Effect of on-chip filter on Coulomb blockade thermometer

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Abstract. Coulomb Blockade Thermometer (CBT) is a primary thermometer based on electric conductance of normal tunnel junction arrays. One limitation for CBT use at the lowest temperatures has been due to environmental noise heating. To improve on this limitation, we have done measurements on CBT sensors fabricated with different on-chip filtering structures in a dilution refrigerator with a base temperature of 10 mK. The CBT sensors were produced with a wafer scale tunnel junction process. We present how the different on-chip filtering schemes affect the limiting saturation temperatures and show that CBT sensors with proper on-chip filtering work at temperatures below 20 mK and are tolerant to noisy environment.

1. Introduction
Coulomb blockade effect in arrays of normal tunnel junctions is observed as suppression of electrical conductance. In the regime of weak Coulomb blockade, where charging energy $E_C$ is small compared with thermal energy $k_B T$, the conductance of tunnel junction arrays can be utilized as a primary thermometer known as Coulomb blockade thermometer (CBT) [1]. Due to limited electron-phonon coupling of islands separated by tunnel junctions, appropriate filtering is needed to block environmental heating of the electron system in a CBT sensor at the lowest temperatures. Heating is assumed to be due to high-frequency radiation [2] and additional noise from the measurement leads.

In this work, we study how on-chip filtering affects the electron temperature of the CBT structure. We will show that on-chip filters lower considerably the saturation temperatures of CBTs in non-optimized measurement setups where radiation and noise heating are inevitably present.

2. Experimental
Several different CBT sample types were fabricated in a single process run on 150 mm Si wafers. Here we will focus on three sample types labelled as 1, 4, and 6. All samples have 20 parallel arrays of 100 junctions in series with nominal tunnel junction diameter of 800 nm. The complete chip layout and schematic cross-section around a single tunnel junction of CBT type 1 are illustrated in Fig. 1. All four metal layers are Al and the tunnel barrier between metal 1 and metal 2 is amorphous $\text{AlO}_x$. Details of the fabrication process can be found from Ref. [3].
main difference here is that in addition of the metal 1 and metal 2 we have two additional metal layers: bottom shield and top shield. These layers form the on-chip shield that is depicted in the layout schematic of Fig. 1a. Both shield layers were connected to ground in the experiment. The CBT islands (in metal 1 and metal 2 layers) in all samples extend outside the junction region with total area of \(25 \times 100 \mu m^2\) for a single island. This design was adopted in order to enhance the thermalization of the sensors. Type 1 CBT sample is on-chip shielded and has an on-chip RC-filter (see Fig. 1(a)). The resistors of the RC-filter are formed from tunnel junctions. The capacitor is defined by metal 1 and metal 2 layers with the 250 nm-thick SiO\(_2\) layer in between. The area of the capacitor is \(\sim 0.85 \text{ mm}^2\). The type 4 sample is similar to type 1 but without on-chip shielding. Type 6 does not have any on-chip RC filtering or shielding. Cut-off frequency of the on-chip RC-filter in types 1 and 4 is around 20 kHz. Sample parameters are summarized in Table 1. Measurements were conducted in Bluefors BF-SD250 cryogen-free dilution refrigerator system with base temperature around 10 mK. The refrigerator had no extra filtering added to the thermalized twisted pair wires (100 \(\Omega/m\)). Sample stage at mixing chamber had 2 meters of thermocoax [4] and 300 \(\Omega\) resistors near the sample in every line. In spite of sample stage filtering, the system represented non-optimized setup and was appropriate for testing on-chip filtering. Measurements were conducted by using a commercial

Table 1. Sample parameters. \(E_c\) is charging energy, \(R_T\) is resistance per junction at low temperatures, increased by about 20% with respect to the room temperature values. \(T_{\text{min}}\) is the saturation temperature in the experiment.

|        | shield | filter | \(E_c\) \(\text{mk}\) | \(R_T\) \(\text{k\bar{\Omega}}\) | \(T_{\text{min}}\) mK |
|--------|--------|--------|----------------|----------------|----------------|
| type 1 | yes    | yes    | \(~7\) | \(40\) | \(18.9\) |
| type 4 | no     | yes    | \(~11\) | \(35\) | \(27.6\) |
| type 6 | no     | no     | \(~11\) | \(30.6\) | \(~50\) |
current preamplifier (DL Instruments Model 1211) and a voltage preamplifier (DL Instruments Model 1201) and two lockin-amplifiers (Stanford Research Systems SR830 DSP). Samples were glued with vacuum grease and were wire-bonded with Al-wires to custom made compact sample stage made out of brass. The magnetic field keeping aluminium in normal state was created by using two neodymium magnets, one on both sides of the brass cap covering the samples. Four-wire measurement scheme was employed.

3. Results
The three sensors were measured after running the cryostat for about 24 h at base temperature. Figure 2 shows measured differential conductance of type 1 CBT sensor as function of sensor bias voltage and a numerical fit to the theory. Theoretical expressions and the fitting procedure, which takes into account sensor self-heating, are described in Ref. [5]. The fit gave temperature of 19.7 mK. Temperature readings of different sensors (obtained by the same fitting algorithm) are shown in Fig. 3(a) (see also Table 1). The temperature reading of the bare junctions of type 6 saturated already around 50 mK, suggesting a noise heating of about 100 fW. (1 fW per junction overheats the sensor to 22 mK). Clearly lower saturation was achieved with the RC on chip filter of type 4 at 27.6 mK. We observe the best result of 18.9 mK with the type 1 sensor, which has the on-chip shield and RC-filter. The temperature readings of the CBTs and the ruthenium oxide resistor (calibrated by nuclear orientation thermometer at lowest temperatures) agreed very well above 50 mK. The RuO resistor temperature vs. CBT 1 temperature data in Fig. 3(a) is obtained during a very slow temperature sweep (total duration 30 h). The temperature readings of CBT sensor 1 and RuO resistor as a function of time after the temperature sweep are shown in Fig. 3(b).

4. Discussion and conclusions
The discrepancy between type 1 CBT sensor and the mixing chamber plate temperature (with the RuO temperature sensor) can be explained by the observed long time constant [Fig. 3(b)]: obviously, a temperature gradient exists between the mixing chamber plate and the sample stage. The CBT sensor reading falls with a very long time constant as observed at the end of the temperature sweep. This weak coupling also allows the reasonable conclusion that a constant temperature difference caused by a heat load from the thermocoax lines will persist even after longer relaxation time. No proof of saturation of the sensor type 1 itself is showing up using the actual experimental setup towards the lowest temperatures.

In the experiment three different CBT sensor types with varying on-chip filterings were compared. In our non-optimized test system (noise and radiation present) clear differences were
Figure 3. (a) Measurement results of three sample geometries at temperature reading of 16.5 mK at the mixing chamber (■, ▽, *) and a slow temperature sweep with type 1 sensor (●) total duration of 30 hours, 30 minutes for a single temperature point. (b) Reading of CBT type 1 at the end of the temperature sweep for additional few hours at a constant base temperature reading of 15.8 mK.

seen between the saturation temperatures of the different sensors. Sample without filtering saturated to a temperature around 50 mK. Sample with on-chip RC-filter showed an improved performance with saturation temperature ∼28 mK. The sample with on-chip RC-filter and on-chip shield showed the best performance. The shield has an effect to reduce disturbance presumably due to high-frequency radiation [6]. In a later experiment there were no such clear effect of on-chip filtering anymore when there was added shielding to the sample volume and to all electrical connectors, thermodoxax were covered with an additional grounded shield, a strong fixing was added to thermocomaxes to prevent vibrations, separate ferrite filters were added at room temperature for every twisted pair and additional filtering was added to all service lines (thermometers and heaters).

In the experiment there was no clear sign of saturation of the on-chip shielded and RC-filtered CBT sensor, partly due to the limited heat conductivity and mass of the sample stage. Therefore, we conclude that on-chip filtering makes CBT sensors more robust against external noise/radiation that can be present in non-optimized experimental setups.

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