Tip-assisted Dopant Incorporation Process for Atomic Precision P-in-Si qubit devices

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Various P-dopant-based atomic-scale devices have been fabricated with near-atomic precision using H depassivation lithography (HDL) to write patterns on a Si(001) surface, onto which PH_3 is adsorbed. The P from the PH_3 is incorporated into the surface with a brief anneal to 350°C, and buried using low-temperature Si MBE[1,2]. For devices such as the 'single atom transistor' [1], a single isolated P atom needs to be incorporated into the surface at a particular distance from other electrodes. In this case, a 3-dimer pattern is created, into which three PH_3 molecules are adsorbed at room temperature. The anneal process drives off two PH_3 molecules, and the third incorporates into the Si surface. However, three issues remain with the current process. First, the yield of single P atom incorporation is around 70% for a 3-dimer pattern, with 0, 1, or 2 incorporated atoms possible. Second, the exact position of the P atom cannot be controlled. Finally, P atoms can diffuse in x,y, or z during the incorporation anneal, even when using optimized incorporation conditions[2]. Since the patterned deposition and anneal happen at different temperatures, STM metrology becomes difficult for checking the number or exact position of the incorporated P atoms.

We have developed a single-temperature process for P incorporation. We perform HDL on PH_3-saturated Si(001) surfaces and in PH_3 patterned areas of H-terminated Si(001) surfaces at room temperature, and at elevated temperatures up to 300°C. We present STM data at elevated temperatures below 300°C, demonstrating that the P incorporation reaction can be activated by an STM tip, and resulting in the formation of short Si islands (as in Fig.1), similar to those obtained from a 350°C Rapid Thermal Anneal (RTA) process (see Fig.2). By performing HDL on the PH_3 saturated surface, we can cause P incorporation at a lower temperature than the thermal annealing process, reducing dopant diffusion. More importantly, it allows for instant metrology on the success of P atom incorporation and location.

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) DOI: 10.1038/nnano.2012.21
2: J. G. Keizer, S. Koelling, P. M. Koenraad, and M. Y. Simmons *ACS Nano* **9** 12537-12541 (2015) DOI: 10.1021/acsnano.5b06299

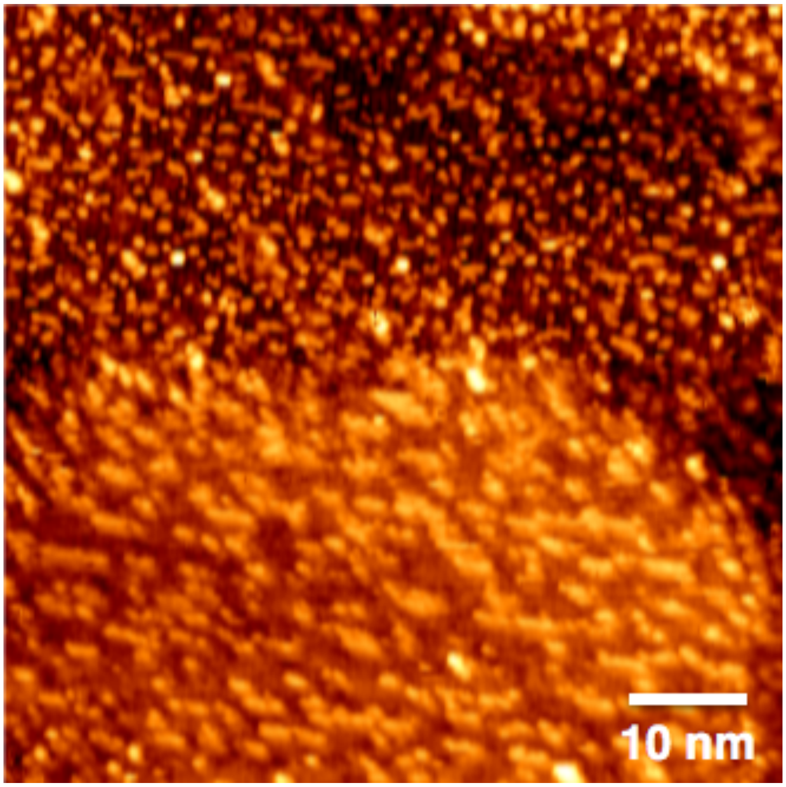

Figure 1: PH_3-terminated Si(001) surface at 250°C. The upper half of the image is unreacted PH_3 fragments. In the lower half, STM lithography was performed, causing P incorporation as identified by the presence of short Si islands.

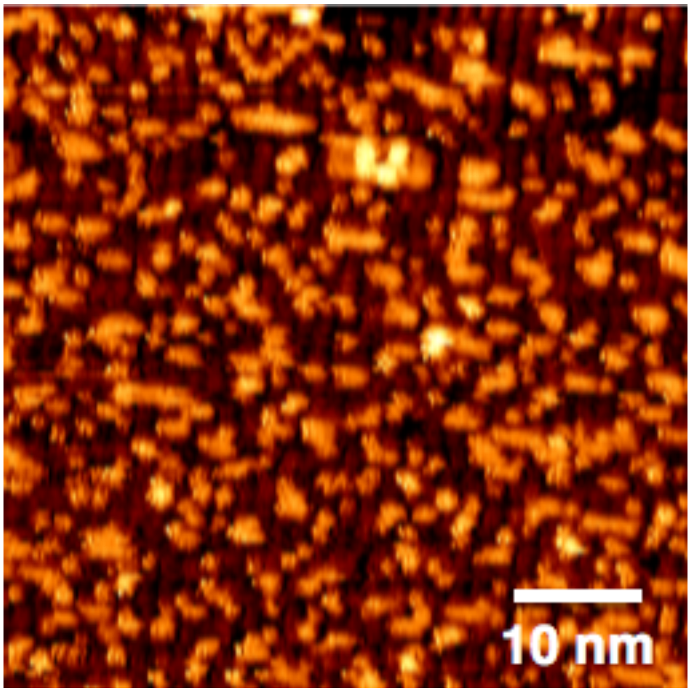

Figure 2: Si(001) surface after incorporation anneal to 350°C for 14s, using Rapid Thermal Anneal recipe as described in [2].