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Yifei Wang, Vinh X. Ho, Prashant Pradhan, Michael P. Cooney, Nguyen Q. Vinh, "Graphene-germanium quantum dot photodetector with high sensitivity," Proc. SPIE 11088, Optical Sensing, Imaging, and Photon Counting: From X-Rays to THz 2019, 1108809 (9 September 2019); doi: 10.1117/12.2529371

SPIE.

Event: SPIE Nanoscience + Engineering, 2019, San Diego, California, United States

Graphene-Germanium Quantum Dot Photodetector with High Sensitivity

Yifei Wang[1], Vinh X. Ho[1], Prashant Pradhan[1], Michael P. Cooney[2], and Nguyen Q. Vinh[1*]

[1] Department of Physics and Center for Soft Matter and Biological Physics, Virginia Tech, Blacksburg, VA 24061, USA
[2] NASA Langley Research Center, Hampton, Virginia 23681, USA

* Corresponding author: vinh@vt.edu; phone: 1-540-231-3158

ABSTRACT

Graphene-based photodetectors have attracted strong interest for realizing optoelectronic devices, including photodetectors. Here we report a simple fabrication of graphene-germanium quantum dots for broadband light detection from visible to infrared region. The photodetectors show an improved responsivity and response speed. Specifically, the fabricated germanium quantum dots on graphene photodetector shows a responsivity of 1,500 A/W at room temperature and the response time is as fast as ~ 1 ms. These results address key challenges for broadband photodetectors from visible to infrared region, and are promising for the development of graphene-based optoelectronic applications.

Keywords: Graphene, Photodetectors, Germanium Quantum Dots, Infrared Photodetector

1. INTRODUCTION

The realization of low-cost photodetectors with high quantum efficiency, high sensitivity, and fast photo-response in the visible and infrared remains one of the challenges in optoelectronics. Ideally, these photodetectors should be based on Complementary Metal-Oxide-Semiconductor (CMOS) compatible platform for monolithic integration with read-out electronics to provide for high-density, high-throughput and low-cost manufacturing. Graphene[1] and quantum dots (QDs)[2] are two material platforms that have proved to fulfil those requirements. Germanium (Ge) is an important semiconductor material in group IV, and currently are employed to fabricate visible and infrared (IR) photodetectors. Because of the unique property including low cost, large absorption coefficient at IR frequencies, and excellent compatibility with the silicon technology, great efforts have been dedicated to fabricating on-chip Ge photodetectors with exceptionally high responsivity and speed.[3] A number of IR Ge-based photodetectors have been developed, including semiconductor/metal Schottky junction photodetectors,[3] p-i-n,[4] Ge/Si junction,[5] metal-semiconductor-metal.[6] In spite of anomalous efforts, however, the fabrication of these devices normally requires complicated instruments. This leads to energy consumption and high cost, and therefore constitutes the main obstacle to their wide applications.

To increase the photo-responsivity of graphene-Ge photodetectors, apart from methods of increasing the absorption efficiency of graphene including plasmonics, patterning graphene nanoribbon arrays, or nanomesh structures, we employ an absorber layer deposited on the top of graphene layer using e-beam thermal evaporation. This layer is called the seed-layer in our photodetectors. Under a specific condition, Ge QDs are form in this seed layer. This layer is also important for the atomic layer deposition (ALD) process to produce a dielectric layer in our

Optical Sensing, Imaging, and Photon Counting: From X-Rays to THz 2019, edited by
Oleg Mitrofanov, Proc. of SPIE Vol. 11088, 1108809 · © 2019 SPIE
CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2529371

devices. In this paper, we investigate the photo-response of the graphene-Ge QD photodetector under different electrical and optoelectronic conditions.

2. METHODS AND EXPERITMENTAL DETAILS

2.1. Field effect transistor device fabrication

To fabricate the graphene photodetector, we used a *p*-doped Si wafer (1 – 10 Ω.cm). The surface of the Si substrate was covered by 300-nm-thick silicon dioxide and pre-patterned alignment marks. A metal back-gate directly contacting to the Si wafer was designed using photolithography, then HF buffer etching solution was used to remove the SiO_2 layer completely, after that metal films of 10-nm Cr and 100-nm Au were deposited using e-beam evaporation. Metal source and drain contacts (Cr/Au with 10/100 nm thickness) for transport measurements were deposited directly onto the wafer by photolithography to form a field effect transistor (FET).

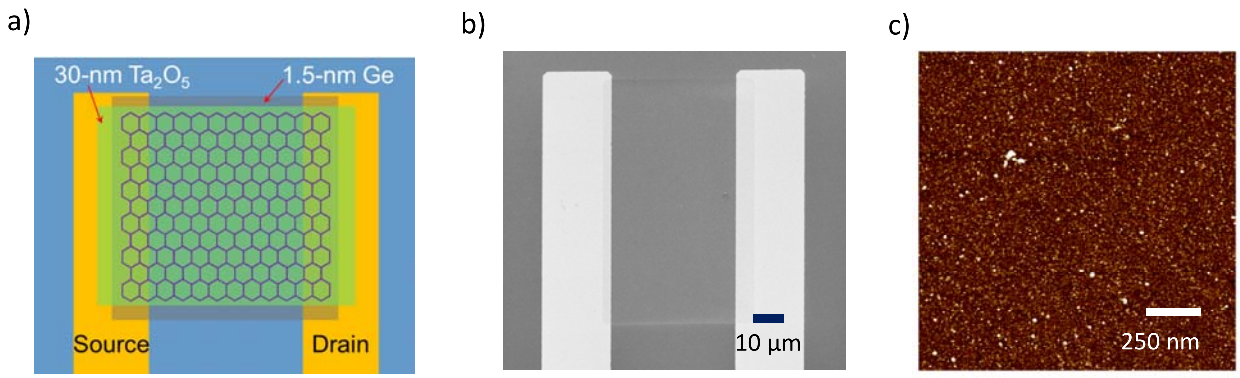

Figure 1: Structure of a graphene-Ge QD photodetector. (a) Schematic diagram of the graphene-Ge QD device including source, drain contacts, graphene, 1.5-nm Ge QD layer, and 30-nm ALD Ta_2O_5 layers. (b) TEM image of the graphene-Ge QD photodetector, and (c) Atomic force microscopy image of the Ge-QD film deposited on the surface of the CVD graphene.

The chemical vapor deposition (CVD) monolayer graphene film on a copper foil from Graphenea Inc. was transferred onto the Si/SiO_2 substrate.[1] The CVD graphene on the Cu foil was spin-coated by poly-(methyl-methacrylate) (PMMA), then the Cu foil was removed by using 0.3 M ammonium persulfate solution in 2 hours. Graphene with the PMMA film was rinsed with high purity deionized water and transferred onto the Si/SiO_2 wafer with metal contacts. The sample was stored in vacuum for 12 hours to create good adhesion. The sample was baked in 120 ºC in 15 minutes, and then cleaned PMMA by acetone in 1 hour. Photolithography and oxygen plasma etching were employed to fabricate a (50 × 100) μm^2 graphene pattern between metal contacts. The process helps us to eliminate residue of photoresist that cannot removed completely by acetone during lift-off steps. After that, a 1.5-nm germanium (Ge) seed layer was deposited on the top of the CVD graphene by e-beam thermal evaporation with a slow rate of 0.1 Å per second. Under this process, Ge QDs were form on the surface of the graphene.[7] Then, the device was covered with a 30-nm Ta_2O_5 film using the atomic layer deposition method at 250 ºC to prevent the Ge QD seed layer from native oxidation in air. The Ge QD and Ta_2O_5 ALD layers cover the whole surface of the device, thus, photolithography was used to redefine source, drain, and back-gate contacts. These layers was removed by SF_6 plasma dry-etching. A schematic diagram of our graphene-Ge QD photodetector is shown in the Figure 1a.

In order to check the structure of our device, we have taken SEM images of the photodetector using a field-emission scanning electron microscope, LEO (Zeiss) 1550. Figure 1b shows a SEM image of our photodetector before we deposit a Ge QD layer. The image shows the CVD graphene layer on the device with metal contacts. To verify Ge QDs forming on the top of the CVD graphene of our device, Figure 1c shows atomic force microscope image of the Ge QD layer using Bruker DektakXT. The size of Ge QDs deposited on the CVD graphene is around 1.5 nm.

2.2. Electrical and optoelectronic measurements

The electrical characteristics were examined by two Keithley 2400 source-meters units. The first unit, Keithley 2400, is used to control the back-gate voltage, V_{BG}. The second one, Keithley 2450, is used to set a constant voltage between source and drain, V_{SD}, and to measure the drain current, I_D. Two light sources have been employed in our experiments. In the visible region, a diode-pumped laser operating at 532 nm (Coherent Verdi-V2) has been used. To control the power of the laser beam, we have used a half-wave plate and a polarizing beam-splitter. For infrared experiments, we have used a broadband infrared lamp (Stabilized Silicon Nitride Globar Light Source, SLS303, Thorlabs) with wavelengths from 550 nm to 15 μm. We used a near infrared bandpass filter (FB900-40 from Thorlabs) to select the 900-nm wavelength from the broadband IR source. To control the power of the IR light source we use neutral density filters. The spot size of the light source is large. We have employed a diaphragm with a diameter of 10 mm to form the light source with a uniform intensity distribution. The light sources cover the whole graphene FET photodetector. By knowing the active size as well as illumination power, we can estimate the power of the light source on the graphene-Ge QD photodetector.

3. RESULTS AND DISCUSSIONS

The effect of light illumination on the graphene-Ge QD photodetector is shown in the Figure 2. Specifically, we have observed the drain current, I_D, as a function of the back-gate voltage, V_{BG}, with and without illumination of the diode-pumped laser operating at 532 nm. The power of pump laser was varied from 9.3 nW to 186.9 nW.

The source-drain bias voltage, V_{SD}, was set at 0.5 V. As can be seen from Figure 2-left, the transfer characteristic (I-V) curves shift toward positive of the back-gate voltage, V_{BG}, with increasing of illumination power, and a shift of the Dirac point voltage about 7 V is observed.

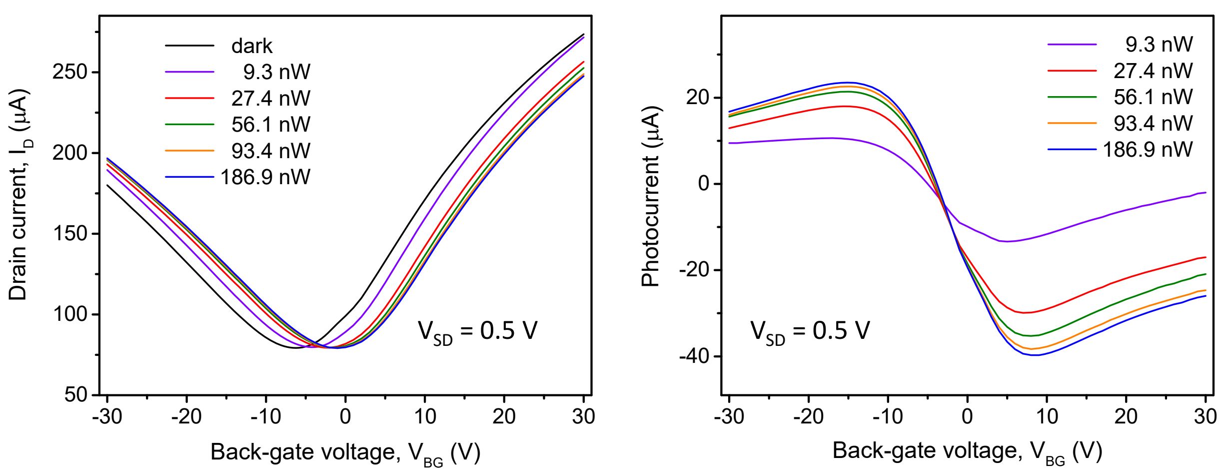

Figure 2: (left) I_D–V_{BG} characteristics of the graphene FET photodetector under different illumination conditions (dark and 532-nm laser with power values of 9.3, 27.4, 56.1, 93.4, 186.9 nW). The source-drain bias voltage, V_{SD}, is 0.5 V. (right) Photocurrent as a function of back-gate voltage under different laser illumination of 9.3, 27.4, 56.1, 93.4, 186.9 nW.

The net photocurrent can be obtained by subtracting the dark-current from the illumination current ($I_{illumination}$ – I_{dark}). The photocurrent curves under different illumination powers are plotted in Figure 2, right. A net photocurrent of ~40 μA has been observed at V_{bg} = 8 V and V_{sd} = 0.5 V. It shows clearly that the magnitude of photocurrent increases with illumination power.

To gain insight into the characteristics of the graphene-Ge QD photodetector, we extracted the power dependence of the photocurrent current (Figure 3, left) and calculated the responsivity of the device (Figure 3, right) for the 532-

nm illumination, at V_{BG} = 8.0 V and V_{SD} = 0.5 V. Under low illumination power of 9.3 nW, the device shows a responsivity of 1,500 A/W, suggesting that the graphene as well as the seed-layer absorber (Ge QDs) can efficiently convert the photon energy into a large electrical signal. This value is significant higher than other values for Ge QD photodetector in the literature.[8, 9] The photocurrent increases linearly from low illumination power to ~27 nW and saturates at high illumination power. In an equivalent way, the responsivity shows a constant value at low illumination power and reduces after that. The responsivity reduces from 1500 A/W to 200 A/W when the excitation power is higher than 27 nW. The decrease of the responsivity with the increase of the illumination is typical for photodetectors.[10, 11]. In addition, the photocurrent also shows a linear dependence on the source-drain bias voltage, V_{SD},[12] suggesting that higher photo-responsivity can be readily achieved by applying a larger bias voltage.

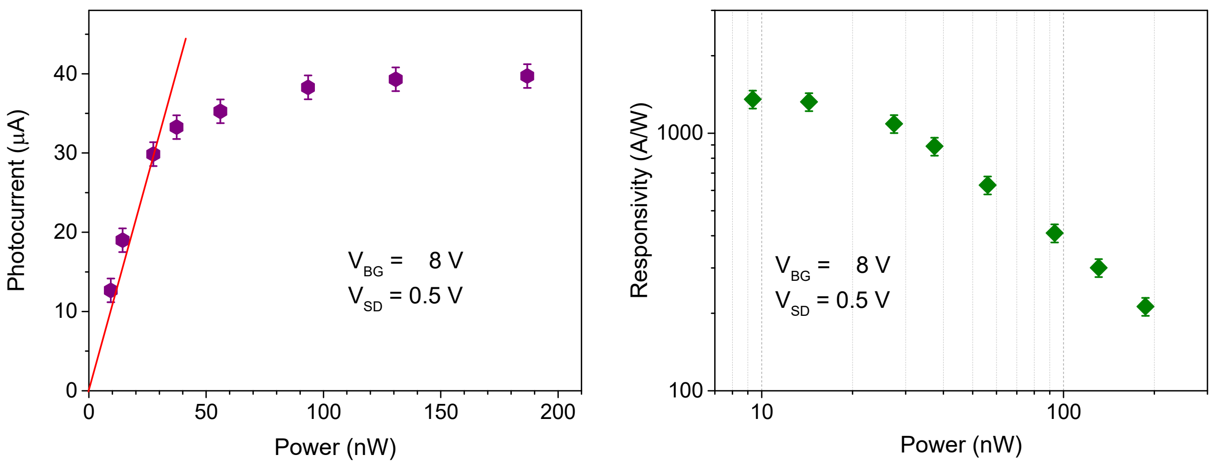

Figure 3: (left) Power dependence of photocurrent at 8 V back-gate voltage and 0.5 V source-drain voltage, and (b) responsivity as a function of 532-nm laser irradiance power.

To explore the photo-response of our graphene-Ge QD photodetector in the IR region, we illuminated the device with 900-nm wavelength from the broadband IR Thorlabs light source. The net photocurrent under 900-nm illumination as a function of back-gate voltage is plotted in Figure 4 at the power of 1.7 μW and V_{SD} = 0.5 V. The maximum photocurrent of ~1 μA has been observed at V_{bg} = 2 V and V_{SD} = 0.5 V. And we can estimate the responsivity of 0.59 A/W for the photodetector under 900-nm illumination.

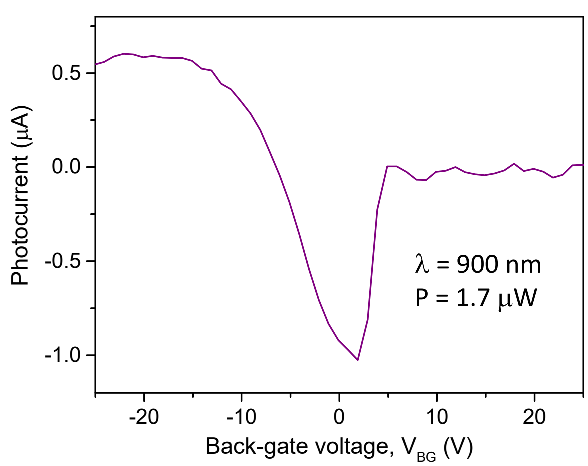

Figure 4: Photocurrent of the graphene-Ge QD photodetector under near IR illumination (900 nm) at V_{SD} = 0.5 V and the irradiance power of 1.7 μW.

For transient measurements of the photo-response of the device, we have used a mechanical chopper to produce *on* and *off* time of the light source. A time-dependent photocurrent of the graphene-Ge QD photodetector is shown in the Figure 5 under 532-nm illumination at V_{BG} = 8 V, and V_{SD} = 0.5 V. It was found that under the 532-nm illumination, the response time (τ_r) and recovery time (τ_f) are 1.8 ms and 2.6 ms, respectively. The response time as well as the recovery time from the graphene-Ge QD prepared by e-beam thermal evaporation show significant faster than those reported in the literature.[13, 14] A typical response time as well as the recovery time from other graphene-QD photodetectors prepared by nanoparticles spun-coated onto the graphene are in the order of 10s seconds. These detectors can provide an ultra-high sensitive photo-detection in the order of 10^9 A/W,[15] but the response time is very slow, thus it cannot be useful in a practical system.

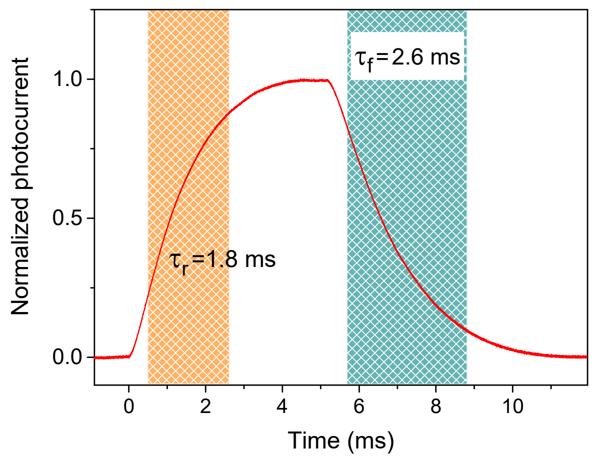

Figure 5: Photo-response of the graphene-Ge QD photodetector to pulsed light illumination at 532 nm with a frequency of 20 Hz. An estimation for both response (τ_r) and recovery (τ_f) times are 1.8 ms and 2.6 ms, respectively.

4. CONCLUSIONS

In conclusion, we have demonstrated the fabrication of a high performance FET broadband photodetector based on graphene-Ge QDs. Our analysis including electrical optical measurements indicates that the photodetectors were highly sensitive to visible light and IR irradiation with fast response and recovery time. The responsivity of the device was estimated to be 1,500 A/W, and the response time is as fast as 1 ms, much faster than other conventional photodetectors and graphene-QD devices. The simple fabrication with high-performance of the graphene-Ge QD photodetectors will have potential applications for future broadband sensing from visible to IR region.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of this effort by the Earth Science Technology Office (ESTO), NASA.

REFERENCES

[1] Novoselov, K. S., Jiang, D., Schedin, F., Booth, T. J., Khotkevich, V. V., Morozov, S. V. and Geim, A. K., "Two-dimensional atomic crystals," P. Natl. Acad. Sci. USA 102(30), 10451-10453 (2005).

[2] Aivaliotis, P., Zibik, E. A., Wilson, L. R., Cockburn, J. W., Hopkinson, M. and Vinh, N. Q., "Two photon absorption in quantum dot-in-a-well infrared photodetectors," Appl. Phys. Lett. 92(2), 023501 (2008).

[3] Cao, L. Y., Park, J. S., Fan, P. Y., Clemens, B. and Brongersma, M. L., "Resonant Germanium Nanoantenna Photodetectors," Nano Letters 10(4), 1229-1233 (2010).

[4] Vivien, L., Osmond, J., Fedeli, J. M., Marris-Morini, D., Crozat, P., Damlencourt, J. F., Cassan, E., Lecunff, Y. and Laval, S., "42 GHz p.i.n Germanium photodetector integrated in a silicon-on-insulator waveguide," Opt. Express 17(8), 6252-6257, (2009).
[5] Sahni, S., Luo, X., Liu, J., Xie, Y. H. and Yablonovitch, E., "Junction field-effect-transistor-based germanium photodetector on silicon-on-insulator," Opt. Lett. 33(10), 1138-1140 (2008).
[6] Colace, L., Masini, G., Galluzzi, F., Assanto, G., Capellini, G., Di Gaspare, L., Palange, E. and Evangelisti, F., "Metal-semiconductor-metal near-infrared light detector based on epitaxial Ge/Si," Appl. Phys. Lett. 72(24), 3175-3177 (1998).
[7] Wan, Q., Wang, T. H., Liu, W. L. and Lin, C. L., "Ultra-high-density Ge quantum dots on insulator prepared by high-vacuum electron-beam evaporation," J. Cryst. Growth. 249(1), 23-27 (2003).
[8] Liu, C. H., Chang, Y. C., Norris, T. B. and Zhong, Z. H., "Graphene photodetectors with ultra-broadband and high responsivity at room temperature," Nat. Nanotechnol. 9(4), 273-278 (2014).
[9] Zhang, Y. B., Tang, T. T., Girit, C., Hao, Z., Martin, M. C., Zettl, A., Crommie, M. F., Shen, Y. R. and Wang, F., "Direct observation of a widely tunable bandgap in bilayer graphene," Nature 459, 820-823 (2009).
[10] Konstantatos, G., Badioli, M., Gaudreau, L., Osmond, J., Bernechea, M., de Arquer, F. P. G., Gatti, F. and Koppens, F. H. L., "Hybrid graphene-quantum dot phototransistors with ultrahigh gain," Nat. Nanotechnol. 7(6), 363-368 (2012).
[11] Liu, Y. D., Wang, F. Q., Wang, X. M., Wang, X. Z., Flahaut, E., Liu, X. L., Li, Y., Wang, X. R., Xu, Y. B., Shi, Y. and Zhang, R., "Planar carbon nanotube-graphene hybrid films for high-performance broadband photodetectors," Nat. Commun. 6, 8589 (2015).
[12] Ho, V. X., Wang, Y., Cooney, M. P. and Vinh, N. Q., "Graphene-based photodetector at room temperature," Proc. of SPIE 10729, 1072907 (2018).
[13] Yang, F., Cong, H., Yu, K., Zhou, L., Wang, N., Liu, Z., Li, C. B., Wang, Q. M. and Cheng, B. W., "Ultrathin Broadband Germanium-Graphene Hybrid Photodetector with High Performance," ACS Appl. Mater. Inter. 9(15), 13422-13429 (2017).
[14] Zeng, L. H., Wang, M. Z., Hu, H., Nie, B., Yu, Y. Q., Wu, C. Y., Wang, L., Hu, J. G., Xie, C., Liang, F. X. and Luo, L. B., "Monolayer Graphene/Germanium Schottky Junction As High-Performance Self-Driven Infrared Light Photodetector," ACS Appl. Mater. Inter. 5(19), 9362-9366 (2013).
[15] Ni, Z. Y., Ma, L. L., Du, S. C., Xu, Y., Yuan, M., Fang, H. H., Wang, Z., Xu, M. S., Li, D. S., Yang, J. Y., Hu, W. D., Pi, X. D. and Yang, D. R., "Plasmonic Silicon Quantum Dots Enabled High-Sensitivity Ultrabroadband Photodetection of Graphene-Based Hybrid Phototransistors," ACS Nano 11(10), 9854-9862 (2017).