Published in final edited form as:

Adv Mater. 2013 July 5; 25(25): 3433–3437. doi:10.1002/adma.201300292.

Broad-Spectral-Response Nanocarbon Bulk-Heterojunction Excitonic Photodetectors

Yu Xie, Dr.,

Department of Chemistry University of Kansas Lawrence, KS 66045, USA

Maogang Gong, Dr.,

Department of Chemistry University of Kansas Lawrence, KS 66045, USA

Tejas A. Shastri,

Department of Materials Science and Engineering and Department of Chemistry Northwestern University Evanston, Illinois 60208, USA

Jessica Lohrman,

Department of Chemistry University of Kansas Lawrence, KS 66045, USA

Mark C. Hersam, Prof., and

Department of Materials Science and Engineering and Department of Chemistry Northwestern University Evanston, Illinois 60208, USA

Shenqiang Ren, Prof.

Department of Chemistry University of Kansas Lawrence, KS 66045, USA

Shenqiang Ren: shenqiang@ku.edu

The sp^2 carbon allotropes - carbon nanotubes, fullerenes, and graphene - are widely reported as alternative materials for nanoelectronics,^[1] as silicon-based devices approach their scaling and performance limits.^[2] As one of the potential candidates for next-generation electronics, nanocarbon devices pose several advantages, such as solution processability for large-scale production, and extraordinary electronic properties.^[1b] Consequently, there is great interest in developing carbon-based solar cells, transparent conductors, capacitors, transistors, light-emitting diodes, and photodetectors.^[1a,b, 2, 3] Among these, carbon-nanotube-based photodetectors have been developed based on the thermal bolometric mechanism, which is distinguished from efficient excitonic photovoltaic processes.^[4] In addition, excitonic photodetectors based on carbon nanotube/organic polymer, carbon nanotube/silicon and single-carbonnanotube devices have been reported.^[4, 5] However, concurrently achieving a fast response and a high photodetectivity (D^*) in nanocarbon-based excitonic photovoltaic photodetectors remains challenging.^[3h, 6]

In this communication, we report broad-spectral-response excitonic nanocarbon bulk-heterojunction (BHJ) photovoltaic photodetectors consisting of semiconducting single-walled carbon nanotubes (s-SWCNTs) and (6,6)-phenyl-C₇₁-butyric acid methyl ester (PC₇₁BM), interfaced by a graphene oxide (GO) barrier layer. This approach takes advantage of the broad absorption spectrum, photovoltaic response, and solution processability of sp²-carbon allotropes. Generally, the polymer mixture, poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) is used as a hole-transporting layer (HTL) in traditional organic photovoltaics. The deposition of PEDOT:PSS usually provides a highly acidic environment, which may be corrosive to the indium tin oxide (ITO) layer of the electrode. The usage of GO can solve this issue as it disperses readily in water but it does not offer a strongly acidic medium, although macroscopic flakes of GO may make the morphology non-uniform. Since the chirality distribution of the s-SWCNT component is expected to be critical to the photodetector performance, our polychiral s-SWCNTs display a high level of photodetectivity (D^*) of 9×10^{11} Jones, which is more than 30 times higher than the D^* of single-chirality (6,5)-rich s-SWCNT-based nanocarbon photodetectors at the same wavelength (860 nm). The preparation of polychiral and (6,5)-rich s-SWCNTs is shown in the Experimental Section.

In addition, to demonstrate the figure of merit for superlative photodetectors, magnetic-field effects (MFEs) on nanocarbon BHJ devices are explored. Previously, MFEs have been studied in traditional organic solar cells,^[7] in which donor-acceptor interactions upon influences of a magnetic field provide the insight that can rationally inform efforts to improve the efficiency of organic solar cells.^[8] Similarly, in this communication, we explore MFEs on the excitonic processes in nanocarbon photovoltaic photodetectors and introduce possible mechanisms. In particular, by utilizing the MFEs, a fast photoresponse that exhibits a sharp decrease on both the rise and reset time at a 0.2 V bias is observed. Overall, by combining device demonstration with fundamental characterization, this investigation is likely to influence the design of future high-performance nanocarbonbased photodetectors.

The active layer of the nanocarbon photodetector consists of s-SWCNT and PC₇₁BM, with GO as the HTL material instead of traditional polymer-based composites (Supporting Information, Scheme S1). The term “s-SWCNT” will be used subsequently to describe (6,5)-rich s-SWCNTs only, if there are no other specific indications. The nanoscale morphology of the nanocarbon blend can be observed in the transmission electron microscopy (TEM) and atomic force microscopy (AFM) images in Figure 1a and 1b. Minimal bundling of the s-SWCNTs is observed in both images, and large PC₇₁BM aggregates are absent in the AFM image. An average roughness of 3 nm suggests a well-dispersed s-SWCNT/PC₇₁BM blend. Figure 1c shows the photo-absorption spectrum of the nanocarbon BHJ film. Light absorption from the s-SWCNTs and PC₇₁BM is observed at both visible and near-infrared (NIR) wavelengths, which is critical for the broad spectral photoresponse of these nanocarbon photovoltaic photodetectors.

Figure 1d shows the current density-voltage (J - V) plots of the nanocarbon s-SWCNT/PC₇₁BM BHJ photovoltaic photodetector under AM 1.5 illumination. The diode shows a dark current density (J_d) at zero bias voltage (V_{bias}) of $\approx 1.7 \times 10^{-6}$ A/cm². The dark current rectification ratio is less than 10, which suggests a relatively low shunt current. It should be

noted that the nanocarbon photodetector benefits significantly from the high purity of our SWCNTs since previous reports have shown that a high density of metallic nanotubes leads to relatively large shunt currents.^[4] The J - V plot exhibits a photovoltaic response with an open-circuit voltage (V_{oc}) of ≈ 0.7 V and a short-circuit current density (J_{sc}) of $\approx 2.2 \times 10^{-3}$ A/cm². The broad-spectrum external quantum efficiency (EQE) supports the measured J_{sc} of the device, as shown in Figure S1 in the Supporting Information. The EQE in the NIR region for the nanocarbon BHJ photovoltaic photodetector is comparable to a previous report on CNT/photoactive polymer/C₆₀-based photodetectors with a 2.3% EQE at 1155 nm under zero V_{bias} .^[4] These results indicate that our nanocarbon BHJ photodetector is not based on thermal effects, but rather on a photovoltaic excitonic mechanism that leads to rapid dissociation of photogenerated electron-hole pairs at zero V_{bias} .^[4] Band alignments (Supporting Information, Scheme S1) between s-SWCNT and PC₇₁BM are sufficient for both charge injection and exciton dissociation at the donor-acceptor interface.

In addition to the photovoltaic response, the nanocarbon BHJ photodetector exhibits excellent photoresponse reversibility. Figure 2a shows the on/off current density plots of the photodetector at different V_{bias} . After more than three cycles of the “on” and “off” states, a stable current density level at each V_{bias} is retained, demonstrating photo detection reversibility. These results are consistent with the J - V plots in Figure 1d. Figure 2b shows the wavelength-dependent photoresponsivity (R) of the nanocarbon photodetector, where a broadband R is demonstrated for each V_{bias} . The R value is ≈ 260 mA W⁻¹ and ≈ 20 mA W⁻¹ under 500 nm and 1010 nm illumination, respectively, at $V_{bias} = -0.6$ V. The R values in the visible region are comparable to some reported inorganic photodetectors, such as the 1D In₂Te₃-based device (0.3 A/W under $V_{bias} = 10$ V).^[9] The calculation of R , which is the ratio of photocurrent density (J_{ph}) and incident light intensity (I_{light}),^[10] is shown by Equation S1 in the Supporting Information. The broad photoresponse is supported by the EQE spectrum (Supporting Information, Figure S1a), which confirms that the NIR photons absorbed by the s-SWCNTs contribute to the photocurrent.

The photodetectivity (D^*) is calculated based on R and J_d ^[10] according to the following equation:

$$D^* = R / (2qJ_d)^{1/2} = (J_{ph} / I_{light}) / (2qJ_d)^{1/2} \quad (1)$$

where q is the fundamental unit of charge. The shot noise is considered here, while the Johnson thermal noise is ignored (Supporting Information, Equation S2–S4). Figure 2c shows the wavelength dependent D^* of the nanocarbon photodetector at different V_{bias} . At zero V_{bias} , the D^* is $\approx 2 \times 10^{10}$ Jones (1010 nm) and $\approx 2 \times 10^{11}$ Jones (500 nm), respectively. The latter is several times higher than polymer-based ($\approx 4 \times 10^{10}$ Jones at 500 nm) and carbon nanotube/organic-semiconductor-based photodetectors ($\approx 3 \times 10^{10}$ Jones at 500 nm).^[4, 10] The linear dynamic range (LDR) of the photodetector is ≈ 40 and ≈ 20 dB level at zero V_{bias} upon the illumination at 500 and 1010 nm, respectively (Supporting Information, Figure S1b). These results stem from the visible absorption of PC₇₁BM, the NIR absorption of s-SWCNTs, and the high carrier mobility ($\approx 10^5$ cm² V⁻¹ s⁻¹) and excellent charge collection of the s-SWCNTs.^[3h] When V_{bias} is applied, the decrease of D^* is due to the limitation from a high J_d , which can be deduced from the diode equation

(Supporting Information, Equation S5).^[10] It should be noted that the internal gain could influence J_d upon the application of V_{bias} .^[11]

The MFEs on the intersystem crossing could lead to higher exciton dissociation and charge separation, which can improve the performance of nanocarbon BHJ photovoltaic photodetectors. Figure 3a shows the R change of the photodetector under the application of a magnetic field with different V_{bias} while the R value is normalized to be 100% under zero bias without the magnetic field. The change is calculated based on this control value. The R improvements of the photodetector under MFEs are induced by a change in the photocurrent density at different V_{bias} (Supporting Information, Figure S2). The broad photoresponsivity under the applied magnetic field are shown in Figure S3a in the Supporting Information. In our nanocarbon BHJ photodetector and magnet design, the magnitude of the magnetic field is 15 mT at the position of the device (Supporting Information, Scheme S2), which is shown in our previous report.^[11]

Photocurrent enhancements due to MFEs were previously reported in organic solar cells.^[7b] Two factors, polaron-pair dissociation and charge reaction, are generally considered to explain the magnetic-field dependence of the photocurrent at low fields. The improved singlet-to-triplet ratio in the polaron-pair states has a positive effect on the photocurrent, as the singlet and triplet polaron pairs have high and low dissociation rates.^[12] A negative effect on the photocurrent can be attributed to the decreased charge reaction rate constant upon the application of the external magnetic field, as excitons can release charges and separate electron-hole pairs via interaction with trapped and free carriers.^[7a, 13] The change of singlet-to-triplet ratio can primarily be attributed to intersystem crossing between the two electronic states with different spin multiplicity.^[7a, b] Photocurrent enhancements due to MFEs in this work suggest that the improved singlet-to-triplet polaron pair ratio is sufficient in the nanocarbon BHJ system, although the s-SWCNT content is only ≈ 3 wt% loading (Figure 3c).^[14] In the traditional P3HT/PCBM BHJ solar cell systems, dissociation of the the singlet photoexcited states happens at a time scale of sub-picosecond or several hundred femtoseconds,^[1g, 15] while triplet exciton dissociation is relatively slow. Because the s-SWCNTs are highly pure with a 1D structure that is analogous to many conjugated polymers, the dynamics in s-SWCNTs and polymers may have some similarity. Some of the magnetic flux is perpendicular to the internal electric field (IEF) direction of the device, under the current magnet-device arrangement (Supporting Information, Scheme S2).^[11] The charge transport is considered along the direction of the IEF, along which the Lorentz force does not contribute to the charge transport. Thus, Lorentz force effects (LFEs) may not be relevant for the MFEs in this work, although LFEs have been reported to cause large MFEs by others.^[16]

The photoresponse time plays an important role in photodetector behavior. Figure 3b shows the reset and rise time upon $V_{bias} = 0.2$ V for the photodetector with/without a magnetic field under AM 1.5 illumination. The reset time is defined as the time gap from the “on” to the “off” state, while the rise time is defined as the opposite. The reset time shows a decrease from 55 to 37 ms, while the rise time decreases from 50 to 40 ms, after the magnetic field is applied. The photoresponse of the nanocarbon device is faster than those of most other photodetectors, some of which are ≈ 0.3 s scale.^[17] When the magnetic field is applied, the

positive MFEs on exciton dissociation can explain the decrease in the rise time. The increased kinetic energy under an applied magnetic field enhances the possibility of charge collision, which may explain the decrease of the reset time. The internal gain, which is due to the extra driving force of the applied V_{bias} could magnify MFEs on the reset and rise time, explaining the difference between situations with and without the bias.

To investigate the effect of s-SWCNT chirality on the performance of nanocarbon photovoltaic photodetectors, polychiral s-SWCNTs are blended with PC₇₁BM in the BHJ device. The wavelength-dependent broad-band photodetectivity of the polychiral s-SWCNT based photodetector upon $V_{\text{bias}} = 0$ V is shown in Figure S5a in the Supporting Information. A high level D^* (9×10^{11} Jones) at 860 nm is observed, corresponding to an R of ≈ 250 mA W^{-1} (Supporting Information, Figure S5b). This peak may be attributed to (12,4) s-SWCNTs, of which the S_{11} absorption is around this wavelength. However, the interaction between the s-SWCNTs and PC₇₁BM can cause an absorption shift via altering the electronic structure of the s-SWCNT by surface hybridization. This value of D^* is the highest value for s-SWCNT-based photodetectors reported, compared with 6×10^{11} Jones in previous reports.^[3h, 6] The maximum D^* of the polychiral s-SWCNT based photodetector is higher than the that of the (6,5)-rich s-SWCNT-based device, which can be contributed into the broader absorption due to the more-dispersed chirality distribution of the polychiral s-SWCNT component. The photon-electron conversion at the S_{11} band of (6,5) s-SWCNT is relatively low in the (6,5)-rich s-SWCNT based device (Supporting Information, Figure S1a), which is another reason.

In conclusion, we have fabricated high-performance broad-spectrum nanocarbon BHJ photovoltaic photodetectors. Low shunt currents are suggested by the dark-current rectification ratios, which are less than 10 at ± 1 V. For the (6,5)-rich s-SWCNT-based photodetector, the photoresponsivity R value is 260 mA W^{-1} (500 nm) and 20 mA W^{-1} (1010 nm), under a V_{bias} of -0.6 V with a corresponding photodetectivity D^* of 2×10^{11} Jones (500 nm) and 2×10^{10} Jones (1010 nm). Both the photocurrent density and R values increase upon the application of a magnetic field. In addition, a sharp decrease in the reset and rise time is observed due to magnetic-field effects (MFEs). The performance enhancement because of MFEs implies that the magnetic field-dependent component of exciton dissociation is significant in s-SWCNT/PC₇₁BM nanocarbon BHJ systems. Finally, a high level of D^* (9×10^{11} Jones) is obtained at 860 nm for the polychiral s-SWCNT-based photodetector. From both a fundamental and applied perspectives, this work provides quantitative insights that can advance ongoing efforts to realize high-performance broad-band nanocarbon BHJ photovoltaic photodetectors.

Experimental Section

Solution Preparation

The (6,5)-rich s-SWCNTs (> 97% semiconducting purity, content of (6,5)-SWCNT is up to 50% content) were produced from the cobalt-molybdenum catalytic (CoMoCAT) process, while the polychiral s-SWCNTs (> 97% semiconducting purity) were produced from the high-pressure carbon monoxide (HiPco) process. The high semiconducting purities were isolated from the two raw materials via the density-gradient ultracentrifugation

methodology.^[18] The fullerene derivative (6,6)-phenyl-C₇₁-butyric acid methyl ester (PC₇₁BM) (American Dye Source) was used in this study. Trace ($\approx 1\%$) poly[(9,9-dioctylfluorenyl-2,7-diyl)-*co*-(4,4'-(N-(4-*s*-butylphenyl))-diphenylamine)] (TFB) (American Dye Source) was used as the surfactant for the blend solution of 3 wt% s-SWCNTs and PC₇₁BM. Graphene oxide was prepared via the method previously reported.^[1a]

Photodetector Fabrication and Characterization

Indium tin oxide (ITO) glass substrates (0.5 in $\times$ 0.5 in) (Thin Film Devices) were prepatterned and cleaned. The GO layer was deposited on cleaned ITO substrates via spin-coating and then baked at 100 °C. The s-SWCNT and PC₇₁BM blend solution (1% TFB, 1,2-DCB/CHCl₃) was spin-coated on GO/ITO substrates in a glove box to make ≈ 100 nm-thick active-layer films. The wet film was dried in a covered plastic Petri dish and baked at 100 °C. The top Ca/Al electrode was deposited onto the dry film by a thermal evaporator, leading to the device structure in Scheme S1 in the Supporting Information.

A Keithley 2400 source generator was used to take both current density–voltage (J – V) and photoresponse plots (on/off states) upon illumination by a solar simulator (≈ 100 mW/cm² AM 1.5, Newport). A magnet was positioned under the middle position of the device substrates for the study of magnetic field effects (MFEs), as shown in Scheme S2 in the Supporting Information. More details of the magnet setup and its flux are shown in one of our previous reports.^[11]

Transmission Electron Microscopy (TEM)

An FEI Tecnai F20 XT field-emission transmission electron microscope was used to take the TEM image of the nanocarbon blend.

Atomic Force Microscopy (AFM)

A Digital Instruments LFM-2 AFM/SPM microscope was used to take the AFM image of the nanocarbon blend film (Silicon probes: nanoScience Instruments, Vista Probes, CLR-25).

Absorption Spectroscopy

A Shimadzu UV–vis–NIR UV-3600 spectrophotometer was used to take the absorption spectrum of the nanocarbon blend film.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

S.R. acknowledges funding from the National Science Foundation under Award No. EPS-0903806 and matching support from the State of Kansas through the Kansas Board of Regents, and the National Institute of General Medical Sciences of the National Institutes of Health under Award Number P20GM103638. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health, while M.C.H. acknowledges funding from the National Science Foundation (DMR-1006391). T.A.S. is supported by a National Science Foundation Graduate Research Fellowship and the ANSER Center, an Energy

Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award Number DE-SC0001059.

References

1. a) Bernardi M, Lohrman J, Kumar PV, Kirkeminde A, Ferralis N, Grossman JC, Ren S. ACS Nano. 2012; 6:8896–8903. [PubMed: 22953746] b) Ramuz MP, Vosgueritchian M, Wei P, Wang C, Gao Y, Wu Y, Chen Y, Bao Z. ACS Nano. 2012; 6:10384–10395. [PubMed: 23113673] c) Jariwala D, Sangwan VK, Lauhon LJ, Marks TJ, Hersam MC. Chem. Soc. Rev. 2013; 42:2824–2860. [PubMed: 23124307] d) Tung VC, Huang JH, Tevis I, Kim F, Kim J, Chu CW, Stupp SI, Huang JX. J. Am. Chem. Soc. 2011; 133:4940–4947. [PubMed: 21391674] e) Ren SQ, Bernardi M, Lunt RR, Bulovic V, Grossman JC, Gradecak S. Nano Lett. 2011; 11:5316–5321. [PubMed: 22023484] f) Liu J, Xue YH, Gao YX, Yu DS, Durstock M, Dai LM. Adv. Mater. 2012; 24:2228–2233. [PubMed: 22488820] g) Guilbert AAY, Reynolds LX, Bruno A, MacLachlan A, King SP, Faist MA, Pires E, Macdonald JE, Stingelin N, Haque SA, Nelson J. ACS Nano. 2012; 6:3868–3875. [PubMed: 22533706] h) Dai LM, Chang DW, Baek JB, Lu W. Small. 2012; 8:1130–1166. [PubMed: 22383334]
2. Avouris P, Chen ZH, Perebeinos V. Nat. Nanotechnol. 2007; 2:605–615. [PubMed: 18654384]
3. a) Jain RM, Howden R, Tvrdy K, Shimizu S, Hilmer AJ, McNicholas TP, Gleason KK, Strano MS. Adv. Mater. 2012; 24:4436–4439. [PubMed: 22740144] b) Hatakeyama R, Li YF, Kato TY, Kaneko T. Appl. Phys. Lett. 2010; 97:013104.c) Prato M. J. Mater. Chem. 1997; 7:1097–1109.d) Geim AK, Novoselov KS. Nat. Mater. 2007; 6:183–191. [PubMed: 17330084] e) Geim AK. Science. 2009; 324:1530–1534. [PubMed: 19541989] f) Schnorr JM, Swager TM. Chem. Mat. 2011; 23:646–657.g) Baughman RH, Zakhidov AA, de Heer WA. Science. 2002; 297:787–792. [PubMed: 12161643] h) Bindl DJ, Arnold MS. Int. J. High Speed Electron. Syst. 2011; 20:687–695.i) Tyler TP, Brock RE, Karmel HJ, Marks TJ, Hersam MC. Adv. Energy Mater. 2011; 1:785–791.j) Shastry TA, Seo J-WT, Lopez JJ, Arnold HN, Kelter JZ, Sangwan VK, Lauhon LJ, Marks TJ, Hersam MC. Small. 2013; 9:45–51. [PubMed: 22987547] k) Sangwan VK, Ortiz RP, Alaboson JMP, Emery JD, Bedzyk MJ, Lauhon LJ, Marks TJ, Hersam MC. ACS Nano. 2012; 6:7480–7488. [PubMed: 22783918] l) Green AA, Hersam MC. Nano Lett. 2008; 8:1417–1422. [PubMed: 18393537] m) Tyler TP, Shastry TA, Leever BJ, Hersam MC. Adv. Mater. 2012; 24:4765–4768. [PubMed: 22833215] n) Kinoshita M, Steiner M, Engel M, Small JP, Green AA, Hersam MC, Krupke R, Mendez EE, Avouris P. Opt. Express. 2010; 18:25738–25745. [PubMed: 21164919]
4. Arnold MS, Zimmerman JD, Renshaw CK, Xu X, Lunt RR, Austin CM, Forrest SR. Nano Lett. 2009; 9:3354–3358. [PubMed: 19637853]
5. a) Zhang JB, Xi N, Chen HZ, Lai KWC, Li GY, Wejinya UC. IEEE Trans. Nanotechnol. 2009; 8:245–251.b) Zeng QS, Wang S, Yang LJ, Wang ZX, Pei T, Zhang ZY, Peng LM, Zhou WW, Liu J, Zhou WY, Xie SS. Opt. Mater. Express. 2012; 2:839–848.c) Lu R, Christianson C, Kirkeminde A, Ren S, Wu J. Nano Lett. 2012; 12:6244–6249. [PubMed: 23130570]
6. Bindl DJ, Wu M-Y, Prehn FC, Arnold MS. Nano Lett. 2011; 11:455–460. [PubMed: 21166422]
7. a) Xu Z, Hu B. Adv. Funct. Mater. 2008; 18:2611–2617.b) Yan L, Wu Y, Xu ZH, Hu B. Synth. Met. 2009; 159:2323–2325.c) Hu B, Yan LA, Shao M. Adv. Mater. 2009; 21:1500–1516.
8. Zang H, Liang Y, Yu L, Hu B. Adv. Energy Mater. 2011; 1:923–929.
9. Wang Z, Safdar M, Jiang C, He J. Nano Lett. 2012; 12:4715–4721. [PubMed: 22908854]
10. Gong X, Tong MH, Xia YJ, Cai WZ, Moon JS, Cao Y, Yu G, Shieh CL, Nilsson B, Heeger AJ. Science. 2009; 325:1665–1667. [PubMed: 19679770]
11. Gong M, Kirkeminde A, Xie Y, Lu R, Liu J, Wu J, Ren SQ. Adv. Opt. Mater. 2013; 1:78–83.
12. Xu ZH, Hu B, Howe J. J. Appl. Phys. 2008; 103:043909.
13. Tolstov IV, Belov AV, Kaplunov MG, Yakuschenko IK, Spitsina NG, Triebel MM, Frankevich EL. J. Lumin. 2005; 112:368–371.
14. Meshot ER, Patel KD, Tawfi ck S, Juggernaut KA, Bedewy M, Verploegen EA, De Volder MFL, Hart AJ. Adv. Funct. Mater. 2012; 22:577–584.
15. a) Jamieson FC, Domingo EB, McCarthy-Ward T, Heeney M, Stingelin N, Durrant JR. Chem. Sci. 2012; 3:485–492.b) Xie Y, Li Y, Xiao LX, Qiao QQ, Dhakal R, Zhang ZL, Gong QH, Galipeau D, Yan XZ. J. Phys. Chem. C. 2010; 114:14590–14600.c) Kurniawan M, Salim T, Tai KF, Sun SY,

- Sie EJ, Wu XY, Yeow EKL, Huan CHA, Lam YM, Sum TC. *J. Phys. Chem. C*. 2012; 116:18015–18022.
16. Shao M, Yan L, Pan HP, Ivanov I, Hu B. *Adv. Mater.* 2011; 23:2216–2220. [PubMed: 21462373]
17. a) Li L, Lee PS, Yan CY, Zhai TY, Fang XS, Liao MY, Koide Y, Bando Y, Golberg D. *Adv. Mater.* 2010; 22:5145–5149. [PubMed: 20859947] b) Zhai TY, Ye MF, Li L, Fang XS, Liao MY, Li YF, Koide Y, Bando Y, Golberg D. *Adv. Mater.* 2010; 22:4530–4533. [PubMed: 20836072]
18. a) Green AA, Hersam MC. *Adv. Mater.* 2011; 23:2185–2190. [PubMed: 21472798] b) Arnold MS, Green AA, Hulvat JF, Stupp SI, Hersam MC. *Nat. Nanotechnol.* 2006; 1:60–65. [PubMed: 18654143]

Figure 1.

a) TEM and b) AFM images of nanocarbon blends. The white arrows indicate the bundling of s-SWCNTs. c) Absorption spectrum of the nanocarbon blend film. d) Current density–voltage (J – V) plot of the nanocarbon photovoltaic photodetector upon AM 1.5 illumination.

Figure 2.

a) The time-dependent on/off current density plots of the nanocarbon photodetector upon different V_{bias} under AM 1.5 illumination. b) Wavelength-dependent broad-band photoresponsivity. c) Photodetectivity of the nanocarbon photodetector upon different V_{bias} .

Figure 3.

a) Plot of the V_{bias} -dependent photoresponsivity change of the nanocarbon photodetector with an applied magnetic field, where the photoresponsivity upon zero bias under illumination at 500 nm without the magnet field is normalized to be 100%. b) Plots of reset and rise time upon $V_{\text{bias}} = 0.2$ V for the nanocarbon photodetector with/without the magnet field under AM 1.5 illumination. c) Schematic of singlet and triplet charge-transfer complexes in SWCNT and PCBM blends.