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Optically Detected Magnetic Resonance Study of 3D Arrayed Silicon Vacancies in SiC pn Diodes

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Abstract. We demonstrate optically detected magnetic resonance (ODMR) of three-dimensional (3D) arrayed silicon vacancies (V_{Si}'s) within in-plane SiC pn diodes. The 3D arrayed V_{Si}'s were created by proton beam writing using different ion (proton) energies. The photoluminescence (PL) mapping analysis indicates that the features of the luminescent spot, such as size and depth, can be estimated by a Monte Carlo simulation (SRIM). This suggests that assessment at any location within the SiC device can be realized using V_{Si} quantum sensors. Luminescent spots, with depth ranging 4-60 μm, showed similar ODMR spectra including contrast which indicates that similar sensor sensitivity can be realized. This suggests that the 3D arrayed V_{Si} implemented in this work can act as quantum sensor elements with uniform sensitivity in SiC devices.

Introduction

Quantum technologies have attracted much interests from a wide range of scientific and engineering fields. The well-known nitrogen-vacancy center (NVC) in diamond is a promising building block for various quantum applications such as quantum computers, communication, and sensors [1, 2]. Recently, it has been reported that several color centers in silicon carbide (SiC) show similar quantum properties to NVC [3-5]. Among them, silicon vacancy (V_{Si}) is one of leading candidates for realizing quantum applications because of experimental proof of quantum sensing [6]. Since an electron spin in a V_{Si} is easily influenced by its surrounding environment, (e.g. by temperature and magnetic field), sensing with high sensitivity and spatial resolution sensor is expected. Unlike diamond, SiC is commercially available in large size wafers and sophisticated device fabrication processes (growth, doping, etc.) will enhance practical realization of quantum applications.

SiC-based power devices have actually already been commercialized. To improve their performance, it is first important to understand their internal state (electric, magnetic and the temperature). However, there are currently no methods that are capable of detecting the internal state directly. We propose SiC devices embedded with V_{Si}'s can be used as a quantum sensor to directly measure the internal state of these devices.

V_{Si}'s are usually created by energetic particle irradiation. Irradiation gives rise to not only V_{Si} but also other various defects in the SiC crystal, which can be detrimental to the operation of the SiC devices as well as quantum sensing ability of the V_{Si}'s. Proton beam writing (PBW) is a suitable method to create V_{Si} because it can control both the position and the density of V_{Si}, single to ensemble [7]. Therefore, in order to minimize the degradation of device performance while simultaneously maximizing the number of imbedded V_{Si} to maintain high sensitivity, the V_{Si}'s are implanted in a three-dimensional (3D) grid manner.

In this study, we perform optically detected magnetic resonance (ODMR) measurements, which is a standard technique for quantum sensing, on 3D arrayed V_{Si}'s within in-plane SiC pn diodes.

Experimental

The samples used in this study are an in-plane pn (p^+nn^+) junction diodes fabricated in epitaxial 4H-SiC layers as schematically shown in Fig. 1 (a). A n-type epitaxial SiC layer grown on a 4H-SiC substrate (Si face, 4° off) was utilized as a starting material. The thickness and the doping concentration of the epilayer were 5.6 μm and 1.5×10^{16} cm^{-3}, respectively. The p^+- and n^+-type regions were sequentially formed by aluminum (2.0×10^{20} cm^{-3}) and phosphorus (5.0×10^{19} cm^{-3}) ion implantations, respectively, at 800 °C. Subsequent annealing was performed at 1800 °C for 5 min in Ar atmosphere for dopant activation. Finally, a metal electrode was formed onto the p^+- and n^+-type regions using Al evaporation and lift-off processes.

To introduce V_{Si}s into the pn diodes, PBW was carried out using the 3MV single-ended accelerator at TIARA, QST Takasaki [8]. The focused proton (H^+) beam with beam diameter of ~ 1 μm (full width half maximum) were irradiated in close proximity to two electrodes in a 3D grid manner at room temperature. The H^+ fluence was set to 1×10^6 H^+ ions/spot, which is equivalent to 1×10^{14} ions/cm^2. We have confirmed that no significant degradation of luminescence properties resulted from the H^+ fluence [9]. The PBW pattern was 10-μm-pitch dot array with pattern area of 400 × 400 μm^2 (yellow hatched area in Fig. 1 (b)). To change the depth of V_{Si}'s, three different ion energies were used (0.5, 1.5 and 3 MeV, corresponding with ~4, 20 and 62 μm estimated from a Monte Carlo simulation code, SRIM [10], respectively) using the same dot pattern where the sample was shifted upon each irradiation.

Photoluminescence (PL) mapping and ODMR spectra were measured using a home-built confocal scanning microscope (CFM) at room temperature. The CFM system is shown in Fig. 2. A 671 nm laser with 0.5 mW was used for photoexcitation of V_{Si}'s. 830 and 900 nm long pass filters (LPFs) were utilized for selective detection of PL from V_{Si} (V2, zero-phonon line=917nm at 80 K [11]) out of two types of V_{Si} (quasihexagonal (V1) and quasicubic (V2) sites) in 4H-SiC [12] because V1 does not show spin resonance signal at room temperature [11]. A loop coil was set just behind the sample

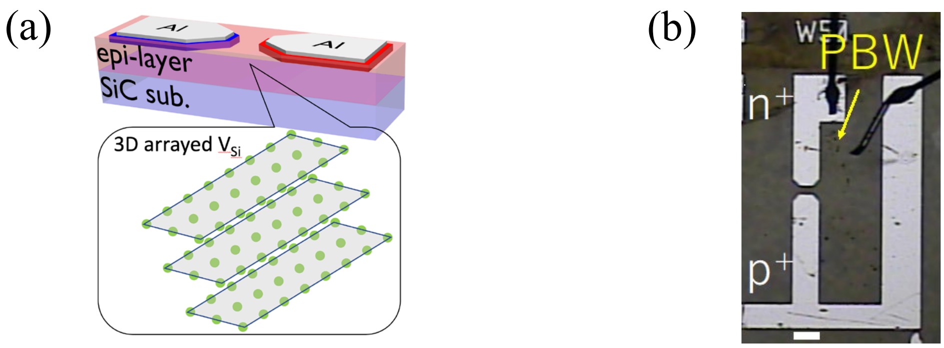

Fig. 1. (a) Schematic image of the SiC pn (p^+nn^+) junction diode. A 3D arrayed V_{Si} was created in close proximity to two electrodes. (b) Optical microscope image of the sample. A yellow hatched square indicates a PBW pattern area. Scale bar (write line), 100 μm.

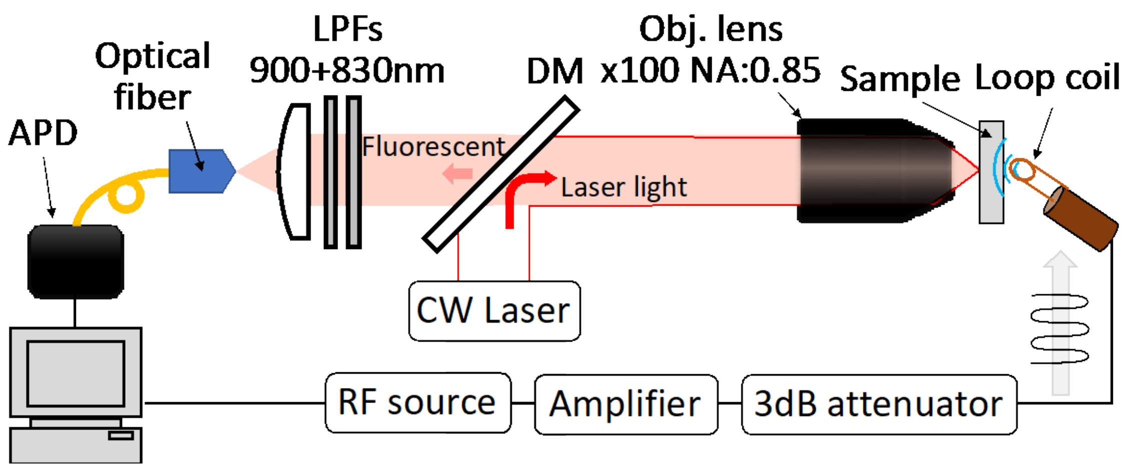

Fig. 2. Schematic image of a home-built confocal scanning microscope (CFM).

for radio-frequency (RF) field exposure (RF power of 33 dBm at the coil). A 3 dB attenuator was inserted after an amplifier to minimize the effect of return wave. All measurements were conducted at room temperature.

Results and Discussion

Figure 3 (a) shows an in-plane (XY) PL mapping of a 3D arrayed V_{Si}. Dot array consisting of three different luminescent spots were clearly observed, which is consistent with the number of PBW processes. Since no significant degradation of current-voltage characteristics was observed, the 3D arrayed V_{Si}'s was successfully introduced into the pn device without a significant device degradation. Changing the focus position tending toward a deeper region with respect to the sample surface, the spot that showed the brightest luminescence was shifted from right to left in the three spots as shown in Fig. 3 (b). This indicates that the relative depth of each spot (right, center and left spots) were assigned to be at the shallowest, middle and the deepest in the sample. In addition, the size of luminescent spot, which was indicated by black broken line in the Fig. 3 (b), became larger with increasing the depth of the spot. This result was attributed to the straggle of implanted H^+. As illustrated from the PL intensity profile of each spot along X axis shown in Fig. 3 (c), the size of luminescent spot was measured to be ~4, 6 and 10 μm for the shallowest, middle and the deepest spots, respectively. According to the SRIM simulation, lateral straggling of H^+ was calculated to be 0.25, 1 and 5.6 μm. Therefore, using spread of the H^+ beam of 2.6 μm (= ±3σ of Gaussian distribution), a theoretical luminescent spot size was estimated to be 2.85, 3.6 and 8.2 μm. Experimental values roughly corresponded with these calculated values. A cross-section (XZ) image was measured to estimate the depth of each spot. Three lines of luminescent spots were confirmed as shown in Fig. 3 (d), where a slight gradient of the lines with respect to horizontal axis was attributed to the misalignment of the sample. The Z axis was corrected for the influence of refractive index mismatch between air (n_1=1) and SiC (n_2=2.6) using the following equation; AFP = (n_2/n_1)×NFP, where AFP and NFP are actual and nominal (position of objective lens) focus position, respectively. Although Z = 0 does not accurately reflect the surface of the sample, from the corrected Z value, the depth of each spot was estimated to be ~5, 20 and 60 μm for the shallowest, middle and deepest spots, respectively. These were in good agreement with the values expected by SRIM simulation. The comparisons with experimental data and SRIM simulation suggest that the features of luminescent spot, such as size and depth, can be estimated by the simulation, and therefore beneficial to design a V_{Si}-based quantum sensor in SiC devices.

ODMR measurements were carried out for three different depth spots under zero magnetic field. Figure 4 illustrates the ODMR spectra obtained from each spot. All peaks around 70 MHz were assigned as ODMR peaks from V_{Si} at zero magnetic field [13]. Since the thickness of a typical SiC device is on the order of 10 μm at most, the 3D arrayed V_{Si} is capable of measuring the entire area of

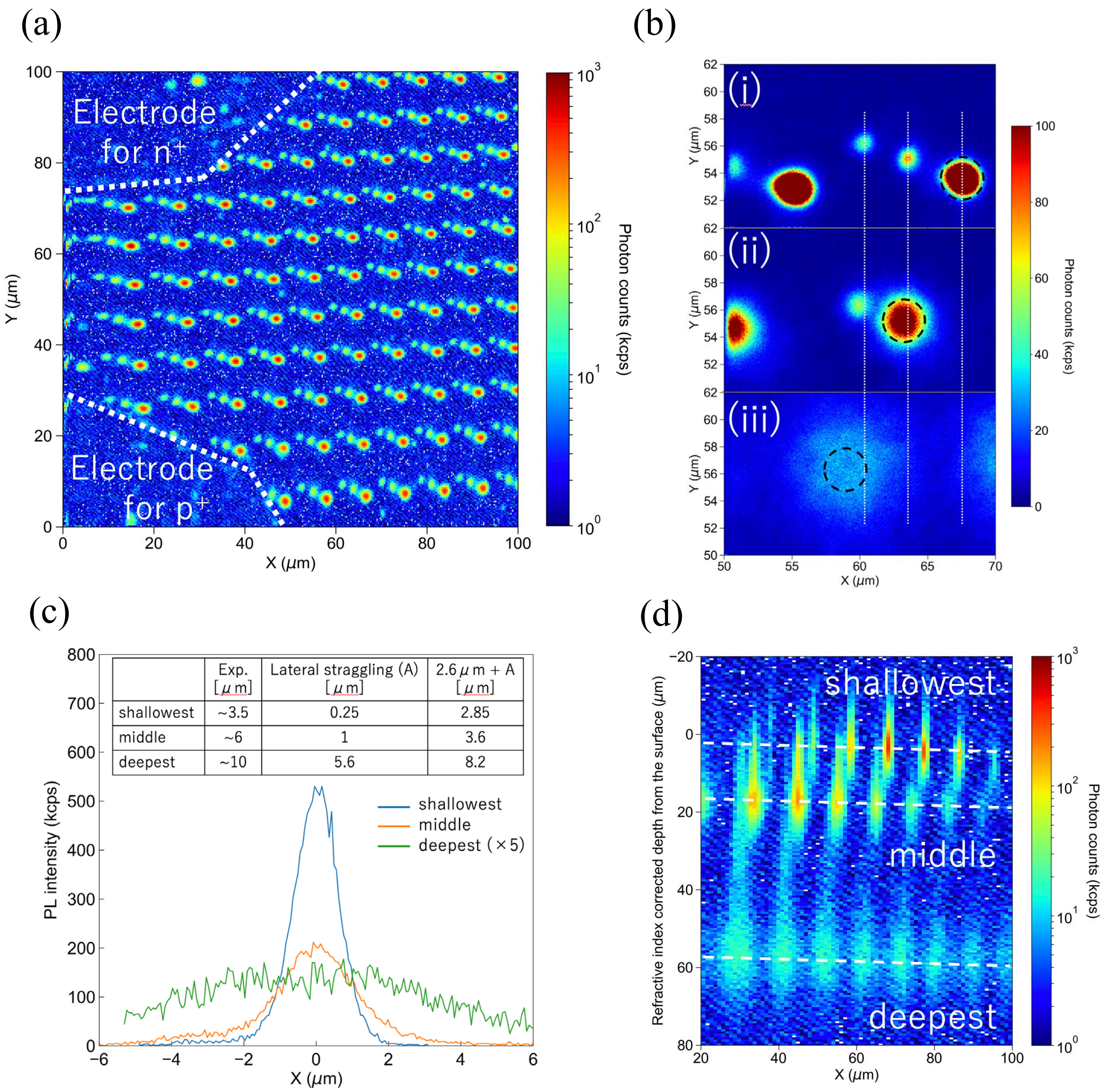

Fig. 3. (a) An in-plane (XY) PL mapping of a 3D arrayed V_{Si}'s (a focus position was adjusted to the shallowest spot). (b) Enlarged PL mapping under three different focus positions, (i) on right (shallowest), (ii) on center (middle) and (iii) on left (deepest) spot. Black broken circles are depicted as the luminescent size of the shallowest spot for purpose of size comparison. White broken lines are presented for reference of the corrected depth. (c) PL intensity profile of each spot along X axis. Inset table summarizes experimental and simulated values of the size of each luminescent spot. (d) A cross-section (XZ) PL mapping of a 3D arrayed V_{Si}'s. A slight gradient of the lines with respect to horizontal axis (white broken lines in the figure) was attributed to the misalignment of the sample.

a SiC device. The results confirm that there was no depth dependence on ODMR contrast. Magnetic-field sensitivity of quantum sensor η, for example, is written by,

$$\eta \propto \frac{1}{C\sqrt{n\tau T_2}} \tag{1}$$

where C, n, τ and T_2 are ODRM contrast, the number of spin centers, the detection efficiency and spin-relaxation times, respectively [14]. From this equation, a similar sensor sensitivity is expected for three different depth spots under the conditions of same number of spin centers and spin-relaxation

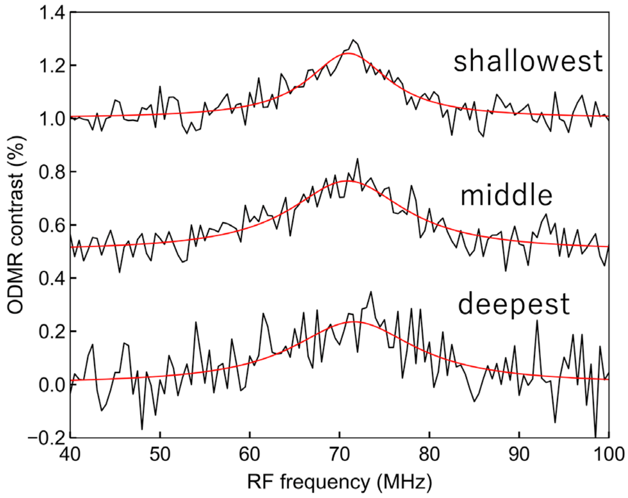

Fig. 4. ODMR spectra obtained from three different depth luminescent spots under zero magnetic field. Red lines show Lorentzian fit of the data.

times. These results suggest that 3D arrayed V_{Si} can act as quantum sensor elements with uniform sensitivity in SiC devices.

Conclusion

We demonstrated ODMR measurements on 3D arrayed V_{Si}'s within in-plane SiC pn diodes. PBW successfully created a 3D arrayed of V_{Si}'s using different ion energies. The PL mapping analysis performed herein indicates that the features of luminescent spot, (e.g. size and depth) can be estimated by SRIM simulation. This is a very useful finding for designing V_{Si}-based quantum sensors within a SiC device. We demonstrated that that three different depth luminescent spots revealed similar ODMR spectra including its contrast, which indicates that all exhibit similar sensitivity. These results suggest that 3D arrayed V_{Si}, implanted into SiC devices, can act as quantum sensor elements with uniform sensitivity.

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