Spatial-phase locking with shaped-beam lithography

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Spatial-phase-locked electron-beam lithography is a method of precisely locating pattern elements on a substrate by providing real-time feedback of the beam's location by means of a fiducial grid located on the substrate surface. Previously, this technique has been demonstrated in Gaussian-beam systems, in one and two dimensions. In this note we propose a method of extending the spatial-phase-locking concept to a vector shaped-beam architecture. In the proposed method, an image of a screen grid is superimposed on the projected shape, and this grid image is dithered in *X* and *Y* to provide a periodic signal whose phase can be interpreted to determine the position of the projected shape relative to the fiducial grid. © *2003 American Institute of Physics.*
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I. INTRODUCTION

In conventional round-beam and shaped-beam electron lithography, the location of the beam or projected shape relative to the substrate is not directly monitored. Instead, the position of the stage that holds the substrate is monitored by a laser interferometer, and stage position errors are fed back to adjust the beam location. This approach does not accomplish a fully closed feedback loop, and, as a result, there are a number of shortcomings. For example, shift of the beam relative to the substrate, due to electrical charging, differential thermal expansion, etc., is not continuously monitored. In addition, calibration and orientation of the scan field is generally done relative to the stage, not the substrate. Spatial-phase-locked electron-beam lithography (SPLEBL) attempts to overcome these shortcomings by placing a spatially coherent fiducial grid directly on a substrate, and taking from it positional and calibration signals using the beam itself; in effect, closing the feedback loop.[1–7]

Previously, several modes of SPLEBL have been described, as applied to a round-beam system.[2–7] In the most recent results the mean-plus-3-sigma placement error was 6 nm.[7] In this note we describe a proposal for accomplishing spatial-phase locking with a vector shaped-beam projection system.

Ideally, the fiducial grid used in SPLEBL should have long-range spatial-phase coherence. This is best achieved by means of "conventional" interference lithography,[8–10] or an achromatic,[11] or near-field scheme[12,13] using master plates made with interference lithography. Spatial periods as fine as 100 nm are readily achieved.[11] Further requirements on the fiducial grid are that it be nonperturbative to the electron-beam lithography and that it yield sufficient signal level.

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II. SPLEBL IN SHAPED-BEAM SYSTEMS

In a round-beam system, a signal can be obtained as the grid is scanned with a fine probe. That is not the case with a shaped-beam system [Fig. 1(a)] where the rectangular shape projected onto the substrate varies in size and $X-Y$ dimensions (it is generally significantly broader than the minimum resolvable feature). Moreover, the shape remains stationary during its exposure.

In order to extract positional information from a fiducial grid in a shaped-beam system, we propose inserting a screen grid into an early stage of the projection system [Fig. 1(c)] such that the demagnified image of the screen grid matches the spatial periods in *X* and *Y* of the fiducial grid [Fig. 1(d)]. The screen grid, the first shaping aperture, and the second shaping aperture, are all maintained electron-optically conjugate with the writing surface. This is accomplished by electron lenses (not shown in the figures). The screen-grid image is dithered electronically, in *X* and *Y*, to yield oscillatory signals whose phases are indicative of the position of the projected shape relative to the fiducial grid. The dithering of the screen grid accomplishes two functions: (1) extraction of oscillatory signals from the substrate fiducial grid, and (2) ensuring that the dose is uniform over the entire area of the projected shape. In order to distinguish between the *X* and *Y* signals, the *X* and *Y* dithering can be done at different frequencies, and the signals subsequently separated by processing. Alternatively *X* and *Y* spatial periods of the fiducial grid can be set to different values and the *X* and *Y* dithering done at the same frequency.

A potential problem exists in that the shaping action causes the image of the screen grid to become displaced by an amount which is exactly equal to the displacement of the image of the first shaping aperture. This affects the position of the screen-grid image relative to the fiducial grid. This

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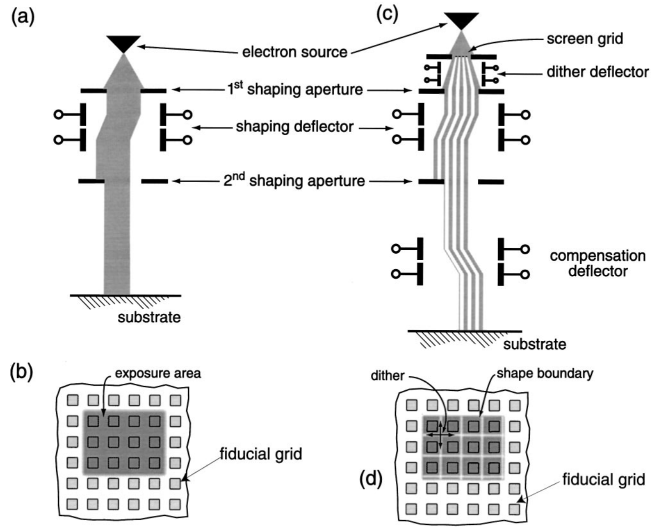

FIG. 1. (a) Simplified diagram of a shaped-beam electron-projection column. For clarity, the condenser and projection optics have been omitted as well as the shape deflection. (b) Depiction of the projected rectangular shape on the substrate, superimposed on a fiducial grid to show relative sizes. (c) The shaped-beam system modified to enable spatial-phase locking. (d) The shadow of the screen grid, which is located before the first shaping aperture, is superimposed on the projected rectangular shape. The shadow image is dithered in X and Y relative to a spatially coherent fiducial grid on the substrate by means of dither deflectors. The dithering results in detectable X and Y oscillatory signals whose phases are indicative of the position of the projected rectangle relative to the fiducial grid. The shift in the grid induced by the shaping deflector is corrected by the compensation deflector.

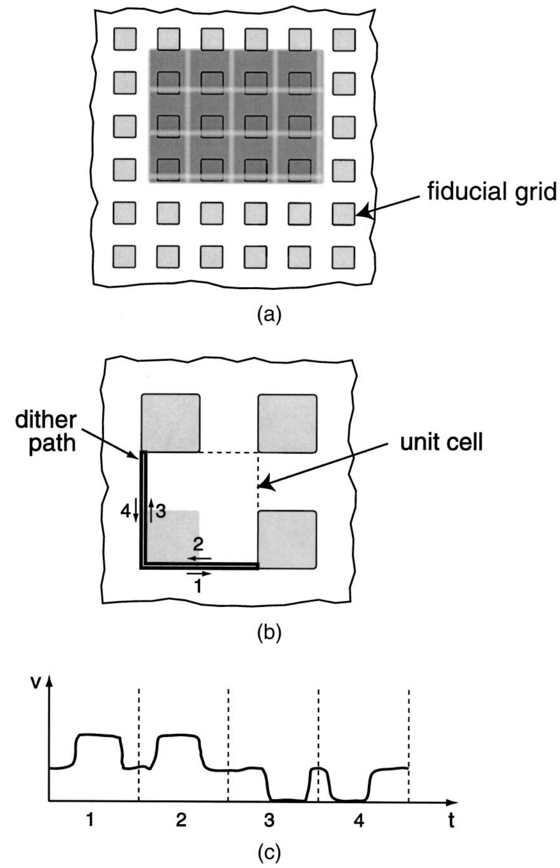

FIG. 2. (a) Depiction of the rectangular shape and screen grid, as imaged on the substrate plane. The grid image is dithered along X and Y paths that cover the fiducial-grid unit cell, as depicted in (b). This enables distinct X and Y signals to be collected from the fiducial grid, and makes the dose within the shape more uniform. (c) Depiction of the X or Y signal expected by dithering along the path shown in (b).

problem can be eliminated by adding a compensation deflector, which operates in sympathy with the shaping.

The projected image of the screen grid should ideally have lines that are finer than half the spatial period of the fiducial grid. Due to the vector nature of the stepping from one projected shape to the next, the exposure tool is constrained to maintain a blind accuracy better than half the period of the fiducial grid.

Since the grid image [Fig. 2(a)] is superimposed on the projected rectangular image, it is necessary to properly select the dither characteristics. Figure 2(b) illustrates that the dither path should match the X and Y dimensions of the fiducial-grid unit cell (or be an integer multiple thereof). Ideally, the exposure time for the projected rectangle should be either an integer multiple of the dither period or a large noninteger multiple. Otherwise, dose nonuniformity over the projected rectangle may result in edge-placement errors.

A common strategy for proximity-effect correction is to modulate the exposure dose from one projected rectangle to the next by modulation of the exposure time.[14] A maskwriter, such as the IBM EL-5 system[15] uses a 1 ns least-significant bit (lsb) in its exposure control in order to achieve sufficient dose resolution for accurate proximity correction. The exposure time for any given shape is typically many nanoseconds, e.g., 50 ns. If the dither periods for X and Y are integer multiples of the lsb, dose nonuniformities will be avoided. For example, the X dither frequency could be 1 GHz and the Y dither frequency 500 MHz.

Clearly, there is an advantage in keeping the unit cell of the fiducial grid as small as possible in order to ease the requirements on the electronics for the dither deflectors and to achieve finer positional precision. Moreover, in order for the control system to receive a feedback signal from every projected shape, the smallest projected rectangles must enclose at least half a unit cell of the fiducial grid. If spatial-phase locking for shaped-beam systems is to be used for direct writing, in addition to mask making, this would argue in favor of fiducial grids with spatial periods as fine as 100 or 50 nm.

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