Coulomb peak shifts under terahertz-wave irradiation in carbon nanotube single-electron transistors

T. Fuse, Y. Kawano, and M. Suzuki

Advanced Device Laboratory, The Institute of Physical and Chemical Research (RIKEN), 2-1, Hirosawa, Wako, Saitama 351-0198, Japan

Y. Aoyagi

Department of Information Processing, Tokyo Institute of Technology, 4259, Nagatsuta-cho, Midori-ku, Yokohama 226-8503, Japan

K. Ishibashi

Advanced Device Laboratory, The Institute of Physical and Chemical Research (RIKEN), 2-1, Hirosawa, Wako, Saitama 351-0198, Japan

(Received 17 October 2006; accepted 1 December 2006; published online 5 January 2007)

The authors have studied the effect of terahertz irradiation on single-electron transistors (SETs) based on single-wall carbon nanotubes, and have observed that the radiation generates Coulomb peak shifts. Time-resolved measurements of the terahertz response have revealed that the peak-shift signal has very long time constants, measured in seconds, and that the time trace of the signal after the terahertz irradiation is turned off deviates from a single-exponential curve. These experimental results suggest that the terahertz irradiation causes a charging process in trap states in the close vicinity of the SET, leading to a change in its effective gate voltage. © 2007 American Institute of Physics. [DOI: 10.1063/1.2430078]

Single-wall carbon nanotubes (SWNTs) with extremely small diameters (~1 nm) offer the promise of realizing uniquely powerful electronic and optical devices.1–4 Single-electron transistors (SETs) based on SWNTs are particularly attractive because their much smaller size allows higher-temperature (in principle, room temperature) operation than do conventional SETs formed in a two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure.5–7 We have recently observed terahertz-photon-assisted tunneling in SWNT-SETs.8 This new finding suggests the interesting possibility using the SWNT-SET as a highly sensitive detector in the terahertz region. Such a device is strongly in demand in various research fields, such as radio astronomy, biochemical spectroscopy, and medicine, as well as solid-state physics. In this letter, we discuss another type of terahertz response of SWNT-SETs: Coulomb peak shifts induced by terahertz irradiations. From time-resolved measurements of the terahertz response, we have found that the recovery process of the peak shift after the terahertz irradiation is turned off is characterized by seconds long time constants and a nonexponential form. These features could be interpreted as arising from terahertz-induced charging processes of trap states close to the SWNT-SETs, which, in turn, change the electrostatic potential in the SWNT-SETs. We have observed that the present terahertz sensing can function in a standard 4He refrigerator and that the response signal is detectable, even for extremely weak terahertz illuminations (~1 fW). These results lead us to expect that the SWNT-SET could be used as a practical, high performance terahertz detector.

The inset of Fig. 1(a) displays a scanning electron microscope image of our SWNT-SET and a schematic drawing of the device structure. The SWNT with a diameter of ~1 nm is used to make a SET by placing it between source and drain electrodes with an interval of ~300 nm, deposited on a highly doped silicon substrate with a thermally oxidized surface of ~200 nm thickness. In this device, a metal sheet...
detected by the peak shift and the recovery in the Coulomb blockade regime. In order to investigate the recovery dynamics of the peak shift, we replotted, with a logarithmic scale, the recovery curve of $I_{sd}$ just after switching off the terahertz irradiation, and display it in Fig. 2(c). The $I_{sd}$ curve reveals that the recovery process is very slow, with the time constant being on the order of seconds. Furthermore, it shows that the curve deviates from a simple single-exponential form and includes slower components as well.

Based on the features presented above, we discuss the mechanism of the terahertz response of the SWNT-SET. The very slow relaxation kinetics observed suggest that the terahertz response does not originate from electronic processes inside the SWNT-SET. In general, a nonexponential process is characteristic of dynamics in the presence of some disorder.\textsuperscript{10} It is well known that there are many trap and impurity states in the SiO$_2$ layer,\textsuperscript{11,12} on which the SWNT-SETs were placed, and that they typically have shallow energy levels of several meV. When a terahertz wave with a photon energy higher than a value of several meV irradiates the SET sample, the electrons captured in one disorder site can be excited, and then can travel to other disorder sites. It is therefore possible that the photoexcited electrons are trapped within disorder sites in the close vicinity of the SET. Such excess electrons produce additional electric fields and are equivalent to the application of a “negative” $V_g$ for the SET. This effect manifests itself as the appearance of a Coulomb peak shift in the direction of the “positive” $V_g$ to compensate for the generation of the additionally negative $V_g$ mentioned above. When the terahertz irradiation is turned off, the excited electrons will release their excess energy, and the whole system will eventually return to an equilibrium state. Because of the existence of a number of disorder sites, this relaxation process is expected to include multiple-step relaxations with different time constants. This supposition is actually observed in the $I_{sd}$ curve in Fig. 2(c). Assuming that most of the trap sites are located at the interface between Si and SiO$_2$,\textsuperscript{11} and considering a typical trap site density of $10^{10}$ cm$^{-2}$ and the SiO$_2$ thickness of $\sim$200 nm, we roughly estimate that the potential change for the SET via an electron trapping event is 1.8 mV, the order of which agrees with the measured peak shift of 3.6 meV. At a frequency of 1.6 THz ($\hbar \nu$=6.7 meV), we carried out the same measurement as in Fig. 2 and obtained similar results, a finding indicating that the trap levels are shallower than 6.7 meV. We expect that measuring an excitation spectrum of the terahertz response would provide more detailed information on energy states of relevant traps. Such a spectroscopic study is our next step.

In order to examine how well the SWNT-SET can sense weak terahertz illumination, we shone a terahertz cyclotron emission with a typical output power of 50 fW, which is far weaker than the terahertz laser. The cyclotron emission is radiated from a 2DEG in GaAs/AlGaAs heterostructures under a magnetic field of 6.9 T, where the corresponding wavelength is 105 $\mu$m. We then modulated, at 24 Hz, the amplitude of the terahertz emission between zero and a finite value and monitored the change $\Delta I_{sd}$ in $I_{sd}$ with a lock-in amplifier. By this means, we measured $\Delta I_{sd}$ vs $V_g$ for $V_{sd}$=−0.35 and 0.35 mV, and showed the results in Fig. 3. With this technique, even smaller peak shifts can be detected.\textsuperscript{13} The observed value of $\Delta I_{sd}$ is $\sim$1 pA, a few percent of the total current in the Coulomb peak. We observe that $\Delta I_{sd}$ is detectable even when the incident terahertz power becomes extremely weak.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2}
\caption{(a) Source-drain current $I_{sd}$ vs gate voltage $V_g$ with and without terahertz-wave irradiation. A terahertz laser with the frequency of 2.5 THz was used. (b) Time trace of $I_{sd}$ for an on/off sequence of the terahertz irradiation. These data were taken at the fixed value of $V_g$=−460.8 V, indicated by the arrow in Fig. 2 (c) Replot of current recovery curves (indicated by circles with error bars) measured just after turning off the terahertz-wave irradiation. The measured current is normalized such that the current value at the start time is $\theta$. The solid line indicates a first decay component, which is an exponential function with a time constant of 1.9 s.}
\end{figure}

\textbf{FIG. 2.} (a) Source-drain current $I_{sd}$ vs gate voltage $V_g$ with and without terahertz-wave irradiation. A terahertz laser with the frequency of 2.5 THz was used. (b) Time trace of $I_{sd}$ for an on/off sequence of the terahertz irradiation. These data were taken at the fixed value of $V_g$=−460.8 V, indicated by the arrow in Fig. 2 (c) Replot of current recovery curves (indicated by circles with error bars) measured just after turning off the terahertz-wave irradiation. The measured current is normalized such that the current value at the start time is $\theta$. The solid line indicates a first decay component, which is an exponential function with a time constant of 1.9 s.
extremely low (≈ 1 fW). This means that the SWNT-SET has a very high sensitivity to the charging process triggered by the terahertz irradiation.

In summary, we have observed Coulomb peak shifts caused by terahertz-wave irradiations in SWNT-based SETs. We suggest the following response mechanism: the terahertz irradiation induces a charging process in the trap states in the close vicinity of the SWNT-SET, a change which is equivalent to the application of an additional gate voltage for the SWNT-SET. We observe that the Coulomb peak shift is visible even for the extremely weak terahertz irradiation (≈ 1 fW). It should be noted also that this terahertz sensing can operate in a standard 4He refrigerator and without a magnetic field. These advantageous properties lead to potential applications of the SWNT-SETs in practical and powerful terahertz devices, which are inaccessible via conventional GaAs-2DEG- and aluminum-based SETs.

The authors thank M. Mihara in RIKEN for experimental assistance.

13As shown in Fig. 3, the polarity of the lock-in signal is altered for the polarity change in $V_{sd}$. This rules out the possibility that the observed signal is due to the rectification effect that arises from coupling with an electromagnetic wave (Ref. 14).