Surface Acoustic Wave Induced Electron Transport through Carbon Nanotube

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Abstract. By combining surface acoustic wave (SAW) filters with a carbon nanotube (CNT) we could generate SAW-induced electron transport at zero bias. We observed non-zero electric current through the CNT when injecting 2.72 GHz SAW through the CNT on a GaAs substrate. The sign of the SAW-induced current depended on gate voltages.

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INTRODUCTION

SAW-induced single electron pump devices have been investigated for many years for various systems such as single electron tunneling (SET) array of Al/AlO_x junctions [1], quantum point contacts or quantum dots made of GaAs two dimensional electron gas systems [2], and recently carbon nanotubes (CNT's) [3]. Although the role of SAW in each device is different from each other, it has been commonly designed to promote electron transport one by one. SAW-induced single electron transport has potential applications to the current standard and single photon source [2].

EXPERIMENTS

In order to implement the idea of SAW induced single electron transport using CNT we fabricated SAW filters in the vicinity of a SET device made of CNT (inset of Figure 1). The double-wall CNT's were dispersed on the GaAs substrate which is known to be piezo-electric material. The CNT shown in the inset of Figure 1 looks like a bundle of CNT's. The SAW filters consist of 15 pairs of inter-digitated fingers made of Al. The distance between the fingers is about 0.5 μm corresponding to a frequency of 2.88 GHz. SAW filters have been fabricated using the conventional e-beam lithographic techniques. The mismatch angle between the SAW filters and the direction of the CNT was found to be about 25 degrees. This mismatch would not change the following interpretations of our data. The CNT SET device consists of source, drain and gate electrodes all made of PdAu (inset of Figure 1). The $I-V$ curves of the CNT showed both the Coulomb gap and 'semiconducting' gap with the gap size of about 6 meV (not shown here). The tunneling resistance was 200 kΩ .

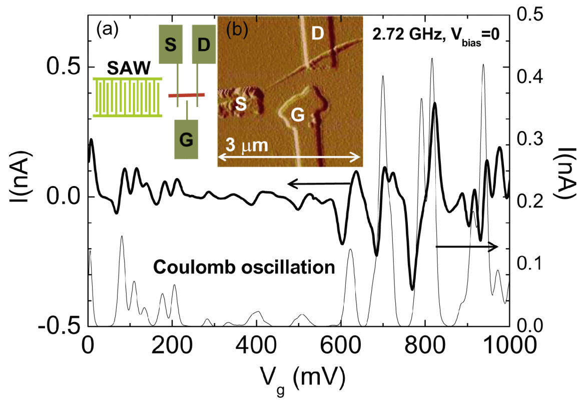

FIGURE 1. SAW-induced electric current at zero bias as a function of gate voltages (thick line). The applied rf frequency and power are 2.72 GHz and -30 dBm, respectively. The Coulomb oscillation with a bias voltage of 0.83 mV (thin line) is also shown for comparison. Inset: schematic diagram of the sample (a) and the AFM picture of the CNT (b).

We have measured SAW-induced current through the CNT at zero bias while applying rf signals through the SAW filters that generates SAW propagating beneath the CNT along the surface of GaAs substrate. All the measurements have been performed at the temperature of 2.0 K. BeCu cryogenic rf coaxial lines with -10 dB attenuator attached have been used for the carrying of the rf signals and lossy DC lines with low pass filters

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for the high frequency noise filtering. Figure 1 shows the measured SAW-induced electron transport through the CNT depending on the gate voltages. Here we used the resonant frequency 2.72 GHz of the SAW filters which was determined by measuring the frequency dependent SAW-induced electric current at $V_g = 0$ mV (not shown).

Our SAW-induced electric current data (Figure 1) show couple of interesting features. Induced current shows positive and negative current depending on the gate voltages: positively induced electric current for the gate voltages corresponding to the single electron tunneling regime while negative current for the Coulomb blockade regime. The positive or negative current peaks occur at the crossover point where the Coulomb blockade and tunneling regimes switch to each other. Thus the gate voltage dependent SAW-induced electric current looks like the first derivative of the coulomb oscillation curves. The SAW-induced electric current also shows a current plateau as a function of power of rf signals [Figure 2(b)].

These features can be explained qualitatively in terms of SET turnstile model. Figure 2(a) shows the schematic energy diagram explaing how the SAW-induced electron transport occurs. When the applied gate voltage is in the electron tunneling regime or when the single electron energy state of CNT is unoccupied [upper diagram of Figure 2(a)], the varying height of the potential barriers modulated by the SAW field could lead to the generation of positive current assuming the SAW drives the potential barriers out of phase. Because the wavelength of the SAW ($\lambda \sim 1\mu$m) is comparable to the length of the CNT it is not a wrong assumption that the SAW wavelength happens to be like as depicted in Figure 2(a). Here is another assumption that the SAW does not affect the energy state of the CNT. Consequently maximum current could be induced when the unoccupied electron state of the CNT is aligned with the Fermi energy level of the electrodes. On the other hand, when the CNT in the Coulomb blockade regime or the single electron state of CNT is occupied, the reverse current is possible as schematically shown in Figure 2(a). As for the negatively induced current, one can suggest that the reflected SAW from the edge of the GaAs substrate or from other obstacles could generate the reverse current. However this scenario could not explain the gate voltage dependent sign of the SAW-induced current.

As the power of rf signals to the SAW filters increases the amplitude of SAW will increase resulting in an increase in the tunneling probability of electrons from the leads to the CNT. Thus the the magnitude of the induced current increases monotonically as a function of the rf power before heating effects appear [as shown in Figure 2(b)]. The current plateau in Figure 2(b) might manifest the fact that the tunneling rate becomes maximum at the rf power that is large but small enough not to break the Coulomb blockade. The plateau changes to a rise at the higher rf powers where the heating effects become dominant. The magnitude of the current plateau was expected to be ef ($f = 2.72$ GHz, e = electron charge) which equals about 435 pA. However our data shows that it corresponds to $6ef$ not ef. We are tempted to attribute this mismatch to the co-tunneling events but we need further study on this point. On the other hand, the negative current plateau corresponded to $-ef$ [inset of Figure 2(b)].

As the temperature increased the amplitude of the SAW-induced current was suppressed. The induced current oscillation was observed to survive up to 10 K. We believe that thermal fluctuation washed out the SET effects and consequently suppressed the SAW-induced electron transport.

In summary, we observed the SAW-induced electron transport through the CNT whose charge state was controlled by the gate voltages. The sign of the SAW-induced current depended on the gate voltages. We explained our observations in terms of SET turnstile model.

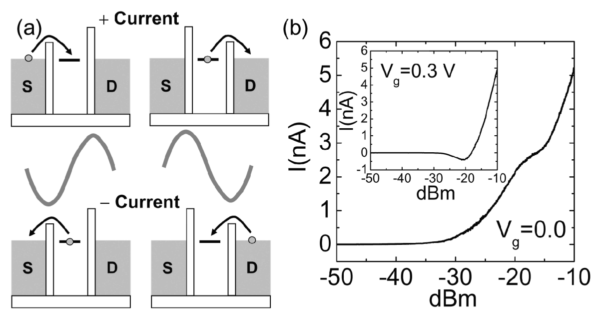

FIGURE 2. (a) Schematic energy diagram with the tunneling potential barriers modulated by the SAW field. (b) SAW-induced current in the tunneling regime as a function of applied rf power. Inset of (b): in the Coulomb blockade regime.

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