Advancements in Single Ion Geiger Mode Avalanche Photodiodes (SIGMA) Detectors for the QIST Grand Challenge

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Motivation—Electronic devices that are designed to use properties of single atoms such as donors or defects have recently shown great promise with recent demonstrations of donor spectroscopy, single photon emission sources, and magnetic imaging using defect centers in diamond. In building single atom devices one of the key issues is the detection of the arrival of a single donor atom during the implantation step. We propose avalanche photodiodes (APD to detect the arrival of a single atom. APDs have been used to sense single e-h pairs generated by the arrival of single photons through the use of passively gated Geiger mode (GM) operation of the APD. Over the last two years, we have demonstrated single ion detection at 300 and 77K using similar techniques. Single ion Geiger mode avalanche diode (SIGMA) detectors operate by over-biasing past reverse breakdown for a short time period (which we call the gating window) during which the detector can be sensitive to a single electron or hole injected into the junction. The high fields produce an avalanche cascade leading to a Geiger signal. The gating window can coincide with a pulsed ion beam configuration to insure that the detector is on when an ion is expected to arrive. A challenge in this configuration is the high number of dark counts, due to thermally generated e-h pairs, that obscures the detection of a single ion arrival. Furthermore, extension of the lateral sensitivity using this approach has not been well established. Increased flexibility in remote lateral sensing is important for future integration with single donor device with additional nanostructures such as a double quantum dot structure.

Accomplishment—We report a mapping of the remote lateral sensing of the SIGMA detector combined with demonstrating a significant reduction in dark count. A dark count reduction by three orders of magnitude was accomplished through the introduction of a 77K cooled stage (see figure 1). The mapping of the lateral sensitivity was determined using the ion beam induced current (IBIC) response of the detectors. The lateral sensitivity of the SIGMA detector with a ~150 μm diameter has an estimated upper bound of 600 e-h pairs while maintaining 100% detection efficiency, within the uncertainty of the measurement (see figure 2). The SIGMA sensitivity provides a means of detecting lower energy ions (i.e., smaller straggle) and greater flexibility in the layout of single ion detector integration with the single donor device construction zones.

Significance—We have reported single ion detector performance at 300 and 77K that represents progress towards laterally remote, low energy (i.e., minimum straggle), single ion implant detection for single donor device fabrication. Detection of remote single ion strikes at least as far as ~75 μm from the ion detector with 100% detection efficiency is demonstrated. In principle, this lateral sensitivity provides a sufficiently large region to construct future single ion implanted Si devices. The detector sensitivity is bounded at ~600 e-h pairs which extends ion detector sensitivity to lower energies than previously reported and leads to potentially smaller ion straggle (i.e., improved longitudinal control in atom placement). The ion detector false count probability is significantly decreased by 77 K operation, leading to a drop from 10^{-1} to 10^{-4} false count probability at 300 and ~77K respectively. This reduction in false count probability has important implications for using this approach to reliably implant single ions.

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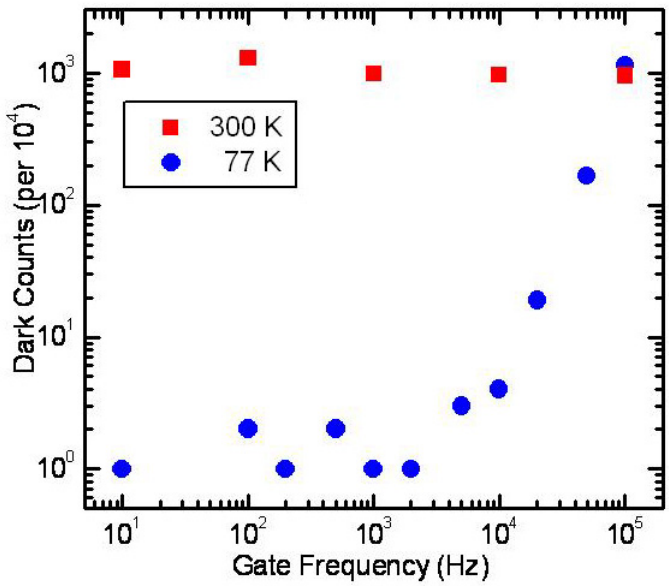

Figure 1. The dark counts from 10^4 gatings of the SIGMA detector with individual durations of 230 ns, pulsing 6.5 V past breakdown, as a function of the gate frequency taken at 300 K (squares, red) and LN_2 temperature (circles, blue).

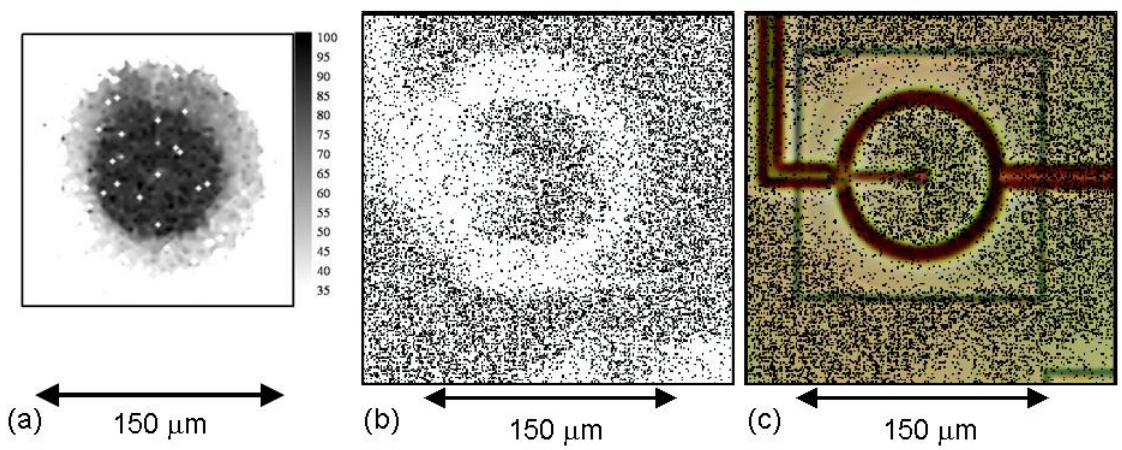

Figure 2. (a) The charge collection efficiency percentage of the APD in the SIGMA detector at zero bias as determined from IBIC with 250 keV H^+. Only inside the APD is the collection efficiency greater than the noise floor of 35%. (b) The digital IBIC map from the GM operation of the SIGMA at liquid nitrogen temperature. (c) GM-IBIC map superimposed upon a micrograph of the SIGMA detector. The low detection efficiency ring correlates with the anode metal contact and a heavily doped n^+ gettering ring.