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Tuning and Operation of Quantum Dots and Related Apparatus

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Nanonis Modules in Use

- Base Package with standard 8 inputs and 8 outputs
- Octa lockin module (LD-8)
- FPGA Oscilloscope

Introduction

Spin qubits in quantum dots are promising candidates towards quantum computation [1, 2]. However, a considerable amount of technical development is still necessary before the advent of a quantum computer. For quantum dots, this involves independently controlling and sweeping the voltages of a multitude of electrostatic gates and monitoring several charge sensing signals. Thus, a fast measurement device with a high number of inputs and outputs is critical for the efficiency of the development of multiple quantum dot devices. The group of Michel Pioro-Ladrière at Institut Quantique, Université de Sherbrooke, Canada, have recently conducted measurements on quantum dots and related components using the Nanonis Tramea instrument, which will be discussed in this application note.

Quantum Dots Basics

Quantum dots are based on trapping single electrons and controlling and reading out their charge. In most architectures, each quantum dot requires several gates to trap the electrons. The occupancy of the dot is inferred by charge sensing methods [3, 4], which allows the mapping of charge stability diagrams in the Coulomb blockade regime. The charge sensor, typically a single-electron transistor (SET), needs separate contacts to operate. Furthermore, a recent improvement to the readout process consisting of amplifying the output current of the SET with a cryogenic heterojunction bipolar transistor (HBT) was achieved [5]. This technique greatly enhances the signal to noise ratio of the output current, but the transistor also requires its own contacts as well as tuning of the operating point. For our current technology, the number of input and output channels required to control the gates and measure the SET signals can be up to 30 for a double-dot device. Here, we show a conceptual version of a typical setup (Fig. 1). To operate such a setup, all outputs must be able to very precisely apply DC as well as AC voltages. As an example, we may want to apply a 2V DC bias to a gate, but modulate it with an AC amplitude of only 100 µV. Additionally, some measurements, such as SET transconductance charge sensing, can only be done using lock-in demodulation, so the ability to demodulate multiple input signals at once is a must. Finally, it's also paramount to be able to capture real-time measurements, as spin readout requires the ability to detect individual steps of the SET current. The duration of those steps depends on the tunnel rates to and from the dot, but can be as short as a few tens of microseconds while representing a current change of less than 1 nA, so real-time acquisition is needed. All of those requirements are met by the Nanonis Tramea instrument. Its voltage output range fully cover the range of voltages that might be useful to output on our quantum dots (±10V), and have a noise density in the nV/√Hz range, making them ideal for outputting small signals on components with a high sensitivity to noise. Equipping all the ports with Mini Circuits BLP-1.9+ low-pass filters makes the noise performance of the instrument even better by cutting off high-frequency parasitics. The octa lock-in module makes it possible to demodulate up to 8 signals simultaneously, which means it is possible to measure multiple SETs at once. Finally, the oscilloscope FPGA module combined with low noise and 100 kHz bandwidth inputs permits the fast acquisition of time traces, enabling fast charge detection. The following sections will show results from a HBT and tuning of a quantum dot using the Nanonis Tramea system.

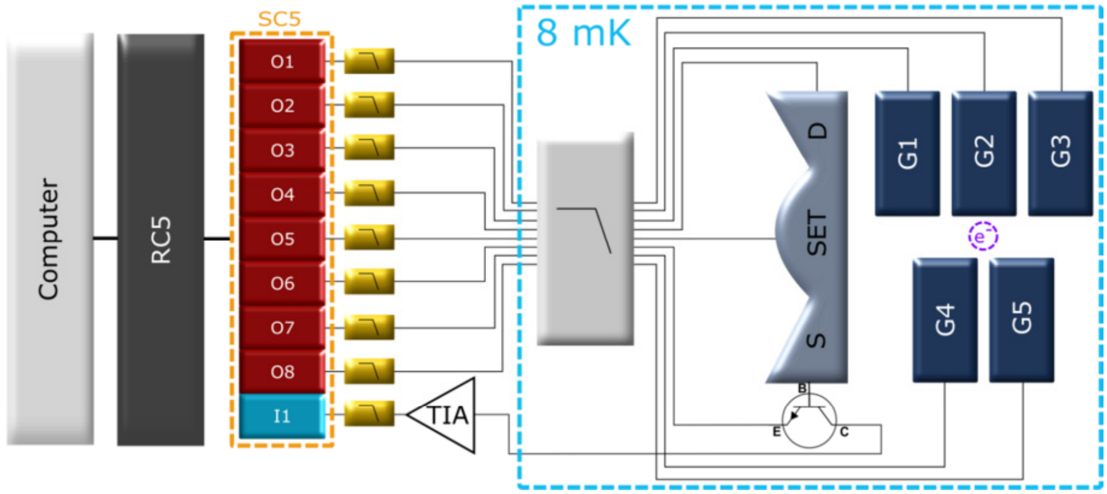

Figure 1 A conceptual schematic of the experimental setup in use for the quantum dot measurements. The area enclosed in the blue broken line is the part of the circuit that is cooled inside a dilution refrigerator. It is composed of the quantum dot dev device, itself defined by electrostatic gates (dark blue) trapping single electrons (purple), and of a SET (dark grey) acting as a sensor. The source contact of the SET is wire-bonded to the base of a HBT, whose emitter is connected to a room-temperature TIA to further amplify the signal and enable voltage readout. Most cables go through RC low-pass filters (light grey) to cut high-frequency noise that would otherwise reach the device. Outside the fridge, every cable is connected to the Nanonis Tramea instrument. Here, everything that finds itself inside the orange broken line is a port of the SC5 module, either an input (blue), or an output (red). Additional Mini Circuits BLP-1.9+ low-pass filters (yellow) are connected to each port. The SC5 module is itself connected to the RC5 module (black), where the signal is processed before being sent to the control computer (silver).

Cryogenic Amplifier Tuning

Firstly, we needed to characterize the cryogenic HBTs. Using the Nanonis Tramea instrument, we were able to quickly measure the current-voltage (I-V) curves of multiple transistors and decide which ones to couple with quantum dot devices. The setup used for this experiment (Fig. 2) consists of connecting a HBT cooled in a dilution refrigerator to the Nanonis Tramea. A 1M□ resistor was used to simulate the presence of a SET, and a transimpedance amplifier was used to convert the collector current into a voltage readable by the Nanonis Tramea. Using the 1D sweeper module, it was easy to vary a voltage and see its effect on the current. The measurements produced functionally identical results to the ones done with a source-measure unit (SMU) (Fig. 3, left). However, using the 1D sweeper module of the Nanonis Tramea gave us access to parameters that weren't possible to precisely control using the SMU, such as the settling time and the measurement period. For this measurement, the period was 100 ms, resulting in signal oversampling and less noisy data. The conversion factor feature of the Nanonis Tramea software was also useful because it meant that the measured voltage from the TIA was directly recorded as a current in amperes and required one less data processing step later on.

We also examined the frequency response of the transistor up to 10 kHz using the frequency sweeper module (Fig. 3, right). This measurement was done by using the same setup as previously, but the signal was this time sent and measured using the lock-in module of the Nanonis Tramea. In a traditional setup, we would have had to change measurement instruments, which is avoided with the Nanonis Tramea. Using a previous calibration to know the input current corresponding to the applied voltages, calculating the gain was done easily.

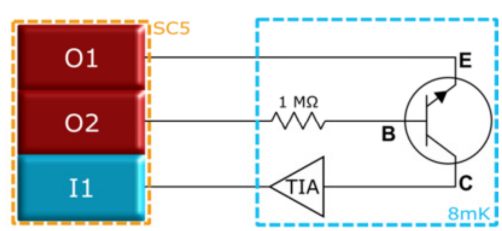

Figure 2 Schematic of the circuit used to characterize the HBTs, showing the connections made between the HBT and the SC5 module of the Nanonis Tramea system. Only input(blue) and output(red) ports in use are shown.

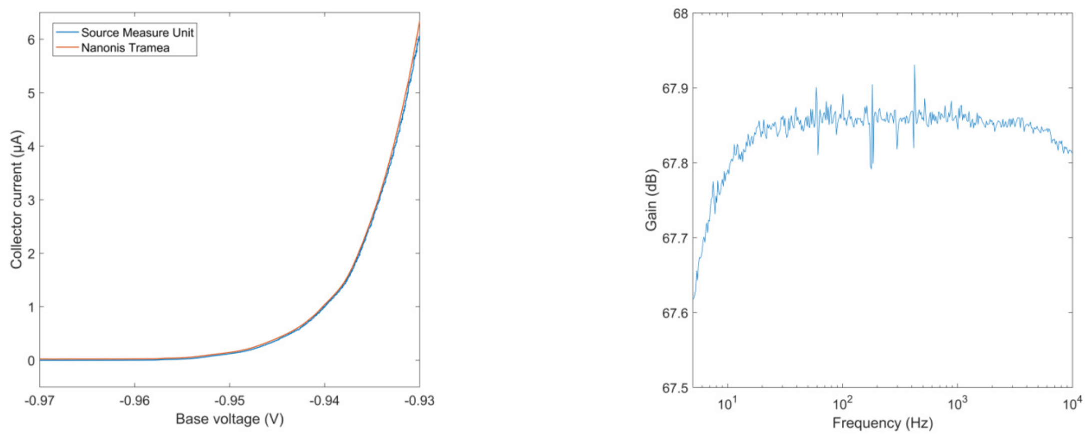

Figure 3 Left: Comparison of the HBT IV curves acquired with the Nanonis Tramea device and a SMU unit. Both curves are equivalent up to some random fluctuations of the collector current. Right: A frequency sweep done with Nanonis Tramea which makes it possible to characterize the gain with respect to frequency.

Measurement of Quantum Dots

After having tuned the HBTs and wire-bonding them to the SETs, tuning of the quantum dots was done. Using our current experimental setup (Fig. 1), five gates of the device and a SET can be completely operated by the Nanonis Tramea instrument with only one SC5 module. As previously stated, a usual device has more than five gates and one SET to control, so additional static voltages were applied with an external DAC. If those voltages required tuning by sweeping gate voltages, it was initially done with the Nanonis Tramea and then the cable was transferred to a output of the DAC which was set to the optimal voltage value determined with the Nanonis Tramea. Another solution would have been to use more SC5 modules, which would have enabled us to sweep any gate voltage without having to transfer cables. Now, let's look at tuning measurements done with a SET. Using the 3D Sweeper module of the base package the simplest measurement that can be done is a DC measurement where the voltages of two gates are swept, and the amplified SET current for each of those points is captured. The graph in Figure 4a has a resolution of 1201 x 601 points (721 801 points total) and was captured in less than one hour which is remarkable considering the quality of the data. A 100 x 100 sweep (10 000 points total) with our previous measurement solution also required about one hour, so the increase in acquisition speed with Nanonis Tramea is dramatic. Furthermore, by taking the derivative of this data with respect to one of the voltages, the transitions become much clearer (Fig. 4b). It is also possible to do this directly in the software, which enables a quicker analysis. Furthermore, the Nanonis Tramea device allows for application of a DC bias and an AC modulation simultaneously on any given channel and for lock-in measurements with a large range of filters on all channels. This versatility facilitates the realization of transconductance measurements on QD systems, a method that is known to improve visibility of transitions compared to DC measurements (Figs. 4c and 4d). Using an excitation frequency of 1 kHz, it was possible to recover the lock-in signal using an integration time of only 2 ms. The resulting graph (Fig. 4c) has the same resolution as the DC one (Fig. 4a) and took the same time to capture. Finally, using the oscilloscope FPGA module of the Nanonis Tramea, it is easy to acquire time traces of the SET current. Under the right conditions, which are determined by tuning the dot as shown previously and setting the voltages to be directly on a transition, it is possible to bring the dot in a state such that random tunneling to and from the dot occurs (Fig. 5). The two distinct current levels correspond to two different electron numbers in the quantum dot. Such a curve is used to determine the tunnel rates between the reservoirs and the quantum dot. Prior to using the Nanonis Tramea, curves had to be taken with a separate oscilloscope so the instrument once again simplifies the experimental setup and facilitates the quick capture of data.

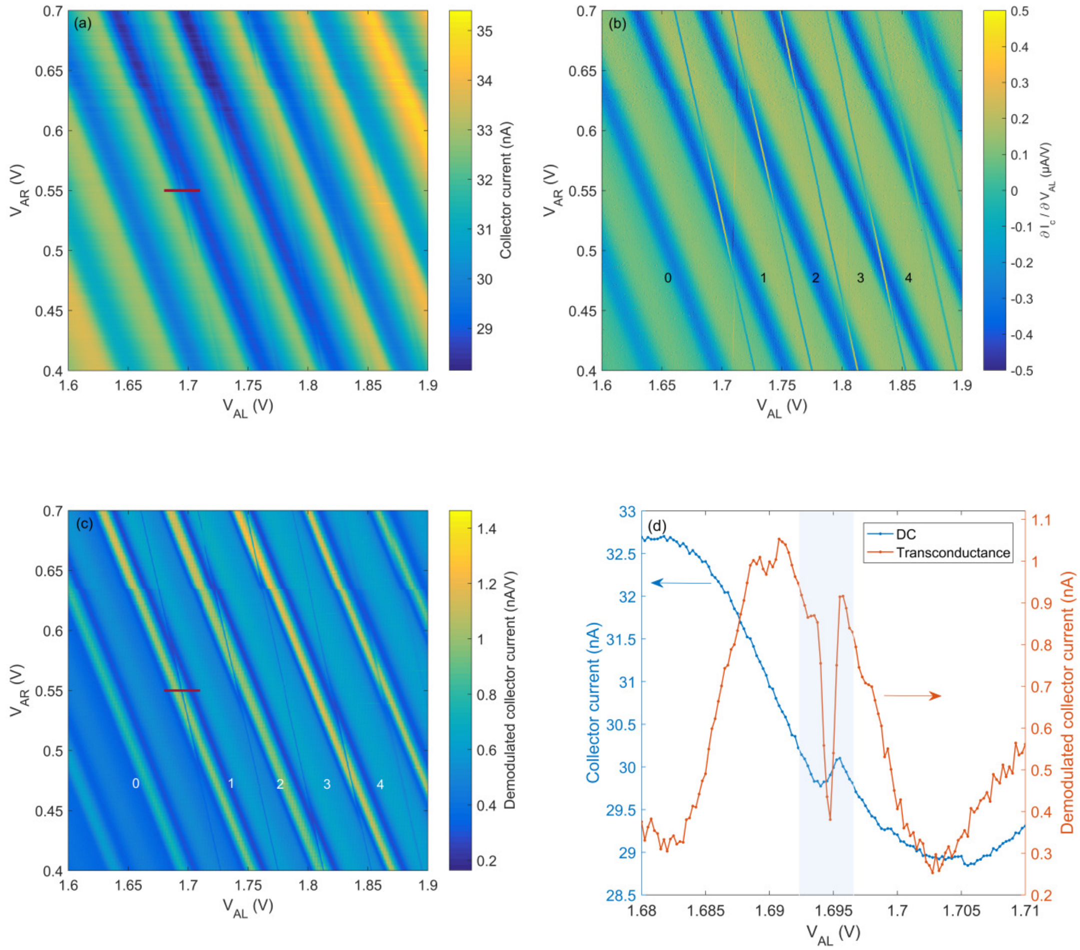

Figure 4 Stability diagrams captured by using a DC measurement (a) and a transconductance measurement (c). Each of the diagrams shows two types of lines. There are the wider and more slanted lines, which correspond to SET Coulomb peaks, and there are finer and m more vertical lines, which correspond to transitions of the charge state of the QD. The numbers that are present between transitions correspond to the number of electrons in the quantum dot. It is also visible that transconductance data is less subject to noise than DC data. Transitions are also much less visible in DC than in transconductance, as can be seen in (d), where the shaded area corresponds to the transition. The range of VAL plotted corresponds to the red lines visible on Figs. (a) and (c). Section (b) corresponds to the derivative with respect to VAL of the DC data presented in (a) to better show transitions.

Outlook

The new measurement capabilities offered by the Nanonis Tramea system will enable us to do faster measurements on quantum dots while achieving the same level of data quality as with previous methods. This is a critical advantage as the yields of semiconductor quantum dots are still low and a quicker measurement means being able to differentiate between a good device and a bad device in less time, thus focusing on working with good devices. The Nanonis Tramea system also replaces several lab devices, particularly lock-in amplifiers, which greatly reduces the complexity of the experimental setup.

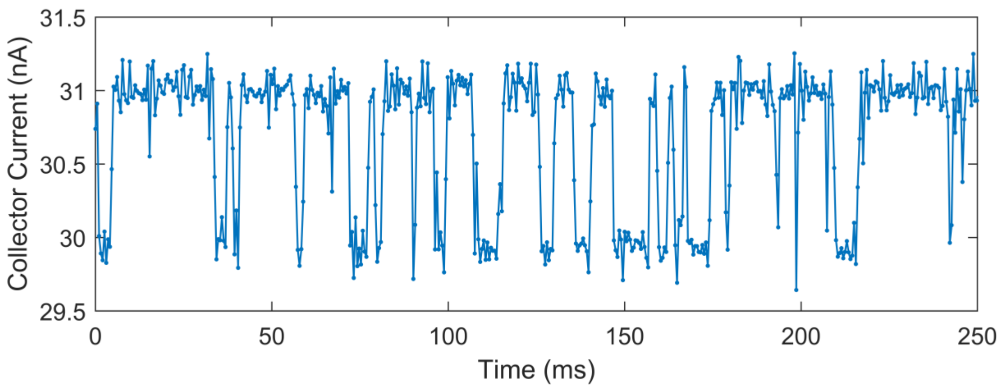

Figure 5 A 250ms excerpt from a 12.2s trace taken with the oscilloscope FPGA module showing electron tunneling. The two current states visible at approximately 30 nA and 31 nA correspond to different electron numbers inside the quantum dot. This curve was taken using a 1.95 kHz sampling rate.

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