Ultra-low-noise transimpedance amplifier in cryogenic STM for studying novel quantum states by measuring shot noise: Postprint

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Abstract

An ultra-low-noise large-bandwidth transimpedance amplifier (TIA) for cryogenic scanning tunneling microscope (CryoSTM) is proposed. The TIA connected with the tip-sample component in CryoSTM is called as CryoSTM-TIA. Its transimpedance gain is as high as 1 GΩ, and its bandwidth is over 300 kHz, but its equivalent input noise current power spectral density is less than 4 (fA)2/Hz at 100 kHz. The low inherent noise for the CryoSTM-TIA is due to its special design: (1) its pre-amplifier is made of a pair of low-noise cryogenic high electron mobility transistors (HEMTs); (2) the noise generated by one HEMT is eliminated by a large capacitor; (3) the capacitance of the cable connected the gate of the other HEMT to the tip is minimized; (4) thermal noise sources, such as the feedback resistor, are placed in the cryogenic zone. The dc output voltage drift of the CryoSTM-TIA is very low, as 5 V/°C. The apparatus can be used for measuring the scanning tunneling differential conductance spectra, especially the scanning tunneling shot noise spectra (STSNS) of quantum systems, even if the shot noise is very low. It provides a universal tool to study various novel quantum states by measuring STSNS, such as detecting the Majorana bound states.

Full Text

Preamble

Ultra-low-noise transimpedance amplifier in cryogenic STM for studying novel quantum states by measuring shot noise

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An ultra-low-noise large-bandwidth transimpedance amplifier (TIA) for cryogenic scanning tunneling microscope (CryoSTM) is proposed. The TIA connected with the tip-sample component in CryoSTM is called CryoSTM-TIA. Its transimpedance gain is as high as 1 GΩ, and its bandwidth is over 300 kHz, but its equivalent input noise current power spectral density is less than 4 $(\text{fA})^2/\text{Hz}$ at 100 kHz. The low inherent noise for the CryoSTM-TIA is due to its special design: (1) its pre-amplifier is made of a pair of low-noise cryogenic high electron mobility transistors (HEMTs); (2) the noise generated by one HEMT is eliminated by a large capacitor; (3) the capacitance of the cable connecting the gate of the other HEMT to the tip is minimized; (4) thermal noise sources, such as the feedback resistor, are placed in the cryogenic zone. The dc output voltage drift of the CryoSTM-TIA is very low, at 5 V/°C. The apparatus can be used for measuring the scanning tunneling differential conductance spectra, especially the scanning tunneling shot noise spectra (STSNS) of quantum systems, even if the shot noise is very low. It provides a universal tool to study various novel quantum states by measuring STSNS, such as detecting Majorana bound states.

Keywords: cryogenic scanning tunneling microscope, transimpedance amplifier, high electron mobility transistor, equivalent input noise current power spectral density, scanning tunneling shot noise spectra, Majorana bound states.

1. Introduction

As the nonequilibrium transport statistics of time-dependent fluctuations, shot noise yields information in mesoscopic systems that is not present in the time-averaged transport characteristics (differential conductance spectra) [?]. Therefore, shot noise has been a powerful tool to investigate novel quantum states in mesoscopic systems experimentally, such as verifying the statistical properties of anyons in fractional quantum Hall systems [?], studying the electron correlation mechanism of high-Tc superconductors [?, ?, ?, ?], observing Andreev reflection [?, ?] and Kondo effect [?], among others.

Cryogenic scanning tunneling microscope (CryoSTM) has been used to measure shot noise in quantum systems at atomic scale [?, ?, ?, ?, ?, ?]. For measuring shot noise with CryoSTM, the amplifier as a key element must be able to work at high frequencies, since the pink noise component of the tunneling current noise is almost zero and the shot noise component becomes dominant at high frequencies. In addition, the amplifier's inherent noise must be low enough to avoid disturbing the tunneling shot noise measurements. In Refs. [?, ?], it has been reported that a voltage amplifier containing an LC resonator in CryoSTM (denoted as CryoSTM-LC-Amp) is used to measure tunneling shot noise. With CryoSTM-LC-Amp, only signals at frequencies near the resonant frequency (1 MHz [?] or 3 MHz [?]) can be amplified with high gain. Some excellent works on high-Tc superconductors have been performed with this apparatus [?, ?, ?].

However, the amplifier's inherent noise, i.e., its equivalent input noise current power spectral density (PSD), is quite high, at about 700 $(\mathrm{fA})^2/\mathrm{Hz}$, making it difficult to obtain the Fano factor accurately by measuring very weak shot noise with this apparatus.

Theoretical works show that topological qubits can be constructed by Majorana bound states (MBSs), so large-scale topological quantum computers will be realized by arbitrary expansion of these qubits [?]. Many experimental works have suggested the existence of MBSs based on observed zero bias conductance peaks (ZBCP) [?, ?, ?, ?]. However, despite promising signatures, more mundane explanations still exist and the interpretation of experiments continues to be debated [?]. For example, Andreev bound states (ABSs) representing pairs of "fake" MBSs cannot be ruled out yet. Therefore, theorists have predicted shot noise behaviors for some topological quantum systems in which MBSs may exist, to distinguish MBSs from "fake" ones [?, ?, ?, ?, ?, ?, ?]. However, shot noise measurements for MBSs should be performed near zero bias, which is about tens to hundreds of V, so the tunneling current is quite small and the shot noise PSD is very weak. Up to now, no attempt has been made to measure shot noise for MBSs, since no equipment meets the required noise measurement accuracy.

Transimpedance amplifier (TIA) is the most commonly used amplifier in scanning tunneling microscopy/spectroscopy [?, ?, ?], amplifying tunneling current signals to output voltage signals. The TIA with the tip-sample component in CryoSTM is called CryoSTM-TIA. In Ref. [?], a CryoSTM-TIA design was proposed with transimpedance gain of 1 GΩ and bandwidth over 300 kHz, and its equivalent input noise current PSD was 21 $(\mathrm{fA})^2/\mathrm{Hz}$ at 100 kHz.

In this work, an improvement on the CryoSTM-TIA in Ref. [?] is proposed. The transimpedance gain of the proposed CryoSTM-TIA remains as high as 1 GΩ and its bandwidth remains above 300 kHz, but its equivalent input noise current PSD is only 3 $(\mathrm{fA})^2/\mathrm{Hz}$ at 100 kHz, which is only 1/7 of that in Ref. [?]. Moreover, the dc output voltage drift of the CryoSTM-TIA is very low, at 5 V/°C. Therefore, with this apparatus, lower tunneling shot noise of quantum states can be measured at atomic scale in CryoSTM.

2. Circuit of the proposed CryoSTM-TIA

Figure 1 [Figure 1: see original paper] shows the circuit of the proposed CryoSTM-TIA. It consists of four components: the pre-amplifier (Pre-Amp) shown in dashed boxes (a1) and (a2) in Fig. 1, the post-amplifier (Post-Amp) shown in dashed box (b), the compensated feedback network shown in dashed box (c), and the signal source circuit shown in dashed box (d). The two-stage amplifier comprising the Pre-Amp and Post-Amp is called an inverting amplifier, denoted as Inv-Amp. The Inv-Amp is connected with the feedback network to form the TIA. The input N of the TIA is connected to the signal source circuit to form the CryoSTM-TIA. Components placed in the cryogenic zone are shown in the dotted box. The parameters of all components in the CryoSTM-TIA circuit are listed in Table 1 .

2.1. Design of Pre-Amp

The Pre-Amp is the same as that in Ref. [?]. All parameters are listed in Table 1. The differential amplifier part of the Pre-Amp is shown in dashed box (a1) in Fig. 1. H1 and H2 are cryogenic high electron mobility transistors (HEMTs), specifically CNRS-HEMTs developed by CNRS/LPN in France [?, ?]. Their performance parameters are listed in Table 1, where S_v^{HEMT} is the equivalent input noise voltage PSD of CNRS-HEMT and S_i^{HEMT} is its equivalent input noise current PSD [?]. In the circuit, R_λ is a potentiometer, and λ, R_1, and R_2 can vary from 0 to 1.

Gate N of H1, serving as the Pre-Amp input, is connected to the CryoSTM tip, and gate P of H2 is permanently connected to ground. R_A is the gate-source resistance of H1 and also the Pre-Amp input resistance. It is larger than 10 TΩ, so it can be considered infinite. C_A is the Pre-Amp input capacitance. The capacitor C_{ac} serves as the ac short-circuit capacitor, with $C_{\text{ac}} = 0.1$ mF, while capacitors C_1 and C_2 are 10 F. H1, H2, R_1, R_2, C_1, and C_2 are placed in the cryogenic zone. H1 is positioned as close as possible to the CryoSTM tip to minimize the capacitance of the cable connecting gate N of H1 to the tip. This capacitance is denoted C_c, which is reduced to less than 0.5 pF. The voltage gain of the Pre-Amp in (0, 3 MHz] can be considered constant, $A_{\text{Pre}} = 20$ dB. The input capacitance of the Pre-Amp is $C_{\text{in}} = C_{\text{gs}} + C_{\text{gd}} + C_c$, where C_{gs} is the gate-source capacitance and C_{gd} is the gate-drain capacitance. For the Pre-Amp with component parameters listed in Table 1, $C_{\text{gs}} = 0.3$ pF, $C_{\text{gd}} = 0.2$ pF, and $C_{\text{in}} \approx 0.5$ pF.

In Fig. 1, the constant-current source part of the Pre-Amp is shown in dashed box (a2). For a given resistance R_{const}, there is almost no fluctuation in the current generated by the constant-current source, even when the voltage of the positive voltage source fluctuates greatly, which ensures the stability of the static operating point of H1 and H2.

2.2. Design of Post-Amp and composition of Inv-Amp

The Post-Amp circuit is shown in dashed box (b) of Fig. 1. It contains a commercial operational amplifier (OPA) called Rear-OPA, which is THS4021 [?] in this work. R_i and C_i are the input resistance and capacitance of the Rear-OPA, respectively. The feedback resistor R_f is 1 MΩ. There are two cables in the Post-Amp circuit: one connects the output of the Pre-Amp to the noninverting input of the Rear-OPA, and the other connects the output of the Pre-Amp to the inverting input of the Rear-OPA through a 500 Ω resistor in the cryogenic zone. The capacitances of the two cables are C_{i1} and C_{i2}, respectively, with $C_{i1} = C_{i2} = 10$ pF. In this work, C_{i2} is also connected with a ground short-circuit capacitor of 10 F, which filters out noises generated by H2 and serves as the ac ground resistance at the inverting input of the Rear-OPA.

Cascading the Pre-Amp and Post-Amp forms the Inv-Amp. The voltage gain of the Inv-Amp is the ratio between the ac voltage at the output and the ac voltage at the input. Since ac signals from one branch of the Pre-Amp are filtered out by C_{i2}, the circuit topology of the Inv-Amp is completely different from that of the Macro-OPA in Ref. [?]. In the Macro-OPA, the output impedance of the Pre-Amp serves as the ground impedance at the inverting input of the Rear-OPA. However, in the Inv-Amp in this work, as output O2 of the Pre-Amp is shorted to ground through C_{i2}, a resistor R_{i2} must be added as the ac ground resistance at the inverting input of the Rear-OPA. The voltage gain of the Inv-Amp is expressed as:

$$A_{\mathrm{Inv}}(f) = \frac{v_o}{v_i} = \frac{A_{\mathrm{Pre}}A_{\mathrm{Rear}}}{1 + A_{\mathrm{Rear}}\frac{R_{i2}}{R_f}} \approx \frac{A_{\mathrm{Pre}}A_{\mathrm{Rear}}}{1 + A_{\mathrm{Rear}}\frac{R_{i2}}{R_f}}$$

By the nodal analysis method, $A_{\mathrm{Inv}}(f)$ can be obtained with the equations listed in Supplemental file 1 [?]. In [10 mHz, 3 MHz], $A_{\mathrm{Inv}}(f)$ calculated by the nodal analysis method is almost identical with results simulated by TINA-TI [?], as shown in Supplemental file 1 [?]. Then, with $A_{\mathrm{Inv}}(f)$, A_{Rear} can be obtained, where A_{Rear} is the open-loop voltage gain of the Rear-OPA. For THS4021, A_{Rear} can be approximately expressed as:

$$A_{\mathrm{Rear}}(f) = \frac{A_0}{1 + j\frac{f}{f_c}}$$

where $A_0 = 86$ dB and $f_c = 14.5$ kHz. In [1 kHz, 3 MHz], $A_{\mathrm{Inv}}(f)$ calculated by these equations is almost identical with simulation results using the parameters in Table 1 [?].

2.3. Frequency compensation of feedback loop

In order to increase the bandwidth of the CryoSTM-TIA for the high feedback resistor R_f with parasitic capacitance C_f, frequency compensation must be used in the feedback loop [?, ?]. In Ref. [?], it was demonstrated that a compensated feedback network can broaden the bandwidth to MHz in experiments. For the feedback network with component parameters listed in Table 1, Z_f can be considered as the impedance of the feedback network:

$$Z_f(f) = \frac{R_f}{1 + j2\pi f R_f C_f}$$

where C_f is the parasitic capacitance of R_f, so it can be considered that $C_f \approx 0.1$ pF [?, ?]. In (0, 1 MHz], $|Z_f(f)|$ is equal to R_f.

2.4. Circuit stability of the proposed CryoSTM-TIA

In Fig. 1, the signal source circuit is shown in dashed box (d), with parameters in Table 1. The differential resistance of the tip-sample tunnel junction (TJ) in CryoSTM is R_J, which is limited to no less than 1 MΩ. The capacitance of TJ is C_J, estimated as several fF. C_J is at least two orders of magnitude less than C_{in}, so it can be ignored in parallel with C_{in} [?]. The source BMS provides the dc bias and sinusoidal modulated signal voltage to the CryoSTM-TIA. In simulations, C_J is always taken as 0.5 pF.

The TIA connects the signal source circuit to form the CryoSTM-TIA. According to circuit parameters in Table 1, performances can be simulated by TINA-TI. The loop gain of the proposed CryoSTM-TIA [?] is:

$$T(f) = A_{\text{Inv}}(f)\beta(f)$$

where $\beta(f)$ is the feedback factor, and its reciprocal is:

$$\frac{1}{\beta(f)} = 1 + \frac{Z_f}{R_J} + j2\pi f C_{\text{in}} Z_f$$

Figure 2 Figure 2: see original paper shows calculated results of $|1/\beta(f)|$ and $\angle(1/\beta(f))$. For the Inv-Amp, Figs. 2(a) and 2(b) show curves simulated by TINA-TI. By $|1/\beta(f)|$ and $\angle(1/\beta(f))$, $|T(f)|$ can be calculated. Figure 2(a) shows those with $|A_{\text{Inv}}(f)|$, and Fig. 2(b) shows those with $\angle A_{\text{Inv}}(f)$. Both figures show $|T(f)| < 0$ dB at $f = 529$ kHz and $\angle T(f) > -180°$ at $f = 529$ kHz. Hence, the CryoSTM-TIA is stable enough. Therefore, the CryoSTM-TIA is stable with gain margin more than 10 dB and phase margin more than 43° [?].

2.5. Voltage gain and transimpedance gain of the proposed CryoSTM-TIA

With frequency compensation as mentioned in Sec. 2.3, it can be considered that $|Z_f| \approx R_f$ in (0, 1 MHz]. Considering the TJ capacitance C_J, the TJ impedance should be $Z_J = R_J \parallel (1/j2\pi f C_J)$. As $C_J \ll C_{\text{in}}$, $Z_J \approx R_J$. The ac input voltage v_i is applied by BMS, and the output voltage of the CryoSTM-TIA is v_o. The voltage gain of the CryoSTM-TIA is $A_v = v_o/v_i$. By the nodal analysis method, in (0, 1 MHz]:

$$A_v(f) \approx -\frac{R_f}{R_J} \cdot \frac{A_{\text{Inv}}(f)}{1 + A_{\text{Inv}}(f)\beta(f)}$$

Setting $v_i = 0$ and applying a sinusoidal current source i_s in parallel with TJ, the output voltage v_o is generated at the output of the CryoSTM-TIA. $Z_T = v_o/i_s$ is called the transimpedance gain of the CryoSTM-TIA. In [0, 1 MHz]:

$$Z_T(f) \approx \frac{R_f}{1 + j2\pi f R_f C_{\text{in}} / A_{\text{Inv}}(f)}$$

Figure 3 [Figure 3: see original paper] shows $|Z_T(f)|$ simulated by TINA-TI. The simulation results show its –3 dB frequency is 326 kHz. Additionally, $|Z_T(f)|$ decreases monotonically, and there is no “gain peaking” on the curve, which also indicates the circuit is quite stable [?].

In Supplemental file 3 [?], $|Z_T(f)|$ calculated by Eq. (9) with parameters in Table 1 are identical with TINA-TI simulation results, which verifies the correctness of Eq. (9) for $|Z_T(f)|$. Comparing Eqs. (8) and (9), as $R_J \gg R_f / A_{\text{Inv}}(f)$, the upper cut-off frequency of the CryoSTM-TIA is approximately equal to $f_h = A_{\text{Inv}} / (2\pi R_f C_{\text{in}})$, but a little smaller than f_h.

2.6. Transient response of the proposed CryoSTM-TIA

Simulation results for the transient response of the proposed CryoSTM-TIA are shown in Supplemental file 4 [?]. For the CryoSTM-TIA, the time from adding the input step signal voltage to when the output response stabilizes within a certain error is called the transient response time t_r. For simulations, a resistor with constant resistance R_J replaces the tip-sample junction. When $R_J = 30$ MΩ, $t_r < 3.5$ s for 0.1% error, $t_r < 30$ s for 1% error, and $t_r < 3$ ms for 3% error. When $R_J = 1$ MΩ, $t_r < 3.5$ s for 0.1% error, and $t_r < 30$ s for 1% error.

3. Inherent noise of the proposed CryoSTM-TIA

For the circuit shown in Fig. 1, the differential equivalent circuit with all noise sources is used to calculate its equivalent input noise. Details for noise calculations are shown in Supplemental file 5 [?].

3.1. Equivalent input voltage noise and equivalent input current noise of Inv-Amp

The noise voltage and noise current of H1 are denoted as e_{H1} and i_{H1}, respectively. The noise voltage of resistors R_1, R_2, and R_f are thermal noise, and they can be neglected [?]. The equivalent input noise voltage and equivalent input noise current of Rear-OPA are denoted as e_A and i_A, respectively. These noise sources are independent. The equivalent input noise voltage and equivalent input noise current of the Inv-Amp are denoted as e_{Inv} and i_{Inv}, respectively. By the nodal analysis method and Wiener–Khinchin theorem, ignoring minor terms:

$$e_{\text{Inv}}^2 \approx e_{H1}^2 + e_A^2 \left(\frac{C_{\text{gs}} + C_{\text{gd}}}{C_{\text{in}}} \right)^2$$

$$i_{\mathrm{Inv}}^2 \approx i_{H1}^2 + i_A^2 + \frac{4kT}{R_{i2}} + (2\pi f)^2 e_A^2 C_{\mathrm{in}}^2$$

According to Inv-Amp parameters in Table 1, $e_{\mathrm{Inv}}^2 = 0.27$ (nV)^2/Hz and $i_{\mathrm{Inv}}^2 =$ 0.13 (fA)^2/Hz at $f = 10$ kHz, and $e_{\mathrm{Inv}}^2 = 0.08$ (nV)^2/Hz and $i_{\mathrm{Inv}}^2 = 2.7$ (fA)^2/Hz at $f = 100$ kHz. For the Macro-OPA in Ref. [?], $e_{\mathrm{Inv}}^2 = 0.5$ (nV)^2/Hz and $i_{\mathrm{Inv}}^2 = 0.8$ (fA)^2/Hz at $f = 10$ kHz, and $e_{\mathrm{Inv}}^2 = 0.14$ (nV)^2/Hz and $i_{\mathrm{Inv}}^2 = 20$ (fA)^2/Hz at $f = 100$ kHz.

Comparing with the Macro-OPA in Ref. [?], the output of H2 in the Inv-Amp is grounded through large capacitor C_{i2}, so high-frequency noises generated by H2 are filtered out. In this work, R_{i2} is added, but its resistance is only 500 Ω and it is placed in the cryogenic zone. The noise generated by R_{i2} is three orders of magnitude smaller than that generated by H2 in Ref. [?]. Therefore, the equivalent input noises of the Inv-Amp are much lower than those of the Macro-OPA in Ref. [?].

3.2. Equivalent input current noise of the proposed CryoSTM-TIA

The equivalent input noise current PSD of the proposed CryoSTM-TIA is:

$$S_i^{\mathrm{in}}(f) = S_i^{\mathrm{Inv}}(f) + S_i^{\mathrm{FB}}(f) + S_i^{\mathrm{TJ}}(f)$$

where $S_i^{\mathrm{Inv}} = i_{\mathrm{Inv}}^2$, $S_i^{\mathrm{FB}} = 4kT/R_f + (2\pi f)^2 e_{\mathrm{Inv}}^2 C_{\mathrm{in}}^2$, and $S_i^{\mathrm{TJ}} = 4kT/R_J$ [?, ?]. Substituting these into the equation:

$$S_i^{\mathrm{in}}(f) \approx \frac{4kT}{R_f} + (2\pi f)^2 e_{\mathrm{Inv}}^2 C_{\mathrm{in}}^2 + i_{\mathrm{Inv}}^2$$

For the proposed CryoSTM-TIA, $R_f = 1$ GΩ, $C_{\mathrm{in}} = 0.5$ pF, and $C_J = 10$ fF. R_f, R_{i2}, and TJ are in the cryogenic zone at 4.2 K. Its four noise components are listed in Table 2. Noise components of the CryoSTM-TIA in Ref. [?] are also shown in Table 2. The CryoSTM-TIA proposed in this work has equivalent input noise current PSD of 0.6 (fA)^2/Hz at 10 kHz and 3 (fA)^2/Hz at 100 kHz, which is much lower than in Ref. [?].

4. CryoSTM-TIA operating state adjustment and dc tunneling current measurement

For the proposed CryoSTM-TIA, CNRS-HEMTs H1 and H2 should be selected with identical performance characteristics as closely as possible. Disconnect the Pre-Amp from the Post-Amp and ground the Pre-Amp input N. Adjust potentiometer R_λ. Adjust the current generated by the constant-current source in dashed box (a2) in Fig. 1 to $I_{\mathrm{const}} = 0.1$ mA. Adjust resistances R_1 and R_2

for operating points near the ideal values: gate-source voltage $V_{\text{gs}} = 100$ mV and drain-source current $I_{\text{ds}} = 0.1$ mA, as closely as possible.

Cascade the Pre-Amp and Post-Amp to form the Inv-Amp. The dc voltage at the Inv-Amp output is called the output offset voltage V_{OS}. As H1 and H2 are identical, V_{OS} is caused by: common-mode dc voltages on Rear-OPA inputs [?, ?], its input offset voltage, input bias currents, and input offset current. Usually, V_{OS} is small. The dc voltage gain of the Inv-Amp is $A_{\text{Inv}}(0) = A_{\text{Pre}} \cdot A_{\text{Rear}}(0) \approx 85$ dB, consistent with simulation results [?].

V_{OS} is only the input offset voltage of the Inv-Amp, as shown in Fig. 4 [Figure 4: see original paper]. Since input resistances of H1 and H2 can be considered infinite, input bias currents and input offset current can be considered zero. V_{OS} and its drift are presented in Supplemental file 6 [?]. The power of the constant-current source is about 24 mW. As is common in industry, a simple temperature control system based on TEC devices [?] can control temperature fluctuations of the constant-current source within 0.1 °C and those of Rear-OPA within 1 °C, so fluctuations of V_{OS} are estimated at 60 V, and drift can be controlled within 1 V. Dissimilarities between H1 and H2 cannot affect TIA ac performance, since ac signals from one Pre-Amp branch are filtered out by C_{i2}. Therefore, excluding fluctuations of V_{OS} within 1 V, fluctuations of V_{OS} provided by BMS can be controlled within 1 V.

Connect input N to the Inv-Amp output with feedback resistor R_f, then disconnect it from ground to form the TIA, as shown in Fig. 4. Here, switch K is off, i.e., the signal source circuit is disconnected. The TIA output voltage is V_{TIA}, equal to voltage at TIA input N. For $V_{\text{OS}} \ll V_{\text{TIA}}$, $V_{\text{TIA}} \approx V_{\text{OS}}$, so V_{OS} can be measured. V_{OS} can be lowered by adjusting R_λ, even to 0.

Switch on K, i.e., connect the signal source circuit to the TIA to form the CryoSTM-TIA, as shown in Fig. 4. As dc bias is applied by BMS, TJ dc resistance is R_J, and $V_N = V_{\text{TIA}} + V_{\text{OS}}$. The CryoSTM-TIA output voltage is $V_o = V_{\text{TIA}} + V_{\text{OS}}$, and dc tunneling current is $I_{\text{dc}} = (V_{\text{bias}} - V_N)/R_J$. For most applications, the transimpedance gain modulus should be measured first. In [1 kHz, 300 kHz], $|Z_T(f)|$ is expressed by Eq. (9). Since $|A_{\text{Inv}}(f)| > 85$ dB as shown in Fig. 2, $|Z_T(f)|$ in [1 kHz, 300 kHz] can be approximated by $|Z_T(f)| \approx R_f$. Measurement procedures are described in Ref. [?].

5. Applications in spectra measurements

5.1. Measuring scanning tunneling differential conductance spectra

The differential conductance of TJ as a function of voltage is:

$$G(V) = \frac{dI}{dV} = \frac{1}{R_J}$$

With modulated signal voltage v_{ac} applied to TJ at low frequency (e.g., $f = 1$

kHz as shown in Fig. 2), the measured ac current is $i_{\text{ac}} = v_{\text{ac}}/R_J$. Therefore, measured differential conductance spectra $G(V)$ can be obtained. Increasing modulation frequency can speed up measurements. In [1 kHz, 300 kHz], with $R_J \geq 1$ MΩ, the relative error is:

$$E_r = \left|\frac{G_{\text{meas}} - G}{G}\right| = \left|\frac{1}{1 + j2\pi f R_J C_{\text{in}}/A_{\text{Inv}}(f)} - 1\right|$$

By Eq. (20), $E_r < 57$ ppm, consistent with simulation results [?]. By Eq. (21), with $R_J \geq 1$ MΩ, $E_r < 0.1\%$. Thus, scanning tunneling current spectra $I(V)$ can be accurately obtained, where $V \in [V_L, V_H]$ are lower and upper voltage limits. As mentioned, V_{OS} fluctuations can be controlled within 1 V, so $I(V)$ can be measured accurately.

Selecting two different frequencies $f_1, f_2 \in$ [1 kHz, 300 kHz], two $G(V)$ values are obtained. Since inherent noise is very small, modulation voltage amplitude v_{ac} can be very small ($v_{\text{ac}} < 100$ V), greatly improving energy resolution for STS measurements.

5.2. Measuring scanning tunneling shot noise spectra

The measurement method for tunneling shot noise spectra is basically the same as introduced in Ref. [?]. Before tip-sample approach, $R_J \to \infty$. The output noise voltage PSD S_v^{out} can be measured, and equivalent input noise current S_i^{in} is obtained by Eq. (22).

To measure STSNS of a quantum system, adjust tip-sample distance so tunneling noise measurements are performed in selected bias domain $[V_L, V_H]$ [?]. Output noise voltage PSD $S_v^{\text{out}}(V, f)$ is measured. Tunneling noise current PSD is $S_i^{\text{tun}}(V, f)$. CryoSTM-TIA equivalent input noise current PSD is $S_i^{\text{in}}(f)$. With Eqs. (23) and (24):

$$S_i^{\text{tun}}(V, f) = \frac{S_v^{\text{out}}(V, f)}{|Z_T(f)|^2} - S_i^{\text{in}}(f)$$

From Eq. (18), $S_i^{\text{in}}(f)$ is smaller than 0.3 $(\text{fA})^2/\text{Hz}$ in [10 kHz, 100 kHz) and 0.1 $(\text{fA})^2/\text{Hz}$ in [100 kHz, 300 kHz]. $S_i^{\text{in}}(f)$ can be neglected compared with S_i^{tun} as long as S_i^{tun} is not too small. Therefore, $S_i^{\text{tun}}(V, f)$ can be obtained from measured $S_v^{\text{out}}(V, f)$. Then STSNS are obtained, and Fano factor $F = S_i^{\text{tun}}/(2eI_{\text{dc}})$ can be extracted.

5.3. Detecting Majorana bound states by measuring shot noise

In Ref. [?], several evidences with ZBCP were provided for vortex MBSs in iron-based superconductors, ruling out nine other possible mechanisms. For example, incoherent multiple Andreev reflection was ruled out by weak tunnel coupling conditions (large tunnel junction resistance) [?]. MBS existence can be further verified by shot noise measurements using the proposed CryoSTM-TIA.

With iron-based superconductor sample at 0.55 K and 2.5 T magnetic field, superconducting gap $\Delta \approx 1.8$ meV. Under different tunnel junction conductance conditions, tunneling current and differential conductance spectra are measured (Fig. 3(A) in Ref. [?]). Taking bias interval $[V_L, V_H] = [0.2$ mV, 1.8 mV$]$, select condition $G(V) \leq 0.2$ S so minimum differential conductance is not more than 0.2 S. A measurement domain can be found. Selecting longest possible bias interval, measure STSNS in [10 kHz, 300 kHz] and find corner frequencies f_{c1}, f_{c2}. At frequency $f > \max\{f_{c1}, f_{c2}\}$, shot noise can be considered white noise. With tunneling current spectra $I(V)$, STSNS are obtained and Fano factor extracted.

For vortex MBSs in Ref. [?], with bias in [0.2 mV, 1.8 mV], tunneling current I_{dc} is not constant. If 100 points are selected with step $\Delta V = 16$ V, corresponding current increment is only 3.2 pA. As V_{OS} fluctuations can be controlled within 1 V (much less than ΔV), accuracy is guaranteed. For sub-Poissonian shot noise of MBSs, S_i^{tun} may be smaller than 1 (fA)^2/Hz. The CryoSTM-LC-Amp in Ref. [?] has inherent noise of about 700 (fA)^2/Hz, far from meeting accuracy requirements. The CryoSTM-TIA in Ref. [?] with 21 (fA)^2/Hz at 100 kHz is barely acceptable. The CryoSTM-TIA proposed here, with only 3 (fA)^2/Hz at 100 kHz, meets accuracy requirements for high-precision STSNS measurements of vortex MBSs.

For these 2-terminal systems, tunneling noise corner frequency is usually small, making shot noise measurements easy. By the same means, STSNS for MBSs in 2D topological insulator/superconductor heterojunctions [?] and ferromagnetic chain/superconductor systems [?, ?] can also be investigated. Ref. [?] predicted theoretically that Fano factor is constant at 0.5 for MBSs.

6. Conclusions

This work presents a transimpedance amplifier (TIA) design for cryogenic STM (CryoSTM). The TIA connected with the tip-sample component is called CryoSTM-TIA. The Macro-OPA of the TIA in Ref. [?] is replaced with the Inv-Amp. The Pre-Amp remains the same as in Ref. [?], but the noninverting output of the Pre-Amp in the Inv-Amp is ac-grounded through large capacitor C_{i2} and connected to the Rear-OPA inverting input through small resistor R_{i2} as ac ground resistance. Ac signals from one Pre-Amp branch are filtered by C_{i2}, making Inv-Amp topology completely different from Macro-OPA in Ref. [?]. Noises from this branch are filtered by C_{i2}. Therefore, CryoSTM-TIA maintains transimpedance gain of 1 GΩ and bandwidth over 300 kHz, but inherent noise is reduced to 3 (fA)^2/Hz at 100 kHz (only 1/7 of Ref. [?]).

With this apparatus, fast high-energy-resolution scanning tunneling spectra measurements can be performed and very low tunneling shot noise of quantum systems measured with higher precision, making it more universal than Ref. [?].

This apparatus can study novel physical properties of various quantum systems, such as detecting Majorana bound states in topological quantum systems.

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