Current suppression in a double-island single-electron transistor for detection of degenerate charge configurations of a floating double-dot

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We have investigated a double-island single-electron transistor (DISET) coupled to a floating metal double-dot (DD). Low-temperature transport measurements were used to map out the charge configurations of both the DISET and the DD. A suppression of the current through the DISET was observed whenever the charge configurations of the DISET and the DD were energetically co-degenerate. This effect was used to distinguish between degenerate and non-degenerate charge configurations of the double-dot. We also show that this detection scheme reduces the susceptibility of the DISET to interference from random charge noise.

Single-electron transistors (SETs), the operation of which is governed by Coulomb blockade effects, are highly sensitive electrometers. Their capability to amplify small charge signals on fast time scales has made them interesting detectors for a variety of applications. In particular, some alternative concepts to conventional computers - namely quantum dot cellular automata (QCA) and solid-state quantum computers (e.g. Refs. 4,5,6) - rely on detection of small charge signals to read out a computational result. The charge signals arise from different, spatial charge distributions on two sites (such as metal islands, quantum dots or donor atoms) that are separated by a tunnel barrier.

In this letter, we present work on a double-island SET (DISET, or single-electron pump) capacitively coupled to a floating double-dot (DD). We show that the DISET can sense electrostatically degenerate charge configurations of the DD. This capability arises from current suppression due to dynamic charge correlations between the DISET and the DD, which was first described in work related to QCA. We suggest using this ability of the DISET for detecting the propensity for charge motion between other spatially localised sites, such as quantum dots and donor atoms. Uses for such a detector could be in monitoring spin-charge conversion in solid-state quantum computers, e.g. the models proposed by Kane and Vrijen et al.

The high charge sensitivity of SETs leads to high susceptibility to random charge noise in the environment, which can result in spurious signals. The operating conditions for the DISET are different from those for conventional SET electrometers: whereas the SET is generally biased to a point of maximum transconductance, we operate the DISET at zero transconductance, which greatly reduces the effects of background charge noise.

The devices were fabricated on a silicon substrate using standard shadow-mask evaporation of aluminium with in-situ oxidation to form Al/Al2O3/Al tunnel junctions. Fig. 1a shows a SEM image of a typical device and Fig. 1b a simplified schematic. The devices consist of a DISET, a capacitively coupled DD and four control gates. The physical gap between the DISET and the DD was engineered to be < 25 nm in order to maximise capacitive coupling. Electrical measurements were carried out in a dilution refrigerator at base temperature \( T \approx 20 \text{ mK} \), and a magnetic field of \( B = 1 \text{ T} \) was applied to suppress superconductivity. Standard, ac lock-in measurement techniques were used, with a source-drain bias of \( V_{DS} = 300 \mu \text{V} \) (charging energy for our DISETs \( E_C \approx 0.8 \text{ meV} \)).

In order to map the charge configurations of the DISET, we recorded the source-drain current \( I_{DS} \) as a function of gate voltages \( V_{G1} \) and \( V_{G2} \) (Fig. 2a). Due to Coulomb blockade effects, the peaks in \( I_{DS} \) define a honeycomb pattern (grey lines), the shape of which depends on gate capacitances as well as the inter-island coupling. Each hexagon corresponds to an energetically stable charge configuration \((n, m)\) of the DISET, where \( n \) and \( m \) are the number of excess electrons on islands I1 and I2, respectively. For temperatures \( T \ll E_C/k_B \) and source-drain biases \( V_{DS} \ll E_C/e \), a current from source to drain can only be observed where three charge configurations are energy-degenerate (i.e. the system has equal electrostatic energy for all three configurations). Such points in the charge configuration map are termed triple-points. Current peaks are broadened at increased \( T \) and \( V_{DS} \). Even at the relatively high \( V_{DS} \) used in our experi-

![FIG. 1: (a) SEM image of the DISET (source S, drain D and islands I1 & I2 - connected by tunnel junctions), the capacitively coupled, floating DD (dots D1 & D2 connected by a tunnel junction) and four control gates (G1 & G2 and A1 & A2). (b) Simplified, schematic diagram of the device showing voltage sources and key capacitances.](image-url)
FIG. 2: (a) Contour plot of the source-drain current $I_{DS}$, exhibiting the characteristic honeycomb pattern. Each hexagon corresponds to a specific charge configuration $(n,m)$ of the DISET. Straight lines indicate energy degeneracy of charge configurations, and current peaks occur where three charge configurations are degenerate. (b) Grey-scale plot of the source-drain current $I_{DS}$ as a function of $V_G$ and $V_A$ (see arrow in (a)) maps out the charge configuration space of the DISET/DD system. The top and bottom sets of numbers denote the charge configurations of the DISET and the DD, respectively. White corresponds to zero and black to the maximum peak current (181 pA).

ments, Coulomb blockade effects are well resolved. Since the A-gates also capacitively couple to the DISET, a similar plot is obtained when sweeping $V_{A1}$ and $V_{A2}$ (not shown), allowing control of the charge configurations of the DD as well as the DISET.

We now turn to study the passage of electrons from source to drain via the DISET islands when the charge configurations of both the DISET and the DD are electrostatically degenerate. In general, the mechanism behind electron transport on two coupled double-dots - irrespective of whether they are connected to source and drain leads or not - applies to arbitrary charge configurations of the system. However, the concept becomes clearer if one considers a special case, where two floating double-dots are coupled in a square arrangement with one excess electron per DD. When the charge configurations of both double-dots are co-degenerate (i.e. an electron has equal probability of being on either dot of a DD), electrostatic repulsion energetically favours charge configurations where the two electrons are diagonally opposite each other. For symmetry reasons, the two possible configurations are energetically degenerate, and tunnelling between the two configurations can occur. This tunnelling primarily takes one of two forms: energetically favourable, simultaneous tunnelling of both electrons (co-tunnelling), and correlated tunnelling. The latter involves sequential tunnelling of one electron via an excited state, followed by tunnelling of the other electron to restore a diagonal charge configuration. In both cases, the tunnel rate is reduced compared to the single-electron tunnelling rate ($\Gamma = k_B T/\epsilon^2 R_t$, where $R_t$ is the tunnel junction resistance). This reduced tunnelling rate can be observed by replacing one of the double-dots with a DISET biased to a triple-point. Current flow through the DISET requires the tunnelling of single electrons between the two DISET islands. If the charge configurations of the DISET and the DD are co-degenerate, there is a reduction of the measured source-drain current (compared to when the charge configurations of the DD are non-degenerate).

Experimental investigation of this current suppression is best achieved by keeping the total charge of the combined system constant, while measuring the source-drain current for different charge configurations. The arrow in Fig. 2 marks a trajectory for G-gate biases $V_{G2} = −\gamma V_{G1}$ across a triple-point, which keeps the total charge of the DISET constant. This trajectory defines an effective, combined G-gate bias $V_G = V_{G1} \sqrt{1+\gamma^2}$. A similar procedure was used to determine an effective A-gate bias $V_A = V_{A1} \sqrt{1+\alpha^2}$, along which the total charge of the DISET remains constant. Fig. 2 shows a greyscale plot of $I_{DS}$ as a function of $V_A$ and $V_G$. In this plot the total charge of the combined DISET/DD system is kept constant. The upper and lower sets of numbers denote the charge configurations of the DISET and the DD, respectively, and define hexagonal charge configuration domains. As we are only interested in relative changes in electron occupancy, we arbitrarily define one of the configurations as $(0,1)(0,0)$. Due to the island-dot coupling, the trajectories of maximum current (black) exhibit kinks each time the charge configurations of the DISET and the DD are co-degenerate.

To study the effect degenerate charge configurations of the DD have on the source-drain current of the DISET in more detail, traces were taken with a constant $V_G$ and varying $V_A$. $V_G$ was chosen such that varying $V_A$ would include a point of co-degeneracy, and two points where the DISET but not the DD is degenerate (arrow in Fig. 2(b)). Fig. 2(b) shows the average and standard deviation obtained from 62 individual traces. The shape of the traces depends on temperature, source-drain bias and the trajectory taken through gate voltage space. In this letter, however, we focus on the absolute values of the maximum and minimum observed source-drain current. A maximum current of $I_{DS} = 181$ pA is observable at the left and right edge of the graph, where the DD adopts well-defined charge configurations, and predominantly sequential single-electron tunnelling through the DISET occurs. In the centre of the graph, the charge configurations of the DISET and the DD are co-degenerate. At this point, we observe a current suppression of $\Delta I_{DS} = 7.5$ pA (well above the average noise level of $\delta I_{DS} \approx 0.90$ pA), which we attribute to the reduced tunnelling rates. This behaviour suggests that a DISET, biased to a triple-point, may be used as a detector for degenerate charge configurations of a floating double-dot.

We now briefly investigate the charge noise sensitivity of this detector. SETs are known to be susceptible to random charge noise, and it is important to discriminate such random telegraph signals (RTSs) from signals originating from the DD. We investigated the effect of weakly coupled charge traps, which lead to small fluctuations of the electrostatic environment, and more
FIG. 3: (a) A cross-section along the white arrow in Fig. 2(b) clearly shows the current suppression dip. Average and standard deviation were obtained from 62 individual sweeps. (b) Repeated observation of the current suppression dip shown in (a) as a function of time (1 min per sweep, followed by a fast reset). A random charging event at \( t \approx 6 \) min moved the DISET off its operating point causing a reduction in source-drain current.

strongly coupled traps, which may induce spurious signals. To have maximum charge sensitivity, SETs are conventionally biased to a point of maximum transconductance \( \partial I_{DS}/\partial V_G \), which is accompanied by increased charge noise susceptibility. The largest signal-to-noise ratios for our device, however, were observed when biasing the DISET to triple-points, i.e. \( \partial I_{DS}/\partial V_G = 0 \), where the effect of charge noise due to small fluctuations is minimised. To investigate the influence of more strongly coupled charge traps, we repeatedly monitored the same current suppression feature (that shown in Fig. 3(b)) with one minute per trace followed by a fast reset (Fig. 3(b)). At time \( t \approx 6 \) min, a large random charging event was observed, leaving a characteristic signature: the DISET was suddenly moved off the triple-point and the current dropped abruptly to a lower level, where it remained for many minutes. Empirically, RTSs that induced signals well above the average noise level did not seem to switch back for times much longer than typical measurement times (\( \leq 1 \) min). This qualitative behaviour can be used to identify and therefore reject such spurious signals.

So far, we have performed our experiments at low frequencies below 500Hz. Fast operation, however, opens up the possibility of investigating processes that otherwise would be inaccessible due to fast decay or relaxation processes. In the DISET, fast operation at radio-frequencies should be possible by inclusion in a \( LCR \) tank circuit, as has been achieved for conventional SETs\(^2\) and twin-SET architectures\(^1\).

In conclusion, we have observed current suppression due to correlated electron transport in a DISET and a coupled, floating DD, thereby detecting degenerate and non-degenerate charge configurations of the DD. The maximum signal-to-noise ratio was observed when biasing the DISET to a triple-point of its charge configuration map. Furthermore, these biasing conditions also provide a means for rejection of spurious charge noise.

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