Effect of an Impurity in a Single-Electron Transistor

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The influence of a potential barrier or a dip, which are caused by an impurity or size variations, on the characteristics of a single-electron transistor is numerically studied. It is found that a single impurity adds two conductance oscillations, i.e. the oscillations corresponding to all the combination of barriers are observed. This effect is characterized by multiple-period Coulomb oscillations, a characteristic temperature dependence of conductance, and reversal of the oscillation phase. It is also demonstrated that atomic-level potential variations in actual FETs can be analyzed by using such single-electron resonances.

1. INTRODUCTION

Single-electron charging effects, which cannot be explained without considering that a charge is quantized to integer-multiples of e, have recently attracted much attention [1]. Although, so far, basic physical phenomena have been the main interest in this field, studies on device/circuit applications will also be targeted. Conventionally doublebarrier systems (or single-electron transistors) have extensively been studied. However, the other essential situations for actual device design/evaluation have not been well understood. These include systems having three or more barriers, or an accidental impurity ion, or a local channel-width variation, or an attractive potential.

The purpose of this paper is to clarify the effect of these microscopic potential variations by using numerical simulations. The simulation method used is "molecular" dynamics (MD) [2], which simulates the dynamics of all individual electrons by solving the classical equation of motion without approximation. Those real-space potential variations, which are difficult to treat within the conventional equivalent capacitance treatment [2], are naturally included in the MD. The MD was shown to quantitatively reproduce the characteristics of a single-electron transistor in the low electron-density regime[2].

2. RESULTS AND DISCUSSIONS

The system studied is a quasi-onedimensional semiconductor wire (Fig. 1) having intentional double barriers and an additional potential barrier (or dip), which represents an acceptor (donor) ion or local channel-width narrowing (widening). This single-electron transistor under the influence of an barrier shows two additional conductance oscillations having different periods of electron density (or gate voltage) as shown in Fig. 2. This means that the charging effect corresponding to all three combination of barriers are observed (inset of in Fig. 3c). This result is interesting because the two barriers (1 and 2), which have an another barrier 3 between them, show a Coulomb oscillation and the longrange electron-electron interaction is found to be important. This multiple-period conductance oscillation is characterized by its unique temperature dependence of ID-VG curve (Fig. 3). With decreasing temperatures, the dominant longest period oscillation is observed first, the fine structures on the peak

are observed next, and finally peaks are decomposed into multiple complex peaks. The longest period oscillation is observed even at high temperatures because the Coulomb energy is the largest. This explains the experimental observations in [3] from the microscopic point of view.

When a potential dip is added to the single-electron transistor, similar multipleperiod Coulomb oscillations are observed (Figs. 2d, and 2h). However, the phase of oscillations, surprisingly, is shifted by the amount of π when it is compared to the case of the barrier (namely the on-conditions and the off-conditions are reversed). This is explained as follows. The electrons are stable when one electron is placed at the dip and no electron is placed at the top of the barrier. This corresponds to the electron density at which average number of electrons between the barrier and the dip is n+0.5 (n is an integer), and under such stable conditions the current flow is suppressed by the Coulomb blockade. On the other hand in the conventional double-barrier case, electrons are stabilized when the average number of electrons between two barriers is an integer.

Based on this, we propose the analysis method of microscopic potential variations in FETs by using the current-voltage curve (Fig. 4). When an I_D -V_G curve at a low temperature with Coulomb-oscillations (like in Fig. 3c) is Fourier transformed, the oscillation periods can be extracted as shown in Fig. 3d. Each period is related to an interbarrier distance. The set of inter-barrier distances provides combined linear equations, whose solution gives locations of potential barriers and dips. This is termed as PASER (Potential Analysis using Single-Electron Resonances). The simulated characteristics shown in Fig. 3c is used to test the validity of this technique, and the barrier locations are successfully regenerated.

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Fig. 1 Quasi-one-dimensional electron system assumed in the simulation (Scott-Thomas el al). The current flows perpendicular to the figure.





Fig. 2 Effect of a potential barrier (barrier3) or a dip on the conductance oscillation of the single-electron transistor (barrier 1 and 2). Electron density is directly related with the gate-voltage of the FET. a-c, e-g: barrier potential is added; d,h: dip potential is added. Temperature is 4.2 K.



Fig. 3 a-c:Temperature dependence of the conductance oscillation in the triple-barrier system. The inset in Fig. 3c shows the peak positions corresponding to three different barrier distance; d:Fourier spectrum of the data in Fig. 3c.

