Fabrication and characterization of quantum dots with carbon nanoutbe-molecule heterojunctions

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ABSTRACT

We have developed a technique to fabricate quantum dot (QD) based nanostructures by using single wall carbon nanotube (SWCNT)/molecule heterojunctions. Ends of individual SWCNT were chemically modified to form carboxylic groups which were used to connect with collagen model peptide molecules. Two kinds of structures have been fabricated and characterized by the scanning tunneling microscopy (STM) and spectroscopy (STS). In one structure, three different individual SWCNTs were connected in series with the molecules, and in the other structure, both ends of an isolated individual SWCNT was terminated with the molecule. In the latter structures, STS measurements indicated the molecule induced confinement potential in the QD.

Keywords: single wall carbon nanoutbe, quantum dot, heterojunction

1 INTRODUCTION

Single wall carbon nanotubes (SWCNTs) are an attractive material for building blocks of quantum dots because of their extremely small diameter (~1nm) which cannot be realized by conventional top-down nanofabrications based on electron beam lithography. The energy scales associated with the QD, such as single electron charging energy and level spacing between the confined states, are more than an order larger compared with submicron-scale QDs fabricated by standard top-down techniques [1]. This is good for single electron devices that only need the large single electron charging energy. The low-temperature electrical measurements have revealed artificial atom behaviors with simple shell structures [2]. These observations suggest that the SWCNT is attractive for the spin based quantum bit (qubit) because a single spin state is easily realized by putting the odd number of electrons in the dot. It would be also advantageous in terms of long spin coherence because a majority of carbon atoms do not have nuclear spins which are known to be a dominant decoherence source in the GaAs QDs [3].

Semiconducting SWCNTs emit light with a wavelength which depends on a diameter of the tube and can be in a optical communication range [4]. One-dimensional nature could make an exciton binding energy much larger than that in bulk materials [5].

Despite many potential advantages of the SWCNT for the quantum-dot devices, we do not make full use of them. This is mainly because of lack of reliable, reproducible and flexible device fabrication processes at this state. For example, it is not always easy to fabricate coupled quantum dots [6,7], or more complex structures. For optical emission, it is experimentally known that the SWCNTs should not form bundles [8] and should not be put on a surface [9], to have efficient light emission. Edges of the SWCNTs may work as non-radiative centers, but, may not be a serious problem when they are long enough. Light emission from well-defined quantum dot has not been reported so far except for our very recent work [10].

To realize complex and functional quantum-dot based devices, flexible techniques to form a tunnel barrier have to be developed. Although there are some attempts for the techniques, such as a technique that uses local ion beam irradiation [11], they are still not reliable and not controllable enough to realize more complex structures.

We use another unique feature of the SWCNT, which is a possible chemical modification of SWCNT ends with functional chemical groups. With these, molecules are chemically connected to the ends of the SWCNT, a SWCNT/molecule heterojunction which can be used as a building block of molecular scale nanostructures, where the molecule would work as a tunnel barrier.

2 RESULTS AND DISCUSSIONS

Figure 1 shows STM images of fabricated structures with the present technique [10]. In Fig.1 (a), three different SWCNTs are connected with molecules. In this structure, we expect that an entire SWCNT between the molecules work as a single quantum dot. The two SWCNTs extending from the molecules could be used for leads in transport measurements. In this case, we expect that the molecule would work as a tunnel barrier. Figure 1(b) shows a zoom-up image of the connection part. In between the SWCNTs, the collagen model peptide is embedded. Figure 1(c) shows an individual SWCNT with both ends terminated by the collagen model peptide molecules. We expect an entire SWCNT to work as a single quantum dot.

To further examine spatial distribution of electronic states along a length direction, the STS measurements were performed, and the result are shown in Fig.2(a). As seen in the figure, Density-of-State (DOS) patterns change, depending on the levels. As a tip voltage was changed, current was injected into a different level from the ground state to the 4th excited state in this case. It appears that the states are confined in the parabolic-like potential well. This can be understood by taking the electronic dipole moment of the molecule into account. The collagen model peptide is known to have a permanent dipole moment [12], a direction of which is determined how it is chemically connected. In this case with bonding of carboxylic anhydrides, the dipole moment pushes electrons into a center of the quantum dot as shown schematically in Fig.2 (b). The overall confinement potential would be formed by adding an effect of the dipole moment of the molecule (dotted line) to the hard-wall potential of the SWCNT with a finite length (solid line).

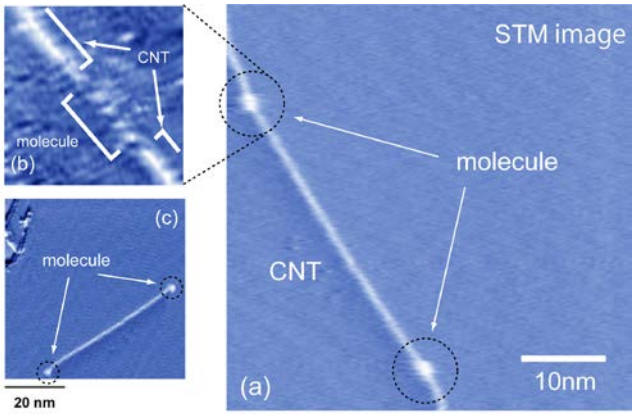

Figure 1: (a) Three SWCNTs are connected with colagen model peptide molecules (b) A zoom-up image of the connection part (c) Isolated single quantum dot structure with both ends of the SWCNT terminated by the molecules (taken from [13])

3 SUMMMARY

We have presented a novel technique to fabricate molecular scale nanostructures with SWCNT/molecule heterojunctions. Two structures are shown, and the DOS of the isolated quantum dot with both ends terminated by the molecules were characterized the STS measurements. It was found that the confinement potential profile was affected by the dipole moment of the molecule.

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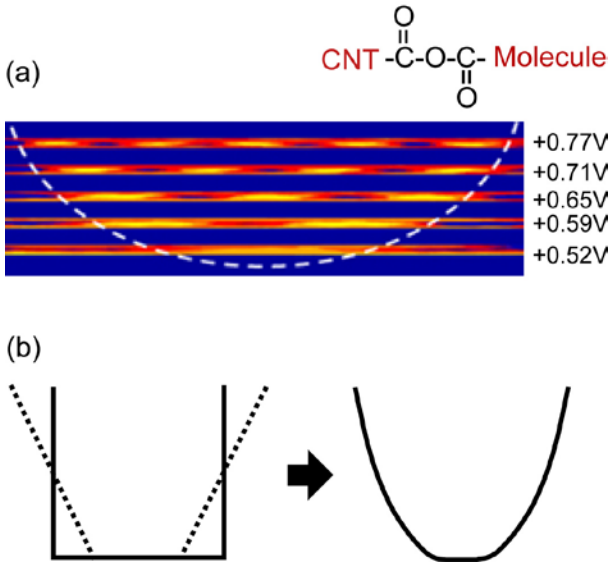

Figure 2: (a) Measurend DOS along the SWCNT (taken from [10]) (b) Schematic explanation on how the confinement potential is formed. The solid line in the left figure shows a hard-wall potential formed by the SWCNT, and the dotted line shows the potential due to the dipole moment of the molecule.

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