Towards Single Atom Doping and Control in Silicon

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Quantum computing holds the potential to revolutionize many areas of science and industry, such as cryptography, scientific computing and secure commerce. However, at present, there is no clear path to make reliable operational qubits on a practical scale. An important step towards this goal and towards other 'quantum' devices would be the ability to accurately image and even position individual dopant atoms inside materials.

Single dopant atoms in a semiconductor would provide a promising framework with which to construct qubit systems. Silicon is an ideal substrate for this challenge because it is compatible with existing manufacturing technology and because it can be isotopically purified. Bismuth is an appealing dopant because it has strong spin-orbit coupling, and the high atomic number (Z) makes it amenable to Z-contrast imaging in a scanning transmission electron microscope (STEM), as shown in Figure 1. However, obtaining films doped with bismuth presents several challenges for epitaxial growth as it is not readily soluble in silicon, meaning that the dopants tend to migrate out of position, necessitating careful control of the growth conditions, and resulting in interesting low-dimensional structures.[1]

In high-resolution electron microscopy, changes to the sample due to interaction with the electron beam are often ignored and are usually regarded as undesirable. Here we show how the electron beam can be used to position dopants inside a material, opening a new pathway for making quantum structures atom-by-atom[2,3].

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[1] J. Song, et al, Nanoscale 10 (2018) 260-267.
[2] O. Dyck, S. Kim, S. V. Kalinin and S. Jesse, Appl. Phys. Lett. 111 (11), 113104 (2017).
[3] B. M. Hudak, J. Song, H. Sims, M. C. Troparevsky, T. S. Humble, S. T. Pantelides, P. C. Snijders and A. R. Lupini, ACS Nano (2018).

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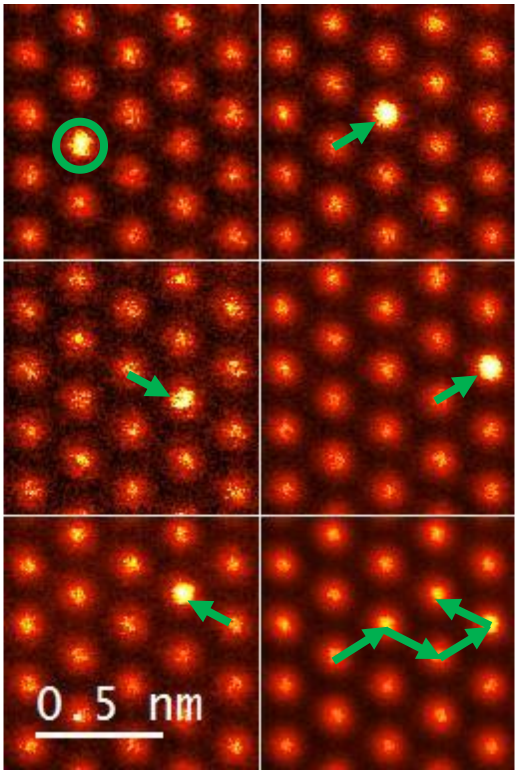

Figure 1. Consecutive positions of a single Bi dopant in Si moving under the influence of the electron beam. Drift-corrected mages are extracted from a sequence of 50 frames taken in a 200 kV STEM. Each panel is the average of all the frames at each position, apart from the final panel that shows the sum of all 50 frames with the full path overlaid.