The Development of Nanoscale Deterministic Ion Implants into Si and Diamond

Andrew D. C. Alves, Jessica van Donkelaar, Jonathan Newnham, Samuel Thompson, Brett Johnson
Jeffrey McCallum Kumaravelu Ganesan, Changyi Yang, Steven Prawer, David Jamieson

Australian Research Council Centre of Excellence for Quantum Computer Technology, School of
Physics, The University of Melbourne, Melbourne Victoria 3010, Australia
aalves@unimelb.edu.au

Low energy ion implantation is seen as a critical enabling technology in new electronic, spintronic and photonic devices which are being continually proposed [1-3]. The ultimate goal of the implant in this context is to reduce the implant energy and increase spatial resolution so that the implanted atom resides in an extremely well defined location. The impurity atom must be placed relative to gates controlling local electronic and magnetic fields and to couple emitted photons to optical waveguides or photonic crystals. The desired end; to load, transport, store or read out quantum states without losing the quantum encoded information to decoherence. Two popular quantum systems to be used in quantum computation and communication are the electron spin on a donor atom in Si, or a single photon emitted from a color centre in diamond. These systems rely on impurity atoms placed with nanometer scale precision inside the bulk. The preferred implant technique is to mask the substrate material with a nanometer scale aperture (Typically tens of nm wide) which can be moved relative to the substrate [4, 5].

In this paper we demonstrate the placement of both 14 keV P into Si and 14 keV N into diamond. At this energy the ion straggle is limited to a few tens of nm and one can begin to experiment with impurities one-by-one, such as measuring the spin on a single electron [6]. In the first instance donor implants are timed to demonstrate the high spatial precision of the process. Atomic force microscopy has been used to probe a Si substrate implanted with P donors and confocal microscopy has been used to image a diamond implanted with N (Fig. 1 a, b). To further understand the spatial limit of the implant process we demonstrate measurements of the amount of ion scatter from an aperture and compare this result with modeling of the ion scatter (Fig. 1 d). This modeling offers further insight into the masking process and guides the experimental conditions in a deterministic implant scenario. We also demonstrate in-situ optical alignment which allows us to align the mask with pre-existing features on the substrate.

These implants are ultimately governed by stochastic processes and the number of atoms is not precisely controlled. To implant each atom deterministically we must also detect each implant. Methods of low energy ion detection, via charge collection in a PIN structure or charge action in a MOSFET structure, have been demonstrated in Si [7, 8]. We have coupled the detection and placement aspects of deterministic implants using a higher energy 500 keV He ion beam (to ease the low noise demands on detection). This coupling of detection and placement has allowed us to register the implant to a pre existing static feature on the substrate beyond the finest spatial resolution that could be achieved with only optical alignment (Fig. 1 c).

We have also investigated the detection of single ion impacts in diamond using a metal-diamond-metal structure biased to collect ion beam induced charge in the diamond. The results show the charge collection efficiency is maximized when high purity single crystal CVD diamond is used and it is promising that low energy N implants may also be detected (Fig. 1 e).

In summary many aspects of low energy deterministic implants of single impurities into Si and diamond are investigated.

References

[1] G.P. Lansbergen, R. Rahman, C.J. Wellard, I. Woo, J. Caro, N. Collaert, S. Biesemans, G. Klimeck, L.C.L. Hollenberg, S. Rogge, Nature Physics, **VOL 4** (2008) 656
[2] B.E. Kane, Nature, **VOL 393** (1998) 133
[3] J.O. Orwa, A.D. Greentree, I. Aharonovich, A.D.C. Alves, J. Van Donkelaar, A. Stacey, S. Prawer, Journal of Luminescence, ARTICLE IN PRESS
[4] A. Persaud, S.J. Park, J.A. Liddle, T. Schenkel, J. Bokor, I. W. Rangelow, Nano Letters **Vol. 5, No. 6** (2005) 1087
[5] C.D. Weis, A. Schuh, A. Batra, A. Persaud, I.W. Rangelow, J. Bokor, C.C. Lo, S. Cabrini, E. Sideras-Haddad, G.D. Fuchs, R. Hanson, D.D. Awschalom, T. Schenkel, J. Vac. Sci. Technol. B **26** (2008) 2596
[6] A. Morello, J.J. Pla, F.A. Zwanenburg, K.W. Chan, H. Huebl, M. Mottonen, C.D. Nugroho, C. Yang, J. A. van Donkelaar, A. Alves, D.N. Jamieson, C.C. Escott, L.C.L. Hollenberg, R.G. Clark, A.S. Dzurak, http://arxiv.org/abs/1003.2679

[7] D.N. Jamieson, C. Yang, T. Hopf, S.M. Hearne, C.I. Pakes, S. Prawer, M. Mitic, E. Gauja, S.E. Andresen, F.E. Hudson, A.S. Dzurak, R.G. Clark, Appl. Phys. Lett. **86** (2005) 202101

[8] A. Batra, C.D. Weis, J. Reijonen, A. Persaud, T. Schenkel, S. Cabrini, C.C. Lo, J. Bokor, Appl. Phys. Lett. **91** (2007) 193502

Figure

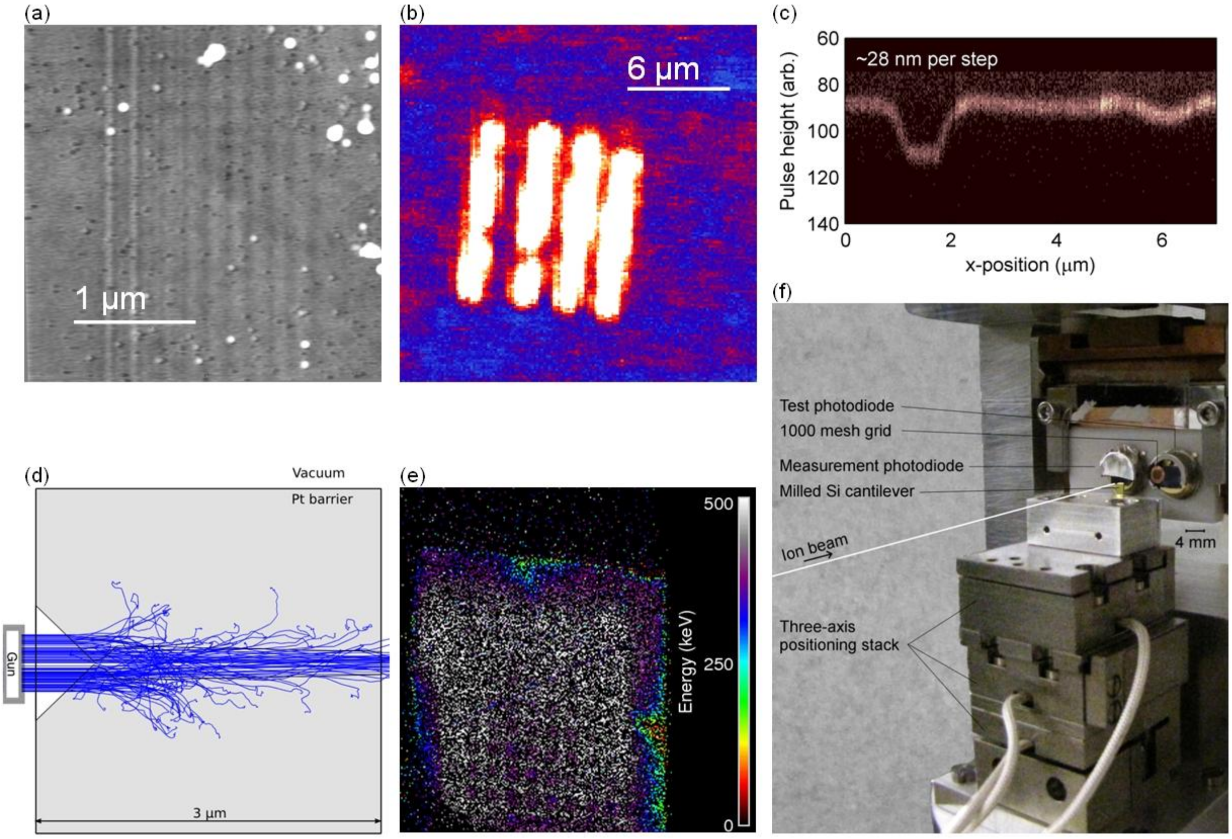

Figure 1.

(a) AFM image of 14 keV P implants into Si. The ion implants cause the SI surface to swell and to dip depending on the dose of the implant. A 60 nm wide aperture was used to define the beam and the step size of the scanned aperture was 200 nm.

(b) Confocal map of 14 keV N implants into diamond. The ion implantation results in N-V color centers after 1100 °C anneal. A 100 nm wide aperture was used to define the beam and the step size was 2000 nm. In this case the resolution of the image is not limited by the implant but rather by the confocal microscopy.

(c) A 500 keV He ion beam was scanned across a PIN detector with a patterned PMMA coating using a 100 nm wide beam defining aperture. The transmitted ions produced a pulse in the detector electronics proportional to the thickness of PMMA traversed, thus producing a map of the topography.

(d) A simulation of ion scatter from a 60 nm wide focused ion beam milled aperture. The internal geometry of the aperture has been tailored so the energy spread of exiting ions matched the measured energy spectrum during experiment. This model can be used to predict the ion scatter when attempting a deterministic implant of a low energy ion.

(e) An ion beam induced charge map of a metal-diamond-metal charged particle detector. 500 keV He ions were used to map this device and determine the noise floor for this device.

(f) The apparatus used to scan a nanoscale beam defining aperture over a PIN charged particle detector.