Advances in Positioning Precision for Atomically Precise STM Lithography on Silicon

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Hydrogen depassivation lithography has enabled unprecedented sub-nanometer precision in the positioning of dopant atoms in silicon,[1] advancing the field of silicon quantum electronics. However, as donor-based Quantum Information Processing devices scale from single-qubit devices towards multi-qubit devices such as crossbar architectures[2], and other applications such as artificial 2D materials made from large arrays of dopant patches are proposed[3], atomically precise lithography is required over increasingly large areas with improved reproducibility.

After developing the ZyVector™ automated STM lithography system with real-time piezo creep correction, we have previously demonstrated open-loop atomic precision patterning (i.e. lithography errors of less than one dimer row or pixel) over length scales up to 100 nm. On scales up to 500 nm, position errors of up to 2.5% were observed. These errors on the larger scale are caused by hysteresis, both directly and through the effect of the hysteresis on the creep errors.

In this work, we address these errors by continuing to optimize the correction of piezo creep, and also implementing real-time correction of hysteresis. Data comparing the effect of the real time positioning corrections on creep in xy and z will be offered. For movements within small areas, creep correction reduces positioning errors by more than 90%. Our current hysteresis model, which we continue to improve, corrects hysteresis errors by about 80%. Real-time corrections in the z direction greatly reduce the settling time of the tip after landing, from about 90 minutes to about 30s. The reduced settling time and minimized z drift after landing allows processes which require the feedback loop to be switched off, such as spectroscopy or atom manipulation, to be performed more efficiently.

In parallel with real-time position corrections, we have developed automatic fiducial alignment routines, allowing any remaining errors to be corrected. The tip position can either be aligned to previously-drawn patterns or to deliberate fiducial marks. A large pattern can therefore be stitched together from an array of write fields, i.e. areas within which atomic precision can be obtained. Thus, the precise patterning achieved for small areas can be scaled to large areas.

Taking all these techniques together, we present a set of design rules, which will allow for successful atomic-precision patterning from the single-atom to the micron scale.

1 M. Fuechsle, et al. *Nat Nano* **7** 242-246 (2012) DOI:: 10.1038/nnano.2012.21
2 C. D. Hill, et al. *Science Advances* **1** (2015) DOI: 10.1126/sciadv.1500707
3 J. Salfi, et al. *Nat. Commun.*, vol. 7, p. 11342, 2016. DOI: 10.1038/ncomms11342