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Multibit optoelectronic memory functions of graphene/diamond heterojunctions

Kenji Ueda, Yuki Mizuno and Hidefumi Asano

Graduate school of Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Phone: +81-52-789-3567 E-mail: k-ueda@numse.nagoya-u.ac.jp

Abstract

This work demonstrates graphene/diamond (carbon sp^2-sp^3) heterojunctions can be used as multibit optoelectronic memory, where light information is stored as multilevel resistance in nonvolatile manner. The carbon heterojunctions exhibit an apparent response to optical pulses and the resistance of the junctions increased step by step in responce to each optical pulse and was kept in nonvolatile manner. Simple optical arithmetic operations such as addition can also be performed by using the multiple resistance states of the heterojunctions.

1. Introduction

Recently, interfaces between graphene and diamond (that is, carbon sp^2-sp^3 interfaces) has attracted much attention because the carbon sp^2-sp^3 interfaces become sources of various interesting electronic phenomena. It has been theoretically suggested heterojunctions using graphene and diamond should exhibit many interesting electronic characteristics such as spin polarization without magnetic ions, highly efficient photoelectric conversion, etc. [1, 2]. Graphene and diamond are important not only on their own, but also as building blocks for fabricating novel electronic devices through the use of carbon sp^2-sp^3 interfaces. However, in spite of these interesting theoretical predictions, experimental results regarding the electronic properties of such interfaces have rarely been reported. More recently, we newly found vertically aligned graphene (carbon nanowalls: CNW)/diamond heterojunctions, that is, carbon sp^2-sp^3 interfaces became photo-controllable memristors [3, 4], which are optically controllable memory-resistors with nonvolatile memory and switching functions.

One of the most important application of the photo-controllable memristors is thought to be optoelectronic memory, which possess both photo-sensing and data storage function. In this study, we show the CNW/diamond heterojunctions (C sp^2-sp^3 interfaces) can be used as multibit optoelectronic memories, where light information stores as multilevel resistance in nonvolatile manner, and that simple optical arithmetic operation such as addition is possible using them.

2. Experimental

Heterostructures of vertical aligned graphene (carbon nanowalls: CNW) and boron doped semiconducting diamond were grown *in situ* by using microwave plasma CVD [3]. Junctions with diameters of 40-160 μm were fabricated using the CNW/diamond heterostructures by a standard photolithographic process and RIE. Current-voltage characteristics of the junctions were measured at RT in air, with or without photo-irradiation by using visible LED.

3. Results and Discussion

In the Raman spectrum of the CNW on diamond (Fig. 1), four major peaks were observed: G, 2D, and D peaks, which are typical of graphene layers with edge structures, D' peak at 1620 cm^{-1}, which is characteristic of CNW. The TEM image of the interfaces of the CNW/diamond bilayers also indicates CNW with good crystallinity and clear interfaces were formed on the diamond layers (Fig. 1 inset). The interlayer spacing of each graphene layer was estimated to be 0.36 nm based on the FFT analysis, which agreed well with the interlayer spacing of the graphene sheet of the AA stacked graphite (~0.36 nm). These Raman and TEM results suggest CNW layers were successfully grown on diamond and the CNW/diamond bilayers have interfaces of sufficient quality to fabricate CNW/diamond heterojunctions.

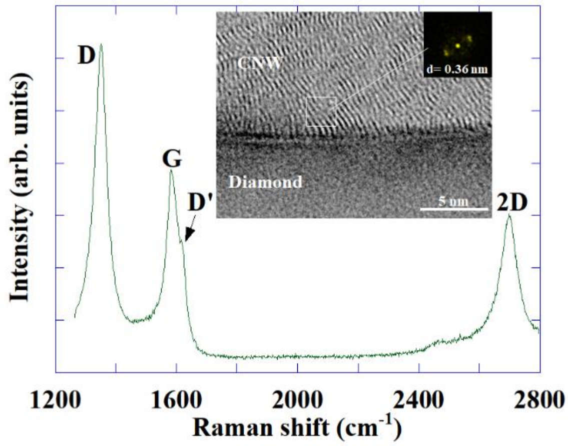

Fig. 1: Raman and TEM results of the CNW/diamond layers.

Figure 2 shows current-voltage (*I-V*) characteristics of the junctions measured at RT and light irradiation was only performed at maximum voltage for ~10 sec. The junction's exhibited hysteretic I-V behaviors, and resistance of the junctions was changed to low (LRS) or high resistance states (HRS) by the light irradiation with bias voltage application. A large resistance switching ratio of $\sim 10^4$ was obtained, and the resistance switching behaviors could be observed even at lower bias voltage (~ ±1 V). The resistive switching behaviors were typical characteristics of memristors, which have multiple resistance states and nonvolatile memory functions. However, the CNW/diamond memristor is special because the change of the resistance states is caused by photo-irradiation, whereas resistance states of usual memristors were switched only by applying bias voltage. These kind of photo-switching behaviors of memristors were quite rarely observed. Those behaviors were considered to be caused by redox reaction of graphene layers in CNW and/or CNW-diamond interfaces through the movement of oxygen ions by bias with photo-irradiation [3, 4]. These results suggest the graphene/diamond heterojunctions are photo-controllable memristors (photomemristors) with photo-switchable resistance states and multiple nonvolatile memory functions.

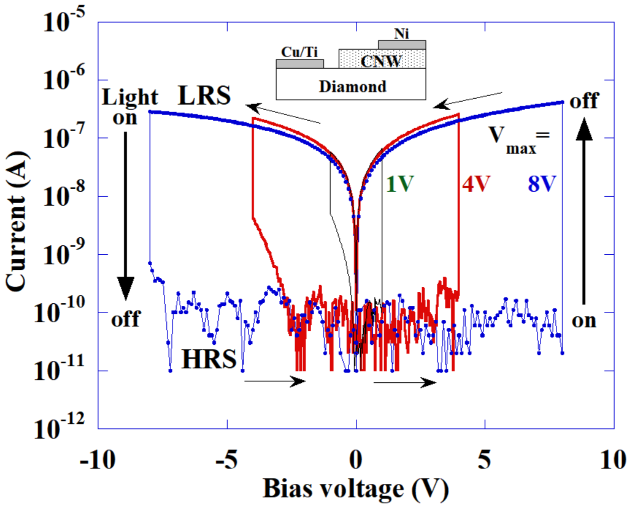

Fig. 2: *I-V* characteristics of the CNW/diamond junctions measured upon brief photoirradiation at room temperature. The inset shows schematic of the device structure using the CNW/diamond junctions.

The CNW/diamond photomemristors also show apparent response to optical pulses (Fig. 3). The output current (conductivity) was increased in proportion to the number of optical pulses under positive bias and decreased under negative bias. The numer of levels and heights of the curren steps can be controlled by changing optical pulse intensity, pulse width, bias voltage, etc. To determine the relationship between output current and applied pulse numbers precisely, multiple (~10) optical pulses were applied to the photomemristors. The output current increased linearly from 2 nA to 142 nA in response to the total optical pulse numbers from 1 to 10 (reference curve in Fig. 3 inset). The linear relationship between the number of optical pulses (n) and the output current [$I(n)$ (nA)] can be expressed as "$I(n)$= 14.26*n + 2.27" [equation (1)]. Application of one optical pulse induces current increase of ~14 nA. These results suggest that our photomemristors, which have optical-input and electrical output functions, are capable of being as optical computing devices with arithmetic functions such as counting and addition. For example, if an output current of 74 nA is obtained for the photomemristors, the total number of light pulses (= n) is estimated to be 5 from equation (1) (photocounting function). The photomemristors also have the addition function. When a bundle of 4 and 3 optical pulses were sequentially applied to the devices with positive bias voltage, total output current of 104.0 nA was obtained, and the current value was kept in nonvolatile manner (Fig.3 inset). The output current value is equal to the photoresponse of 7 optical pulses because n is estimated to be 7.1 by using equation (1) and because the obtained output current corresponds to the output current of position '7' in the reference curve. These results show simple adding operation of '4 + 3 = 7' was done by using the CNW/diamond photomemristors. The arithmetic results are stored in nonvolatile manner, and they can be read out as necessary and erased out by light irradiation with negative bias voltage. These results indicate that the CNW/diamond photomemristors can be used as novel types of optical computing devices with nonvolatile memory function. Optical sensing, memory and computing functions are available in the single device for the carbon photomemristor, leading to fabrication of novel computing devices with multifunctional integration of sensing, data storage, and processing function.

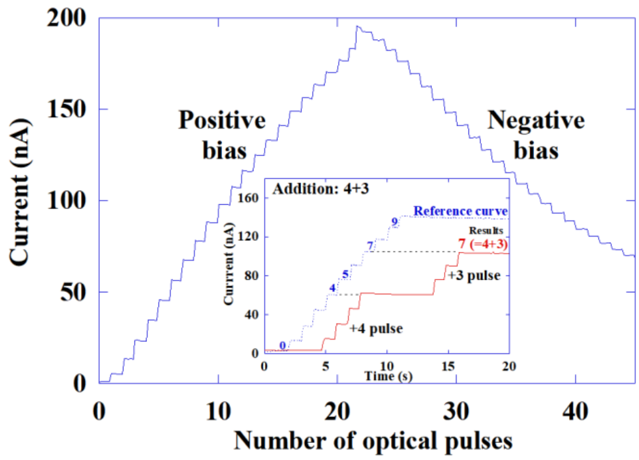

Fig. 3: Dependence of the output current on the optical pulse number for the CNW/diamond photomemristors under positive or negative bias voltage (±8 V). The inset shows demonstration of optical addition functions using the photomemristors.

4. Conclusions

We have demonstrated CNW/diamond photomemristors can be used as multibit optoelectronic memory, where information is stored as multilevel resistance in a nonvolatile manner. The carbon photomemristors have light sensing, memory and arithmetic functions; therefore, multifunctional integration of optical sensing, storage and calculation can be realized by using the photomemristors.

Acknowledgements

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References

[1] S. Konabe et al., APEX 6 (2013) 045104.
[2] Y. Ma et al., Phys. Rev. B 85 (2012) 235448.
[3] K. Ueda et al., J. Mater. Res. 34 (2019) 626.
[4] K. Ueda et al, Appl. Phys. Lett., 108 (2016) 222102.