Few-Electron Quantum Dot in a Fast Turnaround Dilution Refrigerator

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Abstract

In this semester project, work was done on the electrical setup of a fast turnaround dilution refrigerator. The system of the fridge was completely electrically isolated and grounded at only one point to reduce electrical noise. A cooldown was then successfully performed and a few-electron quantum dot could be formed. First estimates of the electron temperature in this setup are also presented.

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1 Introduction

Using quantum mechanical superposition states and entanglement in a quantum computer would allow solving complicated mathematical and physical problems much faster than with classical computers.[1] But the realization of such a computer is a challenge because it requires precise control of fragile quantum states. Nevertheless, the state of the electron spin has been identified early as an attractive realization of a quantum bit.[2]

As a host for the electron spin, semiconductor quantum dots seem to be a promising approach. In the last years, many of the elements necessary for quantum computation have been experimentally realized in semiconductor quantum dots, showing the auspicious advances for such a host system. Nowadays, a single electron can be isolated[3] and the spin can be initialized in the ground state[4]. Spin-states are long-lived, i.e. spins have long relaxation times.[5] (Decoherence times of up to one second have been measured recently.[6]) A single-shot read-out of one single spin state is possible[5] as well as inducing coherent spin rotations of a single electron spin[7].

In this project, work was done on the electrical setup of a fast turnaround dilution refrigerator. A simple bias-circuit was built for the application of the AC and DC voltages to the sample. The fridge was also completely electrically isolated from the ground and then grounded at one single point to avoid ground loops and to reduce electrical noise from the surrounding. Furthermore, a cooldown of the system was performed successfully and a few-electron quantum dot could be formed. The electron temperature of the system then was estimated.

2 Materials & Methods

2.1 Sample

The sample is an in-house fabricated device with evaporated TiAu-gates on a GaAs-AlGaAs-heterostructure (Figure 1). The two-dimensional electron gas (2DEG) is approximately 100nm below the surface. The gates are designed to form a double quantum dot, including two quantum point contacts (QPC) for read-out of the charge-state on each dot.

In the experiments described in this report, a single quantum dot has been formed by using the three plunger gates in the middle as one gate. The QPCs were not used; the conductance through the dot has been measured by using ohmic contacts S1 and S2 as source and drain.

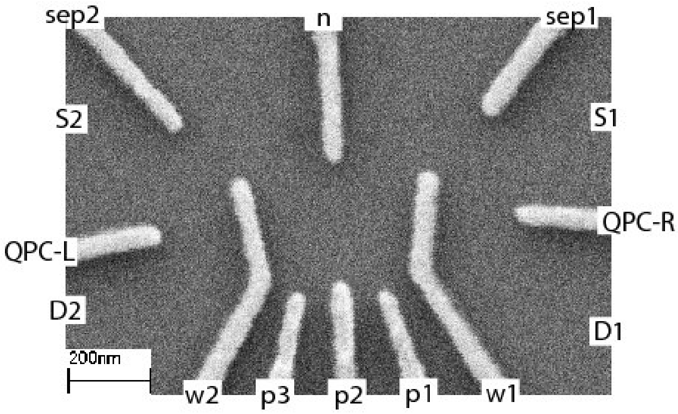

Figure 1: Scanning electron microscopy (SEM) image of the measured sample. n=nose, w1=right wall, w2=left wall, p1,p2,p3=plunger gates.

2.2 Setup

2.2.1 Cryostat and magnet [8]

The cryostat (Cryogenic Ltd, London, UK) is a low boil-off helium cryostat with a helium reservoir designed to fully integrate with the magnets and electronics. The current leads, syphon and level gauge fittings as well as electrical and exhaust ports are mounted in the top plate. The cryostat top plate, neck, helium reservoir and tail are all of stainless steel and the radiation shields and outer case are of welded aluminium alloy. Radiation heat load is minimized by using gas-cooled and nitrogen-cooled radiation shields and multi-layer insulation. The cryostat has a single vacuum space which is evacuated via the port on the wall.

The cryostat tail thermometer has a well defined response between 300K and 4.2K, providing an immediate indication of temperatures from four terminal resistance measurements.

The high-field superconducting magnet solenoid (Cryogenic Ltd, London, UK) produces a maximum central field of 9T. It consists of a single section producing a high field region at its centre. A superconducting persistent mode switch is connected in parallel across the magnet. Resistive heaters in the switch enable it to be either resistive or superconducting.

2.2.2 Insert [9]

The dilution refrigerator (Leiden Cryogenics BV, Leiden, NL) consists of an insert and a gas handling system, coupled to each other by flexible stainless-steel hoses and cables for the valves and gauges of the insert. The fridge has a very fast turnaround time of a few hours from room temperature to nearly base temperature. The mixture is circulated by a turbo-molecular drag-pump backed by a dry rotary pump so that the refrigerator is fully oil-free. A sorption pump is used for the final evacuation of the inner vacuum chamber (IVC).

The dilution refrigerator unit is attached to a 1K pot and further consists of a still, a heat exchanger body and a mixing chamber (MC), which are entirely made of high resistance plastic, making it insensitive to eddy-current heating. The inside of the MC is easily accessible through a greased conical plug and contains a connector ring with 40 pins. The wires are twisted shielded pairs that enter through the top part of the unit into the still and are thermalized by the liquid mixture. A conical plug fitted with a cold-finger and a 40 pin feed-through allows performing experiments outside the MC.

The temperatures of the 1K pot, still and mixing chamber are measured with RuO_2 resistance thermometers using 8 of the 40 wires leaving thus 32 for measurements. There are three heaters for the still, mixing chamber and sorb pump ending at room temperature in a Fisher hermetic socket. The still liquid level is measured using a capacitance level gauge connected to two Lemo sockets. Before starting an experiment, the sample has to be installed onto the cold finger with good thermal contact to the MC and a thorough test of the electrical leads has to be run.

The insert is made of a stainless steel tube with 50mm outside diameter and has a 50mm vacuum chamber. A 1K pot is included for fast condensation of the mixture. The ^{4}He liquid is fed to the 1K pot via an input line placed just above the IVC conical joint. The input line is fitted with a sintered metal filter.

The head of the insert is made of anodized aluminium. The bolts assure electrical contact between the parts. On the head there are four 24V DC valves and three inlet/outlet NW 16 ports. At the top of the insert there's a wire box with a Fisher 6 pin hermetic socket for the heaters, two Lemo hermetic coax sockets for the read out of the level gauge in the still and two 24 pin hermetic sockets for the wiring. Just below are located the 1K pot port, the IVC port, the gate valve for the still, the ^{3}He input port, the vacuum gauge for the still, the IVC valve and the IVC vacuum gauge.

2.2.3 Gas handling system [9]

The gas handling system (GHS) consists of a stainless steel cabinet made of hollow square tubes welded so as to make two leak-tight reservoirs. One is used for storing ^{3}He (20 litres), the other one is used for the ^{4}He-rich mixture (70 litres).

A control panel is embedded in the front side of the GHS cabinet with which the valves and pumps of the system can be controlled. The MaxiGauge vacuum gauge controller (Pfeiffer Vacuum, Asslar, D), placed also on the front of the cabinet, is used to monitor the Pirani pressure gauges (Pfeiffer Vacuum, Asslar, D) of the IVC and the still. A turbo pump controller (Varian Vacuum Technologies, Torino, I) is placed next to the vacuum gauge controller. Also on the front side, there's the AVS47 resistance bridge (Picowatt, Vantaa, FIN). A Triple Current Source (Leiden Cryogenics BV, Leiden, NL), placed below the AVS47 resistance bridge, has three independent low-noise outputs for heating the sorb-pump, the still and the MC. It can be used in combination with the resistance bridge to adjust the temperature.

Inside the cabinet there's a turbo pump (Varian Vacuum Technologies, Torino, I), two pumps for the ^{3}He circulation and the 1K pot, as well as a nitrogen cold trap.

2.2.4 Electrical control

The voltages that are applied to the sample are controlled on the computer with the software Igor Pro (WaveMetrics, Lake Oswego, USA). The signal is transmitted over GPIB and optical fibres (National Instruments, Austin, USA) to the Digital to Analog Converter (DAC). A self-built AC/DC bias box (Figure 2) is used to apply an AC modified DC signal to the source of the sample. The AC signal is generated and read out by a Lock-In Amplifier (EG&G Instruments Corporation, Princeton, USA). The DC input for the bias box and the signals for the gates are coming from the DAC. All the electrical signals are then transmitted to the insert via one of two breakout boxes.

The current that is measured on the sample is amplified by a current amplifier and filtered with the Lock-In Amplifier. The signal is then transmitted back to the computer via optical fibres to be analyzed in Igor Pro.

The whole system with the fridge and the control instruments has been electrically isolated from the ground by using optical fibres for signal transmission and using transformers for power supply. The system then has been grounded at one single point. Noise due to ground loops could be reduced significantly in this way, i.e. response to other electrical systems (e.g. a crane) was eliminated. But 50Hz noise from to the power supply system was barely reduced, despite using transformers for all power supplies to the system. Further investigations have to be done on that problem in the future.

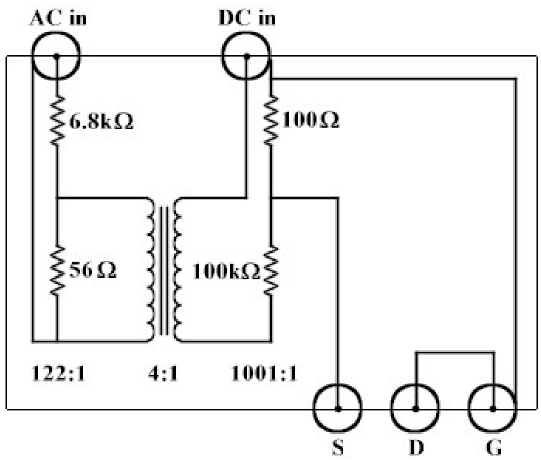

Figure 2: Electrical circuit of the AC/DC bias box, which divides the applied voltages by approximately 500000:1 (AC) and 1000:1 (DC) respectively.

2.3 Temperature measurement [10],[11]

In a lateral single quantum dot, three temperature regimes can be distinguished by comparing thermal energy $k_B T$ to charging energy e^2/C, average energy level spacing Δ and tunnelling rate Γ.

$\Delta, e^2/C << k_B T$: In this high temperature regime there are no charging effects and no Coulomb blockade. The discreteness of charge can therefore not be discerned.

$\Gamma, \Delta << k_B T << e^2/C$: The regime of the classical Coulomb blockade is thermally broadened. Transport takes place through several quantum dot energy levels. The peak conductance is independent of T and its full width at half maximum (FWHM) is proportional to $k_B T$ ($\sim 4.35 k_B T$) (Figure 3).

In the quantum Coulomb blockade regime, a temperature broadened and a lifetime broadened regime can be distinguished. In both cases only one dot level is involved in transport through the dot.

$k_B T << \Gamma, \Delta << e^2/C$: In the lifetime broadened regime, the peak conductance is independent of T. The peak has a Lorentzian line shape and its FWHM is proportional to Γ.

$\Gamma << k_B T << \Delta << e^2/C$: The peak conductance in the temperature broadened regime is proportional to $1/T$. The peak's line shape is different from the lifetime broadened regime, its tails are exponentially decaying. The FWHM is approximately $3.5 k_B T$ (Figure 3). Because of the small tunnelling rates the broadening of the energy levels is mainly due to the thermal energy. Tuning the dot into this regime, the electron temperature can be estimated by measuring the FWHM.

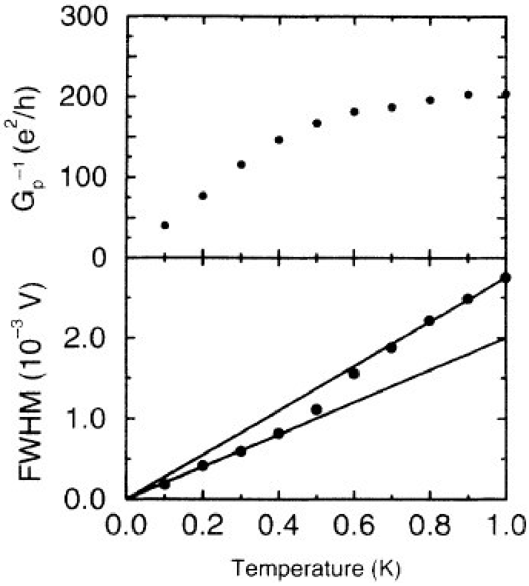

Figure 3: Temperature dependence of the conductance peak height (upper diagram) and the conductance peak width (lower diagram). In the temperature broadened quantum Coulomb blockade regime, the peak conductance is proportional to 1/T and the FWHM is approximately $3.5k_BT$. [11]

3 Results & Discussion

3.1 Characterization of quantum dot

To check if a quantum dot can be formed on the sample and to get an idea of the scope of the voltages that have to be applied therefore, so-called wall-walls have been performed. The plunger gate and the nose are held constant and the left and right walls are scanned over a range of voltages while measuring the conductance from source to drain through an eventually formed quantum dot. These measurements then have been carried out at different values for the plunger and nose (Figure 4).

The results show that a quantum dot can be formed, but quite high voltages are needed therefore. The risk of electrons striking through from the gates is getting bigger at such high voltages. Nevertheless, the few-electron regime probably can be reached. Some isolated conductance peaks at the highest wall gates voltages represent this few-electron regime most presumably.

In the experiments, a single quantum dot is formed. But since the sample actually is a double quantum dot device, a partial double dot character can be suggested in some plots as a slight honeycomb pattern in the conductance peaks.

A region of an isolated conductance peak of amplitude of approximately $0.1 e^2/h$ in the few-electron regime was selected in order to perform a coulomb diamond measurement (Figure 5). The nose and wall gates are held constant while a 2D scan is performed over the voltage of the plunger gate and the source-drain DC voltage. The source-drain voltage splits a conductance peak into two peaks giving the plot a diamond-like pattern. This plot also suggests that the measurements take place in the few-electron regime, since going to higher plunger gate voltages reveals no further conductance peaks.

Most of the plots still reveal a quite high noise level whereof most is 50Hz noise. For a first characterization of the device this noise level is not that troublesome, but for further experiments it should be clearly reduced to get reliable results.

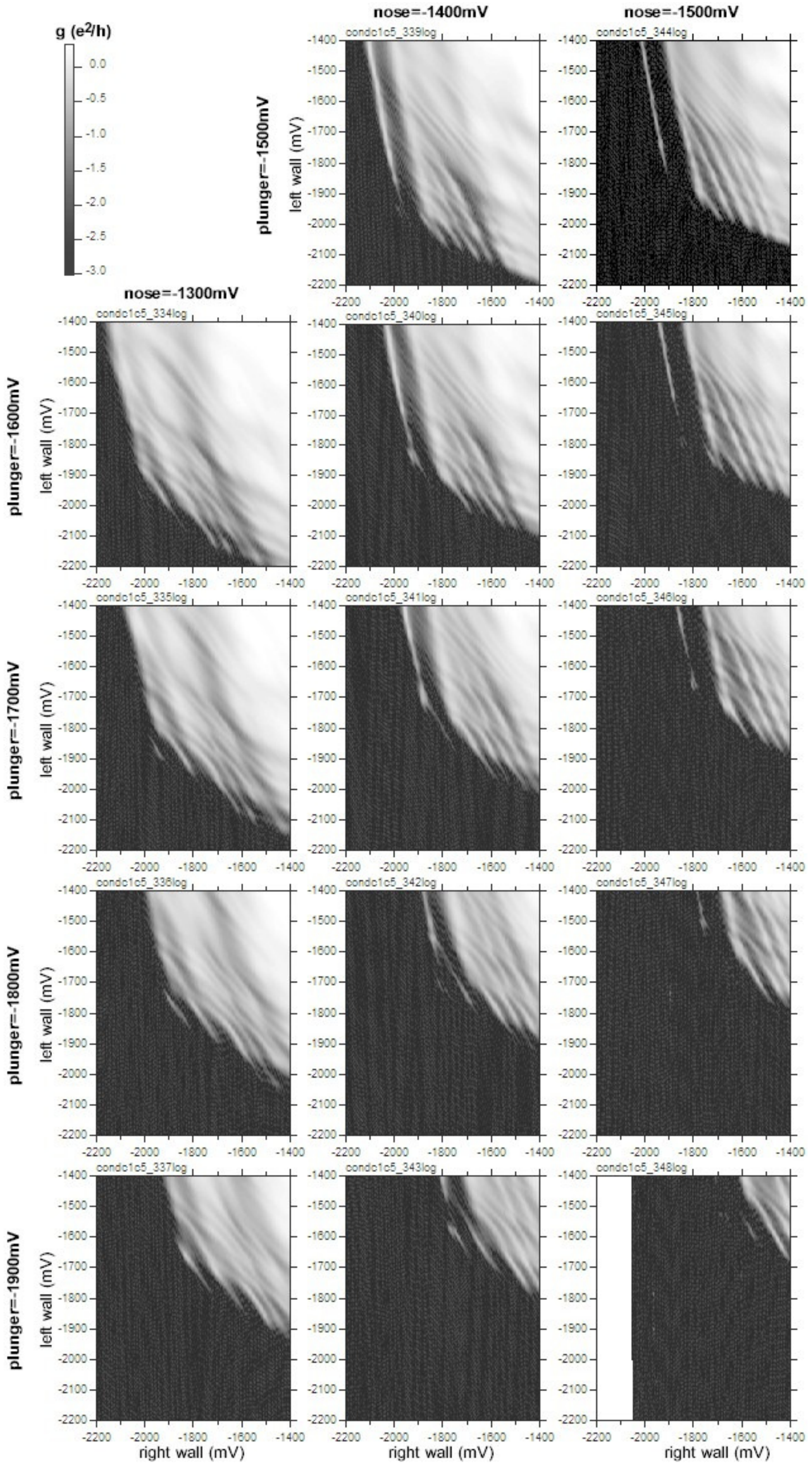

Figure 4: Wall-wall conductance plots for different voltages on plunger and nose gates. Since no further conductance is measured for higher voltages, the dot probably is in the few-electron regime. A partial double dot character can be suggested in the slight honeycomb pattern in some plots (e.g. in the one with plunger=-1700mV and nose =-1500mV)

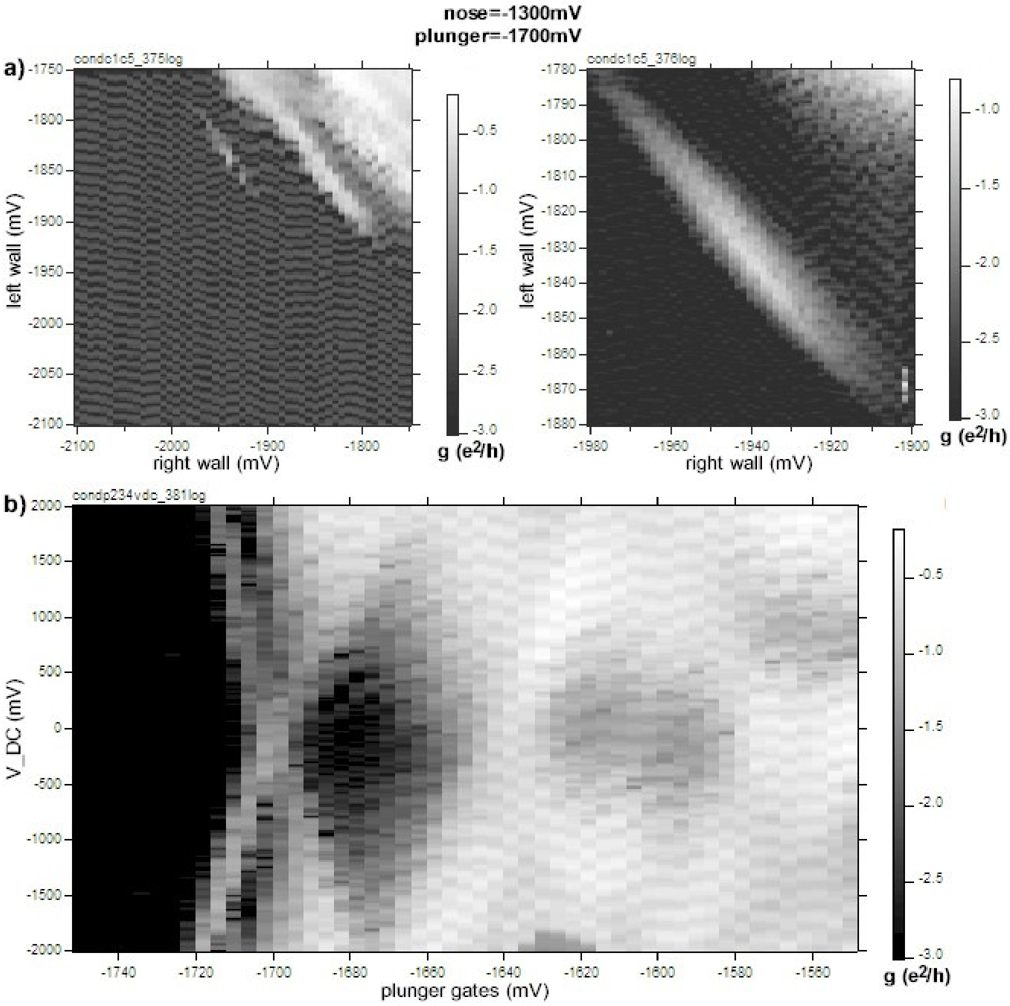

Figure 5: a) Selected conductance peak to perform a coulomb diamond. **b)** Coulomb diamond: measuring conductance through the dot while scanning over the applied DC voltage and the plunger gate voltage. No conductance is measured for higher plunger gate voltages, which is a prove that the few-electron regime is reached.

3.2 Temperature measurement

To estimate the electron temperature on the quantum dot, the device is tuned into the temperature broadened regime. Conductance through the dot is then measured while varying the plunger gate voltage. One single isolated peak of height ~0.1e^2/h is selected. The selected conductance peak is clearly exponentially decaying, as can be seen in the logarithmic plot, which is prove for being in the temperature broadened regime. A curve is fitted to the peak to calculate the FWHM (~1.18mV). This number in mV is converted to an energy with 1mV=95μeV. This factor is calculated from the amount of peak splitting due to a certain DC voltage that is applied. The energy corresponding to the FWHM is then equal to $3.5k_BT$, so that the temperature can be calculated. An electron temperature of ~372mK was estimated in this way. This value seems to be quite high but the range of 350 to 400mK has been confirmed in further measurements.

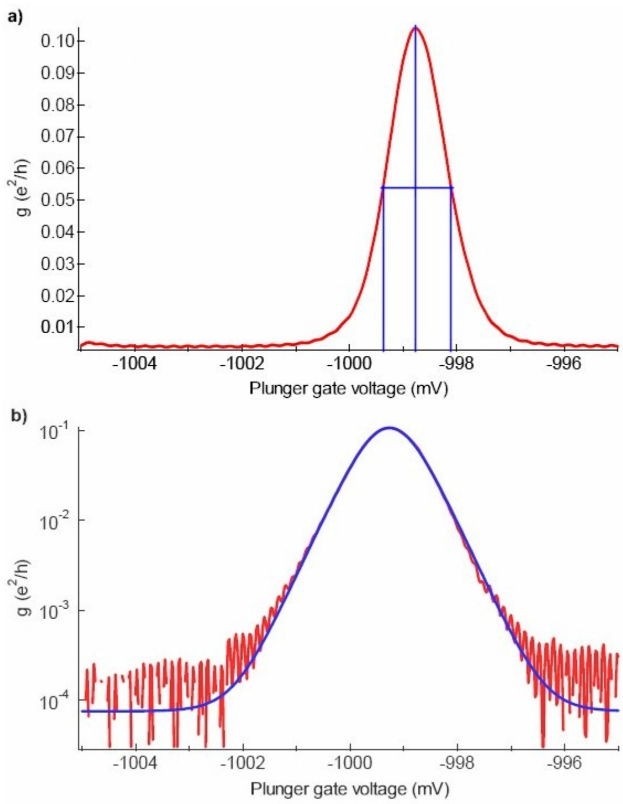

Figure 6: Conductance peak in a linear (a) and logarithmic (b) scale. The FWHM can be used to determine the electron temperature.
(peak position=-999.26mV, peak height=0.1076e^2/h, FWHM=1.1788mV)

4 Conclusion

Generally, the setup and cool-down of the fridge have been successful and the problem with electrical ground loops could be solved. But still some work needs to be done on electrical setup to reduce the noise at 50Hz. By locating the noise sources it could possibly be minimized.

A quantum dot could be formed and tuned into the few-electron regime, but relatively high voltages have to be applied therefore. The masks in the sample fabrication process could be readjusted to a smaller size to be able to form a quantum dot with even lower voltages.

Finally, the electron temperature is very high and should definitely be improved. Using better conductors in the coldfinger and replacing plugs in the coldfinger by soldered joints could give improved thermal conductivity and a lower electron temperature.

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