Quantum Cable as transport spectroscopy of 1D DOS of cylindrical quantum wires

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Abstract

We considered the proposed Quantum Cable as a kind of transport spectroscopy of one-dimensional (1D) density of states (DOS) of cylindrical quantum wires. By simultaneously detecting the direct current through the cylindrical quantum wire and the leaked tunneling current into the neighboring wire at desired temperatures, one can obtain detailed information about 1D DOS and subband structure of cylindrical quantum wires.

PACS numbers: 73.23.-b, 73.23.Ad, 71.20. -b, 73.50.-h

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Nanometer structure and materials are of great interest as potential candidates for future electronic devices of greatly reduced size. The fundamental physics underlying these devices is quantum coherence and quantum confinement. Rational design and fabrication will require a better understanding of how the properties of these materials depends on, for example, their dimensionality and size. With the rapid development of nanofabrication and synthesis technology, a variety of low-dimensional nanostructures with unusual characteristics have been realized, such as quantum well, quantum wire, quantum dot as well as their composite structures.

As a kind of quantum wire structure, nanotubes have received extensive attention both theoretically and experimentally. Most recently, the group of Iijima has successfully synthesized a new kind of coupled nanotube structure - coaxial nanocable, in which two conducting cylindrical layers are coupled through a very thin insulating layer. Motivated by this new nanostructure, we proposed Quantum Cable similar to coaxial nanocable structure, and have studied its energy subband spectrum and ballistic transport properties. Quantum Cable comprises two cylindrical quantum wires and a tunable potential barrier, which is sketched in Fig. 1 (a). It is achievable either by confining electrons in the nanocable-like potential wells, or by curling multilayer heterostructure into a solid cylinder or hollow cylinder with nanometer width. Since Quantum Cable is a coupled-quantum-wire structure, it is very akin to the usual coupled dual-quantum-well waveguides (DQWs) in two-dimensional electron gas (2DEG). On the other hand, Quantum Cable is different from the DQWs due to its cylindrical symmetry. For this reason Quantum Cable is a unique nanostructure and expected to be used as some kind of quantum-effect device. In this letter, we considered Quantum Cable as a transport spectroscopy for detecting quasi-one-dimensional density of states (1D DOS) (bound states) in cylindrical quantum wires. The system will be studied is two GaAs cylinder wires surrounded by Ga$_{0.7}$Al$_{0.3}$As for which the parameters are $U_B = 100$ mev, $m_1^* = 5.73 \times 10^{-32}$kg and $m_2^* = 1.4m_1^*$. The widths of two cylindrical wires are both 50 nm and the barrier width is set to be 5 nm.

The bias configuration [see Fig. 1 (b)] is as follows: a small constant bias $V_D$ (100 µv) drives electrons' direct flowing through one of the cylindrical quantum wires into the drain, while another variable bias voltage $V$ is applied to the side-wall of the same quantum wire to adjust the electrons' Fermi potential. In the forthcoming calculations, we directly relate the applied side-wall voltage to the Fermi potential of electrons in quantum cylinder for simplicity. In fact, this needs self-consistent
calculation. Note that such simplification will not lead to any confusion. The potential barrier is set to be good isolation for quantum wires, yet allow for electron’s tunneling between two wires. Then tunneling current through the barrier can be measured simultaneously in another wire. From Landauer-Büttiker formula, the direct current $I_D$ along the cylindrical wire from source to drain can be derived as

$$I_D = \frac{2e^2}{h} \sum_{mn} \int_{E_{mn}}^{\infty} dE \left[ -\frac{\partial f(E-E_F-eV)}{\partial E} \right] V_D,$$

and the tunneling current $I_T$ from one cylinder wire to another is given by

$$I_T = e \sum_{mn} \int_{-\infty}^{+\infty} dE v_{\perp} (E-E_{mn}) g_{\text{1D}}^{1D}(E-E_{mn}) T_{mn}(E-U_B) [f(E-E_F-eV) - f(E-E_F)],$$

where we have accounted for the contribution to the current from every occupied subband $(mn)$. $E_F$ is electrons’ Fermi energy as $V = 0$, and will be set to be zero for convinience in our actual numeration, $E_{mn}$ is the energy to be determined of the $(mn)th$ subband and $U_B$ is the height of the tunneling barrier.

$$f(E) = [1 + e^{E/(k_bT)}]^{-1}$$

is the Fermi distribution function with $k_b$ the Boltzmann constant. $v_{\perp} (E-E_{mn}) = (2E_{mn})^{1/2}/(2m^*_1)$ is the velocity of tunneling electrons at subband $(mn)$. $g_{\text{1D}}^{1D}(E-E_{mn}) = \theta(E-E_{mn})(E-E_{mn})^{-1/2}/(\pi\hbar)$ is the 1D DOS. The transmission coefficient is approximated to be that through a 1D square barrier, i.e., $T(E-U_B) = [1 + s\hbar^2(\sqrt{2m^*_1(E_B-E)}R_B/\hbar)/(E/U_B - E^2/U_B^2)]^{-1}$ ($E < U_B$). The subband energy $E_{mn}$ is followed from

$$J_n(\sqrt{2m^*_1ER_1/\hbar})Y_n(\sqrt{2m^*_1ER_2/\hbar}) - Y_n(\sqrt{2m^*_1ER_1/\hbar})J_n(\sqrt{2m^*_1ER_2/\hbar}) = 0,$$

where $J_n(x), Y_n(x)$ are the first-order, second-order Bessel functions, $R_1, R_2$ are the inner and outer radius of the hollow cylindrical quantum wire considered, respectively.

Once the subband energy is obtained, the 1D DOS of the cylindrical wire can be calculated. In Fig. 2 we present the calculated 1D DOS for a hollow cylindrical quantum wire of width 50 nm, in the approximation of infinite potential well. It is worth noting that subband spectrums are the same in the cases of both infinite and finite confining potential well model, except that subband energy in the case of infinite potential well is slightly higher than that in the finite potential well case for not very small wire width. From Fig. 2, one can find that, over the consecutive energy range, subband structure and 1D DOS of a hollow quantum cylinder are very similar to that of a single 2D quantum waveguide (SQW). Whereas irregular subband arrangement appears in the intersection
between two energy regions with SQW-like subband structure. This feature arises from the mixing of subbands of lowest-order azimuthal quantum number \( m \) and higher-order radial quantum number \( n \) with that of large \( m \) and small \( n \). For solid cylinder, its energy subbands are organized somewhat irregularly\(^6\).

In Fig. 3, we give the direct current \( I_D \) through a quantum cylinder and tunneling current \( I_T \) leaked into another cylinder at absolute zero temperature, as the side-wall voltage bias is adjusted. It can be shown that the direct and tunneling currents decrease as \( V \) is made smaller, until at \( V < 2.2 \) mV, all current-carrying channels (subbands) are turned off and no direct and tunneling current is observed. If one examines carefully the detailed structure of direct and tunneling currents, one can see the perfect quantized steps in the direct current \( I_D \), and the 1D DOS-similar peak oscillation in the tunneling current \( I_T \). Moreover, the start of each step in \( I_D \) lines perfectly up with the corresponding peak in \( I_T \), as indicated by the arrows in Fig. 3. By counting the number of steps in \( I_D \) and peaks in \( I_T \), we find they are the same. In addition, two steps of conductance magnitude \( 2e^2/h \) can be discerned from the other steps of conductance unit \( 4e^2/h \). The former steps come from the contribution of the conducting subbands belonging to the azimuthal quantum number \( m = 0 \), while the later result from the conducting subbands \( m \neq 0 \) which are doubly degenerated. This reflects the cylindrical symmetry of cylindrical quantum wires. As the side-wall voltage increases, electron’s Fermi potential sweep the transverse energy subband one by one and thus conducting channels, each of which carrying the same amount of current, opens up progressively. Then we can observe quantum steps in \( I_D - V \) characteristic. As to the peak structure in the tunneling current \( I_T \), it is the direct consequence of tunneling current being proportional to the 1D DOS for a given subband, as can be found in Eq. (2).

At nonzero temperature, it is expected that the plateaus in the direct current will be rounded and the peak in tunneling current will be broadened, until these steps and peaks are smeared out by thermal effect. Fig. 4 shows the currents \( I_D \) and \( I_T \) vs side-wall bias at temperatures \( T = 0.2, 1, 3.5 \) K. It is evident that, with the increase of the temperature, the plateaus in \( I_D \) are more rounded and the peaks in \( I_T \) more broadened. As the thermal energy is comparative to the energy interval between two adjoining subbands, the original two distinct steps at low temperature will be blurred, and two narrow peaks will be mingled into one broadened peak. At around \( T = 3.5 \) K, the step-fasion structure in \( I_D \) as well as the peak oscillations of \( I_T \) is washed out. This is consistent with the
predicted smearing-out temperature by Bagwell and Orlando\textsuperscript{10}. If the width of cylindrical quantum wires is decreased, intersubband energy spacing will increase, which implies a higher operation temperature, though the quantum steps in direct current still will be smeared out at about $T = 3.5$ K because of fixed height of current step. As a result, it is more convenient and more accurate to determine the 1D DOS and subband structure of cylindrical quantum wire from the leaked tunneling current than from the direct current into the drain. However, one can not gain detailed insight into the 1D DOS and subband structure of cylindrical quantum wire simply from the data of tunneling current. Since at some temperature, two narrow peaks in tunneling current corresponding to the neighboring subbands of small energy interval will be smeared into one broadened peak, at this moment one can notice this fact according to the slope of the direct current at corresponding sidewall bias, and make good resolution of such neighboring subbands. Therefore it is necessary to measure simultaneous the direct current in the drain and leaked current into another cylindrical quantum wire.

Based on the aforementioned observations, one can determine the energy subband structure and 1D DOS of cylindrical quantum wire from the simultaneous measurement of the direct current through the wire and the leaked current into the neighboring cylinder wire at accessible temperatures. To do so, one should first form Quantum Cable structure from a single cylindrical quantum wire using either fabrication or synthesis approach. Then apply bias voltages with the configuration mentioned above to the obtained Quantum Cable. By simultaneous measuring the direct current and tunneling current at desired temperature, one can capture detailed information about the subband structure and 1D DOS of a cylindrical quantum wire. Experimentally, such transport spectroscopy is feasible, since two-terminal\textsuperscript{11} and multi-terminal\textsuperscript{12} measurement of probing electrical transport in individual single-wall carbon nanotubes have been achieved.

This work is supported by a key project for fundamental research in the National Climbing Program of China, one of us (ZYZENG) would like to thank Prof. G. H. Li, Prof. G. W. Meng, Dr. Z. Cui for helpful discussions.

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Figure Captions

**Fig. 1**  (a) Schematic view of Quantum Cable structure, (b) bias configuration to the probing of direct and tunneling currents in Quantum Cable.

**Fig. 2**  1D DOS of hollow quantum cylinders with width 50 nm in the approximation of infinite potential well.

**Fig. 3**  Variation of the direct current $I_D$ through the quantum cylinder and tunneling current $I_T$ as the side-wall voltage bias is altered, at absolute zero temperature.

**Fig. 4**  Variation of the direct current $I_D$ through the quantum cylinder and tunneling current $I_T$ as the side-wall voltage bias is altered, at nonzero temperatures.
a

b

V = 0

V

V_D

I_T

I_D
Fig. 2   Zeng, Xiang and Zhang

![Graph of DOS vs. Energy (meV)](image)
Fig. 3 Zeng, Xiang and Zhang
Fig. 4  Zeng, Xiang and Zhang