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Photo-Response of Carbon Nanotube FETs with Thick Piezoelectric Gate Insulator

Naoki Nei[1], Toshio Ikeyama[1], Takayuki Arie[1,2], and Seiji Akita[1,2]

[1] Department of Physics and Electronics, Osaka Prefecture University
1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan
Phone: +81-72-254-9261 E-mail: akita@pe.osakafu-u.ac.jp
[2]CREST-JST, 4-1-8 Honmachi, Kawaguchi, Saitama 331-0012, Japan

1. Introduction

Carbon nanotubes (CNTs) are one of promising candidates for nanoscale electronic devices. To extend the potential functions of CNT-FETs, we have successfully demonstrated CNT-FETs integrating ferroelectric thin films as gate insulators (ferroelectric-gate CNT-FETs) with non-volatile memory operation [1]. Since ferroelectrics exhibit several interesting properties, such as switchable spontaneous polarization and extremely large piezoelectric and pyroelectric coefficients, the ferroelectric-gate CNT-FETs offer potential as nonvolatile memory elements and high sensitivity sensors. In this study, we investigate photo-responses of the ferroelectric-gate CNT-FETs to realize a micro- to nano-scale photo-detector from visible to infrared regions.

2. Device fabrication

$PbZr_{0.5}Ti_{0.5}O_3$ (PZT) ceramic plates with a thickness of 300 μm were used as the ferroelectric layer. The dielectric constant of the PZT is around 3000 which is much larger than that of SiO_2 (~3). Thus, the effective thickness of the gate insulator (thickness / dielectric constant) is comparable to that of the conventional CNT-FETs with SiO_2 gate insulator. Single wall CNTs (SWNTs) used in this study were synthesized by alcohol chemical vapor deposition (CVD), where Mo and Co were used as catalysts. The SWNTs were dispersed in isopropyl alcohol and the mixture was dropped on the PZT plates. After the isopropyl alcohol was vaporized, the SWNTs were distributed uniformly on the PZT plates. The source and drain electrodes of Pd were fabricated on the SWNTs by photolithography. Figure 1(a)-1(c) show schematic structures of PZT-gate CNT-FETs. In this study, we have examined two types of FETs; one consists of a few SWNT-bundle channels (Fig. 1(b)) and another is a film type channel FET (Fig.1 (c)). A white light source with the intensity of ~ 100 μW/cm^2 was used to examine the photoresponse of the PZT-gate SWNT-FETs. All measurements were performed in air at room temperature.

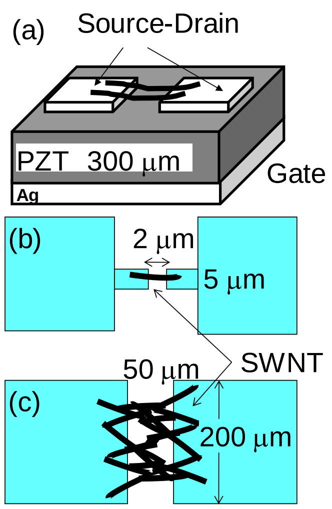

Fig. 1 (a) A bird's-eye view of schematic illustration of the PZT-gate CNT-FET, (b) a few SWNT device, and (c) a film type device.

3. Results and Discussions

Figure 2 shows a transfer (I_d-V_g) property for the PZT-gate CNT-FET. The drain current, I_d, is successfully modulated by the gate voltage (V_g) even under the condition of the 300 μm-thick PZT-gate insulator because of the high dielectric constant of the PZT. Furthermore, the transfer property shows very small hysteresis in comparison of the hysteresis for usual SiO_2-gate CNT-FETs. This might be due to the huge remnant charge induced in the PZT compensating the trapped charge and/or induced dipole from the adsorbed water around the channel CNTs.

Figure 3(a) shows the photoresponse of the PZT-gate CNT-FET. The drain current for the PZT-gate CNT-FET responses the light irradiation. It is noted that no photoresponse has been observed on the SiO_2-gate CNT-FET irradiated by the light source used in this experiment. The time-constant for the response is in the order of several tens minutes. This slow response may originate not only from

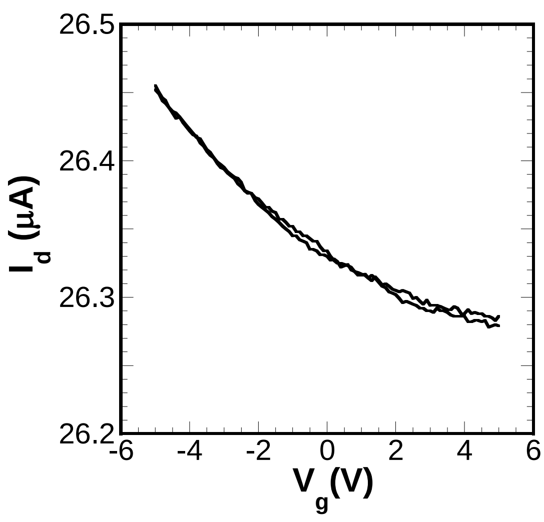

Fig. 2 Transfer characteristic for PZT-gate CNT-FET

the pyroelectric effect but also the other effect such as large temperature dependence of the dielectric constant of the PZT. This is one of subjects for further study. To eliminate the metallic CNTs in the channel we applied the electrical breakdown method to the device. After the breakdown procedure, both of the response time and the on/off ratio to the light were successfully improved as shown in Fig. 3(b). Thus, the semiconductive CNTs in the channel play an important role for the photoresponse. Assuming the presence of only a few CNT between source and drain electrodes, the number of photons per CNT channel is estimated to be 600 photons/sec from the light intensity. This value is much smaller than that expected number of photons estimated from the amplitude of the current modulation. Thus, the charge affecting to the current should be induced "around" the CNT channels by the light irradiation.

Figure 4 shows the photoresponse of the film-type device. In this case, the effective area for photo-detection is 1000 times larger than that for the "a few SWNT" device. Thus, the current is effectively modulated by the light on/off, but the on/off ratio is smaller than that for the breakdown treated "a few CNTs" device. It is noted that the conductivity change originates from the semiconductive CNTs as mentioned above, so that the barrier at the interconnection of CNTs is less effective to the photoresponse in the film type device.

The polarity of the remnant charge in the PZT gate is normal direction to the surface, where the negative and positive sides correspond to the surface and the backside of the device, respectively. Thus, holes are induced in the CNT channel according to the polarity of the remnant charge. Under a model for the pyroelectric effect, the light irradiation reduces the trapped charge on the surface and the surface charge recovers gradually under the dark condition. Based on this scheme, the light irradiation reduces the hole density in the CNT channel. As a result, the current passing through the semiconductive CNTs are modulated by the light on and off.

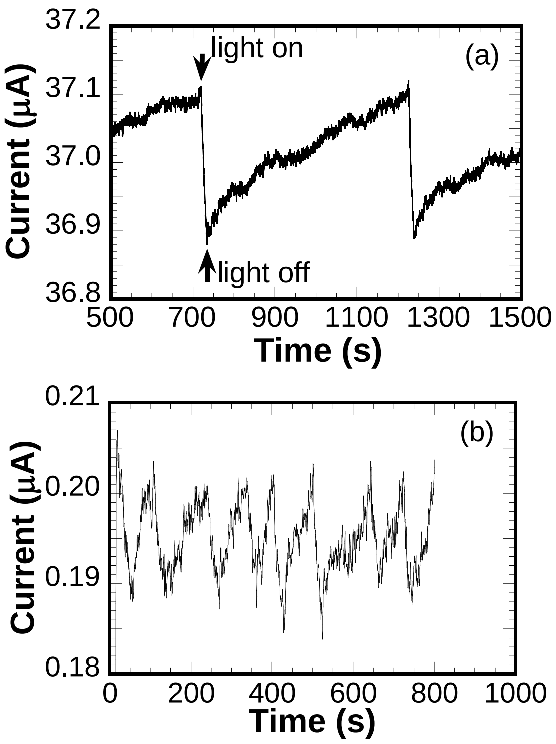

Fig. 3 Photoresponse curve (a) as fabricated and (b) after the breakdown procedure.

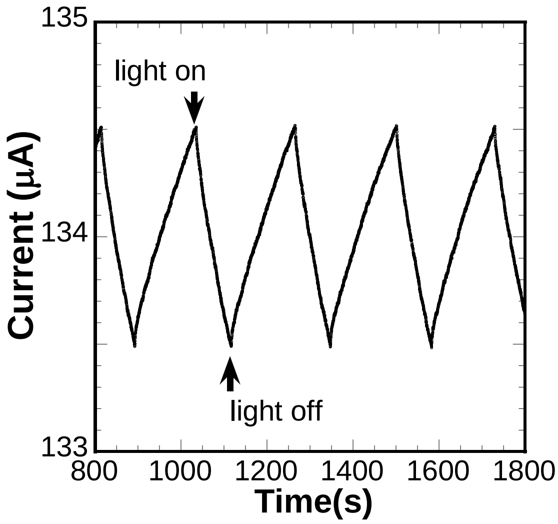

Fig. 4 Photoresponse curve for the film type device

3. Conclusions

We have investigated photo-responses of the PZT-gate CNT-FETs. The device successfully sensed the light with a intensity around 100 μW/cm^2 white light. The mechanism of the photoresponse was interpreted based on the pyroelectric effect of the PZT-gate.

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