High Sensitivity, Ultra-Broadband SWNT-Graphene Hybrid Photodetector

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Abstract

A photodetector based on SWNT-graphene hybrid films and facile fabrication steps is demonstrated, which exhibits a remarkably high photoresponsivity of ~ 100 A/W, across visible (400 nm) to the telecommunication wavelengths (1550 nm).

I. INTRODUCTION

Due to ultra-broadband absorption and intrinsic high operation frequency [1-3], graphene based photodetectors have received considerable research attentions in recent years [4-6]. However, the relatively low absorbance of a single sheet of carbon atoms adversely limits the photoresponsivity of graphene-based photodetectors to a level of ~10^{-2} A/W [3]. A number of approaches have been proposed and demonstrated to enhance the device photoresponsivity [6-8]. However, enhancement in these device proposals either requires sophisticated fabrication steps that are not manufacturing scalable or is at the expense of the devices' optical bandwidth or response time.

Single-walled carbon nanotubes (SWNTs) are the one-dimensional (1D) quantum-confined form of carbon allotropes, which also possess intriguing optoelectronic properties. For example, SWNTs are effective light absorbers in a wide spectral range [9, 10]. In addition, free carriers in semiconducting tubes can have mobilities as high as 10^5 $cm^2V^{-1}s^{-1}$ [11]. The compatibility with solution processing further enables the deposition of nanotube thin-films onto flat and flexible optical substrates in a cost-effective manner [12]. The combination of 1D SWNTs with 2D graphene represents an interesting and promising all-carbon composite material for optoelectronic applications. Recently, efficient charge transfer has been identified at junctions formed by graphene and SWNTs [13]. This prompts us to investigate the graphene/nanotube composite materials for photodetector operation.

In this paper, large-scale CVD grown graphene and liquid-processed SWNT dispersions are used to fabricate a phototransistor with a graphene/nanotube hybrid channel. The phototransistors show an ultra-broadband photoresponse across visible to near-infrared range (400 nm – 1550 nm). Our results demonstrate that graphene/nanotube composites have great potential in light harvesting and related optoelectronic applications.

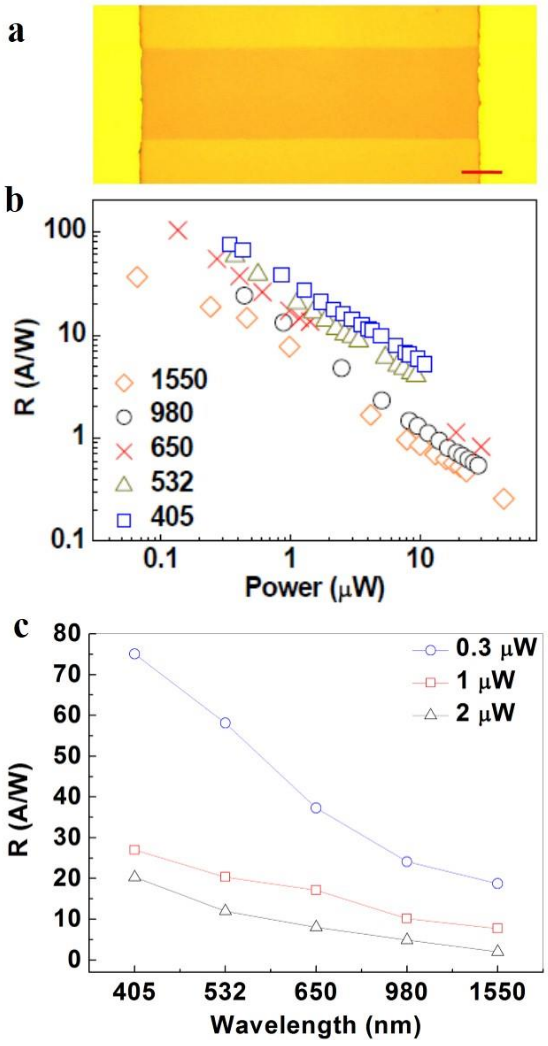

Fig. 1. (a) Optical micrograph of the fabricated SWNT-graphene hybrid phototransistor. (Scale bar, 10 μm) (b) Photoresponsivies as a function of the optical power for different illumination wavelength (405, 532, 650, 980 and 1550 nm). (c) Spectral responsivity for different illumination power of 0.3, 1 and 2 μW. V_{SD}=0.5V

II. DEVICE FABRICATION

We use SWNTs from a commercial supplier (Carbon Solutions Inc.). The graphene sample is grown by CVD method. Raman spectrum combined with optical microscope characterization points to a high quality single layer sample. The phototransistor is fabricated as follows: CNT suspensions are produced by ultrasonicating 2 mg nanotube in 20 mL NMP. The resulting suspensions are ultra-centrifuged with 10,000 g for 1h before the supernatant is collected for the deposition of SWNTs thin films on a SiO_2/Si wafer. CVD graphene is transferred on top of the CNT layer using the standard PMMA supported procedures. Electrodes are patterned by standard photolithography. Different metal composition (Ti/Au and Pd/Au) are subsequently deposited. The electrical measurements are carried out in a cryogenic probe station under vacuum (10^{-6} Torr) at room temperature. Fig.1 (a) shows an optical micrograph of the device.

III. RESULTS FOR BROADBAND PHOTORESPONSE

Fig. 1(b) illustrates characteristics of broadband photoresponse over a range of incident wavelengths (405, 532, 650, 980 and 1550 nm). Higher responsivities were obtained at lower incident power levels. At a moderate illumination power of ~0.3 μW, all wavelengths exhibit a responsivity > 10 A/W, a typical specification for commercial photodetectors. The responsivity value is higher for shorter wavelengths than for longer ones, as shown in Fig. 1(c). From the wavelength dependence, even higher photoresponsivities are expected for ultraviolet wavelengths. Photogating provided by the nanotube ensembles is attributed to the observed large photocurrents and investigation of the detailed charge transfer scenario at the SWNT-graphene junction as well as the device transient characterisitics is currently underway.

IV. CONCLUSIONS

In summary, by combining large-area CVD grown graphene with atomically-thin SWNT layer, we have formed a quasi-2-dimensional SWNT-graphene hybrid film. Such hybrid film based photodetectors exhibit an ultra-broadband sensitivity across visible to near-infrared telecom bands, demonstrating the potential for facile fabrication of high-performance all-carbon optoelectronic devices.

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REFERENCES

[1] T. M. F. H. L. Koppens, Ph. Avouris, A. C. Ferrari, M. S. Vitiello and M. Polini, "Photodetectors based on graphene, other two-dimensional materials and hybrid systems," *Nat. Nanotechnol.*, **9**, pp. 780-793, 2014.

[2] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," *Nat. Photonics*, **4**, pp. 611-622, 2010.

[3] F. Xia, T. Mueller, Y. Lin, A. Valdes-Garcia, and P. Avouris, "Ultrafast graphene photodetector," *Nat. Nanotechnol.*, **4**, pp. 839-843, 2009.

[4] T. E. Murphy, H. D. Drew, and M. S. Fuhrer, "Sensitive room-temperature terahertz detection via the photothermoelectric effect in graphene," pp. , 2014.

[5] C. O. Kim, S. Kim, D. H. Shin, S. S. Kang, J. M. Kim, C. W. Jang, S. S. Joo, J. S. Lee, J. H. Kim, and S.-H. Choi, "High photoresponsivity in an all-graphene p–n vertical junction photodetector," *Nat. Commun.*, **5**, pp. 3249(3241-3247), 2014.

[6] X. Wang, Z. Cheng, K. Xu, H. K. Tsang, and J. B. Xu, "High-responsivity graphene/silicon-heterostructure waveguide photodetectors," *Nat. Photonics*, **7**, pp. 888–891, 2013.

[7] G. Konstantatos, M. Badioli, L. Gaudreau, J. Osmond, M. Bernechea, F. P. G. de Arquer, F. Gatti, and F. H. L. Koppens, "Hybrid graphene-quantum dot phototransistors with ultrahigh gain," *Nat. Nanotechnol.*, **7**, pp. 363-368, 2012.

[8] T. J. Echtermeyer, L. Britnell, P. K. Jasnos, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari, and K. S. Novoselov, "Strong plasmonic enhancement of photovoltage in graphene," *Nat. Commun.*, **2**, pp. 458, 2011.

[9] F. Wang, G. Dukovic, L. E. Brus, and T. F. Heinz, "The optical resonances in carbon nanotubes arise from excitons," *Science*, **308**, pp. 838-841, 2005.

[10] M. S. Strano, C. A. Dyke, M. L. Usrey, P. W. Barone, M. J. Allen, H. Shan, C. Kittrell, R. H. Hauge, J. M. Tour, and R. E. Smalley, "Electronic structure control of single-walled carbon nanotube functionalization," *Science*, **301**, pp. 1519-1522, 2003.

[11] T. Dürkop, S. Getty, E. Cobas, and M. Fuhrer, "Extraordinary mobility in semiconducting carbon nanotubes," *Nano Lett.*, **4**, pp. 35-39, 2004.

[12] T. Hasan, Z. Sun, F. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, "Nanotube–polymer composites for ultrafast photonics," *Adv. Mater.*, **21**, pp. 3874-3899, 2009.

[13] G. L. C. Paulus, Q. H. Wang, Z. W. Ulissi, T. P. McNicholas, A. Vijayaraghavan, C. J. Shih, Z. Jin, and M. S. Strano, "Charge Transfer at Junctions of a Single Layer of Graphene and a Metallic Single Walled Carbon Nanotube," *Small*, **9**, pp. 1954-1963, 2013.