Optoelectronics in Carbon Nanotube Photodiodes and Graphene Hetero-Interface Devices

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Abstract:
The excellent thermal, electronic and optical properties of carbon nanotubes (NTs) and graphene strongly motivate the use of these materials in optoelectronic devices. Here, we review our recent investigations of NT and graphene optoelectronic devices. By studying individual NT and graphene devices, we aim to uncover novel physical phenomena and establish a foundation for future applications in carbon nanoelectronics. We present photocurrent measurements of NT gated p-n junctions and graphene hetero-interface field effect transistors. In NTs, we observe dramatic photocurrent gain at high photon energies that we attribute to multiple electron-hole pair generation. In graphene, we observe pronounced photocurrent generation at the interface between single and multi-layer graphene as well as at the interface between suspended and unsuspended graphene sheets.

Summary of Research:
The NT p-n junction devices (Figure 1) consist of individual NTs in a split-gate field effect geometry. Three independent gates, \( V_1 \), \( V_2 \), and global back gate \( V_G \), allow selective electrostatic doping along the length of the NT. By applying voltages of opposite polarities on \( V_1 \) and \( V_2 \), a p-n junction is realized, which yields a built-in electric field \( E \) along the length of the nanotube. Photo-generated electron hole-pairs created in the junction are separated by the built-in potential and accelerated to the device contacts, leading to photocurrent at zero bias.

Current-voltage characteristics are measured while the p-n junction is illuminated at low temperatures. Figure 2 shows \( I-V_{SD} \) data at 60 K under illumination at several photon energies (labeled). As the photon energy is increased, we observe very striking behavior. The reverse-bias photocurrent increases with increasing photon energy and evolves into a series of steps with increasing reverse bias. By combining spatially and spectrally-resolved photocurrent measurements, we attribute these photocurrent steps to highly efficient particle-antiparticle creation by high-energy charge carriers in the
second nanotube subband. In the particle-antiparticle creation process requiring the lowest excess energy, the excess subband energy of the second subband carriers is combined with the kinetic energy of the electric field to create a low energy carrier plus electron-hole pairs. This process occurs with extremely high efficiency for electrons and holes leading to large photocurrent increases in the device characteristics. The electron-hole pair production process observed here may make possible increased power conversion efficiency in future photovoltaic devices and our results show that multiple electron-hole pairs can be generated and collected in a NT p-n junction device.

Graphene transistor devices consist of single- and multi-layer graphene sheets configured into gated field effect transistors (Figure 3). We prepare the graphene sheets by mechanical exfoliation method. After peeling the Kish graphite with Scotch tape, we rub the graphene sheets onto a 90 nm SiO2 on n+ silicon substrate. We use standard photolithography to pattern the electrodes (Au (250 nm)/Cr (5 nm)). Figure 3(a) and 3(b) are microscope images of graphene transistors formed by monolayer and bilayer graphene and by suspended and unsuspended monolayer graphene, respectively.

The experimental setup is illustrated in Figure 3(c). Using the n+ silicon substrate as a backgate, we adjust the Fermi level of the graphene. Continuous wave laser light at 635 nm is focused on the graphene device by a microscope objective. Photocurrent images are obtained by spatially sweeping the laser. The spatial position of the photocurrent is correlated to the reflection image of the device, which is formed by measuring the reflected laser intensity.

The obtained photocurrent images at room temperature are shown in Figure 4. Figure 4(a)-(c) shows reflection, photocurrent and overlay images for the monolayer/bilayer interface device, respectively. Besides the photocurrent generated at the metal contact-graphene interface, we observe the photocurrent generation from the graphene single-layer/bi-layer interface. Figure 4(d)-(f) show the reflection, photocurrent, and the overlay images of the suspended monolayer device for which graphene is suspended over a hole of ~ 4 µm. We observe clear photocurrent generation at the suspended-unsuspended interface.

In the graphene gated field effect transistors, we can tune carrier doping from electron doping to the hole doping by varying the backgate voltage from positive to negative. Surprisingly, we observe that the photocurrent exhibits a clear sign change (switching from negative to positive) at the graphene interface junctions as we tune from electron to hole doping. The detailed mechanism of this sign switching is not fully understood. Further measurements and theory are in progress.

Interestingly, we also observe dramatic increase of the photocurrent amplitude as we cool the graphene devices to low temperatures (T = 10 K). The observed temperature dependence (not shown) may indicate that phonon scattering plays an important role in the photocurrent generation and will be the focus of future experiments.

In summary, we have reviewed recent results of optoelectronic measurements on carbon nanotube and graphene nanoelectronic devices. In NT p-n junctions, we observed photocurrent characteristics which suggest that a single photon is converted into multiple electron-hole pairs. In graphene transistors, we observe photocurrent generation at both the graphene single-layer/bi-layer interface and suspended/unsuspended interface. We observe anomalous increase of the photocurrent amplitude at low temperatures and demonstrate the control of the photocurrent polarity by controlling the carrier doping in the graphene. This work has shown that advanced device geometries incorporating carbon based nanomaterials may reveal novel optoelectronic processes that will have applications in future photodetector and photovoltaic technology.