Ion Beam Program

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1. Overview

The quantum device (Ion Beam) program at the University of Melbourne collaborates closely with the quantum device program at the University of New South Wales on the fabrication, by top-down methods, of Si:P devices containing single or few dopant atoms. Over the past decade we have perfected an integrated method of counting single atoms into silicon devices. As the result of industry interest in this work we now refer to the method as "deterministic doping". In 2009 a number of our devices showed extremely interesting characteristics based on the transfer of single electrons consistent with the control of the electron spin orientation. These exciting results are documented elsewhere in this report. During 2009 we also commenced work on experiments aimed at the detailed investigation of the environment of the implanted donors that will continue in 2010. A highlight of 2009 was the invitation to present our work at an interdisciplinary workshop "Atomics09" in Germany with delegates working on different strategies for the exploitation of the quantum attributes of single atoms.

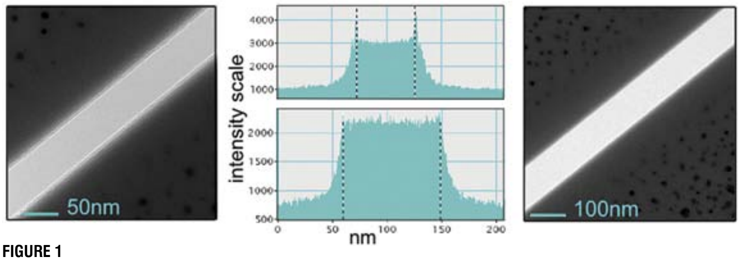

FIGURE 1

The heart of the step-and-repeat system is a nano-scale aperture milled into a 200 nm thick SiN membrane as shown here where characterisation of the aperture dimensions has been performed with Transmission Electron Microscopy. The minimum slot width is 50 nm.

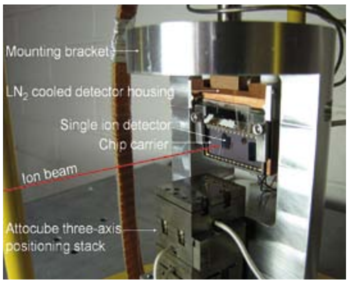

FIGURE 2

The prototype apparatus designed to allow the collimation of an ion beam using a scanned nano-scale aperture such as the one shown in Figure 1. A single ion detection capability is housed behind the aperture for controlled deterministic doping of devices.

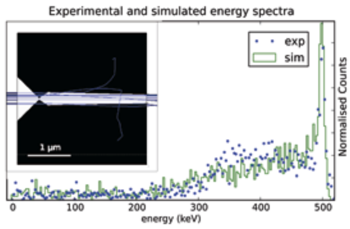

FIGURE 3

The energy spread in the transmission of ions through a nano-scale aperture has been measured for 500 keV He ions and modelled with the GEANT4 simulation package. The model for the internal geometry of the aperture has been fitted to simulate the experimental data.

2. Technological development toward deterministic doping control

The deterministic doping capability has been the main objective in the development of the ion beam program. We have been developing a step-and-repeat system that incorporates our on-chip single ion detectors and employs a scanned nano-scale aperture which collimates the ion beam to less than 100 nm. We fabricate nano-scale apertures by focused ion beam milling of Si cantilevers and SiN membranes and use SEM and TEM imaging to characterise the milling process (shown in Figure 1). Aperture scanning is achieved with a piezoelectrically driven Attocube™ three axis positioning stack. In 2009 the hardware was developed to mount the positioning stack and the beam collimating aperture in front of a single ion detector (shown in Figure 2). This second generation single ion detection system will operate in parallel with the first generation system already developed by the ion beam program. With the first generation system we have demonstrated sub-100 nm ion localisation by writing structures ion beam lithography in PMMA photoresist. We have now begun characterisation of the noise threshold of the new system and in 2010 will apply it to the detection of low energy single ion implants. Detailed modelling of the ion scatter in the aperture has been performed with the Monte Carlo ion transport code GEANT4. This was done to evaluate the spatial precision of the system and to evaluate the experimental results. We find that the energy spectrum produced experimentally was closely replicated in simulation for MeV ions (shown in Figure 3). We intend to now use this simulation to model the spatial precision of aperture-defined implant of ions in the keV energy regime.

3. Characterization and evaluation of new detectors for single ion implantation

In the middle of 2009 a new device structure was developed for the integration of p-i-n structures for single atom deterministic doping incorporating p-type channel-stop regions to eliminate parasitic leakage currents in *n*-MOS structures. The structures are configured for the assembly of a metal-oxide-semiconductor (MOS) spin-qubit architecture based on phosphorus donors in silicon. The devices were fabricated on a 10 kΩ-cm *n*-type high resistivity <100> silicon wafer (double-sided polished, 525 µm thick) using standard micro-fabrication processes. The n^+ (source, drain and backside contact) and p^+ regions were produced via high concentration phosphorus and boron diffusions respectively, each with peak densities of approximately 10^{20} cm^{-3}. The p^+ regions function as both: i) single-ion implant detector electrodes; and ii) channel stoppers to eliminate electron leakage paths between the n^+ source and drain, which form below the SiO_2 field oxide due to trapped positive charge in the oxide. Additional *p*-type channel-stop fingers

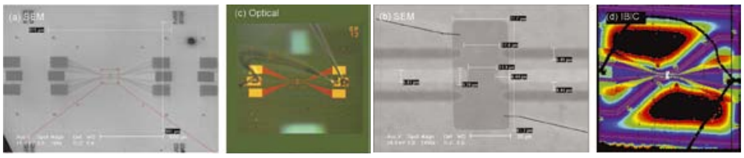

FIGURE 4

Characterization of the new detector which incorporates a channel stopper structure. (a) Scanning Electron Microscope (SEM) image of the entire device; (b) zoom-in SEM image shows details of the device central area; (c) optical image of the device; (d) IBIC image shows the charge collection efficiency as a grey-scale with white corresponding to an efficiency of 100%.

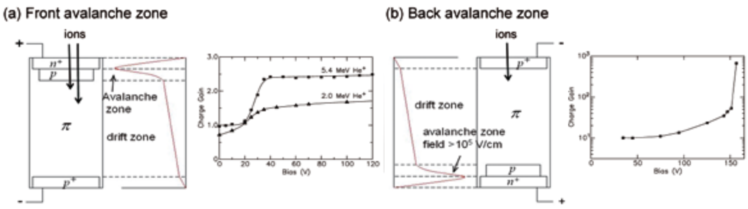

FIGURE 5

The two APD architectures, typical of commercially devices, investigated for high sensitivity single ion impact detection: (a) 2 MeV He^+ ions enter into the APD device with the avalanche zone constructed at the entrance side. The internal charge gain is saturated a relatively low value. (b) The 0.5 MeV He^+ ions enter into the APD device through the drift zone and the avalanche zone is constructed at the backside of the device. The internal charge gain reaches a very high value (>100).

were produced via low concentration boron diffusion with a peak density of approximately 10^{16} cm^{-3}. Both p^+ detectors and *p*-type channel stopper regions are connected together. The structure of these new devices is shown in Figure 4 along with the single ion detection efficiency measured by Ion Beam Induced Charge (IBIC). The IBIC analysis provided the following crucial information (1) the construction zone at the device central area has 100% charge collection efficiency; (2) the virtual detector-electrode area at the surface extends over a large area and hence produces an extra device capacitance arising from channel stoppers and n-type contacts. However it is remarkable that the channel stopper electrodes can serve the dual purpose of charge suppression *and* single ion implant detection.

The new devices need to be further evaluated with the measurement of keV x-rays and the detection of keV ions to investigate the signal-to-noise ratio arising from the extra capacitance. This issue has been of continuous interest to the device program since the commencement of CQCT. We have identified three types of noise sources encountered during the single ion implantation applications and developed strategies for their minimisation. The first type of noise is associated with the detector leakage current, the second type from device capacitance and the third from thermal noise originating from resistive elements such as the feed-back and detector resistances. These noise sources are well-understood and controlled in the single ion implantation system. In 2009 we recognized a fourth type of noise source in the new devices. This noise originates from trapped charges associated with device defects from material imperfection or device interface defects related to fabrication issues.

4. Top-down developments for higher spatial precision

The challenge of improving the spatial precision of our top-down implantation strategy will require lower energy implants that our present 14 keV P^+ in order to reduce the ion straggling. Our roadmap to address this challenge is to develop new detector architectures with higher signal to noise ratios for low energy ions. One solution, being developed by our colleagues at the Sandia National Laboratory, is to employ avalanche detectors operated in Geiger mode and we had the opportunity to characterize these devices in our laboratory in 2009. We also investigated two different architectures used in commercially available avalanche photodiodes (APD) shown in Figure 5. The response of these devices to ions differs from the response to photons because of the different nature of the initial charge carrier production along the path of the incident ion and the position of the avalanche zone in the device. Since ion impacts can produce initial charge carriers at a well-defined depth, predominantly at the end of range, the charge gain measurement provides a unique insight into the drift and avalanche process within the structure of the APD.

We found that a high charge gain can be achieved in an APD device only if the ions impinge into a drift zone at a location with a considerable distance (>10 micrometers) from the avalanche zone. For CQCT applications involving keV heavy ions, it is also essential to have an ultra-thin passivation layer (5 nm or less SiO_2 equivalent) on the surface to allow ions to enter the active regions of the device without losing a large amount initial kinetic energy. We conclude that it will be possible to integrate an APD device with an ultra low noise charge read-out system that will allow deterministic doping with use single sub-20 keV ion implants. We also conclude that there are fruitful opportunities for shared experience between the quests to detect single ions and single photons. Both these technologies will be required for the quantum computer internet of the 21st C.

5. Conclusion and future developments

In 2009 we commenced collaborations with the group of Dr Martin Brandt at the Walter Schottky Institute in Germany to investigate the environment of the ^{31}P implanted ions. This offers the potential to perform sensitive magnetic resonance measurements on clusters and single implanted ions and look forward to this continuing into 2010. With regard to future applications of our step-and-repeat deterministic doping system: in 2010 we will collaborate with our UNSW colleagues on the fabrication of devices for high-sensitivity single-shot readout and control of the electron spin of individual donors in silicon [1] which build on our successful pilot experiments [2]. In the longer term we foresee devices for coherent transport for which the architecture is evolving [3] and the fabrication strategy was the topic of our review [4] presented at the Atomics09 conference. We look forward to addressing these major challenges in 2010.

6. References

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