Vertically Stacked Junction Devices Fabricated Using Single-Crystal Graphene on SiC Substrate

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Two types of vertically stacked graphene junction diodes were fabricated in this study. Samples of single-crystal graphene measuring 100 mm^2 were epitaxially grown on SiC substrate using the thermal decomposition method and were bonded using the direct bonding technique. The direct-bonded stacked junction diode exhibited nonlinear current-voltage characteristics and acted as a far-infrared emitter. Fowler-Nordheim tunneling phenomena with a strong nonlinear behavior was observed in the tunneling diode with a thin insulative layer (air gap or structured water). By using simple device-assembly processes, vertically stacked graphene diodes with new functions were successfully fabricated.

Introduction

Graphene is predicted to become a fundamental component in future electronic devices because of its exceptional electrical properties, such as high mobility and unique band structure (1). Recently, vertically stacked graphene junctions have attracted significant attention because they exhibit properties such as superconductivity (2). Generally, stacked graphene devices are fabricated using graphene flake or poly-crystal graphene. Because a complex assembly process is required, the reproducibility of these devices is low. Therefore, we propose a fabrication process for the stacked graphene devices based on the direct bonding technique. The samples of single-crystal graphene grown on SiC substrate were bonded in a face-to-face configuration. The contact pins were in direct contact with the graphene layer to form electrical connections. A far-infrared emitter diode and tunneling diode were fabricated using this simple method.

Results and Discussion

Two types of stacked graphene junction diodes are discussed in this paper − the directly bonded graphene-graphene junction diode, shown in Fig. 1(a), and tunneling diodes with a tunneling barrier, depicted in Fig. 1(b).

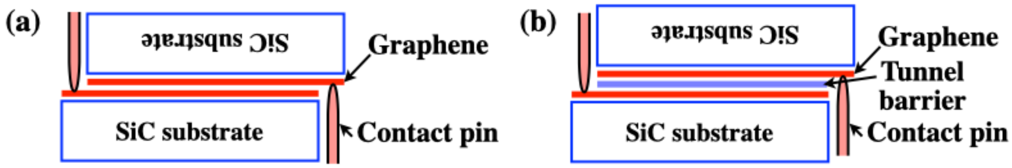

Figure 1. Schematic of vertically stacked junction device.
(a) graphene-graphene junction diode. (b) tunneling diode.

Graphene on SiC Substrate

The single-crystal graphene was epitaxially grown on a semi-insulating SiC (0001) substrate using the thermal decomposition method (3). The diced sample measuring 100 mm^2 was annealed in a rapid thermal annealer (SR-1800: Thermo-Riko). The crystals were grown at 1600 ˚C for 5 min in Ar (100 Torr). Surface roughness (a crucial factor to realize direct bonding) below 1 nm was ensured using the surface structure control technique.

Fabrication of Device

Two graphene samples were bonded with each other in a face-to-face manner and fixed with an acrylic mold. The gold-coated contact pins were in direct contact with the graphene surface. Because the contact resistance of epitaxial graphene on SiC was significantly smaller (4) than that of other graphene types (such as chemical vapor deposited graphene), ohmic contact was easily established by assembling the contact pins without using lithographic techniques. An air gap was used as a tunneling barrier, necessary for a tunneling diode, in the softly bonded samples. Here, the ohmic contact between two the graphene layers was established by increasing the bonding load. A structure water layer (5) formed using deionized water (DI) treatment was also used as a tunneling barrier. As the thickness of the structured water layer was less than 1 nm, it was suitable for the tunneling diode. The fabrication procedures for direct contact diode and tunneling diode were almost the same.

Graphene-graphene Stacked Junction

Graphene-graphene junction (6) exhibited ohmic properties under a low bias voltage condition. As depicted in Fig. 2(a), a nonlinear characteristic was observed under a high bias voltage condition (>10 V). Since the density of state (DOS) of graphene linearly increased near the Dirac point, it was verified that the graphene-graphene junction was ohmic, as reported in several papers. The DOS of graphene far from the Dirac point increased non-linearly and had a divergence at van Hove singularity (7). Fig. 2(b) shows the estimated junction voltage dependence of the differential conductance. The conductance at low bias voltage was 80 μS. The differential conductance increased with an increase in the bias voltage and became approximately 8 times the initial value at an estimated junction voltage of 5 V.

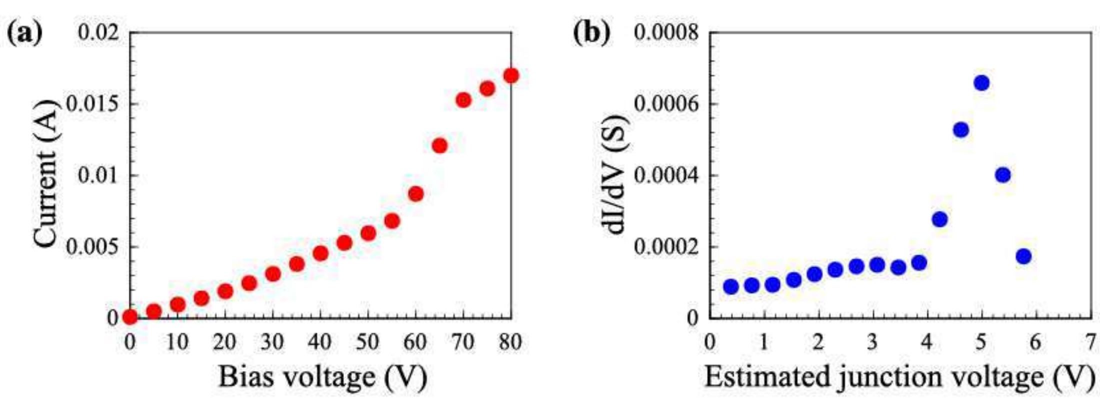

Figure 2. (a) Current-voltage characteristics of graphene-graphene junction.
(b) Differential conductance as a function of estimated junction voltage.

Infrared emission from graphene-graphene junction was expected because of the high electrical power at the high bias region. Figure 3 shows the radiation spectrum of the stacked graphene junction at 80 V, 1.3 W measured using a Fourier-transform infrared (FTIR) spectrometer. The dotted line represents the reference blackbody emission curve calculated at 300 K. A blackbody-like emission was observed. The peak wavelength of the measured infrared spectra at various power values was almost constant, 10.2 µm, which corresponds to a blackbody temperature of 284 K estimated by Planck's law. If the infrared emission from the stacked graphene junction originated from the blackbody emission, the peak wavelength should shift toward the short wavelength with an increase in input power. However, the peak wavelength of the measured FTIR spectra was almost constant with a change in electrical power. A light wavelength of 10.2 µm corresponds to a photon energy of 122 meV. The Fuchs-Kliewer (F-K) surface phonon energy of SiC (0001) is 117 meV, which is close to the measured value. The blackbody-like emission from the vertically stacked graphene junction diode should originate from the strong plasmon-phonon coupling between the graphene plasmon and the F-K phonon of the SiC substrate.

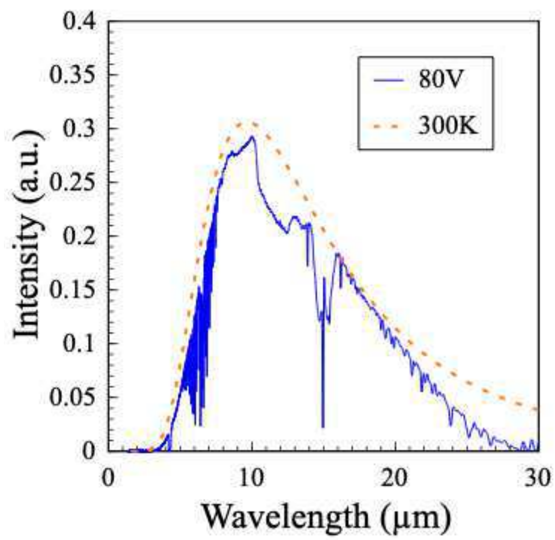

Figure 3. Radiation spectra of the stacked graphene junction measured by FTIR.

Tunneling Diode with Air Gap

As a result of the insulative layer thickness between the grapheme layers, tunneling current can flow through the barrier layer (Fig. 4(a)). Figure 4(b) shows the current-voltage (I-V) characteristics of the stacked graphene diode with an air gap insulator. A strong nonlinear I-V curve was observed. A Fowler-Nordheim (FN) plot is shown in Fig. 4(c) to revel the electrical transport mechanism. The negative linear slope of the FN plot demonstrates that the FN tunneling phenomenon was dominant in the high-electronic field region (>1 V). Tunneling electrons emitted from one graphene layer were transported across the triangular potential (Fig. 4(a)). Since controlling the thickness of the air gap was difficult, a formation of a thin dielectric layer on graphene would be the preferential choice.

Tunneling Diode with Structured Water Layer

A structured water layer with sub-1-nm-thickness was formed on the epitaxial graphene surface using DI water treatment (8). After performing DI water treatment on one of the graphene samples, the two graphene samples (both with and without the structured water layer) were bonded using the direct bonding technique. As depicted in Fig. 3(a), the structured water layer acts as a tunneling barrier. Here, the maximum tunneling current was 1 μA at +6 V. The tunneling current from the graphene layer flows through the structured water layer. The tunneling barrier thickness, estimated from the slope of the FN plot, had a value of 0.70 nm, assuming an effective electron mass ratio of 0.06. Since the electrically measured thickness coincided with the thickness measured by scanning probe microscopy, it was verified that the structured water layer acted as an insulative barrier layer.

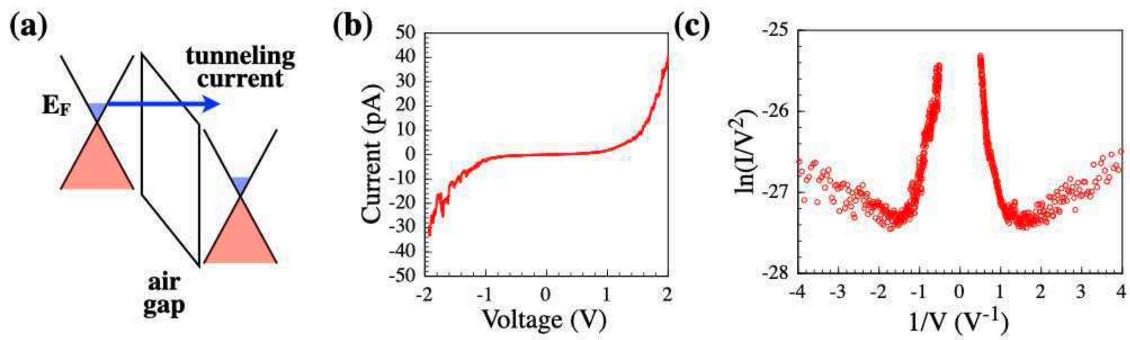

Figure 4. (a) Illustration of band diagram of FN tunneling.
(b) I-V curve of stacked graphene diode with air gap insulator.
(c) F-N plot.

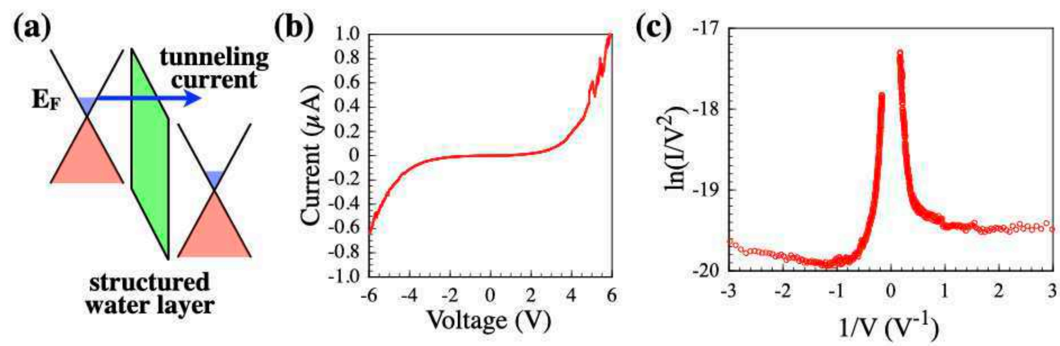

Figure 5. (a) Illustration of band diagram of FN tunneling.
(a) I-V curve of stacked graphene diode with structured water layer.
(b) F-N plot.

Conclusions

Vertically stacked graphene-graphene junction diodes were fabricated using a direct bonding technique. A high electric field was applied to the junction using single-crystal graphene on SiC substrate. A far-infrared emitter with a constant peak wavelength was realized using a new emission mechanism based on the coupling of graphene plasmon and SiC surface phonon. Tunneling diodes with an air gap and structured water layer were formed. FN tunneling characteristics were observed. Stacked graphene diodes with new functions were realized using simple device assembly processes.

Acknowledgments

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