Measuring electron temperature using Nanonis Tramea
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Introduction

The Nanonis Tramea Quantum Transport Measurement System (QTMS) was used to measure electron transport through an electrostatically defined Gallium Arsenide (GaAs) quantum dot in an Oxford Instruments Triton 200 dilution refrigerator. The high-speed demonstrated by Nanonis Tramea allowed for a significant reduction in the measurement acquisition time and the low noise environment of the Oxford Instruments dilution refrigerator combined with the Tramea system, allowed us to measure an electron temperature of 35 mK. This was equal to the base temperature of the cryostat with customised wiring installed.

Equipment Used

- Nanonis Tramea with 3D sweeper module
- Oxford Instruments Triton 200 dilution refrigerator
- DL-1211 current preamplifier

Background

A single quantum dot is ideal for device thermometry at millikelvin temperatures due to the strong temperature dependence of the zero-bias conductance peak width and height in single-level transport. This is described by the equation:

\[ G(V_g, T) \approx \frac{e^2}{h} \frac{C_2}{k_B T_e} \text{sech}^2 \left( \frac{\alpha(V_g - V_o)}{2k_B T_e} \right) \]

where \( G \) is the conductance through the dot, \( h \) is Planck's constant, \( e \) is the electron charge, \( k_B \) is the Boltzmann constant, \( C_2 \) is an amplitude fitting parameter, \( T_e \) is the electron temperature, \( \alpha \) is the gate lever arm, \( V_o \) is the applied gate voltage at which the peak is maximum (resonant tunnelling), and \( V_g \) is the plunger gate voltage.

Experimental set-up

The GaAs quantum dot was fabricated on Al_{0.33}Ga_{0.67}As/GaAs heterostructure wafer, where the two dimensional electron gas (2DEG) is located 110 nm from the surface. The heterostructure has a 10 nm Silicon (Si) cap and a \( \delta \)-doping layer buried 70 nm from the surface (n-type doping = 5x10^{11} cm^{-2}). The quantum dot is formed by applying negative voltages on a set of titanium gold, Ti/Au (20/20 nm), metal gates, shown in Figure 1. These gates deplete the buried 2DEG such that a small amount of charge is isolated in a region of approximately 100 nm². The sample was made at the Quantum NanoFab facility at the University of Waterloo.

An image of the device was taken using scanning electron microscopy (SEM) and is shown in Figure 1, also showing a schematic of the experimental setup with electrical connections to Nanonis Tramea. The plunger gate \((V_g)\), source \((S)\) and drain \((D)\) are shown. A customised filter in the MHz range was mounted on the mixing chamber of the Oxford Instruments Triton 200 using copper powder loaded epoxy on the PCB board. Additional low pass RC filters were also mounted on the cold plate at 150 mK to provide filtering down to 25 kHz and room temperature filters with a cut off frequency of 1.5 Hz were used outside Triton. A voltage divider is added to the source output voltage.

Figure 1. A schematic of the measurement setup. The GaAs quantum dot location is shown in the dotted white circle.
The GaAs quantum dot device was mounted on the cold finger of an Oxford Instruments Triton 200 dilution refrigerator. With customised DC wiring, coaxial cables and extra radiation shielding of the mixing chamber, a temperature of 35 mK was recorded as the base temperature, measured using a calibrated ruthenium oxide thermometer, mounted on the mixing chamber. All voltages were supplied by Nanonis Tramea and the output current from the device was amplified using a DL-1211 current preamplifier (battery-operated), whose output was connected to a Tramea input channel.

**Experimental Results**

After tuning the gate voltages to define the quantum dot, a clear conductance pattern referred to as ‘Coulomb diamonds’ shown in Figure 2, was observed. The experimental data was fit to the equation described previously, using the experimentally determined \( \alpha \), shown in figure 2, and three fitting parameters: \( V_o \), \( T_e \), and \( C_2 \). The lever arm \( \alpha \) is a conversion factor between energy and gate voltage and is calculated as the ratio between the energy and gate voltage difference between adjacent conductance Coulomb peaks and the charging energy of the quantum dot.

Figures 3 and 4 show a close-up of a single Coulomb diamond vertex measured with integration times of 1 ms and 50 ms (total acquisition time of 90 seconds and 35 minutes), respectively. The fact that both the voltage outputs and current inputs for the measurement were handled by Nanonis Tramea, removed the usual experimental barrier of communicating with a range of instruments connected over slow communication buses. This allowed for a decreased acquisition time and enabled quick device tuning and exploration of the gate voltage parameter space.
At the base temperature of 35 mK, a selected conductance peak, shown in Figure 5, was fit to the equation on page 1, giving an electron temperature of $35.5 \pm 1.3$ mK. This fitting procedure was repeated for 5 different mixing chamber temperatures $T_{MC}$ controlled by a resistive heater on the mixing chamber plate.

The resulting electron temperatures are plotted as a function of $T_{MC}$ in Figure 6. The agreement between the lattice and electron temperatures, extending all the way to the base temperature, indicates that Nanonis Tramea voltage noise levels are negligibly small in this experimental context.

**Conclusion**

In conclusion, Nanonis Tramea enables high-speed control over several output voltages with a negligible amount of electrical noise introduced into the measured device, which is essential in quantum transport measurements of quantum dots and other devices. The high-precision, high-bandwidth capabilities of the Tramea system could be combined with automation/machine learning algorithms to efficiently auto-tune and calibrate quantum devices for desired experiments. The high speed capability of the Tramea combined with the stable millikelvin environment of the Oxford Instruments Triton 200 dilution refrigerator meant an electron temperature of 35 mK could be measured using a GaAs quantum dot.