## Charge sharing in multi-electrode devices for deterministic doping studied by IBIC

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**Abstract**

Following a single ion strike in a semiconductor device the induced charge distribution changes rapidly with time and space. This phenomenon has important applications to the sensing of ionizing radiation with applications as diverse as deterministic doping in semiconductor devices to radiation dosimetry. We have developed a new method for the investigation of this phenomenon by using a nuclear microprobe and the technique of Ion Beam Induced Charge (IBIC) applied to a specially configured sub-100 m scale silicon device fitted with two independent surface electrodes coupled to independent data acquisition systems. The separation between the electrodes is comparable to the range of the 2 MeV He ions used in our experiments. This system allows us to integrate the total charge induced in the device by summing the signals from the independent electrodes and to measure the sharing of charge between the electrodes as a function of the ion strike location as a nuclear microprobe beam is scanned over the sensitive region of the device. It was found that for a given ion strike location the charge sharing between the electrodes allowed the beam-strike location to be determined to higher precision than the probe resolution. This result has potential application to the development of a deterministic doping technique where counted ion implantation is used to fabricate devices that exploit the quantum mechanical attributes of the implanted ions.

**Introduction**

Fifty years ago the metastable energy levels in Cr doped Al2O3 were used to create the required population inversion for the first laser [[[1]](#endnote-1)]. Associated with this development was a widespread search for other long-lived excited states in the solid state. The exceptionally long relaxation time of electron spins in P doped Si were identified as specially promising [[[2]](#endnote-2),[[3]](#endnote-3)]. This long relaxation time is now recognised as having potential applications in solid state quantum information processing devices [[[4]](#endnote-4),[[5]](#endnote-5)] and successful coherent control of electronic states in this system has recently been demonstrated [[[6]](#endnote-6)]. Fabrication useful devices depends on (i) the development of single atom deterministic doping techniques which are now emerging [[[7]](#endnote-7),[[8]](#endnote-8),[[9]](#endnote-9)] and (ii) techniques to probe and control the quantum states of single atoms which have now been demonstrated [[[10]](#endnote-10),[[11]](#endnote-11),[[12]](#endnote-12)]. Deterministic doping by ion implantation has been used to configure a two P atom device in which the charge state of the individual donors was controlled [[[13]](#endnote-13)]. Even more promising is the successful demonstration [[[14]](#endnote-14)] of control and readout of a single electron spin on an implanted P atom which shows the immense potential of this class of devices.

The deterministic doping method for these devices relies on the detection of the charge transients induced on surface electrodes by single ion impacts where the incident ion kinetic energy is partially dissipated by electronic stopping processes that ionise the substrate. The aim of the present work it to investigate the diffusion and drift of the induced charge by means of two separated electrodes and the use of nuclear microprobe to control the ion strike location relative to the electrode positions. This will allow the proportion of charge shared between the electrodes to be used to estimate the ion strike location independent of knowledge of the position of the beam. This method offers several advantages over traditional silicon position sensitive detectors [[[15]](#endnote-15)] because the substrate does not have to be doped or subject to damage gradients [[[16]](#endnote-16)] and higher spatial resolution is possible compared to silicon strip detectors [[[17]](#endnote-17)] where new designs [[[18]](#endnote-18)] offer resolution down to 25 m. In the present experiments the electrode separation was the same order of magnitude as the ion range and the microbeam resolution was about an order of magnitude smaller.

**Experiment**

The details of our device and the experimental configuration have been previously described [7]. Briefly, we employ a p-i-n structure fabricated in a high-purity silicon substrate (>18,000 cm) [[[19]](#endnote-19)] configured with two independent front surface aluminium detector electrodes which make contact with two boron-doped p-wells (~1020 cm-3) (see schematic in Fig. 1 and images in Fig. 3a,b). These electrodes will be termed “L” and “R” hereafter. A further n-type back contact is fabricated from a phosphorus-diffused layer (1020 cm-3) and Al metallisation. The two front detector electrodes, L and R, overlap the edges of a central 12x12 m2 zone of thin surface oxide of 5 nm thickness (confirmed with transmission electron microscopy) and a surrounding region with a field oxide of thickness 200 nm. Previous IBIC measurements [[[20]](#endnote-20)] confirm that the electrical dead layer thickness of this device has an upper bound of 7 nm and hence is nominally the same as the oxide layer thickness to the measurement precision.

Each surface electrode was connected to independent data acquisition systems (hereafter “stations”) consisting of Ortec type 142B charge sensitive preamplifiers, Ortec type 576 amplifiers, ORTEC type 800 ADC units and a MicroDas [[[21]](#endnote-21)] multi-station nuclear microprobe data acquisition system. The electrodes are independently biased to –20V relative to the back contact by an Ortec 710 quad bias supply resulting in a leakage current of about 100 pA at room temperature. With this bias voltage the charge collection efficiency is maximised and we assume the detector is fully depleted. The MicroDas system generates a scan signal that positions the microbeam on the sample and the independent stations record event-by-event lists and pulse height spectra registered to the scan position. The nuclear microprobe employed for the work was the MP2 system [[[22]](#endnote-22)] at the University of Melbourne with a 2 MeV He+ ion beam from the NEC 5U Pelletron accelerator with a nominal probe size of 1 m. SRIM calculations [[[23]](#endnote-23)] show the range of these ions in the sample, measured from the surface, is 7.3 m with a lateral and longitudinal straggle of 0.4 and 0.3 m respectively. Hence the range is comparable with the 12 m separation of the two surface electrodes (shown to scale in Fig. 1) and the straggle is comparable with the nominal probe diameter. The device was mounted on room temperature stage fixed to a 4 axis goniometer which allowed the device to be positioned under the nuclear microprobe scan area.

The data acquisition system was triggered by ion impact events on the sensitive region of the device with a nominal rate of 2 kHz. Each ion impact induces a cloud of electron-hole pairs distributed along the path of the ion. This charge then rapidly drifts away from the path under the influence of the internal electric field of the reverse biased detector electrodes as shown by the TCAD [[[24]](#endnote-24)] simulation in Fig 2. The charge drift induces charge on the electrodes [[[25]](#endnote-25)] which produce a charge pulse signal that triggers the data acquisition system. After processing by the electronics chain on each station, it is traditional to refer to this as the “energy signal” meaning that it is the incident ion kinetic energy equivalent of the induced charge in the electrode. Each energy signal event is tagged by the data acquisition system with the electrode that generated the trigger pulse and the spatial coordinates of the scanning system. In the present system it is not possible to tag coincident events which are expected from single impacts where the induced charge is shared between the electrodes. However inspection of the combined event-by-event record of the impacts allows pairs of sequential events from different electrodes that are generated from a single ion impact to be identified from pairs of time-sequential events that sum to the nominal beam energy.

**Results**

Two separate scans of the device are presented here. In the first scan, a single-station IBIC map of the device was obtained from the L and R electrodes connected together as shown in Fig 3c. This map reveals the highest charge collection efficiency is from the thin oxide region of the device as expected and the associated energy spectrum (not shown) has a Full Width at Half Maximum (FWHM) of 15 keV which is the system noise corresponding to the electronics (in this and subsequent measurements presented here the experimental and statistical uncertainly is about 10%). From the FWHM of the rise in energy signal as a function of position over the edge of the thin oxide region the nominal beam spot size, convolved with the sample topography, is found to be <1.5 m. In the second scan, two independent station IBIC maps were obtained from the separated L and R electrodes as shown in Fig 3d for L only and Fig 3e for R only. In both these maps the diminished charge collection efficiency away from the respective electrodes is immediately evident.

The relationship between the energy signal and an ion strike location will be governed by the geometry of the device and statistical effects which include diffusion. This is also suggested by the 2D simulation in Fig 2, where diffusion is shown by the lateral spread of the charge plume. The issue of diffusion can be examined in more detail from the histograms shown in Fig 3f,g,h which show normalized energy spectra in the regions labelled A, B and C in Fig 3d. These histograms show the upper limit for the contribution of statistical variations in the energy signal due to diffusion convolved with the variations from the spatial resolution of the microbeam. The asymmetry in each histogram arises from the asymmetry in the charge collection efficiency as a function of position, with much greater variations expected for ion strikes in the side of regions A, B or C facing away from the respective electrode where the spatial gradient in the charge collection efficiency is steeper. The histograms of energy signals from the three regions have half widths of the order of 250 keV and this corresponds to a spatial uncertainly of 1.25 m using the energy to distance conversion of 200 keV/m suggested by Fig 3d,e. This uncertainty is consistent with the nominal probe diameter which therefore suggests the effect of lateral diffusion is smaller than the spatial resolution of the microbeam in the present device. We note that the carrier diffusion distance [[[26]](#endnote-26)] calculated from the characteristics of the substrate material previously described (electron mobility e=1.4x103 cm2V-1s-1 [[[27]](#endnote-27)]) and the device internal field strength from TCAD (*E* = 6x10-2 V/cm) is about 10 m for the expected electron collection time of 30 ns. Diffusion is not a concern for this technique because even for very-low-energy implantations, thousands of carrier pairs are generated each time an ion strike occurs. A homogeneous diffusion process will statistically distribute approximately equal numbers of carriers to each electrode and the charge sharing ratio will still identify the position of the ion strike (after accounting for a constant background signal due to diffusion, as observed in Figure 5).

With the event-by-event list used to construct the maps in Fig 3, it is possible to test the hypothesis that the charge sharing can be used as a proxy for the ion strike location. This is done by applying a cut to the data that selects only events in a horizontal slice about 10 m wide through the centre of the 12 m wide thin oxide region of the sample. For a strike within the thin oxide region, the ordered pair of energy signals, (EL, ER), add up to the beam energy and each energy signal should be proportional to the spatial location of the ion strike in the horizontal direction relative to the edge of the L or R electrode respectively. These ordered pairs are shown in Fig 4. The pair distribution forms a broad envelope linking the nominal incident beam energy on each axis. Note that a threshold on the ADC units suppresses energy signals below about 10% of the incident beam energy. The horizontal and vertical FWHM of the envelope of (EL, ER) pairs is about 75 keV or about five times larger that the energy resolution of the detectors themselves when operated with the associated electronics chain.

The more interesting result that can be obtained from the (EL, ER) map in Fig 4 is the equivalent spatial uncertainty that can be deduced by converting the share of the energy in a given electrode to a distance from the electrode by assuming that the energy share is linear with distance. In this case the 75 keV FWHM envelope of (EL, ER) pairs corresponds to an uncertainty of 0.5 m in position again using the energy to distance conversion of 200 keV/m suggested by Fig 3d,e. The position orthogonal to the line between electrodes is not determined by this technique but could be identified by adding at least one more electrode to the device. Note that this spatial resolution is independent of the fact a nuclear microprobe was used to collect the data and Fig 4 did not employ the position information recorded in the list of events. If the sample had been masked so that an unfocused beam could only reach the sample at the equivalent region to the data cut described above, the same (EL, ER) map shown in Fig 4 would be obtained. Further evidence that this is the case can be obtained from a map of EL or ER as a function of the microprobe position recorded in the list of events. This is shown in Fig 5. Here (EL, ER) pairs each induced by a single ion strike are mapped as a function of the ion strike location recorded in the list of events. In this case the ion strike location is uncertain by the diameter of the microprobe convolved with the diffusion effect in the charge sharing process described above. The FWHMs of the L and R signals from this map are both greater than 4 m which is more than eight times the result using the energy signal alone.

**Conclusion**

We have demonstrated that it is possible to employ the independent IBIC signals from surface detector electrodes to measure the ion strike location in a silicon device. For MeV ions incident on a suitably configured device, sub-micron precision is possible. Configuration of the device with an orthogonal third electrode could potentially allow maps to be made with an unfocused beam to sub-micron precision. By scaling the system down and employing sub-15 keV ions for sub-20 nm deep implants of donors in silicon, the electrode signals could be used to measure the implant locations of two deterministically implanted ions, including those from ordered ion traps [[[28]](#endnote-28),[[29]](#endnote-29)] or scanned cantilevers [[[30]](#endnote-30),[[31]](#endnote-31),[[32]](#endnote-32),[[33]](#endnote-33)]. By application of appropriate criteria, such information could be used to assess the suitability of the atom locations in a deterministically implanted device for further processing as the key component of a two-atom quantum device.

**Acknowledgements**

This work was funded by the Australian Research Council Centre of Excellence scheme and the US Army Research Office under Contract No. W911NF-08-1-0527. The authors are grateful for technical support from Roland Szymanski and Alberto Cimmino.

**Figure Captions**

Figure 1: Detector electrode geometry in cross section with the ion range and surface oxides shown to scale. The spacing between the edge of the L and R electrodes is 12 m. Implanted ion coordinates are from SRIM convolved with a random transverse displacement.

Figure 2: TCAD simulations of the negative charge drift and diffusion from a 2 MeV He ion strike midway between the L and R electrodes. The images show two dimensional simulations to provide a guide to the phenomena expected in the true three dimensional device. The electrodes are on the top surface with the ion trajectory incident normal to the top surface. The distance from the top to the bottom is 300 m corresponding to the actual device. The L and R electrodes are on the upper edge of the images but not clearly visible at this scale.

Figure 3: (a) Optical micrograph and (b) SEM image of the surface electrodes; Median energy IBIC maps of the device showing (c) the left (L) and right (R) electrodes connected together to a single data acquisition system; (d) and (e) the L and R electrodes connected to independent data acquisition systems; (f-g) histograms of the yield of energy signals for sub-regions (A-C) in (d) respectively for the left (L) and right (R) electrodes. In (c-e) the dashed line represents the nominal position of the thin oxide region and the electrodes. In (f-g) the horizontal bar indicates the mean and standard deviation energy in the corresponding histogram.

Figure 4: The distribution of (EL, ER) ordered pairs from each single ion impact in the event list without regard to the spatial information. The energy signal acts as a proxy for the ion strike location, for example (xL, xR), measured relative to the L and R electrodes respectively.

Figure 5: Coupled ordered pairs corresponding to individual ion strikes from the event list: (xL, EL) (filled circles) and (xL, ER) (open circles). Each coupled pair is shown connected by a vertical line. Only 50 randomly selected ordered pairs are shown from a total data set of more than 20,000 pairs.

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