Deterministic Focused Ion Beam Implantation with 99.6% Yield for High-Fidelity Shallow Donor Arrays in Silicon

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The demonstration of universal quantum logic operations near the fault-tolerance threshold establishes near-surface implanted donor spin qubits as a plausible platform for scalable quantum computing in silicon. The next technological step to realise this vision is a deterministic fabrication method to create shallowly placed donor arrays. Here, we present a new approach to manufacture such arrays using custom-fabricated single ion implantation. By combining a focused ion beam system incorporating an electron-beam-ion-source with in-situ ion detection electronics, we first demonstrate a versatile method to spatially evaluate the device response characteristics to near-surface implanted low-energy 1H2+ ions. The results aid in understanding the critical role that the oxide interface plays in the ion detection response, and support the development of a new generation of single ion detector technology incorporating an ultra-thin 3.2 nm gate oxide. Next, deterministic implantation of individual 24 keV 40Ar2+ ions is demonstrated with ≥99.99% detection confidence. With the forthcoming installation of a 31P+ ion source, this equates to an projected controlled silicon doping yield of 99.62% for 14 keV 31P+ ions, lying well beyond current qubit loss fault threshold estimates for surface code quantum error correction protocols. Our method thus represents an attractive framework for the rapid mask-free prototyping of large high-fidelity silicon donor spin-qubit arrays.

I. INTRODUCTION

Devices based on complementary metal–oxide semiconductor (CMOS) technology, both in established applications for classical information technology and in emerging applications for quantum computing, depend on the precise control of electric fields in the near-surface region. In classical silicon transistors, the source-drain current flowing beneath a thin (<10 nm) gate oxide is modulated by the electric field from a surface gate [1]. The current flows in thin sheets, with the highest density closest to the Si-SiO2 interface [2]. With the transistor size inside modern processors now approaching 5 nm [3], the concentration of fabrication defects on the nanoscale is becoming a critical issue. For example, local oxide thickness fluctuations, trapped interface charge, and atomic-scale interface roughness can strongly affect the device internal electric field, leading to device reliability issues and breakdown [4–6]. In devices engineered for quantum applications, the electronic and nuclear spin of near-surface donors in silicon are used to encode quantum information [7]. Each atom’s quantum state is programmed and read-out by electric fields from surface gates isolated from the substrate by a thin gate oxide [8]. Small-scale devices have demonstrated nuclear coherence times exceeding 30 s [9], gate fidelities beyond 99.9% [10], and more recently, universal quantum logic operations with >99% fidelity in a three-qubit electron-nuclear quantum processor [11]. To satisfy surface code error-correction specifications, operational quantum devices will require a large number (>10⁶) of physical qubits, arranged in a near-surface (~20 nm deep) arrays [8]. Besides being an enormous fabrication challenge in its own right, careful control of the internal electric field profile is critical for these devices to perform as intended.

Among the possible fabrication pathways to incorporate donors in silicon, scanning probe lithography can be used to produce few-donor clusters [12] with sub-nanometre placement precision [13]. An alternative placement approach uses low-energy ion implantation to produce well-separated individual near-surface donors. Already the industry standard for fabricating classical CMOS devices [14], this concept has recently been extended with the development of a deterministic ion implantation system that uses the electric field within a silicon device to register stochastic arrival-time single ion implantation events [15]. Furthermore, the inherent uncertainty of each ion’s final resting position in the silicon lattice has been addressed with the emergence of a “flip-flop” qubit architecture that permits 100 – 500 nm inter-donor spacing [8]. Using an ion beam collimated to ~10 µm diameter by an in-situ microstencil, we previously demonstrated post-implant counted detection of a few thousand 14 keV P+ ions in Si with 99.85% detection confidence [15]. Adaptation of this approach to produce true large-scale donor arrays via an upgraded nanostencil is currently under investigation.

As an alternative to collimation, the present work investigates a mask-free approach to create such donor arrays in silicon. We employ focused ion beam (FIB), a well-understood...
analysis and fabrication technique that has been used within materials science for decades. Typically incorporating a Ga liquid-metal ion source with a ~5 nm beam spot size, FIB is frequently used for milling microstructures in a variety of materials. More recently, the use of light ion sources such as He and Ne has reduced the beam spot size to <0.5 nm, leading to applications in photonics and quantum materials. Here, we combine a modified FIB system with single ion detector technology to deterministically implant ions into predefined positions. By scanning a focussed 12 keV $^3$H$_2^+$ beam across silicon devices that can be configured for donor spin readout and control, we first measure the device’s response to each ion as a function of beam position. These results are useful to evaluate the near-surface electric field profile and identify fabrication defects. For devices that meet appropriate quality acceptance criteria, we then adapt the approach to perform counted 24 keV $^4$He$^+$ and $^3$He$^+$ implants into a micro-volume and calculate the ion detection confidence and controlled silicon doping yield. The similarity of the detection response to that of 14 keV $^3$P$^+$ ions allows us to evaluate the suitability of using the devices to host large-scale donor arrays for application in spin-based quantum computing.

II. METHODS

A. The Modified FIB System

Experiments took place using a commercially available FIB machine (Raith GmbH) that has been modified for this work (schematic shown in Fig. 1(a)). Full details of the machine are available in [21]. Briefly, the conventional liquid metal ion source was replaced with an electron-beam-ion-source (EBIS) from DREEBIT GmbH [22]. This is a versatile high-brightness gas plasma source that can produce ions in multiple charge states $q = \{1, 2, \ldots \}$ up to complete ionisation [23]. In this study, Ar$^{+q}$ and H$_2^+$ molecule ions were employed. The base pressure in the ion source chamber was kept below 10$^{-9}$ mbar. The source potential can vary between 3 – 20 kV, but was set to 12 kV for the presented experiments, resulting in a kinetic ion implantation energy of $E = q \times 12$ keV. Mass and charge-state selection occur via an integrated Wien filter, with a retractable Faraday cup located at the source output for ion beam diagnostics. Ion focusing optics comprise of objective and condenser apertures ranging from 5 – 200 µm in size, selectable via an electrically-driven aperture stage. An octopole stigmator ensures a circular ion beam profile. The beam is de-magnified by the FIB lens system, and can be scanned across the sample stage using the integrated high-speed pattern generator. The working distance is 10 mm. Additionally, the interferometrically controlled sample stage can be positioned to <2 nm accuracy across its entire 200 mm travel range and provides an alternative precision sample stepping method. Coarse lateral ion beam alignment (~10 µm) is accomplished by an optical camera, and secondary electron imaging via an integrated Everhart-Thornley detector enables precision sample alignment to within ~20 nm. Beam currents as low as 0.1 – 100 ion/s, compatible with deterministic ion implantation, are achieved by combining direct filament current control and Wien filter detuning.

B. Ion Detection Electronics

The ion beam is focused onto a specially-configured silicon diode (referred hereafter as a detector) mounted on a miniature preamplifier printed circuit board. The assembly is housed within a metal case (see Fig. 1(b)) which is fixed to the FIB sample stage. The detector design incorporates a localised p-doped top electrode region and a uniform n-doped back contact in 520 µm-thick uniform high purity [001] float zone Si (n-type, 9250 Ω cm) to form a vertical “sandwich type” p–i–n structure, as shown in Fig. 1(c)-(f). The top electrode (region B) is surrounded by a buried floating n-doped guard ring (region D) to screen against excess leakage current from surface, interface, and bulk defect states from the surrounding region [25]. The design allows for either four circular CS, each with 20 µm diameter (“Type I”, Fig. 1(d)), or one square CS of 60 µm edge length (“Type II”, Fig. 1(e)). Full details on the detector design and fabrication are described elsewhere [15]. Key properties of the specific detectors employed in this work are summarised in Table I.

Each ion impact event is measured using the ion beam induced charge (IBIC) technique [26]. As each ion strikes the detector, a cascade of electron-hole (e-h) pairs is created along its deceleration trajectory. The number of e-h pairs produced in the sensitive silicon detection volume $n_0$ is proportional to the remaining kinetic ion energy after passing through the oxide passivation “dead” layer $E = E - \delta E$ and is made up of contributions from the primary ion as well as those of respective recoiled target atoms. Through a process of diffusion and drift (from the internal electric field or with an additional external reverse bias), the e-h pairs become separated. A fraction may recombine at trapping sites in the silicon bulk as well as at the Si-SiO$_2$ interface, resulting in $n < n_0$ e-h pairs reaching the electrodes. By connecting the detector to a charge-sensitive preamplifier circuit, the electrical impulse due to ion-induced charge movement towards the electrodes can be measured. The detector’s ion detection ability is typically quantified by the charge collection efficiency $\eta = n/n_0$.

In this work, an ultra-low noise preamplifier based on the design of Bertuccio et al. [27] is employed. It incorporates a forward-biased junction field effect transistor (JFET) which, together with the detector, is mounted on an integrated thermoelectric cooling element (see Fig. 1(b)). The detector is operated under reverse bias by applying +10 V to the lower electrode and connecting the top electrode to the JFET gate via a wire bond. Further signal processing occurs entirely within the integrated preamplifier. Modest cooling...
FIG. 1. (a) Schematic of the FIB machine, equipped with an electron-beam-ion-source and integrated single ion detector electronics mounted on a precision sample stage. The ion beam profile is based on an actual ray tracing simulation [21]. (b) Computer-aided design image of the single ion detector setup. It consists of a preamplifier circuit board housed in a metal case of 4 cm diameter. The ion beam (green) is focused onto an on-chip silicon p–i–n diode detector that is directly connected to a low noise junction field effect transistor (JFET). Both the detector and the JFET are mounted on a thermoelectric cooling element at the centre of the board. (c) Optical micrograph showing the top-view layout of the ion detector diode. Two different layouts of (d) 4 × 20 μm-diameter construction sites (CS) or (e) one central 60 × 60 μm² CS are available. (f) Cross-sectional schematic of the detector (as indicated in (e)) showing the sandwich-type p–i–n diode structure. The gate oxide inside the CS is between 3 – 6 nm thick, whilst the surrounding field oxide exhibits ∼65 nm thickness. The aluminium electrodes are approximately 200 nm thick. (g) Representative cross-sectional transmission electron microscope image of the CS of a detector.

TABLE I. Summary of the individual properties of each detector used in this work

| Detector name | Wafer ID | Gate oxide thickness (nm) | Field oxide thickness (nm) | CS type |
|---------------|----------|--------------------------|---------------------------|---------|
| A-1           | A        | 5.4                      | 62                        | II      |
| B-1           | B        | 5.9                      | 65                        | I       |
| C-1           | C        | 3.2                      | 68                        | II      |
| C-2           | C        | 3.2                      | 68                        | II      |

* An additional 500 nm thick layer of SU-8 resist was deposited on the gate oxide and developed into a calibration pattern via electron beam lithography.

III. RESULTS AND DISCUSSION

A. Setup Characterisation

1. FIB Performance

Evaluation of the ion beam profile took place with detector A-1, where an additional 500 nm-thick layer of SU-8 resist was deposited on the surface and selectively developed into a calibration pattern using electron beam lithography. A checkerboard layout with pitch size ranging from 0.5 – 4 μm was formed inside the CS, as shown in Fig. 2(a). The detector was subsequently placed inside the FIB, where a 12 keV $^1$H⁺ beam was then scanned over a 25 × 25 μm² area inside the CS. Light ions are employed for the initial characterisation because they produce less sample damage and greater ionisation than heavier species for the same kinetic energy [30]. Each $^1$H⁺ molecule ion dissociates quasi-instantaneously upon surface impact, due to the energy transfer exceeding the binding energy by several orders of magnitude [31]. The constituent H⁺ ions share the total kinetic energy in equal parts (6 keV per H⁺) and decelerate simultaneously inside the detector. Ions that strike areas protected by the resist cannot produce signal pulses, due to its thickness being large enough to prevent incident ions from entering the sensitive detector volume [32]. In resist-free areas, the average penetration depth is ∼87 nm below the Si-SiO₂ interface, and a combined sum of 3100 e-h pairs is produced per H⁺ ion [32]. The shallow implantation depth compared to the overall detector thickness...
and left-hand edges gives FWHM values of (651 ± 49) nm, respectively. The latter result compares well with other results in the literature, where FWHM values of between 0.5 – 1 µm have been reported [23 34 35].

2. Detector Response Characteristics

Quantitative evaluation of the response to single ion impacts is performed by scanning a 12 keV H\textsuperscript{+} beam over a large area (400 × 400 µm\textsuperscript{2}) of detector B-1 and mapping the signal pulse amplitudes. In the absence of incident ions, a r.m.s. noise of ∼110 eV was recorded. This is about 40 eV greater than other detectors from the wafer and can be attributed to an additional capacitance at the JFET input gate from a second detector that was connected in parallel during this experiment. However, the given noise performance is sufficient for high confidence low-energy single ion detection, as discussed later. A total of 10,000 single ion impact events were recorded, with the resulting signal pulse spectrum shown in Fig. 1(a). The spectrum is dominated by a broad main peak centred at 2.5 keV, with a fraction of its lower energy side cut off due to the noise discriminator threshold. On the high-energy side, a separate small signal peak occurs at 5.8 keV and approximately 700 eV FWHM. One further isolated small peak, centred at 11.3 keV and approximately 600 eV FWHM, can also be identified.

The corresponding spatially-resolved signal pulse map is shown in Fig. 2(b) and reveals the origin of each peak. Each pixel is colour-coded according to the charge collection efficiency η determined from the charge signal pulse recorded at the given location. The overall map features agree well with the optical top-view micrograph of the same device shown in Fig. 1(f). Here, the initial ion energy loss from stopping in the thin gate oxide (see Table I) is nearly negligible, thereby maximising the number of ion-induced e-h pairs produced in the sensitive detection volume. In addition, the low bulk defect concentration in the high-purity silicon wafer and the high-quality thermal gate oxide interface [15 36] practically eliminate charge carrier recombination processes, resulting in η ≈ 1. For a 12 keV H\textsuperscript{+} molecule ion, ∼95% of its kinetic energy is dissipated in electronic stopping by e-h pair generation according to the model of Funsten and Ziegler [32 37].

With the signal peak centre located at ∼11.3 keV, our experimental results are consistent with this model. Spectra obtained from independently scanning each individual CS are also shown in Fig. 2(c). There appears to be minimal variation in η between each CS and the absence of isolated events outside the main signal peak indicates negligible artificial influences – e.g. from ion scattering or gate oxide effects such as thickness fluctuations and surface debris.

Outside of the CS, the top metal electrode pad (region B) yields no single ion detection events, agreeing with TRIM simulations that predict 100% of 12 keV H\textsuperscript{+} molecule ions should stop completely within the metal layer [32]. Next, the narrow undoped region between the top electrode and the guard ring (region C) gives rise to the satellite signal peak lo-
The hatched interval [0.0, 0.84] keV indicates the noise discriminator regime. The red dashed line indicates an average charge collection efficiency of $\langle \eta \rangle = 1$. (b) Spatially resolved 128 $\times$ 128 pixel map of the data presented in (a). The dark strip extending to the bottom-right corner is due to the shadowing effect of the 20 µm-thick wire bond attached to the metal top electrode. (c) Signal pulse spectra extracted from detailed scans performed inside each construction site (as indicated in each highlighted area in the inset optical image). Each spectrum is comprised of ~650 single ion impact events.

FIG. 3. (a) Signal pulse spectrum of detector B-1 exposed to a scanned 12 keV H$_2^+$ beam. The three peaks correspond to different regions of the device with varying $\eta$, as discussed in the main text. The hatched interval [0.0, 0.84] keV indicates the noise discriminator regime. The red dashed line indicates an average charge collection efficiency of $\langle \eta \rangle = 1$. (b) Spatially resolved 128 $\times$ 128 pixel map of the data presented in (a). The dark strip extending to the bottom-right corner is due to the shadowing effect of the 20 µm-thick wire bond attached to the metal top electrode. (c) Signal pulse spectra extracted from detailed scans performed inside each construction site (as indicated in each highlighted area in the inset optical image). Each spectrum is comprised of ~650 single ion impact events.

cated at 6 keV. Here, the ions experience increased stopping in the thicker field oxide (see Table I) and lose approximately half of their initial kinetic energy before reaching the sensitive detector volume [32]. Hence, only approximately half the number of e-h pairs is generated in this region, compared to in the CS (region A). Further, no signal events are recorded within the n-guard ring area (region D) due to the very high phosphorous doping concentration ($3 \times 10^{19}$ cm$^{-3}$), representing a volume of very effective e-h pair recombination.

Finally, the outer area (region E) yields the dominant signal peak in Fig. 3(a), with the peak size coming from its relatively large area fraction of the detector. Here, the n-guard ring strongly attenuates the internal reverse bias drift field, rendering the slower charge carrier diffusion process (minority carrier lifetimes typically $\sim$100 ns, compared to ps drift times [38]) as the dominant transport mechanism. This causes holes of the ion-induced e-h pairs to contribute to a greater extent to the charge pulse signal formation [30]. The spatially isotropic nature of e-h pair diffusion, combined with lifetime-limiting interface and bulk defects, results in a quick decline of $\eta$ with growing lateral distance from the n-guard edge. However, we emphasise that ions are not actually designed to be implanted and detected in this region. Instead, the earlier result showing $\eta \rightarrow 1$ within each CS (region A) is the key conclusion to draw from this initial experiment.

B. Defect Measurement and Analysis

Turning to our application to silicon donor-based quantum computing, we now evaluate Type II detectors incorporating a large-area CS needed to construct large-scale donor arrays. To construct such arrays, every implanted ion must be detected with a high degree of confidence at its predefined target location. Specifically, $\eta$ must meet two criteria in the CS: (1) the average value must be near-unity, and (2) it must be spatially homogeneous. As previously introduced, the IBIC technique is inherently sensitive to defects located in the bulk [40, 41] and at interfaces [42, 43] that act as trapping/recombination centres for ion-induced free e-h pairs. Especially for criterion (2), local effects such as gate oxide thickness fluctuations or residual nanoscale surface debris can contribute towards increased ion stopping before an ion reaches the sensitive detector volume, leading to highly localised areas of reduced $\eta$.

To evaluate the presence of such defects, two representative detectors from the same fabrication wafer (see Fig. 4(a) and (b)) were selected at random and mapped with a scanned 12 keV H$_2^+$ beam. Fig. 4(c) shows a high-resolution map of $\eta$ in detector C-1. The CS exhibits ideal signal characteristics and clearly fulfills both criteria. A linescan taken along its cross-section (Fig. 4(e)) confirms fluctuations in $\eta$ of $< 3\%$. These can be attributed to the statistical nature of a multi-atom collision cascade each ion experiences, comprising (i) variations in the residual kinetic ion energy after transmitting the gate oxide, (ii) variations in the electronic ion stopping fraction in the active region, and (iii) Fano statistics of e-h pair generation due to electron and hole scattering in the silicon lattice [43]. This is also the origin of the signal peak FHWM visible in Fig. 4(c). The sharp decrease in $\eta$ at the CS perimeter is due to a sudden transition between the gate oxide and the thicker surrounding field oxide.

The situation is markedly different for detector C-2. As shown in Fig. 4(d) and (e), three distinct regions of different $\eta$ are observable within the CS. The right-hand third (region I) exhibits comparably uniform signal characteristics with near-unity $\eta$, similar to detector C-1. However, the remaining regions indicate the presence of defects. Two pockets of degraded $\eta < 0.5$ occur at the top and in the centre of the CS (region II). They span approximately 10 $\times$ 20 µm in lateral dimensions. In the left-hand third of the CS (region III), a more uniform spatial detector response is apparent, albeit with a reduced average $\eta \approx 0.9$. To better understand the charge collection dynamics, a COMSOL simulation [39] of the internal detector electric field $\mathbf{E}$ was run, with the results shown in Fig 4(f). $\mathbf{E}$ is largely uniform and vertically aligned deep under the CS surface, but increasingly re-aligns horizontally in the vicinity of the surface. This is accompanied by a lateral gradient in the absolute field strength, with a near field-free region existing in the centre of the CS to a depth of a few µm. This is many times the ion implantation depth ((88 ± 30) nm [22]), suggesting that the initial motion of free e-h pairs (induced by H$_2^+$ ions striking the CS) is initially characterised by diffusion and only afterwards becomes dominated by drift transport in the deeper silicon bulk. Remarkably, a high-quality Si crystal with no point/extended defects and a well-passivated surface
Det. C-1
20 μm
Det. C-2

FIG. 4. 100× optical micrographs showing the construction sites of (a) detector C-1 and (b) detector C-2. (c), (d) Corresponding spatially-resolved 256 × 256 pixel signal pulse maps captured using a scanned 12 keV H$_2^+$ beam with a ~20 ion/s incidence rate and a fixed 8 ms dwell time. A two-pixel binning algorithm was applied to compensate for some void pixels. (e) Line profiles of η, extracted from across the construction site of each detector (white lines in (c) and (d)). Regions of similar η for detector C-2 are indicated and discussed in the main text. (f) COMSOL® simulation [39] showing the strength and direction of the electric field (V/cm) across the construction site with a −10 V external reverse bias applied. Peak doping concentrations of $1 \times 10^{16}$ cm$^{-2}$ were specified in the p and n ohmic contact regions against a $1 \times 10^{11}$ cm$^{-2}$ n-type background. An interface defect density of $D_i = 1 \times 10^{11}$ cm$^{-2}$eV$^{-1}$ and a fixed oxide charge of $Q_f = 1 \times 10^9$ cm$^{-2}$ were assumed in the gate oxide. The white dot at the image centre indicates the expected average implantation depth of 12 keV H$_2^+$ ions according to TRIM calculations [40]. (g) Topography map of detector C-2 obtained with atomic force microscopy. The scan area is indicated by the dashed white rectangle in (d).

(due to a high-quality thermal oxide [45]) appears sufficient to create an environment with diffusion lengths spanning tens of μm, as exhibited by detector C-1. This is clearly not the case in detector C-2.

To determine the physical origin of the defects seen in detector C-2, atomic force microscopy was performed in the affected area (indicated in Fig. (d)) of the CS. The corresponding topography map is shown in Fig. (g). A hairline crack extending from the top corner to the centre of the CS can be identified, with lateral dimensions varying between a few hundred nm to a few μm. In some areas, the crack has a depth of up to 4 nm, comparable to the gate oxide thickness, suggesting that an error during the fabrication process (e.g., residual surface debris present during spin coating or a mechanical scratch from wafer handling) resulted in local etching of the gate oxide. The removal of a thermally-grown oxide and subsequent exposure of the underlying silicon material leads to the formation of a low-quality native oxide (2 – 3 nm thickness), which can trap charge and result in poor spin-dependent tunnel coupling of the donors.

The investigation of detector C-2 is revealing. By using a high-quality thermal oxide and a low interface density, the effective e-h pair trapping and recombination are minimized, allowing for enhanced detection efficiency.

C. Deterministic Ion Implantation for Donor Arrays

1. Depth Straggling and Controlled Silicon Doping Yield

With detector C-1 confirming it is possible to meet the criteria for reliable donor array construction, controlled implantation of individual 24 keV $^{40}$Ar$^{2+}$ ions (acceleration potential = 12 kV) was subsequently performed on the same device. Although the electronic and spin properties of $^{40}$Ar do not make it compatible with quantum information processing in silicon, its ion stopping characteristics are very similar to the $^{31}$P donor-qubit [49], providing a good estimate of the ion detection signal response. In the near future, $^{31}$P$^+$ and other ion species will also become available in this FIB machine. Each $^{40}$Ar$^{2+}$ ion penetrates approximately (28 ± 13) nm below the Si-SiO$_2$ interface and generates an average of ~1700 e–h pairs in the active detection volume [47]. In the context of an operational large-scale quantum device incorporating surface gate control circuitry [8, 50], minimising the depth placement uncertainty (longitudinal straggle) of each donor is essential for reliable device operation. Too deep placement results in poor spin-dependent tunnel coupling of...
the donor electron, whereas too shallow placement causes the donor to be located adjacent to or in the oxide and consequently inactivated. As shown in Table II, the straggles can be reduced by lowering the implantation energy. However, this also has the effect of reducing the number of ion-induced e-h pairs and thus causes the amplitude of the single ion implantation charge pulse signal to lie near the noise threshold. This would likely result in implant sites with more than one donor, leading to reduced coherence times from uncontrolled nearby donor-donor coupling. To ensure that the fraction of addressable single donors remains above the qubit loss fault threshold of 1.9% of the incident ions relevant to the flip-flop qubit architecture predict an equally-high detection confidence in η. Additional simulations for near-surface (∼20 nm deep) 14 keV $^{31}$P$^+$ ions relevant to the flip-flop qubit architecture predict an equally-high detection confidence of $\Xi(q_{0}) = 99.98\%$.

Compared to our previous detector generations incorporating a standard 6 – 8 nm gate oxide [15], the device presented here features an ultra-thin 3.2 nm gate oxide (see Fig. 1(g)). Similar devices have been shown to be susceptible to elevated defect concentrations typical of sub-5 nm gate oxides [52]. However, the near-unity η value obtained with the present detector C-1 suggests that the density of interface defect traps and fixed oxide charge within this ultra-thin gate oxide is in fact comparable to those employed in devices previously demonstrating high-fidelity donor qubit control [9, 11]. Moreover, a thin gate oxide provides improved controlled silicon doping yield $Y_{dep}$, defined as the fraction of detectable single ion impacts where the primary dopant ion also entirely transmits the gate oxide to stop inside the silicon crystal. Events where a primary ion stops inside the oxide may still produce a detectable signal, because forward-recoiled Si and O atoms from the oxide can also contribute to an overall charge signal pulse event. In a previous study, we reported a single ion detection confidence of $\Xi(q_{0}) \approx 99.85\%$ for 14 keV $^{31}$P$^+$ ions, but the actual doping yield was limited to $Y_{dep} \approx 98.1\%$, due to 1.9% of the incident $^{31}$P$^+$ ions stopping inside the 6 nm gate oxide [15]. Based on the present detector generation incorporating a 3.2 nm gate oxide, our new results predict a factor 5 enhancement to $Y_{dep} = 99.62\%$ for the same ion species and energy, comfortably exceeding present estimates on tolerable donor qubit loss fault thresholds (≈ 90 – 95 %) [53].

2. Lateral Straggling and Donor Array Formation

The lateral placement accuracy of each implanted ion is an additional component in determining the setup’s suitability to fabricate scalable donor arrays in silicon. To assess this factor, we present simulations of individual implanted ion positions modelled by considering two independent scattering processes. First, the uncertainty of each ion’s lateral impact point on the detector surface comes from an assumed Gaussian cross-sectional beam intensity distribution produced by the FIB machine. Second, lateral ion straggling occurs inside the target material (here, the silicon detector) as a direct result of the random collision cascade each ion makes with target atoms upon stopping. The latter can be readily determined us-

| Species | $E_{kin}$ (keV) | Implantation depth ± straggling (nm) | Lateral straggling (nm) | $n_0$ (e-h pairs) | $\Xi(q_{0})$ (%) | $Y_{dep}$ (%) |
|---------|----------------|------------------------------------|------------------------|-----------------|----------------|-------------|
| $^{1}$H$^+$ | 12 | 86.9 ± 31.2 | 40.3 | 3112 | >99.99 | 99.91 |
| $^{40}$Ar$^{3+}$ | 36 | 40.3 ± 17.6 | 14.4 | 2764 | >99.99 | 99.99 |
| $^{40}$Ar$^{2+}$ | 24 | 27.8 ± 13.0 | 10.6 | 1695 | >99.99 | 99.95 |
| $^{40}$Ar$^+$ | 12 | 14.6 ± 7.8 | 6.3 | 625 | 99.84 | 99.68 |
| $^{31}$P$^+$ | 14 | 19.7 ± 10.7 | 9 | 1108 | 99.98 | 99.62 |
| $^{31}$P$^+$ | 9 | 12.9 ± 7.7 | 6.5 | 643 | 99.85 | 98.98 |

TABLE II. Properties of selected ion species (and in some cases, varied kinetic energies) when implanted through a 3.2 nm-thick SiO$_2$ layer into (100) Si, as modelled by Crystal-TRIM [48]. The implantation depth is calculated from the Si-SiO$_2$ interface. The number of e-h pairs is calculated in the sensitive detection volume, with a 640 eV noise floor assumed to determine the ion detection confidence.
As a small-scale simulation, we consider a 5 × 5 surface code donor arrangement with a target inter-donor pitch of 200 nm which can be constructed for multi-qubit entanglement studies based on the flip-flop qubit control scheme [8]. In this regime, effects from the spot size and the lateral ion straggling in silicon contribute more or less equally to the overall ion placement precision. Furthermore, the expected reduction in beam current from the smaller aperture size can be offset by the highly adjustable nature of the EBIS emission intensity, yielding a similar expected on-target implantation rate to that used in the present experiments. Precision localisation of single ions has already been demonstrated with the use of an atomic force microscope nanostencil placed directly above the device [54]. However, adapting this approach below the 30 nm level may be technically challenging due to expected lateral and axial ion aperture straggling effects [55]. Such concerns do not apply in this approach, given the lack of a mechanical mask. Alongside encouraging recent studies from systems that detect single ions just prior to the implantation event [56, 57], our results represent a promising avenue towards the scalable engineering of near-surface donor qubit arrays with nanoscale placement precision.

IV. CONCLUSION

We have introduced a FIB system equipped with an electron-beam-ion-source as well as ultra-low noise single ion detection technology to enable deterministic control over the number and position of implanted ions. The ion source allows the selection of a wide range of ion species and charge states, with precise control of the beam current to yield average on-target implantation rates between 0.1 – 100 ion/s. Through the ion beam induced charge principle, we use silicon p–i–n diode devices to detect electron-hole pairs generated by each ion impact event and correlate this with the beam spot position. We first evaluate the functionality of the system by mapping to become quickly become unmanageable beyond the 2-donor qubit level. However, the spot size obtained in this study was actually artificially elevated by a technical defect in the Wien filter assembly at the time measurements were conducted. In fact, with the same FIB column configuration an improved FIB spot size of 160 nm was previously demonstrated [21].

By employing a custom-fabricated 200 nm diameter ion condenser lens aperture, we predict a further spot size reduction to 30 nm to be realistically achievable. This is illustrated in Fig. 5(c) where now the total lateral ion placement precision lies within a ≤20 nm radius of the targeted placement position for all 25 ions, fully compatible with the lateral donor placement constraints of the flip-flop donor qubit control scheme [8]. In this regime, effects from the spot size and the lateral ion straggling in silicon contribute more or less equally to the overall ion placement precision. Furthermore, the expected reduction in beam current from the smaller aperture size can be offset by the highly adjustable nature of the EBIS emission intensity, yielding a similar expected on-target implantation rate to that used in the present experiments. Precision localisation of single ions has already been demonstrated with the use of an atomic force microscope nanostencil placed directly above the device [54]. However, adapting this approach below the 30 nm level may be technically challenging due to expected lateral and axial ion aperture straggling effects [55]. Such concerns do not apply in this approach, given the lack of a mechanical mask. Alongside encouraging recent studies from systems that detect single ions just prior to the implantation event [56, 57], our results represent a promising avenue towards the scalable engineering of near-surface donor qubit arrays with nanoscale placement precision.

![Simulation of ion placement](image)

**FIG. 5.** (a) Signal pulse spectrum of detector C-1 irradiated with 2,000 24 keV Ar$^{2+}$ ions, raster-scanned over a 5 × 5 μm$^2$ area inside the construction site (as indicated in the left inset; scale bar = 20 μm). The dwell time was set to 1 ms and the incidence rate was ~10 ion/s. The low level discriminator was set to 640 eV, corresponding to the hatched region. Also shown are the results of normalised CrystalTRIM simulations [48] of the same experiment, performed with 20,000 ions. Right inset: sub-spectra from the first and last 200 recorded counts. (b) Simulated locations of single 24 keV Ar$^{2+}$ ions implanted and arranged in a 5 × 5 array with a 200 nm target stepping pitch. The blue plus marks (+) indicate lateral offsets considering the FIB spot size (sampled from a Gaussian distribution with 477 nm FWHM), whereas the red crosses (×) refer to the lateral offsets due to simulated spatial ion straggling upon stopping in silicon [52]. The final placement positions (○) are the convolution of both quantities. (c) Data as for (b), but with a simulated 30 nm (FWHM) FIB spot size.
response. Next, we perform mask-free counted implantation of 2000 $^{40}\text{Ar}^+$ ions implanted at 24 keV into a $5 \times 5 \mu m^2$ area with no detectable signal degradation from ion implantation-induced damage. Using a new generation of detectors incorporating an ultra-thin 3.2 nm gate oxide, we model a projected single ion detection confidence of $\geq 99.99\%$ for 14 keV $^{31}\text{P}^+$ ions. When ions that stop in the oxide are excluded, a controlled silicon doping yield of 99.62% is determined, a factor 5 enhancement compared to our previous work. With an upcoming system upgrade to incorporate a $^{31}\text{P}^+$ ion source and yield a sub-30 nm FIB spot size, we aim to establish a viable method to fabricate high-fidelity near-surface $^{31}\text{P}$ donor arrays in silicon for multi-qubit entanglement studies.

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