Patterning nitrogen-vacancy color centers in diamond using scanning focused helium ion beam

Wen-Di Li[1], Zhihong Huang[2], Charles Santori[2], Wei Wu[1] and R. Stanley Williams[1]
[1]Nanoelectronics Research Group, Hewlett-Packard Labs, Palo Alto, CA
[2]Intelligent Infrastructure Lab, Hewlett-Packard Labs, Palo Alto, CA

In the diamond lattice, nitrogen-vacancy (N-V) centers are the nearest-neighbor pairs of a lattice vacancy and a nitrogen atom substituting for a carbon atom. Physical properties of N-V centers recently received significant research interests due to its outstanding properties for quantum information processing as spin qubits, and for magnetometer applications [1, 2]. Coherent manipulation of an individual electron spin associated with a nitrogen-vacancy center in diamond can be used to realize spin readout and quantum entanglement. To build quantum photonic networks based on N-V spin properties, one difficulty is to precisely place N-V centers on designed photonic network, another is to create N-V centers near diamond surface for efficient output coupling and spin manipulation [3]. Previously, ion implantation and electron irradiation have been demonstrated to create N-V centers in diamond [4], however there are still significant challenges for accurately patterning N-V centers. Nitrogen implantation doesn't have high enough resolution to create N-V centers with nanometer accuracy and the N-V spin properties were also proven to be deteriorated [4]. Electron irradiation showed improved N-V spectral-diffusion, however, electrons have a large penetration depth resulting in a highly spread distribution of created N-V centers in the vertical dimension. To create N-V centers precisely, gallium ion based Focused Ion Beam (FIB) can be used to achieve high lateral resolution, but gallium ions may introduce significant contamination to the electronic and optic properties of the diamond material. The recent reported mask based ion implantation may also introduce electron-created N-V centers, but involves several lithography steps [5].

With the helium ion microscope (HIM) recently introduced by Carl Zeiss, focused helium ions demonstrate a world-record imaging resolution of 0.24 nm and our recent helium ion beam lithography results show a lithography resolution of 4 nm half pitch which is higher than published EBL records [6]. In this work, we demonstrate formation of N-V centers in diamond with arbitrary patterns by directly exposing the diamond (with nitrogen impurity) using a scanning focused helium ion beam.

One advantage of creating N-V centers using helium implantation is that the injected helium ions have a small interaction volume in the diamond substrate, therefore diamond lattice vacancies created by helium ions have a small spread in both lateral and vertical dimensions. Figure 1 shows the SRIM simulation of the trajectory of helium ions injected into the diamond with energies of 15, 25 and 35 KeV, respectively. It is clearly seen that the recoiling of the diamond lattice (i.e. creation of lattice vacancies) occurs within 100~200 nm depth below the diamond surface with a lateral spread of similar value. We also notice that lower energy ions have a smaller and shallower interaction region.

Our HIM is equipped with a Raith ELPHY pattern generator to steer the focused helium ion beam and expose the diamond substrate in arbitrary patterns. In our experiment, a

HPHT Type Ib diamond plate (element six) was used, the estimated intrinsic nitrogen concentration is in the range of 100 ppm. Since the focused helium ion beam has a very small spot size, we can create N-V centers with very high resolution. We used 35 kV acceleration voltage in this writing and the sample was annealed at 875°C in forming gas ambient after helium ion exposure for nitrogen to capture moving vacancies. Optical measurement of the photoluminescence was done using a custom-built confocal microscopy setup with an excitation wavelength of 532 nm. Figure 2a shows a series of squares exposed at different helium ion doses (increasing from left bottom to right top). Figure 2b shows images of the photoluminescence from arbitrary patterns such as "HP" and concentric circles. Figure 2c shows N-V centers in a dot array of 1 μm period. Higher spatial patterning resolution is also achievable.

In summary, we demonstrate the application of the helium ion microscope in creating nitrogen-vacancy centers in diamond for quantum devices. This approach can create locally defined N-V centers close to sample surface with high resolution. More study can be done in this area to develop novel device applications.

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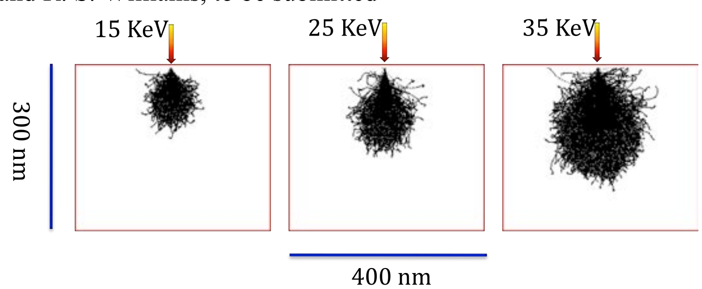

Fig.1 SRIM simulation of helium ions injected into a diamond substrate.

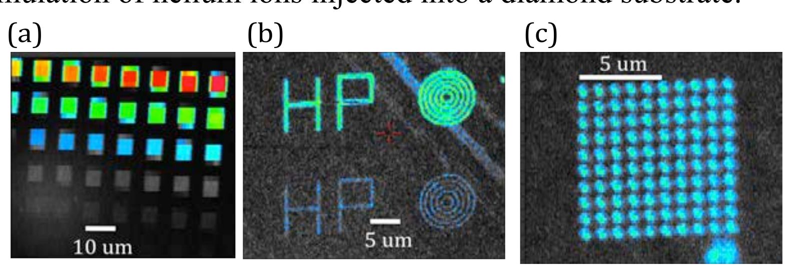

Fig.2 Images of photoluminescence from N-V centers created by focused helium ion beam. (a) Array of 5 um by 5 um squares with different helium ion doses; (b) Arbitrary patterns of "HP" and concentric circles with different doses; (c) N-V centers in a dot array of 1 um pitch.