Localization Microscopy for Process Control in Nanoelectronic Manufacturing

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INTRODUCTION

Optical microscopy beyond the resolution limit enables critical measurements in nanoelectronic manufacturing. At the state of the art, scatterfield microscopy is a mature method of quantifying target dimensions and overlay, combining prior knowledge of target structures, optical models, and microscope calibrations to achieve parametric uncertainty of less than one nanometer and total uncertainty of a few nanometers.[1] In comparison, localization microscopy is a maturing method of imaging and tracking with diverse applications,[2] combining prior knowledge of sparse structures, optical models, and microscope calibrations to achieve localization precision of less than one nanometer and total uncertainty of a few nanometers.[3,4,5] Although localization microscopy is largely unexplored in the context of nanoelectronic manufacturing, the method has significant potential for characterization of lithographic materials, localization of device features, and detection of interfacial defects, among other possibilities.[6,7] A critical issue to address, however, is the need for a traceable and total uncertainty of less than one nanometer, throughout a focal volume of considerable extent, to exploit the high throughput that is possible by optical microscopy.

In the localization analysis of a point source, random effects, such as from a finite count of signal photons and mechanical vibration of microscope parts, yield uncertainty components that can be far less than one nanometer,[8] limiting localization *precision*. However, systematic effects, such as from variation of magnification across imaging fields and experimental conditions,[9] and mismatch between model and experimental point spread functions, can become orders of magnitude larger, limiting localization *accuracy*. Such an extreme discrepancy between precision and accuracy would be intolerable to feature localization or defect detection for process control. Moreover, claims of localization traceability to the International System of Units (SI) are challenging to validate, further limiting the reliability of position data, and potentially confounding the registration of features across multiple nanofabrication and microscopy systems. The root cause of this problem is the lack of standards and calibrations that are fit for the purpose of achieving a traceable and total uncertainty of less than one nanometer in localization microscopy.

To address this issue, we are developing nanostructure arrays that provide reference positions throughout the focal volume of an optical microscope, enabling its calibration. A central goal of our work is to achieve accuracy and efficiency in the fabrication and measurement of such standards, which involves representative aspects of process control. In a previous study,[3] we tested the accuracy of electron-beam lithography to place nanoscale apertures in rectilinear arrays. Two lithography systems each used two interferometers to measure stage positions and correct for electron–optical aberrations within the patterning process. By localizing apertures and comparing arrays from the two

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systems, we estimated a difference of mean distance between apertures of one part in five thousand, or approximately one nanometer, and a standard deviation of the distances between apertures of a few nanometers from random effects during lithographic pattern transfer. In a recent study,[5] we validated our estimate of array pitch using critical-dimension atomic-force microscopy,[10] which is traceable to the SI, and we propagated scale uncertainty to establish a traceable and total uncertainty of less than one nanometer across an imaging field of a certain extent.

In the present abstract, we briefly summarize the traceable validation[5] of an aperture array that we fabricated by electron-beam lithography,[3] confirming fabrication accuracy and yielding a master standard that enables a new test of placement errors from focused-ion-beam machining. These results demonstrate progress toward bridging the gap between the common practice of localization microscopy and process control in nanoelectronic manufacturing.

RESULTS

We apply critical-dimension atomic-force microscopy to traceably measure the distance between apertures that we fabricated by electron-beam lithography.[3] In an initial test,[5] we analyze the sidewall positions around the bottoms of a representative pair of apertures (Figure 1a). Either by fitting elliptical models to or by directly centroiding the sidewall positions, the distance between the apertures is within one nanometer of the nominal value of 5000 nm. Sampling multiple pairs of apertures in the two lateral dimensions yields a traceable mean distance or pitch between the apertures of 5000.71 nm ± 0.54 nm (Figure 1b). This uncertainty is a 68 % coverage interval, building confidence in the placement accuracy of electron-beam lithography for a representative array, and yielding a master standard. Propagation of scale uncertainty and localization error yields a traceable and total uncertainty of less than one nanometer across an imaging field of more than 150 μm^2, which both sets a record and motivates improvement.

With this master standard in hand, we can calibrate our optical microscope[3-5,8,9] and apply the considerable area of its imaging field to traceably measure aperture placement with high throughput (Figure 2). This new measurement capability allows rapid tests of the machining of aperture arrays with a focused ion beam, eliminating the need for lithographic pattern transfer and facilitating rapid prototyping. However, without the interferometric measurements and internal corrections of stage positions of our electron-beam lithography systems, our focused-ion-beam system places apertures into arrays with significant errors across the patterning field (Figure 2a-c). Systematic effects are evident from the position errors, depending on process parameters such as raster scanning or random scanning of the focused ion beam (Figure 2c-d), and motivating further study. The localization data present the future opportunity for an external correction of such errors, to achieve both accuracy and efficiency of the machining process.

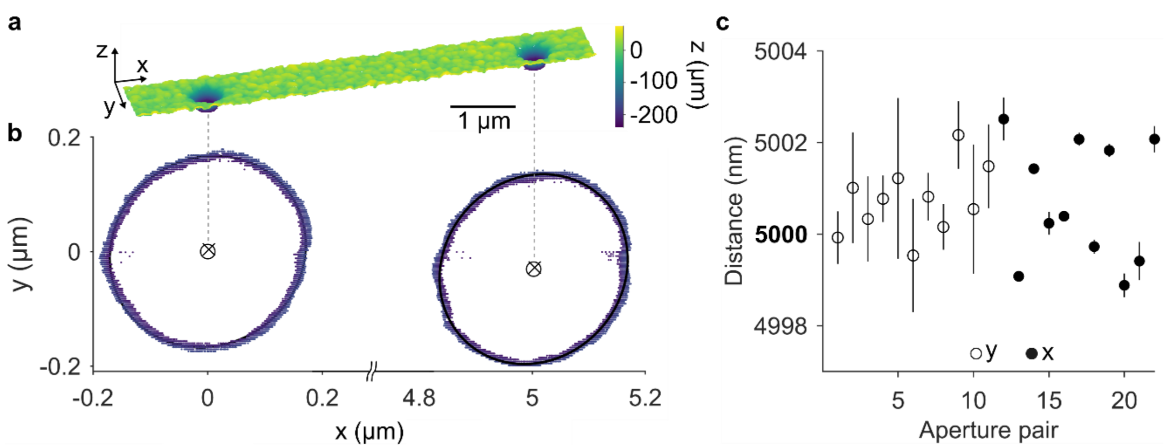

FIGURE 1. Validation of Aperture Array from Electron-Beam Lithography. (**a**) Critical-dimension atomic-force micrograph showing a three-dimensional image of a representative pair of apertures. (**b**) Plots showing two-dimensional reductions of the sidewall positions around the bottoms of the apertures. The color code is the same in (a) and (b). The central circles are the centroids that result from fitting elliptical models to the sidewall positions. The central crosses are the centroids that result from direct analysis of the sidewall positions. (**c**) Plot showing mean distances between multiple pairs of apertures along the *y* and *x* axes. Vertical bars are 68 % coverage intervals from replicate measurements. The nominal distance between apertures is 5000 nm.

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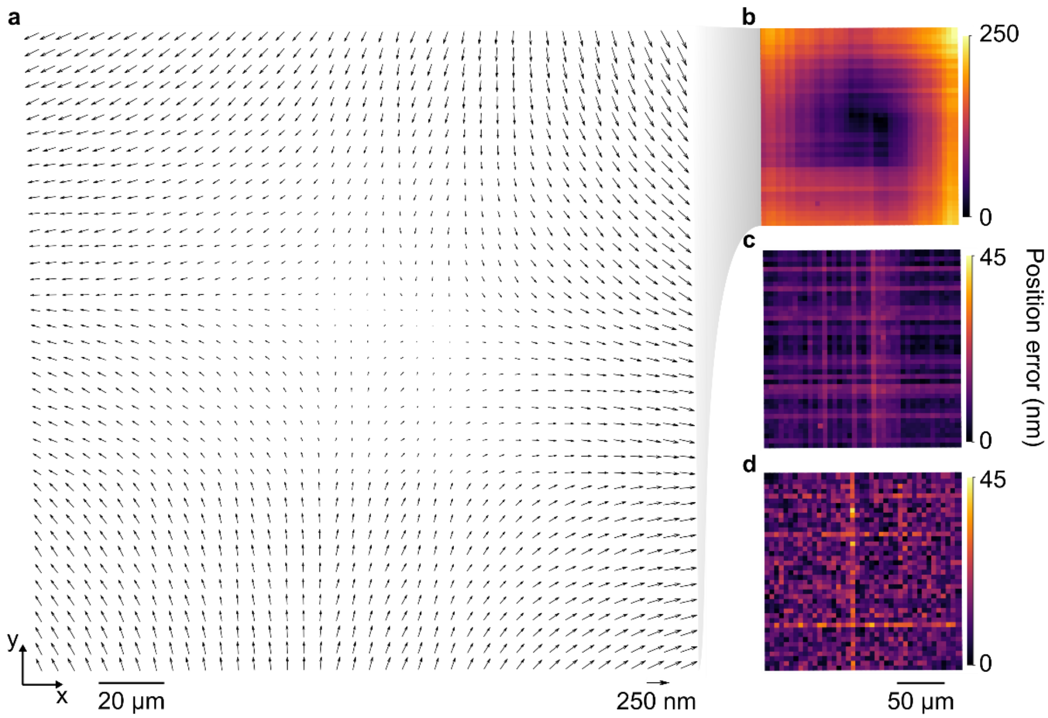

FIGURE 2. Test of Aperture Arrays from Focused-Ion-Beam Machining. (**a**) Vector plot showing representative position errors, with respect to an ideal array, for an aperture array resulting from a raster scan of the focused ion beam. The trend of the position errors indicates compression in y and expansion in x of the patterning field. (**b**) Plot showing magnitudes of position errors in (a). (**c**) Plot showing position errors of higher spatial frequency that remain after a partial correction by a Zernike polynomial model of position errors with lower spatial frequency in (a). (**d**) Plot showing representative position errors, with a spatial frequency that is comparable to that of (c), for a different aperture array resulting from a random scan of the focused ion beam.

CONCLUSION

In this abstract, we summarize our recent progress toward bridging the gap between the common practice of localization microscopy, in which localization precision is readily available, and process control in nanoelectronic manufacturing, in which localization accuracy is equally important. Our standards and calibrations enable the accurate localization of nanostructure placements, such as by electron-beam lithography and focused-ion-beam machining, demonstrating representative aspects of process control. Electron-beam lithography has applications to fabricating photomasks for nanoelectronic devices and reliable standards for localization microscopy. Focused-ion-beam machining has applications to repairing photomasks and editing circuits, and is in current use for the commercial production of aperture arrays with high efficiency but uncertain specification of reference positions, leading to the possibility of unreliable standards and erroneous calibrations. We identify this potential problem and propose a novel solution to it, leading the way toward better reliability and localization accuracy. We conclude by emphasizing the need to develop new standards for localization microscopy with lower uncertainty of scale in all three dimensions. This could enable a traceable and total localization uncertainty of less than one nanometer, throughout a focal volume approaching one million cubic micrometers, to make full use of the ultrahigh throughput of optical microscopy.

KEYWORDS

accuracy, localization, microscopy, optical, traceable