

Photon detector composed of metal and semiconductor nanoparticles

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Received 12 August 2004; accepted in revised form 24 March 2005

Available online 10 May 2005

Abstract

Applying the function of the single electron transistor, a novel photon detector consisting of a self-assembled structure of metal and semiconductor nanoparticles and an organic insulating layer was developed. It showed coulomb blockade behavior under dark conditions and remarkable increase in current corresponding to light intensity under light irradiation. Ultraweak photon emission of about 600 counts per second in the ultraviolet region could be detected at room temperature by this photon counter.

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PACS: 73.23.Hk; 85.30.Vw; 85.60.Gz

Keywords: Nanostructures; Optoelectronic devices; Tunneling

1. Introduction

In recent years, elements for controlling single electrons have been developed with the full use of nanotechnology. Single electron transistor (SET) [1–3] is one of those elements, and its application to single photon counters has been tried [4,5]. The performance of SET is restricted in the region that the charging energy of a quantum dot $e^2/2C$ dominates over the thermal energy $k_B T$, where C is the total capacitance of tunneling junctions. To operate the SET at room temperature, the area of tunneling junctions which compose the SET should be on a few-nanometer scale [3]. However, since in top-down approaches such as electron-beam lithography it is difficult to manipulate the structure of a few-nanometer scale, SETs or SET-based single photon counters fabricated by such methods can work only at very low temperature [1,2,4,5], and moreover, integration or bulk production is difficult because of their laborious fabrication process.

On the contrary, bottom-up approaches using metal or semiconductor nanoparticles have been expected as a method to build such small structures more easily. Indeed, Coulomb blockade was easily observed at room temperature in systems which consist of metal nanoparticles and organic insulating layers [6–9].

In this report, we demonstrate a novel photon detector consisting of a self-assembled structure of metal and semiconductor nanoparticles and an organic insulating layer.

2. Experimental details

As shown by the cross-sectional schematic diagram of the photon detector in Fig. 1(a), the photon detector is composed of two kinds of electrodes (upper side is the ITO (indium tin oxide) transparent electrode and lower side is the gold electrode the surface of which was coated by the organic insulating layer) and two kinds of nanoparticles (gold and TiO_2) which were coated by the organic insulating layer and intervene between these electrodes. Gold nanoparticles and TiO_2 nanoparticles were dispersed planarly so that these disparate nanoparticles adjoin respectively.

A brief fabrication method of photon detector is as follows. The gold nanoparticles of approximately 11 nm in

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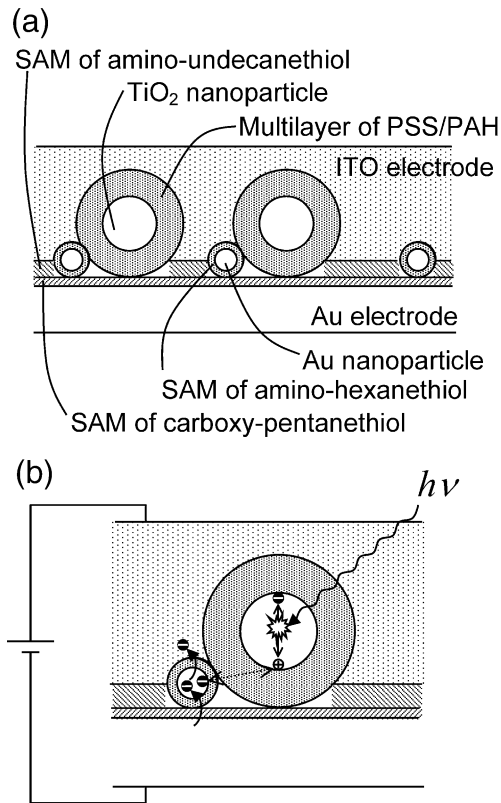


Fig. 1. (a) Cross-sectional schematic diagram of the photon detector. (b) Schematic diagram of a brief mechanism of the detection of photons. The hole which was photo-generated and drifted to the lower side in the TiO_2 nanoparticle changes electrostatic energy stored in the tunnel junctions between the gold nanoparticle and two electrodes (source and drain), by attracting the charge in the gold nanoparticle. Subsequently, an electron is allowed to tunnel into and out of the gold nanoparticle due to the breakup of the Coulomb blockade.

diameter were prepared by the reduction of HAuCl_4 by trisodium citrate dehydrate and tannic acid [10]. Then the colloidal gold nanoparticles were dropped into an *N*-9-fluorenylmethyloxycarbonyl (Fmoc)-amino-hexanethiol/*N,N*-Dimethylformamide solution so that a self-assembled monolayer (SAM) of the *N*-Fmoc-amino-hexanethiol was formed on the gold nanoparticles. TiO_2 nanoparticles of approximately 25 nm in diameter (P25, Degussa Co., Germany) were provided from Nippon Aerosil Co., Ltd. and coated by polymeric layers of about 16 nm in thickness by the method of layer-by-layer adsorption of poly(sodium 4-styrenesulfonate) (PSS) and poly(allylamine hydrochloride) (PAH) [11]. The SAM of the carboxy-pentanethiol was formed on the sputter-deposited gold electrode. The SAM-coated gold nanoparticles from which Fmoc was removed, were conjugated sparsely (not to be packed) with the carboxy-pentanethiol on the gold electrode using *N*-hydroxysuccinimide and *N*-ethyl-*N'*-dimethylaminopropyl-carbodiimide. Subsequently, polyelectrolyte-coated TiO_2 nanoparticles were immobilized next to conjugated gold nanoparticles by the electrostatic interaction between the PSS layer adsorbed at the most outside of TiO_2 nano-

particles and amino groups of SAM-coated gold nanoparticles. After the vacancies of nanoparticles were filled with the amino-undecanethiol, ITO film was sputter-deposited onto those constructed layers of nanoparticles and insulator.

The whole structure is equivalent with SETs which were connected in parallel, regarding the gold electrode as the source, the ITO electrode as the drain, the gold nanoparticle as the quantum dot and the TiO_2 nanoparticle as the gate. The gold nanoparticles form a tunnel junction with two electrodes, while the polymeric multilayer surrounding the TiO_2 nanoparticles is too thick for an electron to tunnel through it. The mechanism of detection of photon is shown in Fig. 1(b). The voltage V_{sd} , the value of which is within the Coulomb blockade, i.e., $V_{\text{sd}} \leq e/2C$, is applied between the source and the drain. The electron and the hole in the TiO_2 nanoparticle excited by the photon drift to the upper side and lower side of the TiO_2 nanoparticle, respectively, due to the electric field between the source and the drain. The electrostatic energy of the tunnel junctions is changed by the hole drifted to the lower side, thereby, the tunneling of the electron from the source to the quantum dot and from the quantum dot to the drain can occur.

3. Results and discussion

At room temperature and under dark conditions, I – V characteristic between the source and the drain was measured (solid line in Fig. 2). In the forward bias case, the current was almost constant and hardly flowed, while in the reverse bias case, coulomb blockade was observed. This commutation may be due to the fact that a part of the electron path, that is, gold nanoparticle-SAM of amino-hexanethiol-ITO electrode, forms the structure of the MIS (Metal-Insulator-Semiconductor) diode. In the MIS junction, the n-type semiconductor surface is in deep depletion by the applied positive bias, thereby the Fermi level in the metal cannot exceed the conduction band minimum of the semiconductor and the tunneling of electrons hardly occurs [12–15]. On the other hand, when the negative bias is applied to the semiconductor, large reverse current flows

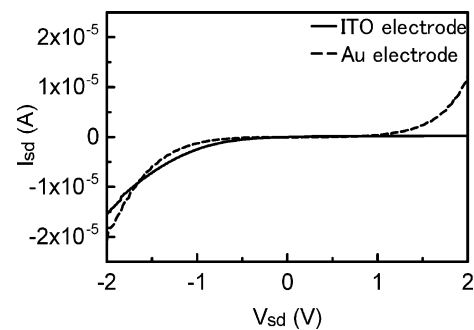


Fig. 2. I – V curves between source and drain measured at room temperature. The drain electrode is the ITO (solid line) and the gold (dashed line).

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