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Microwave-assisted transport through a quantum dot

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Abstract. We present results on microwave-assisted transport through quantum dots. First, the important energy/frequency scales are discussed. Then, measurements of the current versus gate voltage characteristics in the presence of microwaves are presented. At finite source-drain bias, microwave-induced features are observed, and at zero source-drain bias, an oscillating photocurrent is observed. A model of photon-assisted transport is discussed that can account for the experimental observations.

Semiconductor quantum dots have proven to be an excellent system for studying the physics of quantum transport [1]. A schematic diagram of a dot formed in a GaAs heterostructure is shown in figure 1. A small number of electrons (∼100) are confined to a submicron region of two-dimensional electron gas (2DEG) by voltages applied to the surface gates. This dot is coupled to source and drain leads by tunnel barriers. Both the number of electrons on the dot and the transmission properties of the barriers can be adjusted using the gates. These structures exhibit a variety of quantum transport effects at low temperatures. The most important stems from the incremental Coulomb charging of the dot by single electrons as the gate voltage is increased. This charging manifests itself as a series of periodic peaks in the conductance versus gate voltage of the dot (figure 2). Further, the effects of the quantized energy levels of the dot can also be observed [1].

Another desirable characteristic of quantum dots is that the characteristic time scales for transport are in a range that is experimentally accessible. A listing of these energy/frequency scales is given in table 1. The first is the single-particle level spacing ΔE, which is ∼0.02–0.2 meV for typical dots. The second is the charging energy e^2/C, which is typically ∼0.2–2 meV. The effects of thermal broadening of the electron energies (∼4 kT) determine the observability of these two energy scales. At typical experimental electron temperatures of ∼100 mK (4 kT ∼ 0.04 mV), charging effects are clearly resolved, and the effects of the quantized level spectrum are observable in smaller dots.

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Other characteristic times of the dot are transport times. The first is the typical time, τ, that an additional electron spends on the dot when the current is flowing. This time is set by the transmission coefficient T of the barriers and by the larger of ΔE or V_{sd}, the source-drain voltage. It can be very long (0.1 μs) for opaque tunnel barriers. The final time scale is the tunneling time τ_{tunnel}, i.e. the actual time spent tunneling through the barrier. The meaning, if any, of such a time is a subject of much controversy [5]. This time is quite fast (∼2 ps) for typical barriers (calculated, e.g. within the Buttiker–Landauer framework [5]), but should still be experimentally accessible.

At Berkeley, we are probing these time scales using a variety of techniques. At high frequencies, we are using short laser pulses and photoconductive switches to perform time-domain terahertz spectroscopy [4]. Here, however, we will concentrate on experiments at lower frequencies, 10–40 GHz, that were performed using coaxial microwave technology [2, 3]. The measurements were performed by coupling 19 GHz microwaves to the center gate of a quantum dot. The charging energy of the dot was e^2/C ∼ 0.45 meV (∼100 GHz) and the electron temperature ∼125 mK (4kT h^{-1} ∼ 10 GHz). The photon energy was thus greater than the thermal broadening, but less than the Coulomb charging energy. The single-particle level spacing was not well resolved, making the charging energy the only relevant scale.

In the experiments, the DC transport characteristics were measured both with and without microwaves coupled to the gate. Figure 2(a) shows the effect of microwaves on the Coulomb oscillations. The current without microwaves (dotted) is displayed along with the current in the presence of microwaves (dashed). Also shown is the photocurrent

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

Quantity	Equivalent frequency	Typical parameters
Thermal broadening	$\sim$4 kT h^{-1}	10 GHz (at T = 124 mK)
Level spacing (transit time)	$\Delta E\ h^{-1}$	2 GHz–40 GHz
Charging energy	$(e^2/C)\ h^{-1}$	40 GHz–400 GHz
Tunneling rate on/off the dot	$1/\tau \sim ([\Delta E$ or $eV]\ h^{-1})$ T	10 MHz–10 GHz
Tunneling time [5]	$1/\tau_{\rm tunnel} \sim v_{\rm barr}/L_{\rm barr}$	200 GHz–1 THz

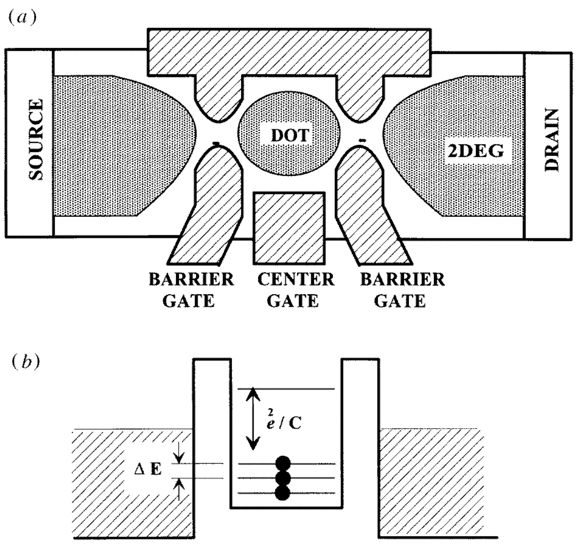

Figure 1. (*a*) Schematic diagram of the device, a gated quantum dot in a GaAs/AlGaAs heterostructure. The dot diameter is approximately 0.5 μm. (*b*) Schematic energy-level diagram of the dot.

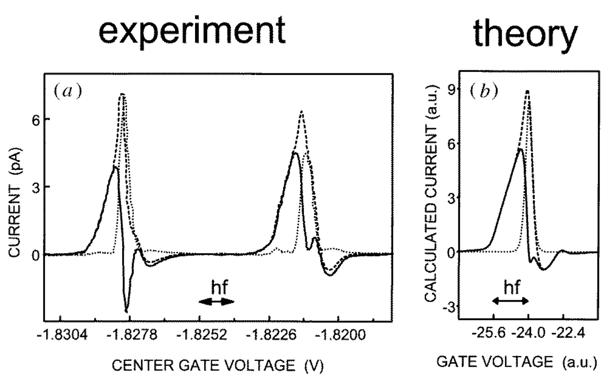

Figure 2. (*a*) Measured I–$V_{\rm g}$ with 19 GHz microwaves for $V_{\rm sd} \sim 10\ \mu$V. (*b*) Calculated I–$V_{\rm g}$ for $V_{\rm S}^{\rm AC} = 0.55hf$ and $V_{\rm d}^{\rm AC} = 0.4hf$, $k_{\rm B}T/hf = 0.1$, $eV_{\rm sd}/hf = 0.1$.

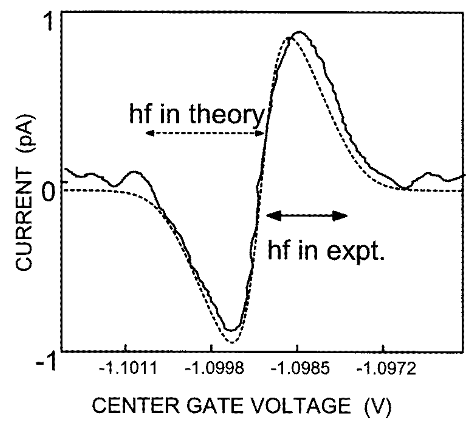

Figure 3. Measured (solid) and calculated (dashed) photocurrent at $V_{\rm sd} = 0$. Numerical parameters are $k_{\rm B}T = 0.2hf$, $V_{\rm S}^{\rm AC} = 0$ and $V_{\rm d}^{\rm AC} = 0.2hf$.

(solid), which is defined as the difference between the current with and without microwaves. Both Coulomb peaks show the same qualitative behavior. The microwave radiation increases the current on the left side of the peak and induces a negative current on the right side. Figure 3 shows a measurement of the photocurrent (solid) measured at *zero* source-drain voltage. The photocurrent oscillates with the same period as the Coulomb oscillations and is centered on the conductance peak (not shown). The microwaves thus pump electrons through the dot in opposite directions on each side of the conductance peak.

To interpret these experiments, we have developed a model of photon-assisted transport through quantum dots [2]. This model assumes that $\Delta E \ll$ kT so that the level spectrum of the dot can be treated as a continuum. It further assumes that $1/\tau \ll$ f $\ll 1/\tau_{\rm tunnel}$, i.e. many AC oscillations occur while the electron is on the dot, but essentially none occur while the electron is actually tunneling. Within these approximations, photon-assisted tunneling can be taken into account by using Tien–Gordon theory [6] in conjunction with the standard Coulomb blockade model [7]. Within this approach, the microwaves are treated as oscillating potentials $V_{\rm s,d}\cos(2\pi f t)$ across the source and drain tunnel junctions. Different AC amplitudes across the source and the drain barriers can be used to allow for an asymmetry in the coupling of the microwaves to the dot.

The results of this model are shown in figure 2(*b*) and figure 3 for reasonable experimental parameters and asymmetric AC coupling. The calculations contain all the major features observed in the experimental curves. For example, in figure 3 the oscillating photoresponse in the experiment is accurately reproduced in the model. This oscillating photocurrent is a direct consequence of the asymmetric coupling of the microwaves across the source and drain barriers. Just below a peak, transport can only occur when electrons tunnel *onto* the dot by photon absorption. They do this preferentially through the barrier with the large AC modulation, leading to a net electron current in a particular direction. Just after a peak, transport can only occur by photon-assisted tunneling *off* the dot. Electrons preferentially tunnel off the dot through the same barrier, resulting in a net current of the opposite sign.

The above experimental results are consistent with the predictions of photon-assisted transport through quantum dots. More recently, our group has observed, in a different device, well resolved features in I versus Vg that scale with the photon frequency and are clearly due to single photon absorption [3]. These results show that time-dependent studies of transport in quantum dots are possible using microwave techniques. Future work will concentrate on the interaction of the photons with other energy/time scales, such as the level spacing, the tunneling time, or the collective excitation frequencies of the dot.

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