Isolation and characterisation of novel isotope clusters for ion-implanted qubits

Maddison Coke
Mason Adshead, Evan Tillotson, Kuxue Li, Katie Moore, Sarah J. Haigh and Richard J. Curry

Department of Electrical and Electronic Engineering, Photon Science Institute, University of Manchester, Oxford Road, Manchester M13 9PL, UK
Maddison.coke@manchester.ac.uk

Single ion implantation has been demonstrated to create spin-centres [1] such as Si:P, which was the basis for the Kane proposal for solid-state qubits in Si platforms [2]. It has been observed that the scaling of quantum information processing may be improved relative to P-based qubits when a higher-spin nucleus is used to provide qudits, which access higher dimensional Hilbert spaces. Enabled by the development of a library of liquid-metal ion sources for focused ion beam implantation in the P-NAME system [3], we present the isotopic isolation of a variety of possible qub(d)it candidates including P, Bi and Sb (**Figure 1**). Specifically, we explore Sb-cluster implantation, using nanoSIMs and TEM to confirm the isotopic composition of the implanted ion species. Analysis demonstrates the ability to implant ^{121}Sb, ^{123}Sb and critically, clusters containing a 1:1 ratio of ^{121}Sb and ^{123}Sb via Wien filter selection. Furthermore, we demonstrate TEM analysis of Sb-cluster implantation into 20 nm thick Si membranes. Sb ions residing within the Si lattice are identified by aberration-corrected STEM. Statistical analysis of Sb-ion separation demonstrates a ~3 nm spacing, (**Figure 2**) indicating the ability to create well-controlled spin-centre pairs. ^{123}Sb provides access to a 16-dimensional Hilbert space through its 7/2 nuclear spin coupled to the spin ½ donor-bound electron. Furthermore, the utilisation of Sb-clusters allows coupled qudits to be envisaged which may be scaled to form larger arrays. These would significantly reduce the complexity of fabricating a D-dimensional computing space in comparison to using qubits.

References

[1] A. M. Jakob, et al., Scalable Atomic Arrays for Spin-Based Quantum Computers in Silicon. Adv. Mater. 2024, 36, 2405006.
[2] Kane, B. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).
[3] Adshead, M et al. (2023), A High-Resolution Versatile Focused Ion Implantation Platform for Nanoscale Engineering. Adv. Eng. Mater., 25: 2300889.

Figures

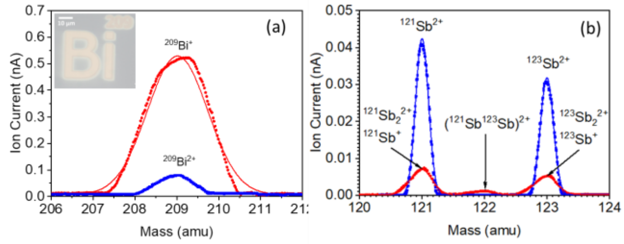

Figure 1: Wien filter mass spectra of B and Sb ion species accessible from the LMAISs so far utilized in the P-NAME system. Spectra were obtained by varying the Wien filter electrostatic plate voltage using a 25 kV acceleration voltage. Insert showing direct write capability.

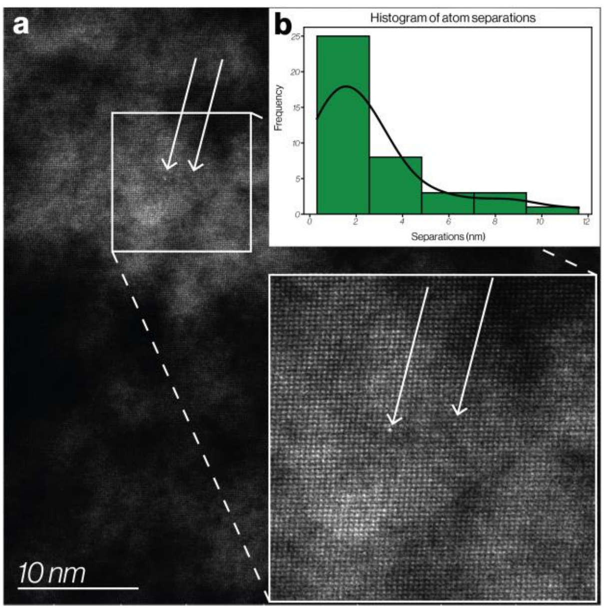

Figure 2: a, atomic resolution STEM characterisation of Sb single-atom dopants with b, histogram of separations for Sb cluster implantations (inset).