MEASUREMENT Application note

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.

Triton and **Nanonis Tramea**

Equipment used

Oxford Instruments **Triton 200** dilution refrigerator
Nanonis Tramea with 3D sweeper module
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:

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

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, α 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.

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Experimental set-up

The GaAs quantum dot was fabricated on $Al_{0.33}Ga_{0.66}As$/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 δ-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 nm^2. 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.

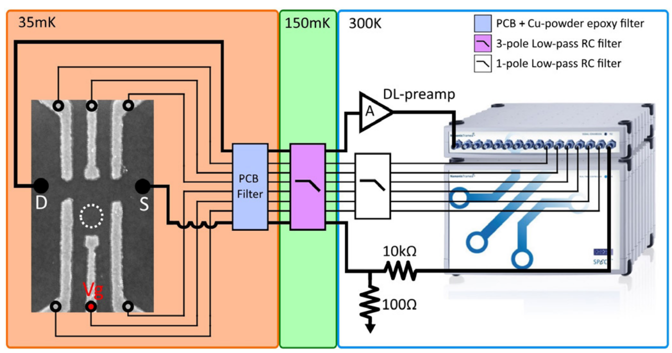

Figure 1. A schematic of the measurement setup. The GaAs quantum dot location is shown in the dotted white circle.

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 α, shown in figure 2, and three fitting parameters: V_o, T_e, and C_2. The lever arm α 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.

Experimental results

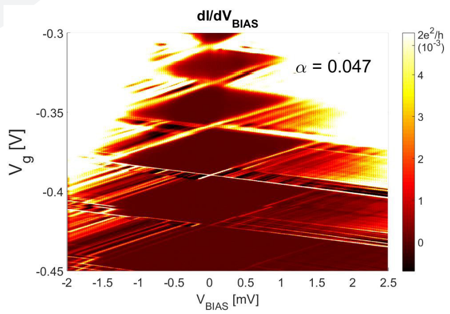

Figure 2: Conductance through the GaAs quantum dot measured at a lattice temperature of 35 mK. The conductance shows clear Coulomb diamonds.

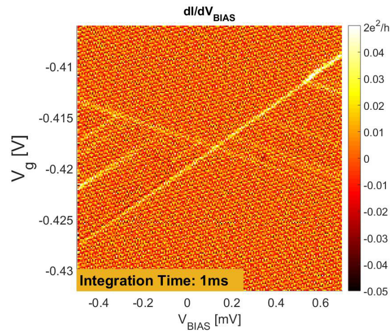

Figure 3: Conductance around a Coulomb diamond vertex measured using an integration time of 1 ms. The total acquisition time was 90 seconds.

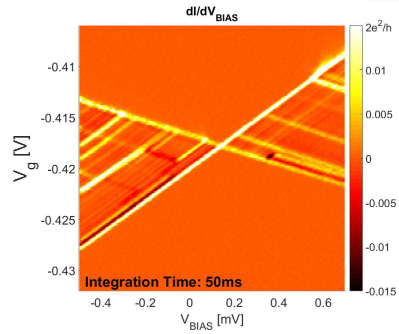

Figure 4: Conductance around the same Coulomb diamond vertex measured using an integration time of 50 ms. The total acquisition time was 35 minutes.

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.

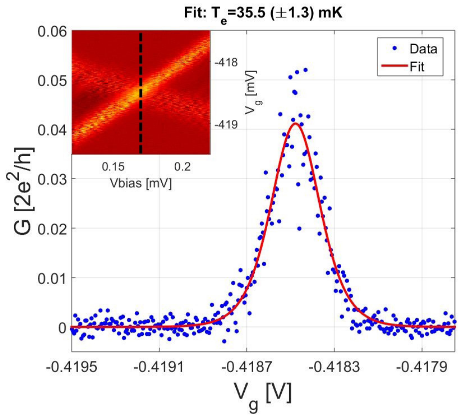

Figure 5: Zero-bias conductance peak fit at a mixing chamber temperature of 35 mK. The electron temperature is estimated to be **35.5 ± 1.3 mK**. The Inset shows the conductance around the Coulomb diamond vertex which is used to extract the zero-bias conductance peak (shown by dashed black line). A constant DC voltage offset on the input of the current preamp causes the observed bias offset of about 170 μV.

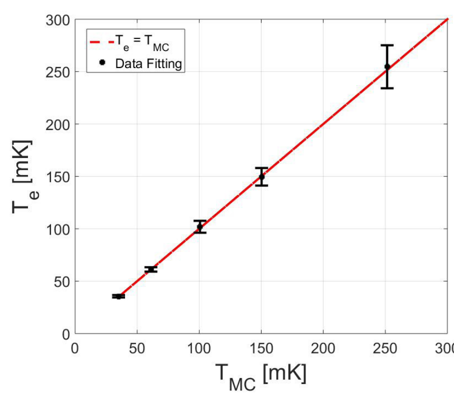

Figure 6: Experimentally measured relationship between the estimated electron temperature vs. the mixing chamber temperature of the dilution refrigerator. The two temperatures are equal within uncertainty down to the base temperature of 35 mK, indicating that voltage noise from the measurement setup is negligible.

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 ± 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.

Experimental results

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.

About **Triton** and **Nanonis Tramea**

The ultra-low temperatures and high magnetic fields provided by the **Triton** dilution refrigerator make it a key research tool in revealing the quantum properties of many materials of interest. The **Triton** systems already lead the way in experiment-readiness with high-density RF and DC wiring capability, unique sample exchange mechanisms, and unbeatable superconducting magnet integration. SPECS' **Nanonis Tramea** QTMS is a natural complementary partner to the **Triton**, with its fast, multi-channel, multi-functional capability. The system enables quantum measurements to be carried out on a variety of samples, as shown in this application note.

Nanonis Tramea multifunctional, low noise, low drift and high resolution electronics.

The latest **Triton** dilution refrigerator with increased experimental space and cooling power.

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