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Fabrication of graphene/diamond heterojunctions and their electronic properties

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Abstract

In this study, we have examined electronic properties of graphene/diamond heterojunctions in detail. The junctions showed photo-induced large conductivity change below 200 °C, and the current change ratio systematically increased with the temperature from ~10 at R. T. to ~10^3 at 200 °C. The mechanism for the large conductivity change was under investigation, however we consider components in air such as oxygen play important roles. These results indicate the graphene-diamond, carbon sp^2-sp^3 heterojunctions can be used as novel photo-controllable electronic devices.

1. Introduction

Diamond and graphene are typical allotropes of carbon that are necessary for the modern information society due to their superior physical properties. Diamond, the sp^3 carbon allotrope, is considered to be one of the most promising semiconductors for high-power devices because of its high breakdown voltage and high thermal conductivity. On the other hand, graphene, the sp^2 carbon allotrope, is expected to have many applications in future electronic devices due to outstanding electronic properties such as high-mobility carriers and high current carrying capacity. Recently, interfaces between carbon sp^2 and sp^3 structures attracted much attention because they are considered to be basis of various physical phenomena and electronic applications. Many theorists suggest hybrid structures of graphene and diamond (carbon sp^2-sp^3 hybrids) exhibit interesting electronic characters such as high-efficiency photoelectric conversion, highly spin-polarized states, etc [1-3]. Diamond and graphene are important not only individually in electronic devices but also as building blocks for innovative electronic devices through the use of carbon sp^2-sp^3 hybrid structures.

In this study, toward creation of novel electronic devices using carbon sp^2-sp^3 hybrid structures, heterojunctions using graphene/diamond layered structures were fabricated and their electronic properties were examined in detail for the first time.

2. Experimental

Graphene layers were formed on homoepitaxial B-doped diamond films (p= ~10^{16} cm^{-3}, μ= ~1000 cm^2/Vs@ R. T. [4]) by a high-temperature annealing method using Cu catalysts [5]. Junctions with graphene/diamond heterostructures (area: 20-200 μm ϕ) were fabricated using a usual photolithographic and etching process. Cu/Ti (post-annealed at 600 °C for metallization to form ohmic contacts) and Ni electrodes were used as ohmic contacts for the diamond films and graphene layers, respectively. The current-voltage (*I-V*) characteristics of the junctions were measured from R.T. to 250 °C in air, with or without photo-irradiation.

3. Results and Discussion

Figure 1 shows the Raman spectrum of the graphene layers on diamond (100) films formed by the annealing of Cu/p-diamond at 950 °C for 90 min [5]. Three major peaks were observed in the Raman spectrum of graphene on diamond: a G peak (1580 cm^{-1}) and a 2D peak (2700 cm^{-1}), which are typical of graphene layers, and a sharp peak at 1332 cm^{-1}, which was attributed to the first order zone-center vibrational mode of diamond. The full width at half maximum (FWHM) of the 2D peak and the peak intensity ratio of the 2D and G peaks (I_{2D}/I_G) were ~33 cm^{-1} and ~2.3, respectively, which suggests that the layers on the diamond were predominantly composed of monolayer graphene. The

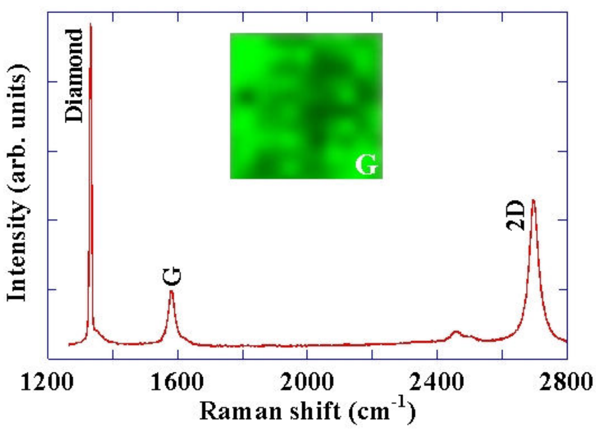

Fig. 1 Raman spectrum for graphene layers on diamond semiconductors. The inset shows two-dimensional Raman mapping of the G peak intensity. Brighter areas in the Raman map indicate regions with strong G peaks.

intensity of the D peak at 1350 cm^{-1} was negligibly small, which indicated that there were almost no defects in the graphene layers. The coverage ratio of the graphene layers was estimated to be ~70% from 2D Raman mapping of the G peaks (Fig. 1 inset).

The graphene layers were p-type, and the typical sheet hole concentration and mobility at room temperature determined from Hall measurements were 4.4×10^{13} cm^{-2} and 479 cm^2/Vs, respectively, which are comparable to those of high-quality graphene layers formed on SiC (~10^{13} cm^{-2} and ~900 cm^2/Vs at 300 K) formed by high-temperature annealing method [6]. These results indicate that relatively uniform graphene layers were formed on the diamond semiconductors by the high-temperature annealing method.

In temperature dependence of current-voltage (I-V) characteristics of the graphene/p-diamond junctions, ohmic behaviors (no rectification) were observed from R. T. to 200°C (Fig. 2). The increase of the current at higher temperature can be explained by considering activation of B acceptors (E_a= ~0.37 eV) in diamond semiconductors. However, at 250°C, current density in negative bias region was drastically decreased, and the *I-V* curves changed from ohmic to rectification like behaviors. The current difference between negative and positive bias region became more than 10^3.

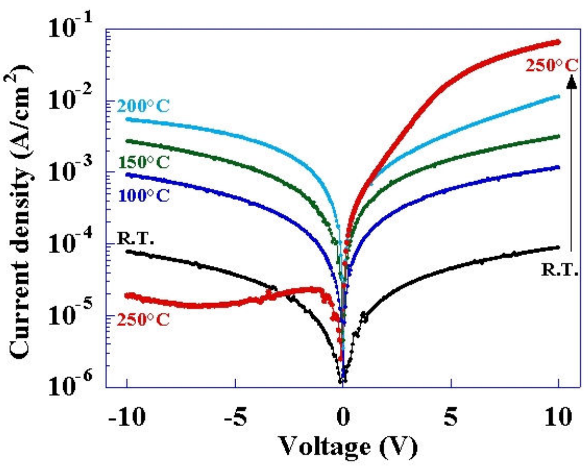

Fig. 2 Current-voltage characteristics of the graphene/diamond heterojunctions measured from R. T. (~25 °C) to 250 °C.

In addition, we also found the large conductivity change was also caused by white light irradiation from a fluorescent lamp below 200°C (Fig. 3). The current change ratio systematically increased with the temperature from ~10 at R.T. to ~10^3 at 200 °C, which indicates that a large conductivity change can be induced by photo-irradiation as well as by heat. The maximum change was ~10^3; however, air exposure for several days was necessary to obtain the largest change.

The mechanism for the conductivity change was under investigation, however we consider components in air such as oxygen, nitrogen, etc. play important roles for the behaviors because air exposure for several days was needed for inducing the largest current change. These results indicate the graphene-diamond heterojunctions can be used as novel photo-controllable electronic devices.

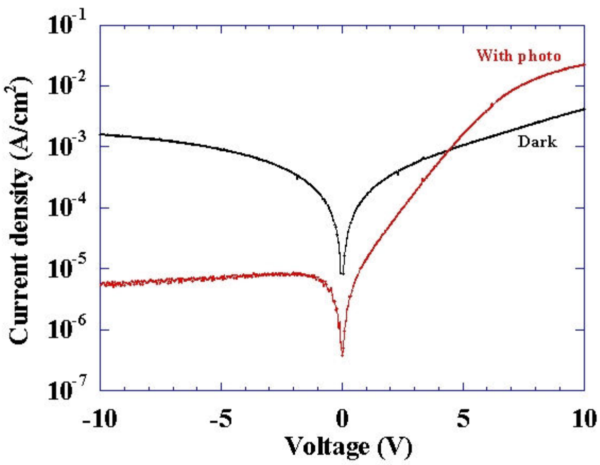

Fig. 3 Current-voltage characteristics of the junctions with and without white light irradiation at 200 °C.

4. Conclusions

In this study, we examined electronic properties of graphene/diamond heterojunctions for the first time. The junctions showed special *I-V* characteristics, which were changed by photo and thermal stimulation. The results indicate the graphene-diamond, carbon sp^2-sp^3 heterojunctions can be used as novel photo or thermal controllable electronic devices.

Acknowledgements

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