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Current Fluctuations in Single Barrier Vertical GaAs/AlAs/GaAs Tunneling Devices

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We report the experimental results of the low temperature ($T = 4.2$ K) low-frequency current fluctuations measurements in the single-barrier resonant tunneling GaAs/AlAs/GaAs device with Si δ-doping in the center of the 10 nm thick AlAs barrier. The dimensions of the device were 200 μm by 200 μm. For the biasing voltages 0.1 V $< |U| <$ 1 V we observed the Fano factors between $F = 0.7$ and $F = 0.95$. We explain it by the existence of the trapping centers/imperfections/resonant levels inside the barrier participating in the transport for this range of voltages. Only for the smallest biasing voltages the Fano factor tends to $F = 1$, expected for a highly nontransparent barrier.

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1. Introduction

Measurements of current fluctuations in mesoscopic systems can provide more insight into the system and its electronic transport mechanisms than the averaged current–voltage characteristics. Time dependent fluctuations of a tunneling current reflect the temporal correlations between charge transfer events through a conductor. For mesoscopic systems, where the Pauli principle and the Coulomb interactions play an important role, the deviations from the classical Poissonian full shot noise power density $2eI$ can provide an additional piece of information about interactions between electrons inside the tunneling barrier and the mechanism of the transport (e.g. the existence and number of localized states which participate in the transport) [1]. The single-barrier resonant-tunneling device is interesting for its simplicity and many authors had investigated electronic transport in this system until now [2, 3]. Incorporating impurities inside the barriers change dramatically its properties, enable resonant transport through the barrier and make it useful for applications. However, not only intentionally introduced impurities exist inside the barrier. Some impurities/imperfections which only slightly influence the $I(V)$ characteristics can manifest its existence in current noise measurements.

2. Sample

Single-barrier resonant tunneling GaAs/AlAs/GaAs structure with Si δ-doping (3×10^9 cm^{-2}) in the center of the 10 nm thick AlAs barrier has been grown by MBE-technique. The dimensions of the mesa structure were *ca.* 200 μm by 200 μm. More details about the sample and its tunneling characteristics can be found in Refs. [4, 5].

3. Experimental method and setup

The current noise measurements have been performed by means of cross-correlation technique [6]. In this technique the signal from the sample is provided by means of two independent signal-carrying and amplifying channels to the correlator, which determines the power signal density of the sample-related correlated signal. The uncorrelated noise of amplifiers will not appear in cross-correlation spectra.

The sample has been placed inside the liquid helium container. The current signal has been provided by means of low-noise cables to the input of two home-made transimpedance amplifiers with a gain ranging from 10^7 to 10^8 V/A and it has been additionally amplified by two voltage amplifiers with a gain of 100 or 500 V/V. A personal-computer-hosted A/D converter card has been driven by Matlab$^{\mathrm{TM}}$ software which performed also the numerical analysis of the signal. The sample was polarized by means of low-noise home-made bipolar voltage source biasing noninverting inputs of the transimpedance amplifiers. A simplified schematic of the experimental setup has been shown in Fig. 1.

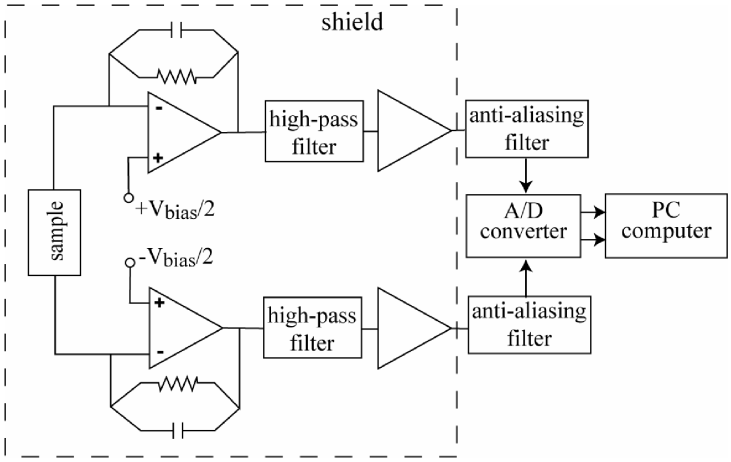

Fig. 1. Schematic of the measurement configuration showing two independent signal-carrying channels with two transimpedance amplifiers, high-pass filters, voltage amplifiers, anti-aliasing filters, A/D-converter, and spectrum analyzer (PC with appropriate software).

4. Results and discussion

The $I(V)$ characteristics of the tunneling device (see Fig. 2a) has been measured in the range from 0 V to –1 V at a temperature $T = 4.2$ K. Minus sign in the biasing voltage means the current flowing from the substrate to metallic contact on the top of the mesa structure. The most important feature of this characteristics is the bump in the region from –0.45 to –0.75 V, where the tunneling current is mediated by silicon impurities in the center of the barrier [4, 5]. More fea-

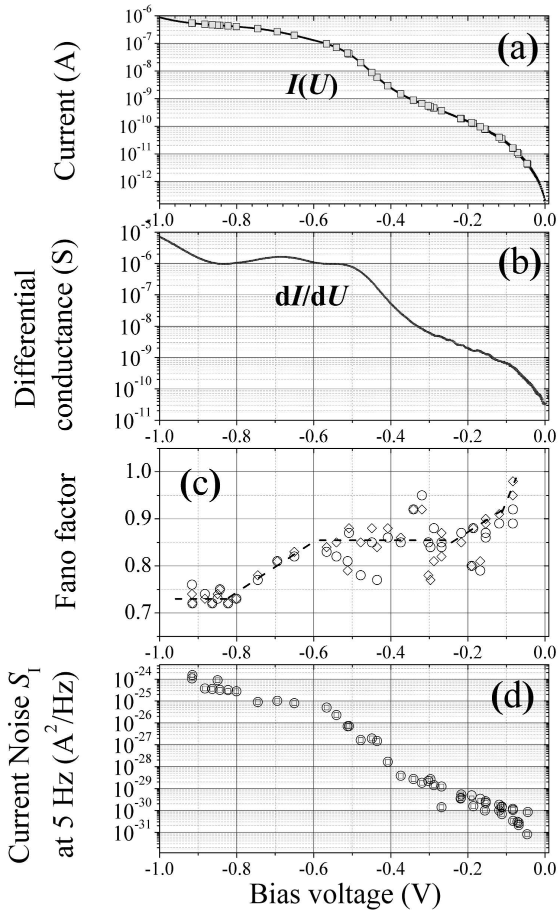

Fig. 2. (a) $I(V)$ characteristics for the sample at $T = 4.2$ K; squares indicate the polarizations for which noise measurements were performed. (b) Differential conductance $\mathrm{d}I/\mathrm{d}U$ numerically calculated from $I(V)$ characteristics; in the region from –0.5 V to –0.8 V one can see two bumps originating from the tunneling process with the participation of the Si impurities in the barrier. (c) Fano factor determined for several bias voltages marked in (a). The dashed line is only to guide the eyes. (d) Current noise S_I at 5 Hz after subtracting the shot noise as a function of bias.

tures can be seen in differential conductance characteristics (Fig. 2b) calculated numerically from $I(V)$ characteristics. Below $|U| = 0.3$ V one can see several small resonances of the tunneling current. The origin of these resonances remains unknown. There are probably some impurities/defects/imperfections inside the barrier which participate in tunneling, opening additional channels for transport through the barrier.

Current noise measurements have been performed for several bias voltages in the region from 0 to –1 V. Typical results for power spectral density (PSD) of the current fluctuations have been shown in Fig. 3. All the spectra shown have a higher frequency tail influenced by low-pass filter of feedback loop of transimpedance amplifiers. Especially for small currents, where higher gains of the amplifiers are necessary, it limits the frequency band of the measurement below 100 Hz (for 10^8 V/A). For the smallest noise measured (*ca.* 10^{-30} A^2/Hz) the raising tail of the spectra at low frequencies comes usually from external electromagnetic interferences and vibrations, depending on the day of the measurement. The observed spectra for small currents are almost flat as expected for white shot noise (Fig. 3). While increasing bias we see more noise which superimposes on the flat shot noise. This part of the noise can have various character. For e.g. $U = -567$ mV and $U = -478$ mV (see Fig. 3) it consists of generation-recombination noise with characteristic bump of a few Lorentzians. For $U = -508$ mV one can observe $1/f$ noise and for $U = -374$ mV — the noise close to $1/f^2$. We explain the variety of the noise spectra by different transport mechanisms at different biases. The Fermi level changes as we apply the bias and it aligns its position to

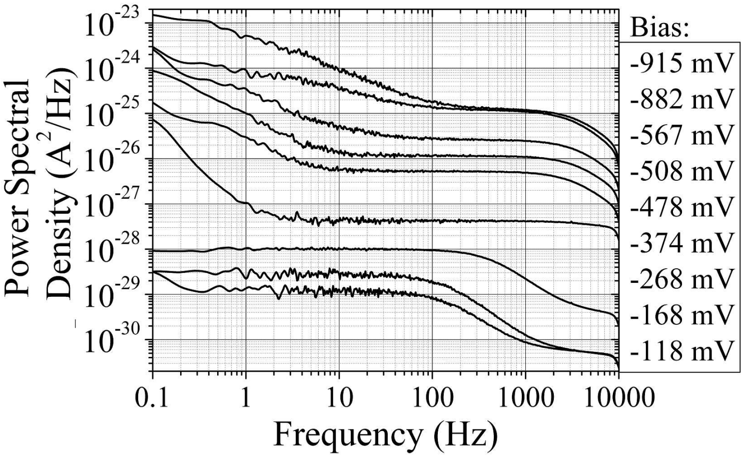

Fig. 3. PSD (cross-correlation) spectra for the sample at $T = 4.2$ K and several biasing voltages indicated on the right hand side. For lower biases the spectra are almost flat (white noise) and starting from *ca.* $U = -0.3$ V they become more and more complicated, revealing different shapes at different biases.

different electronic states inside the barrier. If we have only a few characteristic relaxation times in the system, the trapping and releasing of electrons are seen in noise spectra as a process with definite relaxation time and the bump in PSD is observed. When there is more relaxation times superimposed, we observe $1/f$-like noise. $1/f^2$ can originate from the higher frequency tail of a single Lorentzian. The value of PSD at 5 Hz after subtracting the white shot noise is shown in Fig. 2d as a function of bias.

The Fano factor (the ratio of the measured shot noise to the full Poissonian $2eI$ noise) and the level of the shot noise have been determined from fitting the amplifier characteristics to the high frequency tail of the spectra, assuming that the shot noise is a white noise with PSD independent of frequency. The Fano factor shown in Fig. 2c has values between 0.7 for higher biases and 1 for lower. Astonishingly, the Fano factor close to $F = 0.85$ is observed in the range from –0.4 V to –0.55 V, where in $I(V)$ characteristics the resonant tunneling through the impurity states is observed [4, 5]. The Fano factor close to $F = 0.75$, expected for tunneling through strongly localized states randomly distributed in the center of the barrier [7, 8], is observed for biasing voltages higher than 0.8 V. However, because of the large dispersion of the Fano factors the conclusions from this discussion should be limited.

5. Conclusions

For biases $|U|$ smaller than those for which resonant tunneling through intentionally introduced impurities is observed ($|U| < 500$ mV), we have observed the Fano factors lower than 1, which indicates that even below these voltages we have a variety of different transport mechanisms. Only for the lowest biasing voltages ($|U| < 0.1$ V) the Fano factors tend to the value $F = 1$. Unexpectedly, for higher biasing voltages 500 mV $< |U| <$ 700 mV, where in $I(V)$ characteristics the resonant tunneling through the impurity states is observed, we have measured the Fano factor close to $F = 0.85$. The Fano factor $F = 0.75$, expected for the transport of electrons tunneling the barrier with impurities placed in its center, appeared for biasing voltages $|U| > 800$ mV. Because low frequency noise originating from the trapping electrons on impurities/imperfections superimposes on the shot noise, the measurements of the pure shot noise are difficult in the configuration of experimental setup with transimpedance amplifier, which limits the band below 100 Hz for the highest gains used. However, because in our experiment the Fano factor F does not exceed unity, it means that in our tunneling device we have multiple uncorrelated sequential and/or parallel transport channels, each of which is governed by a full Poissonian process and a resulting transport statistics of a whole system is exclusively sub-Poissonian ($F < 1$).

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