Single ion implantation in the quantum computer construction project

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ABSTRACT

The construction of micro- and nano-scale electronic devices that exploit the properties of single atoms have been proposed. A very promising device is a silicon based solid state quantum computer based on an array of single ^{31}P atoms as qubits in a pure ^{28}Si substrate. Operation of the device requires independent control, coupling and readout of the state of individual qubits. We have developed a construction strategy for a few qubit device based on ion implantation of the qubits into prefabricated cells. An ion energy of less than 20 keV is necessary to ensure the ion range is at the required depth in the substrate which is of the order of 20 nm. Single ion impacts are registered by the electrical transient induced in an external circuit. Electron Beam Lithography fabricated cells, containing electrodes of the required nanometre scale, have been implanted with 14 keV ^{31}P ions and the pulse height spectrum of single ion impacts has been successfully recorded. Discrimination on the pulse height allows rejection of ions that suffer unacceptable straggling. This opens the way to the rapid construction of a two qubit device in the first instance that will test many of the essential mechanisms of a revolutionary solid state quantum computer.

1. INTRODUCTION

Single ion implantation offers a fast route for the construction of devices that exploit the properties of single atoms. This is because ion implantation allows ions to be implanted into a substrate to a depth determined by the initial ion

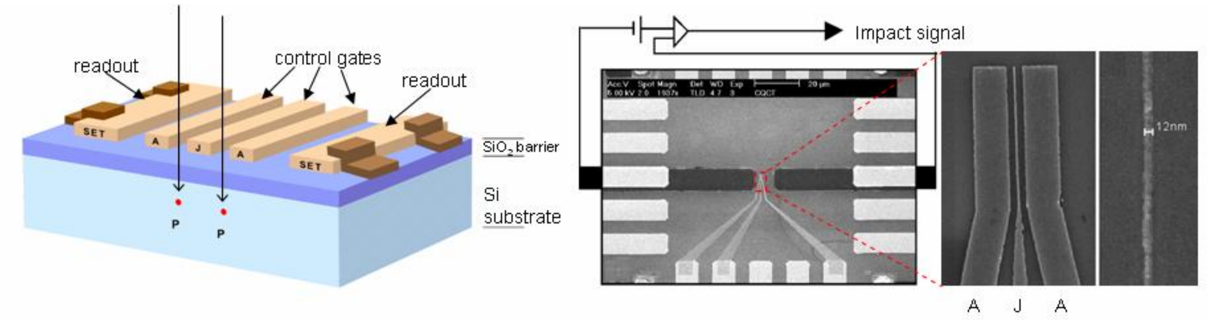

Figure 1: (left) Kane quantum computer [1] schematic showing a 2 donor device and associated A- and J-gate control electrodes with Single Electron Transistors (SET) for readout. (right) SEM image of prototype including aluminium detector electrodes for registration of single ion impact signals. Note that the J gate width in this device is only 12 nm.

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energy, ions can be implanted through surface layers such as oxides and, most importantly, the charge transient induced in or from the substrate can be used to register the impact of single ions. This latter feature of ion implantation means that, although a source of single ions on demand is not available, randomly timed single ion impacts can be detected and used to trigger further actions, such as switching off the ion beam to prevent second or further ion impacts., Our motivation for the development of a single ion implantation system is for the construction of a solid state quantum computer in silicon with an array of qubits consisting of single phosphorus donors [1] as shown in figure 1. Several solid state Si:P architectures have been proposed with inter-donor spacings in the range 20-100nm [2-4]. Phosphorus as an electron donor within a silicon substrate is standard in the microelectronics industry but our application requires precision doping of the silicon substrate at the atomic level. Such precision has not yet been demonstrated, although recent developments [5] show that it will be possible in the near future.

However the ability to implant a single ion into a substrate has been demonstrated. Several techniques for single ion implantation are being developed. A passive technique has been proposed in which random ion impacts are registered by thin resists and post implantation processing [6]. An active technique has been developed that relies on the secondary electrons emitted from the surface following a single ion impact [7]. This technique has the advantage that no special substrate preparation is required in most cases and the secondary electron signal can be detected with close to 100 % efficiency. It may be possible to increase the efficiency by use of highly charged ions [8]. However techniques based on secondary electron detection have the disadvantage that in many cases a signal is produced even if the ion is not implanted into in the substrate. This can occur either due to straggling which may cause the ion to stop in the near surface region or if a mask is used in which case an ion striking the mask can give rise to secondary electrons. In both these cases, a ‘hit’ would be recorded when no ion, in fact, has been implanted into the substrate. We have proposed and demonstrated an alternative technique to detect the arrival of a single ion which takes its inspiration from the strategy used to map the charge collection efficiency across electrically active devices when scanned by a focused MeV ion beam using a technique known as Ion Beam Induced Charge (IBIC) [9]. Electrodes applied to the device record the charge transient induced by single MeV ion impacts which can be detected with standard nuclear instrumentation and the integrated charge used as a measure of the charge collection efficiency at the point of ion impact. Typically the device contains a strong internal electric field from a p-n junction, a Schottky contact or externally biased electrodes that results in separation of the charge caused by ionization following dissipation of the ion kinetic energy in the device. The charge separation then results in the induction of charge on the electrodes by the Shockley-Ramo mechanism [10.]

For construction of the quantum computer, the single ion implantation system must be compatible with the processing steps used for the fabrication of the rest of the device. The requirements are: implantation through a surface oxide layer 5 nm thick (the gate isolation oxide), the donor depth must be 20 nm below the surface, the use of a substrate of pure silicon (undoped) and a means for inserting single donors 20 to 100 nm apart. As a first step in implementing this scheme we have performed simulations of each of the necessary methods to achieve these requirements.

2. METHOD

A two donor device will demonstrate most of the required technology required in a multi-qubit quantum computer, including the ability to transfer charge between qubits. A description of the strategy used to construct the required gate electrodes and single electron transistors has been presented elsewhere [11]. Here we describe those features of the device relevant to implantation and localisation of the two donors subject to the requirements outlined above.

The range and lateral straggling of 1 to 50 keV ^{31}P ions implanted into silicon can be calculated from SRIM [12]. These calculations assume the substrate is amorphous instead of crystalline and therefore ignore the effect of channeling which will mean the real distributions will have a longer range and narrower lateral straggling. Clearly lateral and longitudinal straggling will limit the accuracy of ion placement, but it is feasible to construct a 2 donor device with a donor separation of, for example, 60 nm. For the discussion and experiments to follow we employed either a 14, 15 or 16 keV initial kinetic energy with approximately 11 nm longitudinal and 8 nm lateral straggling and a range of 20 nm.

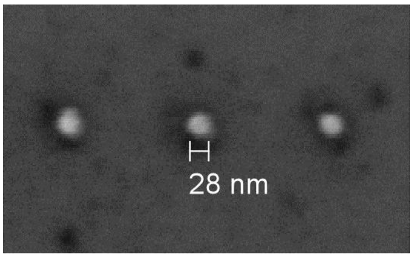

Figure 2: Metal dots produced by metalisation through the 30 nm apertures in the PMMA mask.

To localise the two donors, we employ a thick PMMA resist layer containing two apertures machined with electron beam lithography as a nanomachined mask. The two 30 nm diameter apertures in the mask expose the desired areas in the substrate where single ions are to be implanted. This aperture size can be fabricated by electron beam lithography as is shown by the image in figure 2. This shows the result of using a row of such apertures as a mask to deposit metal confirming the successful fabrication of the apertures.

The two apertures are implanted with a broad beam and ions arrive at random times and locations. If two ion impacts in the substrate are detected, this leads to successful construction of a two donor device with a probability of about 50%. This is because, upon detection of two ion impacts in the substrate, there is a 50% chance of having one ion entering the substrate through each aperture and a 50% chance of both ions entering the substrate through the same aperture. Alternative mask designs are possible that actually employ some of the metal electrodes in the finished device but these are not discussed further here.

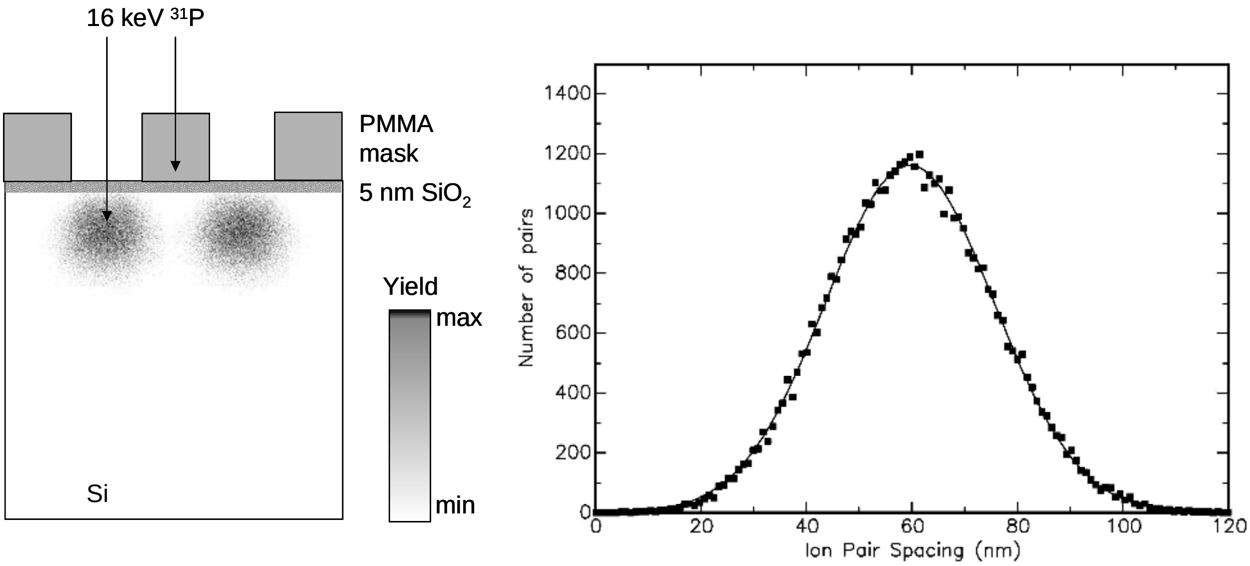

Figure 3: Simulation based on SRIM of the ion location probabilities (shown as a grey scale) for 16 keV ^{31}P ions implanted through 30 nm apertures in a PMMA mask.

We now address the issue of straggling as a limitation to the accuracy of the ion locations when ions are implanted through the mask into the 5 nm surface oxide on the silicon substrate. The final resting positions of 100,000 16 keV ^{31}P ions implanted at the same point were calculated with SRIM then these locations were convolved with a two aperture mask structure and projected onto the plane. The resulting ion location probability contours are shown as a grey scale in figure 3. The probability distribution of the spacing between pairs of ions is also shown in figure 3 which is approximately Gaussian with a FWHM of 38 nm. In the future the aperture sizes and spacing may be reduced further requiring a commensurate reduction in beam energy and range. For example reduction of the beam energy, aperture diameter and spacing to 9 keV, 10 nm and 20 nm respectively reduces the FWHM to less than 20 nm. These tolerances may not be acceptable to a large scale array of donors, but for a simple two donor device, the yield of useful devices will be adequate.

In fact the primary limitation of the ion implantation method of fabrication is the inaccuracy of P donor placement due to ion straggle. However, in the original Kane proposal, each donor has an associated control gate. Therefore, as long as the donors are closer to one control gate than the other, such errors can probably be corrected by appropriate calibration of the control gate voltages.

The simulation in figure 3 also shows that there is a 1.6% probability that the implanted ions will stop in the oxide surface layer instead of the substrate. This will not be a problem for our single ion detection system since these ions will be ignored. A more serious problem is the oxygen knock-ons which cause oxygen atoms to recoil and stop in the substrate. This is highly undesirable because these atoms will introduce deep traps in the silicon. SRIM simulations show that there is a 1 in 40 chance of producing a knock-on which recoils into the substrate and that most of these stop within a few nm of the oxide interface with the substrate as shown in figure 4. Thus there will be a low probability that these knock-ons will disable the device.

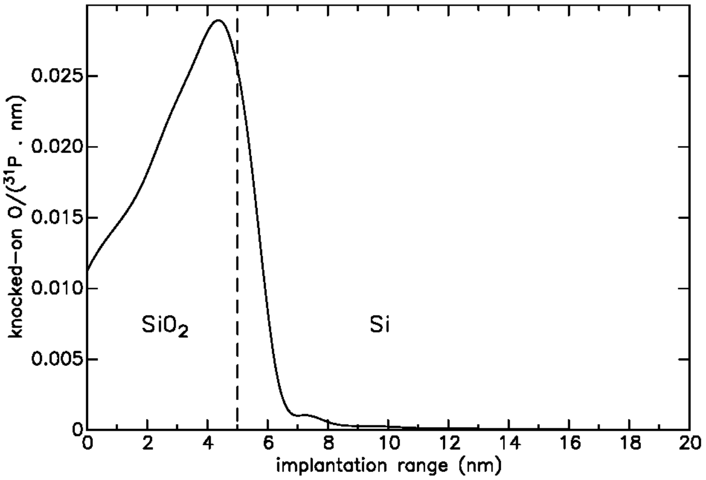

Figure 4: Oxygen knock-on distribution for 16 keV ^{31}P implanted into 5 nm SiO$_2$/Si.

Detection of ion impact signals on silicon devices from MeV ions is straight-forward because of the high signal to noise ratio. Typically, over 200,000 electron-hole pairs are created per ion strike. Hence, the detector may be operated at room temperature and the ion impact signals are well above the electronic noise level. This is because most of the original ion energy is lost in electronic collisions which result in the production of electron-hole pairs in the substrate. This is not the case with sub-20 keV ^{31}P ion impacts where a much larger proportion of the kinetic energy is dissipated by nuclear collisions, which results in the production of phonons, and a relatively small proportion to ionisation which produces a detector signal. A sub-20 keV ^{31}P ion strike will typically produce fewer than 600 electron-hole pairs.

For example a 2 MeV He ion, used for IBIC measurements on a device with a 5 nm deadlayer, deposits 1.4 keV in the deadlayer, 12 keV is lost to nuclear collisions, leaving 1987 keV for electron-hole production which can be detected. By comparison, a 15 keV ^{31}P ion strike on the same device deposits 3.1 keV in the deadlayer, 9.3 keV is lost to nuclear collisions with only 2.2 keV left for e-h production (SRIM calculations).

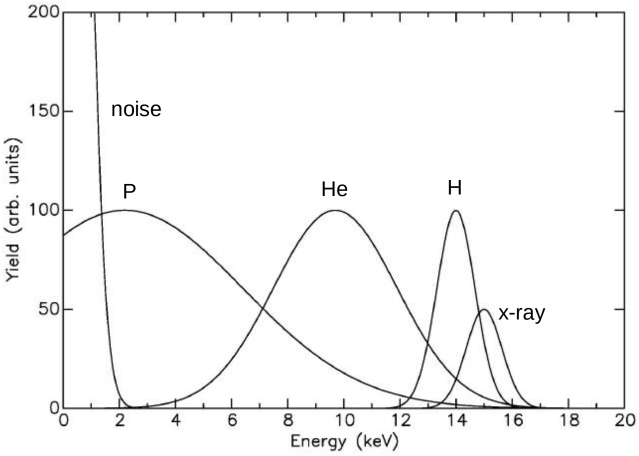

Figure 5: Simulated pulse height spectra for 15 keV ions and x-rays assuming that the FWHM of each peak is the geometric sum of the total nuclear stopping and 1.5 keV of electronic noise.

The difference between the energy lost to ionisation and the initial kinetic energy is known as the pulse height defect (PHD). To show the role of the PHD in detecting heavy ions, the PHD for H, He and P is compared in figure 5 which shows the simulated pulse height spectrum for an initial kinetic energy of 15 keV along with a 15 keV x-ray for which the PHD is zero. In each case the FWHM of the peak for each species is set equal to the total energy loss to nuclear stopping (i.e. straggling) convolved with the electronic noise. The simulation was made from the tables of the nuclear and electronic stopping powers calculated by SRIM. The simulation also assumed a detector energy resolution and noise threshold of 1.5 keV (the FWHM of the x-ray peak). The simulation is compared to experiment in the next section.

To detect the single ion impacts the substrate was used as a detector. As shown in figure 6, two surface electrodes are deposited adjacent to where the ion impacts are to be detected. Following annealing, the electrodes display current voltage characteristics of Schottky barrier behaviour allowing large bias voltages to be applied with a low leakage current and hence high charge collection efficiency from the implanted ions. The substrate was cooled to the temperature of liquid nitrogen using a cold finger and a charge sensitive preamplifier with a cooled JFET was used to register the ion impact signals.

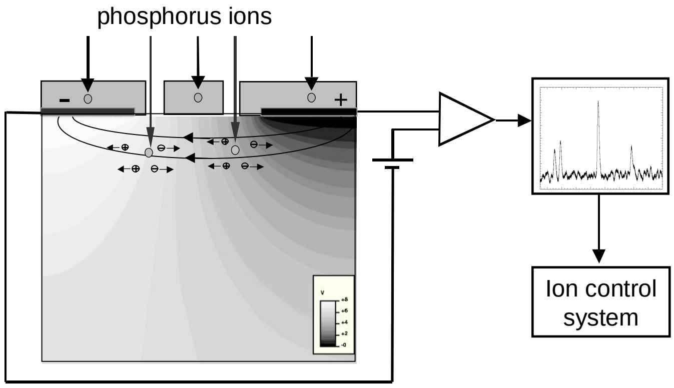

Figure 6: Ion impact detection system. Electric field contours are from TCAD [13].

3. RESULTS

An essential step in the ion detection method is to test the ion detector structure with x-ray impacts to make sure it is working and sufficiently efficient to detect the ion impacts. This is done with a small radioactive source containing ^{55}Fe that is swung into place in front of the substrate to be implanted. The source produces K_α and K_β x-rays from Mn which deposit 5.89 and 6.49 keV energy in the substrate without doing any damage. The pulse height spectrum, see for example figure 7, then provides an indication of the quality of the device. The x-rays penetrate surface layers and can therefore be used even in devices that are completely covered with resist films. The pulse height spectrum in figure 7 shows that the electronic noise in our prototype devices is around 1.5 keV. This is mainly due to the residual leakage current through the device. In the near future this will be reduced to close to the limit for the electronics which is 0.2 keV. Also seen in figure 7 is the low energy tail on the unresolved x-ray peaks. This is due to incomplete charge collection and is to be expected given that the range of the x-rays in the device is

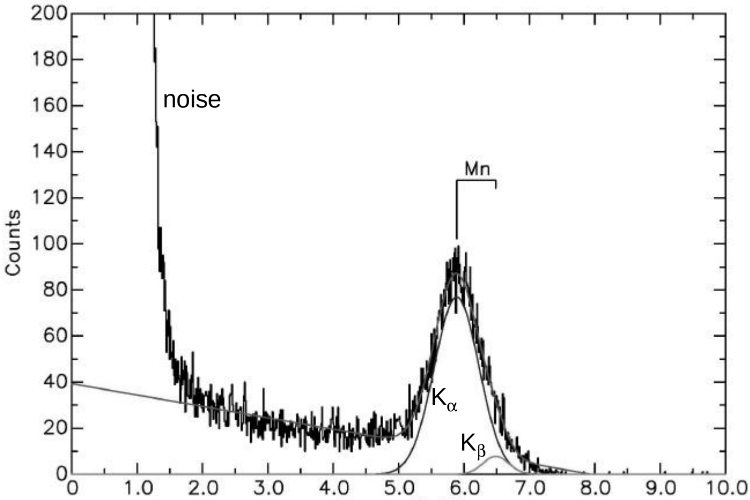

Figure 7: Experimental pulse height spectrum from Mn characteristic x-rays from an actual detector device used for single ion detection.

much deeper than the sensitive volume.

The same detector used for 14 keV ^{31}P ions produces the pulse height spectrum shown in figure 8. There are several interesting features of this spectrum. First: the pulse height spectrum will be affected by the damage inflicted on the surface layer by earlier ion impacts. In the planned application of the device only one ion per area will be detected so pre-existing damage will not degrade the detector performance. Therefore the true FWHM of the signal will be less than that shown in the experimental spectrum. Second: the noise threshold of this prototype device is about 1.5 keV although the signal from the ion impacts extends down into the noise spectrum. Third: the FWHM of the signal is 2.93 (±0.03) keV with a centroid of 1.68 (±0.01) keV. The FWHM from the geometric sum of the noise and the nuclear stopping in the substrate is 9.1 keV with a centroid of 1.99 keV (both numbers obtained from integration of the nuclear and electronic stopping powers respectively obtained from SRIM). The lower experimental centroid compared to the figure from SRIM could be explained by assuming a slightly thicker actual dead layer (surface oxide) of 7.5 nm instead of 5 nm as grown. However the remakably narrow FWHM, a factor of nearly 3 times narrower than expected from the nuclear stopping, remains to be explained.

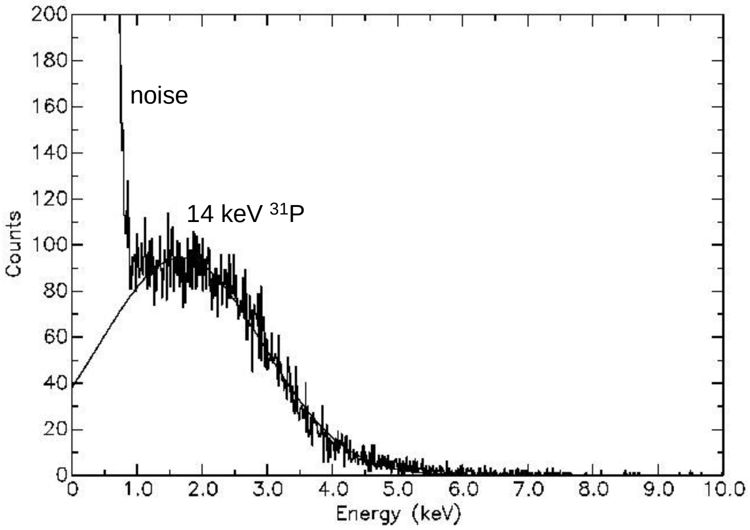

Figure 8: Experimental pulse height spectrum from 14 keV ^{31}P ions using the same detector arrangement as in figure 7.

4. CONCLUSIONS

We have shown that it is possible to detect single ion impacts in a structure compatible with the construction of a quantum computer. Integrated detector electrodes placed outside the construction area can be used to register single ion impacts allowing precision doping of the substrate by ion implantation. The noise level in the prototype detectors had a threshold of around 1.5 keV. To determine the utility of a similar detector system with the same noise level for construction of a quantum computer, assume a 14 keV ^{31}P ion (as in the present experiments) arriving in the substrate dissapates its kinetic energy on a statistical basis between nuclear and electronic processes. If the ion is assumed to undergo a nuclear collision resulting in a large energy loss then it will suffer large straggling compared to the mean ion range. Consider the case where the ion has a residual electonic energy loss of 1.5 keV, which is at the noise threshold of the present detector, after nuclear stopping and energy loss in the dead layer (surface oxide). If it is further assumed that the nuclear stopping is due to a single nuclear collision within the dead layer or just within the substrate, then such an ion will stop in the substrate within 6 nm of the interface. Thus the present detector is sensitive to ions which penetrate deeper than 6 nm into the substrate down to a depth of about 31 nm (the range plus the maximun longitudinal straggle).

With future improvements to the system to reduce the electronic noise, the shallow limit should be significantly reduced as the detector noise is reduced from 1.5 keV to 0.5 keV or better which is the rating of the charge sensitive amplifier. The unexpectedly narrow pulse height spectrum produced by the 14 keV ^{31}P ion impacts suggests that the energy loss to staggling process is less then that expected from the nuclear stopping alone. Possibly some of the recoils produce further ionisation which contributes to the detector signal. With the anticipated reduction in electronic noise, a disciminator placed on the pulse height can be used to reject some of the ions which stop close to the interface and may therefore be inactive in a final device. This will allow a fast route to the construction of a few-qubit quantum computer.

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