

Graphene nano-devices and nano-composites for structural, thermal and sensing applications

by

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ABSTRACT

In this dissertation we have developed graphene-based nano-devices for applications in integrated circuits and gas sensors; as well as graphene-based nano-composites for applications in structures and thermal management. First, we have studied the bandgap of graphene for semiconductor applications. Graphene as a zero-bandgap material cannot be used in the semiconductor industry unless an effective method is developed to open the bandgap in this material. We have demonstrated that a bandgap of 0.206 eV can be opened in graphene by adsorption of water vapor molecules on its surface. Water molecules break the molecular symmetries of graphene resulting in a significant bandgap opening.

We also illustrate that the lack of bandgap in graphene can be used to our advantage by making sensors that are able to detect low concentrations of gas molecules mixed in air. We have shown that 1-2 layers of graphene synthesized by chemical vapor deposition enables detection of trace amounts of NO₂ and NH₃ in air at room temperature and atmospheric pressure. The gas species are detected by monitoring changes in electrical resistance of the graphene film due to gas adsorption. The sensor response time is inversely proportional to the gas concentration. Heating the film expels chemisorbed molecules from the graphene surface enabling reversible operation. The detection limits of ~100 parts-per-billion (ppb) for NO₂ and ~500 ppb for NH₃ obtained using this device are markedly superior to commercially available NO₂ and NH₃ detectors. This sensor is fabricated using individual graphene sheets that are exquisitely sensitive to the chemical environment. However, the fabrication and operation of devices that use individual nanostructures for sensing is complex, expensive and suffers from poor reliability due to contamination and large variability from sample-to-sample. To overcome these problems we have developed a gas sensor based on a porous 3D network of graphene sheets called graphene foam that is macroscopic and easy to mass produce. The walls of the foam are comprised of a few layers of graphene sheets resulting in high sensitivity. We demonstrate parts-per-million (ppm) level detection of NH₃ and NO₂ in air at room-temperature using this sensor. Further, the foam is a mechanically robust and flexible macro-scale network that is easy to contact (without lithography) and can rival

the durability and affordability of traditional sensors. Moreover, Joule-heating expels chemisorbed molecules from the foam's surface leading to fully-reversible and low-power operation.

In the second part of this dissertation the focus is on graphene platelets and their incorporation into polymer matrices to improve their mechanical and thermal properties. We demonstrate the synthesis and fatigue characterization of fiberglass/epoxy composites with various weight fractions of graphene platelets infiltrated into the epoxy resin as well as directly spray-coated on to the glass micro-fibers. Remarkably, only ~0.2wt.% of graphene additives enhances the fatigue life of the composite in the flexural bending mode by up to 1200-fold. By contrast, under uniaxial tensile fatigue conditions, the graphene fillers resulted in ~3 to 5-fold increase in fatigue life. In-situ ultrasound analysis of the nanocomposite during the cyclic fatigue test suggests that the graphene network toughens the fiberglass/epoxy-matrix interface and prevents the delamination/buckling of the glass micro-fibers under compressive stress. Such fatigue-resistant hierarchical materials show potential to improve the safety, reliability, and cost-effectiveness of fiber-reinforced composites that are increasingly the material of choice in the aerospace, automotive, marine, sports, bio-medical and wind energy industries.

We also investigated the effect of graphene platelets on thermal properties of Graphene/1-Octadecanol composite as a nano-structured phase change material (PCM) for energy storage applications. The liquid-solid phase change enthalpy, crystallization, and thermal conductivity of this composite were studied as a function of graphene content. The thermal conductivity (κ) of the nanocomposite increased by nearly 2.5-fold (~140% increase) upon ~4wt. % graphene addition while the drop in the heat of fusion (i.e. storage capacity) was only ~15.4%. The enhancement in thermal properties of 1-Octadecanol obtained with the addition of graphene is markedly superior to the effect of other nanofillers such as silver nanowires and carbon nanotubes reported previously in the literature. Boosting the thermal conductivity of organic PCMs without incurring a significant loss in the heat of fusion is one of the key issues in enabling their practical application as latent heat storage/release units for thermal management and thermal protection.