Distribution of diamond NV centers created by focused helium ion beam exposure and annealing

Zhouyang Zhu[1], Xusan Yang[2], Zhihong Huang[3], Jiaoni Ma[1], Barbara P. Chan[1], Peng Xi[2], and Wen-Di Li[1*]

[1]Department of Mechanical Engineering, Univ. of Hong Kong, Hong Kong, China; [2]Department of Biomedical Engineering, College of Engineering, Peking Univ., Beijing, China; [3]Hewlett-Packard Labs, Palo Alto, CA, USA

*liwd@hku.hk

Nitrogen-vacancy (NV) centers near diamond surface have potential applications in quantum information processing and nanomagnetometry [1]. Deterministically creating NV centers at specific location and required quantity is important for practical device fabrication. Recently, focused helium ion beam has been used to create NV centers in bulk diamond with a high spatial resolution and superior spin coherence properties[2], and was shown to be a promising approach to practical devices. However, the distribution of the NV centers was not only determined by the helium ion implantation and straggling, but also strongly affected by vacancy diffusion and capture behaviors in the subsequent annealing process, which have not been investigated in depth.

In this work, we investigated the distribution of NV centers created by focused helium ion beam implantation through both superresolution microscopy characterization and a lattice Monte Carlo model. Focused helium ions with an energy of 30 keV were implanted into a high-pressure high-temperature synthetic diamond plate with 100 ppm impurity nitrogen atoms. The implantation patterns are dot arrays with a period of 600 nm. Subsequently the plate was annealed at 900 ℃ for 2 hours with H_2 and Ar as forming gas, and at 450 ℃ in O_2. Confocal microscopy and stimulated emission depletion (STED) microscopy were used to characterize the intensity and sizes of NV center spots created at different helium ion implantation doses. The characterization results were compared with a numerical model to obtain in-depth understanding on the vacancy diffusion and capture process for forming NV centers.

Fig.1 shows the schematic of NV center formation. First, as shown in Fig. 1a, implanted helium ions create vacancies and interstitial carbon atoms. Vacancies freely diffuse in the diamond lattice at elevated temperature by overcoming a series of energy barriers to be finally captured by a nitrogen atom to form NV centers, as shown in Fig. 1b. Recombination of vacancies and interstitial carbons also exists and reduces the number of vacancies. Fig. 2 shows the comparison of the characterization result and modeling of the NV center distribution and number. The distribution difference between vacancy and NV centers verified the importance to investigate vacancy diffusion. Our simulation agrees well with STED results. Fig. 2b proved necessity of considering trapping defect other than nitrogen.

Our result will provide important guidance to further improve NV center creation for device applications

1. Acosta, V.M., et al., Diamonds with a high density of nitrogen-vacancy centers for magnetometry applications. Physical Review B, 2009. 80(11): p. 115202.
2. Huang, Z., et al., Diamond nitrogen-vacancy centers created by scanning focused helium ion beam and annealing. Applied Physics Letters, 2013. 103(8): p. 081906.

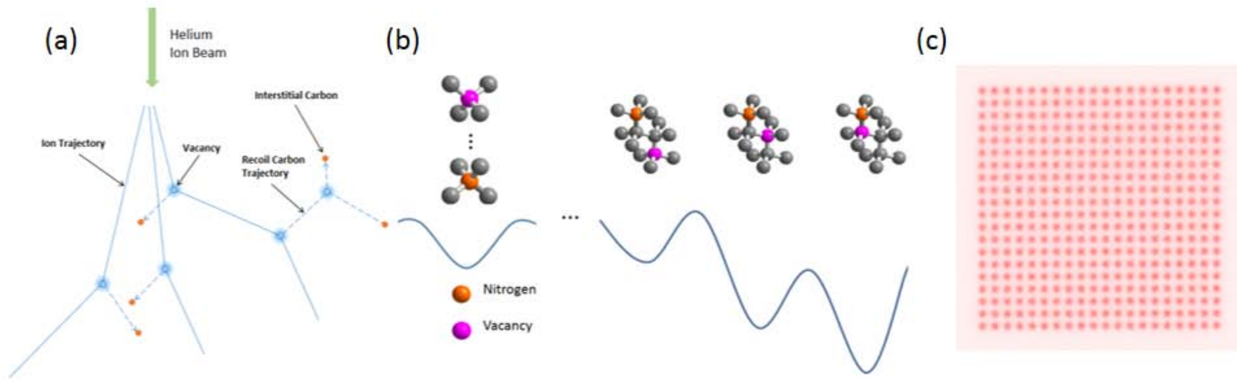

Fig.1 (a) Schematic of vacancy and interstitial carbon creation process; (b) Schematic of vacancy migration in diamond lattice and combination with nitrogen; (c) Confocal images of NV centers assembly spots array. Each spot was exposed by about 40000 helium ions.

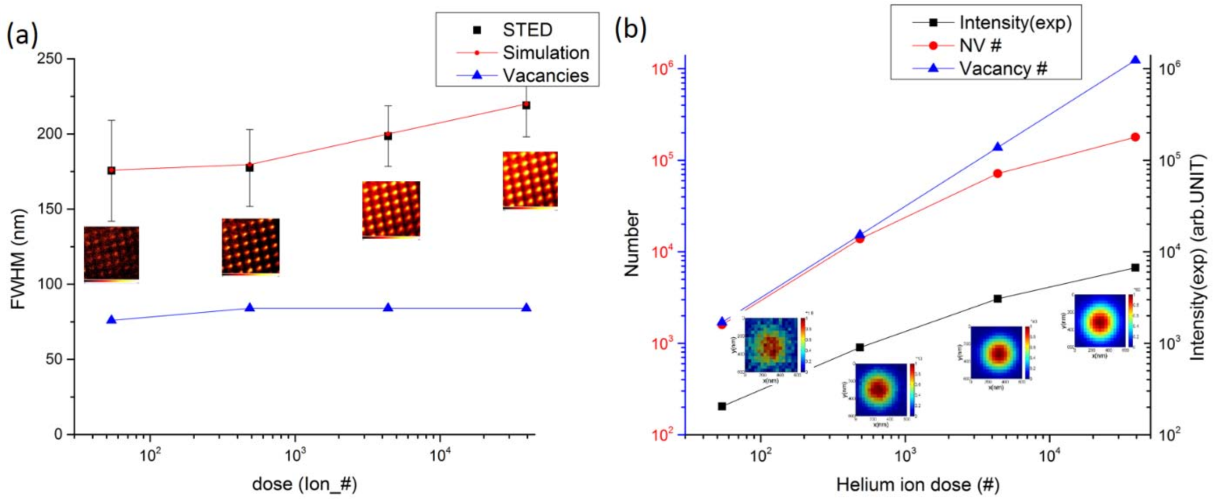

Fig.2. (a) Size of NV spots created under different helium ion doses: STED-measured FWHM of NV spots (black square); simulated FWHM (red dot); and FWHM of vacancies provided by SRIM (blue triangle). Inset figures are STED images. (b) Comparison of photoluminescence intensity measured by confocal microscopy (black square), simulated number of formed NV centers (red dot) and simulated number of vacancies (blue triangle) with different ion doses.