

## Various Single Photon Sources Observed in SiC pin Diodes

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**Abstract.** Luminescence centers formed in the vicinity of SiC surface are expected to be utilized as Single Photon Sources (SPSs) because of the high-brightness and the potential of electric control at room temperature. In order to gain more insight into the surface SPSs, 4H-SiC pin-diodes are fabricated and the surface SPSs formed in the pin diodes are investigated using a confocal laser scanning fluorescence microscope (CFM). Locations where the surface SPSs appear as well as photoluminescence spectra of the observed surface SPSs are presented. Antibunching characteristics of the surface SPSs are also investigated by the second order autocorrelation function measurement. We conclude that two different types of surface SPSs appear in the surface of 4H-SiC. The location dependence of the observed surface SPSs indicates that the oxide layer on 4H-SiC plays an important role in the formation of surface SPSs, whereas neither ion implantation nor donor ions had an effect. The peak wavelength of luminescence spectra widely varies depending on their locations, indicating lattice strain introduced by the oxide layer has the potential to affect the luminescence spectra.

### Introduction

A Single photon source (SPS) in solid-state material, which generates one photon at an arbitrary timing, is indispensable for quantum technology such as quantum computing, quantum sensing, and quantum cryptography communication [1]. One of the attractive host materials for SPSs is Silicon Carbide (SiC) semiconductors because the high-quality and large-diameter wafers are in mass-production and the device fabrication techniques are well developed, and thus a wide variety of advanced electronic and optoelectronic devices based on SiC have been successfully fabricated. Recently, various luminescence centers which act as SPS at room temperature (RT) have been found in SiC semiconductors and their superior characteristics have been demonstrated [2-5]. We have also found that SPSs were formed in the surface of SiC pin diodes (hereafter ‘surface SPSs’) by thermal annealing in oxygen atmosphere. The surface SPSs exhibit high-brightness [5,6] and can be operated by current injection at RT [3]. These facts indicate that electrically driven SPSs based on SiC for practical use are feasible if the substance and formation mechanism of surface SPSs are clarified. However, it is unclear what device fabrication process forms the surface SPSs. In order to gain more insight into the surface SPS, we fabricated 4H-SiC pin diodes and investigated photoluminescence properties of a number of surface SPSs formed in the pin diodes and categorized them according to luminescence spectrum.

### Experimental

In order to form the surface SPSs and investigate the luminescence properties, planar pin diodes were fabricated on an n-type 4H-SiC epitaxial layer with the donor concentration of  $9.1 \times 10^{14} \text{ cm}^{-3}$  which was grown on an n-type 4H-SiC substrate (Si face,  $4^\circ$  off). Phosphorus and aluminum ion implantations at the temperature of  $800^\circ \text{C}$  followed by thermal annealing at  $1800^\circ \text{C}$  in Argon atmosphere were performed to form the *n*- and *p*-type regions, and the dopant concentrations were

$2.0 \times 10^{20} \text{ cm}^{-3}$  and  $5.0 \times 10^{18} \text{ cm}^{-3}$ , respectively. An unimplanted region of the epitaxial layer was used as the *i*-layer. An oxide layer was subsequently formed on the surface for the purpose of stabilization of photon emission properties of surface SPSs [5]. The oxide layer was formed by field oxidation at the temperature of  $1100^\circ\text{C}$  [7]. The thickness of the oxide layer was estimated to be 50 nm. Figure 1 shows a top view schematic structure of the planar SiC pin diode. Luminescence centers formed in the surface of pin diodes were observed at RT using a confocal laser scanning fluorescence microscope (CFM). A second harmonic of a YAG laser with wavelength of 532 nm was used as the excitation source and the net irradiation power was 1 mW. Photoluminescence (PL) measurements were performed to categorize obtained luminescence centers according to the shape of PL spectra. Also the measurement of the second order autocorrelation function was performed to characterize the single photon emission of luminescence centers. Note that the pin diode was not electrically operated during PL measurement and CFM observation.

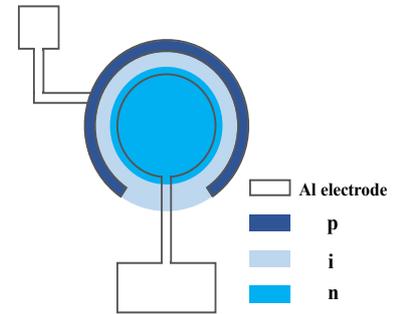


Fig.1. Top view of the structure of SiC pin diode used in this study.

## Results and Discussion

Figure 2 shows an optical microscope image of the pin diode. The yellow line in the figure denotes the border between the *i*- and *n*-region. Note that the near edge of Al electrode on the *n*-region, which is shown as gray in Fig. 2, was not covered by the oxide layer. The width of uncovered area was  $4 \mu\text{m}$  according to the optical microscope image.

Figure 3 shows a luminescence intensity map at the red square region of Fig. 2, which was obtained by the CFM observation. Although a number of luminescence centers were found in both the *i*- and *n*-region, background luminescence intensity at the *i*-region (left-side of the yellow line) was 3.5 times lower than that at the *n*-region. Luminescence centers observed near the Al electrode were unstable and showed lower contrast, since the surface of this region was not covered by the oxide layer (see the bottom illustration of Fig. 2) [5]. This indicates that defect centers which existed in the vicinity of SiC surface were stabilized and showed bright luminescence by the surface oxidation.

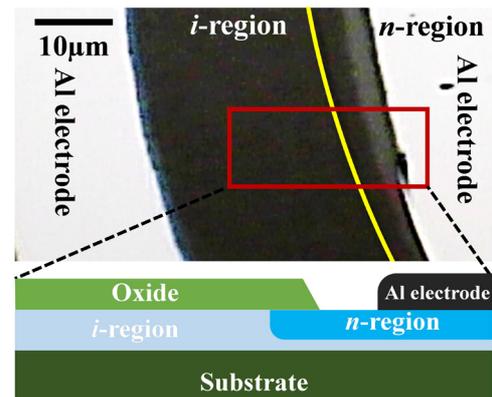


Fig. 2. An optical microscope image of the pin diode. The yellow line denotes the border between *n*- and *i*-region. The red square shows the area observed by CFM (Fig. 3). A cross section of the square region is also illustrated at the bottom.

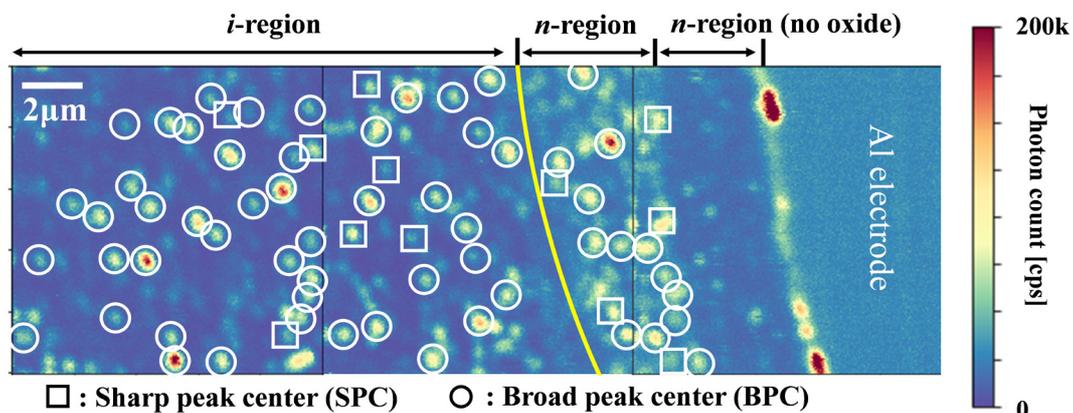


Fig. 3. CFM image of the pin diode. The yellow curve denotes the border between *n*- and *i*-region. Luminescence centers enclosed by white squares and circles show sharp and broad peak spectra, respectively (see Fig. 4).

Figure 4 show typical PL spectra of luminescence centers. All luminescence centers enclosed by squares and circles in Fig. 3 were measured and the obtained PL spectra were categorized into two groups according to the shape of the spectrum: sharp spectrum (spectra C, D, and E in Fig. 4) and broad spectrum (spectra A and B). Hereafter, luminescence centers which have the former and the latter spectrum are represented as SPC (Sharp Peak Center) and BPC (Broad Peak Center), respectively. The peak wavelength widely varied depending on the locations of luminescence centers in both cases. In addition, the population of BPCs was clearly larger than SPCs. However, since no significant difference was found in the population of surface SPSs between the *i*- and *n*-region, we conclude that neither ion implantation nor donor ions affected the formation of surface SPSs.

Figure 5 shows the results of the second order autocorrelation function measurement for SPC and BPC. Both centers showed clear antibunching characteristics and this fact indicates both centers act as single photon sources (SPSs). The antibunching characteristics are represented by the following equation:

$$g^2(\tau) \approx 1 - (1 + \alpha) \exp\left(-\frac{\tau}{\tau_1}\right) + \alpha \exp\left(-\frac{\tau}{\tau_2}\right) \quad (1)$$

where  $\tau$  is the delay time of the second order autocorrelation function measurement. The values of  $\alpha$ ,  $\tau_1$ , and  $\tau_2$  are fitting parameters relating to the nonradiative decays and transitions via a metastable state, the transition between ground and excited state, and the behavior of the metastable state, respectively [6]. The obtained values are also shown in Fig. 5. The values of  $\tau_1$  for SPC and BPC were estimated to be 2.01 ns and 1.64 ns, respectively. These values corresponded to the values reported previously [2,3] and are ten times shorter than the values of the NV center in diamond, which is one of the most well-known SPSs [8]. Since the shorter  $\tau_1$  implies a higher photon pumping rate to the excited state and thus the higher brightness of SPS, the surface SPSs in 4H-SiC are more advantageous than diamond NV centers in terms of the brightness of SPS.

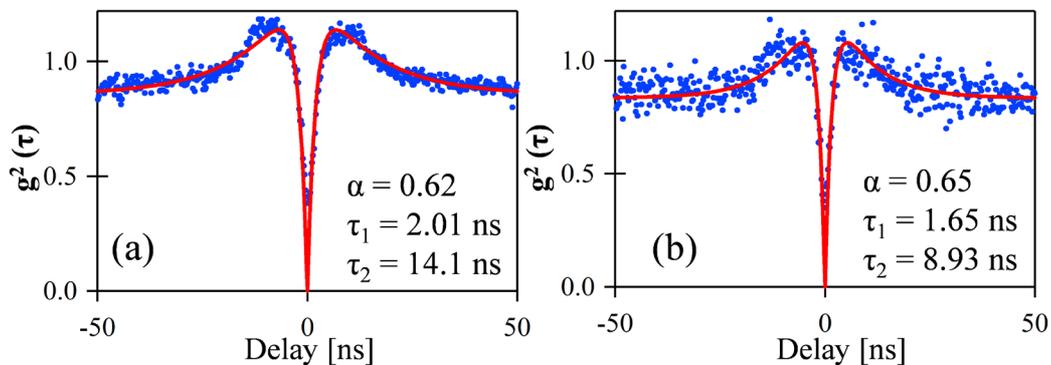


Fig. 5. Results of time correlation measurement for (a) SPC and (b) BPC. Experimental data and fitting results by equation (1) are shown by blue dots and red curves, respectively. The fitting values are shown in the figure.

Figure 6 shows peak energy distributions of the obtained PL spectra. Although the peak energy ranged from 1.62 eV to 1.99 eV in SPC and from 1.71 eV to 2.06 eV in BPC, these peak energy distributions are almost equivalent (0.37 eV and 0.35 eV). These facts indicate that although the origin (defect structure) of SPC and BPC are different, the peak energy distributions are caused by the

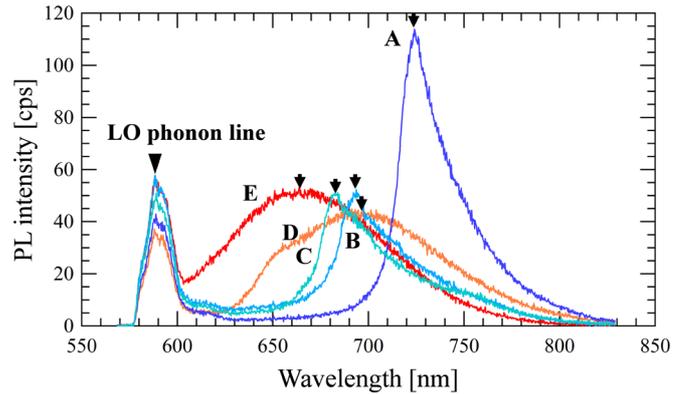


Fig. 4. Typical PL spectra of the luminescence centers enclosed by circles (A and B) and squares (C, D, and E) in Fig. 3. The peak observed at around 580 nm in all spectra is the LO phonon line. The arrows show the peak position of spectra.

same origin. One of the possible causes of the peak energy distribution is lattice strain at the surface of 4H-SiC. The surface oxidation introduces a lattice strain into the vicinity of the surface and causes stacking faults, resulting in the peak energy distribution of surface SPSs. Further study is required to verify the effect of lattice strain on the surface SPSs.

### Summary

We investigated luminescence centers formed at the surface of 4H-SiC pin diodes using the CFM. A number of luminescence centers appeared in both the *i*- and *n*-region, although they were hardly found in the region not covered by the oxide layer. This result indicates that the oxide layer on 4H-SiC plays an important role in the formation of surface SPSs, whereas neither ion implantation nor donor ions had an effect. We conclude from PL spectra and antibunching characteristics of the observed surface SPSs that two types of surface SPSs were formed in the 4H-SiC surface and the peak wavelength of luminescence spectra widely varied depending on the location of surface SPSs. The peak wavelength distribution is thought to be due to the influence of lattice strain in 4H-SiC which was introduced by the formation of the oxidation layer.

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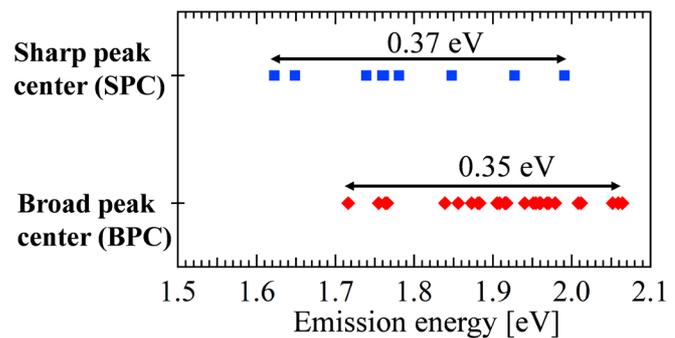


Fig. 6. Peak energy distributions of the obtained PL spectra. Blue squares and red diamonds show the peak values of SPC and BPC, respectively.