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High-frequency transport through mesoscopic structures

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Abstract

We have measured DC transport through a GaAs/AlGaAs quantum dot in the presence of a microwave signal of frequency *f*. We find features related to the photon energy *hf* whose positions in gate voltage are independent of the microwave power but vary linearly with frequency. The measurements demonstrate photon-assisted tunneling in the mesoscopic regime.

Keywords: Electrical transport measurements; Gallium arsenide; Heterojunctions; Quantum effects; Semiconductor–semiconductor heterostructures; Tunneling

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1. Introduction

We have studied single electron tunneling in the time- and frequency-dependent regime where the photon energy *hf* of a microwave signal exceeds the thermal energy k_BT. The main idea is that electron tunneling can be accompanied with absorption or emission of quanta (i.e. photons) from the external high-frequency signal [1]. The measurements on our dots, which are defined with metallic gates in the 2DEG of a GaAs/AlGaAs heterostructure, were performed at an effective electron temperature of about 100 mK [2,3]. We find that electrons can overcome the Coulomb gap in the quantum dot when discrete photons of energy *hf* are absorbed from the applied microwaves. These measurements agree well with our model calculations based on Coulomb blockade theory with the inclusion of Tien and Gordon's theory [1] for time-dependent tunneling.

2. Time-scales and regimes of operation

Transport processes through quantum dots encompass a variety of time-scales. A list of these energy/frequency scales is given in Table 1. The single-particle level spacing ΔE is 0.02–0.2 meV for typical dots, and the charging energy e^2/C is usually 0.2–2 meV. The effects of thermal broadening of the electron energies ($\sim 4k_BT$) determine the observability of these two energy scales.

Other characteristic times for the dot are transport times. Γ is the typical time required to tunnel

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Table 1
A list of the important energy and frequency scales for transport through quantum dots

Quantity	Equivalent frequency	Typical parameters
Thermal broadening	$\sim 4k_B T/h$	10 GHz (at $T = 125$ mK)
Tunneling rate on/off the dot	$\Gamma \approx ([\Delta E \text{ or } eV]/h)\|t\|^2$	0–10 GHz
Level spacing (transit time)	$\Delta E/h$	4–40 GHz
Charging energy	$(e^2/C)/h$	40–400 GHz
Tunneling time	$1/\tau_{\text{tunnel}}$	200 GHz–1 THz

on or off the dot. This time is set by the transmission coefficent $|t|^2$ of the barriers, and by ΔE or the source–drain voltage V_{sd}, whichever is the larger. It can be arbitrarily small for opaque tunnel barriers. The final time-scale is the tunneling time, i.e. the actual time spent during tunneling through the barrier. This time is quite fast (~2 ps) for typical barriers (calculated, for example, within the Büttiker–Landauer framework [4]).

To access these time-scales, AC signals can be applied to the dot, and the effects on the DC transport can be measured. In the experiments reported to date [2,3,5] the frequencies of the applied signals have varied from the RF ($f \approx 1$ MHz) to the microwave ($f \approx 40$ GHz). In these experiments, the level spacing of the dots was not an important parameter (i.e. $\Delta E \ll 4k_B T$), and it will be neglected here.

Another transport division is shown in Table 2. If $f \ll \Gamma$ the electrons see an essentially static potential and we are in the *adiabatic* regime. If $f \gg \Gamma$ the electron experiences many cycles of the AC signal while it is on the dot (i.e. the *non-adiabatic* regime). The second issue is whether the photon energy hf is greater or less than the thermal smearing of $4k_B T$. If $hf < 4k_B T$, single photon processes are masked by thermal fluctuations, and a classical description is appropriate. If $hf > 4k_B T$, single-photon processes should be observable. We refer to this as the quantum or time-dependent regime. To describe this quantum regime one needs to solve the time-dependent Schrödinger equation for the tunneling electron.

Table 2
Overview of different AC transport regimes

<table>
<tr><th></th><th>Adiabatic ($f \ll \Gamma$)</th><th>Non-adiabatic ($f \gg \Gamma$)</th></tr>
<tr><td>Classical ($hf \ll k_B T$)</td><td>(1) Classical adiabatic wiggle</td><td></td></tr>
<tr><td></td><td colspan="2">(2) Turnstile</td></tr>
<tr><td>Quantum or time-dependent ($hf \gg k_B T$)</td><td></td><td>(3) Photon-assisted tunneling</td></tr>
</table>

3. Classical, time-independent regime

In the classical adiabatic regime the device behavior can be understood entirely in the context of the DC characteristics. Fig. 1 shows Coulomb blockade oscillations where, in addition to the DC voltages, an AC gate voltage of $f = 10$ MHz was applied to one of the gates [3]. The different curves correspond to different amplitudes of the AC signal. To understand these results we note that the AC voltage simply modulates the electrostatic potential of the dot sinusoidally. The result is a Coulomb peak that is, in effect, wiggled back and forth by an amount proportional to the ampli-

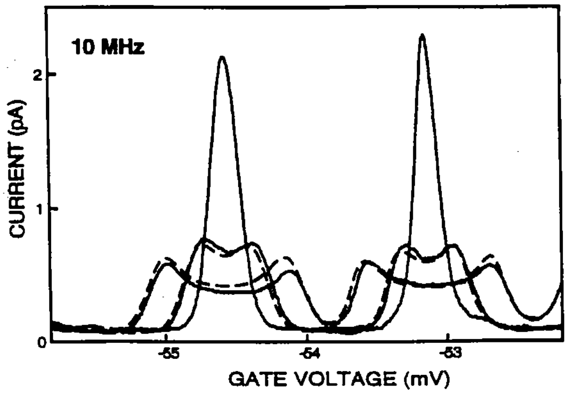

Fig. 1. Coulomb blockade oscillations of a dot measured with a low frequency (10 MHz) AC signal to one of the gates. The narrow peak is for no AC signal. The broadened peaks are for two different AC amplitudes. The dotted line is the expected "adiabatic" result, obtained by convolving the DC data with a sinusiodal AC gate voltage.

tude of the AC signal. The expected current, obtained by convolving the DC I–V_g characteristic with a sinusiodal AC signal is in good agreement with the data. Note that the amplitude of the current at any given V_g is proportional to the time that the oscillating gate voltage spends at that value of V_g. Since a sine wave spends most of its time near its extreme, the result is a broadened current peak that is maximal at its edges.

If the barrier height, and hence the tunneling rate Γ, is made to oscillate by the AC signal, the device can cross over from the adiabatic to the non-adiabatic regime within a given cycle of the AC potential. This is the basis for the quantum dot turnstile [5], a device that moves one electron through the dot per AC cycle and thus produces a current of $I=ef$. Note that turnstile and pump devices do produce frequency-dependent currents [5,6]. However, the photon energy hf at MHz frequencies is much too small to be of importance energetically. Therefore, these devices operate in the classical, time-independent regime.

4. Photon-assisted tunneling

At higher frequencies, the photon energy becomes important and we move into the quantum regime. In this regime the effect of the AC potential on electron tunneling can be described in terms of the absorption and emission of photons [1]. For example, an electron may be able to tunnel onto the dot by the absorption of a photon, as shown in Fig. 2. These photon-assisted tunneling (PAT) processes strongly affect the DC currents in a quantum dot. Fig. 3a shows the effect of microwave photons on the Coulomb oscillations. The current without microwaves, (dotted) is displayed along with the current in the presence of microwaves at various powers. Results for three different frequencies are shown. The most notable feature is the presence of a shoulder on the left-hand side of the Coulomb-blockade peak. Fig. 3b shows the derivative dI/dV_g, of the data in Fig. 3a. The shoulder in Fig. 3a results in a peak in dI/dV_g in Fig. 3b, as indicated by the arrows. In contrast to the classical data of Fig. 1, we see that the position of this peak is independent of the microwave power, but shifts with photon frequency. This shoulder/peak is due to PAT onto the dot, as illustrated schematically in Fig. 2. An electron absorbs a photon when tunneling onto the dot, producing extra current up to hf away from the Coulomb-blockade peak. The fact that the position of this shoulder is independent of the microwave amplitude but varies linearly

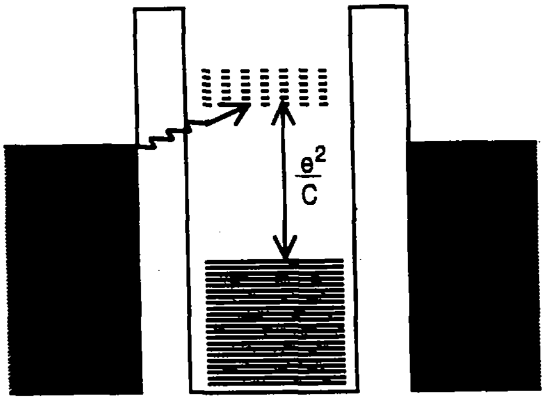

Fig. 2. Energy level diagram for a quantum dot illustrating photon-assisted tunneling (PAT). Solid lines are occupied levels, while dotted lines are unoccupied. Shown is the configuration just before a peak in G versus V_g. In the presence of microwaves an electron can overcome the Coulomb gap and tunnel onto the dot via the absorption of a photon. This leads to a shoulder in the Coulomb peak.

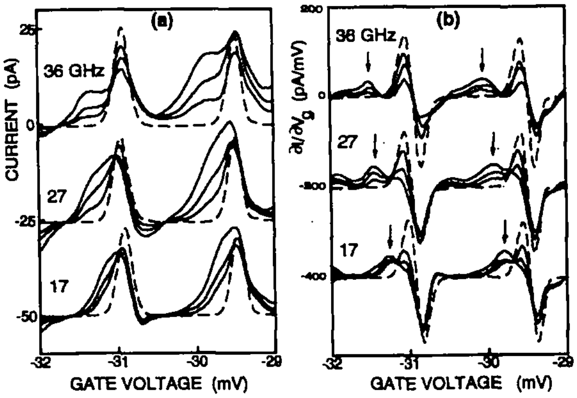

Fig. 3. Current versus gate voltage V_g for a quantum dot irradiated by microwaves at three different frequencies. Dashed curves without microwaves. Solid lines: increasing power. A photon-induced shoulder is observed whose position is independent of power but linearly dependent upon frequency. (b) Derivatives dI/dV_g of the data in (a). The arrows indicate the photon-induced features.

with frequency, is a direct proof of the single-photon origin.

5. Conclusions

We have reported experiments on mesoscopic structures in the time-dependent regime. The observed microwave-induced features in the current can be described quantitatively with a model based on the orthodox Coulomb blockade theory with the inclusion of the Tien–Gordon model (see Ref. [2] for details and more references).

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