Do you know where your focused ion beam is? Placement correction by localization microscopy

Andrew C. Madison,[‖] Craig R. Copeland,[‖] Ronald G. Dixson, B. Robert Ilic, J. Alexander Liddle, and Samuel M. Stavis[*]

National Institute of Standards and Technology, Gaithersburg, Maryland 20899,
[‖]*Equal contribution,* [*]*samuel.stavis@nist.gov*

As applications of focused ion beams become more demanding, feature placement accuracy becomes more important.[1] At EIPBN 2021, we identified systematic errors of feature placement across an ultrawide field.[2] Such errors are a general problem and of particular concern for machining standards that provide reference positions, such as aperture arrays for optical microscopy.[3,4] Conversely, our recent advances of localization traceability[5] present an opportunity to improve placement accuracy. In this study, we quantify feature positions by critical-dimension localization microscopy with ultrahigh throughput, revealing complex errors that extend to egregiously large values of several micrometers across a submillimeter field. We introduce a novel correction that reduces scale errors by three orders of magnitude and distortion errors by more than a factor of 40. Our study greatly improves the placement accuracy of a common type of focused-ion-beam system in a research context.

We begin by designing a square array with a lateral extent of 200 µm by 200 µm, a nominal pitch of 2502 nm, and apertures with a nominal diameter of 500 nm. This particular value of pitch separates aperture centers by an integer number of pixels across our wide patterning field and separates the aperture images beyond the resolution limit for optical microscopy and localization analysis. After fabrication, we transilluminate the aperture array, localize each aperture, and register the resulting positions with those of the design through a rigid transformation. This analysis reveals total errors with magnitudes extending beyond 2 µm, with root-mean-square values of 528.9 nm in the x direction and 1007.7 nm in the y direction (Figure 1a,c-d). A similarity transformation between the experimental and nominal positions distinguishes errors of uniform scale factor and complex distortion effects, returning the pitch of the experimental array as 2472.01 nm ± 0.27 nm, which is a scale error of 1.20 %, with additional systematic errors of distortion as large as approximately 1 µm and with root-mean-square values of 399.3 nm in both the x and y directions (Figure 1c-d). We report uncertainties as 68 % coverage intervals.

We modify the array design to negate these errors and improve placement accuracy, uniformly increasing the array pitch to account for the 1.20 % scale error and achieve a nominal pitch of 2500 nm, and modeling the distortion errors by an interpolant that adjusts the design position of each aperture. We machine and measure a new array and apply a similar analysis, registering the localization data with the new design. We measure a pitch of 2500.03 nm ± 0.27 nm, corresponding to a scale error of 0.001 %, and additional distortion errors extending up to approximately 40 nm and with root-mean-square values of 9.0 nm in the x direction and 9.4 nm in the y direction (Figure 1b,c-d). In this way, we have found our focused ion beam, which had gone several micrometers astray, and returned it to its proper place to within tens of nanometers.

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[1] C. Scheffler *et al*., *ISTFA*, istfa2016p0382 (2016).
[2] C. R. Copeland *et al*., *EIPBN* (2021).
[3] J. R. James et al., *Nature,* **487**, 64-69 (2012).
[4] M. A. Dewitt *et al*., *Science*, **335**, 221 (2012).
[5] C. R. Copeland *et al*., *arXiv*, 2106.10221 (2021).

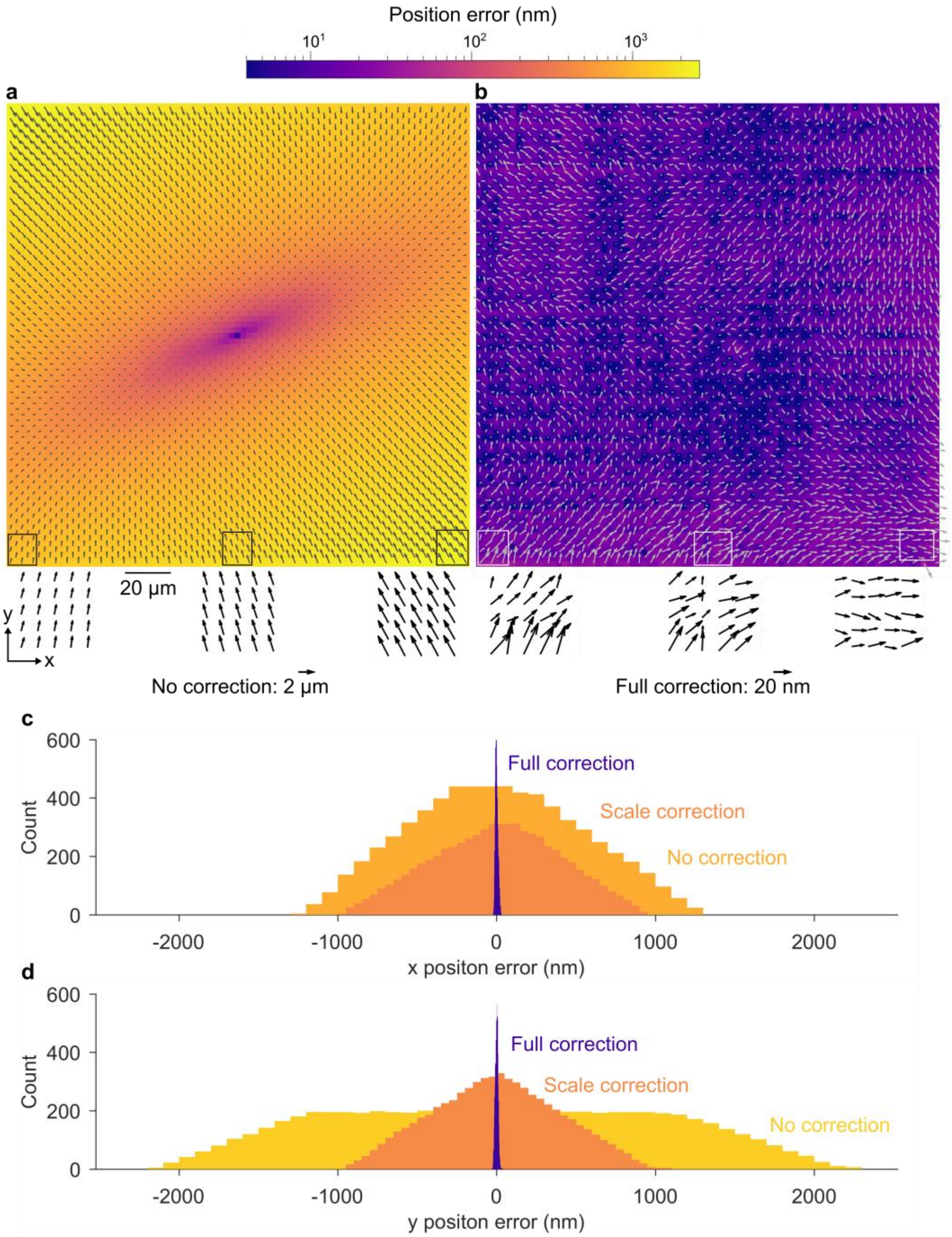

Figure 1. Feature placement correction. (**a, b**) Color maps and vector plots showing position errors with respect to the array design, for patterning processes with (a) no correction and (b) full correction. For the color maps, square markers correspond to every aperture. For the vector plots, the two main plots show position error arrows for every other aperture, whereas the six outset plots show position error arrows for every aperture. (**c, d**) Histograms showing magnitudes of position errors in the (c) x and (d) y directions for patterning processes with no correction, scale correction without distortion correction, and full correction. Root-mean-square values of position errors are (No correction) 528.9 nm in the x direction and 1007.7 nm in the y direction, (Scale correction) 399.3 nm in the x direction and 399.3 nm in the y direction, and (Full correction) 9.0 nm in the x direction and 9.4 nm in the y direction. The colors of the histograms map to their root-mean-square values.