

Resonant tunneling through zero-dimensional impurity states: Effects of a finite temperature

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Abstract We have performed temperature dependent tunneling experiments through a single impurity in an asymmetric vertical double barrier tunneling structure. In particular in the charging direction we observe at zero magnetic field a clear shift in the onset voltage of the resonant tunneling current through the impurity. With a magnetic field applied the shift starts to disappear. The experimental observations are explained in terms of resonant tunneling through a spin degenerate impurity level.

Resonant tunneling experiments through a single impurity [1] mainly reflect the energetic position of an impurity level and the Fermi-Dirac distribution in the emitter. In order to refine the concept of such tunneling processes, in particular as far as the temperature dependence is concerned, we investigated an asymmetric double-barrier resonant-tunneling device (DBRTD) consisting of a 10 nm GaAs quantum well (QW) and two 5 nm and 8 nm wide $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers. The structure is sandwiched between highly doped GaAs electrodes (Si-doped with $n_{Si} = 4 \times 10^{17} \text{ cm}^{-3}$) separated from the barriers by a 7 nm thick nominally undoped GaAs spacer. From this wafer we processed a vertical tunneling diode with a mesa diameter of 2 μm . When applying a bias voltage V between the top and the bottom electrode the sample displays the normal behavior of a resonant tunneling diode with pronounced current peaks at $V_r^+ = 82 \text{ mV}$ and $V_r^- = -183 \text{ mV}$. For lower voltages additional small current steps are observed. We assign them to tunneling through zero-dimensional impurity levels originating from donor atoms unintentionally present in the GaAs QW [1,2]. In this work we concentrate on the first current step due to resonant tunneling through the energetically lowest lying impurity state. We will show that the spin degeneracy of this ground state and the Coulomb blockade causes a shift of the step position as a function of temperature [3].

For a theoretical description of the effects observed we regard the situation as sketched in Fig. 1. A zero-dimensional impurity with a spin-degenerate ground state ϵ is situated inside the central well of the DBRTD. It is coupled via two tunneling barriers (characterized by tunneling rates $\Gamma_L < \Gamma_R$) to three-dimensional reservoirs with chemical potentials μ_L and μ_R . Applying a finite transport voltage V to the structure induces a difference in the chemical potentials, $eV = \mu_L - \mu_R$. A resonant current through the impurity shows up as a current step at a voltage $V_+ > 0$ (or $V_- < 0$, respectively) when μ_L (or μ_R , respectively) equals ϵ [3]. Two possible spin

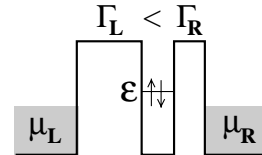


Fig. 1 Energy-level scheme showing the two-fold spin-degenerate ground state of an impurity at energy ϵ coupled to electrodes with chemical potentials μ_L and μ_R . The tunneling rates through the two barriers are Γ_L and Γ_R .

states can be occupied by an electron during a tunneling event. However, Coulomb blockade prohibits simultaneous occupancy of both states at the same time. With this condition the tunneling current I through the impurity can be calculated as [4]:

$$I = 2e \Gamma_L \Gamma_R \frac{f_L(\epsilon) - f_R(\epsilon)}{\Gamma_L + \Gamma_R + \Gamma_L f_L(\epsilon) + \Gamma_R f_R(\epsilon)} \quad (1)$$

where $f_L(\epsilon)$ and $f_R(\epsilon)$ are the Fermi-Dirac distributions in the left and right reservoirs.

For a finite bias $|eV| \gg kT$ we have $f_R \ll 1$ for $V > 0$ (and $f_L \ll 1$ for $V < 0$) and the current as a function of an applied bias V simplifies to:

$$I = 2e \Gamma_L \Gamma_R \frac{f_L(\alpha_L e(V_+ - V))}{\Gamma_L + \Gamma_R + \Gamma_L f_L(\alpha_L e(V_+ - V))} \quad (V > 0) \quad (2a)$$

$$I = -2e \Gamma_L \Gamma_R \frac{f_R(\alpha_R e(V - V_-))}{\Gamma_L + \Gamma_R + \Gamma_R f_R(\alpha_R e(V - V_-))} \quad (V < 0) \quad (2b)$$

The prefactors α_L and α_R account for the fact that only a part of the bias voltage drops between the emitter reservoir and the impurity, see also below.

An experimental example for the I - V characteristic of our sample is shown in Fig. 2. Clear current steps due to resonant tunneling through the energetically lowest lying impurity level are observed for both bias directions in the two top figures. For positive bias (right panel) the electrons tunnel into the impurity through the thicker barrier Γ_L and leave it through the thinner one Γ_R . The impurity is mostly empty and both degenerate states of ϵ are available for tunneling (non-charging direction). For negative bias the tunneling current is limited by the small tunneling Γ_L for electrons leaving the impurity. As a consequence, one of the two states of ϵ is mostly occupied and Coulomb blockade suppresses a simultaneous tunneling event through the other spin state (charging direction). Therefore, the resonant current is smaller than in the non-charging direction. This current

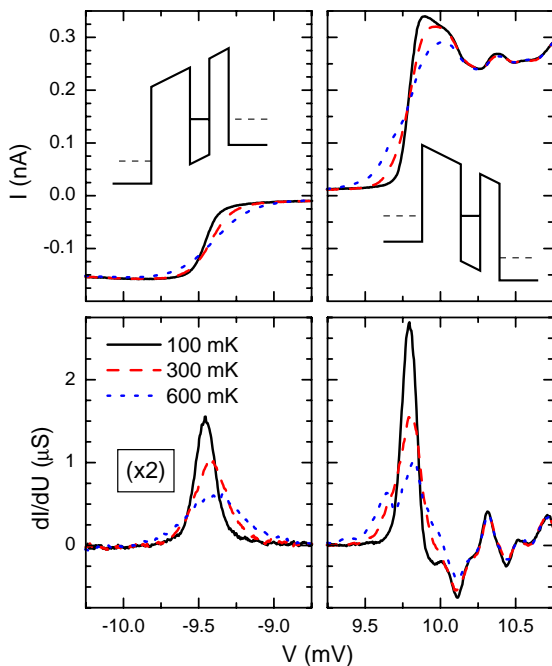


Fig. 2 Current voltage characteristics (top) and differential conductance (bottom) of a vertical asymmetric DBRTD for different temperatures. The steps are due to resonant tunneling through a single impurity. The left panels represent the charging direction, the right panels show the non-charging direction at positive bias voltages. The insets sketch the energy-level schemes of the structure at the step voltages V_- and V_+ for the two bias directions.

suppression follows from Eqs. (2a) and (2b) which predict for $\Gamma_R \gg \Gamma_L$ and $T = 0$ current steps $\Delta I^+ = 2e\Gamma_L$ in the non-charging direction and $\Delta I^- = -e\Gamma_L$ in the charging direction.

Effects of temperature can be visualized more clearly when plotting the differential conductance $G = dI/dV$ as a function of bias voltage. The current steps show up as peaks in G . Fitting its half width ΔV_{HW} as a function of temperature to Eqs. (2a) and (2b) allows to determine the lever factors α_L and α_R , see Fig. 3, top panels. For both bias directions we find $\alpha \approx 0.5$ indicating that the impurity is approximately situated half way between the two reservoirs.

Eqs. (2a) and (2b) also predict that the maximal conductance at finite temperature is not always observed at the voltage where the chemical potential in the source (i.e. μ_L for positive bias and μ_R for negative bias) equals ϵ . In particular in the charging direction the step voltage shifts to a lower absolute value when T is increased. This is indeed observed experimentally and shown in the left bottom curve of Fig. 3. The solid line shows a theoretical fit as expected from Eq. (2b) and yields $\Gamma_R/\Gamma_L = 10$ in reasonable agreement with the expected tunneling rates through the two barriers. For the non-charging direction the shift observed is negligible and consistent with $\Gamma_R/\Gamma_L = 10$.

When applying a magnetic field the Zeeman effect lifts the spin-degeneracy of ϵ . As a consequence the cur-

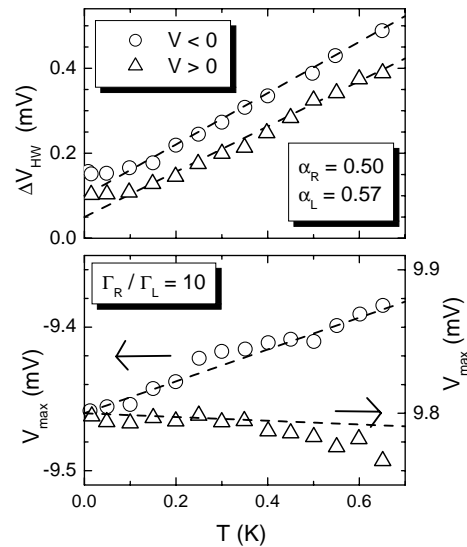


Fig. 3 Top: Temperature dependence of the half-width ΔV_{HW} of the conductance peak for the two bias directions. The lines show fits for lever factors. Bottom: Experimental temperature dependent shift of the conductance-peak position for both bias directions (symbols) compared to the theoretical behavior using $\Gamma_R/\Gamma_L = 10$ (dashed lines).

rent step in the SET direction splits into two steps corresponding to tunneling of electrons with a different spin orientation [5,6]. From the magnetic field dependence of this split we extract a Landé factor $g^* = -0.14$ for the impurity ground state [6]. In the charging direction Coulomb blockade still prohibits simultaneous tunneling through both energy levels and only one current step is observed. However, since the degeneracy is lifted the shift of the step voltage is no more observed as long as $3.5k_B T > g^* \mu_B B$. For $3.5k_B T < g^* \mu_B B$ the energy splitting of the ground state ϵ is no more resolved and ϵ can be again regarded as a virtually degenerate level. Finally it is worthwhile remarking that the effects described in this paper also influence the spin splitting of the current steps in the SET direction and a direct determination of g^* is only possible if $3.5k_B T < g^* \mu_B B$.

In conclusion we have shown that the actual voltage position of a resonant current step through a zero-dimensional state is not only given by the energetic position of this state but can also be strongly influenced by temperature.

References

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