Engineered Carbon Nanotubes and Graphene for Nanoelectronics and Nanomechanics

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ABSTRACT

We are exploring nanoelectronic engineering areas based on low dimensional materials, including carbon nanotubes and graphene. Our primary research focus is investigating carbon nanotube and graphene architectures for field emission applications, energy harvesting and sensing. In a second effort, we are developing a high-throughput desktop nanolithography process. Lastly, we are studying nanomechanical actuators and associated nanoscale measurement techniques for re-configurable arrayed nanostructures with applications in antennas, remote detectors, and biomedical nanorobots. The devices we fabricate, assemble, manipulate, and characterize potentially have a wide range of applications including those that emerge as sensors, detectors, system-on-a-chip, system-in-a-package, programmable logic controls, energy storage systems, and all-electronic systems.

INTRODUCTION

A key attribute of modern warfare is the use of advanced electronics and information technologies. The ability to process, analyze, distribute and act upon information from sensors and other data at very high-speeds has given the US military unparalleled technological superiority and agility in the battlefield. While recent advances in materials and processing methods have led to the development of faster processors and high-speed devices, it is anticipated that future technological breakthroughs in these areas will increasingly be driven by advances in nanoelectronics. A vital enabler in generating significant improvements in
nanoelectronics is graphene, a recently discovered nanoelectronic material. The outstanding electrical properties of both carbon nanotubes (CNTs) [1] and graphene [2] make them exceptional candidates for the development of novel electronic devices. Ballistic electron transport in graphene could enable faster and smaller electrical devices and charge carriers that can be tuned continuously between electrons and holes in concentrations as high as $10^{13}$ cm$^{-2}$ with mobilities exceeding 15,000 cm$^2$/Vs even under ambient conditions [2-5]. Importantly, the planar form of graphene allows for top-down CMOS compatible process flows, an advantage for potential industrial fabrication of electronic devices. Graphene has already been used in laboratory demonstrations of spin valves, electromechanical resonators, quantum interference devices, and, significantly, field-effect transistors (FET) [6-9]. It can further be used as a chemical sensor capable of detecting minute concentrations (1 part per billion) of various active gases, allowing the detection of individual events. However, despite the promise of graphene-based devices’ vastly superior performance, several fundamental issues in the fabrication and characterization of such devices need to be resolved in order to realize their full potential. In this regard, we are investigating low-dimensional materials such as CNT and graphene to develop nanoelectronic devices, nanoactuator systems and nanosensors, for cross-disciplinary applications.

**GRAPHENE FIELD EMISSION, NANORIBBONS AND QUANTUM DOT TRANSISTORS**

Our interdisciplinary research focus is to design, fabricate, and characterize graphene nanostructures towards graphene-based nanoelectronics. We are investigating the field properties of graphene nanostructures for vacuum electronics applications [10] (Figure 1). Field emission is a quantum mechanical tunneling phenomenon in which electrons escape from a solid surface into vacuum, as explained theoretically by R. H. Fowler and L. Nordheim in 1928. Field emission is widely used in many kinds of vacuum electronics such as flat panel displays, microwave power tubes, electron sources, and electron-beam lithography [11, 12]. Over the past decade, research groups have shown that CNTs are excellent candidates for electron emission [13, 14]. CNTs have high aspect ratios, small tip radius of curvature, high chemical stability, and high mechanical strength. Furthermore, CNT emitters operate stably at moderate vacuum conditions. However, issues related
to the placement and throughput of CNT arrays have hampered the development of such arrays for commercial applications. The planar form of graphene allows for top-down CMOS compatible lithography and etching process flows, an advantage for potential industrial fabrication of electronic devices. Here, we use graphene for field emission. A graphene triode structure can be used as a fundamental unit for vacuum nanoelectronics [10], with a graphene emission tip and three electrodes as source, drain, and gate on the device substrate. To measure field emission, graphene sheets are prepared by mechanical exfoliation and placed on an insulating layer, with the resulting field emission behavior investigated using a nanomanipulator operating inside a scanning electron microscope (SEM). The graphene layer starts emitting current at around 20V, increasing exponentially up to 170 nA, following the behavior of the Fowler-Nordheim relationship. The maximum emitted current is found to be 170 nA with a turn-on voltage of 12.1V. We are further investigating field emission properties as a function of the number of graphene layers and the directions of the atomic crystal. Future studies include a triode structure with gate electrodes.

Further, in collaboration with Prof. Stefan Strauf’s group at Stevens Institute of Technology, we have recently constructed a nanoscopic graphene transistor and showed the evidence of Klein tunneling. Currently, we are investigating the effects of material properties and fabrication techniques on the ballistic and phase coherent transport in graphitic devices, such as multi-channel and single electron transistors and solid-state interferometers. Finally, we are exploring an energy conversion idea using graphene. In recent studies, a continuous energy bandgap opening of up to 250 meV has been reported by using various techniques such as

![Figure 1: F-N plot for emission current from this experimental study on field emission characteristics of individual graphene layers. [10]](image_url)
applying electric field [15], substrate doping [16,17], controlling graphene ribbon width [18] and applying strain and curvature [19-21]. Besides its exceptional electric and mechanical properties, graphene also exhibits extraordinary optical properties. Optical absorption of single layer graphene for white light is reported to be as high as 2.3% [22] with high photocurrent generation efficiency [23,24]. Our research involves development of a high efficiency infrared photocell which utilizes strain induced tunable bandgap opening in graphene which allows generation of photocurrent, in available infrared radiation spectrum. In spite of the inherently low energy associated with infrared radiations, a well engineered array of tunable graphene photocells has the potential to harvest a substantial amount of energy using infrared radiation.

HIGH-THROUGHPUT AFM NANOLITHOGRAPHY

This research explores the adaptation of the atomic force microscope (AFM) tip-based oxidation lithography technique for the ultimate purpose of high-throughput nanolithography on graphene layers. Several methods for graphene/CNT nanoscale patterning exist but are limited in speed, ease of use, or in the production of patterns [26-31]. High throughput is achieved through the transfer of patterns via oxidation using a pre-nanopatterned chip in a manner similar to mold based transfer. While the AFM oxidation lithography has been demonstrated in some cases over small areas, the proposed research is focused on developing a basic understanding of the underlying phenomena governing large-area oxidation lithography of graphene as our model material system. Therefore, we are systematically studying local oxidation lithography to precisely fabricate nanometer-scale structures from graphene and carbon nanotube material.

Our technique has lately been shown to address the issues of fabrication speed and device size and can be used to fabricate graphitic nanodevices on the order of tens of nanometers [25]. By applying an appropriate electric field between the AFM tip and substrate in humid atmosphere, oxidation of the substrate occurs. Depending on such process parameters like applied voltage, pulse width, tip dimensions, contact force, and humidity, the oxidation of the graphitic material into carbon oxides enables the formation of insulating trenches to make various nanostructures. Using this technique, we can locally oxidize few layer graphene,
segmented single wall carbon nanotubes, and draw nanoscale insulating patterns on highly ordered pyrolyzed graphite (HOPG) [25]. Forthcoming experiments include the patterning of less than 20 nm features on single-layer graphene to create quantum dots, and segmentation of single-wall nanotubes into quantum dots for electron transport studies.

**CARBON NANOTUBE QUANTUM DOTS TRANSISTORS**

The inexorable scaling trend in electronics has resulted in the continuous reduction of the number of electrons participating in device operations, ultimately scaling to single-electron device operation. Averin and Likharev proposed a three-terminal, single-electron tunneling structure, consisting of just one small conducting island separated from two larger electrodes (electron sources) by two quantum-mechanical tunneling barriers [32]. In contrast to earlier studies of individual tunnel junctions allowing single electron tunneling processes, the double barriers described by Averin and Likharev form a quantum dot-like nanostructure with distinct internal energy states. Such a device follows the Coulomb staircase behavior [32-38] for single electron devices. This allows precise control of a small number of electrons in the conducting islands, inducing periodic oscillations of the current as a function of the voltage.

We are developing single electron transistors from CNTs operating at elevated temperatures. The approach is followed in order to fabricate nanosegments along the nanotube effectively, creating a CNT quantum dot with large charging energy and large level spacing. A number of novel applications can be conceived using single electron tunneling devices, including displacement sensors [39], superconducting devices with a quantum cooling effect [40], and water pumps using the drag of single electrons without tunneling barriers [41] in addition to their typical applications such as highly sensitive electrometers [42,43].

**NANOMECHANICAL ACTUATORS AND NANOSCALE MEASUREMENT TECHNIQUES**

A nanoscale actuator or an array of such actuators can be used for many potential applications, for example, to investigate how external forces applied to a cell membrane affect mechanisms such as inter-cell signaling,
cell growth, and cell adhesion. For such applications, production of nanoactuators with repeatable and controllable properties and performances is of utmost importance - therefore the characteristics of such individual nanoactuators need to be studied. As an early stage of this project, we are developing bimorph nanoactuators based on multiwall carbon nanotubes coated with a thin metal film on one side using pulsed laser deposition [44]. Actuation and characterization of the resulting nanoactuators are conducted using a temperature stage operating within an SEM. As the temperature is increased from 300K to 550K, the measured displacement of the nanoactuators is $500 \pm 100$ nm. Using Lateral Force Microscopy (LFM), the forces generated from the tip are found to be on the order of microNewtons. To extend this work we are currently seeking to develop polymer-based vertical nanoactuator arrays with various actuation modes.

Further, a novel calibration technique has been developed for LFM [45] (Figure 2). Typically, special preparation of the atomic force microscope (AFM) cantilever or a substrate is required for LFM calibration. Our new calibration technique greatly reduces the required preparation processes by simply scanning over a rigid step and measuring the response of the AFM photodiode in the normal and lateral directions. When an AFM tip touches a step while scanning, the tip experiences a reaction force from the step edge, and the amount of torsion can be estimated based on the ratio of the normal and torsional spring constants of the AFM cantilever. Therefore, the torsion can be calibrated using the measured response of the photodiode from the lateral movement of the AFM tip. This new

**Figure 2:** Distortion of a Ni nanowire during lateral force microscopy [45]. (a) Before the AFM tip touches the Ni nanowire, there is no distortion of the AFM cantilever and the laser reflection is at the center of the photodiode. (b) When the AFM head moves laterally by $\Delta_0$, the AFM cantilever distorts by an amount $\delta$ and the reflection is now biased in one lateral direction.
calibration technique has been tested and confirmed by measuring Young’s modulus of a nickel (Ni) nanowire.

CONCLUSIONS

We are pursuing the fabrication, assembly and manipulation of carbon nanotube and graphene architectures. Along with graphene research, we are exploring a new high-throughput desktop nanolithography process. On the mechanical engineering side, nanomechanical actuators and associated nanoscale measurement techniques are being developed for re-configurable arrayed-nanostructures for applications in antennas, remote detectors, and biomedical nanorobots. Overcoming the technical challenges of scaling up such results, including reliability and repeatability of the assembled structures, will enable one to leverage the outstanding properties of these low dimensional nanomaterials in the development of next-generation nanodevices. Such capabilities show potential widespread application in areas such as sensors, detectors, system-on-a-chip, system-in-a-package, programmable logic controls, energy storage systems, and many other future electronic systems.

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