Abstract

Hybrid structures involving atomic/molecular membranes from two or more layered materials are emerging as a platform for novel class of field effect transistors (FETs), $p-n$ junctions, photo-detectors, photo-voltaic devices and so on. The interface formed by dissimilar materials gives rise to new functionalities, which are otherwise unattainable with individual constituent species. In addition to enormous potential in device application, these hybrid devices have raised several fundamental questions, especially in the context of inter-layer transfer of charge when subjected to external electric field, optical excitation *etc.* It is essential to explore the microscopic nature of the interface, which plays a significant role in efficient charge transfer dynamics from one material to the other. Moreover, the accumulation of charge carriers at the interface can control the optical properties of the individual materials by modifying their band structures as well as energetics of the fundamental excitations, namely, excitons or trions, which are now generating great interest.

The hybrid photo-detector is one such class of device, which is becoming popular because of its direct application to various fields as well as novel scientific research purposes. A single layer graphene has traditionally been of great interest for photo-detection due to a strong radiation coupling over a broad wavelength spectrum ($\sim 0.3-6$ μm). Although the sensitivity of these bare graphene devices are comparatively poor because of its low optical absorption ($\sim 2\%$) of electromagnetic radiation. In order to overcome this issue, graphene-based hybrid structures (made of graphene with an optically active material) are being investigated, which are relatively new and innovative. When the optically active material is irradiated using an optical source, electron and hole pairs are generated, out of which one species of the charge carriers gets collected in graphene. Because of high carrier lifetime in graphene, most of these graphene-based hybrid devices reach remarkably high sensitivity. In this thesis, our main objective will be to investigate the charge transfer mechanism from the optically active material to graphene *via*

opto-electronic measurement. This work has been divided into two parts:

In the first part, we look into the opto-electronic response in graphene - WSe_2 (Tungsten diselenide) hybrid structure. WSe_2, a member of transition metal dichalcogenides (TMDC) family, is also a two-dimensional van der Waals material. By fabricating a hybrid structure made of single layer graphene and single layer WSe_2, we achieve significantly high photo-responsivity value ($\sim 10^{10}$ AW^{-1}). While taking the photo-current spectra by sweeping the excitation wavelength (λ) from $550 - 800$ nm, we find that both the photo-response (ΔR) and the relaxation time (τ) are sensitive to the signatures of both A and B excitonic peaks (at 712 and 570 nm respectively) of WSe_2. By using a coherent charge transfer model, we find that graphene - WSe_2 hybrid structure forms a new coherent ground state for the excitons by transferring electrons into graphene and keeping holes in WSe_2. The slow relaxation in the time scale has been explained by incoherent back transfer of charge from graphene to WSe_2. We have also found an alternative method to calculate the binding energy of the excitons from the photo-current spectra.

In the second part, we investigate the photo-response of uniformly dropcast TeNW (Tellurium nanowire) on graphene in the near infra-red (NIR) regime ($920 - 1720$ nm). We start with the basic opto-electronic characterization in bare TeNW, and find that TeNW because of its low band gap indeed shows infra-red detection. But the sensitivity of such devices is very poor ($\sim 10^{-2}$–10^{-4} AW^{-1}). On the other hand, photo-responsivity in graphene - TeNW hybrid device exceeds $\sim 10^{6}$ AW^{-1} at 175 K. The corresponding specific detectivity ($\sim 10^{13}$ Jones) reaches the highest order of magnitude reported for infra-red detectors. The charge transfer from TeNW to graphene is dominated by photogating mechanism, which gets suppressed at high temperature because of conduction through the TeNWs. This sets the upper limit for the operating range of temperature, which can still be improved by controlling the defect density and inter-wire electronic coupling.

In summary, our experimental results open up a new direction to investigate the charge transfer dynamics as well as the nature of the interface between the materials in a hybrid structure at the microscopic level. The understanding of light-matter interaction at the atomic scale will impact now opto-electronic designs as well as hybrid materials with unprecedented functionality.