Fabrication of Single Atom Devices by Direct Write Nanofabrication

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We present on-going work to fabricate single atom devices via direct write nanofabrication using the Sandia National Laboratories nanoImplanter (A&D FIB100NI). This is a multi-species 10-100 kV focused ion beam system with a minimum spot size of 10 nm setup for both mass resolution using an ExB filter and single ion implantation using fast blanking and chopping (see Figure 1 for system overview and typical mass spectrum). We use a Raith lithography pattern generator for nanofabrication. The combination of high spatial resolution, variable energy and the ability to implant a range of elements from the periodic table makes this a versatile machine for a range of topics such as deterministic seeding of TaOx memristor devices[1], high resolution ion beam induced charge collection (IBIC) for probing the structure of defect cascades[2], deterministic single donor devices for quantum computing research[3], as well as, the formation of individual SiV centers in diamond[4,5] using in-situ detectors[6].

The idea for donor based quantum computing goes back to Kane[7]. We implement a fabrication pathway that combines focused ion implantation (FIB) with *in-situ* counted ion detection. We integrate avalanche photodiodes with quantum transport nanostructures and demonstrate low temperature transport in counted samples[3]. This FIB approach allows for a positioning accuracy of <35 nm, limited by the beam spot size. Figure 2 shows (a) the combined ion detector and nanostructure, (b) quantized ion detection and (c) transport data showing a charge offset from a counted donor at low temperature.

Color centers in diamond have been used for a range of applications from metrology to single photon sources for secure quantum communication[8]. We demonstrate the ability to deterministically implant ions into photonic nanostructures with high spatial resolution[4,5]. Separately, we demonstrate the ability to detect single ion implants using an *in-situ* diamond detector with a SNR approaching 10 for detection of single 200 keV Si ions[6]. Figure 3 shows (a) an SEM image of a 2D photonic crystal in diamond, (b) IBIC map for in-situ diamond detectors fabricated at SNL.

A versatile multi-species FIB capability demonstrates utility for a range of applications including the direct write nanofabrication of single atom devices in both silicon and diamond substrates.

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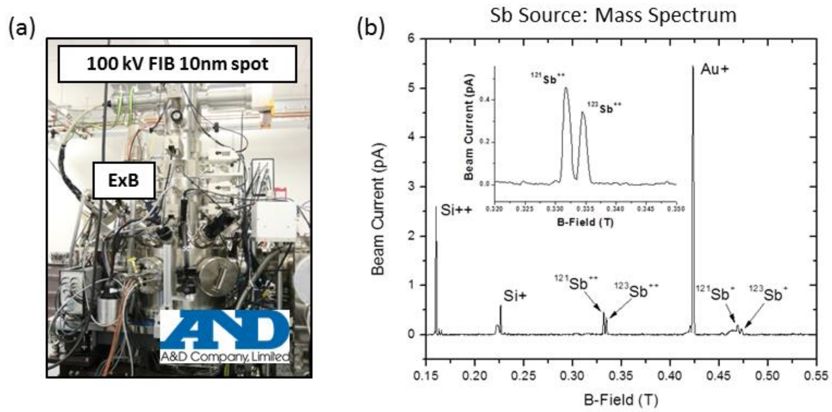

Figure 1: (a) SNL's nanoImplanter, a dual beam multi-species FIB system. (b) Mass spectrum for a AuSiSb source.

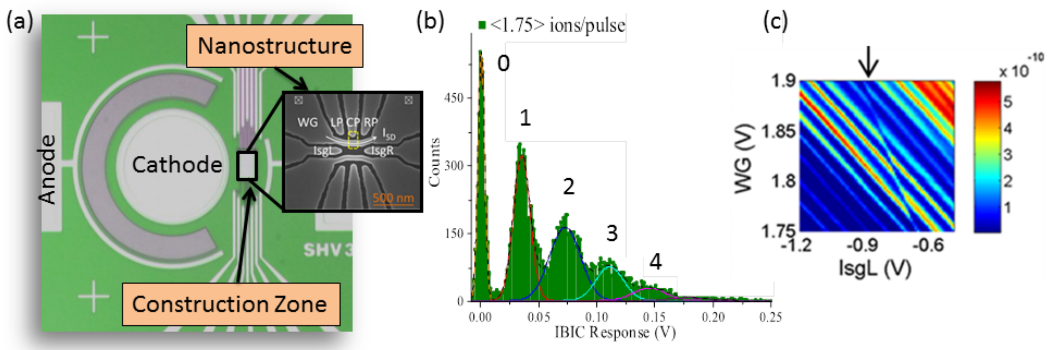

Figure 2: (a) Optical image of the integrated *in*-situ single ion detector and SEM of the nanostructure for low temperature transport. (b) Histogram of the detector response showing quantized single ion detection for 200 keV Si ions with an average of 1.75 ions per pulse. (c) Low temperature transport data taken on a counted implant sample, the charge offset shown is likely due to an electron tunneling between the electrostatically formed SET and the donor.

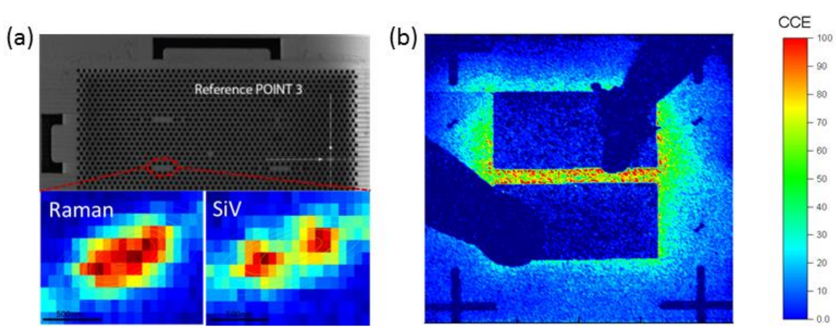

Figure 3: (a) SEM image of a 2D photonic crystal (fabricated at MIT) showing the resulting Raman of the cavity and PL of the implanted SiV centers. (b) IBIC for SNL's in-situ single Ion detectors on diamond substrates showing ~100% charge collection efficiency (CCE).