

# Division of Materials Chemistry – Inorganic Photonics Materials –

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## Scope of Research

NV center in diamond has been extensively interested because the single spin of it can be manipulated and detected at room temperature. Furthermore, spin coherence time of the NV center is very long. The coherence time is the time to retain coherence (superposition state) and directly relates to the sensitivity of sensor of magnetic field, electric field and temperature. Therefore, the unique and excellent properties of the NV center are expected to be applied for quantum computing, quantum communication, bio-imaging, and high-sensitive sensor with nano-scale resolution.

### KEYWORDS

Diamond

Quantum Materials

NV Center

Quantum Sensing

Quantum Information Science



## Selected Publications

Fukui, T.; Doi, Y.; Miyazaki, T.; Miyamoto, R.; Kato, H.; Matsumoto, T.; Makino, T.; Yamasaki, S.; Morimoto, R.; Tokuda, N.; Hatano, M.; Sakagawa, Y.; Morishita, H.; Tashima, T.; Miwa, S.; Suzuki, Y.; Mizuochi, N., Perfect Selective Alignment of Nitrogen-vacancy Center in Diamond, *Appl. Phys. Express*, **7**, 055201 (2014).

Doi, Y.; Makino, T.; Kato, H.; Takeuchi, D.; Ogura, M.; Okushi, H.; Morishita, H.; Tashima, T.; Miwa, S.; Yamasaki, S.; Wrachtrup, J.; Suzuki, Y.; Mizuochi, N., Deterministic Electrical Charge State Initialization of Single Nitrogen-vacancy Center in Diamond, *Phys. Rev. X*, **4**, 011057 (2014).

Mizuochi, N.; Makino, T.; Kato, H.; Takeuchi, D.; Ogura, M.; Okushi, H.; Nothaft, M.; Neumann, P.; Gali, A.; Jelezko, F.; Wrachtrup, J.; Yamasaki, S., Electrically Driven Single Photon Source at Room Temperature in Diamond, *Nat. Photonics*, **6**, 299-303 (2012).

Zhu, X.; Saito, S.; Kemp, A.; Kakuyanagi, K.; Karimoto, S.; Nakano, H.; Munro, W. J.; Tokura, Y.; Everitt, M. S.; Nemoto, K.; Kasu, M.; Mizuochi, N.; Semba, K., Coherent Coupling of a Superconducting Flux-qubit to an Electron Spin Ensemble in Diamond, *Nature*, **478**, 221-224 (2011).

Neumann, P.; Mizuochi, N.; Rempp, F.; Hemmer, P.; Watanabe, H.; Yamasaki, S.; Jacques, V.; Gaebel, T.; Jelezko, F.; Wrachtrup, J., Multipartite Entanglement Among Single Spins in Diamond, *Science*, **320**, 1326 (2008).

## Perfect Selective Alignment of Nitrogen-vacancy Center in Diamond

Nitrogen-vacancy (NV) centers in diamond have attracted significant interest because of their excellent spin and optical characteristics for quantum information and metrology. In the diamond crystal structure, the orientations of NV centers are classified according to the alignment along one of four possible crystallographic axes:  $[111]$ ,  $[1\bar{1}\bar{1}]$ ,  $[\bar{1}\bar{1}1]$  or  $[\bar{1}1\bar{1}]$  (Fig. 1). In most diamond samples, NV centers equally occupy these four orientations. To take advantage of the characteristics, the precise control of the orientation of the N–V axis in the lattice is essential. It is because improvement in readout contrast and a magnetic field sensitivity can be expected when compared to with those of standard samples with equal population of all NV orientations. Furthermore, spin and optical characteristics strongly depend on this orientation. In cases where photoluminescence (PL) is detected from the  $[111]$  direction, the PL intensity from N–V centers in which the N–V axis is parallel to  $[111]$  (NV  $\parallel$   $[111]$ ) is higher than others because electric dipole transitions are allowed for dipoles in the plane perpendicular to the N–V axis. With respect to spin, it is expected to play a key role at the quantum interface with photon and superconducting flux qubits.

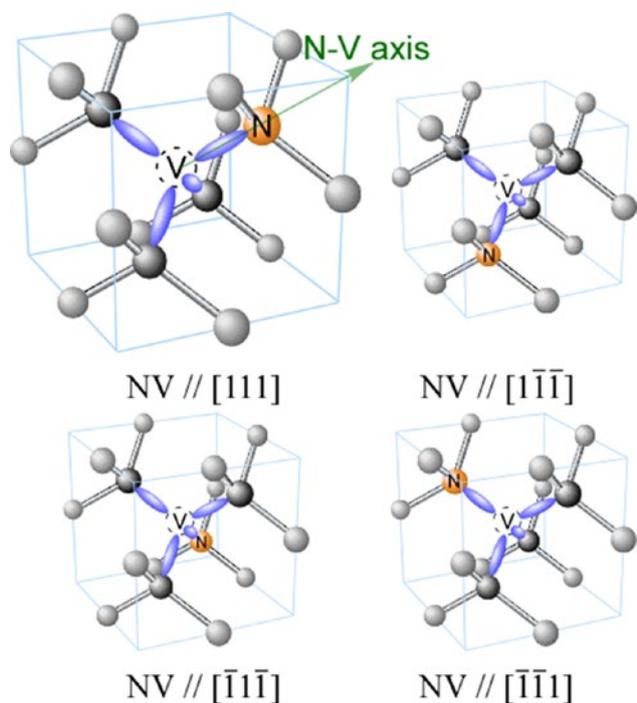


Figure 1. Four possible orientations of NV centers in diamond crystal.

We experimentally showed that the orientation of more than 99 % of the NV centers can be aligned along the  $[111]$ -axis by CVD homoepitaxial growth on  $(111)$ -substrates. We also discuss about mechanisms of the alignment. We examined the atomistic generation mechanism for the NV defect aligned in the  $[111]$  direction of C(111) substrates with first-principles electronic structure calculations. Our result enables a fourfold improvement in magnetic-field sensitivity and opens new avenues to the optimum design of NV center devices.

## Pure Negatively Charged State of NV Center in n-type Diamond

For the applications of NV center, controlling the charge state 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 a dark state of a neutral charge state of the NV center ( $NV^0$ ) as shown in Fig. 2. For example, upon excitation around 580 nm, where  $NV^-$  has the highest absorption,  $NV^-$  easily turns into the dark state of  $NV^0$  and the steady-state-population of  $NV^-$  decreases to about 10%, which could be revealed from single-shot charge-state measurements. 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%. We experimentally showed Fermi level control by phosphorus doping generates  $99.4 \pm 0.1\%$   $NV^-$  under  $1 \mu W$  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. These results are expected to significantly enhance the versatile potential of NV centers.

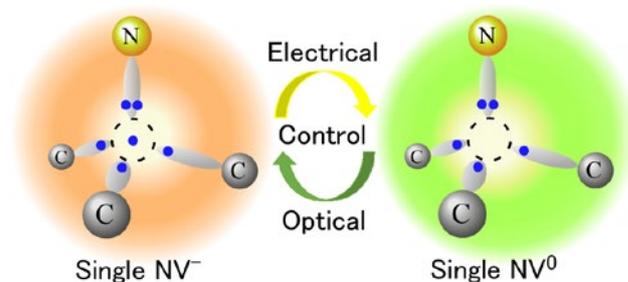


Figure 2. Stochastic charge-state transitions between  $NV^-$  and a dark state of a neutral charge state of the NV center.