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Asymmetrically Contacted Carbon Nanotubes and Their Photovoltaic Properties

Sheng Wang and Lian-Mao Peng

Department of Electronics, Peking University, Beijing 100871, China

Semiconducting single-walled carbon nanotubes (SWCNTs) are 1D and direct band gap materials with unique electric and optical properties, and are promising candidates for future nano-electronics and optoelectronics [1]. The use of carbon nanotube (CNTs), nanowires and other nanomaterials represents a typical approach to reduce both cost and size and to improve efficiency in photovoltaic application. In a typical optoelectronic device, a build-in field is essential for effectively separating photon excited electron-hole pairs and for observing photovoltaic effects. In a p-n junction, the maximum achievable photovoltage is determined by the energy level difference between that of the donors (in the n-region) and acceptors (in the p-region), and typically this is smaller than the energy bang gap E_g of the corresponding intrinsic semiconductor. On the other hand, a Schottky barrier (SB) between the metal electrode and semiconductor may also provide the required field for separating electrons and holes. But again the SB will reduce the maximum achievable photovoltage. Here we consider a recently developed new device, i.e. barrier-free bipolar diode (BFBD) [2]. The BFBD consists of an intrinsic SWCNT which is asymmetrically contacted with Pd and Sc [Fig. 1(a)]. It has been shown that carriers can be injected, barrier freely, into the valence band of the CNT from the Pd contact [3] and into conduction band from Sc contact [4]. Since neither SB nor sharp p-n junction exist in the BFBD [2], in principle a maximum photovoltage which is ultimately determined by the band-gap of the CNT may be obtained for a given SWCNT with this device geometry.

The BFBD device exhibits a typical diode rectifying I-V characteristic [Fig. 1(b)]. When a large forward bias is applied [schematic A of Fig. 1(c)], both electrons and holes may be injected into the CNT channel barrier freely. This diode acts therefore as a barrier-free bipolar diode (BFBD). At zero or small bias, e.g. as shown in schematic B of Fig. 1(c), the current is dominated by thermionic electrons and holes current. The potential barrier for both types of carriers is basically equal to the band gap of the CNT Eg.When the bias is increased beyond V~Eg, the current is no longer limited by the potential barrier near the Pd contact for electrons and that near the Sc contact for holes. Instead the electron (hole) injection is now limited by a barrier of ~Eg/2 near the Sc (Pd) contact [see schematic B of Fig. 1(c)]. For reverse bias [schematic C of Fig. 1(c)], the dark current is first dominated by thermionic current over the potential barrier ~Eg near Pd (Sc) contact for electrons (holes). At larger bias, the barrier for the carrier injection is thinned and tunnelling current starts to dominate at point D [schematic D of Fig. 1(c)] of Fig. 1(b) with V<-1.5V.

The device responses to the infrared laser beam [Fig. 2(a)]. Figure 2(b) shows the dependence of both open circuit voltage V_{OC} and short circuit current I_{SC} on the illumination power. For a power density lower than 45kW/cm^2, I_{SC} varies linearly with the power density, but starts to saturate for larger density. This is because larger illumination power may lead to higher sample temperature which in turn results in higher recombination rate of the photogenerated e-h pairs. V_{OC}, on the other hand, follows a logarithmical dependence with the illumination power density for small power density and begins to saturate at about 45kW/cm^2[5].

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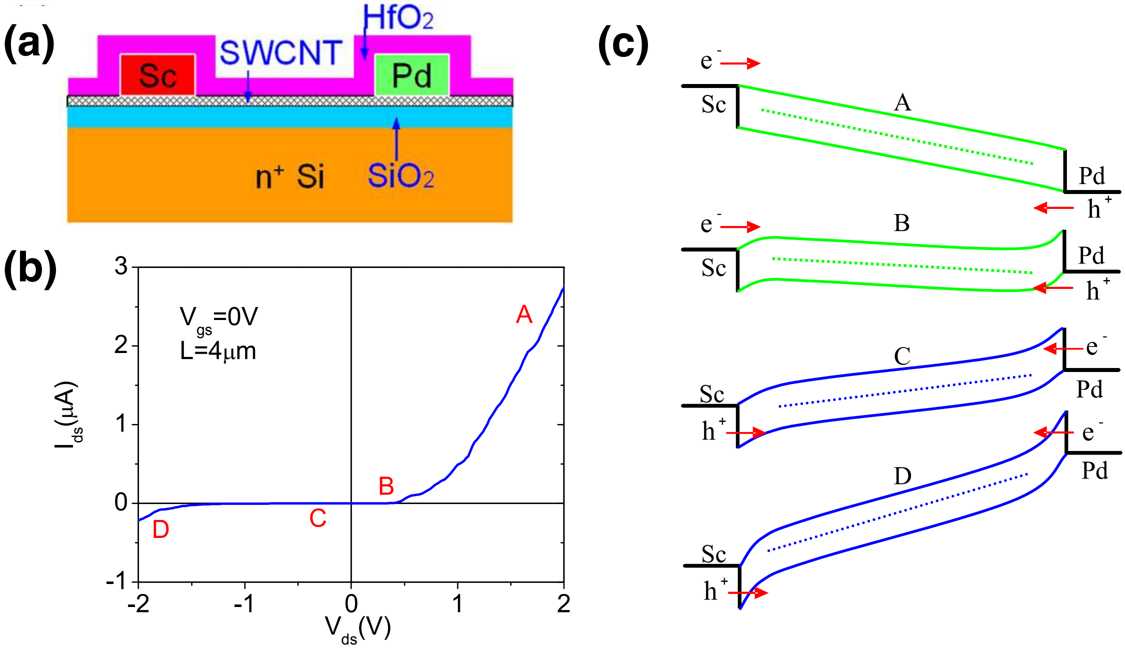

FIG. 1. (a) Schematic diagram showing a BFBD device. In the real device, the diameter of the SWCNT channel is about 1.5nm, which is laid on a 500nm $SiO_2$and contacted by Sc and Pd electrodes. The inter electrodes distance is about 800nm. (b) Room-temperature I–V characteristic of the BFBD device, showing rectifying diode characteristics. (c) Energy band diagrams corresponding to the four points A, B, C, and D of (b), respectively.

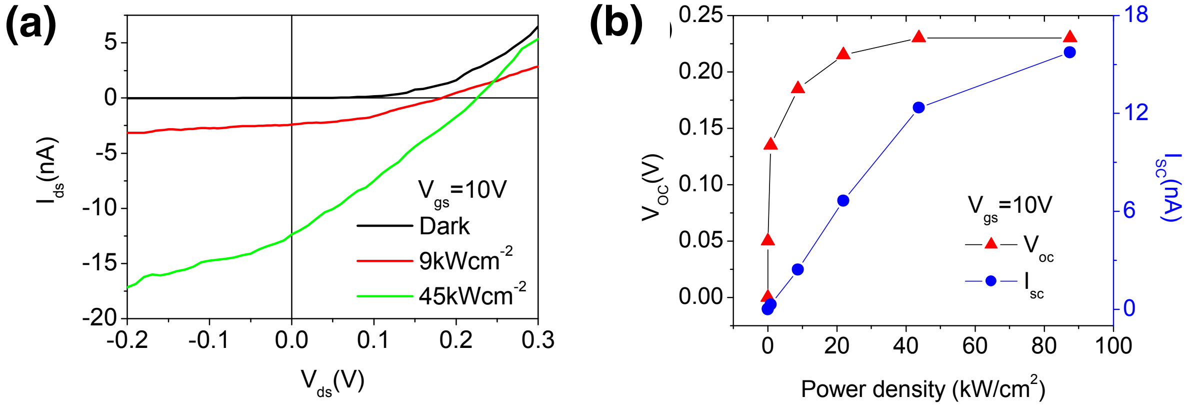

FIG. 2. (a) I-V characteristics measured in the dark and under illumination at V_{gs}= 10V, showing a progressive shift into the fourth quadrant (PV effect) with increasing light intensity. (b) Photocurrent and photovoltage as a function of the illuminated laser power density at V_{gs}=10V.