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Shot noise in tunneling through single localized states

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Abstract

We have measured the noise properties of a resonant tunneling structure in a voltage regime where single electron tunneling is observed. We find different values of the shot noise suppression depending on whether the transport is governed by a single impurity or an ensemble of zero-dimensional states. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Studying the noise characteristics of mesoscopic systems has gathered some interest lately. One reason is the fact that time-dependent fluctuations of the current due to the discrete nature of the electron charge give information that is complementary to that obtained by stationary transport measurements. Usually shot noise is characterized by the Fano factor α being defined by $S_{\text{noise}} = \alpha 2eI$ with the spectral noise power density S_{noise}, the electron charge e and the current I. Some mesoscopic systems feature a specific shot noise suppression: an ideal tunnel barrier shows $\alpha = 1$ while in symmetric resonant tunneling $\alpha = \frac{1}{2}$ is expected [1].

The sample we use is a double-barrier resonant-tunneling structure (DBRTS) biased in a regime, where the current through the device is carried by a single impurity or small numbers of impurities, that form zero-dimensional states between the tunneling barriers [2]. This distinguishes our experiments from other work where resonant tunneling transport occurs through single subbands (see for example Ref. [3]). Shot noise measurements in the single-electron tunneling regime have been performed in metallic systems [4].

2. Sample and experiment

Our sample consists of a nearly symmetric DBRTS grown by molecular beam epitaxy on a n^+-type GaAs substrate. The heterostructure is formed by a 10 nm wide GaAs quantum well sandwiched between two $Al_{0.3}Ga_{0.7}As$-tunneling barriers of 5 and 6 nm thickness. The contacts consist of 300 nm thick GaAs layers doped with Si (4×10^{17} cm^{-3}) and they are separated from the active region by a 7 nm thick undoped GaAs spacer layer. Current steps in the I–V curve indicate the existence of single impurities in the nominally undoped GaAs. The diameter of the diode is 1 μm.

The experiments were done in a ^{4}He-cryostat using a variable-temperature insert that allows for a minimal temperature of 1.3 K. One terminal of the sample is connected to a voltage source, the second one is grounded with the virtual mass of an ultra-low

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noise current amplifier. This allows monitoring the DC-current through the sample while the noise spectra are acquired by a spectrum analyzer in the range between 0 and 100 kHz. To reduce the amplifier-noise due to capacitive loading connection to the sample is realized with a low-capacitance line (∼ 10 pF).

The current-induced noise power originating from the DBRTS was calculated from the difference between two measurements with and without voltage bias after correcting the spectra for the amplitude response of the amplifier.

3. Experimental results and discussion

In Fig. 1 the I–V characteristics of the DBRTS are plotted. At bias voltages below 10 mV two current plateaus are visible with some finestructure. These are due to resonant tunneling through single or small numbers of impurities. The finestructure originates most likely from the influence of fluctuations in the local density of states of emitter and collector.

In Fig. 2 we show two spectra at the two bias voltages indicated by the arrows in Fig. 1. At small bias the spectra show white noise. At the onset of the current plateau and above $1/f$ noise develops, but with negligible contribution to the noise power at frequencies above 40 kHz. This justifies averaging the spectra between 40 and 100 kHz to increase the signal-to-noise ratio of the data in analyzing the shot noise of our sample.

In Fig. 3, the noise power measured in the single electron tunneling regime is plotted as a function of applied bias voltage in comparison with the theoretically calculated shot noise values for $\alpha = 1$ and $\alpha = \frac{3}{4}$.

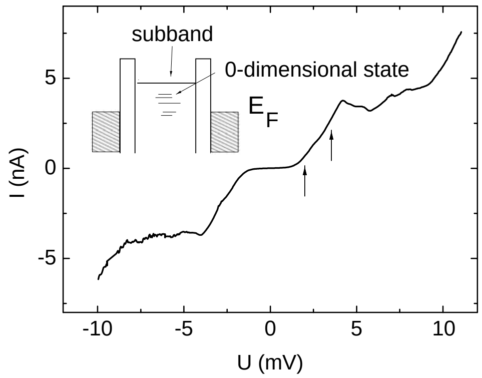

Fig. 1. I–V characteristic of the sample in the single electron tunneling regime at $T = 1.3$ K. The steps in the curve are fingerprints of zero-dimensional impurities between the barriers. The arrows indicate to the voltage positions where we show the corresponding spectra in Fig. 2. Inset: schematical view of the electronic structure of the sample.

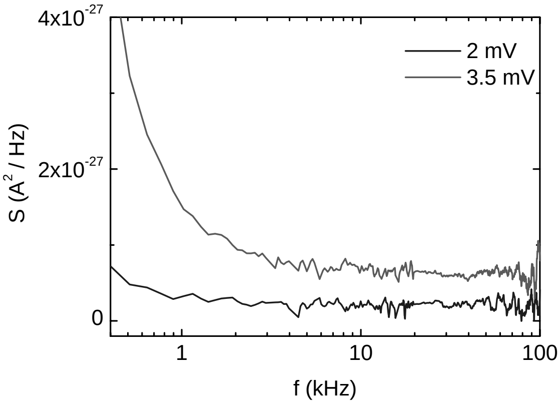

Fig. 2. Noise spectra of the DBRTS at different bias voltages. At frequencies above 20 kHz the data have been smoothed using a boxcar average to compensate for the degrading signal-to-noise ratio at high frequencies due to capacitive loading of the current amplifier.

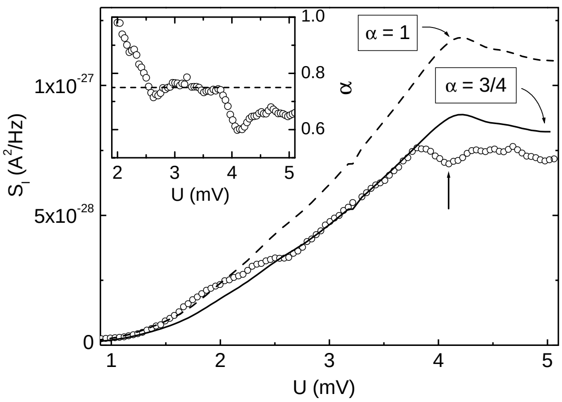

Fig. 3. The noise power of the sample in the single electron tunneling regime at $T = 1.6$ K. The open circles represent the average noise power between 40 and 100 kHz. The plot has been smoothed using a five-point boxcar average. The dashed lines represent the theoretically calculated shot noise for $\alpha = 1$, the straight line for a suppression of $\alpha = \frac{3}{4}$. The arrow indicates the voltage position where α reaches a value of 0.6. Inset: corresponding Fano-factor α.

At small bias voltages ($< \pm 2$ mV) the sample produces full shot noise $S_{\text{noise}} = 2eI$ proportional to the current I. Full shot noise is associated with a single tunnel junction. This indicates that below 2 mV the sample acts effectively as a single barrier.

However, for larger bias voltages a suppression of the shot noise between 2.5 and 3.8 mV occurs. The noise signal is in good agreement with the theoretical curve for $\alpha = \frac{3}{4}$ (see Fig. 3 with inset). On the current plateau the suppression increases up to values of $\alpha = 0.6$. This suppression of $\alpha = 0.6$ is not temperature sensitive in a range between 1.3 and 4 K (data not shown). The current plateau in the I–V curve—that we attribute to tunneling through a single impurity—is still existent at 4 K although the overshoot at the onset does vanish. So we believe that the noise suppression at this specific bias voltage is a fingerprint of resonant tunneling through one zero-dimensional state.

In resonant tunneling through a single state one would expect $\alpha = \frac{1}{2}$ for symmetric barriers and $\alpha = 1$ for an extremely asymmetric situation [5]. The observed suppression of $\alpha = 0.6$ thus indicates the slight asymmetry of the structure.

Astonishingly in the range between 2.5 and 3.8 mV a constant suppression of the shot noise with a Fano-factor of $\alpha = \frac{3}{4}$ is observed, there a third effect may come to play a role. Nazarov and Struben proposed a theoretical model for shot noise in a disordered resonant tunneling system with a predicted suppression of $\alpha = \frac{3}{4}$ [6]. It is originally based on the existence of strongly localized states inside a single barrier randomly distributed in energy and space. If the number of contributing states is large enough to allow for averaging over the disorder in the system this value for α should be universal. Only those states situated close to the center of the barrier play a role in transport. So this situation can be effectively regarded as a two-barrier problem [1, p. 24]. Thus this model could be applicable to our DBRTS.

If we interpret our data accordingly this would implicate that in the voltage range from 2.5 to 3.8 mV transport occurs through an ensemble of impurity states that is large enough to allow for a suppression of $\alpha = \frac{3}{4}$, whereas for bias larger than 3.8 mV tunneling through a single impurity dominates the current.

4. Conclusions

We have measured the noise properties of a double-barrier resonant tunneling structure in a voltage regime where transport occurs through single or small numbers of localized states. These states are formed by impurities. We observe a shot noise suppression of $\alpha = \frac{3}{4}$ as long as the current is not governed by single electron effects. If any single electron tunneling effects come to play a role, we observe a further suppression down to $\alpha = 0.6$.

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