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14. ABSTRACT

This is a highly productive research project (12 papers in three years) aiming to understand the potential of conjugated polymer in a wide range of organic electronic devices – vertical transistors, solar cells and photodetectors, memory devices, as well as graphene. We demonstrate both evaporated small molecule and solution process polymeric vertical organic transistors in the project through nanoscale interface engineering. X-ray radiation degradation and recovery of polymer solar cell is observed and is encouraging for OPV application in space. Photomultiplication with high EQE is achieved by introducing interface carrier traps in both small molecule and polymer D/A systems, which has high potential for detector application. Working mechanism of organic memory devices is studied. Also we showed high quality transparent conductor based on chemically converted graphene and CNT composite. An easy transfer process is also developed to facilitate the application of graphene transparent electrode.

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Final Report

High performance vertical organic field effect transistors

Grant Number: FA9550-07-1-0264

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This is a highly productive research project (12 papers in three years) aiming to understand the potential of conjugated polymer in a wide range of organic electronic devices – vertical transistors, solar cells and photodetectors, memory devices, as well as graphene. The achievements are describes below.

1. Vertical transistors

Organic field-effect transistors have been the subject of much recent inquiry due to their unique properties. Especially the vertical structure provides a large cross section and a short channel length to counter the inherent limitations of the organic materials.

a. In this funding period, we first demonstrated an ambipolar vertical organic field-effect transistor,^[1] which consists of a capacitor cell vertically stacked with an organic active cell, separated by a thin source electrode. By inserting a nanoscale transition-metal-oxide layer at the source/organic interface, the authors fabricated the organic ambipolar transistors with low working voltage and high current output. The thin transition-metal oxide and partial oxidization metal grains form a unique nanostructure that balances the injection barrier height of two types of carriers at the source/organic contact.

b. Following the success of evaporated vertical transistor, we also successfully demonstrated the fabrication and operation of a solution-processed vertical organic transistor.^[2] By studying the device performance at different temperatures and in solvent environments, an operating mechanism that occurs via an ion drift and doping process was proposed. The drift direction of the dissolved Li⁺ ion can be controlled by altering the gate voltage bias in order to change the carrier injection barrier.

2. Organic solar cells & Photodetectors

The OPV related works in the funding period have the following highlights:

a. Working with Dr. Devine in Univ. of New Mexico, we studied the x-ray radiation induced damage of P3HT:PCBM based solar cell and for the first time observed a recovery of OPV performance after the radiation. The polymer solar cell device remained functional with exposure to a considerable dose (500 krad (SiO₂)) and showed clear signs of recovery upon removal of the irradiation source (degraded from 4.1% to 2.2% and recovered to 2.9%). The results suggest that organic solar cells could be sufficiently radiation tolerant to be useful for space applications

b. We studied the photomultiplication effect in both evaporated (pentacene/C60 bilayer) and bulk-heterojunction donor/acceptor systems. In pentacene/C60 bilayer system,^[4] we showed that both the disordered structure of C60 and the charge trapping effect at the C60 /PEDOT:PSS interface contribute to the photomultiplication effect, and further identified that photomultiplication induced by C60 disordered structure is much less significant than that by charge trapping at the interface. We also demonstrated that blending CdTe nanoparticles into a polymer–fullerene matrix^[5] followed by solvent annealing can achieve high photoconductive gain under low applied voltages. An external quantum efficiency (EQE) as

high as 8,000% at 350 nm was achieved at -4.5 V. It is believed that the nanoparticles and trapped electrons assist hole injection into the polymer under reverse bias, contributing to EQE values in excess of 100%. The high EQE value is very critical for photodetector application.

c. We demonstrated a vacuum free lamination fabrication process for OPV.^[6] An electronic glue-based lamination process combined with interface modification is presented as a one-step process for semitransparent polymer solar-cell fabrication. The finished device is metal free, semitransparent, flexible, self-encapsulated, and highly efficient (with a maximum external quantum efficiency of 70% and power efficiency of 3%).

d. Other works include: synthesized low bandgap silole-containing polymers for OPV application;^[7] and studied Anisotropy in Organic Single-Crystal Photovoltaic devices based on tetracene single crystals and C60.^[8]

3. Memory device

The third type of devices we studied is organic memory device.

a. We studied the charge transfer effect in the polyaniline-gold nanoparticle memory system.^[9] A composite system comprised of polyaniline nanofibers bonded with gold nanoparticles is shown to possess a memory effect via a charge transfer mechanism. The charge transfer occurs between the imine nitrogen in the polyaniline and the gold nanoparticles and is confirmed by x-ray photoelectron spectroscopy and Raman spectroscopy. This charge transfer enables a bistable electrical conductivity, allowing the material system to be used as a digital memory device.

b. We demonstrate a nonvolatile memory device having tristates, one OFF state and two different ON states in the metal-insulator-metal (MIM) structure.^[10] Detailed study has revealed that different switching mechanisms are responsible for these two stages of switching: filament formation is the dominant mechanism for switching from the OFF state to the lower ON state while Poole-Frenkel effect governs the switching from the lower-ON state to the higher-ON state.

4. Graphene

Graphene is a fantastic material for both fundamental research and electronic application.

a. We first report the formation of a nanocomposite comprised of chemically converted graphene and carbon nanotubes.^[11] Our solution-based method does not require surfactants, thus preserving the intrinsic electronic and mechanical properties of both components, delivering 240 Ω/sq at 86% transmittance. This low-temperature process is completely compatible with flexible substrates and does not require a sophisticated transfer process. We believe that this technology is inexpensive, is massively scalable, and does not suffer from several shortcomings of indium tin oxide.

b. We then investigated the application of graphene transparent electrode by demonstrating a soft transfer printing process that allows precise patterning of chemically converted graphene.^[12] The use of a polydimethylsiloxane (PDMS) stamp and surface energy manipulation resulted in successfully transferring spin-coated materials from one substrate to another. The method is capable of transferring sharp features to precise locations. This represents large-scale, high-throughput transfer printing of chemically converted graphene and paves the way for future complementary circuit design.

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