Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.216-217

I-2-1

N-type Diamond Schottky Diodes

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1. Introduction

Diamond has attracted much attention as a material for high-power devices, high-frequency devices and ultraviolet light emitting devices. High-quality diamond and electrical conduction (p-type or n-type) control are desirable to realize these devices. It is still difficult to obtain n-type conduction for diamond, because of deep donor states and/or of difficulties in incorporation of donor dopants [1-5]. Recently, n-type conduction has been obtained in phosphorus (P)-doped diamond grown by microwave plasma chemical vapor deposition (CVD) [1,6,7]. The temperature-dependent Hall effect measurements have clearly shown n-type conductivity, and have revealed a P-related thermal activation energy of 0.6 eV. Additionally, the realization of p-n junctions in diamond has been reported [8-10]. However, electrical characteristics are not well understood. In this work, we have systematically investigated electrical properties of phosphorus doped n-type diamond associated with donor by capacitance-voltage (C-V) measurements. Also, we have investigated the properties of n-type diamond Schottky barrier diodes with several kinds of metals to reveal the surface state of n-type diamond. C-V measurements are useful for investigating deep traps, which affect the free carrier densities [11], and built-in potential. We have shown the relation between net donor concentration and phosphorus concentration. The phosphorus electrical activity (the ratio of donor concentration to incorporated P concentration) was found to be high independent from the phosphorus concentration. This result indicates that high ratio of the incorporated P atoms can be ionized. Furthermore, the results of comparison of the built-in potential between several kinds of metals implied pinning of the Fermi level at the n-type diamond surface.

2. Experiments

The P-doped diamond layers were grown by microwave plasma CVD on Ib {111} diamond substrates, using CH_4 [1]. The dopant source was PH_3. Lateral dot-and-plane (with ring-shaped-gap) Schottky barrier diodes have been fabricated using Ni, Pt, Al or Ti for Schottky contacts and Au/Pt/Ti for ohmic contacts. Before fabricating Schottky barrier diodes, the samples were kept in a mixture of sulfuric acid (H_2SO_4) and nitric acid (HNO_3) at 200 ^{o}C for 30 minutes to remove any graphitic layer. Individual Schottky contact pad was surrounded by the ohmic contact with 20μm gap. The ohmic contact was annealed at 973K in N_2 ambient and the area was greater than 150 times that of the largest Schottky contact pad area. I-V measurements and C-V measurements were carried out to investigate the Schottky junction properties and the donor characteristics, respectively (300K-573K). The concentrations of phosphorus and residual impurities were determined by SIMS (secondary ion mass spectroscopy).

3. Results and discussions

Figure 1 shows the typical I-V curve. The observed I-V properties clearly showed n-type conduction. The rectification ratio was more than 10^8 at ±10V at 473K. The ideality factor decreased from 3.3 to 1.4 with increasing temperature from 300K to 473K, however at 573K it slightly increased to n=1.6. The most plausible reason for the improvement in the ideality factor is reduction in resistivity of the diamond layer with increasing temperature. The increase of ideality factor and the large leakage current in reverse bias at 573K is attributed to the degradation of the Schottky contact or the interface between the contact and

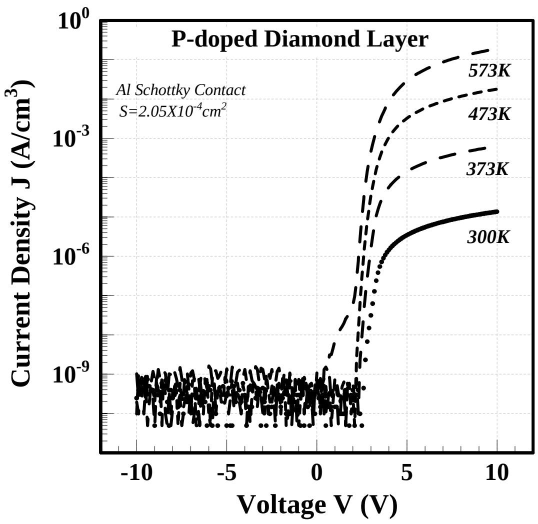

Fig. 1. Typical I-V curve at 300K, 373K, 473K and 573K in P-doped homoepitaxial diamond.

the diamond.

The capacitance had a constant value in the low frequency region but it abruptly decreased with increasing frequency. This threshold frequency decreased with decreasing temperature and it was not obtained at 300K. The observed variation in capacitance could be due to the high resistivity of the diamond and/or the well-known dispersion effect, which occurs when a deep level is unable to follow the high-frequency voltage modulation and contribute to the net space charge in the depletion region [14]. These results indicates that the existence of one deep donor state and the net donor concentration should be determined in higher temperature and low frequency region in these n-type diamond.

A typical result of C-V measurements at 1kHz, for the P-doped diamond layer at 473K is shown in Fig. 2. The net donor concentration was evaluated to be $6.2X10^{17}$ cm^{-3} and the corresponding built-in potential (V_{bi}) was 4.0eV, when the P concentration was $8.3X10^{17}$ cm^{-3}. The value of V_{bi}, 4.0V, is consistent with the expected value of the n-type diamond Schottky junction formed with Ni and P-doped diamond. However, it was almost independent of the metal species. This could be due to pinning of the Fermi level at the diamond surface.

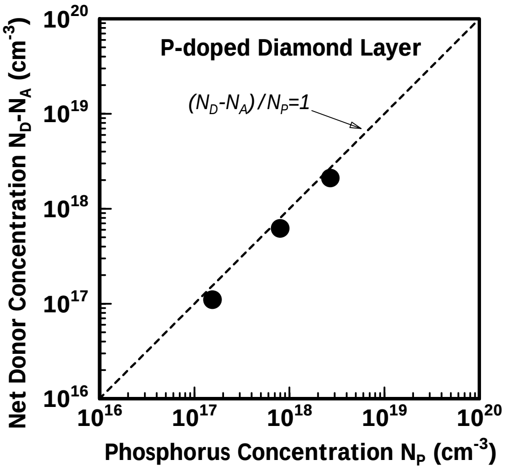

Fig. 3. The net donor concentration as a function of the phosphorus concentration.

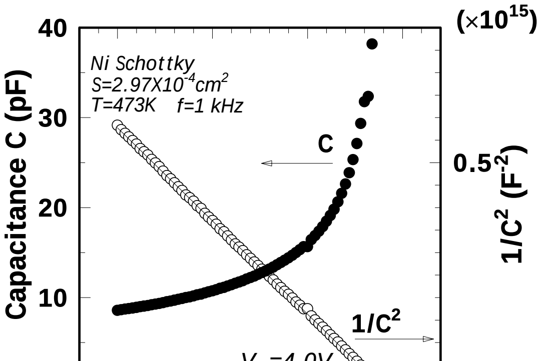

Fig. 2. Typical C-V curve at 473K in P-doped homoepitaxial diamond. The applied frequency was 1kHz.

The net donor concentration linearly increased with increasing the phosphorus concentration as shown in fig. 3. Phosphorus electrical activity (or P-doping efficiency) was about 0.75. It was found that a relatively high ratio of the incorporated P atoms is ionized.

4. Summary

We have systematically investigated the electrical properties of n-type diamond associated with phosphorus related donor. I-V and C-V measurements were carried out to investigate the electrical properties of P-related donors in P-doped homoepitaxial diamond with lateral dot-and-plane (with ring-shaped gap) Schottky barrier diodes.

The net donor concentration linearly increased with increasing the phosphorus concentration. It was found that a high ratio of the incorporated P atoms is ionized.

The result that the built-in potential was almost independent of metal species implied pinning of the Fermi level at the diamond surface.

Acknowledgements

The authors would like to thank to Y. Takada, Dr. S. Nunoue, Dr. M. Ezaki, T. Oka, M. Onomura and K. Tsuda for their help and advice concerning electrode fabrication.

This work has been performed as a part of Advanced Diamond Device project, which is supported by METI through NEDO.

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