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Pentacene phototransistor with gate voltage independent responsivity and sensitivity by small silver nanoparticles decoration

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ABSTRACT

In this study, a Pentacene phototransistor (PT) decorated with silver nanoparticles (Ag-NPs) in bottom gate structure was demonstrated. With the ultra-small Ag-NPs, this device exploits surface plasmon resonance at 445 nm and established a stable surface conduction channel under light illumination. Therefore, the PT exhibit gate voltage independent responsivity and photosensitivity in broad range of gate voltage. The light-induced magnetized in ultra-small Ag-NPs that generate polarized surface electrons were used to explain the gate-voltage independent photocurrent. The maximum photosensitivity and responsivity are 2.1×10^3 and 17.7 mA/W, respectively, under white-light illumination. They are enhanced around 25 times at gate voltage of 20 V than conventional phototransistor. This device may be used in flexible optical interactive display, white-light indoor communication, or optical sensors.

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1. Introduction

Organic optoelectronics have attracted much attention in recent years for it is potentially for flexible applications with low cost. The reasons are organic optoelectronic devices could be made on the plastic substrate by variety of coating methods at low temperature with large scale. Among all optoelectronic devices, photodetector is a unique device that converts optical signal into electrical current in optoelectronic systems, such as receiver in optical communication, image plate for flat-panel X-ray radiography and optical sensors in interactive display. In general, a complicate and high-gain circuit is required to amplify the small optoelectronic signal in a photodetector. A simplified device design is required for organic optoelectronic to enable ease of manufacturing in low cost by large scale printing method. Therefore, a phototransistor (PT) consisting of a photosensitive semiconductor that could combine light detection and signal amplification in one device has attracted considerable attention [1]. Pentacene is one of the most preferred organic semiconductor (OSC) materials for its high field-effect mobility, bio-friendly, light sensitive and environmental stability.

The pentacene-based PT has been investigated regarding wavelength-dependent sensitivity [2], the effect of light intensity [3], size of active area [4], effect of gate dielectric [5], and bias stress reliability [6]. Due to the thin absorption thickness, the performance of Pentacene PT is hard to be enhanced. In addition, the PT can not achieve high sensitivity and high responsivity simultaneously. For instance, the PT can be operated either in an “off” state (in which the PT exhibits low current under dark conditions) [7] or in an “on” state (in which the PT exhibits high current under dark conditions) [8]. Off-state operation generally exhibits high photosensitivity, low responsivity. By contrast, on-state operation exhibits high responsivity but low photosensitivity. Furthermore, in both operation schemes, the responsivity is voltage-dependent. A small variation in operation voltage will cause large deviation in responsivity, and hence the photocurrent. Even though the performance of Pentacene-based PT had been investigated, further improvement to achieve high and stable responsivity and photosensitivity simultaneously within a broad voltage range is crucial for applications.

Recently, surface plasmon resonance (SPR) initiated by metal nanostructure has provided a unique setting for manipulating light by confining the electromagnetic field to a dimension substantially below the diffraction limit [9]. As a consequence, strong and enhanced local electromagnetic field with the presence of silver nanoparticles (Ag-NPs) [10] causes the phenomenon of optical

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trapping were demonstrated. As mentioned above, the metal nanoparticles decorated on top of semiconductor to initiate plasmon were well studied. Metallic particle was worked as an antenna that interacts to the incoming light either by plasmonic resonance [11] or by scattering, especially Rayleigh scattering [12]. However, the interaction of light with organic semiconductor decorated with ultra-small metallic nanoparticles in an optoelectronic device are rarely reported.

In this work, we applied ultra-small Ag-NPs to decorate a bottom-gated Pentacene transistor, in which the SPR in metal nanoparticles establish an anomalous, but useful gate independent high photosensitivity and high responsivity simultaneously in a pentacene PT. Several size distributions for Ag NPs were used. They were investigated by scanning electron microscopy (SEM). And, the surface plasmon effect was evaluated by the transmittance spectra. Pentacene phototransistors with different size of Ag NPs decoration were also made and explored for comparison.

2. Experimental

A schematic diagram of the proposed Ag-NP-decorated pentacene PT in a bottom-gate structure on a glass substrate is shown in Fig. 1(a). A layer of poly(methyl methacrylate) (PMMA) (Mw = 120,000) was used as a gate dielectric. The gate material was Ag, deposited on a glass substrate through a shadow mask by a thermal evaporator in a thickness of 40 nm. The PMMA was dissolved in n-butyl acetate with a concentration of 92 mg/mL as a precursor solution. After being stirred overnight, the solution was spin-coated on the Ag gate at 2000 rpm for 30 s. The PMMA layer was dried on a hot plate at 160 °C for 30 min. The thickness of the PMMA was approximately 650 nm. After the application of the polymer gate dielectric, the pentacene active layer, in 100 nm thick, was deposited through a shadow mask from thermal evaporator. The pentacene was obtained from Sigma–Aldrich and was used as received. The Ag was used for both source and drain electrodes deposited through an associated shadow mask in 120-nm thick. In the final step, the Ag-NPs were deposited by thermal evaporation. During the Ag evaporation, the Ag will form separated islands before it connect into a film. Therefore, the Ag-NPs silver nanoparticle is formed by the nominal deposition thickness of 0.5, 1.0, 2.0, and 4.0 nm. To get Ag-NPs, the extremely slow deposition rate about 0.004 Å/s is used. The channel length (L) and channel width (W) of the pentacene PTs were 200 μm and 1000 μm, respectively. A large channel area enables light coupling. The electrical characteristics of the pentacene PTs were measured using an Agilent 2192 semiconductor-parameter analyzer in a dark environment. The light source for photocurrent measurement was a white light-emitting diode (LED) array (THORLAB LIU104) to simulate the interactive display. The absorption spectrum of Ag-NPs on pentacene was measured using a Hitachi U-3300 spectrophotometer.

3. Results and discussion

The absorption spectra of pentacene decorated with Ag NPs are shown in Fig. 1(b). In general, strong absorption was found between 500 and 700 nm for pentacene. With Ag-NPs decoration, the absorption at approximately 445 nm was largely enhanced for all Pentacene with different thickness of Ag. The enhancement factor was defined as the absorbance of Ag-NP-decorated pentacene to the absorbance of pentacene. Fig. 1(c) shows the enhancement factor, which is approximately 1.6 at 445 nm owing to the plasmon-resonance of the Ag-NPs. For comparison, the spectrum of white LED was also shown. The enhancement factor increased with the increased of the Ag thickness. For 4 nm thick Ag, the enhancement factor is over 4 at 440 nm. The samples with either 2 or 4 nm thick

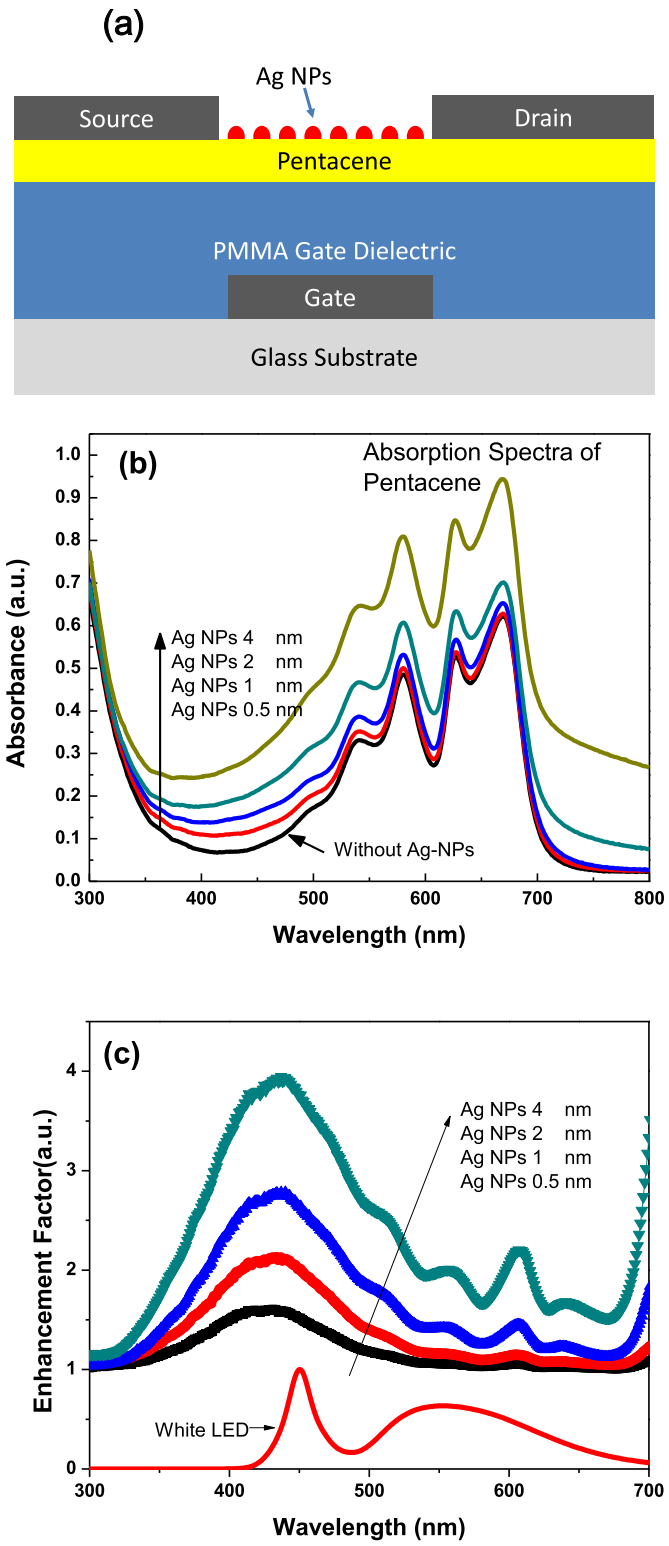

Fig. 1. The device structure and optical properties of Ag-NPs decorated Pentacene PT. (a) The schematic structure of Ag-NPs decorated pentacene phototransistor, (b) the absorption spectrum of Pentacene with 0, 0.5, 1, 2, and 4 nm thick Ag layer, and (c) absorption enhancement factor of Ag-NPs decorated Pentacene and the emission spectrum of the white light LED.

Ag layer exhibit broad range of enhancement in addition to around 440 nm, which is probably due to the cavity effect. The almost fully Ag covered Pentacene surface by 4 nm thick Ag was found by SEM

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