Observation of Conductance Fluctuation due to Zitterbewegung in InAs 2-dimensional Electron Gas

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Abstract. Zitterbewegung (ZB; trembling motion) is one of the peculiar phenomena predicted in the Dirac equation in that the velocity and the spatial coordinate cannot be well defined kinetic constant. While the ZB in vacuum is far out of reach, feasibility of observation in solids has been discussed though very few experiments have been reported yet. We here report the ZB in two-dimensional electron gas with strong Rashba-type spin-orbit coupling causes large fluctuation in conductance. Such an experiment was impossible until recent development of point contact injectors with spin-polarised electrons. Numerical calculations on a simple model successfully simulate the experimental observations.

1. Introduction

A characteristic oscillation in the velocity of a free electron which obeys the Dirac equation, was first found by Schrödinger [1]. The phenomenon, now is called “Zitterbewegung” (ZB; German word for trembling motion), is however far out of experimental reach in its amplitude and frequency [2]. While some successful imitations [3–5] have been reported, very few have been reported on electrons in “emulated vacuums” like graphene [6] or semiconductors [7] due to the still stringent conditions. For example in two-dimensional electron gas (2DEG) with strong Rashba-type spin-orbit coupling (SOC), the ZB should appear as a meandering of electrons with amplitudes around ten nanometers [7], which is now barely observable by nanoscale techniques.

Here we report observation of the ZB in an InAs 2DEG with strong Rashba SOC as conductance fluctuations (CFs). For the emitters and the collectors of spin-polarised electrons, we used quantum point contacts (QPCs). The amplification of the ZB here is by virtue of small scattering range of impurities. The experimental observation can be simulated by a numerical calculation based on a simple tight-binding model.

2. Experimental

Figure 1(a) is the cross section of the layered structure grown by molecular beam epitaxy. The 2DEG has the mobility $\mu = 65900 \text{ cm}^2/\text{Vs}$, the sheet carrier concentration $n = 1.1 \times 10^{12} /\text{cm}^2$ and the Rashba parameter $\alpha = 3.6 \times 10^{-11} \text{ eVm}$, which were obtained from Hall and Shubnikov-de Haas measurement. Figure 1(b) is a scanning electron micrograph image of the sample fabricated with electron-beam lithography and Ar dry-etching. Electrodes 1, 2, 4, 5, 6 are connected through QPCs while 3 and 7 are through 1.8 $\mu\text{m}$ wide strips. The sample was cooled down to 70 mK in a dilution fridge with a superconducting magnet. Conventional lock-in technique was used for measuring two-wire conductances with frequencies lower than 1 kHz.
The conductances of the QPCs in the present experiment were tuned to the conductance plateau at $2e^2/h \equiv G_q$, on which the emitted electrons are highly polarised as established theoretically [9] and experimentally [10]. In the two-terminal conductance measurements between the QPCs, the electrons emitted from a QPC should experience several scatterings during the traversal to the collector QPC because the mean free path $1.1 \mu m$ is a few times shorter than the length between the confronted QPCs (Fig. 1(c)). Though the opening of the QPCs is in the same order as the amplitude of the ZB, the range of scattering potential can be much shorter. Hence if a trajectory meandered by the ZB is modified by e.g. external magnetic field $B$ [2], the scattering cross section should be largely modified resulting in the modification of conductance.

3. Results and Discussion

In conductance between terminals 1 and 5 ($G_{1-5}$), we observe reproducible CF as a function of $B$ (Fig. 2(a)). Here “reproducible” means patterns of aperiodic variations are almost the same for independent sweeps of $B$. Cooling the sample from 1.0 K to 70 mK enhanced the amplitude of the CF from 3 % to 15 % of the averaged conductance, suggesting that the CFs originate from some quantum effect. These characteristics are reminiscent of so called “universal conductance fluctuation” (UCF) in mesoscopic conductors though this is not the case as we see in the following.

Figure 2(a) also shows angular dependence of the CF when $B$ was rotated in $y$-$z$ plane from $\theta = 0^\circ$ (perpendicular to the 2DEG) to $90^\circ$ (parallel to the 2DEG). Though the pattern of CF changes with $\theta$, the amplitude and the averaged frequency versus $B$ are almost constant manifesting that the CF does not contain the portion by interference between spatial orbits in 2DEG. Particularly the CF around $\theta = 90^\circ$ is the evidence that some mechanism through electron spin should be the origin. A dramatic change occurs when we switch to the conductance between electrodes 3 and 7 ($G_{3-7}$), the path of which has no QPC on it. As shown in Fig. 2(b), CF is negligible for both the parallel and the perpendicular field even if we consider the channel-averaging effect. For the perpendicular field, even a large Shubunikov-de Haas oscillation is observed just like an ordinary 2DEG. We also should add that much smaller CF is found in the transport through a single QPC in the present sample.

Because these two measurements are on the same part of the sample, we should look for the

![Figure 1](image_url)

**Figure 1.** (a) Cross sectional view of the layered structure. (b) Scanning electron micrograph of the sample. Red shaded areas are gates of QPCs. (c) Illustrates how the ZB occurs and affects a scattering by an impurity.
origin of the difference in the nature of emitted electrons, which should be highly spin-polarized by the emitter QPC. Hence what we can consider as the origin of the CF is nothing but the ZB, the effect of which is amplified with the small range of the impurity scattering potentials.

In order to see the feasibility of our inference, we next conduct numerical calculations on the program package "Kwant" [11]. The parameters, the QPC width 400 nm and the Rashba strength $3.6 \times 10^{-11}$ eVm are directly taken from the experiment. The effective mass $0.023m_0$ (where $m_0$ is the electron mass in vacuum) and g-factor $-14.9$ are extracted from data of bulk InAs. Fermi energy $\varepsilon_F$ is estimated from the above parameters under the condition that the QPC conductance is $1G_0$. The model area ($3.6 \mu m \times 3.0 \mu m$) is divided into square unit cell (the lattice constant $25 \mu m$). The boundary condition is absorption walls except for the QPCs. The scattering center s are introduced by adding randomly-distributed values on on-site energy with amplitudes of $0.2$ eV.

First we calculate distributions of the charge density near the emitter QPC for the case of no scattering center and for the electrons spin-polarised along x-direction, the results of which are given in Figs.3(a)(b)(c). Clear meandering pattern due to the ZB is visible in Fig. 3(a). The oscillation period is modulated by applying $B_y = \pm 2.0$ T (Fig. 3(b)(c)) as predicted theoretically by Zawadzki and Rusin [2].

Next we introduce impurities and change the polarisation of emitted electrons to those along y. Figure 3(d) shows thus calculated $G_{1-5}$. In spite of the simpleness in the model, the calculated conductance between two QPCs really shows aperiodic fluctuation against the in-plane magnetic field, supporting the essential legitimacy of our model for the experiment.

![Figure 2.](image-url)
Figure 3. (a)(b)(c) Calculated space distributions of charges. From the QPC at the origin, electrons polarised along \( x \) are injected. \( B_y \) is 0 T, -2.0 T and +2.0 T for (a), (b) and (c) respectively. (d) \( G_{1-5} \) as a function of \( B_y \). The polarisation of the electrons is along \( y \)-axis.

4. Summary

We found that the ZB appears in a 2DEG with strong Rashba SOC as a reproducible CF versus magnetic field. The small range of scattering centers amplifies the ZB through modulation of the scattering cross section. This picture is reproduced in a numerical calculation on a simple model.

5. Acknowledgment

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