

Design and Experimental Testing of Nano Antenna for Carbon Nanotube (CNT) Based Infrared Sensors

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Abstract—We report the fabrication and experimental characterization of a nano antenna for carbon nanotube (CNT) based infrared (IR) sensors. By designing a nanosized antenna and integrating with CNT sensing element, the electric field intensity at the position of the sensing element can be enhanced and so a very sensitive infrared nanosensor is developed. The efficiency and characteristics of the nano antenna were studied experimentally by measuring the photocurrent response of the sensor before and after the nano antenna is implemented. The experimental result has shown the nano antenna increases the photocurrent by an order of magnitude. This implies that the electric field in the vicinity of the detector is enhanced by the nano antenna. The proposed fabrication process enables easily and directs integration of the nano antenna into the manufacturing of infrared devices. Therefore, this opens the possibility developing high fidelity infrared sensors with a wide sensing range.

I. INTRODUCTION

The development of infrared (IR) detectors using nanostructural materials has attracted increasing interest in recent years. CNTs have been found to be promising candidates for photodetection due to their low thermal noise. It is well known that the electronic properties of CNTs are different and they can exist in two forms, conducting and semi-conducting. Semi-conducting CNTs are natural candidates for IR detector as they have a bandgap in the IR range. Our group has already developed a single CNT based nano infrared detector [1], which exhibited IR response and small dark current. However, the photocurrent response of CNT sensors has been relatively low because of the small sensing area. Thus, an enhancement technology is developed in this paper to increase the electric field at the sensing area. Since the size of the CNT is in nano scale, the technique to enhance the electric field that is incident on such small sensing element is challenging. In this paper, a nano antenna is used to increase the response of the sensor. These are not antennas in the traditional sense, in that we are not interested in the radiated field. However, this terminology has been used extensively in the optics literature to refer to metallic field enhancement structures in the near field, especially in development of plasmonic devices. On the other hand, dipole

antennas have been widely used in electromagnetics because of their simplicity and special features. Recently, antennas in nano scale have been investigated theoretically [2][3] and explored in various applications such as optoelectronics and nanophotonics [4]. However, the experimental realization of practical nano antenna for quantum infrared detector has not been reported.

In this paper, the fabrication of the ultra-small and sensitive CNT based IR detector with the nano antenna will be presented. To investigate the electric field enhancement effect of the antenna, experiments have been performed to measure the photocurrent response of the sensor with and without the nano antenna. Preliminary results showed the photocurrent was increased by an order of magnitude, and the I-V characteristic of the device has also been obtained. To study the enhancement effect of the nano antenna, two different types of CNT based detectors combined with the antenna have been tested experimentally. We demonstrated that the nano antenna is efficient in near field. Several issues such as the conductivity of the nano sized antenna and factors to affect the antenna gain will also be discussed.

II. DESIGN AND FABRICATION PROCESS

The nano antenna was designed for our CNT based nano IR detectors as depicted in Figure 1. It consists of two symmetric thin metal wires which are separated by a nanometric gap. When the antenna is illuminated with an infrared source, a plane wave incident from above is collected over the entire area of the antenna and a standing-wave current pattern is generated along two metal wires. The field in the vicinity of the electrically conducting object is finally enhanced. The CNT sensing element is then aligned to the position of the maximum estimated field near the antenna. The maximum radiation occurs at the point that is perpendicular to the antenna axis.

After designing the antenna, the fabrication process of the CNT based IR detector with the nano antenna was developed and the schematic structure is shown in Figure 2, which employs the nanoassembly of CNTs and standard photolithography processes.

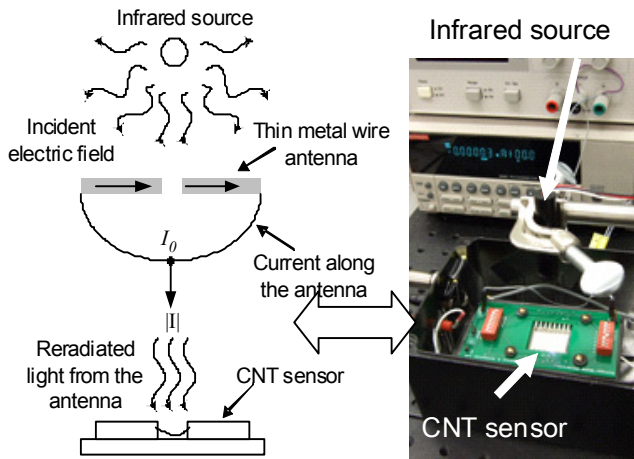


Figure 1. Illustration showing the setup of the infrared detection system with the nano antenna.

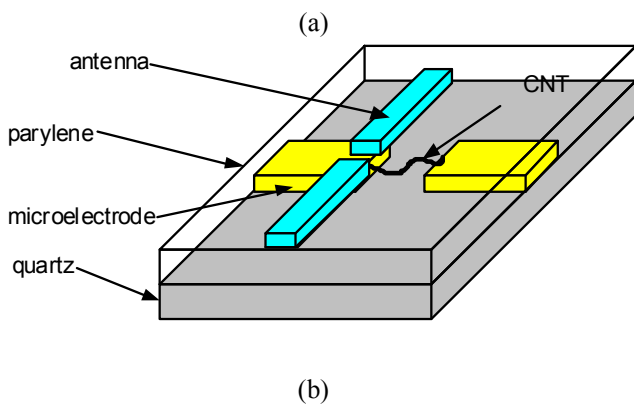
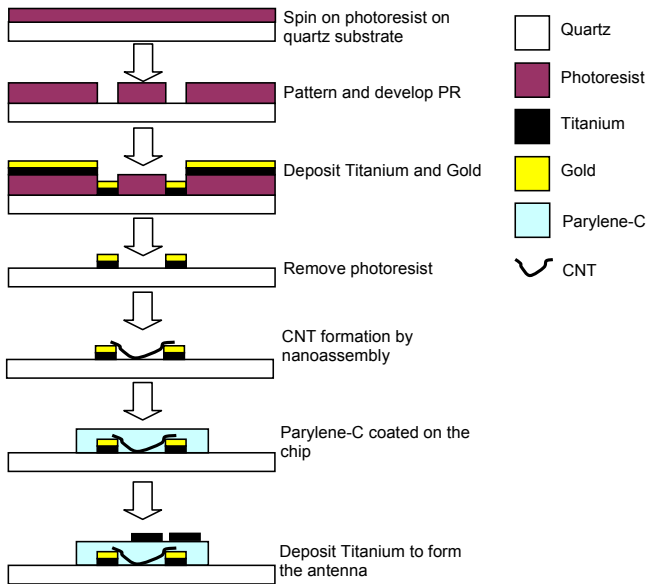


Figure 2. (a) Fabrication process and (b) schematic structure of a CNT based IR detector with a nanoscale antenna.

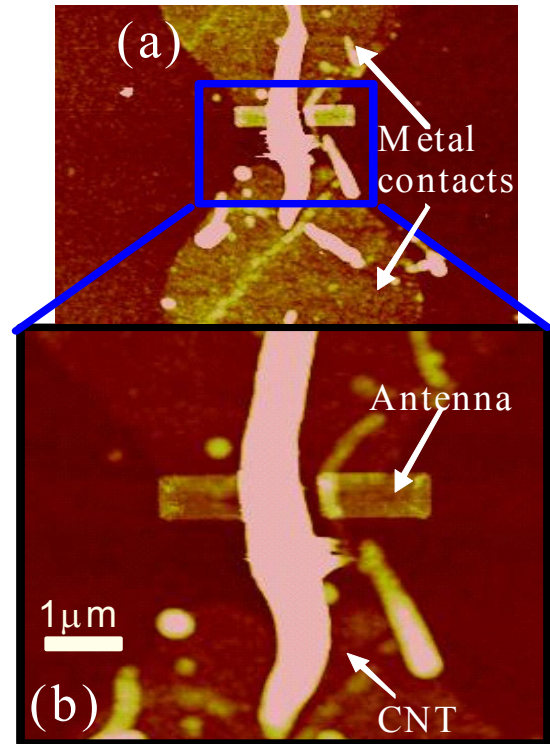


Figure 3. (a) AFM images of the fabricated CNT IR detector with the nano antenna. Parylene thin film was coated between the antenna and CNT. A pair of antenna is aligned to one of the symmetric metal contact electrodes.

The single CNT sensor was first fabricated by using nanoassembly to form the CNT across micro electrodes. A pair of symmetric micro electrodes was evaporated on the quartz substrate by using thermal evaporation. Titanium was used to improve the adhesion of gold to the substrate. The gap distance between the micro electrodes is from 1 to 3 μm . Then a drop of CNT suspension was dispersed on the substrate and an ac voltage was applied. CNTs were then formed between the pair of micro electrodes by the dielectrophoresis force. CNT's responsibility to IR has been proposed as the Schottky barrier effect at the CNT-metal contact and reported previously by our group in [1]. When the IR irradiates the CNT, electrons and holes inside the CNT are excited by the photons and results in the generation of current. As a result, the current from the CNT-metal contact is affected by the concentration of the photo generated carriers in CNT under the incident IR excitation. Therefore, if the CNT-metal contact is placed to the position of the maximum field output near the antenna, then the current can be increased due to the increasing IR power at the sensing region. This alignment process can be performed by the following steps. Firstly, the CNT formation between the microelectrodes was observed by using an atomic force microscope (AFM) so that the position of the CNT-metal electrode was known and estimated. Afterwards, a parylene C thin film layer was coated on the CNTs to act as an insulating layer for separating the antenna and the sensor.

The advantage of using parylene C is that it can be deposited conformally at room temperature and it can also cover CNTs from contamination. The IR sensing ability of the CNT detector after packaging by parylene has been reported in [5]. The separation distance between the antenna and the sensor was determined by the thickness of the parylene layer. In principle, the field enhancement effect is larger when the sensor is closer to the antenna. The thickness of the parylene layer is 500nm. Since the position of the sensing region (CNT-metal contact) was estimated by the AFM, the antenna was then patterned and aligned to the sensing region by using e-beam lithography. During this process, a layer of 950PMMA (polymethylmethacrylate with molecular weight of 950) resist was spin-coated on the substrate. After the bakeout curing of the PMMA, the nano antenna design pattern was written directly on the resist by an electron beam writer. As mentioned before, the position of the maximum field output is at the center of the antenna. By using the above processes, the position of the antenna can be precisely controlled and the nano antenna structure can be fabricated. Finally, a pair of thin metal wires was deposited on top of the parylene C layer by thermal evaporation and the nano antenna was formed after the lift-off process. The fabricated device is shown in Figure 3. As seen from Figure 3, a nano antenna was fabricated on one of the symmetric CNT-metal contacts. The total length, width and thickness of each antenna are 5 μ m, 1 μ m and 300nm, respectively. Titanium was used as the material of the antenna. On the other hand, we have also used the above process to integrate the antenna to a heterogeneous asymmetric CNT detector which is designed by using different materials as the metal contact electrodes. By choosing two different materials, one of the metal-CNT contacts is designed to form a Schottky barrier and the other formed an Ohmic contact. Detailed explanation of the heterogeneous structure has been reported in [1]. Since electrons and holes are excited at the Schottky contact, the antenna is then fabricated and aligned on the Schottky contact to increase the total photocurrent. Detailed experimental results will be presented in the next section.

III. IR SENSING EXPERIMENT

A. Experimental setup

An IR sensing experiment was performed to validate the field enhancement effect on the CNT sensor with the nano antenna. The experimental setup is shown in Figure 1 and the experiment was performed at room temperature. During the experiment, the device was put in the chamber and illuminated by the incident IR laser source (power: 30 mW, wavelength: 830 nm, World Star Tech). By connecting the sensor chip to a measurement circuit, the current from the CNT based detector was then measured and recorded with an Agilent analyzer.

B. Experimental result

The photocurrent response for multiple on/off IR illumination cycles was obtained and plots of the detector

with and without the nano antenna were compared and shown in Figure 4.

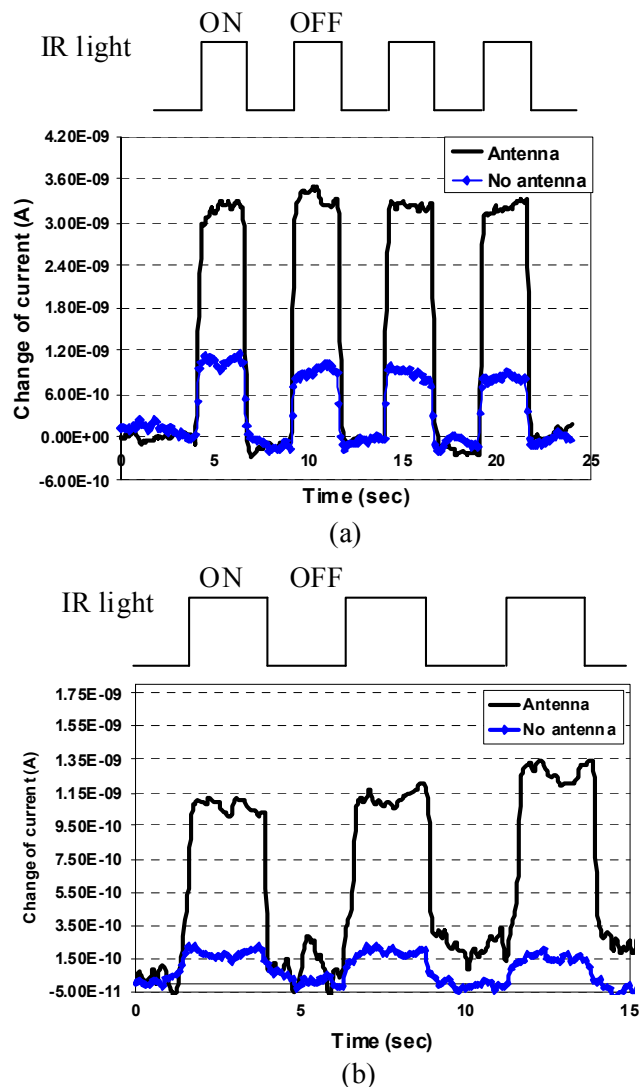


Figure 4. Comparison of the temporal photocurrent response plots of (a) symmetric and (b) asymmetric CNT based IR detector with and without nano antenna.

The photocurrent was taken as the current change when IR is on. It has been seen that the current was increased when the IR laser was on and it dropped to its original value when IR was off. Both of the symmetric and asymmetric detectors with nano antennas were tested and their IR response curves are shown in Figure 4(a) and Figure 4(b), respectively. Our preliminary results show both devices exhibited fast response to IR and the photocurrent change was increased after adding the nano antenna. Before adding the antenna, the current change of the original CNT based IR detector was small, which implied the low sensitivity of the sensor. On the other hand, the CNT based sensor with the nano antenna was more sensitive to IR because the incident power was enhanced by

the antenna. This implies the antenna can be incorporated into different structures and the response of the detector can be increased. Moreover, it can be seen that the photocurrent and the gain of the asymmetric structure is larger.

I-V characteristics of the symmetric and asymmetric CNT-metal electrodes after adding the antenna were also investigated and are shown in Figure 5(a) and Figure 5(b), respectively. It shows the behaviors of two different structures.



Figure 5. I-V characteristics of a (a) symmetric and (b) asymmetric CNT IR detector with nano antenna.

The photocurrent response is increased while the electric field near the antenna is enhanced and it is influenced by the gain of the antenna. The gain increases while the size of the antenna is reducing. This is caused by the increasing the conductance of the antenna when the size of the antenna decreases. The conductivity directly affects the current distribution and also the electric field in the vicinity of the antenna. Therefore the gain of the antenna for IR detection significantly increases when the wave length and antenna

length get smaller. Moreover, the gain of the antenna is also affected by several factors such as the length of the antenna, the alignment of the sensor to the maximum field output near the antenna, the material of the antenna, and the separation distance between the sensor and the antenna. It has been reported that the response maximizes when the antenna length is a proper multiple of the half-wavelength of the incident radiation [6]. Therefore, the antenna length effect on the field enhancement by the nano antenna has to be further studied.

IV. CONCLUSION

The design and fabrication process of a novel CNT based IR detector with a nano antenna have been presented. By integrating the nano antenna, the incident electric field at the sensor was increased leading to an order of magnitude increase in the photocurrent of the sensor. The antenna in nano environment is more efficient and can be incorporated into the manufacturing process of present day infrared detectors. The practical nano antenna for quantum infrared detector has been realized experimentally, which successfully demonstrated and verified that the IR response of the sensor can be greatly increased by the electric field enhancement in the vicinity of the nano antenna. This represents a major breakthrough in sensor research since this will lead to a dramatic improvement in the performance of infrared imaging systems, which are important for future civilian and military applications.

ACKNOWLEDGMENT

This research work is partially supported under NSF Grants IIS-0713346 and DMI-0500372, and ONR Grants N00014-04-1-0799 and N00014-07-1-0935.

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