Visible light detection using single-walled carbon nanotube film and gold nanoparticles or nanorods

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Visible light detection using single-walled carbon nanotube film and gold nanoparticles or nanorods

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Visible light sensing devices using single-walled carbon nanotube (SWNT) film and gold nanoparticles or nanorods were reported. In the devices, half of the SWNT film was decorated with gold nanoparticles or nanorods. When visible light is incident on the device, a temperature difference can be built up between the SWNT film with and without gold nanoparticles (nanorods) due to surface plasmon resonance. As a result, an open circuit voltage can be obtained. The *Voc* induced and responsivities of these devices are closely related to the wavelength and the intensity of the incident light, indicating the application in visible light detecting. © *2010 American Institute of Physics*. [doi:10.1063/1.3418440]

I. INTRODUCTION

The conversion of visible light into electrical signals plays a central role in processes such as image acquisition and video acquiring.[1–4] Single-walled carbon nanotube (SWNT) has unique structure and its outer surface is highly sensitive to the local environments,[5–7] and its characteristics as chemical sensors has been extensively studied. In order to detect optical signals, devices with SWNTs can be functionalized with light-absorbing chemical or biological materials.[8–10] When visible light is incident on the device, the electrical properties (resistance, etc.) of SWNTs will change, which can be used to detect light. Recently, St-Antoine *et al.*[11] have shown that a thin film of pure SWNT can be used as a photothermoelectric device, in which the energy of light can be transferred into electrical signals of voltage. This kind of light detection device has the advantage of external electrical power source independent since the detection is based on the induced voltage by incident light. Meanwhilt, the device proposed by St-Antoine *et al.* is not sensitive to the wavelength of the incident light and in some positions the voltage will restore to zero in spite of the light. In this work, we report an improved design of SWNT film with partly decoration of gold nanoparticles (NPs) or nanorods (NRs). Because of the efficient heat generation of gold NPs or NRs,[12,13] which is dependent on the wavelength and intensity of incident light, the device with SWNT film and gold NPs (NRs) shows the advantage of detecting both the color and intensity of the incident light.

II. EXPERIMENTS

The Au NRs and NPs were synthesis by seed-mediated growth.[14–16] It is mainly divided into the two following steps: the fabrication of Au seeds and the fabrication of Au NRs and NPs. The Au seeds were synthesized by chemical reduction in $HAuCl_4$ with $NaBH_4$; 7.5 ml CTAB (Cetyl trimethylammonium bromide, 0.1 mM) aqueous solution was mixed with 100 μl of $HAuCl_4$(24 mM) and diluted with water to 9.4 ml. Then, 0.6 ml ice-cold $NaBH_4$ (0.01 M) was added while stirring magnetically. After 3 min, the stirring was stopped and the seed solution was kept undisturbed at room temperature for 30 min prior to any further experimentation. The growth solution of Au NRs with aspect ratio of 2 was prepared by gently mixing CTAB (100 ml, 0.1 M), $HAuCl_4$(2.04 ml, 0.024 M), H_2SO_4(2 ml, 0.5 M), $AgNO_3$(0.4 ml, 10 mM), and AA (800 μl, 0.1 M) together at room temperature. 240 μl seed solution was added to the above growth solution to initiate the growth of the Au NRs. $AgNO_3$ played a key role in regulating the growth of Au NRs, the Au nanospheres were prepared in the absence of $AgNO_3$. After 12 h, the Au NRs and NPs were purified by centrifugation (12 000 rpm for 10 min). The precipitates were collected and redispersed in de-ionized water for further use. To get gold NRs or NPs with narrower dispersion of size and shape, the solution of gold NPs or NRs was kept still for several days and then the upper part of the solution was picked up for this experiment. The SWNT film used in this work were synthesized by floating catalytic chemical vapor deposition.[17,18] A rectangular piece of SWNT film (4.5×10 mm^2) was placed upon a glass slide and two aluminum adhesive tapes were used as the electrodes and to fix the SWNT film (Fig. 1). Usually 2–3 droplets (~40 μl) of aqueous gold nanostructures solution with concentration of 3×10^{14} nanoparticles/1 were dropped on the right part of the SWNT film and dried at room temperature of 25 °C, which is important to obtain uniform distribution of NPs or NRs for at higher temperature, the NPs or NRs tend to be clustered together. A typical optical image of the device is shown in Fig. 1(a). The SWNT film (left part) can be readily identified from that decorated with NPs or NRs from the color contrast [Fig. 1(a)]. Figures 1(b)–1(d) show the SEM (scanning electron microscopy, Hitachi S-4800) images of

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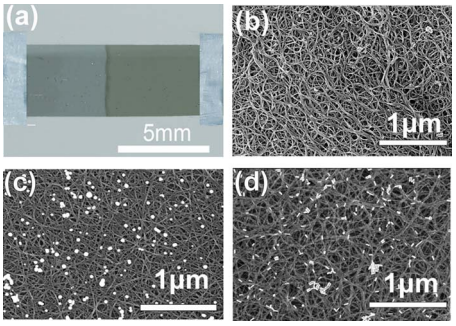

FIG. 1. (Color online) Optical and SEM image of the light detection device. (a) Optical image of the device. The left and right parts correspond to SWNT film without or with gold NPs, respectively. The boundary can be clearly seen at the middle. (b) Typical SEM image of SWNT film before the deposition of gold NPs. (c) Typical SEM image of SWNT film decorated with gold NPs. (d) Typical SEM image of SWNT film decorated with gold NRs.

SWNT film, SWNT film decorated with gold NPs and SWNT film decorated with gold NRs. From the images, gold NPs with average size of 40 nm and NRs of 40 nm(length)×20 nm(diameter) randomly distributed on the SWNT film with uniform dispersion can be observed, respectively.

The device was connected to Keithley 4200 (voltage resolution ~1 μV) and its electrical properties were studied under the illumination of light with different wavelengths. The light source is Xe lamp and bandpass filter (410–690 nm) with transparency as high as 95% was used to pick white light with energy density of 0.16 W/cm^2 To obtain red, green, and blue light, filters with band width of 80 nm and transmittance of 85% were used and the intensity of each light was 0.045 W/cm^2.

III. RESULTS AND DISCUSSION

For devices of SWNT with gold NPs, the current-voltage (*IV*) curve is shifted to the left with no observable slope change upon illumination of white light, indicating no change in resistance and the inducing of an open circuit voltage (*Voc*) [Fig. 2(a)]. The dynamic characteristics of the *Voc* is studied and shown in Fig. 2(b). It can be seen clearly that under the illumination of white light (bottom), a negative *Voc* of about 50 μV can be generated in about 2 s and remain stable upon illumination. When the light is turned off, the *Voc* will restore to its original value in a similar period of time. If the intensity of white light is reduced by half using a circular polarizer, the induced *Voc* decreases to a value of 20 μV. The circular polarizer was used to exclude the possible influence of the polarization of the incident light on the voltage generated. Similar results can be obtained when the color of the light is switched to red (610–690 nm), green (510–590 nm), and blue (410–490 nm), which are also shown in Fig. 2(b). The decreasing in the induced *Voc* shows that the *Voc* is dependent on the intensity of the light. By comparing *Voc* by light with different wavelengths, we can see that for device decorated with gold NPs, the *Voc* generated by green light is larger than that by red light, showing the dependence of the *Voc* on the wavelength of the incident light. The *Voc* generated by blue light is the smallest.

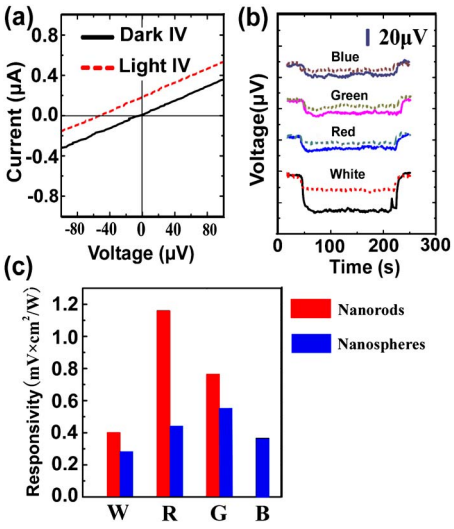

FIG. 2. (Color online) (a) *I-V* curve of the device with and without illumination of white light. (b) Dynamic characteristics of the induced *Voc* for devices decorated with gold NPs when the light is turned on and off. From top to bottom, the light corresponds to blue, green, red, and white, respectively. The two curves in each group corresponds to the full and half power of the incident light. There are offset in these curves for clarity. (c) Comparison of the responsivities for devices with gold NPs or NRs.

The sensitivity cannot be used to characterize our light detecting devices since the change in resistance of these devices is too small to be observed [Fig. 2(a)].[19] Thus, responsivities rather than sensitivity of the these devices were calculated in a similar way to that of Liu and Zhang.[20,21] For example, to white light (wavelength 410–690 nm) of Xe lamp, *Voc* of 50 μV can be obtained at energy density of 0.16 W/cm^2. Then we can get the responsivity to the white light of about 0.31 mV cm^2/W. We also calculated the responsivities of other lights and the results are plotted in Fig. 2(c).

The characteristics of the device are also studied when the gold NPs are replaced by gold NRs. The corresponding responsivities are plotted in Fig. 2(c). It is interesting to note that the responsivity to the red light is larger than that for green light with gold NRs devices, which is contrary to that for devices with gold NPs.

The mechanism of these observations, we propose, is schematically showed in Fig. 3. When the light is incident on the SWNT film, the light can be absorbed both by the SWNTs and gold NPs or NRs. In the part of SWNT film that is decorated with gold NPs or NRs, more light would be absorbed through surface plasmon resonance. This results in a temperature difference between the two parts of SWNT film with and without gold NPs. Figure 3(b) shows the dynamic characteristics of temperature for devices with gold NRs or NPs. It can be seen clearly that the temperature of SWNT film without NPs will increase by about 0.7 °C; while the temperature of SWNT film with NPs will increase by about 1.5 °C. This temperature difference can induce a *Voc* in the devices because of thermo electrical properties of SWNT film.[22]

For gold NPs or NRs, their absorbance spectra are different as shown in Fig. 3(c). There is only one peak centered at ~540 nm in the absorbance for gold NPs; while there are

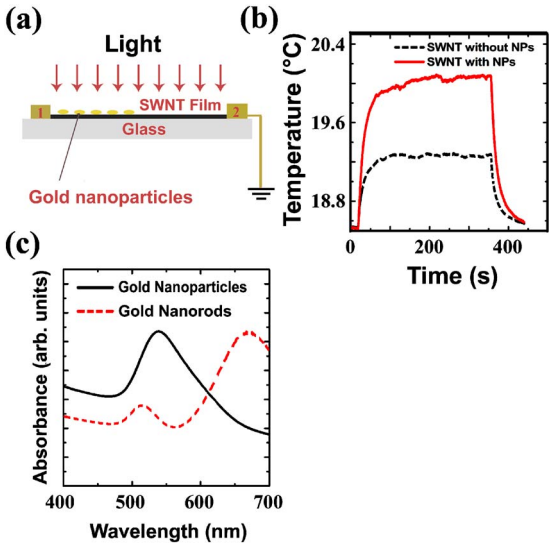

FIG. 3. (Color online) (a) Schematic showing the mechanism of the induced *Voc*, which is due to the temperature difference between the SWNT film and that film with gold NPs or NRs. (b) Experimental results of the temperature for the two parts when white light is on and off. A clear difference can be observed when light is turned on and this difference disappears when the light is turned off. (c) The absorbance spectra of gold NPs and NRs.

two peaks centered at 515 and 675 nm in the absorbance for gold NRs. This is the reason why the responsivity of 0.55 mV cm^2/W for green light is larger than that of 0.48 mV cm^2/W for red light in the devices decorated with gold NPs. For devices decorated with gold NRs, the red light is preferentially absorbed than green light [Fig. 3(c)]. Therefore, the responsivity for red light (1.16 mV cm^2/W) is larger than that for green light (0.76 mV cm^2/W). From Fig. 2(c), it can be seen that the responsivities of device decorated with gold NRs are higher than those with gold NPs and the white light has the smallest responsivities. The possible reasons may include different absorbance behaviors and quite different contact area between SWNT with individual NPs or NRs. The longitude direction of NRs is usually parallel to the axial of SWNTs, which results in a larger contact area and efficient heat transfer from NRs to SWNT, which can induce a larger temperature difference and *Voc*.

IV. CONCLUSIONS

In summary, we have demonstrated that SWNT films with partly decorated with gold NPs or NRs can be used to detect visible light. The detection is based on the induced *Voc* by the incident light. Comparing to those light devices reported before, which are based on the change in resistance or characteristics of field effect transistor, this *Voc* based technique shows the advantage of no external power source and capability of scaling down to smaller scale.

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