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Pure negatively charged state of the NV center in n-type diamond

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Abstract

Optical illumination to negatively charged nitrogen-vacancy centers (NV^-) inevitably causes stochastic charge-state transitions between NV^- and neutral charge state of the NV center.It limits the steady-state-population of NV^- to 5% at minimum (~610 nm) and 80% (~532 nm) at maximum in intrinsic diamond depending on the wavelength.. Here, we show Fermi level control by phosphorus doping generates 99.4 ± 0.1% NV^- under 1 μW and 593 nm excitation which is close to maximum absorption of NV^-. The pure NV^- shows a five-fold increase of luminescence and a four-fold enhancement of an optically detected magnetic resonance under 593 nm excitation compared with those in intrinsic diamond.

Nitrogen-vacancy (NV) centers in diamond are the most promising candidate for various applications such as quantum information science [1–8], magnetometry [9–13], and biosensing [14–16]. For these applications, controlling the charge state of the NV centers is crucial, because optical initialization and readout of the spin state of the NV centers are only possible in negatively charged one (NV^-). However, upon illumination, the NV centers undergo stochastic charge-state transitions between NV^- and neutral charge state of the NV center (NV^0) [17,18]. For example, upon excitation around 580 nm, where NV^- has the highest absorption [17,19], NV^- easily turns into the NV^0 and the steady-state-population of NV^- decreases to about 10%, which could be revealed from single-shot charge-state measurements [17]. Therefore, illumination at 532 nm is usually used in the experiment of NV^-. This charge-state interconversion occurs upon illumination at any wavelength, so the steady-state NV^- population is always less than 75%–80% [17,20].

Generating a pure state including the charge state, close to 100% NV^- population, is very important for quantum information applications. Studies involving the pre-selection and reset of the charge state were carried out to achieve high-fidelity operation because of the instability of the charge states [1,4,5]. However, this approach makes scaling up of diamond quantum registers more challenging. Furthermore, single-shot readout of a nuclear spin indicates that the spin-flip probability of the conditional gate operation decreases because of the stochastic charge-state transitions [6,21]. In addition, such charge-state transitions lead to spectral diffusion [18,22,23] of the zero-phonon line of NV^-, which reduces the efficiency of two-photon quantum interference [4]. For nanoscale sensing applications, it is crucial to keep NV^- stable near the surface for high spatial resolution [15]; however, NV^- near the surface is unstable [24]. In addition, high-contrast fluorescence switching between pure bright NV^- and the pure dark state (NV^0) is also very important for super-resolution microscopy [25].

Previously, NV charge states were controlled by heavy neutron irradiation [26], surface termination [27–29], and combined optical and electrical operations [30–33]. Most of them were

investigated by photoluminescence (PL) spectra, which only reveals a ratio of the charge states of the bright state. On the other hand, single-shot charge-state measurements can reveal the ratio of NV^- and NV^0 during illumination. Recently, deterministic control from NV^- to NV^0 by a purely electrical operation was revealed from the single-shot charge-state measurements [34]. Doping with nitrogen is considered to be one way to control the NV^- population. Nitrogen donors (P1 centers) can donate electrons to NV^0 in the dark region (without laser illumination), thereby changing its state to NV^-, because the activation energy (E_A =1.70 eV) of P1 is less than the energy difference between the acceptor level, labeled (−/0), of the NV center [35] and the conduction-band edge, as shown in Fig. 1(a). Recently, charge states of ensemble NV centers were modulated by ion-implantation of phosphorus and boron atoms [36]. However, pure NV^- charge state, which can be revealed by the single-shot charge-state measurements, has not yet been realized in nitrogen doping and ion-implantation of phosphorus. Based on the activation energy, phosphorus doping during chemical vapor deposition (CVD) appears promising because that of phosphorus (E_A = 0.57 eV) [37] is much less than that of P1. It should be noted that, so far, n-type conductivity in diamond has been only realized by the CVD synthesis technique. In the present study, we quantitatively investigate the charge-state population of NV centers by using single-shot readout measurements in slightly phosphorus-doped n-type diamond. We obtain a pure NV^- population (> 99% NV^-) and report its dynamics.

Phosphorus-doped n-type diamond samples were epitaxially grown by CVD onto Ib-type (111)-oriented diamond substrates with phosphorus concentrations of 5×10^{16} atoms/cm^3 (sample A) and about 5×10^{15} atoms/cm^3 (sample B) [38]. A homebuilt confocal microscope system was used to optically address single NV centers [38]. All experiments were conducted at room temperature.

No color centers other than single NV centers were detected in our high-quality samples under visible illumination. Typically, a high incorporation of nitrogen (such as more than 10^{15} atoms/cm^3) during CVD growth generates many NV centers. It makes difficult to detect single NV centers. The

fact that we detect many single NV centers in our samples reflects an advantage of phosphorus doping. Figures 1(b) and 1(c) show PL raster scan images of n-type diamond (sample A) illuminated at 532 and 593 nm, respectively. Upon 532 nm illumination, the single NV center, labeled NV1, produces almost the same count rate (~55 kcounts/s) as does the NV center labeled NV2. Upon 593 nm illumination, the counts rates of NV1 decreases because of the reduced NV^- population, as reported previously [17]. However, the counts rates from NV2 is about five times larger than that from NV1 (50 vs 10 kcounts/s). Moreover, in another area of samples A and B, more than ten single NV centers are bright under 593 nm illumination.

Weak excitation (typically 1 μW) at 593 nm wavelength makes the charge-state interconversion of NV center gently. Thereby this is used to real-time detection of the charge states [17]. The charge states are distinguished by photon counts with optical filters (we used a 650-nm longpass filter) which blocks the fluorescence of NV^0. From the real-time fluorescence trace of NV1, shown in Fig. 2(a), the optically induced charge-state interconversion is recorded as telegraph signals of fluorescence from NV^- (high counts) and NV^0 (low counts). In contrast to NV1, NV2 continuously keeps the fluorescence level of NV^- (Fig. 2(b)). These results suggest that NV2 populates to pure NV^- under 1 μW, 593 nm illumination.

In order to know charge-state population under 532 nm and 593 nm illumination, photon statistic measurements after illumination are performed. At NV1, average lifetimes of NV^0 and NV^- are 2.92 and 0.59 s, respectively, as determined by the hidden Markov model [17]. Therefore, for detection with 1 μW illumination at 593 nm, if the detection time is sufficiently less than 0.59 s, we can nondestructively determine charge-states population from histogram of photon counts after arbitrarily initialization (single-shot charge-state measurement). Figures 3(a) and 3(b) are measurement sequences and histograms of photon counts of NV1 after initialization by 30 μW, 532 nm and 1 μW, 593 nm illumination. For both initializations, the charge-state population of NV1 has a double Poisson distribution. For initialization at 532 nm, the charge-state populations are estimated

to be NV^0 : NV^- = 0.21 : 0.79 from area of each peaks. Upon initialization at 593 nm, NV^- decreases to 0.12 on NV1 (Fig. 3(b)). These populations are almost the same as single NV centers in intrinsic diamond [17]. In contrast to NV1, NV2 has only one peak on the both sequences (Figs. 3(c) and 3(d)). Peak widths and positions are quite similar to those of NV^- in Fig. 3(a). This result strongly suggests that detected photons in single-shot measurements come from pure NV^-. The difference in the NV^- population between NV1 and NV2 might be attributed to their different local environments (i.e., impurity and/or defects).

On the other hand, under 100 μW, 532 nm illumination, the PL spectrum and the optically detected magnetic resonance (ODMR) intensity of NV^- on NV2 are the same as those of NV1 [38]. These results suggest that, under 100 μW, 532 nm illumination, the charge-state population of NV2 is the same as that of NV1, despite a single peak being observed in Fig. 3(c). This fact implies that the charge state changes during the dark period (10 ms) between initialization and detection. To elucidate this fact, we average the PL intensity of NV2 after a time delay T_d. A 593 nm illumination with power of 230 μW is used to observe decay of fluorescence. The measurement sequence and results are shown in Fig. 4(a). For T_d = 0.1 ms, the PL intensity does not change during illumination. This means the charge state of NV2 is in a state of equilibrium during T_d and illumination. However, when T_d increases to 50 ms, increases of intensity and exponential decay of PL are observed. The increase of intensity can be attributed to the increase of the NV^- population during the dark period (T_d). The subsequent decay is attributed to the decrease of the NV^- population during illumination by relatively higher power (230 μW) compared with 1 μW in single-shot charge-state measurement.

To reveal the transition rate of the charge states during T_d, the PL intensity was measured as a function of T_d as shown in Fig. 4(b). The PL intensity clearly increases with T_d up to a saturation level. By fitting with a single exponential function, the transition rate from NV^0 to NV^- during T_d ($\lambda_{\mathrm{dark}}^{0-}$) is estimated to 1/(3.55 ± 0.42 ms) = 0.282 ± 0.033 ms^{-1}.

Next we investigate the dynamics during 593 nm illumination with several powers to show that the time constant for the charge-state transition is much longer than 30 ms under 1 μW, which is the power of the charge detection in Figure 3. Figures 4(c) and 4(d) show the accumulated PL intensity of NV2 under 100 and 1 μW, 593 nm illumination after initialization by 532 nm laser. The time delay T_d between the 532 and 593 nm laser pulses was set to 10 ms, which is long enough for the NV^- population to grow to more than 99%. At 100 μW, 593 nm illumination, the PL intensity decays exponentially, as shown in Fig. 4(c). This result indicates that the rate from NV^- to NV^0 by 593 nm illumination ($\lambda_{593\,\mathrm{nm}}^{-0}$) at 100 μW is greater than $\lambda_{\mathrm{dark}}^{0-} + \lambda_{593\,\mathrm{nm}}^{0-}$, where $\lambda_{593\,\mathrm{nm}}^{0-}$ is a rate from NV^0 to NV^- by 593 nm illumination. It was observed that the rate $\lambda_{\mathrm{dark}}^{0-} + \lambda_{593\,\mathrm{nm}}^{0-}$ becomes smaller as the laser power decreases. At 1 μW illumination, no decay in fluorescence intensity is observed, as shown in Fig. 4(d). This also supports charge-state is at equilibrium and purely populated to NV^- under 1 μW, 593 nm illumination.

We quantitatively estimate population of NV^- to use transition rates. Under 593 nm cw illumination, the steady-state-population of NV^- (p_{NV^-}) can be calculated as follows [17,34]:

$$p_{NV^-} = \frac{\lambda^{0-}}{\lambda^{0-} + \lambda^{-0}} = \frac{\lambda_{593\,\mathrm{nm}}^{0-} + \lambda_{\mathrm{dark}}^{0-}}{\lambda_{593\,\mathrm{nm}}^{0-} + \lambda_{\mathrm{dark}}^{0-} + \lambda_{593\,\mathrm{nm}}^{-0}} . \quad (1)$$

We omitted $\lambda_{\mathrm{dark}}^{-0}$ because it is negligibly smaller than other rates (if it is not zero, histogram of Figs. 2(c) and (d) must contain two Poisson distributions.). Here the optically induced transition rates ($\lambda_{593\mathrm{nm}}^{0-}$ and $\lambda_{593\mathrm{nm}}^{-0}$) for NV1 under 1 μW, 593 nm illumination can be obtained by average lifetimes of NV^0 and NV^- in Fig. 2(a). These rates are estimated to be $\lambda_{593\mathrm{nm}}^{0-} = 1/2.92\mathrm{s} = 0.342\mathrm{s}^{-1}$ and $\lambda_{593\mathrm{nm}}^{-0} = 1/0.59\mathrm{s} = 1.7\,\mathrm{s}^{-1}$. If these values of NV2 are assumed to be the same as those for NV1, p_{NV^-} for NV2 under 1 μW, 593 nm illumination is estimated to be p_{NV} = 0.994 ± 0.001 from

equation (1). For reference, p_{NV^-} for NV1 is calculated to be 0.170 (where $\lambda_{dark}^{0-} = 0$), which is consistent with the charge-state population in Fig. 3(b). The case for the 532 nm excitation can be analyzed and it is indicated that a population consisting solely of the NV^- charge state can be generated by low-power 532 nm illumination [38].

In NV2, we found a four-fold enhancement of an ODMR under 593 nm excitation compared with that of NV1. Figure 4(e) shows ODMR spectra of NV1 and NV2 with a 1 mT magnetic field along the [111] direction of the diamond crystal under 200 μW, 593 nm illumination. From NV2, the ODMR signal intensity from NV^-, which is the normalized fluorescence intensity, is almost 4.18 times larger than that from NV1. This result confirms that the NV^- population of NV2 is much larger than that of NV1 and single peaks in Figs. 3(c) and 3(d) are from the NV^- charge state. To measure the ODMR spectra, we increased the 593 nm laser power to 200 μW. At 200 μW, the charge state is not considered to be a purely negative state. Under 593 nm, 1 μW illumination, the ratio of NV^- population between NV2 and NV1 is calculated to be 100% / 12% = 8.33 from the results of Fig. 3 (b) and 3 (d). The enhanced ratio of ODMR signal intensity (= 4.18) is smaller than it. The main reason is considered to be due to the smaller ratio of NV^- population at the high laser power (200 μW). In our case, NV1 and NV2 are aligned to [111] direction of diamond crystal. Therefore, we assume the microwave power, the amplitude and the polarization of laser of NV2 are the same with those of NV1. In the general case that NVs feels different microwave power, amplitude and polarization of laser with each other, we need to consider the effects of broadening of the spectra [39].

Finally, we measured spin-coherence time T_2 by Hahn echo technique, because a long T_2 is critical for quantum information and sensing. As a result, T_2 is estimated to be 19.77 ± 0.27 μs for NV2 in sample A ([P] = 5×10^{16} atoms/cm^3) and 49.6 ± 2.2 μs for sample B ([P] = 5×10^{15} atoms/cm^3) [38]. Previously, dependence of nitrogen donors (i.e., P1 centers) concentration on T_2 of P1 centers was investigated and T_2 of P1 centers is estimated to be about 1 ms and 100 μs for the P1

concentration of 5×10^{15} and 5×10^{16} cm^{-3}, respectively [40]. We expect that the dependence of the phosphorus concentration on T_2 of NV centers to be almost the same as that of the P1 center because the unpaired electrons localize on their atoms. However, the present results of T_2 are shorter than the expected values. It can be attributed to other impurities or defects [41]. In other words, if these impurities or defects could be removed and if ^{12}C could be enriched, T_2 in n-type diamond should become comparable to the long (millisecond order) T_2 of high-quality intrinsic ^{12}C-enriched diamond [13,42].

In summary, we investigated the NV^- population and its dynamics in phosphorus-doped n-type diamond by using nondestructive, single-shot readout measurements of the NV charge state. In phosphorus-doped n-type diamond, the results reveal that the NV^- charge state that populates over 99% of the NV centers is generated by 1 μW illumination at 593 nm. Under these illumination conditions, we obtain an almost five-fold increase in luminescence and a four-fold increase in the ODMR signal compared with the corresponding results for NV centers in intrinsic diamond. By analyzing the NV^- population as a function of illumination, we show that this approach would increase the NV^- population not only under 593 nm illumination but also under illumination by other wavelengths, such as 532 nm. These results are expected to significantly enhance the versatile potential of NV centers.

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FIGURES

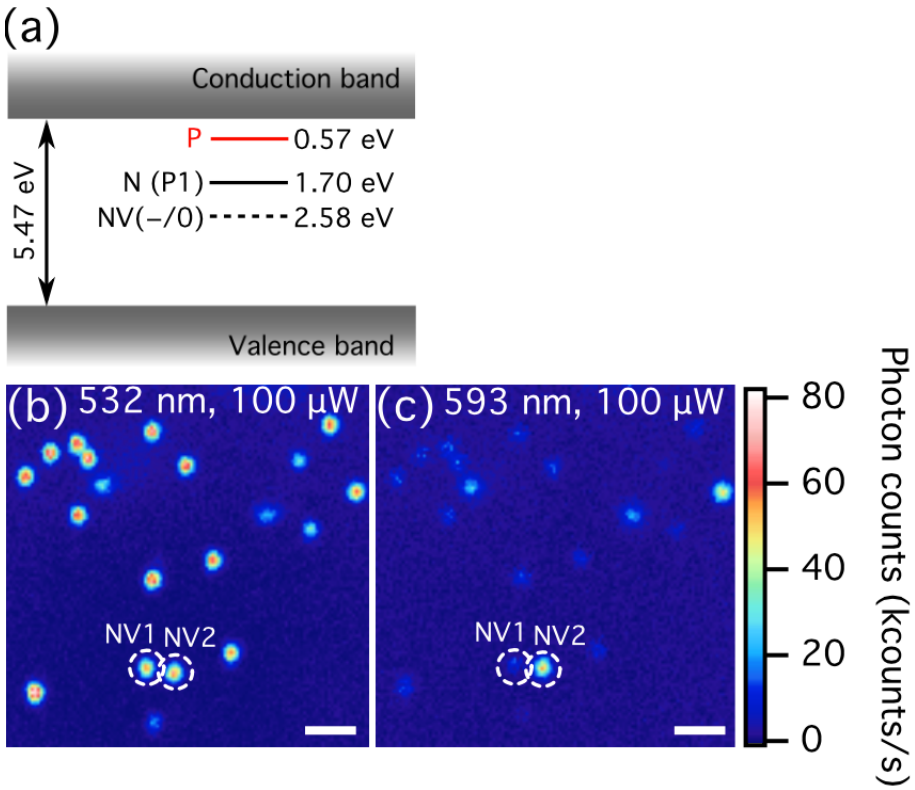

Figure 1: (a) Donor energy levels of phosphorus (P) and nitrogen (P1) donors and acceptor level labelled (-/0) of the NV center with respect to conduction-band edge of diamond. (b) PL raster-scan images of single NV centers in n-type diamond (sample A, [P] = 5×10^{16} atoms/cm^3) under 100 µW, 532 nm illumination. Most single NVs show similar optical properties under these illumination conditions. (c) Same as panel (b) but for 100 µW, 593 nm illumination. Fluorescence count rate of NV2 is about five times larger than that of NV1.

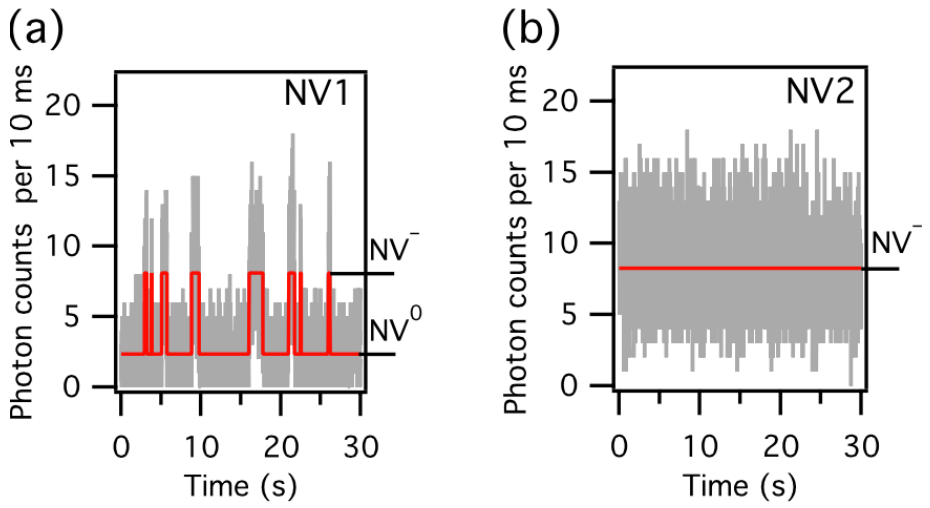

Figure 2: (a) Time trace of fluorescence of NV1 under continuous 1 μW, 593 nm illumination. Photon bursts occur when the charge state transforms into the NV^- state. The solid red line shows the most probable fluorescence levels, as obtained by the hidden Markov model. Here the average lifetimes of the two charge states are 2.92 s (NV^0) and 0.59 s (NV^-). (b) Time trace of fluorescence of NV2 under the same illumination condition as for NV1. NV2 does not show photon bursts in the trace. A solid red line is the average count rate and is almost the same as the higher counts (NV^-) of NV1 in panel (a).

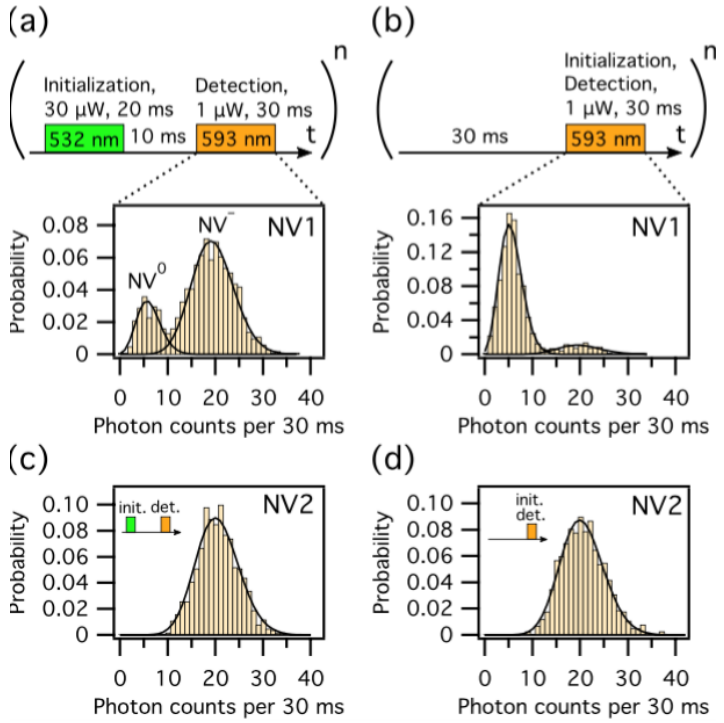

Figure 3: Nondestructive single-shot charge-state measurements with two types of charge state initialization: (a) 30 μW, 532 nm illumination and (b) 1 μW, 593 nm illumination. NV1 population exhibits a double Poisson distribution that is due to two different charge states. Initialization at 593 nm drastically decreases the population of the NV^- charge state. (c), (d) Conversely, NV2 has a single peak at the same position as NV^- irrespective of initialization conditions. We repeated each sequence n=1000 times for each histogram.

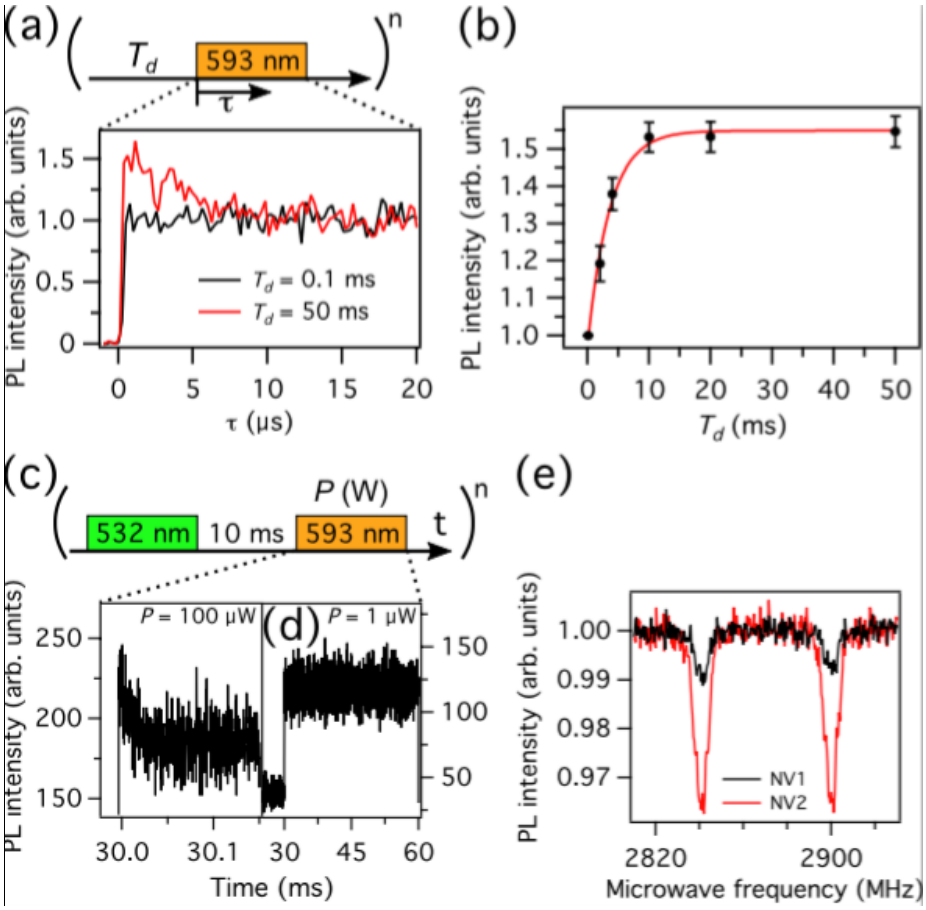

Figure 4: (a) Increase of initial PL intensity of NV2 after time delay T_d = 0.1 and 50 ms under 230 μW, 593 nm illumination. PL intensity of NV2 increases after T_d = 50 ms. We repeated sequence n=12,209 times. (b) PL intensity as a function of T_d. The fluorescence intensity is normalized to unity for T_d = 0.1 ms. The solid red line is a fit to a monoexponential with a time constant of 3.55 ms. (c) PL intensity for 593 nm illumination pulse T_d = 10 ms after initialization by 532 nm illumination pulse. For 100 μW illumination, the PL intensity decays exponentially. (d) Same measurement as for panel (c) except the illumination was 1 μW, 593 nm. No decay in fluorescence intensity is observed. We repeated sequence n=17,219 and 9130 for P = 100 μW and 1 μW illumination, respectively. (e) ODMR spectrum of NV1 and NV2 under 200 μW, 593 nm illumination. Signal intensity from NV^- of NV2 is almost 4.18 times larger than that from NV1.. The amplitude of the applied magnetic field was 1 mT along the [111] direction of the diamond crystal.