Shot noise in tunneling through a single InAs quantum dot

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Abstract. We examine the dynamical properties of resonant tunneling through single InAs quantum dots by measuring the shot noise of the current. We observe an approximately linear voltage dependence of both the shot noise, characterized by the Fano factor, and the tunneling current itself. We ascribe this to the three-dimensional density of states of the emitter and collector and are able to model the voltage dependence using a master equation approach.

Shot noise measurements allow us to access the dynamical properties of a resonant tunneling device which are not accessible by measuring solely the average current. This offers the possibility to study the individual tunneling rates and their dependence on e.g. the bias voltage and thus yields a complete characterization of the device. We employ this to thoroughly characterize a single electron resonant tunneling device based on InAs quantum dots and point out the influence of the density of states of the emitter and collector contacts.

Shot noise was initially discussed for vacuum tubes and later on for any kind of single tunneling barriers. For all such systems the current $I(t)$ displays a frequency independent noise power density $S = 2q\langle I \rangle$ with $q = e$ the elementary charge and $\langle I \rangle$ the mean or DC-current, further on just denoted by I. However, the shot noise in a double-barrier structure displays a reduced shot noise power below the full shot noise value $2eI$ of the single barrier system. The degree of reduction, characterized by the so called Fano factor $\alpha = S/2eI$ with S being the measured shot noise power, yields a direct measure of the ratio of the tunneling rates through both barriers.

In this paper we present noise measurements on self assembled InAs quantum dot (QD) systems. The InAs QD's are embedded into the AlAs barrier of a GaAs-AlAs-GaAs tunneling device. Due to the growth of InAs on AlAs we achieve small dot sizes of $10-15$ nm diameter and 3 nm height. The InAs dots are grown on a 4 nm AlAs layer and overgrown by another 6 nm of AlAs, resulting into effective tunneling barrier thickness of 4 nm (bottom) and 3-4 nm (top). Graded n-doped GaAs on both sides of the barrier acts as leads. Au/Ge/Ni contacts are used as etch mask to prepare diode structures with an area of $40 \times 40\,\mu$m. Only a small fraction of the InAs dots if electrically active [1].

Throughout this paper we choose the bias polarity in such a way that the electrons first tunnel through the thicker (bottom) barrier and then through the thinner (top) barrier. Due to the higher collector tunneling rate $\Gamma_C > \Gamma_E$ compared to the emitter tunneling rate the dot is mostly empty which allows to examine the influence of the emitter density of states.

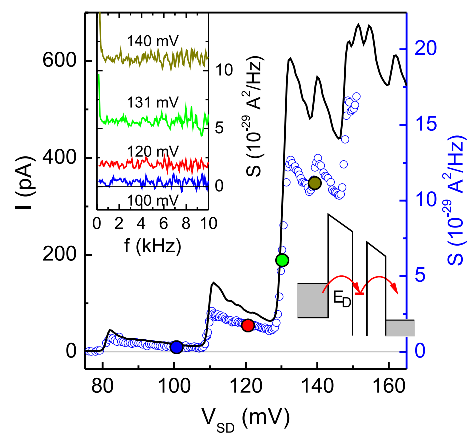

FIGURE 1. Measured current (line, left axis) and shot noise (circles, right axis) for the first few QD's ($T = 1.5$ K). Mapped onto the right axis the line corresponds to full shot noise $S = 2eI$. *Inset:* Spectral density measured for different voltages V_{sd} is frequency independent for $f > 0.5$ kHz.

Without bias voltage the ground state energy of all dots lies above the Fermi energy due to the small size of the InAs dots on AlAs. The current is blocked until the energy of the largest dot with lowest ground state energy is aligned with the Fermi energy of the emitter. For the device under study this happens for a voltage $V_{sd} =$ 80 mV at which a resonant tunneling current through the first dot sets in. Successive steps show up in the current with rising voltage (Fig. 1), each denoting another QD

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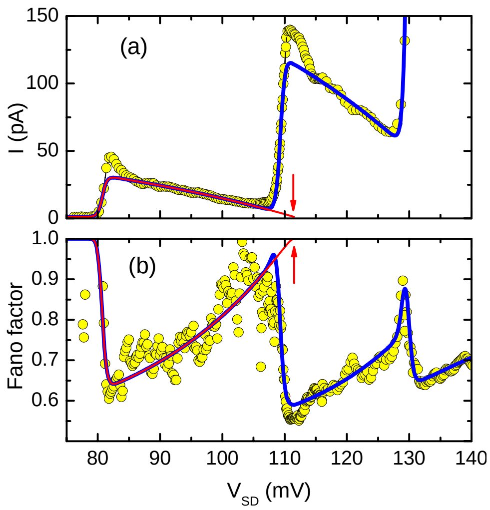

FIGURE 2. (a) Resonant tunneling current as measured (circle) and modeled (line). (b) Same for the Fano factor $\alpha = S/2eI$.

coming into resonance.

The measured noise spectra $S(f)$ are shown in the inset of Fig. 1 for different voltages. As expected for shot noise $S(f)$ is essentially frequency independent, and we determine the shot noise density S by averaging the spectra from 1 to 10 kHz. The result is displayed by the circles in Fig. 1 (right scale). Comparison to the full shot noise $2eI$ (line mapped to right scale) reveals a suppression of noise which is well understood as a consequence of Coulomb repulsion on the QD's [2].

The large spacing between the current onset through the first few dots allows us to examine the noise properties for resonant tunneling through a single InAs-QD. The resonant tunneling current and the corresponding Fano factor $\alpha = S/2eI$ characterizing the noise are shown in detail for the first two dots and the onset of the third one in Fig. 2.

One striking feature of both the current I and the Fano factor α is the nearly linear decrease of I resp. increase of α which follows the initial step. This voltage dependence is distinct from the one observed in resonant tunneling devices realized by patterning two-dimensional systems and is caused by the three-dimensional nature of the emitter and collector. It was pointed out by Liu and Aers [3] that the tunneling rates are proportional to the area $A(E_D)$ in momentum space with QD energy E_D. In three dimensions $A(E_D) \propto E_D - E_C$ with E_C the conduction band edge and thus $\Gamma(E_D) \propto E_D - E_C$ with $E_D(V_{sd}) = e\beta(V_{sd} - V_0)$ depending on the bias voltage (lever arm $\beta \approx 0.4$). Assuming $\Gamma_E \ll \Gamma_C$ the current $I \approx e\Gamma_E(V_{sd}) \propto V_{sd} - V_0$ depends approximately linearly on the voltage and vanishes at V_0, shown by the arrow in Fig. 2, where the QD energy E_D crosses the band edge of the emitter. The same behavior is also mirrored by the Fano factor which in first order of Γ_E/Γ_C follows $\alpha \approx 1 - 2\Gamma_E/\Gamma_C$. Due to the large bias we can assume $\Gamma_C \approx$constant.

The window of transport ΔV between the onset of current when the QD energy crosses the Fermi energy, $E_D = E_F$, and the vanishing of the current through the same dot for $E_D = E_C$ allows us to estimate the Fermi energy. With $\beta \approx 0.4$ from temperature dependent measurements and $\Delta V \approx 32$ mV we find $E_F - E_C \approx 13$ meV which compares well with a Fermi energy of 14 meV estimated from growth parameters.

Closer examination of Fig. 2 reveals deviations from the simple linear dependence of current and Fano factor discussed above. To account for these we have to abandon the assumption of $\Gamma_E \ll \Gamma_C$ and calculate the full expressions using a master equation approach [4, 5], taking into account temperature and spin degeneracy. For a single quantum dot we find

$$I = \frac{2e f_E\, \Gamma_E(V_{sd})\Gamma_C}{(1+f_E)\Gamma_E(V_{sd})+\Gamma_C}\,, \tag{1}$$

$$\alpha = 1 - \frac{4 f_E\, \Gamma_E(V_{sd})\Gamma_C}{((1+f_E)\Gamma_E(V_{sd})+\Gamma_C)^2} \tag{2}$$

with f_E being the Fermi function of the emitter. For transport through multiple dots this has to be extended to $I = \sum I_i$ and $\alpha = \sum (I_i/I)\alpha_i$ with I_i and α_i for each dot given by the above equations. The result for the best fit of the tunneling rates at current onset and the onset voltage for each dot is shown by the lines in Fig. 2. We observe a good agreement between the model and the measured data, and even the peak in the Fano factor at $V_{sd} \approx 129$ mV is nicely reproduced.

Nevertheless, we observe some deviations from our simple non-interacting model directly at the step edge of the current onset for each dot, which we discuss elsewhere and attribute to interaction effects, namely a Fermi edge singularity [5].

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