MEASUREMENT

Application note

Transport and RF-reflectometry measurements of CMOS nanodevices

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Introduction

Pioneering work on semiconductor quantum dots has shown that quantum dots are promising candidates as a building block (qubit) for quantum information and computation. Quantum dots are quasi-zero-dimensional nanostructures which can confine single electrons, whose spin or charge degree of freedom can then be used to represent quantum bits (qubits).

Quantum computing approaches based on semiconductors can build upon mature micro and nano-fabrication technologies, which will be invaluable in scaling up to a large number of reproducible qubits with practical yields, and integrated electronics. As part of the classical information technology industry, CMOS transistors have reached sufficiently small feature sizes that quantum effects can begin to play a dominant role. This motivates the exploration of quantum effects in such transistors fabricated using CMOS processes.

Triton and **Nanonis Tramea**

Equipment used

Triton 200 Dilution Refrigerator, **Nanonis Tramea** with lock-in module, **SR 830** lock-in amplifier.

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Experimental set-up

In this note, we describe experiments on quantum dots created within CMOS finFET (fin Field Effect Transistor) devices.

The transistor consists of multiple silicon fins, sitting on an insulating oxide layer, sharing a common source and drain as well as a wraparound top-gate which is used to control conduction through the fins. Further control is possible by the bulk silicon substrate which can be used as a back-gate.

The field effect of the top-gate is greatest in the corners of the fin cross-section, due to its geometry. This leads to formation of quantum dots when operating the finFET sub-threshold, which can be observed at cryogenic temperatures (see transfer curves at 300 K and 30 mK in Figure 1).

As an alternative to measurements based on transport through the FET, it is possible to characterise, with high sensitivity, the charge transitions of quantum dots even when no signal in transport can be detected. This is achieved by using the top-gate as a dispersive sensor measuring small changes in the capacitance of the device originating from the tunnelling of single electrons, detected by the response of an LC resonator at radio-frequency (RF). The high sensitivity and bandwidth of this measurement makes it ideal for studying the transistor in a regime where transport is pinched off.

In such gate-based RF-reflectometry, weak RF modulation is applied to the top-gate via a bias tee, close to the resonance frequency of an LC circuit consisting of a surface mount inductor and the parasitic capacitance of the PCB and device itself (see Figure 1). The reflected RF signal is amplified at multiple stages followed by IQ-demodulation to obtain the amplitude and phase of the reflected signal. A change in phase of the reflected signal relates to an effective change in device capacitance.

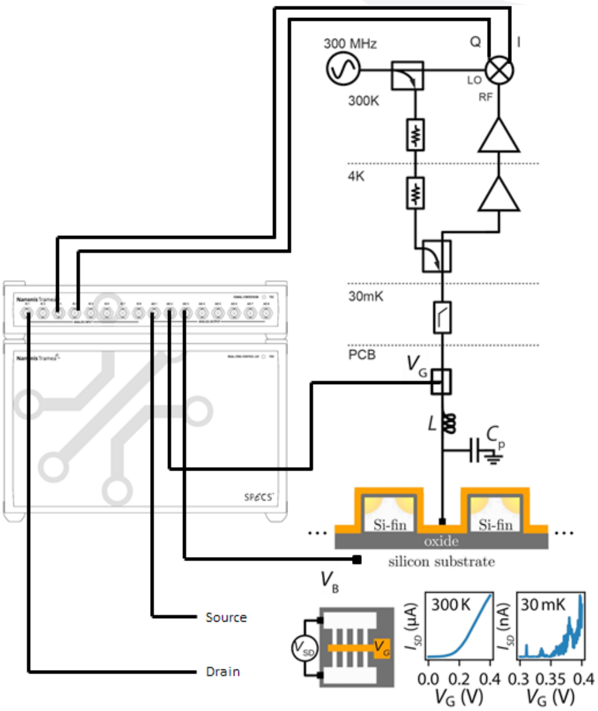

Figure 1. Measurement setup for RF reflectometry and finFET device.

Experimental results

Transport measurements of a quantum dot rely on electrons being able to tunnel on and off the dot. Detecting such electron tunnelling requires the ability to measure very small currents (on the order of picoamps). Furthermore, as tunnel barriers become less transparent, transport measurements become more and more challenging, and substantial integration may be required to achieve adequate signal-to-noise.

In contrast, RF-reflectometry allows fast and sensitive measurements even when tunnel barriers are in-transparent. However, such measurements are often more complicated to interpret as the signal originates from any change in device capacitance.

The **Nanonis Tramea** system is able to improve current measurement procedures in various ways. The integrated solution of very fast logic, data acquisition and storage combined with low-noise inputs allow for an enhancement in the speed of transport measurements, for example by reducing the communication time present when separate instruments (e.g. lock-in amplifiers) are used. Furthermore, transport and reflectometry measurements can be performed simultaneously, allowing for direct comparison between the two methods. This can be particularly useful when exploring a new device where specific operating regions need to be identified by large scans within the parameter space.

A large gate map from a device studied in transport, taken with a GPIB-interfaced lock-in amplifier controlled using a measurement computer, can take several hours. An example is given in Figure 2 which shows Coulomb oscillations as a function of bulk and top-gate voltage. With the Tramea system a similar scan can be obtained in only 10 minutes at the same resolution. Additionally, by comparing the 2 hour and 10 minute scans we observe a drift or instability in the 2 hour scan which is not apparent in the fast scan. Stable and precise voltage sources are other key factors for such measurements as measurements can last several days and quantum devices have small tolerance levels.

By feeding the I and Q outputs from the IQ-demodulator into two other Tramea inputs, we can obtain a reflectometry scan simultaneously with the direct transport measurement. Comparing the reflectometry with the transport scan we observe many additional oscillations at low gate voltage, where tunnel barriers have become opaque.

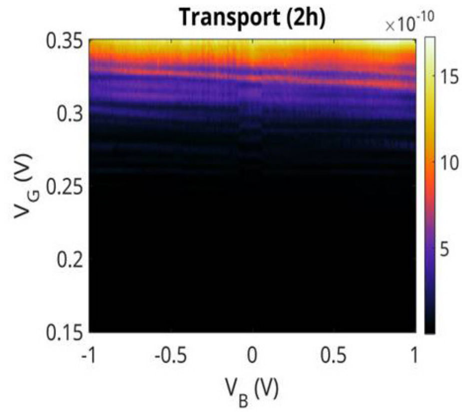

Figure 2: Transport measurement using GPIB interfaced lock-in (SR 830).

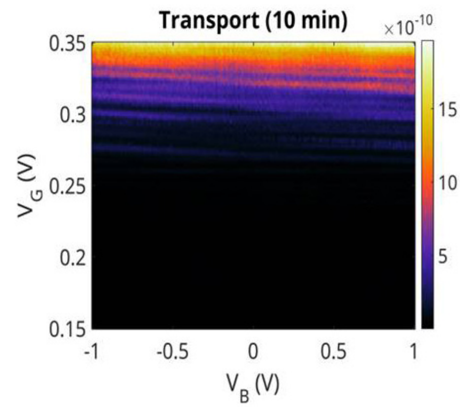

Figure 3: Transport measurement using Nanonis Tramea system.

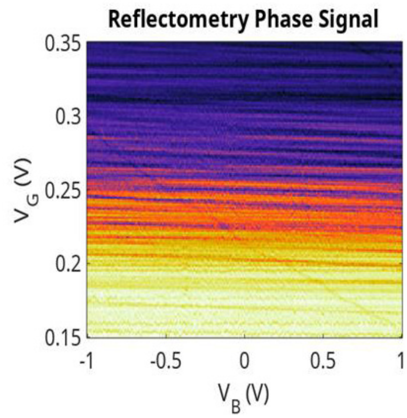

Figure 4: Reflectometry measurement using Nanonis Tramea system.

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Experimental results

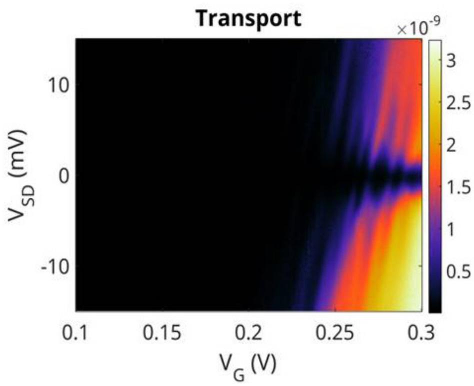

Figure 5: Coulomb diamonds in transport using Nanonis Tramea system.

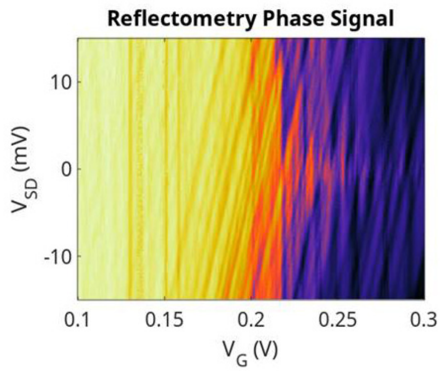

Figure 6: Coulomb diamonds in reflectometry using Nanonis Tramea system.

For further quantum dot characterisation we take a scan varying the source-drain and top-gate voltage. We observe Coulomb diamonds compatible with multiple quantum dots in transport and reflectometry.

Conclusion

In summary, we have studied a CMOS fin-FET device. At cryogenic temperatures we observed signatures consistent with multiple quantum dots. Using the **Nanonis Tramea** system we were able to significantly speed up the characterisation process and simultaneously obtain transport and RF-reflectometry data which is useful when exploring the parameter space of a new device.

Further reading

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