

The Charging-Relaxation of Carriers in High Response Organic Phototransistor with Au Nanoparticles

Shuo-Huang Yuan¹, Zingway Pei^{*2} and Chien-Hsun Chen³

¹Department of Electrical Engineering, National Central University No.300, Zhongda Rd., Zhongli City, Taoyuan County 32001, Taiwan, ROC

²Graduate Institute of Optoelectronic Engineering and Research Center for Sustainable Energy and Nanotechnology, National Chung Hsing University, Taichung 40227, Taiwan, ROC

*Phone:+886-4-22851549 ext. 801 E-mail:zingway@dragon.nchu.edu.tw

³Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Chutung 310, Taiwan, ROC

Abstract

The gold nanoparticles (Au NPs) decoration on top of Pentacene is proposed to enhanced the phtoresponse of organic phototransistor. By introduce the surface plasmon resonance (SPR), photons concentrated at pentacene surface enhanced the density of generated free carriers. The switching characteristics was studied, the trap at pentacene/Au NPs interface is to increase rise time but decreases fall time. Shockley-Read-Hall recombination process through those traps are used to explain this behavior. By manipulating the surface traps, the response time could be further reduced toward high speed operation.

1. Introduction

Phototransistor (PT) integrated the advantages of photodetector and transistor in single device with excellent photon to electrical signal conversion gain are wildly applied in industrial, biomedical and even military [1]. For portable device, organic material has potential to replace the amorphous silicon with flexibility, high optical sensitivity, high carrier mobility, low cost, low manufacture temperature and large manufacture area. The challenge for most of the organic PTs (OPTs) devices is relative low optical conversion efficiency with a thin semiconductor layer which lack effective absorption thickness. The solution for this problem is easily associated with increased the semiconductor thickness. However, the carrier mobility lower in thicker film due to current flow through the highly resistive path in neutral region that leads to the device performance reduced [2]. The physically limitation limited the magnitude of photon absorption in thin film semiconductor, thus, to design a structure to concentrated the light in the semiconductor surface is necessary.

Metallic nanoparticles (NPs) like gold [3], silver [4] and graphene [5] would be the optimal solution to concentrate the light at the particles surface through near-field oscillation to enhanced localized electric field [6]. In addition to plasmonic oscillation, the other benefit like rayleigh scattering scattered the incident light to underlying layer and being absorbed [7]. The PTs with metallic NPs decoration are reported photocurrent enhancement and induced threshold voltage shift in visible region [8] even UV [9]. However, none of the paper discuss about rising time and falling time behavior as the OPTs with Au NPs decoration. In this study, we investigated the

OPTs with Au-NPs decoration to enhance the photocurrent and furthermore analyzing the rising time and falling time behavior to realize the photo carriers generated and recombination behavior.

2. Experiment

To fabricate bottom-gate top-contact Pentacene thin film transistor, an Au gate electrode was first deposited onto a cleaned glass substrate through a shadow mask by thermal evaporation. Later, a 20nm thick Al₂O₃ layer was deposited by atomic layer deposition. An interface treatment layer Poly(methyl methacrylate) (PMMA) was first dissolved in toluene (20mg/ml) and spun coated on the top of Al₂O₃ annealed on a hot plate at 100°C for 30min. A purified pentacene film and Au source-drain electrode both with a thickness of 40 nm was deposited by thermal evaporator through a shadow mask. Finally, Au nanoparticles (Au-NPs) was thermally evaporated onto the pentacene film through a shadow mask. The channel length (L) and channel width (W) of the fabricated phototransistors were kept at 100 and 500 μm, respectively. The current-voltage (I-V) characteristics of the fabricated devices were then measured using an Agilent 2192 semiconductor parameter analyzer. The spectral responses of the devices were measured using 650, 532, 405nm wavelength laser as the light source and the light intensity are both 1mW/cm².

3. Results and discussion

Fig. 1 shows the transfer characteristics of pentacene PTs with and without Au-NPs decoration illuminate under three different light with incremental illumination time. Those curves revealed shift to positive gate voltage under 650nm light illumination due to photovoltaic effect [10]. The absorbed photon energy transfers to excite the carrier in semiconductor. The Au NPs OPTs shows clearly curve shift and significant photo-response larger than without decoration one which contributed to surface plasmon resonance (SPR) of Au NPs interact with photon [11]. The incident photon energy transfer and oscillate the electron cloud at NPs surface and increase the amplitude of oscillation further increase the electric field thus create a surface plasmon wave in the semiconductor.

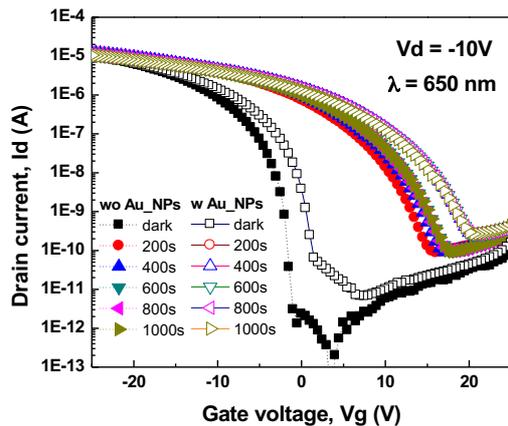


Fig. 1 The transfer characteristics of pentacene PTs

Fig. 2 compares the drain current behaviors of OPTs with and without Au NPs in response to light modulation. Photo- and dark currents of both OPTs keep nearly invariant with time. The drain current of OPTs exhibits distinct on and off states as light are switched on and off. Au NPs OPTs well retain their steady-state photocurrent level as light turn on, and gradually restore to their initial dark current level as light are off. OPTs without Au NPs show same trends in the photo and dark currents in the switch test. With Au NPs, OPTs can generate more photocurrent after receiving the photon energy.

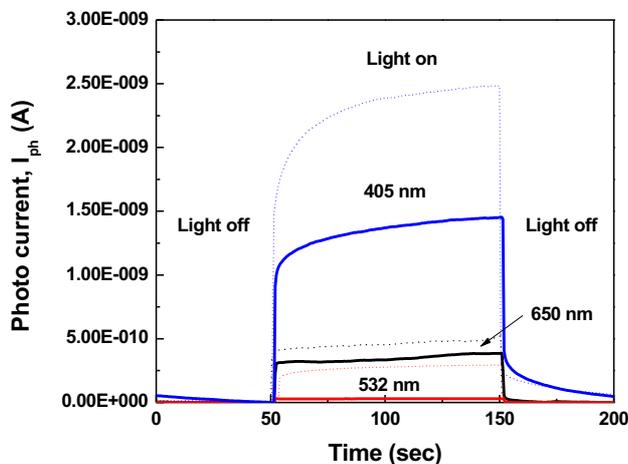


Fig. 2 The time response drain photocurrent I_D of OPT.

The rising time constant and the falling time constant of photocurrent (PC) effect are two critical parameters to realize the photo current generation and recombination behavior as the times required for a channel. The rising time constant can be fitted from a bi-exponential growth equation:

$$I_{gen}(t) = A_1 e^{(-t/\tau_1)} + A_2 e^{(-t/\tau_2)} + I(0) \quad (1)$$

where A_0, A_1 , are positive constants, τ_1 is carrier generation time constant (fast rising time), and τ_2 is charge diffusion time constant (slow rising time). Calculated the Au NPs OPTs

carrier generation time constant from fitting are $\tau_1 = 0.55, 0.62, 0.66$ s illuminated wavelength 650, 532, 405 nm, respectively, which is slightly slower than without Au NPs ($\tau_1 = 0.33, 0.23, \text{ and } 0.30$ s). The carrier generation time constant represents the time of electron in LUMO (E_c) level and hole in HOMO (E_v) level were created as absorb the photon energy. As the carrier be excited and holes flow to drain due to external electric field and the carrier concentration in excited region is lower than nearby. Thus, a concentration degrade is formed force the high concentration charges in semiconductor diffusion to low concentration region. However, the diffusion rate is relative slower than photocurrent generation rate thus limits the magnitude of photocurrent generation as time goes on.

4. Conclusions

In summary, the OPTs with Au NPs was proposed to achieve enhanced photocurrent under light illuminated at three different light. Due to SPR, the enhancement in threshold voltage shift are about 11.90, 130.95, and 11.59% under wavelength 650, 532, and 405nm, respectively. It is found trap exist at the pentacene/Au NPs interface cause larger rising time and smaller falling time. The excited carrier recombination through Shockley-Read-Hall recombination process is attributed to this effect.

Acknowledgements

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References

- [1] N. Ai, Y. Zhou, Y. Zheng, H. Chen, J. Wang, J. Pei, Y. Cao, *Org. Electron.* **14** (2013) 1103.
- [2] A. El Amrani, B. Lucasb, B. Ratier, *Synth. Metals*, **161** (2012) 2566.
- [3] P. M. Hansen, V. K. Bhatia, N. Harrit, L. Oddershede, *Nano Lett.* **5** (2005) 1937.
- [4] L. Bosanac, T. Aabo, P. M. Bendix, L. B. Oddershede, *Nano Lett.* **8** (2008) 1486.
- [5] G. Konstantatos, M. Badioli, L. Gaudreau, J. Osmond, M. Bernechea, F. P. G. de Arquer, F. Gatti, F. H. L. Koppens, *Nat. Nanotechnology*, **7** (2012) 363.
- [6] M. S. Tame, K. R. McEnery, S. K. Özdemir, J. Lee, S. A. Maier, M. S. Kim, *Nat. Phys.* **9** (2013) 329.
- [7] X. Yang, W. Liu, M. Xiong, Y. Zhang, T. Liang, J. Yang, M. Xu, J. Ye, H. Chen, *J. Mater. Chem. A*, **2** (2014) 14798.
- [8] J. Miao, W. Hu, Y. Jing, W. Luo, L. Liao, A. Pan, S. Wu, J. Cheng, X. Chen, W. Lu, *small*, **11** (2015) 2392.
- [9] S. H. Yuan, Z. W. Pei, H. C. Lai, C. H. Chen, P. W. Li, Y. J. Chan, *Electron Device Lett.* **36** (2015) 1186.
- [10] Y. Y. Noh, D. Y. Kim, *Appl. Phys. Lett.* **86** (2005) 043501.
- [11] H. A. Atwater, A. Polman, *Nat. materials*, **9** (2010) 205.