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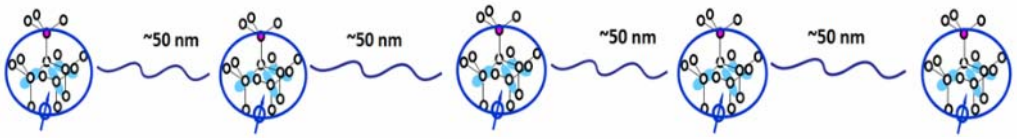
Presentation Title

Quantum computing by isotopically engineered diamond: Material requirement for fabrication of novel mesoscopic structure in quantum grade diamond

Abstract

Diamond provides a lattice for color centers which behave similarly as isolated atoms in vacuum atmosphere. Particularly, the NV center (S=1) in diamond has unique properties suited for solid state quantum information processor which enable at room temperature (RT), (1) optical initialization of spin states, (2) optical readout of individual electron spin states, and (3) extraordinarily long coherence time.

The NV center is a pair of nitrogen and adjacent vacancy with the negative charge state, $[NV]^{-1}$. An array of NV centers is a structure for multi-qubit processor, with single qubit rotations and a two-qubit controlled-NOT (CNOT) gate using electron dipole-dipole interaction between neighboring electron spins as a universal set of quantum logic gates [1], which can be scaled up simply provided that the coherence time is lengthened. Since the dipole-dipole interaction for a distance suited for optical readout of individual spins is weak ($g_e\beta_e/r^3$ ~0.42kHz for r=50nm), i.e, the gate operation time is long, the lengthening of the coherence time, as well as the fabrication of the array structure, is a key role even for a few qubit processor.



Coherence time

The coherence time (T_2) of the NV center is determined by several contributions:

$$\frac{1}{T_2} \quad \frac{1}{T_{2\,^{13}C\ \text{flip-flop}}} + \frac{1}{T_{2\ \text{nitrogen impurity}}} + \frac{1}{T_{2\ \text{paramag. defects}}} + \frac{1}{T_{2\ \text{spin-lattice relaxation}}}$$

The phase relaxation is dominated by spectral diffusion caused by the fluctuation of local fields produced by nuclear spins (^{13}C) in the lattice and distant electron spins associated with impurities

such as the P1 center (substitutional nitrogen in the neutral charge state, $[N_s]^0$) and dislocations. Carbon has two stable isotopes, ^{12}C (I=0, 98.89%) and ^{13}C (I=1, natural 1.11%). It is shown that the coherence time is lengthened by depleting ^{13}C (0.65ms in natural abundance to 1.8ms with ^{12}C 99.7% enrichment) [2].

In our project, we have grown highly ^{12}C enriched single crystals which should eliminate the spectral diffusion due to ^{13}C nuclear spin flip-flops by starting from ^{12}C 99.999% enriched CH_4. The merit of the ^{12}C enrichment on the coherence time is attained only if other sources of spectral diffusion are decreased simultaneously, which means "quantum-grade diamond" requires a level of the purity and the quality (low dislocation density) much higher than those achieved in natural abundance synthetic crystals. Our goal is to reach T_2 limited by the spin lattice relaxation, then the coherence time is tremendously lengthened by lowering the temperature since T_1 is strongly dependent on the temperature. The T_1 at RT attainable has been predicted by estimating intrinsic T_1 from measurement of temperature dependence of T_1.

Toward demonstration of CNOT gate using dipole-dipole interaction of a coupled pair

Nitrogen ion implantation is used to fabricate an array of NV. Even "quantum-grade diamond" is used as substrate, the coherence time of NV produced by ion implantation is easily spoiled by unwanted defects produced by implantation and annealing process. We have achieved T_2~2 ms for an implantation-produced NV (10MeV micro-beam nitrogen ion implantation at RT and annealing at 1000°C). The micro-beam implantation creates several NV centers in a spot by implanting several nitrogen ions per spot. Thus, we are searching a coupled pair with a distance and a coherence time suited for demonstrating a high fidelity CNOT gate using dipole-dipole interaction from implanting many spots. Super-resolution GSD (ground state depletion) technique has been employed for efficient searching.

Critical concentration of nitrogen for deterministic implantation

For deterministic implantation creating NV at a desired position, high yield is important, which has not been achieved for low energy implantation yet. In our high energy micro-beam implantation, a yield of ~100% has been attained. However, by using ^{15}N (I=1/2, natural abundance 0.37%) implantation, ODMR (optically detected magnetic resonance), which distinguish ^{14}NV and ^{15}NV, of single NV centers, has revealed that a significant portion of NV produced is originating from pre-existing nitrogen impurities. This suggests that the negative charge state is achieved partly by using the pre-existing nitrogen impurities as donors. Thus, deterministic implantation requires a nitrogen concentration of substrate lower than that required for a long coherence time and provision of charge compensation mechanism is required.

[1] A. Barenco *et al*., Phys. Rev. Lett. 74, 4083 (1995)

[2] G. Balasubramanian *et al*., Nat, Mater. 8, 383 (2009)