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Detection of Molecular Charge Dynamics through Current Noise in A GaAs-based Nanowire FET

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Abstract

We investigate the detection of charge dynamics in single molecules using a GaAs-based nanowire FET. As the target molecule, Tetraphenylporphyrin (TPP) was put on the nanowire channel. Stochastic charging and discharging of the molecules was detected through drain current noise in the nanowire FET. Under 405 nm light irradiation, the drain current noise exhibited $1/f^2$ noise spectrum, indicating the charge dynamics of the restricted number of molecules, whereas a number of TPP existed on the nanowire channel.

1. Introduction

Recently molecular materials play important roles in electronics, such as organic light emitting diode, dye-sensitized solar cell, organic film solar cell, and etc. [1,2]. Detection and understanding of molecular dynamics are indispensable for precise design and control of not only these devices, but also future single-molecule devices. A problem in this subject is detection of very weak dynamic signal of a molecule. III-V compound semiconductor-based nanowire field-effect transistor (FET) is very sensitive to the surface charge because of high surface-to-bulk ratio of the nanowire channel as well as high electron mobility. The purpose of this study is detection of the charge dynamics in the single molecules using a GaAs-based nanowire FET in terms of drain current noise.

2. Concept and Experimental

Figure 1 shows the set up for detecting the charge dynamics in single molecules using a GaAs-based nanowire FET. The nanowire channel works as a charge sensor. When the charge state of the molecule is changed, the drain current is immediately modulated by Coulomb interaction. In this study, we focus on the noise spectrum in the drain current, since the charging/discharging event in the molecule might be stochastic and it will appear as current noise. In addition the noise spectrum measurement system has wide dynamic range suitable for measuring weak signal. Usually $1/f$ noise is dominant in our GaAs-based nanowire FET [3]. When single carrier charging and discharging occurs in the molecule on the nanowire, random telegraph signal (RTS) noise will be superimpose to the drain current, since RTS is generated by stochastic discrete event. RTS noise results in a Lorentzian spectrum in frequency domain: the slope of the noise spectrum is $1/f^2$, distinguished from the $1/f$ noise [4]. Therefore we can find discrete charge

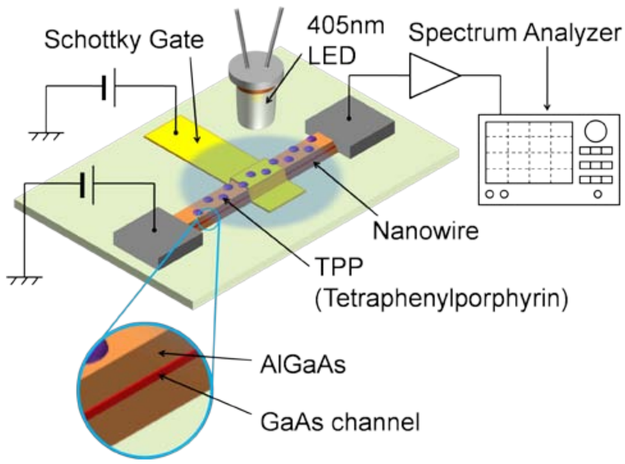

Fig. 1 Experimental set up.

dynamics from the drain current noise spectrum.

The nanowire channel of the FET was fabricated on the AlGaAs/GaAs heterostructure wafer having two-dimensional electron gas (2DEG) by electron beam lithography and wet chemical etching. Source and drain ohmic electrodes and a Schottky gate were formed on the nanowire. The nanowire length and width were 4 μm and 980 nm, respectively. The gate length was 600 nm. In this study, tetraphenylporphyrin (TPP) was used as the target molecular material, which is one of important materials in molecular electronics. TPP excites electrons by absorbing light, which is used as a donor of the dye-sensitized solar cell. TPP diluted in xylene was put on the fabricated FET by spin coating method. Thus many molecules placed on the nanowire channel. The drain current noise was measured by a conventional spectrum analyzer. For charge excitation in TPP, a 405 nm wavelength LED light irradiated on the sample.

3. Results and Discussion

Figures 2(a) and 2(b) show measured drain current vs. gate voltage (I_D-V_G) curves in the bare FET and the TPP-coated FET, respectively, with and without 405 nm LED irradiation. After TPP coating, the drain current obviously decreased. This result suggested that the electrons were transferred from the FET to TPP, which was opposite from the reported behavior in the Si nanowire device [5]. This difference in the current change would arise from the difference in the electron affinity between

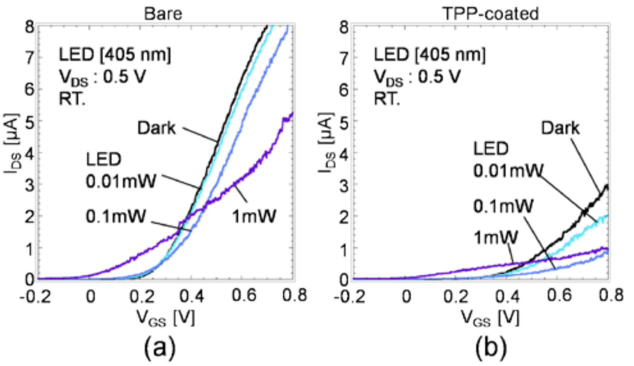

Fig. 2 I_{DS}-V_G characteristics with 405 nm-wavelength LED irradiation in (a) bare FET and (b) TPP-coated FET.

AlGaAs and Si. As the LED light power increased, the drain current further decreased in both the bare and TPP-coated FETs. A possible reason was that the electrons were locally excited and accumulated only in the AlGaAs barrier layer with 70 nm thick, since the penetration length of the 405 nm light was 40 nm in AlGaAs. This might result in the depletion of the 2DEG. We observed increase of the current, when the 658 nm LED whose penetration length was longer than 200 nm was irradiated on the channel.

Figure 3(a) shows the measured drain current noise spectra for the bare FET without TPP. The spectra showed typical 1/*f* spectra regardless the 405 nm light irradiation and the nose intensity was independent on the light power. On the other hand, the TPP-coated FET exhibited different noise spectra as shown in Fig. 3(b). In the dark condition, it showed 1/*f* noise spectrum. However, by the light irradiation, a kink appeared in the spectrum and it became obvious as the light power was increased. This result clarified the contribution of charge dynamics in TPP to the FET noise. Obtained spectra under the light irradiation could be decomposed to a 1/*f* spectrum and a Lorenzian spectrum, which confirmed appearance of RTS noise due to stochastic single-charge event. The corner frequency of the Lorenzian spectrum indicated that the time constant of the charge event was approximately 1 ms.

The obtained result suggested that the restricted TPP molecules contributed to the drain current noise, although there were a lot of TPP molecules on the nanowire. One important factor for this restriction is that the drain current in a FET is controlled by channel pinched off point locating at the gate edge in the drain side. TPP in the gate edge would dominantly affect the noise. We also point out that only TPP contacting with both metal and channel affects the drain current. A simple equivalent circuit analysis indicates that the charge state of TPP is reflected on the channel potential only when the potential of TPP is fixed by another electrode. These factors suggest that a narrow nanowire is preferred for single molecule detection. We also point out that a long gate is also necessary to suppress $1/f^2$ noise generated in the small-size FET itself [6].

4. Conclusions

We investigated detection of charge dynamics in TPP molecules using a GaAs-based nanowire FET through drain current noise. Under 405 nm light irradiation, the drain current noise in the FET with TPP exhibited $1/f^2$ noise component superimposed to conventional 1/*f* noise, indicating stochastic discrete charge event reflecting TPP charge dynamics. From the FET, a limited number of TPP was responsible for the observed $1/f^2$ noise, although there were a large number of TPP on the nanowire channel.

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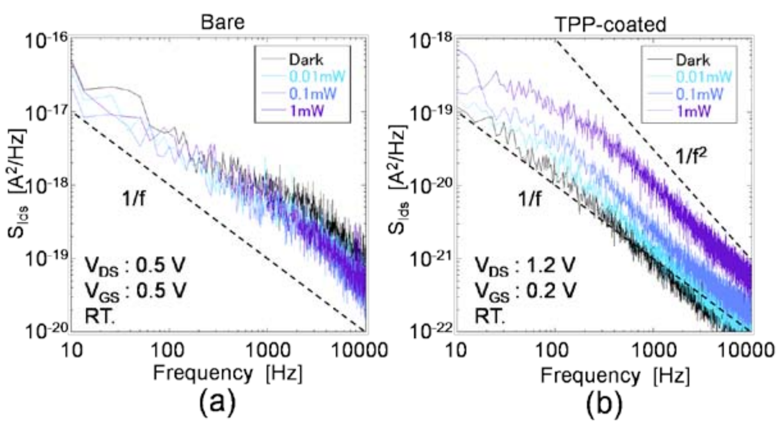

Fig. 3 Drain current noise spectra with 405 nm LED irradiation from (a) bare nanowire FET and (b) TPP-coated nanowire FET.

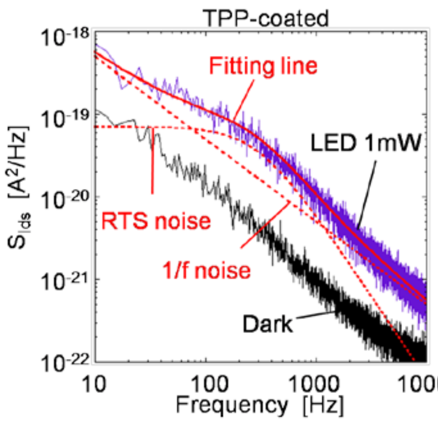

Fig. 4 Decomposition of the noise spectrum from the TPP-coated FET.