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Fabrication of nitrogen-vacancy centers in diamond power devices for electric-field sensing

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Abstract

Diamond semiconductor devices are expected to be next generation low loss power devices. To improve device characteristics, physical quantities in devices become important information. In this study, we fabricated atomic-level sensors, nitrogen-vacancy (NV) centers, in diamond devices to directly measure electric field inside the devices. We confirmed that fabricated NV centers show resonant frequency in optically detected magnetic resonance spectrum, indicating that they work as electric-field sensors.

1. Introduction

Diamond is an attractive semiconductor material for next generation power devices due to its wide band-gap (5.5 eV), high breakdown field (10 MV/cm), and high thermal conductivity (20 W/cmK). These characteristics make diamond devices low-loss and enable to operate in severe temperature and high voltage range. So far, we have demonstrated high temperature and high breakdown field operation of diamond JFETs [1,2]. To further improve the device characteristics, measuring physical quantities inside of the device such as electric field, temperature and leak current is important. Despite this importance, it's generally very difficult to measure them in high resolution and accuracy.

An atomic structure composed of a pair of a nitrogen and a vacancy (NV center) is a nano-scale sensor sensitive to magnetic field [3], electric field [4], and temperature [5]. It can be fabricated by doping nitrogen atoms into the diamond and annealing. The sensing information of NV centers can be read optically under ambient conditions.

In this study, we fabricated NV centers in diamond junction field effect transistors (JFET) [6] and diodes to measure electric field in the devices.

2. Experimental

Figure1 (a) shows schematic of the diamond JFET with a high breakdown voltage of ~500 V (Fig. 1b). The boron-doped p-type channel is sandwiched by two n^+-type diamonds to control the drain current by the gate voltage [1]. For the breakdown measurements, the positive gate voltage was applied to completely close the channel by the depletion layers.

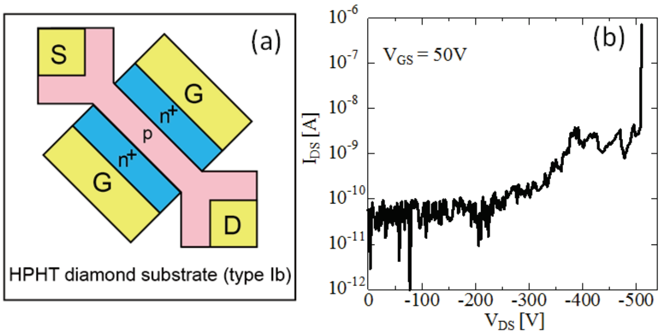

Fig. 1 Schematic (a) and breakdown characteristic (b) of diamond JFET with a channel width of 1 μm.

Atomic-scale NV sensors were formed by ion implantation and subsequent annealing in the diamond devices. The formation of the NV centers was confirmed by home-built confocal microscopy (excitation wavelength: 532 nm).

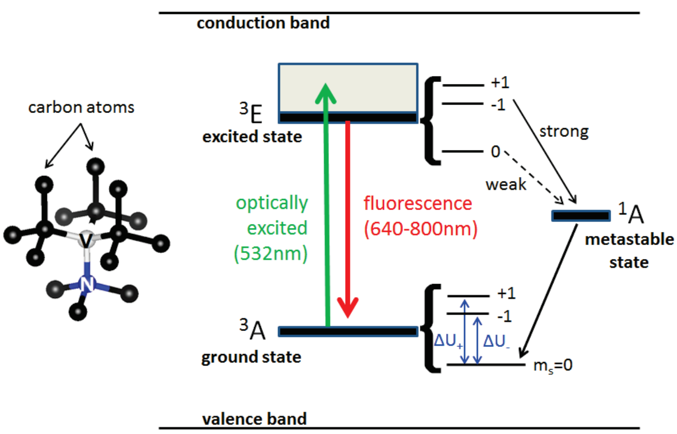

Fig. 2 Structure and energy diagram of NV center

By irradiating with the 532 nm laser, the NV centers show fluorescence with a zero phonon line at 638 nm and side bands in the range of 640-800 nm, as shown in Fig. 2. The electric-field can be measured based on the optically detected magnetic resonance (ODMR) technique. Figure 2 shows energy levels of the NV center in diamond. Both the ground and excited states are spin triplets. In the case of magnetic quantum number (m_s) of electrons = 0, most of electrons directly decay to the ground state and emit fluorescence. On the other hand, when electrons are excited to $m_s = \pm 1$ by electron spin resonance (ESR), they tend to decay via a singlet metastable state (^{1}A) to the ground state, leading to less fluorescence intensity. The NV center exposed to electric-field has different energy levels of the $m_s = \pm 1$ states by the Stark shift ((ΔU_+ and ΔU_- in Fig.2). Thus, the electric field can be obtained by measuring the ESR frequencies. The energy shifts by the electric-filed is described as [4],

$$\Delta U_{\pm} = d_{gs}{}^{\parallel} E_{\parallel} \pm d_{gs}{}^{\perp} E_{\perp} \qquad (1)$$

where ∥ means axial direction of NV center and ⊥ is direction perpendicular to the N-V axis. $E_{\parallel}$ and $E_{\perp}$ has different contribution to the energy shift, so the direction as well as strength of electric field can be measured by this method. This energy shift can be read from frequency shift and split of dip in ODMR spectrum. Electric field is calculated from this shift information.

3. Results and discussion

Figure 3(a) shows the fluorescence intensity mapping of diamond JFET after the NV center fabrication process. We can clearly recognize the structure of the device. The high florescence area around the device is the Ib substrate containing nitrogen. There are some fluorescence spots in p-layer area of the device. Electric field in the JFET is highest at the pn junctions between the gate and channel (blue rectangle area in Fig. 3), so electric field distribution in this area is important to improve JFET breakdown characteristics.

The inset in Fig. 3(b) shows close-up detail of the blue rectangular area in Fig. 3(a). Some of the individual spots in this area are thought to originate from NV centers. To confirm the fabrication of the atomic NV sensors in the device, ODMR measurements were performed at the fluorescence spot indicated by the arrow (Fig. 3(b)). A dip of the fluorescence intensity is observed at about 2.87 GHz. The fact indicates that this NV center is negatively charged (NV^-), which has sensitivity to electric field and can be used as a sensor. The dip is slightly splitting, which is probably caused by strain of diamond. Measurements of ODMR spectra while applying high voltages will be performed to measure electric field in the device.

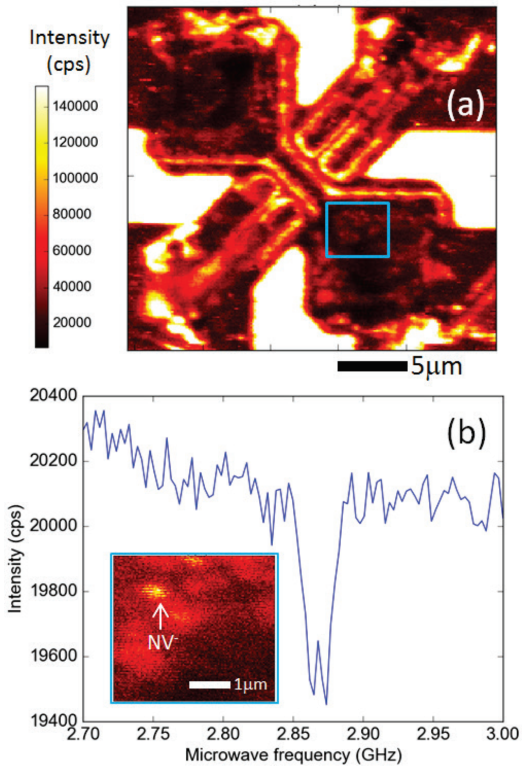

Fig.3 Fluorescence intensity mapping of the JFET(a) and ODMR spectrum of the NV center indicated by an arrow(b)

4. Conclusion

We demonstrated the fabrication of NV centers in diamond JFET. We confirmed by the ODMR measurements that they are negatively charged (NV^-), indicating that the NV centers can work as electric field sensors. Direct measurements of physical properties inside diamond power devices will be done in further studies.

Acknowledgements

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