Diamond nitrogen-vacancy centers created by scanning focused helium ion beam and annealing

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The nitrogen-vacancy (NV) center in diamond has gained much interest in recent years for quantum computing applications due to its long-lived electronic spin coherence, and its capabilities for fast spin manipulation and readout at the single-center level [1]. A remaining challenge is to realize spin entanglement between distant NV centers using schemes based on optical interference. This has motivated many groups to develop optical microcavities with small mode volumes to enhance the photon emission rate into the desired spatial and spectral channel [2]. In such structures the NVs are necessarily located near the diamond surface, and precise control over their position is useful to optimize the cavity coupling. In addition, NV ensembles are interesting for high-sensitivity, micron-scale-resolution magnetometers [3], which also require NVs positioned near a surface. Nitrogen ion implantation can be used to create near-surface NVs, but these NVs typically suffer from increased spectral diffusion of the optical transition and degraded spin coherence properties [4]. Electron irradiation can be used to convert existing substitutional N into NV centers, but for the large energies required to create damage, the correspondingly large penetration depth creates NVs throughout the bulk diamond [5]. In this work, we investigate another technique for formation of NV centers near a surface using a scanning helium focused ion beam. Two types of diamond plates with nitrogen concentration differing by at least two orders of magnitude were implanted, and both showed successful NV creation. NV conversion efficiencies and properties are also discussed below. This result demonstrates a new method to create NVs in diamond and a new application for helium ion beam microscopy.

Recently, focused helium ion beam microscopy has proved its capability for high-resolution imaging (0.24nm) and lithography (4nm) [6]. For implantation into bulk diamond, SRIM simulations indicate that lattice vacancies will be created to a maximum depth of 100~200 nm for implantation energies ranging from 15 to 35 keV, with lateral straggling over similar dimensions. In our experiment, high-temperature-high-pressure grown (HPHT) Type-Ib and CVD grown Type-IIa diamond plates were used with specified nitrogen concentrations below 100ppm and 1ppm, respectively. Both samples were implanted using a 35kV acceleration voltage in writing and subsequently annealed at 900^{o}C for 2 hours in forming gas for vacancy diffusion. Confocal photoluminescent (PL) microscopy was used to measure samples with laser excitation at 532nm. Fig 1(a) shows the confocal PL scan of the helium-ion-implanted region on the Type-Ib plate. The sample was implanted in an array of $5x5\mu m^2$ squares with ion doses increasing geometrically from 10^8 to 10^{14} cm^{-2}. In the PL scan image, different colors indicate the different photon count rates for NV phonon sidebands emission. Fig 1(b) shows the PL spectra for the right-most column of the array, with the NV^- zero-phonon-line (ZPL) at 637nm clearly visible. The image in Fig 1(c) was obtained with one of the scan axes in the vertical direction, indicating that NV centers are positioned within 5μm (n=2.4 in diamond) of the surface, limited by the optical resolution.

Figure 2(a) and (b) show the estimated NV densities and NV conversion efficiencies for the Type-Ib and Type-IIa diamond samples at various helium ion doses. The higher NV density for the Type-Ib material is related to the higher nitrogen concentration. As expected, NV densities increase linearly with the helium ion dose, except for a signature of saturation at a dose of 10^{14} cm^{-2} for the Type-Ib sample. For the conversion efficiency, we assume the maximum specified nitrogen concentrations of 100ppm and 1ppm, respectively, and thus the estimates provide only a lower bound. This provides important information about the dose to use for the specified density we want to create within the film. As a next step, we will study the spin coherence properties and optical linewidths for NV centers created by this method.

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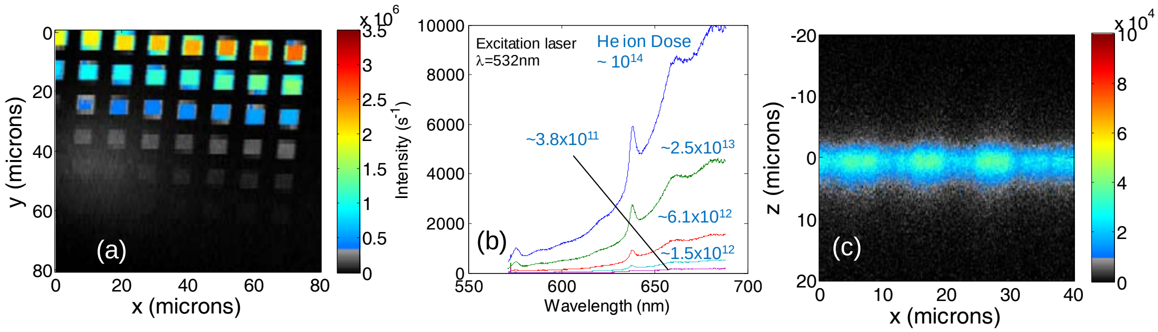

Fig.1 (a) Confocal PL scan image of the He ion implanted Type-Ib diamond, (c) PL spectra for the right-most column, (c) x-z scanning PL image of the sample.

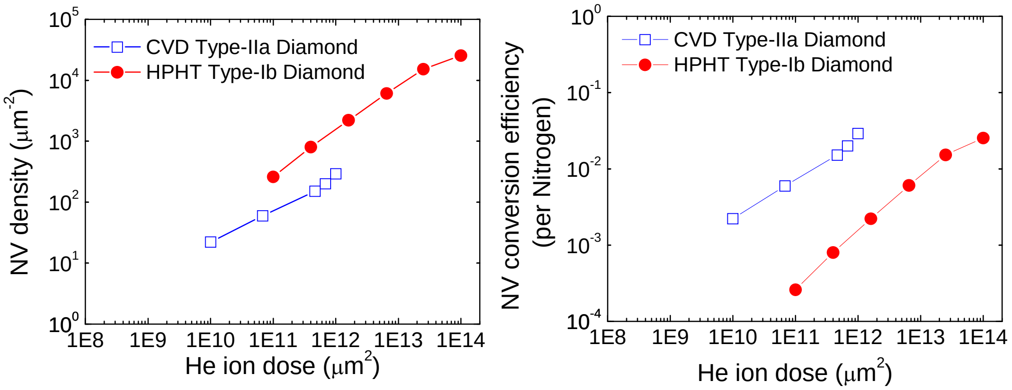

Fig.2 (a) Estimated NV density and (b) NV conversion efficiency versus helium ion doses for Type-Ib and Type-IIa diamond plates after implantation.