Application Note #000003

KeyWords
Nanonis, Tramea, Quantum Dots, Coulomb Diamonds

Nanonis™

Physics on the level of single electrons

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Equipment in use

Nanonis Tramea Base Package with standard 8 inputs and outputs
Oxford Instruments Triton™ 200 Cryofree ® dilution refrigerator

Introduction

When shrinking the size of physical systems, it often becomes unclear in which way the physical laws are still valid. For example, thermodynamics is a phenomenological theory which relies on the assumption that the system under consideration consists of a large (approximated by infinitely many) number of particles. When this limit - the so-called thermodynamic limit - does not hold, fluctuations dominate the physics, and the thermodynamic laws need to be corrected. However, when considering smaller physical systems, not only the number of particles, but also the dimensionality of the system might change. Many laws have been derived for two-dimensional systems, and can be different for the case of one or zero dimensional systems.

Experimental Setup

In our experiment, we study thermodynamics and spin-orbit interactions on the level of single electrons and in zero-dimensional structures. To do this, we form single or double quantum dots (artificial atoms or molecules) in a semiconductor heterostructure. A wafer is grown to host a two-dimensional, highly conductive layer and then patterned with metallic finger-gates on top. We apply negative voltages in order to deplete the electron gas in the two-dimensional structure via Coulomb repulsion. In this way and with a suitable gate design shown in Fig. 1, we are able to form zero-dimensional structures (quantum dots) to capture single electrons. The structures are then cooled to a temperature of 40 mK in a dilution refrigerator.

Tuning Procedure

The tunnelling of electrons between the reservoirs (the dark structures) and the quantum dots as well as the tunnelling between the two quantum dots forming a double quantum dot can be tuned by the voltages applied to the finger gates. Additionally, the depth of the potential wells describing the quantum dots can be also be tuned by applying suitable voltages on the gates. An efficient tuning of all tunnelling rates and potentials to the desired values require fast scanning of a large parameter space (5-7 gate voltages), which is further complicated by the cross-capacitance between the metallic gates.

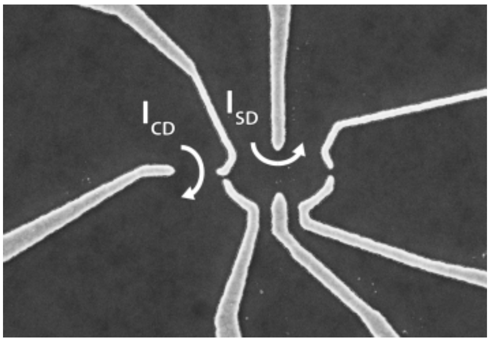


Fig. 1 Device layout with lithographically patterned gates

Usually, some of the gates are set to a fixed voltage and then a measurement is performed to sweep one signal and between each sweep, step a second gate voltage and look for a change in current passing through the quantum dot and through the quantum point contact (I_{CD} in Fig. 1) which indicates occupation of the dot. If an incorrect response is observed, changes to some of the fixed gate voltages or the range of values in the sweep are adjusted and the measurement repeated.

We then measure the charge state of both dots simultaneously by employing real-time charge-sensing techniques. Due to the nature of these single electron transfer events, particularly their sensitivity to external noise, low noise and low drift control electronics are required for accurate measurements. However, traditional measurement electronics typically require about one hour to perform a single scan of any two parameters in the sample space due to low bandwidth and slow communication protocols. This means tuning of the devices can be a laborious undertaking that requires several slow iterations to complete. However, by employing Nanonis Tramea's fast electronics designed for multi-output control measurements, we could drastically increase the speed and favourably reduce the time needed to tune the devices.

A high measurement bandwidth is only possible if the noise background is small, which means that we also require low-noise voltage sources. Additionally, the long-term stability of the voltage sources is a fundamental requirement for precise measurements which in total last several days or more.

Figure 2 illustrates the speed exploited when using Nanonis Tramea as the parameter space of gate voltages is navigated. Each graph took only about three minutes to complete meaning that a wide exploration of the parameter space and the determination of the final working–point are possible in only a few hours instead of a full day. Once the dot is properly tuned the measurement speed can be reduced to optimize the signal to noise ratio and sensitivity to small effects.

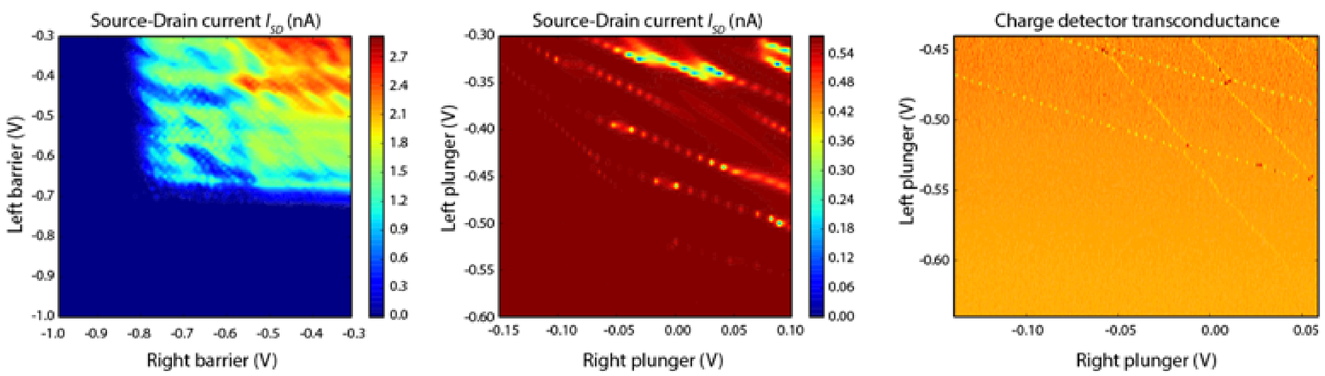
Conclusion

In conclusion, we have studied spin-orbit interaction at the level of a single electron and demonstrated that the spin-orbit coupling is probed from the tunnelling currents between two coupled quantum dots. The correct coupling between the dots is crucial for determining spin-flip rates with high fidelity, and that requires continuous readjusting of the device working point. By utilizing the new Nanonis Tramea's low noise, low drift outputs combined with real-time based control of the experiment routine, we have drastically improved the speed at which we tune the parameter space of viable devices. These advances in control electronics have allowed us to measure the Jarzynski equality - a theorem which relates the fluctuations of work to the change in free energy in a system driven far from the equilibrium - on the level of single electrons.

[1] Hofmann, V. F. Maisi, C. Gold, T. Krähenmann, C. Rössler, J. Basset, P. Märki, C. Reichl, W. Wegscheider, K. Ensslin, and T. Ihn *„Measuring the Degeneracy of Discrete Energy Levels Using a GaAs/AlGaAs Quantum Dot"* **Phys.** Rev. Lett. 117, 206803 (2016)

[2] V. F. Maisi, A. Hofmann, M. Röösli, J. Basset, C. Reichl, W. Wegscheider, T. Ihn, and K. Ensslin *„Spin-Orbit Coupling at the Level of a Single Electron"* **Phys.** Rev. Lett. 116, 136803 (2016)

[3] C. Jarzynski *„Nonequilibrium Equality for Free Energy Differences"* **Phys.** Rev. Lett. 78, 2690



3 minutes ⇨ (*n* images) ⇨ 3 minutes ⇨ (*n* images) ⇨ 3 minutes

t=0 .... 2 hours later

Fig. 2 Three snapshots of stability diagrams during an initial double quantum dot tuning procedure. Each plot was acquired in 3 minutes. A series of plots were acquired between each one which are not shown. The entire procedure from start to finish only required about two hours.