Fabrication of a Single-Electron Inverter in Single-Wall Carbon Nanotubes

To cite this article: Daiju Tsuya et al 2005 Jpn. J. Appl. Phys. 44 1588

View the article online for updates and enhancements.

Related content

- Synthesis of Single-Wall Carbon Nanotubes from Diesel Soot
  Takashi Uchida, Ojji Ohashi, Hironori Kawamoto et al.

- Self-oscillating inverter with bipolar transistors
  I Baciu, C D Cunan and M Florua

- Conductivity Decrease in Carbon Nanotubes Caused by Low-Acceleration Voltage Electron Irradiation
  Satoru Suzuki and Yoshihiro Kobayashi

Recent citations

- Effect of Quantum Hall State of Substrate on Single-Electron Transport of Carbon Nanotube Quantum Dots
  Tomohiro Yamaguchi et al

- SWCNT growth on Al/Fe/Mo investigated by in situ mass spectrometry
  S-M Kim et al
Fabrication of a Single-Electron Inverter in Single-Wall Carbon Nanotubes

Daiju TSUYA, Masaki SUZUKI, Yoshinobu Aoyagi, and Koji Ishibashi

1Advanced Device Laboratory, The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
2Department of Information Processing, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8503, Japan
3CREST, Japan Science and Technology (JST), Kawasaki, Saitama 332-0012, Japan

(Received October 8, 2004; accepted December 17, 2004; published April 8, 2005)

A single-electron inverter has been fabricated in single-wall carbon nanotubes (SWNTs) by connecting two single-electron transistors (SETs) in series. Each SET was fabricated in different SWNTs only by depositing metallic contacts on them. For one SET, SWNTs appeared to be single and semiconducting, while they appeared to form a bundle for the other SET. The inverter performance was obtained at 1.5 K with a full voltage swing and a gain of ~0.6, although the SETs were not fabricated from the simple individual metallic nanotubes. [DOI: 10.1143/JJAP.44.1588]

KEYWORDS: carbon nanotubes, coulomb blockade, single-electron transistor, single-electron inverter

1. Introduction

A single-electron inverter, based on the Coulomb blockade effect, is a basic device for single-electron logic, which would be one possible application of single electronics, and could have advantages such as low power consumption and possible scale-down to an atomic scale. To date, the single-electron inverter has been fabricated with metallic dots, Si dots, and multi-wall carbon nanotubes (MWNTs). An important requirement for the device is to make the dot size as small as possible to reduce the charging energy for a single electron, where is the self-capacitance of the dot, which results in a higher temperature operation. Single-wall carbon nanotubes (SWNTs) with a diameter of a few nanometers are a natural choice for building blocks of single-electron devices. The offset charge, which is always a concern for single-electron devices, might not be a serious concern for nanotube based devices, if nanotubes without any imperfections could be grown, and they could be suspended and separated from the substrate. In a previous paper, we reported on the fabrication of the single-electron inverter in an individual MWNT by applying local Ar beam irradiation for tunnel barrier formation. In the MWNT, the contact resistance between the metal and the MWNT is relatively low, so that the metal-MWNT junction shows Ohmic behavior even at low temperatures. Another advantage from the device process point of view might be that it is easy to find an individual MWNT using scanning electron microscope (SEM). On the other hand, the tunnel barrier needs to be formed artificially for the fabrication of a single-electron transistor (SET) and the charging energy cannot be smaller than its value in the SWNT. We have shown in the previous paper that the tunnel barrier could be fabricated to some extent in a controlled way, however, the unsatisfactory voltage swing of the inverter was attributed to the nonideal performance of each SET included in the inverter.

In this study, we take advantage of the easy formation of the tunnel barrier in the SWNT, simply by depositing metallic contacts on top of them, to fabricate a single-electron inverter. The two different SWNTs used for each SET had different transport properties, with respect to the carrier type; however, the inverter-like performance was obtained at 1.5 K with a full voltage swing and a voltage gain that was slightly smaller than one (~0.6). Although inverter performance was obtained with two SETs with different transport characteristics, it may not necessarily mean that the two SETs which compose the inverter does not need to be exactly identical.

2. Single-Electron Inverter and Characteristics of Each SET

Figure 1 shows (a) an equivalent circuit of the single-electron inverter, (b) a schematic drawing of device structures, and (c) a scanning electron microscope image of one of the two SETs. The single-electron inverter is composed of two independent SETs connected in series. A Coulomb peak of each SET, adjusted out of phase, is used as a complementary switch for the inverter operation. The peak

---

*E-mail address: kishiba@riken.jp

---

Fig. 1. (a) Equivalent circuit of single-electron inverter. (b) Schematic drawing of device configuration. (c) SEM image of one of two SETs.
position of each SET was shifted by applying voltage to the side gates ($V_1$ and $V_2$), fabricated at a position close to each SET on the substrate. For this device, each SET was fabricated in two different SWNTs that were separated by a distance of more than 10 $\mu$m [Fig. 1(b)], to reduce a cross capacitance, such as the one between $V_1$ and SET2. A heavily doped substrate was used for the common input gate.

Figure 2 shows Coulomb blockade characteristics of each SET, the Coulomb oscillations as a function of back-gate voltage with various side-gate voltages. For the measurements, each SET was independently investigated, where the circuit for one SET was open while the other SET was investigated. Almost periodic oscillations are observed for both devices, and the peaks shift almost linearly as the side-gate voltage is applied. We should admit that SET1 happened to be fabricated in an individual semiconducting SWNT. For SET1, the metallic tube is likely to be dominant, with electrons as carriers, while holes are the dominant carriers for SET2. At the moment, we cannot distinguish, in our device fabrication process, whether SWNTs used are semiconducting or metallic as well as if they are bundled or individual before the measurement. The effect of this nonuniformity between the two SETs is discussed later. The typical parameters of each SET are obtained from Fig. 2 and the data of the Coulomb diamonds (not shown here) and are estimated roughly as follows: $E_C \sim 15$ meV, $C_C \sim 10$ aF and $C_g \sim 6$ aF for SET1, and $E_C \sim 12$ meV, $C_C \sim 13$ aF and $C_g \sim 5$ aF for SET2. $\Delta V_p/\Delta V_i$ ($i = 1$ or 2), which indicates the amount of the peak shift due to the side-gate voltage and is a measure of the effectiveness of the side gate, is $-0.016$ for SET1 and $-0.007$ for SET2. Despite the difference in the two SETs in terms of carrier and conduction type, both SETs appear to be similar in terms of the general features of the Coulomb oscillations and the parameters associated with the dots.

The single-electron inverter is composed of two independent SETs connected in series without any quantum mechanical (tunneling) or classical (capacitive) coupling between the dots. To check this, we measured a charge stability diagram for this sample as a two series-dot system, and the result is shown in Fig. 3, where current is plotted in gray scale as a function of the two side-gate voltages ($V_1$ and $V_2$) for the fixed $V_{B0} = 0.5$ mV. The charge stability diagram in Fig. 3(a) shows a gridlike black pattern where current flows. In the white region, current is suppressed due to the Coulomb blockade effect. Figures 3(b) and 3(c) show the corresponding Coulomb oscillations as a function of the side-gate voltage ($V_1$ or $V_2$) when the other gate voltage is set at an appropriate value. The rectangular gridlike pattern in Fig. 3(a) indicates that the cross-capacitance can also be ignored. Another important fact is that the black area, where current flows, does not appear to show any clear splitting, indicating the absence of capacitive or tunneling coupling between the two dots. These results demonstrate that the two SETs are independent. This, of course, is reasonable for the SETs that are connected with macroscopic metallic leads and are separated by more than 10 $\mu$m. The absence of the cross-capacitances makes it possible for the independent peak shift to realize the inverter condition. The side-gate capacitance of SET1 and SET2 is 0.08 aF and 0.02 aF, respectively.

3. Performance of Single-Electron Inverter and Discussion

Having investigated the Coulomb blockade characteristics...
of each SET and the interaction between the two SETs, we now show the inverter performance at $T = 1.5\, \text{K}$. Figure 4(a) shows the Coulomb peak in each SET, shifted using the side-gate voltage to the appropriate positions for the inverter operation. One SET is "on" (Coulomb blockade lifted), while the other SET is "off" (Coulomb blockade) as a function of $V_g$. The inverter performance obtained (transfer characteristics) is shown in Fig. 4(b) for $V_{DD} = 4\, \text{mV}$. As seen in the figure, when the input voltage ($V_{IN}$) is "low", the output voltage ($V_{OUT}$) is "high" and visa versa, the inverter-like characteristic. The on–off characteristics of each SET are also shown in the $I–V$ curves at the value of $V_{IN}$ for which $V_{OUT}$ is maximum [Fig. 4(c)] and $V_{OUT}$ is minimum [Fig. 4(d)]. For this device, the inverter-like characteristics were observed up to ~$10\, \text{K}$, where the Coulomb blockade effect began to fade. The operating temperature for our device is not limited by the charging energy, but it seems to be limited by the tunnel barrier height, the details of which will be reported elsewhere.$^{10}$

The voltage swing is sufficiently large, but the voltage gain that is a maximum slope of the transfer curve is ~$0.6$, less than one. The large voltage swing is attributed to good on–off characteristics of each SET, as shown in Figs. 4(c) and 4(d). The small inverter gain is related to the gain of each SET itself.$^{11}$ It is roughly ~$1.0$ for SET1 and ~$0.7$ for SET2, which are estimated from Coulomb diamond measurements of each SET. It should be noted that the Coulomb diamond shape varied to some extent as the number of electrons was changed, so that it was not possible to obtain an exact gain value of each SET. To increase the gain, the gate capacitance has to be increased. In this device, a heavily doped silicon substrate with a thermally oxidized insulating layer of ~$100\, \text{nm}$ was used for the input gate. To use the substrate as an input gate is not appropriate for the integration of many SET devices, and an improved device process that makes the integration possible needs to be developed. Planar device structures, used in standard semiconductor devices, may be useful also for nanotube devices, and by reducing the thickness of the insulating layer, the gain could be improved as a result of the increase in gate-capacitance. In this case, top gate structures might be used.

In this device, each SET was not identically fabricated, in that the two SETs were made of different types of nanotube, namely bundle or individual, and were either metallic or semiconducting. The carrier types were different in the two SETs, and the Coulomb peaks in both SETs were not completely periodic. The latter observation may indicate that the SETs were made of multidots with a possible dominant dot, and hence the Coulomb blockade effects there might be stochastic to some extent. However, the difference in the two SETs and the nonideal characteristics of each SET may not necessarily hinder the inverter operation, as long as the following requirements are met, since the inverter makes use of only one Coulomb peak among the many peaks. This suggestion could be applicable for any SET inverter devices made of different materials. Despite the experimental conditions used, the inverter-like performance was observed in this device. If the operating principle of the single-electron inverter is understood with a simple "on–off"-type argument of each SET switch as has been mentioned, inverter performance may be obtained regardless of the quality of the inverter when the following requirements are met. First, Coulomb peaks have to be similar for both SETs in terms of gate capacitance and conversion factor, and second, sufficiently large $I–V$ curve differences are necessary between the on and off states for both SETs. In this regard, the present two SETs meet the requirements, as indicated in Figs. 4(a), 4(c) and 4(d). More detailed investigation is necessary for the best performance of the inverter. For example, the high-frequency characteristics may be affected by the nature of each SET, and SETs made of multidots do not appear to be appropriate, since many capacitive couplings exist, which reduce the speed of the device. As for the carrier type differences in each SET, the Coulomb blockade characteristics of an ambipolar SET have recently been reported.$^{12}$ It seems that the characteristics appear to be symmetric between electrons and holes, which might be reasonable from the simple symmetric band structures of carbon nanotubes. This fact may become an advantage, in that the carrier type difference should not be a problem for inverter performance. However, a SET inverter with identical characteristics may be required for more reliable operation in integrated circuits with many SET inverters.

The problem of fabricating a single-electron inverter in carbon nanotubes may be that the height of the Coulomb peaks varies so much in a specific SET, that the peaks with a similar height need to be selected and shifted to use as a switch for any combination of two SETs. This fact may not be a good feature for future integration of many inverter circuits. Each inverter has to be tuned differently by the side gate. The large variation of peak height is frequently observed in semiconductor SETs$^{13}$ in which the quantum confinement in the dot becomes important, and it may be attributed to the variation in the coupling between the each quantum level in the dot and the electrodes. This fact seems to be essential for any SET with important quantum states in the dot. In fact, the metallic SET usually shows uniform
Coulomb oscillations with similar Coulomb peaks, in which the effect of the quantum level spacing is not important in the dot. Similar arguments are possible in the SWNT-SET, in which the effect of the quantum state in the dot increases due to the smaller dot size. To solve this problem is not easy, but it is obviously important to increase the carrier concentration of carbon nanotubes, which may be possible by incorporating something such as a metal fullerene inside the nanotube to serve as an electron donor.

4. Conclusions

In conclusion, we have fabricated single-electron inverters with two different SWNTs, and the performance was measured at 1.5 K. The inverter-like performance was obtained, but the voltage gain must be improved. Despite the fact that the two SETs showed different Coulomb blockade behavior, the device worked as an inverter with a sufficiently large voltage swing. We have shown that deviation from the ideal SET performance does not necessarily hinder the inverter performance and have pointed out the minimum requirements for each SET performance based on the simplest “on–off” switch model to explain our results.