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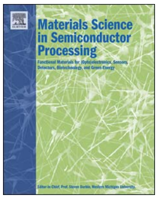

# Deterministic doping

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## ABSTRACT

Emerging programs in a new field of technology that employs quantum mechanical principles in engineered devices has driven new approaches to atomic-scale fabrication. Of crucial importance is the capability to configure single atoms in silicon, diamond and other materials. These engineered materials form the foundations of quantum technology which includes the fields of quantum communication and quantum computing. Quantum technology exploits quantum superposition and entanglement in potentially scalable quantum devices. To insert donor atoms in a large-scale device methods for deterministic ion implantation have been developed. These methods potentially allow the standard techniques developed for engineering materials for the Information Technology industry to be employed to make devices that exploit the new technologies. This paper reviews the emerging new technologies for deterministic doping to address the challenges of engineering atoms in the solid state.

## 1. Introduction

The second quantum revolution, as described by Dowling [1], is the development of new technologies employing quantum mechanics that has now emerged as a significant field of research. These technologies include quantum computing [2–4], quantum cryptography [5], quantum simulation [6,7], quantum metrology [8,9], quantum sensing in biology [10] or geology [11], quantum time keeping [12], quantum imaging [13] and the quantum internet [14]. There has been significant progress in the development of devices based on the new field of silicon quantum electronics [15] or photonics [16]. In the case of solid state devices employing nuclear or electron spins [17] based on silicon [18] or diamond [19] large scale devices will require the precision engineering of single dopant atoms or colour centres in a crystalline matrix. Ion implantation is already highly developed for silicon in the information technology industry [20] and significant progress has been made towards employing ion implantation to build devices engineered with single atoms in silicon and other materials [21]. For the fabrication of arrays of one or more single atoms the technique of deterministic ion implantation has been developed where implantation is done in conjunction with a method for the registration of each implanted ion.

Recent demonstrations of electron and nuclear spin control of single phosphorus dopant atoms implanted into silicon have shown single donor spin qubits in silicon are strong contenders in the quest for the realization of a scalable quantum computer device [22–25]. The next step of demonstrating reliable two qubit coupling is likely achievable with existing technology but for this to be achieved on a larger scale requires new techniques for building atomic arrays of implanted donors into silicon including deterministic ion implantation. Also, although much of the present focus is on phosphorus, the heavy donor atoms of arsenic, antimony and bismuth can be implanted into a silicon lattice at a given depth with higher spatial resolution due their higher mass (see Table 1). Also, in the case of arsenic and antimony, diffusion in silicon is less affected by oxidation enhanced diffusion [28] and hence potentially offers higher placement precision compared to phosphorus considering the need for post-implant annealing steps. In the case of antimony the donor electron Bohr orbit diameter is larger than the other donors [26] which may serve to relax constraints on construction precision. Implantation of heavy donor atoms into silicon will cause significant lattice damage, but it has been shown that an ultra-scaled CMOS device can withstand the implantation of erbium isotopes ($161 < A < 171$, comparable to bismuth: $A=209$) where the optically excited charge and spin state of a single implanted erbium atom was detected electrically [29]. Also bismuth donor electron spin resonance can be successfully measured in ensembles implanted into silicon [30]. A potential new application beyond spin qubits in the case of bismuth donors in silicon arises from the fact that the donor electron exhibits technologically useful clock transitions which are insensitive to external perturbations [31]. This transition has so far only been studied in ensembles not in single donors. This demonstrates that ion

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**Table 1**
Characteristics of implanted donors in Si and C. Bohr orbit data adapted from [26], implantation data from [27], energy per e-h pair in Si 3.6 eV [82], diamond 13.2 eV [83]. In each case the proportion of the initial ion energy that contributes to the production of e-h pairs is close to 40%.

| Matrix: Donor | Bohr orbit diameter (nm) | Energy (keV) | Mean implantation depth (nm) | Lateral straggling (nm) | Number of e-h pairs per impact |
|---|---|---|---|---|---|
| C(diamond): N | – | 15 | 20 | 6.3 | 710 |
| Si: P | 2.44 | 13 | 20 | 9 | 1600 |
| Si: P | 2.44 | 8 | 15 | 7 | 900 |
| Si: As | 1.96 | 20 | 20 | 7 | 2100 |
| Si: Sb | 2.64 | 22 | 20 | 5 | 2250 |
| Si: Er | – | 25 | 20 | 5 | 2700 |
| Si: Bi | 1.94 | 26 | 20 | 4 | 2900 |

implantation into wafer scale arrays of fully fabricated and encapsulated devices is a robust method for the introduction of single and few ions and it can be expected that this will also be true for dopant arrays.

## 2. Materials and methods

By placing single arsenic, antimony and bismuth atoms in arrays, it is possible, at low temperatures, to configure the local electrostatic landscape of the device for manipulation of the associated donor electrons and through spin-orbit coupling, also the donor nuclear spins. Magnetoelectric transport through single donors is affected by the donor electron level structure, which depends on the dopant-specific properties. Some of these applications employ standard analytical spectroscopic techniques of high source-drain voltage bias [32] and electrically detected magnetic resonance (EDMR) spectroscopy [33]. Devices that exploit these methods have already been used to demonstrate the hybrid classical-quantum technology needed for single spin readout such as: (i) the coupling of a single phosphorus [25,34,35], arsenic [36–38] or antimony [39,40] donor to a silicon-based single-electron transistor (SET) or field effect transistor, (ii) spin dependent scattering from antimony ensembles [41], (iii) the coupling of a small ensemble of donor spins to the 2-dimensional electron gas (2DEG) in an accumulation-mode silicon MOSFET [33,42], and (iv) the strong coupling of a Cooper pair box dipole [43] (capacitive-coupling) or an ensemble of electron spins (magnetic-coupling) in either silicon [44], ruby [45] or in diamond using the NV- centres [46,47] to a superconducting transmission-line resonator. These methods have now also been applied to acceptor atoms including boron in silicon [48]. A review [49] presents other applications of single atom doping for applications to new device technologies including single-dopant transistors and photonic devices employing a single dopant atom as a functional component.

### *2.1. Fabrication methods*

This extensive collection of measurements on single atom devices represents the state-of-the-art and justifies the next step of using deterministic methods for fabrication of scaled devices beyond single donors. In the present review we confine our attention to ion implantation. This is because, in many cases, ion implantation is also compatible with the process flow for the fabrication of ultra-scaled devices. Also, as shown in Fig. 1, the limiting precision imposed by ion straggling for a donor implanted 20 nm deep in silicon can be as low as 4 nm for bismuth (see Table 1) which is promising for devices incorporating large-scale arrays. The simulations in Fig. 1 neglect the effect of ion channelling which is known to result in deep, low concentration, tails in the ion distribution. Studies of 14 keV P implanted ion profiles with atom probe tomography reveals [50] approximately 20% of the ions are deeper than the simulations for ions implanted through a native surface oxide. Implantation through a prefabricated gate oxide is likely to suppress the channelling tail to some extent.

For ion implantation to be useful in the construction of single-atom arrays, a deterministic ion implantation signal is required to register single ions either before they impact with the substrate or after impact making use of a signal from the substrate. In the case of pre-impact techniques, these can employ especially configured ion sources which provide one ion at a time to the implanter [51,52] or by pre-assembling an array of ions in a magnetic optical trap [53,54]. In some of these systems the ion source can produce very cold beams allowing the ions to be focused to ~6 nm precision which is an advantage for using a scanned beam to implant large scale arrays [55]. However, as yet these advanced ion sources are not yet readily compatible with the required dopants for silicon.

In the case of post-implant techniques, it is possible to employ several different signals from the substrate. For example, by using secondary electron emission as the implant signal in a focused ion beam microscope it was possible to implant counted 60 keV phosphorus [56], silicon [57] and arsenic [58] ions into silicon devices with an aiming precision around 60 nm. One of the factors that degrades the spatial precision of the implantation is ion straggling (see Table 1). This can be reduced with lower implantation energies. However, it is possible the secondary electron yield will also be lower which could reduce the reliability of the signal. By using higher charge state ions, it is possible to recover this signal and this technique has been used with highly charged antimony and bismuth ions [59].

An alternative signal from the substrate that can be used to count ion implantation events is to employ pre-fabricated ultra-scaled field effect transistors in which the source drain current is sensitive to the damage created by the passage of a single ion through the transistor

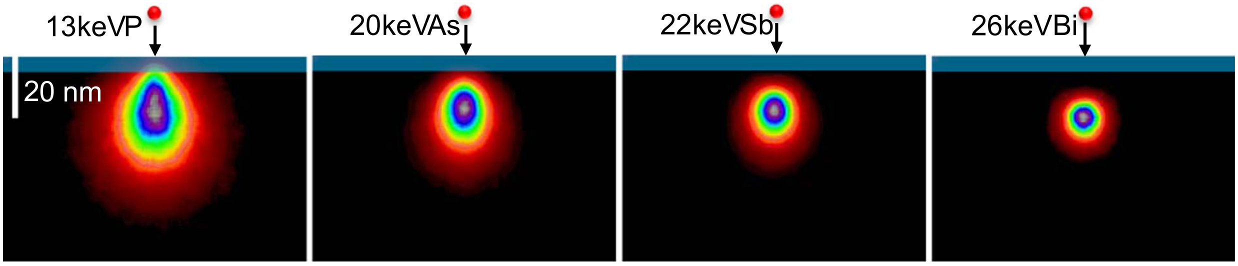

**Fig. 1.** Simulations based on the Stopping and Range of Ions in Matter (SRIM) Monte-Carlo model [27] showing the localisation precision limitation of ion straggling for a common 20 nm implantation depth. The maps represent the probability of the ion position at the end of range for a single ion impact coordinate. Effects from ion channelling were neglected.