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# Electron Spin Coherence Time of Nitrogen-Vacancy Center in Diamond Improved by External Electric Field

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## Abstract

**A nitrogen-vacancy (NV) center in diamond has excellent properties to realize quantum information processing and nano-scale magnetic- and electric-fields sensors. Their performance is limited by decoherence of an electron spin in the NV center. It is caused by a fluctuating magnetic field. Here, we demonstrated an improvement of coherence time of the NV-electron spin as a result of suppression of the fluctuating magnetic field by applying an external electric field. A Ramsey (Hahn-echo) pulse sequence was employed in order to estimate the coherence time of $T_2^*$ ($T_2$). The $T_2^*$ ($T_2$) was improved from 1.3 (118) μsec at 0 kV/cm to 10.4 (167) μsec at 115 kV/cm. These results indicate the effect of a fluctuating magnetic field on the NV-electron spin can be suppressed by the external electric field.**

## 1. Introduction

A single electron spin in a nitrogen-vacancy (NV) center in diamond can be manipulated and read out even at room temperature. Thus it has potentials to realize quantum information processing [1], nano-scale magnetic- and electric-fields sensors [2,3], thermal sensor [4], and bio-imaging [5]. To improve their performance, a coherence time of the electron spin should become longer. This is because their properties are limited by the coherence time. In the past decade or so, the improvement of the coherence time has been demonstrated by reducing surrounding spins of $^{13}C$ nuclear spins and/or electron spins of nitrogen impurities [6,7]. The flips of their surrounding spins generate a fluctuating magnetic field. It causes fluctuations of the electron-spin energy levels (the resonant frequency) and hence the suppression of the fluctuating magnetic field leads to an improvement of the coherence time.

In this presentation, we focus on the electric field effect on the coherence time of an NV-electron spin because magnetic- and electric-fields effects on the electron-spin energy levels have an influence on each other. The NV center is a well-studied defect consisting of a substitutional nitrogen atom and a neighboring vacancy in diamond as shown in Fig. 1(a). It has two unpaired electrons constitut-

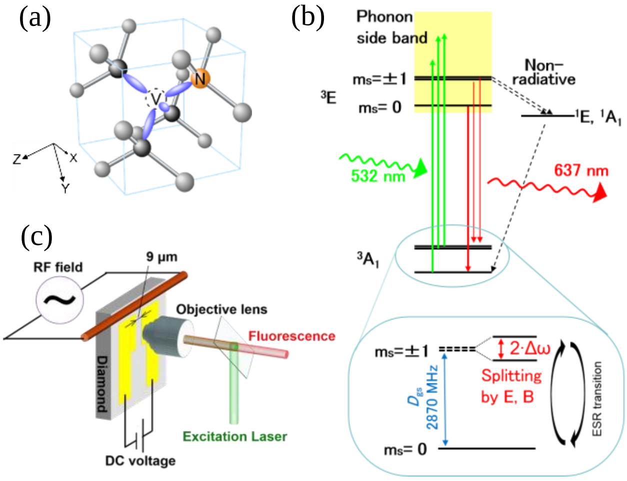


Fig. 1 (a) Schematic illustration of a nitrogen vacancy (NV) center in diamond crystal. (b) Energy level diagram of the NV center. The upper shows electronic transition. Fluorescence processes of the NV center depend on the spin states. The lower shows spin sub-levels and ESR processes. (c) Schematic illustration of our measurement setup. Electrodes were fabricated on a diamond substrate to apply an electric field. The distance between the electrodes is about 9 μm.

ing a spin triplet ($S$ = 1) in an electronic ground state. The spin Hamiltonian $H_{gs}$ of the electronic ground state in the presence of magnetic and electric fields consists of a sum of dipole interaction between the unpaired two electrons and Zeeman interaction of the electron spins [3]:

$$H_{gs} = \left(hD_{gs} + d_{gs}^{\parallel}E_z\right)\left[S_z^{\,2} - \frac{1}{3}S(S+1)\right] - d_{gs}^{\perp}\left[E_x\left(S_xS_y + S_yS_x\right) + E_y\left(S_x^{\,2} - S_y^{\,2}\right)\right] + \mu_B g_e \mathbf{S}\cdot\mathbf{B}, \quad (1)$$

where $h$ is the Planck constant, $D_{gs} \approx 2870$ MHz is the zero-field splitting between the $m_s = 0$ and the degenerate $m_s = \pm 1$ spin sub-levels as illustrated in Fig. 1(b), $\mu_B$ is the Bohr magneton, $g_e$ is the electron $g$-factor, $S$ is the electron spin operator, and $E$ and $B$ are electric and magnetic fields, respectively. $d_{gs}^{\parallel} / h = 0.35 \pm 0.02$ kHz/(kV/cm) and $d_{gs}^{\perp} / h = 17 \pm 3$ kHz/(kV/cm) are the axial and the non-axial components of permanent electric-dipole moment at the ground state, respectively. An externally applied electric field varies electron-orbital shapes and distributions of the NV center. Since it leads to changes of the distance and the angle of the dipole interaction, electric-field effect appears in the terms of the dipole interaction between the unpaired electrons. In the regime where $D_{gs} >> \mu_B g_e B$ and $D_{gs} >> d_{gs}^{\perp} E_{\perp}$, a change in the magnetic transition frequency ($\Delta\omega_{\pm}$) induced by static electric and magnetic fields is described as:

$$\frac{h}{2\pi} \cdot \Delta\omega_{\pm} \cong \pm\sqrt{\mu_B^2 g_e^2 B_z^2 + d_{gs}^{\perp 2} E_{\perp}^{\ 2}}. \qquad (2)$$

Note that the term of $E_z$ was neglected because $d_{gs}^{\parallel}$ is much smaller than $d_{gs}^{\perp}$. According to Eq. (2), the impact of a magnetic field on $\Delta\omega_{\pm}$ is suppressed by an externally applied electric field. It expects that the electric field can suppress fluctuations of the resonance frequency, and hence we present the coherence time of the NV-electron spin improved by the externally applied electric field.

## 2. Experimental results and discussion

Figure 1(c) illustrates a schematic of our home-made confocal microscope and a sample structure for measuring coherence time of single NV centers under the application of an electric field. The single NV centers were created in a natural $^{13}$C-abundance diamond substrate by nitrogen ion-implantation and following annealing. The electrodes for applying the electric field to the single NV centers were fabricated on the diamond substrate by electron beam lithography and metal depositions. The electrodes have gaps of ~ 9 μm. To measure the NV-electron spin state, we employed an optically detected magnetic resonance technique. The technique is based on the spin-dependent fluorescence of the NV center as shown in Fig. 1(b). Due to the spin-dependent fluorescence, we demonstrate the initialization of the spin state to $m_s = 0$ with optical excitation and readout of the spin states by monitoring fluorescence intensity. To measure the coherence time, we employed a Ramsey sequence and a Hahn-echo sequence (see upper illustrates of Fig. 2). When the Ramsey and Hahn-echo sequences were applied, we observed free induction decay and echo signal decay, respectively. The time constants of the free induction decay and echo signal describe $T_2^*$ and $T_2$. They were estimated by curve fittings with $\exp[-(\tau/T_2^*)^n]$ and $\exp[-(2\tau/T_2)^n]$, respectively. In the present study, we measured $T_2^*$ and $T_2$ as a function of an externally applied electric field at room temperature. Noted that there is a residual magnetic field of $B_z$ = 0.013 mT in our measurements.

Figure 2 shows electric-field effects on $T_2^*$ and $T_2$. Both of $T_2^*$ and $T_2$ have been improved under the application of an electric field, but tendencies for the increasing of $T_2^*$ and $T_2$ are different. Eq. (2) indicates the suppression of the impact of a magnetic field on $\Delta\omega_{\pm}$ is enhanced with increasing the strength of the externally applied electric field. Especially, the enhancement of the suppression becomes prominent in the regime where $\mu_B g_e B_z < d_{gs}^{\perp} E_{\perp}$. Our measurement condition is under the regime because the residual

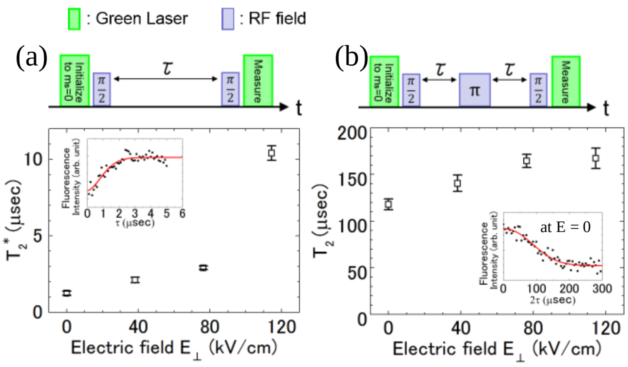


Fig. 2 Electric-field dependence of (a) $T_2^*$ and (b) $T_2$. The upper illustrations show the Ramsey and the Hahn-echo pulse sequences, respectively. The inset figures show signal decays obtained with each sequence at no external electric field. The black dots are measurement results and red solid lines are fits to $\exp[-(\tau/T_2^*)^n]$ and $\exp[-(2\tau/T_2)^n]$, respectively. $T_2^*$ and $T_2$ were estimated from the results of the fits. The all measurements were performed at room temperature. Although no external magnetic field was applied, there is a residual magnetic field of $B_z$ = 0.013 mT.

magnetic field of $B_z$ = 0.013 mT which corresponds to 0.36 MHz and 21 kV/cm in units of frequency and electric field, respectively are much smaller than the strength of the externally applied electric field. Therefore, $T_2^*$ and $T_2$ should increase with increasing the strength of the electric field. The changes in $T_2^*$ shown in Fig. 2(a) quantitatively agree with such an expectation. On the other hand, $T_2$ shown in Fig. 2(b) is saturated at high electric field. This may be due to the high-frequency electrical noise because such noise cannot be suppressed by the externally applied electric field or be canceled out in the Hahn-echo sequence.

## 3. Conclusions

In the present study, we have demonstrated improvement of $T_2^*$ and $T_2$ of the NV-electron spin by applying an electric field. These results indicate the impact of a fluctuating magnetic field on the NV electron spin can be suppressed by an external electric field.


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