NANOTECHNOLOGY: AN OVERVIEW AND INTEGRATION WITH MEMS

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ABSTRACT

There are strong research programs in nanotechnology related to chemical sensors, electromechanical devices, actuators, biosensors, etc. in leading laboratories across the world. In many cases, practical systems demand seamless integration of the nanodevice with higher order structures, for example, MEMS. Examples of this using carbon nanotube based chemical and biosensors are presented.

1. INTRODUCTION

Nanotechnology deals with creation of materials, structures, devices, systems, and architectures *of any size* by controlling matter at the nanometer length scale, and more importantly, by taking advantage of novel properties that arise because of the nanoscale. Indeed, properties of materials - physical, chemical, electrical, magnetic, optical, mechanical, etc. - change when going from bulk to nanoscale. For example, melting point of metals can deviate from the bulk melting point as much as couple of hundreds of degrees for a particle of 5 nm size. Bandgap of silicon can increase from 1.1 eV to near 3 eV for a 5 nm diameter silicon nanowire. Therefore, nanotechnology is not just about size alone but more about how to harness the change in properties and produce useful functionalities. Since the introduction of the National Nanotechnology Initiative in 2000 in the U.S., nanotechnology research has exploded across the world looking into nanomaterials, nanoelectronics, nano-optics, nanomechanics, nanomagnetics, nanoelectromechanical systems (NEMS), nanosensors and actuators, nano-optoelectronics, nanofabrication, nanorobotics, nano-bio fusion etc. Since the breadth of properties that change due to nanoscale and the subject fields are so wide as described above, naturally the economic impact expected is across all sectors: electronics, computing, data storage, materials and manufacturing, energy, transportation, environment, health and medicine, national security, space exploration, etc.

There have been several nanomaterials that are currently produced and investigated for application development: carbon nanotubes (CNTs), inorganic nanowires (semiconductors, metals, dielectrics, high temperature oxides, nitrides, etc.) that can cover from UV to near IR wavelengths, quantum dots, dendrimers, nanoparticles, etc. Of these, CNTs have commanded extraordinary attention because of their unique electronic and exceptional mechanical properties. For example, CNTs can be metallic or semiconducting depending on their chirality. They exhibit an Young's modulus of over 1 TPa and thermal conductivity as high as 3000 W/mK. Their interesting properties have prompted such varied applications as field emission devices for flat panel displays and instrumentation, nanoelectronics, high strength composites, chemical and biosensors, interconnects, thermal interface materials, nanoelectrodes, lithium batteries and several others [1]. Here we would use CNT as prime example of nanomaterial in developing sensor applications.

It is important to point out that most of the applications of nanotechnology would require a seamless integration of nano-micro-macro technologies [2]. It is entirely likely that the central component of the system may be nano derived due to some unique advantages in terms of performance, power consumption, reduced mass for a given performance etc. But practical systems involve numerous auxillary components all of which need to be integrated on a wafer scale when taking advantage of the mass fabrication methods that have been advanced in the last two decades. The current state-of-the-art in the literature is primarily focused on concept demonstrations at the nanoscale, partially due to the early stages of research. Nano-micro integration and system/subsystem development are topics missing at present. For nanotechnology to be beneficial to various economic sectors, the above will constitute a critical path, to be followed by testing and characterization, system-level reliability testing, system level manufacturing standards and design/simulation tools to aid in the development of the above iterative processes [2]. Here we discuss two examples of sensors where initial attempts have been made on the integration front.

2. CHEMICAL SENSORS

Chemical sensors in the market today are based on high temperature oxides (such as tin oxide) or polymers. Demands exist in several areas for much higher sensitivity (ppm to ppb levels), low power consumption, amenability to high yield fabrication of sensor arrays, room temperature operation and other benefits. The tin oxide sensors typically are in the form of a field effect transistor (FET) and indeed, the CNT community has fabricated CNT-FETs to demonstrate sensor operation. In this case, a single CNT or multiple CNTs bridge the source and drain as the conducting channel with a gate providing modulation. When vapors or gases adsorb on the CNT, electrons may be withdrawn from or donated to the CNT; monitoring of the conductivity of the CNTs then forms the basis for sensing. Alternatively, other properties such as capacitance or dielectric characteristics may also serve as the basis for sensing. In the FET fabrication, however, cost levels are high since it involves fabrication of three terminal devices which is complex and

due to demanding steps such as ideally bridging the source-drain gap with specific number of CNTs for transistor operation.

Alternatively, Li et al. [3] developed a simple interdigitated electrode based approach as shown in Fig. 1a. Here the electrodes are microfabricated using standard MEMS techniques where an array of interdigitated fingers with a finger width of 10 μm and a gap size of 8 μm is fabricated. These were made by thermally evaporating 20 nm Ti and 40 nm Au on a layer of SiO_2 thermally grown on top of silicon wafer. Next, few drops of CNTs suspended in a solvent (dimethyl formamide) are deposited (i.e. solution casting) across the interdigitated electrodes. The high boiling solvent evaporates rapidly leaving a film containing statistically meaningful number of CNTs bridging the electrode leads. This simple device works as well as a three terminal device and the response curves for the exposure of NO_2 in nitrogen are shown in Figure 2. The signal increase is significant and rapid upon NO_2 exposure and the signal begins to drop off when the source is removed and the purge gas N_2 is admitted. The recovery time as seen in Fig. 2 is unacceptably slow but the desorption of NO_2 from the nanotubes can be accelerated by slight heating or exposure to UV light [3].

It is important to point out that a single sensor as in Fig. 1a is of limited value. Particularly from the point of view of selective discrimination of a constituent from a mixture, multiplexing using a sensor array has been known to be the most common approach. It is entirely likely that one can coat or dope the nanotubes that would elicit a response only from one species in a mixture and this has been demonstrated (see Chapter 9 in ref. 1). However, there are only a very small set of choices for coatings and dopants which leave multiplexing with proper training of the sensor array as the only universal approach for effective chemical sensing. Figure 1b shows an array of CNT sensors developed using microfabrication. Now, for deployment in a practical application, this sensor array needs to be integrated with a preconcentrator, signal processing chip, a fan or blower that can deliver a sample volume of the gas mixture etc. The size of the final system may be a hand-held device as shown in Fig. 1c.

3. BIOSENSOR

In the previous example, we relied on the charge exchange between CNTs and the vapor/gas leading to a change in the conductance of the nanotubes for selectively sensing that vapor or gas. In developing biosensors, in contrast, CNTs can serve as nanoelectodes. In demanding high sensitivity levels, the size difference between molecules (proteins, DNA, cells) and the traditional macroelectrodes is high, leading to signal to noise issues. If the same electrode is broken into numerous nanoelectrodes, such problems can be minimized and also it is possible to individually address nanoelectrodes within a large microarray if necessary. Figure 3 shows a cartoon where a microarray contains several vertically aligned carbon nanofibers (CNFs) each 50-70 nm in diameter. These CNFs can be functionalized at their ends with a probe DNA and this sequence, when hybridized with its complementary sequence, can yield an electrical or electrochemical signal. In this development, we exploit the chemical amplification property of an electrochemical intermediate such as $Ru(bpy)_3^{2+}$ which is oxidized by the guanine in the incoming sequence.

The fabrication of the electrode arrays follows a well established microfabrication procedure. First, a metallic layer such as Ti or W is deposited on a silicon wafer followed by sputtering of the catalyst needed to grow CNFs (Ni, Co, Fe, or Pd). Then using a plasma enhanced CVD approach, CNFs are grown on individual catalyst dots. In an electrochemical approach, it is important to avoid the overlapping of the radial diffusion layers of the neighboring electrodes. For this, one has to first control the distance between the electrodes, about 1.5 μm for 70 nm CNF. Then, the CNFs need to be electrically isolated by depositing SiO_2 in the spaces between them using thermal CVD. Note that this provides mechanical robustness as well. The next step involves chemical mechanical polishing to provide a planar top surface where only tiny ends of CNFs are exposed. These ends are then functionalized with the probe molecules.

So far, a detection limit of 1000 target molecules has been demonstrated [4] which is already comparable to the laser fluorescence techniques in DNA microarrays. Currently efforts are underway to integrate this nanotube based biosensor with microfluidics for bacteria/water quality monitoring (see Fig. 4). The steps will include filtering the solution and condensing to 1 ml which will then pass through microfluidic channels of 5-10 μm size with multiplex nanoelectrode arrays. Bacteria trapped on some of the arrays will be assisted with electrophoresis. The electrochemical detection will be done by a computer with multiplex interface cards. The goal is to detect 100-1000 bacteria/l in 10-20 minutes with a capability to detect up to 30 types of bacteria.

4. SUMMARY

We emphasize here the need to look beyond single device demonstration in nanotechnology and address nano-micro-macro integration in system development. The advances in MEMS in the last two decades will greatly benefit nano device implementation in practical applications. This will also rejuvenate the field of MEMS with new market possibilities. Here we have discussed two sensor examples involving carbon nanotubes where first steps in integration were taken.

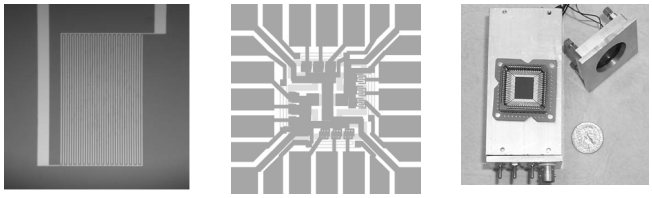


Figure 1. (a) Interdigitated electrode to support a film of carbon nanotubes, (b) a 12 sensor array and (c) a hand-held system consisting of the sensor array, signal processing chip, I/O, etc.

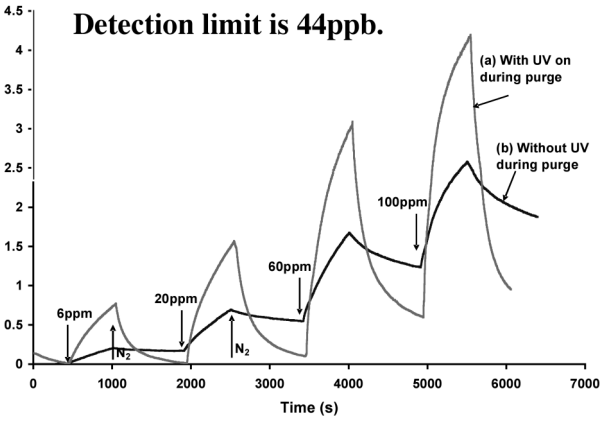
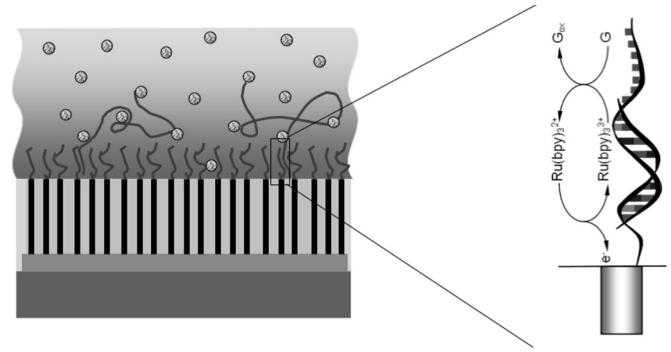


Figure 2. Sensor response to NO_2 in nitrogen.



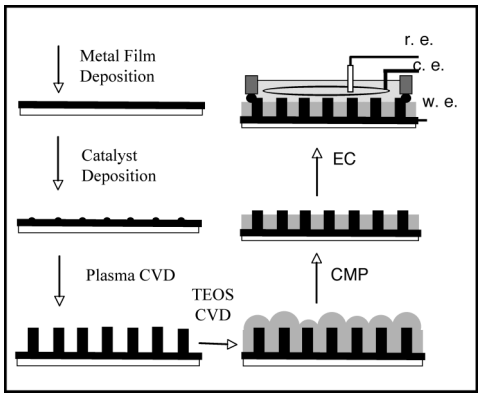


Figure 3. Top: Schematic showing DNA detection using a carbon nanotube electrode array. Bottom: Preparation of the nanoelectrode array

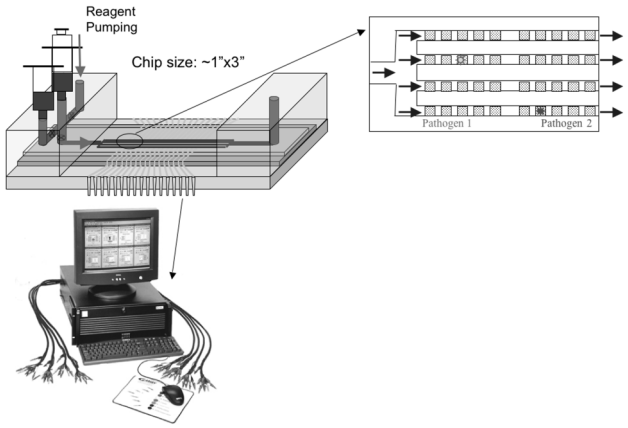


Figure 4. Biosensor system combined with microfluidics for water quality monitoring.

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