Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 1086-1087

H-9-1

Correlation measurement of time-dependent potentials in a semiconductor point contact

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1. Introduction

Recently, time-dependent transport characteristics in semiconductor nanostructures are widely investigated for quantum computing devices [1], single-electron pump devices [2] and dynamical quantum dots [3]. The waveform of the potential has to be designed to manipulate electronic states for each device performance. However, the actual time-dependent potential is generally distorted from the applied voltage waveform, which is one of the experimental difficulties for demonstrating the performance. Here, we propose and demonstrate an experimental technique to investigate correlation between two time-dependent potentials in a semiconductor point contact (PC). The technique can be used to characterize the distortion of the potential waveform.

2. Principle of the Correlation Measurement

We consider a semiconductor PC in the tunneling regime, whose tunneling barrier is electrostatically formed. Conductance of the PC changes linearly by $\Delta G(t)$ with a small change of the barrier potential $\Delta U(t)$, and the current is proportional to the applied bias voltage (bias potential), as illustrated in Fig. 1(a). When the bias potential has time-dependent term $\Delta\mu(t)$, the expected change of the mean current $\Delta I \sim \langle \Delta U(t)\Delta\mu(t)\rangle$ reflects the correlation of the barrier potential and the bias potential. If one of the potential waveform is delayed (for instance $\Delta\mu(t-t_{\mathrm{d}})$ with a delay time t_{d}), the current measures the correlation function $\Delta I(t_{\mathrm{d}}) \sim \langle \Delta\mu(t-t_{\mathrm{d}})\Delta U(t)\rangle$. Therefore, if one of the potential waveform is known, the other waveform can be investigated from the correlation function. In the extreme case when a delta-function-like pulse is applied to the electrochemical potential of the drain electrode, the correlation current measures the time evolution of the barrier potential $\Delta U(t)$.

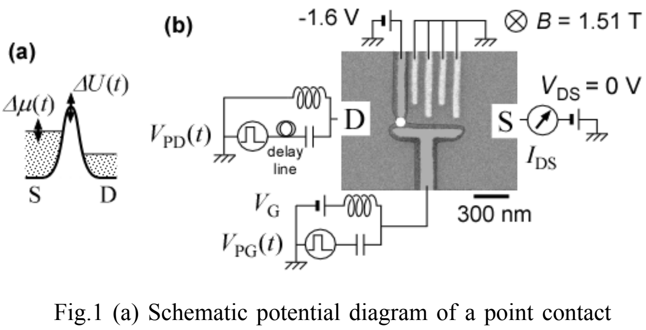

Fig.1 (a) Schematic potential diagram of a point contact device. (b) SEM image of the device and experimental setup for the correlation measurement.

3. Experiments and discussions

The experiments were performed on a PC fabricated by standard split-gate technique in an AlGaAs/GaAs heterostructure as shown in Fig. 1(b). Although the device is designed for forming a double quantum dot, we activated the left tunneling barrier for the present study. The upper-gate voltage was set at −1.6 V and we swept the lower-gate voltage V_{G}. The static characteristics of the PC without applying pulses are shown in Fig. 2. No quantized conductance is seen at zero magnetic field, probably due to the too-narrow gate spacing (small confinement energy). Note that the potential correlation measurement does not require conductance quantization. In a magnetic field of 1.51 T applied perpendicular to the wafer, the quantized conductance steps appear. Following results were measured in a dilution refrigerator at about 50 mK at 1.51 T.

For the correlation experiment, two synchronized pulse voltages are applied to the drain and gate electrodes through bias-Tees as shown in Fig. 1(b). The drain pulse can be delayed up to 10 ns with a coaxial delay line. We

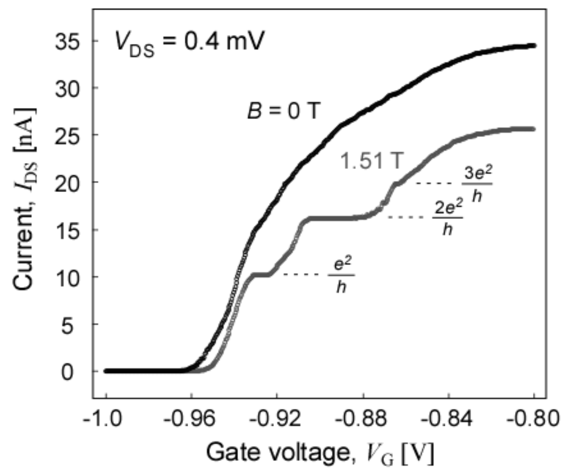

Fig.2 I_{DS}-V_{G} characteristics of the PC without applying pulses. Dashed lines indicate the expected current levels for the first three quantized conductances considering a series resistance at B = 1.51 T.

adjusted the dc bias voltage to be effectively zero ($V_{DS} = 0$) to obtain zero current without applying pulses. The amplitude of the drain pulse (0.4 mV) is set within the linear conductance regime, and the amplitude of the gate pulse is set at 4 mV, which is smaller than the range of the conductance plateau.

Basically, the drain and gate pulses change the bias and barrier potentials, respectively. However, crosstalk between the pulses exists. When only the gate voltage pulse is applied, we observe a large current as shown in Fig. 3(b) for the pulse length of $t_{wG} = 0.5$ ns and the repetition time of $T_{rep} = 8$ ns. No current is expected in the small amplitude regime, if the gate voltage just changes the barrier potential only. We suspect that the gate pulse also changes the bias potential instantaneously through a capacitive coupling (crosstalk) between the gate and 2DEG. Here, we do not focus on the crosstalk signal. In contrast, no current is observed when only the drain pulse is applied (data not shown), indicating that drain pulse changes the bias potential only (negligible crosstalk).

When the two voltage pulses are applied simultaneously, the pulse induced current depends on the phase difference (delay time). Figure 3(c) compares the two cases obtained at the in-phase and out-of-phase conditions. The small difference corresponds to the correlation between the barrier potential induced by the gate pulse and the bias potential induced by the drain pulse. The phase-independent current comes from the crosstalk.

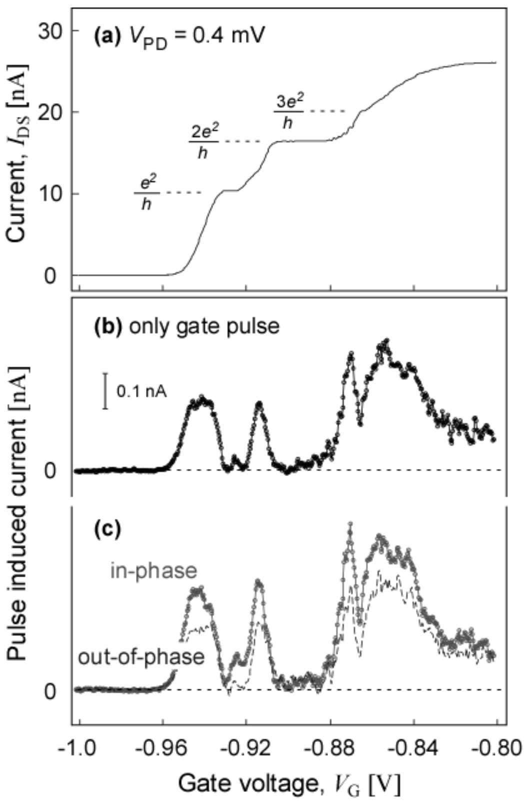

Fig.3 (a) Pinch-off characteristics of the PC. (b) Crosstalk current caused by the gate pulse. (c) Pulse induced current in the presence of the gate and drain pulses.

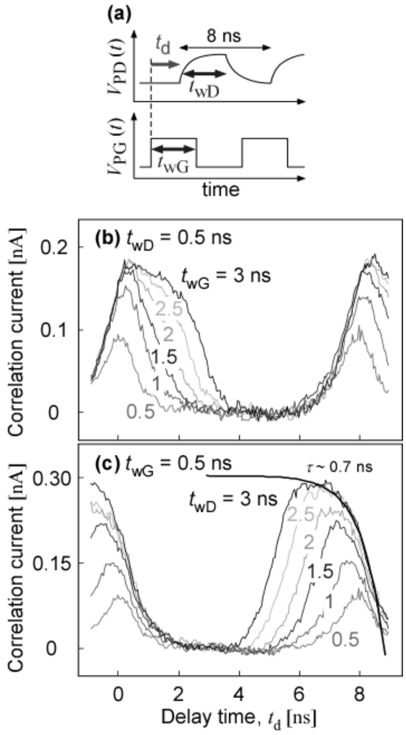

Fig.4 (a) Schematic potential waveforms. (b) Correlation measurements for a fixed drain pulse ($t_{wD} = 0.5$ ns). (c) Correlation measurements for a fixed gate pulse ($t_{wG} = 0.5$ ns). The crosstalk current obtained at the out-of-phase condition [$t_d \sim 5$ ns in (b) and $t_d \sim 3$ ns in (c)] is subtracted for each trace.

Figures 4(b) and (c) show the correlation measurement, where the delay time t_d is swept for various pulse widths (t_{wD} and t_{wG}). If both two potentials have ideal rectangular waveforms, triangular ($t_{wD} = t_{wG}$) or trapezoid ($t_{wD} \neq t_{wG}$) correlation function (overlap integral of the rectangular function) is expected to appear in the current. Actually, the current profile looks like triangular at short pulses (e.g., t_{wD}, $t_{wG} < 1.5$ ns). However, when the pulse length exceeds 2 ns, distorted exponential function [See the solid line in Fig. 4(c)] rather than the trapezoid function is obtained. Comparison with the simulation implies distortion of the bias potential with the time constant of $\tau \sim 0.7$ ns, as illustrated in Fig. 4(a).

4. Conclusion

We have proposed and demonstrated a potential correlation measurement in a semiconductor PC device. We expect that various time-dependent potential in a semiconductor nanostructure, for example "moving quantum dot" formed by surface acoustic wave, can be detected by using this experimental technique.

This work was supported from KAKENHI (19204033).

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