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Presentation Title

Fabrication of Nitrogen-Vacancy Centres in Diamonds by Nitrogen Ion Implantation

Abstract

Deterministic (high-yield, position-controlled) implantation with maintaining the long coherence time is an essential elemental technology to be developed for realizing one of architectonics of multi-qubit system using the NV centers in diamond.

The NV centres can be fabricated by nitrogen ion implantation with a few percent creation yield in low energy 7 keV implantation [1], improving up to over 50 percent by carbon implantation subsequent to $^{15}N_2^+$ (60 keV) implantation [2], and 50 percent by high energy 2 MeV implantation [3]. In the NV centers fabricated by implantation, the coherence time (for example, 18 MeV ^{14}N ions implantation, T_2 = 0.02, and 0.11 ms in a coupled pair in a ^{12}C-99.99 % substrate [4]) is much shortened from that of native NV (T_2 = 0.65 ms in a natural abundance ^{12}C-98.9 % crystal [5], T_2 = 1.8 ms in a ^{12}C-99.7 % enriched crystal [6]), due to the presence of lattice defects which have been produced, transformed, and remained after implantation (room temperature, RT) and annealing (typically 800 °C) processes. In low energy (30-300 keV) implantation, improvement of T_2 by a heat treatment at 1200 °C is still limited to 0.05 ms [7].

To increase the yield and lengthen the coherence time of the NV centers produced by ion implantation are our task. Firstly, the high-purity CVD crystals (Element6, electronic grade) were implanted with N ions at energies between 4 and 13 MeV (7-hold implantation) at elevated temperatures (800 to 1200 °C). The NV^-/NV^0 and the residual defects such as divacancy are characterized by PL and EPR, respectively. From the defect behaviors at different *in-situ* annealing temperatures, we have selected the annealing temperature (1000 ^oC) used after the micro-beam implantation at RT.

To estimate the yield, we use N ion (10 MeV, the FWHM ~ 1 μm of beam profile) micro-beam implantation at RT. The number of incident N ions (N_i) per one spot is controlled by single ion hitting technique. The beam position is scanned with a step of 4-10 μm in a region of 200μm ×200μm, which forms a square grid consisting of many spots. Different N_i was used for different regions. To observe the improvement of T_2 of the NV centers produced by implantation, we used ^{12}C-99.99 % enriched CVD diamond (Element 6) as a substrate, since T_2 of the natural abundance sample is limited to be 0.65 ms by ^{13}C nuclear spin flip-flop. We have attained ~100% yield and the coherence time exceeding ~1ms by the high temperature rapid annealing for a high energy (10 MeV) implantation at RT.

Nitrogen consits of two stable isotopes, ^{14}N (I=1, natural abundance 99.63 %)

and ^{15}N (I=1/2, 0.37 %). To characterize the yield in details, we have carried out $^{15}N^{3+}$ (10 MeV) micro-beam implantation. Scanning confocal laser microscopy (SCLM) was employed to investigate a 2D map of the resultant NV centres. ODMR (optically detected magnetic resonance) of single centers was used to distinguish between ^{15}NV and ^{14}NV. The coherence time (T_2) of electron spin was measured by the Hahn echo.

In a region of 3 implanted ions per spot, the creation yield (ratio of the number of NV centers to the number of implanted ions) has been found to be ~100 % (89 % measured for a grid of 9 spots) by counting the number of bright dots arising from the fluorescence of NV in each spot. In the yield estimation, a single bright spot within the resolution of SCLM which was revealed to be consisting of ^{14}NV and ^{15}NV by ODMR was included. The ODMR measurements enable us to estimate the yield, ^{15}NV/ $^{15}N_i$ to be ~50 % (44 % measured for a grid of 9 spots). Counting all NVs for a region consisting of 9 spots, half of the observed NV centers were created from the implanted nitrogen ions. The remaining centers are produced from pre-existing nitrogen impurities. The ratio observed is [^{14}NV]/[^{15}NV] = ~1.

The spatial distribution of both ^{14}NV and ^{15}NV in each spot is predominantly determined by the beam profile (~1 μm), with the maximum ~2 μm away from the spot center. No distinct difference in the distribution between ^{14}NV and ^{15}NV was noticed within the resolution of SCLM. Thus, the formation of NV by diffusion of vacancy at a distance far from the spot was not evidently noticed.

We have measured the coherence time for two NVs, T_2=1.6 ms for ^{15}NV and T_2=2.0 ms for ^{14}NV, as typical examples. We note that the coherence time of the NV centers produced by implantation is reached to one comparable to the longest (1.8 ms) reported for native NV, which is a grown-in defect in CVD single crystals [6]. This coherence time is sufficiently long to demonstrate a CNOT gate using a closely-located NV pair.

It is expected that the spatial distribution of the NV centers in each spot which is determined here by the beam profile should be narrowed by using N implantation through polymer films with holes, such as polyethylene terephthalate (PET), polyimide, polyallyl diglycol carbonate (CR39) [8,9]. The holes with diameters at micrometer or less are fabricated by heavy ion irradiation and subsequent treatment of ion incident areas using alkali solutions. Implantations using such polymer films have been tried to attain the increase of the probability of creating a coupled pair of the NV centers.

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