, pattern placement errors remain in the tens of nanometer range, even for the most sophisticated tools.1

Rather than individually address each error source affecting pattern placement accuracy, spatial-phase locked electron beam lithography (SPLEBL) has been developed to solve the fundamental problem of open loop operation.2–4 SPLEBL provides closed-loop control of the electron beam position based on the signal from a reference grid located on the substrate to be patterned. As the electron beam scans across the substrate, the phase of a reference grid signal is analyzed to determine the beam position error. Corrections are fed back to the beam control system to ensure pattern placement accuracy. SPLEBL has demonstrated sub-1-nm (one standard deviation) pattern placement precision with respect to an electron-transparent fiducial grid using a raster-scan exposure strategy on a Gaussian beam tool.2 However, use of SPLEBL with vector-scan exposure strategies has been limited to “look-then-write” modes in which the grid is imaged, the beam deflection is corrected, and then the pattern is written open loop.4–8 This approach has produced excellent results ($\sigma=2$ nm stitching errors for grating exposures), but requires the system to be stable while writing, does not correct for deflection dependent placement errors, and reduces throughput due to the time required to look at the grid. As a result, there is a need for real-time feedback control during vector-scan patterning.

In this article, we evaluate a new spatial-phase locking algorithm that provides real-time feedback for vector-scan exposures using a global, electron-transparent, fiducial grid. During a vector-scan exposure, the grid signal is sampled in a complicated, but deterministic sequence. Thus, with an appropriate signal processing algorithm, one can extract the beam position information from this signal. Such an algorithm is described in Sec. II. The remainder of this article demonstrates, through simulation and experiment, that over a broad range of exposure parameters one can phase lock to subnanometer precision during a vector-scan exposure using practical data lengths, exposure doses, and signal-to-noise ratios.

II. VECTOR-SCAN SPATIAL-PHASE LOCKING ALGORITHM

First, we model the fiducial grid as a sum of two spatially orthogonal sinusoids to which the Heaviside step function has been applied to create a binary signal. A grid with period $\Lambda_G$ is rotated with respect to the beam deflection axes by a known angle $\theta$. By rotating the grid, information about both the $x$- and $y$-placement errors can be obtained more rapidly than if the grid is orthogonal to the beam deflection axes. In this case, the two-dimensional (2D) grid signal $S$ can be described by
the amplitude of the fundamental frequency components and various grids such as an array of bright dots/dark lines

\[ \text{SNR} \]

and patterns for which this algorithm is effective. However, it is important to note that, in this case, we use a 2D signal that is not sequentially sampled; whereas, both of these previous efforts focused on using a sequentially sampled one-dimensional (1D) signals. The phase locking algorithm described here makes no assumption about the order in which the pixels are acquired. As a result, one can, in principle, phase lock while scanning the electron beam in an arbitrary manner. The remainder of this article focuses on determining the exposure conditions and patterns for which this algorithm is effective.

III. SIMULATION OF VECTOR-SCAN SPATIAL-PHASE LOCKING

We performed a series of numerical simulations to better understand the influence of various system parameters on the speed and accuracy of vector-scan SPLEBL. For these simulations, the figures of merit considered were the number of data points required for the position estimate to converge to a given precision and the mean residual error for a fixed number of data points. Thus, we ensured that the position error estimate converged rapidly enough for feedback control and with a small enough residual error to allow subnanometer patterning accuracy. All simulations were conducted for both “flyback” and “spiral” fill strategies. Flyback filling is defined by beam blanking after every line of the feature and returning to the leading edge of the feature before continuing patterning. Spiral filling was simulated by scanning the beam from the center of the feature outward in order to achieve phase locking in the noncritical portion of the feature and pattern the edges as accurately as possible.

The first system parameter we investigated was the rotation angle of the grid with respect to the scan direction. The position errors were estimated by taking 5000 samples in a single 100×50 pixel feature. 46 angles spanning 0°−45°
were simulated for both flyback and spiral shape fill strategies. The ratio of grid period to sample spacing was set to 5 (200 nm grid period and 40 nm sample spacing) and the beam radius was chosen as 40 nm. The constant offset \( C \) was set to generate array of bright dots for the grids. The SNR was set to be \( 10^9 \) to eliminate the influence of noise.

Figure 2 shows the estimated x- and y-position errors when rotation angle is 20°. Reciprocals of standard deviations of every 50 error estimates were plotted versus pixel number and a linear fit was applied to find the number of pixels required to converge to 0.5 nm one standard deviation. Figure 3 shows the number of pixels required for phase locking versus the rotation angle of grid. We observe that the fill strategy does not strongly affect the number of pixels required for phase locking and requires less than 1000 pixels for all 0°–45° rotation angles. However, best performance is obtained with grid rotation angles between 15° and 35°, while angles near 0° and 45° should be avoided. We also verified that the mean residual error after sampling the entire feature fell below 1 nm for all angles. It is interesting to note that the selection of an appropriate angle is less critical than when one uses a 1D signal\(^9\) because interference from harmonics is reduced.

The effect of noise was studied by changing the SNR in the numerical simulation and the results are shown in Fig. 4(a). As the noise increases, the number of pixels required for phase locking also increases. In the region of typical SNRs (<1), the performance of the algorithm is limited by the noise. Although not typical in electron microscopy or normal lithographic alignment algorithms, SNRs less than 1 are suitable for spatial-phase locking because accurate phase estimation can be performed after acquiring a suitable number of samples. At higher SNRs, which are not usually attainable at normal exposure doses, the algorithm is limited by interference from other frequency components.

### IV. EXPERIMENTAL VERIFICATION

Two different fiducial grids, both fabricated using Lloyd’s mirror interferometric lithography by MIT’s NanoStructures Laboratory, were used to produce secondary electron signals for algorithm evaluation. To experimentally verify the vector-scan spatial-phase locking algorithm, grids were patterned directly on substrates rather than on top of an e-beam resist. Procedures for patterning fiducial grids on e-beam resists have been presented elsewhere.\(^2,10\) A 400 nm period SiO\(_2\) on Si grid provided higher SNR while a 200 nm period photore sist grid on a SiO\(_2\)-antireflection coating stack proved useful for lower SNR testing.

The University of Kentucky’s Raith 50 SEBL system was used to deflect the beam over various patterns and sample the
The primary beam energy was 30 keV and an Everhart-Thornley detector was used to acquire the secondary electron signal. The grid was manually rotated at an angle of 20° with respect to the stage axes and the system coordinates were mapped on the grid axes. The deflection field was calibrated using the modified coordinate system to compensate for any mechanical alignment error. The flyback exposure mode was used for all experiments because spiral scan is not yet available on our SEBL system.

To evaluate the algorithm performance, we scanned features large with respect to the grid period while varying sample spacing (20, 40, and 80 nm). Signal-to-noise ratio was adjusted by changing the bias on the detector collection grid between −100 and 300 V. For each feature, SNR was calculated by determining the amplitude of the fundamental Fourier components, finding the variance of all frequency components using each exposed line, and finally summing the variances to determine the noise level. The x- and y-position errors were estimated using the algorithm described in Sec. II. Figure 5 shows the secondary electron signal from the 200 and 400 nm period fiducial grids along with their 2D Fourier transforms. Though the grids are somewhat difficult to see from the secondary electron signal, the spatial frequency components are distinctly visible in the Fourier transform.

To determine how quickly the algorithm converges, we mapped the position error versus the number of pixels sampled. As observed in the simulations, the error decreased as reciprocal of the number of pixels acquired, and the number of pixels required was determined by the point at which the best fit curve fell below 0.25% of the grid period. Figure 4 shows both simulations and experimental data for the number of pixels required for convergence versus SNR. In all cases, the pixel spacing was set to 1/5 the grid period, and an exposure dose of 20 μC/cm² was used.

In agreement with the simulations, the experimental data show noise limited behavior at low SNR, but stabilizes at a somewhat larger number of pixels than predicted. This is most likely the result of increased interference from harmonic frequencies. We note that the harmonic frequency components are stronger in the real data than the simulated data. This is a result of a smaller beam diameter and enhanced secondary electron emission from the edges of the experimental grids. Both effects tend to enhance high frequency components, and, as a result, interfere strongly. This is especially problematic when only one or two y-axis positions have been sampled, and the overlap between fundamental and harmonic components is largest. This effect could potentially be reduced using an appropriate window function with the data, or by choosing a slightly different rotation angle. Regardless, locking still occurs within a practical data length for real grid signals.

We also measured the precision with which one can maintain spatial-phase locking after converging to an initial error estimate. In this case, we measured the position error 200 times during the course of scanning a feature with 600 samples per measurements. In order to reduce interference, we used a Hann window function on the time sequenced data. The experimentally measured standard deviation of the position error estimate is plotted versus SNR in Fig. 6. The standard deviation is normalized to the number of pixels used because it is necessary to change the number of acquired pixels to adjust the feedback bandwidth of the phase locking system. In this case, one need only divide by the square root of the number of pixels to find the expected estimation variance. We also plot the theoretical minimum variance determined by the Cramér-Rao bound (CRB) for phase estimation of a single sinusoid in Gaussian white noise. This lower bound has been increased by a factor of 1.5 to account for the use of Hann window. We observe that the experimentally measured variance is only slightly
larger than the fundamental limit and clearly shows the same improvement with increasing SNR. Thus, our phase locking algorithm is nearly a maximum likelihood estimator, and the CRB can be used as a guide to performance.

Given this, one estimates that that number of pixels required for 1 nm precision with a 200 nm period grid and a SNR of 0.1 is approximately 40 000. However, if a slower resist such as polymethyl methacrylate is considered, then the dose would increase by a factor of about 7 and the SNR would improve correspondingly. As a result, the number of pixels required would decrease to about 5000. This indicates that feedback bandwidths in the hundreds of hertz to a few kilohertz range should be achievable with typical vector-scan pattern generation rates (10–50 Mpixels/s).

Finally, we measured the effect of sample spacing on algorithm performance. Figure 7 plots the number of pixels required for 0.5 nm convergence versus the ratio of grid period to pixel spacing. Of course, the sampling frequency must be at least twice the grid spatial frequency; however, increasing the number of samples per period further reduces performance slightly because fewer periods are sampled and interference with harmonic components increases. This suggests that, all other things being equal, one should use the largest pixel spacing possible; however, this is often limited by other exposure parameters.

V. CONCLUSIONS

The simulations and experiments presented here indicate that vector-scan spatial-phase locking has the potential to provide subnanometer pattern placement accuracy for electron beam lithography. Acceptable performance was obtained with different fill strategies (flyback and spiral), and the vector-scan SPLEBL algorithm allows flexibility in choice of exposure parameters. Sub-1-nm beam position estimation can be achieved with practical signal-to-noise ratios, reasonable data lengths, and commonly used exposure doses.

For features with at least one dimension large with respect to the grid period, phase locking can be achieved within a single feature. This suggests that a spiral fill strategy allowing locking in the center of the feature while precisely writing the edges will be most effective. Alternatively, for features with both dimensions small with respect to the grid period, it will be necessary to accumulate data over several features before accurate phase locking can be achieved. This suggests more complex, but still feasible exposure strategies where the less critical or larger features could be patterned first, followed by more critical and smaller features. Similarly, the interiors of several features could be exposed first followed by the edges of the features. Finally, one could expose features in unused areas of the field at a subexposure dose to initially achieve phase locking.

Although, vector-scan SPLEBL is an inherently lower-performance approach than raster-scan SPLEBL, the wide use of vector-scan systems is a strong motivation for its development. The minimal hardware modifications required for use of the vector-scan SPLEBL algorithm described here make it well suited for immediate implementation.

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