Multi-spot-size vector writing approach to atomically precise H depassivation lithography

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Removal of H atoms from a Si(001) surface by an STM tip, to write simple patterns such as dots, lines and rectangles, a technique known as H depassivation lithography, has been demonstrated by many different groups over the past two decades[1]. However, for a practical atomically precise manufacturing process with larger and more complex patterning, required for applications such as P-in-Si quantum computers[2], a more efficient process is necessary.

In our vector writing approach, the tip is moved directly to the area to be patterned, with a positioning precision of around 1 Å. Patterns are written as a series of adjacent lines, such that H is removed from the whole area. The tip can follow several different paths within the pattern, e.g. a series of separate lines, a serpentine pattern, a spiral, or a continuous outline of a larger area. We have used this approach to write 3 nm square boxes, shown in Fig. 1, with a line edge precision, which we have calculated to range between 0.01 – 0.1 nm.

Moreover, additional writing efficiency gains come from taking advantage of two different modes of STM depassivation: at low voltages, around +4 V sample bias, the atomically precise (AP) mode gives a depassivation linewidth of around 1 dimer row with effectively zero line edge roughness. At voltages above 7 V, a field emission (FE) mode takes over from quantum tunnelling, the linewidth becomes broader, and the depassivation efficiency increases dramatically allowing a corresponding increase in writing speed. However, the line edge roughness in the FE mode is large. For the writing of large patterns while maintaining atomic precision at the edges, therefore, we can utilise multi-spot-size lithography, writing the edges of the pattern using the AP mode and fill in the bulk of the pattern using the FE mode, or vice versa.

A simple example is shown schematically in Fig.2. The pattern is divided into interior and edge regions. These are further divided into horizontal and vertical lines, such that there are no overlaps, and each line is as long as possible. The longest line is written first; when finished, the tip moves to the closest start point to write the next line. Writing one line after another, the whole pattern may then be completed with minimized tip transitions and path length.

1. Walsh, M. A. & Hersam, M. C. *Annu. Rev. Phys. Chem.* **60**, 193–216 (2009).
2. Ruess, F. J. Oberbeck, Lars, Simmons, M Y, Goh, K E J, Hamilton, Alex R, Hallam, T, Schofield, S R, Curson, N J and Clark, R G *Nano Lett.* **4**, 1969–1973 (2004).

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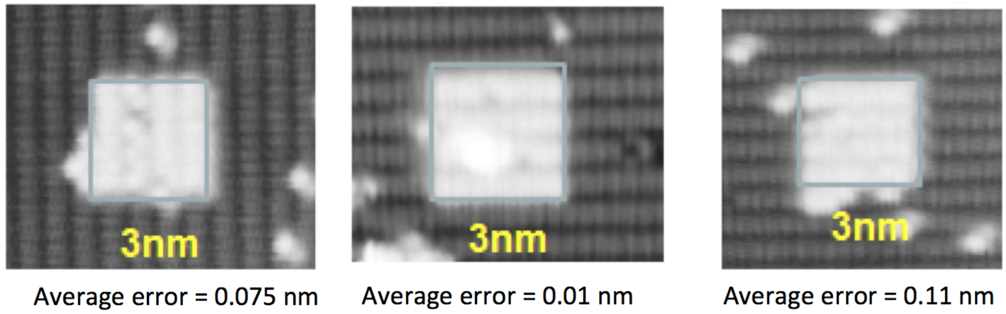

Fig.1: 3 nm boxes written using our vector-based lithography approach. The error has been assessed based upon the number of extra H atoms removed around the edges. For a good example, this can be as small as 0.01 nm.

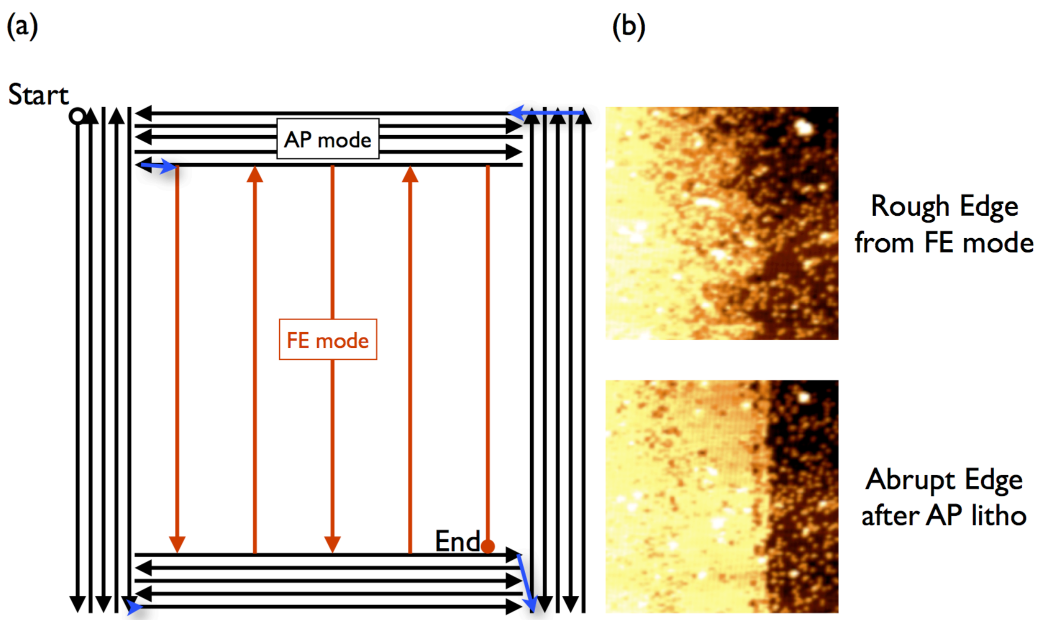

Fig.2: (a): Schematic of an arbitrary pattern broken down into edge and interior parts, and then further divided into tip vectors. Black arrows represent atomically precise lines, and red arrows represent writing in field-emission mode. Where they are not immediately adjacent, the start and end points are joined by the blue arrows. (b): Demonstration of large-area patterning with precise edges using multi-spot-size. Upper: the large pattern in Field Emission (FE) mode has been written, leaving a rough edge. Lower: after performing a series of lines in Atomically Precise (AP) lithography mode, the edge of the large pattern has been made much more abrupt.