Striving for Atomic Precision for large dopant arrays

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For dopant-based atomic-scale devices such as the ‘single atom transistor’ [1] and 2D Quantum Metamaterials[2], arrays of dopant patches need to be fabricated with atomic precision for the size of the patches (to control the number of dopants in each patch) and the spacing between patches. As the number of patches scales up from a 3x3 array to a 32 x 32 array, and even a 100 x 100 array, various types of errors become the most significant. Examples of arrays are shown in Fig. 1 below. ‘Staircasing’ is the gradual upward drift of the boxes along each row, in alternating directions. ‘Phase shift’ is the misalignment of the boxes from one row to the next, which can reach a 180° phase shift in some cases. Curvature or shearing are distortions of the overall array shape. There are various different sources of tip position error which cause these distortions, including lattice lock misalignment, piezo creep and hysteresis, and thermal drift. We are working to remove as many of these sources of imprecision as is possible, so as to achieve atomic precision patterning of dopant arrays of arbitrary size.

Performing simulations of array fabrication which include deliberate errors of one type or another, as shown in Fig.2, helps to isolate the source of the observed distortions. Examples of the simulation results are shown below, showing different types of array distortion. ‘Staircasing’ is the result of slow drift, which can also affect the lattice lock, and therefore cause misalignment of the patterning with the lattice. Curvature can be caused by uncorrected slow creep, or by variation in the rate of drift caused by temperature fluctuations in the lab. By comparing the simulations with experiments, we can then determine which parameter, i.e. creep, hysteresis or drift correction, needs to be adjusted.

Finally, as our correction algorithms are not perfect, and because there are other stochastic sources of errors, such as tip changes, we expect there to be some residual position errors. To correct these, we are developing an image recognition based process based on advanced cross-correlation techniques to align each box pattern to the previous boxes.

In this way, we hope to eliminate these position errors, and be able to draw large arrays while maintaining atomic precision, which will enable Analog Quantum Simulations, and eventually 2D Quantum Metamaterials.

1: M. Fuechsle, J. A. Miwa, S. Mahapatra, H. Ryu, S. Lee, O. Warschkow, L. C. L. Hollenberg, G. Klimeck, and M. Y. Simmons *Nat Nano* **7** 242-246 (2012)
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2: https://www.zyvexlabs.com/2d-workshop/workshop-overview/

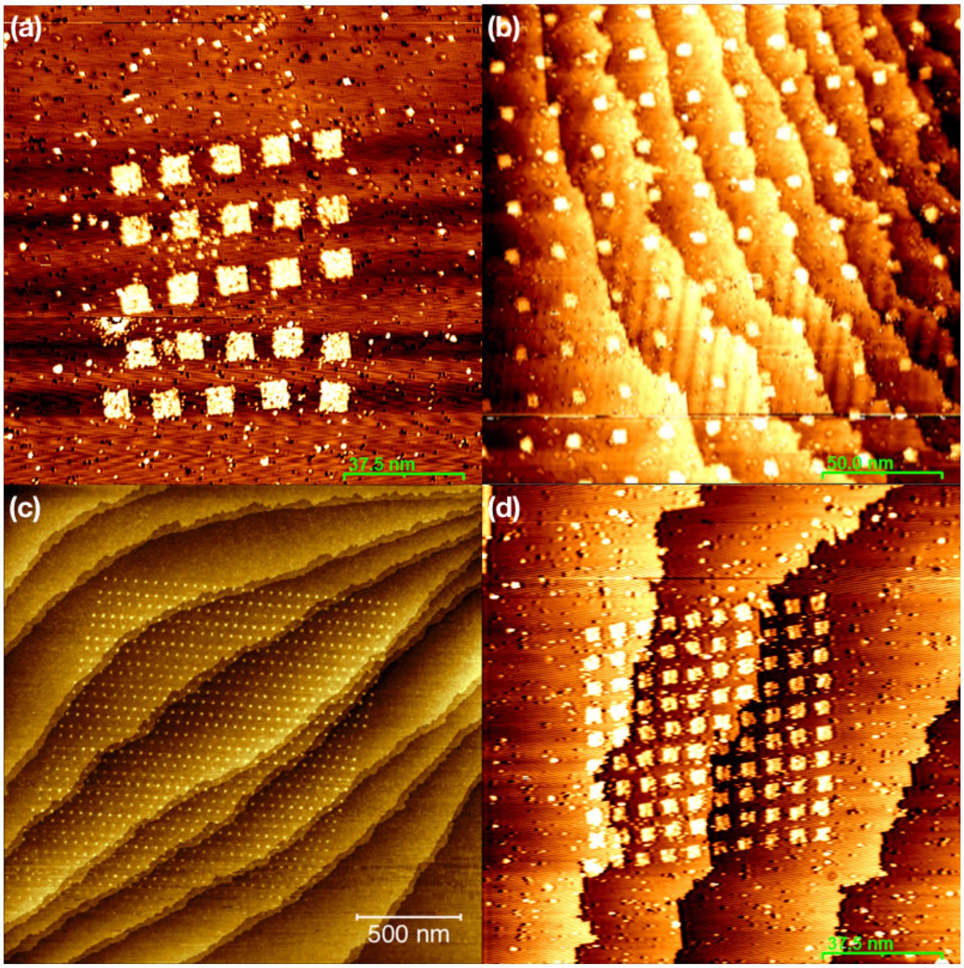

Fig. 1: Experimental arrays showing errors such as staircasing, phase shift, shearing and curvature errors. (d) shows only a small

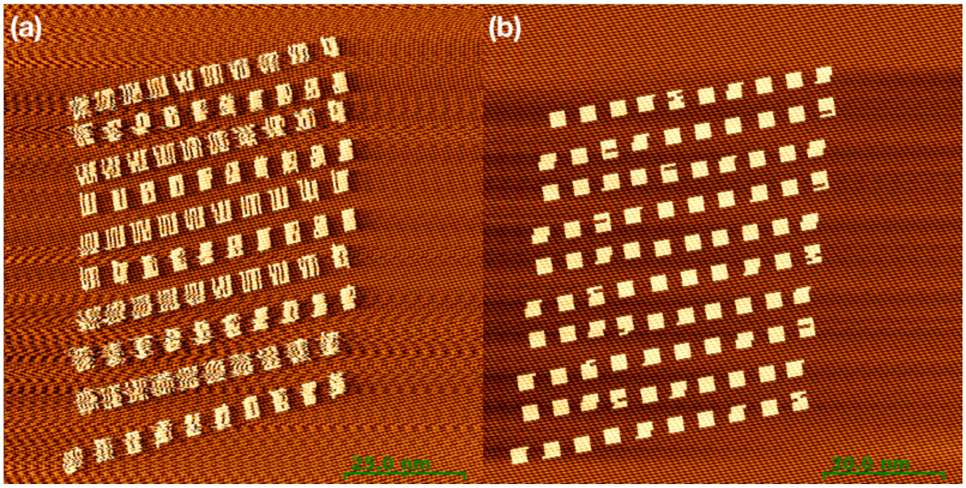

Fig. 2: Simulated STM lithography of arrays, showing the effect of different types of error. (L) : uncorrected creep giving phase shift and a curved edge. (R) : vertical drift, causing staircasing of the rows and shearing of the overall array. The first row distortion is similar in both cases, but drift does not cause a phase shift.