

# Single-Dopant Arrays using Tip-assisted Incorporation Process

J. H. G. Owen, J. Ballard, E. Fuchs, J. N. Randall and J. R. Von Ehr  
Zyvex Labs LLC, 1301 N. Plano Rd, Richardson, TX 75081, USA.  
jowen@zyvexlabs.com

For dopant-based atomic-scale devices such as the ‘single atom transistor’ [1] and 2D Quantum Metamaterials, single isolated dopant atoms need to be incorporated into the surface at a particular distance from other dopants. For desired device properties, certainty over both the number of dopants placed and their positions is required.

The current thermal incorporation process for P involves the deposition of three PH<sub>3</sub> molecules into a 3-dimer pattern. A thermal anneal drives off two PH<sub>3</sub> molecules and the third one incorporates. However, the yield of single P atoms is only 70% for a 3-dimer pattern, and for 4-dimer or larger patterns, there is a possibility to adsorb two P atoms[2], which would have different properties. A proposed process to achieve a higher yield of adsorbed P and remove the possibility of adsorbing two P atoms is to use an STM tip to remove the H from a PH<sub>2</sub> adsorbed species, thereby closing the redesorption pathway[3]. A schematic pathway is shown in Figure 1.

We are developing tip-based incorporation processes for P and Al dopants. First, Feedback Controlled Lithography is used to create single dimer patterns. Single molecules are adsorbed into these patterns. The tip then removes H locally from the adsorbed fragments and the background Si. A short room-temperature deposition of Si is used to bury the P fragments in a locking layer before low-temperature overgrowth, to minimise the diffusion of the P during encapsulation. For Al dopants, we are using Trimethyl Al (TMAI) as a precursor, which shows strong selectivity to the created patterns, and exploring AlH<sub>3</sub>[4]. In this case, single dimer patterns do not appear to be reactive to single TMAI molecules; 2-dimer patterns are required for adsorption of a single molecule, and steric hindrance blocks adsorption of a second dimer, as seen in Figure 2.

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

3: Q. Liu, Y. Lei, X. Shao, F. Ming, H. Xu, K. Wang, and X. Xiao, *Nanotechnology*, **27**(13), 135704, (2016). DOI: 10.1088/0957-4484/27/13/135704

4: R. Smith and D. R. Bowler, Arxiv: 1711.08401, Nov. 2017.

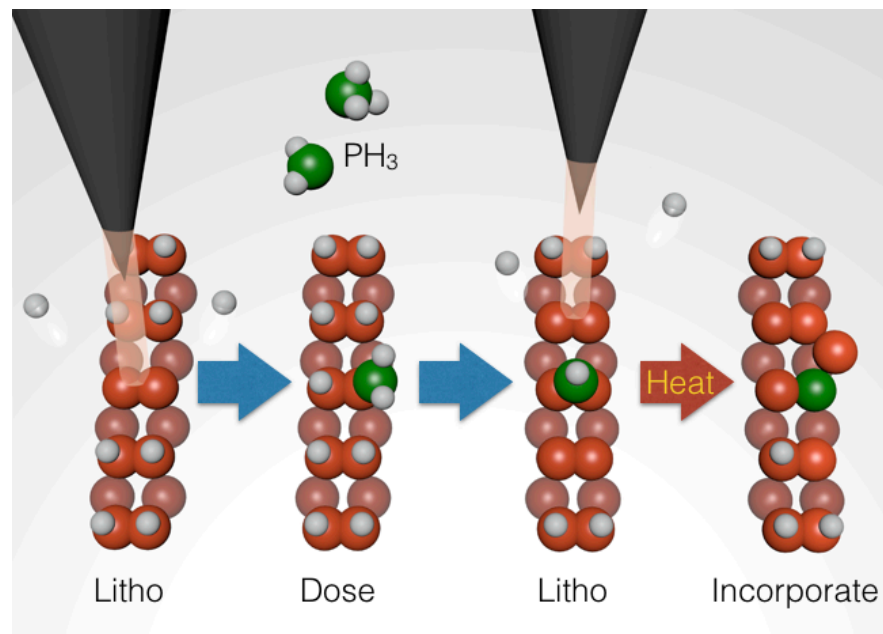


Figure 1: Proposed Tip-based Process for P dopant incorporation. A single dimer pattern is created using STM Lithography. PH<sub>3</sub> is adsorbed, A second round of Lithography removes H from the PH<sub>2</sub>. An incorporation anneal causes exchange of the P atom with a Si dimer atom. The dopant can then be encapsulated.

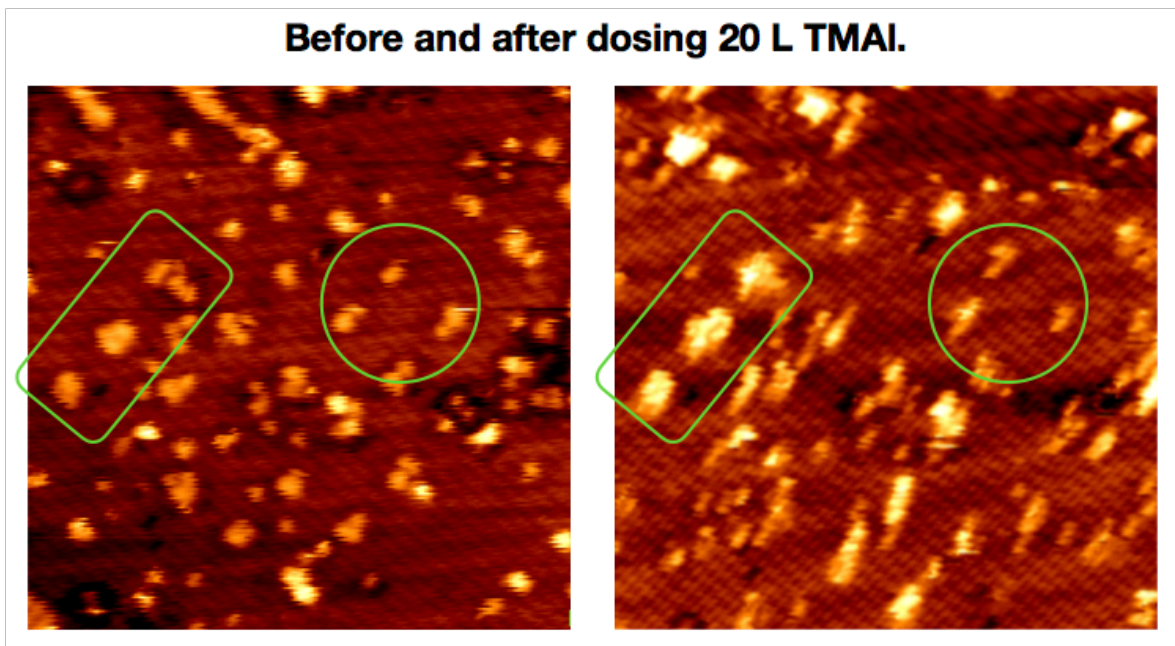


Figure 2: Array of few-dimer patterns before and after adsorption of 20L TMAI. Most of the patterns have adsorbed single TMAI molecules [rectangle]. The smallest 1-dimer-wide patterns (circled), however, show no adsorption, indicating that the minimum size pattern for TMAI adsorption is two dimers.