Multiple-layer conduction and scattering property in multi-walled carbon nanotubes

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Abstract. We present a review of recent fundamental transport research in multi-walled carbon nanotubes (MWNTs). Although carbon nanotubes are showing great promise as nanometre-scale material for advanced device applications, we need a fundamental understanding of the nanotube electrical properties for the conduction mechanism. In particular, MWNT can pass a remarkably high-density current of more than $10^8$ A cm$^{-2}$ in a few tens of nm order. In the high-density current operation, a current-flow mechanism of the multiple-layer structure in current conduction is not clear. Furthermore, there is an unclear fundamental issue regarding the scattering property of an MWNT. Experimental results related to the basic transport property of the lithographically contacted MWNT are discussed in this paper.
1. Introduction

Carbon nanotubes are a novel material system [1]–[4] whose unique properties offer intriguing possibilities [5]–[32] for the fabrication of nanometre-scale molecular electronic devices. Carbon nanotubes can be thought of as naturally occurring nanosize bricks that could act as base components for nano-electronics. By building up the nanobricks, nanoscale device structures, which cannot be fabricated from three-dimensional bulk materials, can be constructed. Prior to construction, there are a number of issues to be addressed.

There are two kinds of nanotube—single-wall carbon nanotube (SWNT) and multi-walled carbon nanotube (MWNT) [2]–[4]. The SWNTs tend to form a bundled structure, which contains many SWNTs of various lengths. It is quite difficult to resolve the SWNT bundle into the individual SWNTs. When we use the bundle of SWNTs as a channel between the two metal contacts, we do not know which tubes in the SWNT bundles bridge over the two contacts. Some of the SWNTs are disconnected between the two contacts. This bundled structure is too complex for the application of the electric device. On the other hand, individual MWNTs can be easily resolved. However, the MWNTs have many unexplained features, e.g. how the multi-layered structure affects electrical conduction in the MWNT devices. Surprisingly, the MWNT can pass a high-density current of more than $10^8$ A cm$^{-2}$, although its cross-section is of the order of a few tens of nm [8]. In relation to the transport mechanism of the MWNT, the unveiled properties of the MWNT will be discussed in this paper.

2. Experimental procedure

2.1. Device fabrication [25]–[30]

For the high-density current, the conduction pass in the MWNT with concentric multiple nanotubes has not been clearly understood. In a low-bias-voltage region, Bachtold et al [9] and Fujiwara et al [10] showed that the outermost nanotube in the MWNT mainly contributed...
to the current conduction by observing the quantum interference effect. In a high-bias-voltage region, Collins et al [11, 12] pointed out the contribution of some outer layers in the MWNT to the current conduction. Using a double-walled nanotube, Kociak et al [13] showed that a charge transport from an outermost nanotube to an inner nanotube might be a tunnel transport. Although it is generally thought that thermally activated carriers dominate the interlayer charge transport, the direct conduction measurement between an outer nanotube and an adjacent inner nanotube could be difficult. The current in the two-terminal device mainly conducts through an outermost nanotube because the outermost nanotube path maintains the lowest resistance. Then, the indirect conduction through inter-nanotube junctions is not clearly seen. To see the indirect conduction directly, one can carefully disconnect the outermost nanotube in an MWNT. In the temperature dependence of such system, Collins et al [11, 12] deduced that the thermal activation energy to feed the conduction charges into the inter-nanotube to be larger than 120 meV.

The MWNTs were produced by an arc-discharge method and used without further treatment to avoid introduction of extra damage into the MWNTs. All the MWNTs described in this paper were made in a synthesis batch. The typical nanotube diameter was about 10 nm. After the deposition of MWNTs on a Si/SiO₂ wafer with predefined alignment markers, the position of a particular MWNT was determined using scanning electron microscopy (SEM). To reduce extra damage introduced into the MWNT in the SEM observation, the magnification of the microscope is kept below ×10,000 with an acceleration voltage of 30 keV. Then, electrodes in a two-probe configuration or in a four-probe configuration were made by e-beam lithography and thermal deposition of the metal electrode. The base pressure of the evaporation chamber was kept below 1 × 10⁻⁶ Torr during evaporation. Figure 1(a) shows an SEM image of a Pt/Au-contacted sample. The MWNT of a length of a few µm lies beneath the source and drain electrodes. The electrodes typically have a thickness of 5 nm of Pt and 40–80 nm of Au. In this device, we examined the two-probe current–voltage (I–V) characteristic in more than 50 MWNT devices at room temperature (RT) or at 4.2 K. To see the quality of the MWNT, electric degradation is a useful method. All the MWNTs, including those that were randomly selected in the synthesis batch and the lithographically formed electric contacts, show clear break-down steps stemming from the rigid multiple-layer structures contained in the MWNT. Since highly defective nanographite fibres never show clear break-down steps [30], the quality of the MWNTs we used in this experiment should be reasonably good in comparison with the defective graphite fibre.

2.2. Current conduction in MWNT or in SWNT

In this section, we investigate electrical conduction in single MWNT, and propose a model of interlayer current switching in the MWNT. For a first understanding of the I–V characteristics in carbon nanotubes, we compared the RT I–V characteristics of a single MWNT and a bundle of SWNTs contacted with Pt/Au ohmic contacts (figure 2). Figure 2(a) shows a typical two-probe source–drain current–voltage (Iₘₚ–Vₘₚ) characteristic in the MWNT as a function of bias voltage Vₘₚ in vacuum at RT. The Iₘₚ–Vₘₚ characteristics between air and vacuum shows very little difference except for a nanotube degradation at the high-bias regime. In a low-bias-voltage region between 0 and 0.1 V, all the devices show ohmic characteristics with the resistances between 20 and 150 kΩ. At a high-bias voltage about 2 V, the current value reached up to about 0.1 mA. In an intermediate voltage range between 0.2 and 0.8 V, we found a clear conduction increase showing a current kink in the Iₘₚ–Vₘₚ characteristic.
Figure 1. An SEM image of (a) as-grown soot of MWNTs used in this experiment and (b) an MWNT placed on the number ‘26’. A lithographically contacted MWNT device image with electrodes (c), and centre part of the device (d). Optical microscope image of the device connected to the outer bonding pads (e), and a whole area image of the device chip (f).

When the $I_{sd}-V_{sd}$ measurement in the SWNT bundles was made (figure 2(b)), no current enhancement was observed. In a comparison of the MWNT device with the SWNT bundle device, we attributed the current enhancement to a structural difference between the MWNT and SWNT. On the basis of the concentric layer structure in the MWNT, we propose an interlayer current switching model in which a current can be injected from the outer nanotube into the inner nanotubes by applying a high-bias voltage. In this model, we assumed there are tunnelling barriers between the layers, and the current channel is the outer nanotube at a low bias and is opened to the inner tubes at a high-bias voltage. A threshold voltage $V_0$ at which the enhancement current starts to flow is plotted in figure 2(c). The average of the threshold voltages for the 12 MWNTs was 0.58 V. In the $I_{sd}-V_{sd}$ characteristics of the MWNTs, there is no multiple enhancement point originating in the multiple nanotube layer structure. Even at 4.2 K, the $I_{sd}-V_{sd}$ characteristic did not show a clear difference compared with the RT characteristic. This could be caused by a self-heating effect in the MWNT by the high power consumption. To explain the observed results, thin inter-nanotube tunnelling barriers at each space between the nanotubes are required (figure 2(d)). If we assume that the charge tunnelling behaved similar to the Fowler–Nordheim (FN) tunnelling event, most of the current flowed through the outermost nanotube and only a small current was injected into the second nanotube at the low-bias voltage (figure 2(e)). Actually, when we fit the observed $I_{sd}-V_{sd}$ characteristic by a two-nanotube conduction model governed by the FN tunnelling, the observed $I_{sd}-V_{sd}$ characteristic was completely traced by the fitting curve. For the FN model,
we need a further assumption: nanotube transport is not ballistic, but rather resistive because all the current flow through only the outermost nanotube if the outermost tube is less resistive and the current cannot be injected into the inner nanotube. This property will be addressed in sections 2.4–2.6. As a possible explanation for the conduction increase, we discuss the intra-nanotube switching effect [31, 32]. In an ideal 10 nm nanotube, there are subbands at every 122 meV. Then, when we apply a high-bias voltage, probably, multiple subbands are opened to conduction. If this occurred in the measurement, the conduction increase would be multiple or continuous instead of the single increase point followed by a superlinear region observed in our experiment. Then, our experimental result supports the assumption that an MWNT with electric contacts is not in the ideal nanotube condition as predicted by theoretical studies.
2.3. A tunnelling device based on the layer space barrier [27]

Based on the model of the inter-nanotube tunnelling barrier, we proposed a tunnelling device fabricated using an MWNT and demonstrated the proposed device. The proposed device structure was a single electron tunnelling (SET) device [31]. By disconnecting the outermost nanotube in the MWNT, we made the SET device and clearly observed the direct conduction through the inter-nanotube tunnelling junctions in the MWNT.

The device composed of a single MWNT with four ohmic electrodes (figure 3(a)). After confirming the ohmic properties of each two-probe MWNT sections, an extra MWNT region between electrodes 1 and 2 was disconnected by keeping a high-bias voltage applied between the two electrodes in air (figure 3(b)). The high-density current could heat up the MWNT and easily burn the MWNT layers one by one [11, 12]. While keeping the fixed bias voltage, the $I_{sd}$ dropped in a series of abrupt steps. Each current step corresponds to sequential destruction of the nanotube layers from the outer layers contained in a concentric MWNT. When we cut down all the layers, we will know the total number of layers. In this experiment, the number of shells was eight. This cut-down process also made the length of the MWNT shorter. The cut-down process was also applied to another MWNT region between electrodes 3 and 4. Then, the MWNT length, originally 5 $\mu$m, was shortened to 1.4 $\mu$m in the middle MWNT region. The shorter MWNT increases the charging energy of the tunnelling island in the SET device. Before and after the cut-down process, there was no change in resistance between electrodes 2 and 3.

Subsequently, the nanotubes in the middle MWNT region, between electrodes 2 and 3, were removed gradually in the same manner as described above. When we disconnected seven of the eight nanotubes in the MWNT, a continuous SWNT with multiple tunnel junctions was formed as illustrated in figure 3(c). Since the disconnected outer tubes formed a series of concentric multiple dots, the two-terminal conduction was through the multiple inter-nanotube junctions (figure 3(d)).

We cooled the device to 4.2 K and measured the electrical characteristics. When the gate voltage ($V_g$) was continuously changed, $I_{sd}$ with a fixed bias voltage oscillated as shown in figure 3(e). The oscillation amplitude becomes larger on increasing the bias voltage. In figure 3(f), the suppressed current regions at a low-bias voltage were modulated by varying $V_g$. The current suppression oscillations are known to be due to a Coulomb blockade effect. The observed non-periodic oscillations of $V_g$ characteristic indicated a model of multiple tunnel junctions. The observed charging energy is about 15 meV, and the total capacitance is deduced to be 11 aF.

2.4. Charge tunnelling control between the nanotubes by $V_g$ and scattering property in MWNT under a Coulomb potential [29]

To explain the conduction increase in the MWNT, we made a second assumption that the MWNT was resistive. Based on the assumption, charge transport in the MWNT must be sensitive to charged particles located near the MWNT channel. Regarding the scattering property of the MWNT, we made an MWNT channel with an additional electrically floating MWNT piece.

Two nanotubes crossing together have a tunnelling barrier between the two nanotubes. There have been experimental and theoretical reports on the transport in a junction between two nanotubes with various properties, commonly showing the high tunnelling resistance [14]–[20]. In a two-MWNT crossing together (figures 4(a) and (b)), we use a main MWNT as the current channel and an additional MWNT as an electrically floating node. In this system, we can control...
Figure 3. (a) An SEM image of our MWNT device. Four Pt/Au probe electrodes are placed on a single MWNT. (b) A schematic cross-section of the MWNT device. Before (top) and after (middle) the electric degradation of the MWNT at the MWNT region 1–2 and the region 3–4 (the extra MWNT region). The extra MWNT regions are used to count the total number of layers in the MWNT (bottom). The MWNT with eight nanotubes between electrodes 2 and 3 is thinned by disconnecting the seven nanotubes. For this process, a $V_B$ of approximately 4.3 V was applied. In an SEM observation, at the disconnected part of the MWNT, there was a thinned region. An initial two-terminal resistance at 4.2 K was 38 kΩ, and the resistance increased to over 1 MΩ after disconnecting seven layers. A schematic device structure with multiple tunnelling junctions formed in an MWNT (c), and circuit diagram (d). (e) A source–drain current ($I_{sd}$) at the source–drain voltage ($V_{sd}$) of 3, 5, 7 and 9 mV at 4.2 K as a function of $V_g$. (f) A three-dimensional plot of $I_{sd}$–$V_{sd}$ characteristics with various $V_g$ values to show the Coulomb blockade effect at 4.2 K in the MWNT device.

charge transfer between the two carbon nanotubes. This structure (figures 4(a) and (b)) is a flash-memory type configuration.

Two electric contacts were lithographically defined on only the longer MWNT for the current channel (channel-MWNT). The shorter MWNT was used as a floating node (node-MWNT), which was a charge-storage node. The two MWNTs were approximately 10 nm in diameter. In addition, a gate electrode was attached 2 μm away from the two crossed MWNTs.
Figure 4. (a) An SEM image of the memory device composed of two MWNTs. An upper MWNT (10 nm in diameter and 5 µm in length) was used as the current channel with ohmic electrodes and a second MWNT (10 nm in diameter and 2 µm in length) was used as the floating memory node located underneath the channel-MWNT. The source and drain electrodes are separated by 2 µm. The node MWNT forms an unexpected ring. (b) A schematic view of the device. (c) Hysteresis loop of $I_{sd}$ in the $V_g$ cyclic scan at 4.2 K. $V_{sd}$ was fixed at 70 mV, and $V_g$ was applied from 0 to 5 V and back to 0 V. The bold arrows show the directions of the hysteresis loop. The inset shows schematic images of the charged and discharged nodes. (d) Hysteresis loops for five different $V_{sd}$ values at 4.2 K. The size of the hysteresis loop depends on $V_{sd}$. (e) Normalized five hysteresis loops. To normalize the hysteresis loops, $I_{sd}/I_0$ was determined for each current at $V_g = 0$. (f) Hysteresis loops of $I_{sd}$ depending on the scanning range ($\Delta V_g$) of $V_g$ at 4.2 K. (g) A plot of $\Delta I_{sd}$ taken from (f) by changing $V_g$. The solid line is drawn as a least-squares fit to the measured data and shows no hysteresis region below $\Delta V_g$ of 2 V.

A gate capacitance ($C_g$) of 0.8 aF is estimated from $C_g = 0.2 \, \text{V} / 1.8 \times 10^{-19} \, \text{C}$. The value of the gate capacitor is nearly consistent with a capacitance value estimated from a structural configuration.

At RT in the three-terminal measurement, the channel-MWNT exhibited ohmic properties with a resistance of 67 kΩ that did not change by applying $V_g$. The MWNT with no gating effect may be belonging to the metallic type. When the device was cooled to 4.2 K, however, the resistance of the channel-MWNT was changed by applying $V_g$. 

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In a cyclic scan of the $V_g$ between 0 and 5 V, a clear smooth hysteresis loop was observed (figure 4(c)). There is no explanation for the hysteresis loop in the MWNT itself, but this hysteresis loop could be explained by a controllable charge transfer based on the charging and discharging effects of the node-MWNT. When the charges were transferred from the node-MWNT to the channel-MWNT, the Coulomb potential from the charged node-MWNT changed the current flow in the channel-MWNT, and the resistance was changed. The transferred charges were assumed to be holes because of the intrinsic carriers in the carbon nanotubes. From the size of the node-MWNT in the device, the charging energy of the node-MWNT was estimated to be 0.12 meV, which is lower than the thermal energy at 4.2 K. Thus, the observed smooth hysteresis loop, instead of discrete steps caused by the discrete charging effect on the node-MWNT due to the Coulomb blockade effect, is reasonable.

Regarding the observed result, an important scattering property of the MWNT should be discussed. The observed hysteresis loop indicates that the transport in the MWNT is sensitive to the charged particle located near the MWNT channel. Since the original nanotube must be less sensitive to the Coulomb potential if the nanotube is metallic, it is assumed that our channel-MWNT might be highly doped in air and the Fermi energy reached a higher subband, resulting in a sensitivity to the background Coulomb potential. The nanotube in this condition drastically differs from the ideal nanotube predicted, where a long-range Coulomb potential would not affect the transport in metallic nanotubes if the Fermi energy in the nanotube is within the first energy-dispersion band [23, 24]. So far, the ballistic transport in the nanotube has been reported to be a quantized transport of a two-terminal measurement through an MWNT fixed at the tip of an atomic force microscope (AFM) [5]. They also claimed that the lithographically contacted nanotube tends to be doped in the fabrication process. If all the lithographically contacted nanotubes on the substrate are doped, it is important to clarify whether the ballistic property can be realized in an electric device structure with electric contacts on a substrate.

As another possibility of the origin of the hysteresis loop, the charge trap in the underlying SiO$_2$/Si substrate [22, 32] can be mentioned. However, in our device with the node-MWNT, we can estimate a value of the capacitor between the gate and node-MWNT from an electric property and a structural configuration. These values are roughly consistent together, indicating that the intentional structure of the node-MWNT behaves as a charge trap instead of the uncontrollable traps in the SiO$_2$/Si substrate.

The current hysteresis loop depends on the scanning range of the applied bias voltage (figure 4(d)). By changing $V_{sd}$ from 30 to 70 mV, the hysteresis loop size was increased. However, five normalized hysteresis loops, with current in the channel-MWNT divided by $I_0$ at $V_g = 0$ V, were overlapped together (figure 4(e)). The loops indicate that the measured transport in the channel-MWNT is within the linear response region for the applied $V_{sd}$.

The $V_g$ scanning range ($\Delta V_g$) also changes the hysteresis loop (figure 4(f)). The size of the hysteresis loop defined as $\Delta I_{sd}$ increased with increasing $\Delta V_g$. By extending the least-squares fit to the measured data (solid line in figure 4(g)), the line crosses the $\Delta V_g$ axis at 0.2 V. Below 0.2 V, no charge transfer between the two crossed MWNTs through the tunnelling barriers occurs. Assuming that a single charge is transferred at $\Delta V_g = 0.2$ V and the channel-MWNT detects a single charge transfer, we can estimate the gate capacitance ($C_g$) to be 0.8 aF. By using the estimated gate capacitance, the number of charges trapped in the node-MWNT is estimated to be about 24 for $\Delta V_g = 5$ V. Since some thermally activated charges in the node-MWNT may escape from the node, the maximum capacity of the charges trapped in the node-MWNT may be larger than estimated.
Figure 5. (a) An SEM image of a memory device composed of an MWNT and Au-colloidal particles. The MWNT is 10 nm in diameter. For the Au-colloidal particles, we used 10 nm particles supplied by ICN Biomedicals (cat#678011). The nanotube with ohmic contacts is used as a current channel to sense the charging state on the Au-colloidal particles. (b) Schematic of the device structure. (c) $V_g$ characteristic of the $I_{sd}$ with a fixed bias voltage of 50 mV. A clear hysteresis loop with discrete steps is observed in a cyclic scan of $V_g$. Measurements were carried out at 4.2 K. These steps include many noise-like unexpected jumps due to thermal excitation.

2.5. Single-charge sensitivity of MWNT transport by controlling the tunnelling charge between a nanotube and nanoparticle

For a more precise control of the single-charge tunnelling, we used Au-colloidal particles as the floating node instead of a piece of MWNT (figures 5(a) and (b)).
A typical diameter of the Au-colloidal particle is about 10 nm with a charging energy $E_c \sim 50 \text{meV.}$ On the channel-MWNT with two ohmic electrodes, the Au-colloidal particles were stacked. For the node formation, we first opened a small window on the electron beam PMMA resistance, and the surface of the opened area was chemically modified by $N$-[3-(trimethoxysilyl)propyl]ethylenediamine diluted with distilled water. In the SEM image of figure 5(a), we can see several Au particles on and near the channel-MWNT. A third electrode was attached away from the MWNT as a gate electrode to change the chemical potential of the Au-colloidal particles. Among the source, drain, gate electrode or the MWNT, no Au-particle chain responsible for a leakage current was formed.

In the measurement under a fixed bias voltage between the source and the drain, the $V_g$ was scanned between $-4$ and $2 \text{V.}$ The $I_{sd}$ in the $V_g$ scan shows a hysteresis loop at $4.2 \text{K}$ (figure 5(c)), and the loop disappeared at $15 \text{K.}$ In the hysteresis loop, discrete steps due to individual charge transfers between the MWNT and the colloidal particles were observed. Owing to the size of the individual Au-colloidal particles, the Coulomb blockade effect occurred in the individual colloidal particles at $4.2 \text{K}$ when the additional electron was transferred into the colloidal particle. Since step heights were not uniform, a few Au-colloidal particles with various influence of Coulomb potential to the channel-MWNT may contribute to the current steps in the hysteresis loop. The result clearly indicates a highly sensitive response of the MWNT to the Coulomb potential from the small number of trapped charges in the nano-particle node.

### 2.6. Influence of scattering property on high-current operation

As seen by the experimental results described in the previous sections, the MWNT with an electric contact on the substrate is diffusive. As shown by the experimental result, however, the high-current operation is possible. However, the slight inconsistency between these experimental results must be clarified. In this section, we focus on the scattering property in the high-density current operation state.

A typical $I_{sd} - V_{sd}$ plot of the MWNT, including the MWNT degradation process, is shown in figure 6(a). On increasing $V_{sd}$, $I_{sd}$ also increases. After reaching the highest current $I_B$, the MWNT...
begins to break down. Finally, the MWNT channel shows no current when the MWNT is completely disconnected. We characterize the break-down process in 25 MWNT devices with ohmic contacts. The SEM image is shown as an inset of figure 6(b), and the two terminal gap length was varied from 1 to 7 µm. All MWNTs break down in the same manner, and the break-down voltage (\(V_B\)) is plotted in figure 6(b). The \(V_B\) was typically a few volts for these MWNTs. When the two-terminal length was longer, \(V_B\) was higher. On the other hand, as shown in figure 6(c), the break-down current (\(I_B\)) was almost constant at 0.13 mA. If we assume the transport in the MWNT to be rather resistive, it is reasonable that a part of the applied \(V_{sd}\) was consumed in the MWNT. From these observed results, it can be concluded that the power dissipation increases linearly on increasing the length of the MWNT between the two terminal metal electrodes. An offset value of the power dissipation will be at the interface between the MWNT and the metal contacts. Then, the results imply that the applicable maximum current to the MWNT was determined by the resistivity of the MWNT. This result on the resistive MWNT is for the high-current operation state, and the result in the previous sections were obtained in the low-bias-voltage region. The two resistive results have not yet been directly linked together. The observed transport property was definitely based on the MWNT synthesized by arc-discharging method, which however showed clear electric degradation steps.

3. Conclusions

Here, we reviewed our recent transport experiments on the MWNT. A surprising experimental result of high-density current (over \(10^8\) A cm\(^{-2}\)) for SWNT motivated us to think about transport mechanism through the multiple layers and a scattering property in an MWNT. The observed results clearly indicate that the main conduction layer at the low-bias voltage is the outermost layer and a few layers contribute to the current conduction for the bias voltage, and the transport in our lithographically contacted MWNT was fairly resistive in contrast with the ideal ballistic transport predicted in pure SWNT.

Finally, a series of experiments indicate the very important property that the resistive outermost nanotube in the MWNT can carry a surprisingly high current. We believe that this property strongly depends on the tight C–C bond forming the carbon nanotube, which keeps the structure intact even under an extremely high current. To extract evidence, further experiments on MWNTs are necessary.

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References

[1] Iijima S 1991 Nature 354 56
[2] Ebbesen T W and Ajayan P M 1992 Nature 358 220
[3] Thess A et al 1996 Science 273 483

New Journal of Physics 6 (2004) 3 (http://www.njp.org/)
[4] Saito R, Dresselhaus G and Dresselhaus M S 1998 Physical Properties of Carbon Nanotubes (London: Imperial College Press)
[5] Frank S, Poncharal P, Wang Z L and de Heer W A 1998 Science 280 1744
[6] Tans S J, Devoret M H, Dai H J, Thess A, Smalley R E, Geerligs L J and Dekker C 1997 Nature 386 474
[7] Bockrath M, Cobden D H, McEuen P L, Chopra N G, Zettl A, Thess A and Smalley R E 1997 Science 275 1922
[8] Wei B Q, Vajtai R and Ajayan P M 2001 Appl. Phys. Lett. 79 1172
[9] Bachtold A, Strunk C, Salvetat J P, Bonard J M, Forro L, Nussbaumer T and Schönenberger C 1999 Nature 397 673
[10] Fujiwara A, Tomiyama K, Suematsu H, Yumura M and Uchida K 1999 Phys. Rev. B 60 13492
[11] Collins P G, Hersam M, Arnold M, Martel R and Avouris Ph 2001 Phys. Rev. Lett. 86 3128
[12] Collins P G and Avouris Ph 2002 Structural and Electronic Properties of Molecular Nanostructures, ed H Kuzumany et al (College Park, MD: American Institute of Physics) p 223
[13] Kociak M, Suenaga K, Hirahara K, Saito Y, Nakahira T and Iijima S 2002 Phys. Rev. Lett. 89 155501
[14] Fuhrer M S et al 2000 Science 288 494
[15] Rueckes T, Kim K, Joselevich E, Tseng G Y, Cheung C-L and Lieber C M 2000 Science 289 94
[16] Postma H W C, de Jonge M, Yao Z and Dekker C 2000 Phys. Rev. B 62 R10653
[17] Ahlskog M, Tarkiainen R, Röschier L and Hakonen P 2000 Appl. Phys. Lett. 77 4037
[18] Buldum A and Lu J P 2001 Phys. Rev. B 63 R161403
[19] Nakanishi T and Ando T 2001 J. Phys. Soc. Japan 70 1647
[20] Paulson S, Helser A, Nardelli M B, Taylor R M, Falvo M, Superfine R and Washburn S 2000 Science 290 1742
[21] Fuhrer M S, Kim B M, Durkop T and Brintlinger T 2002 Nano Letters 2 755
[22] Radosavljevic M, Freitag M, Thadani K V and Johnson A T 2002 Nano Letters 2 672
[23] Ando T 2000 Semicond. Sci. Technol. 15 R13
[24] Ando T and Nakahara T 1998 J. Phys. Soc. Japan 67 1704
[25] Tsukagoshi K, Alphenaar B W and Ago H 1999 Nature 401 572
[26] Kanda A, Ootuka Y, Tsukagoshi K and Aoyagi Y 2001 Appl. Phys. Lett. 79 1354
[27] Watanabe E, Tsukagoshi K, Kanai D, Yagi I and Aoyagi Y 2003 Appl. Phys. Lett. 83 1429
[28] Yoneya N, Watanabe E, Tsukagoshi K and Aoyagi Y 2001 Appl. Phys. Lett. 79 1465
[29] Yoneya N, Tsukagoshi K and Aoyagi Y 2002 Appl. Phys. Lett. 81 2250
[30] Tsukagohsi K, Suzuki At, Yagi I, Watanabe E, Aoyagi Y, Ago H, Ohshima S and Yumura M 2003 J. Appl. Phys. 94 3516
[31] Poncharal P, Berger C, Yi Y, Wang Z L and de Heer W A 2002 J. Phys. Chem. B 106 12104
[32] Anantram M P 2000 Phys. Rev. B 62 R4837
[33] Averin D V and Likharev K K 1991 Mesoscopic Phenomena in Solids, ed B L Altshuler, P A Lee and R A Webb (Amsterdam: Elsevier) p 173

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