Expanding the scale of Atomically Precise STM Lithography

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Hydrogen Depassivation Lithography using an STM tip has become established as a method for atomic-precision patterning for P-dopant-based devices. For fabrication of complete devices, the patterns required span several length scales. First, for a device such as the 'single atom transistor' [1], a single isolated P atom needs to be incorporated into the surface. In this case, a precise 3-dimer pattern is created. The immediately surrounding electrodes, such as source and drain electrodes, and any control gates, need to be positioned close to this single P atom with high precision; the device characteristics will depend on the precise number of atomic spacings from the single atom to the electrode. However, further away from this central device region, the requirements for precision are reduced, as interconnects join the electrodes to relatively large bond pads (> 1x1μm^2) which connect the device to the outside world.

As the number and complexity of these device patterns increases, it is necessary to improve the precision of tip motion over these multiple length scales and to automate the device fabrication processes
Atomic-precision patterning requires the alignment of the STM tip to the dimer rows on the Si(001) surface, and the alignment to previously-written patterns. This is done by taking an image of the area, and determining the local position, angle and phase of the dimer rows, and the location of alignment marks.

The piezo tube scanners common in STM systems suffer from two sources of position error; creep and hysteresis. For small movements, the dominant source of error is which is a time-varying position lag in tip position behind the applied piezo voltage. Piezo creep occurs on timescales from ms up to thousands of seconds, with a total size of about 10% of any movement. We correct this in real time in our software, and can reduced the position errors by about 90%, so that the tip position precision is better than one dimer row over about 100 nm, and 1-2% over larger distances. Hysteresis errors are time-invariant, and vary quadratically according to the distance travelled away from the zero point. Hysteresis errors become particularly significant when the tip writes large bond pads, as they involve large movements to large distances from the origin. Movement away from and back to the central device area to write a bond pad can result in position errors of hundreds of nm. We have developed strategies to reduce the size of the hysteresis errors, combined with automated alignment to fiducial marks to re-align the tip to the pattern after each large move. The smaller hysteresis errors greatly reduce the search area and therefore the time required for the fiducial alignment process. Alignment to fiducial marks also allows for stitching together multiple write fields to make atomic-detail patterns over large areas.

We shall present data showing the effect of the real-time creep correction as in Fig.1, and the effect of the hysteresis correction methods that we have applied, as in Fig.2. Quantitative data on the pattern placement precision achieved over different length scales will be presented. In this way, we are developing strategies for atomically-precise patterning over the whole device area.

[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).

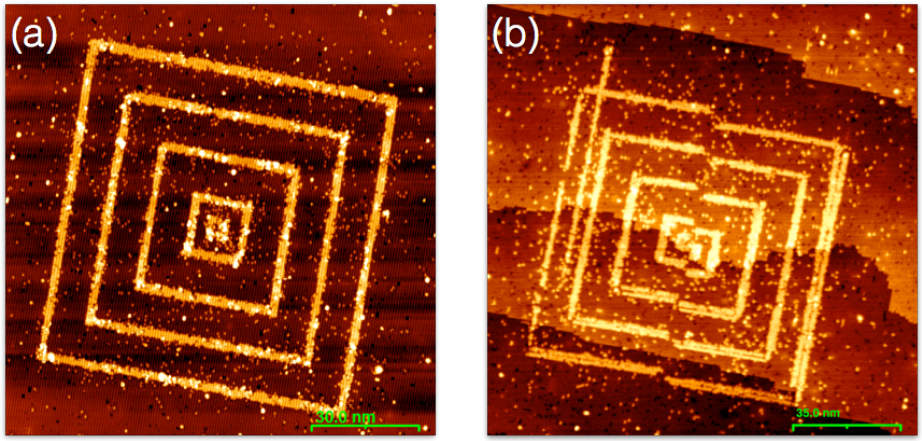

Figure 1. (a): Output of test pattern consisting of 5 concentric squares, written as left half and right half as bitmaps, with creep correction applied. (b): Same test pattern without creep correction applied.

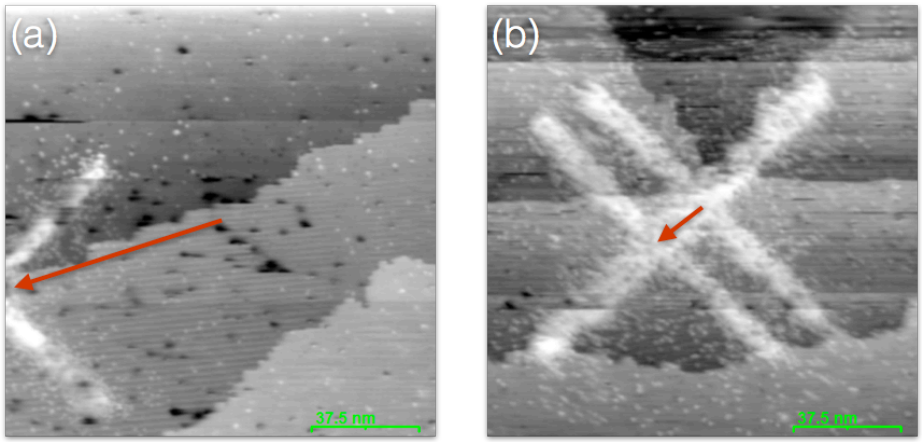

Figure 2. (a): STM image taken after moving 1 µm in x, and returning to the same coordinate. The white cross should be centered; the hysteresis error is about 80 nm. (b): Same process after applying hysteresis amelioration, error is now about 20 nm.