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Photoresponse of Carbon Nanotube Field-Effect Transistors

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Photoresponse of carbon nanotube field-effect transistors (FETs) is investigated using microscopic measurements. The nanotube FETs, with an isolated single-walled carbon nanotube (SWNT) for the channel, were fabricated by means of the position-controlled nanotube growth technique. An increase in the off-state current and the threshold-voltage shift of the FET were caused by laser illumination. The increase in the off-state current is attributed to photocurrent due to carriers excited in the SWNT channel. The excitation spectrum of the photocurrent had a peak corresponding to optical absorption by the third interband gap of the van Hove singularity of the semiconducting SWNT with a diameter of ~2 nm. The photocurrent increased in proportion to incident laser power with a dynamic range over four orders of magnitude. The external quantum efficiency was 2 \times 10^{-7}. An inverter action to optical-signal input was observed near the threshold voltage of the FET. The responsivity was as high as 2 \times 10^{-3} A/W for a single SWNT channel. This high responsivity is explained by the field-effect amplification phenomenon.

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1. Introduction

Carbon nanotubes are promising materials for use in manufacturing nanoscale electron devices such as nanotube field-effect transistors (FETs) for ultrahigh-density integrated circuits and quantum-effect devices for novel intelligent circuits, which are expected to lead to great breakthroughs in the present silicon technology. Because semiconducting nanotubes are direct-transition semiconductor materials similar to compound semiconductors, are able to emit and absorb photons with high efficiency. Therefore, nanotube devices are also useful for electrical/optical (E/O) or optical/electrical (O/E) signal conversion in the field of nano-optoelectronics.

Recently, we have reported the possibility of the characterization of nanotube FETs by measuring the response to light illumination. A photocurrent signal originating from an individual single-walled nanotube (SWNT) was obtained using a microscopic optical measurement setup. The excitation spectrum of the photocurrent had a peak corresponding to the optical absorption by the van Hove singularity of the semiconducting SWNT. Such optical characterizations of nanotube FETs had an advantage because energetic information of the nanotube channel was obtained by spectroscopic analysis.

In this study, we have investigated the photoresponse of nanotube FETs, i.e., O/E signal conversion using a single SWNT. The nanotube FETs were fabricated by means of the position-controlled nanotube growth technique by alcohol chemical vapor deposition (CVD). First, the photocurrent obtained at the off-state region of an FET was investigated. Dependences of the photocurrent on excitation energy and power are discussed. Then, we focus on the inverter action to optical signal input observed near the threshold voltage of the FET.

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2. Experimental

Figure 1 shows the schematic device structure of the fabricated nanotube FETs. The nanotube FETs were fabricated by means of position-controlled nanotube growth technique. A heavily doped p'-silicon wafer with thermally oxidized SiO$_2$ (100 nm) was used as the substrate. The metal catalysts consisting of a double layer of Co/Pt (2/10 nm) were patterned on the substrate using conventional photolithography and metal lift-off processes. The SWNT was synthesized by alcohol CVD. A mixture of ethanol (50 sccm) and argon (100 sccm) was used as the source gas. The total pressure in the furnace was 2 Torr. The growth temperature and time were 900°C and 1 h, respectively. The device fabrication was completed by Au/Ti electrode formation on both the patterned catalysts and the back surface of the substrate. The back surface metal was used as the gate electrode.

In order to determine the quality of the synthesized SWNTs, we employed micro-Raman scattering spectroscopy. Figure 2(a) shows the G-band (graphite mode) and the D-band (disorder mode) of a Raman scattering spectrum of synthesized SWNTs. An Ar-ion laser (488 nm) was used for the excitation. The intensity ratio of G-band to D-band is typically oxidized SiO$_2$.
nanotube FETs have a high quality SWNT channel. Figure 2(b) shows the radial breathing mode for three excitation wavelengths at different positions. Since the full width at half maximum of the observed peaks is as narrow as ~7 cm⁻¹, these peaks originate from individual SWNTs. The diameters of the individual SWNTs were estimated on the basis of the Raman shift of RBM to be 0.9–2.3 nm. These Raman signals from individual SWNTs were obtained only on patterns of catalytic metal, and were not obtained on SiO₂. This is probably because the SWNTs were suspended from the substrate by the catalytic metals which balled up at the high temperature used in CVD. Kobayashi et al. have reported that the Raman signal from suspended SWNTs is much higher than that from SWNTs laying on a substrate.⁹)

Figure 3 shows the setup for measuring the photoresponse of nanotube FETs. A tunable CW Ti/Sapphire laser was used as the excitation source. The excitation power was controlled by a laser-power stabilizer. The laser beam was focused on the sample surface by an objective lens (×50). The diameter of the laser spot was ~2μm. The position of the laser spot was monitored using a CCD camera. Polarization of the excitation laser was parallel to the axis of the nanotube. The device was mounted on the cold finger of a cryostat and cooled to 10 K. Electrical measurements of the nanotube FET were performed using a semiconductor parameter analyzer (Agilent 4156C).

3. Results and Discussion

Figure 4 shows drain current–gate voltage (I_D–V_GS) characteristics of a nanotube FET without illumination (dashed line) and under laser illumination (solid line). Here, the drain voltage (V_D) was 1 V, and the energy and power of the incident excitation laser were 1.73 eV and 62 μW, respectively. The excitation energy corresponds to the absorption energy of the third interband gap of the van Hove singularity of the nanotube, as described later. When the device was illuminated by the laser, the threshold voltage of the FET shifted in the direction of negative V_GS, and I_D at the off-state region (V_GS > −5 V) increased.

We first discuss the photocurrent obtained at the off-state. Since, in the off-state region, carriers were not injected from electrodes, we can expect that the observed increase in I_D would be caused by carriers in the nanotube channel. Figure 5 shows the time-domain response of the photocurrent to laser light chopped at 8 Hz. Here, V_D = 1 V and V_GS = 5 V. Clear switching of I_D was caused by the optical-signal input. The low operation frequency was attributed to the response speed of the experimental setup and the small photocurrent originating from a single SWNT.

Figure 6 shows the photocurrent as a function of the position of the laser spot, which was scanned from A to A’ as shown in the SEM image in the inset. The maximum

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**Fig. 2.** Micro-Raman spectra of synthesized SWNTs. (a) G-band and D-band, and (b) radial breathing mode for three excitation wavelengths at different positions.

**Fig. 3.** Measurement setup for photoresponse of nanotube FETs.

**Fig. 4.** I_D–V_GS characteristics of nanotube FET without illumination (dashed line) and under laser illumination (solid line).
photocurrent was obtained at \( x \approx 27 \mu m \). There was a nanotube at this position as shown in the SEM image. The dotted line in the figure is fitted by a Gaussian function. This fit corresponds to the intensity deviation of the laser spot, which is a Gaussian with a deviation of \( \approx 2 \mu m \). It was confirmed by means of atomic-force microscopy that the nanotube observed in the SEM image in the inset was a SWNT with a diameter of \( 2 \) nm. We have empirically found that SWNTs can be observed by low magnitude SEM when the acceleration voltage of SEM is as low as 0.5 kV, and the SWNTs lay on SiO\(_2\) and are connected to electrodes. This is probably because of the charging effect of SiO\(_2\) due to the electron beam.

By varying the wavelength of the Ti/Sapphire laser, the excitation spectrum of the photocurrent was obtained. Here, the excitation power was set to a condition of a constant photon number in the whole wavelength range by using a laser-power stabilizer. Figure 7 shows the photocurrent as a function of photon energy. A peak was observed at 1.73 eV. If we plot the relation between the absorption energy of the van Hove singularity (1.73 eV) and the diameter (2 nm) of the SWNT on the theoretical plot (also known as Kataura plot), the peak energy of the photocurrent spectrum corresponds to the third interband gap of the van Hove singularity of a semiconducting SWNT.

Figure 8 shows the dependence of the photocurrent on excitation power. The photocurrent increased in proportion to the excitation power over four orders of magnitude. This corresponds to the dynamic range of O/E conversion using nanotube FETs. The linearity of the photocurrent is an attractive feature for a photodetector. Moreover, the linear dependence suggests that the obtained photocurrent originates from the carriers which were excited in the nanotube channel and drawn out to the electrodes. The external quantum efficiency is estimated to be \( 10^{-7} \) by using the following equation, \( \eta_{ext} = \frac{I}{nhf/qP} \). Here, \( I \) is photocurrent, \( q \) is elementary charge, \( P \) is power of the incident laser to the device, and \( hf \) is photon energy. This small quantum efficiency is attributed to the small volume of a single SWNT contributing to optical absorption. If we take into account the fact that the area of the nanotube channel is much smaller than the area of the incident laser spot, the net quantum efficiency is in the order of \( 10^{-4} \).

Next, we focus on the threshold voltage shift caused by the laser illumination as shown in Fig. 4. If the device is biased at \( V_{GS} = -7 \) V near the threshold voltage, a large variation of drain current of \( \approx 58 \) nA is caused by the optical
input. This inverter-switching action to the optical input is due to the threshold voltage shift under the laser illumination. Figure 9 shows the threshold voltage shift and the drain current variation as a function of incident laser power. Here, $V_{GS} = -7$ V. Threshold voltage decreased with increasing incident laser power and saturated at $-7.5$ V, and the maximum threshold voltage shift was $-2$ V. The direction of the threshold voltage shift was negative. This suggests that positive charges were accumulated near the nanotube channel, because the carrier type in the nanotube FET is a hole. A detailed study of the mechanism of the threshold voltage shift will be a subject for further investigation.

The maximum current variation of $-58$ nA at $V_{GS} = -7$ V corresponds to a responsivity of $\approx 2 \times 10^{-3}$ A/W, which is extremely high considering a single SWNT channel. The high responsivity to the optical input is considered the field-effect amplification phenomenon. In conventional semiconductor FETs such as $n$-GaAs FETs, variation of the threshold voltage occurs as a consequence of the non-equilibrium process induced by the electron hole generation in the illuminated depletion layer beneath the gate. This has the same effect as applying a forward bias to the gate, resulting in a large increase in the drain current. In the case of this nanotube FET, the drain current is controlled by the Schottky barrier which is formed at the interface between the nanotube channel and the source electrode (Schottky barrier modulation model). The positive charges that were created by photo excitation accumulated near the nanotube channel. This has the effect of increasing the thickness of the Schottky barrier similar to the effect of the positive gate field, resulting in the large decrease in the drain current.

4. Summary

The photoresponse of carbon nanotube field-effect transistors (FETs) was investigated by using microscopic measurements. The nanotube FETs with an isolated SWNT as the channel were fabricated by means of the position-controlled nanotube growth technique. An increase in the off-state current and threshold voltage shift of the FET were caused by laser illumination. The increase in the off-state current was attributed to the photocurrent caused by the carriers excited in the SWNT channel. The excitations of the photocurrent had a peak corresponding to optical absorption by the third interband gap of the van Hove singularity of the semiconducting SWNT with a diameter of $\approx 2$ nm. The photocurrent increased in proportion to the incident laser power with a dynamic range over four orders of magnitude. The external quantum efficiency was $2 \times 10^{-7}$. An inverter action to optical signal input was observed near the threshold voltage of the FET. The responsivity was as high as $2 \times 10^{-3}$ A/W for a single SWNT channel. This high responsivity was explained by the field-effect amplification phenomenon.

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