A study of transport suppression in an undoped AlGaAs/GaAs quantum dot single-electron transistor

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Abstract

We report a study of transport blockade features in a quantum dot single-electron transistor, based on an undoped AlGaAs/GaAs heterostructure. We observe suppression of transport through the ground state of the dot, as well as negative differential conductance at finite source–drain bias. The temperature and magnetic field dependences of these features indicate the couplings between the leads and the quantum dot states are suppressed. We attribute this to two possible mechanisms: spin effects which determine whether a particular charge transition is allowed based on the change in total spin, and the interference effects which arise from coherent tunnelling of electrons in the quantum dot.

(Some figures may appear in colour only in the online journal)
transport is re-enabled only when the excited state becomes accessible via temperature activation or by increasing the source–drain bias. Interestingly we also observe regions of negative differential conductance (NDC) [16–18], highlighted by the white ellipses in figure 3(b), near peaks P1 and P6. The observed conductance suppression at $V_{SD} = 0$ V, as well as the NDC, can be understood based on the differences in the coupling between the leads to the ground state, and to the excited state of the dot, as we now show.

In the sequential tunnelling model of Qdot-SET transport, the current causes the ground state (GS) of the dot to oscillate between $N$ and $N + 1$ electrons. This current is proportional to the coupling $\Gamma_{GS}$ between the leads and the dot’s ground state [19]. Transport through the ground state is suppressed when $\Gamma_{GS}$ becomes sufficiently low (see figure 4(a)), and hence the corresponding conductance peak will be significantly reduced. However, transport is re-enabled when a nearby excited state (ES), with a much larger coupling rate $\Gamma_{ES}$ to the leads compared to $\Gamma_{GS}$, becomes energetically accessible. Consistent with our observations in figures 2 and 3, this can be achieved by thermal activation, or by increasing the source–drain bias (see figures 4(b) and (c)). In some cases, this suppression can also be lifted by applying a magnetic field $B$ [20]. Conversely if the leads are coupled more strongly to the ground state than the excited state $\Gamma_{GS} \gg \Gamma_{ES}$ (see figure 4(d)), then $g$ will be reduced when the excited state becomes energetically accessible. This reduction in $g$ causes NDC as seen in figure 3.

One explanation for $\Gamma_{GS}$ being smaller than $\Gamma_{ES}$ could be due to fluctuations in the density of state (DOS) in the leads arising from disorder, as has been observed in the leads of self-assembled nanowire quantum dots and silicon MOS devices [21–24]. However in our case it is highly unlikely that the observed ground state transport suppression phenomena could be due to fluctuations in density of states in the leads, since the electron transport is ballistic with a mean free path of $\approx 2.1 \mu m$ and the leads are relatively wide ($\approx 200$ nm) so that multiple 1D subbands are occupied.

3 Note that unlike [20], we do not observe any temperature thresholds. This is because our dot has a smaller single particle energy level spacing, as well as a larger electron temperature.
Figure 3. (a) Bias spectroscopy of the Coulomb blockade peaks in
Figure 2(a), showing differential conductance \( g' \) (colour axis) as a
function of plunger gate voltage \( V_{PG} \) (x-axis) and dc source–drain
bias \( V_{SD} \) (y-axis). Zero bias conductance suppressions for P2–P5
appear as gaps in the Coulomb diamonds. (b) The same stability
diagram as in (a) is shown with suppressed ground states
highlighted by yellow dashed lines. Regions of negative differential
conductance (NDC) for \( g' < -0.1 \mu \text{S} \) are shown in white, and
enclosed by white ellipses.

Instead of disorder, there are two more likely transport
suppression mechanisms which explain our data qualitatively.
The first one relates to the total spin \( S \) of the dot. Weinmann et al performed an analysis of spin blockade effects
in the linear and non-linear transport through a quantum
dot and showed that ground state transport suppression
and negative differential conductance at finite bias can be
explained based on two sets of spin selection rules [25]. These
rules were labelled as spin blockade type-I and type-II, which
we briefly summarize here.

Type-II spin blockade suppresses the linear conductance,
and occurs in transitions where the change in the total spin of
the \( N \) and \( N - 1 \) electron ground states of the dot differs by
more than \( 1/2 \),

\[ \text{GS}(N, S) \leftrightarrow \text{GS}(N - 1, S'), \quad |S - S'| > 1/2. \quad (1) \]

In this case, the transition between the \( N \) and the
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In this case, the transition between the \( N \) and the
\( N - 1 \) electron ground state is spin blockaded, and the
 corresponding low bias conductance peak would be absent
 at \( T = 0 \) K. For example, if \( S = 3/2 \) for \( N = 5 \) and
\( S' = 0 \) for \( N = 4 \), ground state transport is suppressed.
However, transport can be re-enabled by accessing an excited
state via means of temperature activation, or increasing the
source–drain bias. Type-II spin blockade results in suppressed
linear conductance, as seen in figure 1, and the transport
recovery mechanisms are qualitatively consistent with the data
presented in figures 2 and 3 respectively, where increasing \( T \)
or \( V_{SD} \) increases \( g \).

Type-I spin blockade relates to the population of states
with maximal \( S = N/2 \); the transitions,

\[ (N, S = N/2) \rightarrow (N - 1, S' = (N - 1)/2), \quad (2) \]

which decrease the electron number from \( N \) to \( N - 1 \) and start
with a spin-polarized state \( (S = S_{\text{max}} = N/2) \), will always
reduce \( S \) to \( S' = (N - 1)/2 \). In contrast, non-polarized states
with \( S < N/2 \) can either increase or decrease the total spin
after transition. Therefore the \( S = N/2 \) state is stable for a
relatively long time and as a result, when a spin-polarized
excited state becomes accessible, the coupling between the
leads and the dot’s excited state is smaller than the coupling
between the leads and the dot’s ground state \( \Gamma_{GS} \ll \Gamma_{ES} \).
Signatures of type-I spin blockade are observed as regions of
negative differential conductance, as seen in figure 3.

The other possible suppression mechanism relates to the
coherent resonant tunnelling of electrons inside the dot. To
the first order approximation, a Qdot-SET is analogous to a
Fabry–Perot resonator where the amplitudes of the Coulomb
blockade oscillations are modulated based on the interference
conditions [26]. Regions of suppressed Coulomb peaks can
therefore be understood as a result of destructive interference.
These effects can be lifted via thermal broadening, where

the degree of electron coherence is reduced. This behaviour is qualitatively consistent with our data in figure 2. Similar argument can also be applied to our source–drain biasing data in figure 3, where the bias energy changes the interference condition by introducing a phase shift, or by reducing the electron coherence, thereby enabling transport via the excited states. Regions of negative differential conductance can also be understood as a result of the constructive interference condition being lifted by the applied bias.

To test whether the suppressed ground state conductance, and the NDC that we observe, are spin related, we examine the magnetic field dependence of the Coulomb blockade peaks. In figure 5(a), a plot of $g_{peak}$ versus $B$ is shown. The conductance of peaks P2–P5, which was strongly suppressed, rapidly increases with $B$, and then gradually decreases for $B > 0.5$ T. At higher $B$, the overall conductance through the quantum dot decreases because of a gradual compression of the dot's states by the magnetic field [27]. In contrast the amplitudes of peaks P1 and P6 generally decrease as $B$ is raised. This $B$ field dependence mimics the temperature dependence: there are two kinds of behaviour, with P1 and P6 showing different magnetic field dependence from P2 to P5, just as they showed different temperature dependence in figure 2.

In figures 5(b) and (c) we compare the stability diagrams that correspond to P4–P6 at $B = 0.5$ T. (b) A stability diagram for P4–P6 at $B = 0$ T similar to the one in figure 3(a) is shown. The ground state suppression features at P4 and P5 appear as gaps in the diagram, whereas regions of NDC for $g' < -0.1$ µS are shown in white. These spin blockade features are lifted at $B = 1$ T and the corresponding stability diagram is shown in (c); the suppression gaps appear to be closed, and regions of NDC observed in (b) have disappeared in (c).

in figure 5(c). This can be similarly understood as the excited state becomes non-polarized due to level crossing at $B = 1$ T. However, as both the orbital and the spin states are affected by $B$ applied perpendicular to the 2D plane, a study of parallel field dependence of level shifting is required to unambiguously identify spin blockade as the suppression mechanism responsible [18]. Nevertheless, our analysis is completely consistent with [20, 28], which report the observation of spin blockade effects in a modulation doped AlGaAs/GaAs Qdot-SET quantum dot device.

In summary, we have reported transport measurements of an undoped AlGaAs/GaAs quantum dot single-electron transistor where ground state transport suppression, as well as negative differential conductance, were observed. These transport blockade features can be explained based on the relative couplings between the leads and discrete levels in the dot and we attribute the suppression mechanism to two sets of spin selection rules proposed by Weinmann, and the coherent resonant tunnelling of electrons. It might be argued that since our dot is large, and contains at least 60 electrons, spin dependent transport should not be observed. However our observations are consistent with previous experiments on large quantum dots containing ~50 and ~10 electrons, where spin-related effects were also observed [20, 28].

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