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A high speed radio-frequency quantum point contact charge detector for time resolved readout applications of spin qubits

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ABSTRACT

In this paper, we give details related to the implementation of a rf-QPC charge detector coupled to a GaAs/AlGaAs triple dot. Each component of the readout circuit is discussed with emphasis on the isolator. We use a 10K noise temperature HEMT amplifier in the readout and determine that the attenuation of amplifier noise that the isolator provides is not significant. A base electron temperature of 100 mK is reached independent of the existence of the isolator in the readout circuit. We also discuss the use of normal metal and superconducting resonant circuits. Using the superconducting resonant circuit, we detect charge motion in the device and determine that the bandwidth of the readout is at least 1 MHz with a sensitivity of $1.46 \times 10^{-4} e/\sqrt{\text{Hz}}$.

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1. Introduction

Systems of coupled single electron semiconductor quantum dots are being investigated for their use as spin qubits [1]. Many of the quantum information protocols involving these systems require a high-fidelity single-shot readout [2]. Given the coupling of the electron spins to the nuclear spins of the GaAs substrate, leading to T_2^* times of tens of nanoseconds, a readout with a bandwidth of tens of megahertz is needed [3]. This paper details the implementation of such a readout, the radio-frequency quantum point contact (rf-QPC).

Many quantum dot readouts make use of a quantum point contact (QPC), a structure whose resistance can be made a sensitive function of the electrostatic environment [4]. By measuring the conductance of the QPC, information about the charge state of a quantum dot system can be acquired. Readouts that measure this conductance using a room temperature voltage source and current preamplifier have a bandwidth limit of tens of kilohertz [5]. This limitation is due to the RC time constant resulting from the capacitance of the wiring that connects the amplifier to the device on the dilution refrigerator and the resistance of the QPC, usually approximately 50 kΩ. This problem is solved by incorporating the QPC into a resonant circuit. The resonant circuit transforms the QPC resistance down to near 50 Ω

allowing the use of regular coaxial cables and radio-frequency electronics, in particular cryogenic HEMT amplifiers [6–8].

The charge state of the quantum dots is determined by measuring the signal power reflected by this QPC resonant circuit combination when it terminates a 50 Ω coaxial cable. The impedance of this combination is L/CR_{QPC} . When the charge configuration of the dots changes, the electric field at the QPC changes and thus the impedance changes. Information about the charge state of the dots is therefore contained in the amplitude modulation of the reflected signal [7].

2. Experiment

We implement a rf-QPC coupled to a lateral triple dot. A scanning electron microscopy image of the triple dot device is shown in Fig. 1. It consists of a two-dimensional electron gas formed in a high mobility GaAs/AlGaAs heterostructure. The triple dot is created using metal top gates. All measurements of this device were made on an Oxford 600 dilution refrigerator with a base temperature of 4 mK.

We examine the radio-frequency components of the rf-QPC readout circuit in particular the isolator. We measure the electron temperature of the device with and without the isolator in the readout circuit. We use the rf-QPC readout to detect charge motion in the device. This allows us to characterize both the bandwidth and the sensitivity of the readout.

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Fig. 1. Scanning electron microscopy image of the triple dot device. The quantum point contact charge detector is defined by gates G_1 and G_2 . An ac modulation applied to gate G_{ac} is used to measure the bandwidth of the readout.

3. Results

A schematic of the readout system is shown in Fig. 2. A signal at the resonance frequency is sent via semi-rigid coaxial cables from a room temperature signal generator to a directional coupler that is heat sunk to the 1.4 K stage of the dilution refrigerator. The signal is directed to the radio-frequency input of a homemade bias-tee and finally to the device. A fraction of the signal is reflected by the combination of the resonant circuit and QPC. This signal again enters the directional coupler but is now directed to the input of an isolator and then to the input of a cascade of two HEMT amplifiers all of which are thermally anchored to the 1.4 K stage. The purpose of the isolator is to prevent the noise produced by the HEMT amplifiers from influencing the sample. It is essentially a directional attenuator which attenuates the noise produced by the HEMT amplifiers while allowing the reflected signal coming from the device to pass through to the input of the HEMT amplifiers unaffected. The signal is further amplified at room temperature by two more amplifiers before amplitude demodulation using a Schottky diode and a low pass filter.

The directional coupler is model MC3202-30 made by S.M. Electronics. It behaves similarly at room temperature and 1.4 K [9]. The bias tee is homemade and uses a 700A American Technical Ceramics capacitor and a Coilcraft inductor. The components are incorporated into a coplanar transmission line structure. The two GaAs HEMT amplifiers are made by Oleksandr Pylypenko. They each have a gain of at least 26 dB between 200 MHz and 1 GHz and a noise temperature of 10 K when heat sunk to the 1.4 K stage of the dilution refrigerator. The isolator is model UTE1264-K36 made by PAMTECH. The isolator provides at least 20 dB of attenuation between 650 MHz and 1.15 GHz with a maximum attenuation of 42 dB at 925 MHz. The isolator is rather large being 12 cm by 7.8 cm by 1.6 cm and therefore is difficult to fit on most dilution refrigerators. The two room temperature amplifiers are Mini-Circuits model ZRL-1150LN+. They each have a gain of 27 dB and a noise figure of 1.1 dB. The amplitude demodulation of the reflected signal is accomplished with an HP8472B crystal detector and a Mini-Circuits BLP-50+ low pass filter with a 3 dB point of 50 MHz.

Following the work of Refs. [6–8], we start by using a normal metal inductor to create the resonant circuit. We use Coilcraft model 0402CS-68NX, a 68 nH copper inductor. The resonant circuit is formed by fixing the inductor with varnish to the gold ground plane on which the quantum dot sample is also fixed. The

Fig. 2. Schematic of the rf-QPC readout circuit. A signal at the resonance frequency is reflected from the device, amplified by cryogenic amplifiers and finally amplitude demodulated at room temperature. The amount of reflected power is determined by the charge state of the quantum dots.

capacitance needed to form the resonant circuit is the parasitic capacitance between the inductor and the underlying ground plane. The resulting resonance frequency is 980 MHz. The inductor is connected to the center conductor of a coaxial cable and to an ohmic contact of the device on one side of the QPC. The connections are made using aluminum wire bonds. An ohmic contact on the other side of the QPC is wire bonded to a 16 pF capacitor which is connected to the gold ground plane with silver epoxy. This capacitor has an impedance of 10Ω at the resonance frequency. This capacitor establishes a radio-frequency ground. It is required so that the resonant circuit QPC combination forms a variable impedance termination to the coaxial cable. The bandwidth of the readout based on this resonant circuit is measured by applying a $100\mu\text{V}$ oscillation to gate G_{ac} shown in Fig. 1. This measurement is summarized in Fig. 3. It shows a roll-off of approximately 12 MHz which is the result of either the readout bandwidth or the bandwidth of the gate used to apply the ac modulation. The lines running to the gates, which are simply a bundle of $100\mu\text{m}$ diameter enamel coated manganin wire, may be the source of the 12 MHz roll-off. Fig. 3 also displays the system noise as a function of frequency. Both the signal and noise include the gains of the cryogenic and room temperature amplifiers. The noise floor is consistent with the 10 K noise temperature of the HEMT amplifiers. The roll-off of both the signal and noise at about 50 MHz is due to the low pass filter used to amplitude demodulate the reflected signal.

We also investigate the use of a superconducting inductor made using photolithographic techniques [10]. It is a 250 nm thick niobium film in the shape of a square coil of 12 turns. The linewidth is $5\mu\text{m}$ and the turn-to-turn distance is $20\mu\text{m}$. An optical microscope image of the inductor is displayed in the inset of Fig. 4. This inductor is patterned on a $300\mu\text{m}$ thick silicon substrate which, like the copper inductor, is fixed to the gold ground plane using varnish. The frequency response of this resonant circuit is shown in Fig. 4. The figure shows the signal reflected from the resonant circuit QPC combination as measured

Fig. 3. Frequency response of the readout when using a copper inductor in the resonant circuit. The signal is the response of the readout to a 100 μV oscillation applied to gate G_{ac} shown in Fig. 1. Both the signal and the noise include the gains of the cryogenic and room temperature amplifiers. The roll-off at 50 MHz is due to the filter used for amplitude demodulation.

Fig. 4. Frequency response of the resonant circuit that uses a superconducting niobium inductor. Each curve corresponds to a different voltage on the gates labeled G_1 and G_2 in Fig. 1. The resonance frequency is 763 MHz and the full-width at half-maximum is 300 kHz in the optimum matching condition. (Inset: Photolithographically patterned niobium inductor used to form the resonant circuit. It is a 250 nm thick film with a linewidth of 5 μm and a turn-to-turn distance of 20 μm . The wire bonding pads are 200 $\mu\text{m} \times 200 \mu\text{m}$.)

with a network analyzer. The signal plotted is the output directly from the HEMT amplifiers. The resonance frequency is 763 MHz and the full-width at half-maximum is approximately 300 kHz in the optimum matching condition. This resonant circuit transforms a QPC resistance of approximately 6 k Ω to 50 Ω . Given this and the fact that the circuit has a resonance frequency of 763 MHz, the parasitic capacitance to the ground plane is calculated to be 0.38 pF and the inductance to be 114 pH. Since the QPC is most sensitive at a resistance of approximately 30 k Ω , we need to reduce the parasitic capacitance. Xue et al. have a similar lithographically patterned inductor and find a parasitic capacitance of 0.17 pF [10]. To reduce the parasitic capacitance, we will double the substrate thickness to 600 μm and reduce the wiring bonding pad size. We should then be able to increase the inductance by at least a factor of two so that a QPC resistance near 30 k Ω will be transformed to 50 Ω while maintaining a similar resonance frequency.

As mentioned above, the isolator is a large device that is difficult to fit on most dilution refrigerators. As such, we wish to determine whether it is a necessary part of the readout circuit.

That is, does its attenuating of HEMT amplifier noise make a significant difference to the electron temperature of the device. To determine the electron temperature, we measure the conductance of the quantum dot in the Coulomb blockade regime operating the triple dot as one large single dot. We use a room temperature voltage source and current preamplifier to make the transport measurements. The HEMT amplifiers are turned on and the QPC is biased so as to minimize the reflected signal. This procedure maximizes the influence of amplifier noise on the device. We measure a conductance resonance at several temperatures when the readout circuit contains an isolator and plot the full-width at half-maximum (FWHM) as a function of temperature in Fig. 5. As the device is cooled, the FWHM stops changing at approximately 100 mK. Fig. 5 also shows the FWHM of conductance resonances acquired when the isolator is absent from the readout circuit. The electron temperature is also approximately 100 mK in this case.

To measure the sensitivity of the readout, we use it to detect charge motion in the device. The superconducting resonator is used in the measurement. The output of the readout is further amplified with a 1 MHz bandwidth preamplifier and subsequently captured with a digital oscilloscope. By properly setting the gate voltages, we configured the system to switch between two charge numbers. See Fig. 6. It shows that a single electron corresponds to 240 mV. At this time, we do not know which site of the triple dot the moving electron occupies. The system noise floor is measured to be 35 $\mu\text{V}/\sqrt{\text{Hz}}$ after the additional stage of amplification and the readout sensitivity in this case is therefore $1.46 \times 10^{-4} e/\sqrt{\text{Hz}}$. A closer look at the transition rate between the two plateaus shows that the bandwidth is limited by the 1 MHz bandwidth of the preamplifier. The readout bandwidth is therefore at least 1 MHz. In this case, the QPC resistance is not transformed to 50 Ω . If it was, the bandwidth would be approximately 300 kHz as this is the 3 dB bandwidth of the resonance shown in Fig. 4. Given how the QPC was biased to perform the charge detection, we would expect the resonator to limit the readout bandwidth to approximately 10 MHz. A higher bandwidth preamplifier is therefore needed. The Signal Recovery model 5185 having a 100 MHz bandwidth is a possible option.

Fig. 5. Full-width at half-maximum (FWHM) of the conductance resonances as a function of temperature. It is essentially unchanged below a temperature of 100 mK in both cases. (circles—without isolator, squares—with isolator)

Fig. 6. Time resolved charge detection with a 1 MHz measurement bandwidth. By properly setting the gate voltages, we configured the system to switch between two charge numbers. From this data and a measurement of the system noise (see text), the readout sensitivity is calculated to be $1.46 \times 10^{-4} e/\sqrt{\text{Hz}}$. A closer examination of the rise time reveals that the bandwidth of the readout is limited by the 1 MHz bandwidth of a room temperature preamplifier.

4. Summary

We have demonstrated the successful implementation of a rf-QPC that uses a superconducting resonant circuit. For a readout with 10 K noise temperature cryogenic HEMT amplifiers, we have shown that an isolator is unnecessary to reach electron temperatures of 100 mK. Through the detection of charge motion in the

device, we have shown the readout to have a bandwidth of at least 1 MHz with a sensitivity of $1.46 \times 10^{-4} e/\sqrt{\text{Hz}}$.

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