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Title Single-Ion Counting with an Ultra-Thin-Membrane Silicon Carbide Sensor for Quantum Applications

Enrico Sangregorio[1,2], Lucia Calcagno[1], Andreo Crnjac[3], and Massimo Camarda[2,4]

[1] Department of Physics and Astronomy "Ettore Majorana", University of Catania, via Santa Sofia 64, 95123, Italy. [2] STLab srl, Via Anapo 53, 95126 Catania, Italy. [3] Division of Experimental Physics, Ruđer Bošković Institute, 10000 Zagreb, Croatia. [4] SenSiC GmbH, DeliveryLAB, 5234 Villigen, Switzerland.

Recently, deterministic single ion implantation has attracted wide interest among the semiconductor field, because of its application in solid-state quantum technology.
Motivated by quantum applications, the demand for deterministically placing single dopants into nanostructured devices has driven the development of various techniques. Single-atom lithographic techniques based on scanning probes have achieved the positioning of single dopants with nm scale precision. However, this technique is currently relatively slow. In contrast, direct ion implantation offers less precision in terms of atom positioning but allows for faster and more scalable processes. One of the most widely used techniques to monitor the number of ions reaching the sample involves the detection of secondary electrons. This approach can be applied to all samples but requires the presence of a secondary electron detector. Alternatively, integrated structures within the target can be exploited to generate detectable signals during the process. Those structures include PiN diodes, which utilize electron-hole pairs generated by the ion-matter interactions, or FET structures, where ion implantation modulates the drain current. However, these methods are exclusively applicable to samples featuring PiN or FET structures. Recently, we introduced an innovative method for detecting single ions using a sub-micrometre ultra-thin silicon carbide membrane sensor. The SiC membrane was fabricated using a state-of-the-art doping-selective electrochemical etching (ECE) technique. The sensor has been used for detecting ions that lose only a portion of the energy in the device and are transmitted further. With this experimental setup, we achieved a 96.5% ion counting confidence for the sensor. This result demonstrates the potential of utilizing a thin SiC membrane as a high-fidelity in-beam ion detector, useful for novel maskless deterministic implantation schemes needed for the fabrication of novel solid-state technologies and devices. Nevertheless, the presence of the membrane had an impact on the trajectory of the ion beam, introducing ion straggling effects that contributed to increased uncertainty in the ion's final position within the target. To quantify this ion straggling phenomenon, we employed a scanning knife-edge technique, and the results were compared to SRIM simulations. This comparative analysis revealed an increase in the ion beam size from 3.43 µm to 8.15 µm. To mitigate the observed high straggling value, we proposed improvements in experimental conditions. Key optimizations involve minimizing the separation distance between the SiC sensor and the target to a few µm while reducing the initial dimension of the beam to the nm-scale and the membrane thickness to 100 nm. Implementing these conditions enables the achievement of a final beam dimension on the order of 100 nanometres, effectively minimizing the uncertainty associated with the final position of the implanted atom.