Current gain in a quantum dot with three leads

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Conventional field-effect transistors act as almost perfect electronic switches as they are based on the concept of electrostatically tuning an energy barrier for the charge carriers from source to drain by changing the gate voltage V_G. This gives the exponential current vs. gate-voltage characteristics $I_{DS} \propto \exp(\alpha e \Delta V_G / k_B T)$ $(\alpha \approx \pm 1)$ observed in the subthreshold regime of the transistor. In conventional bipolar npn or pnp transistors, the charge carrier flow from emitter to collector is also limited by an energy barrier, present in the base region of the transistor. However, in contrast to the field-effect transistor, this energy barrier is *dynamically* controlled by the base current.

In the late 1980's, the concept of a single-electron transistor was introduced. As sketched in Fig. 74(a), such a transistor consists of a small compartment ('island') where conduction electrons are confined, weakly coupled by tunneling barriers to leads denoted as source and drain. Due to the Coulomb interaction between electrons in a small confinement and their image charges induced in the surrounding electrodes, a single-electron charging energy is required for adding an additional electron onto the island, but also for taking off an electron. As indicated in Fig. 74(b), energy barriers for recharging the island exist, forming an energy gap for electron transport between source and drain. Due to electrostatics, this energy gap scales with the inverse of linear spatial dimensions of the device. By using a gate electrode close-by, the electrostatic potential and therefore the position of the energy gap relative to the Fermi levels of the leads is tunable.

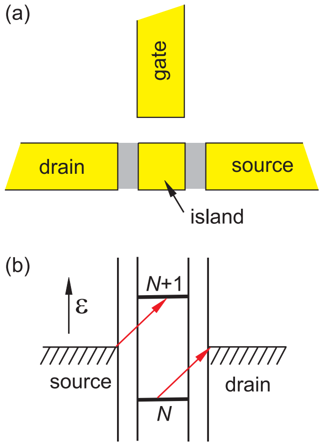

Figure 74: (a) Arrangement of a single-electron transistor. (b) Respective energy scheme for recharging the island by single electrons. For a quantum dot system, the level labeled by N+1 corresponds to the energy difference between the ground state energies of N+1 and N electrons on the quantum dot.

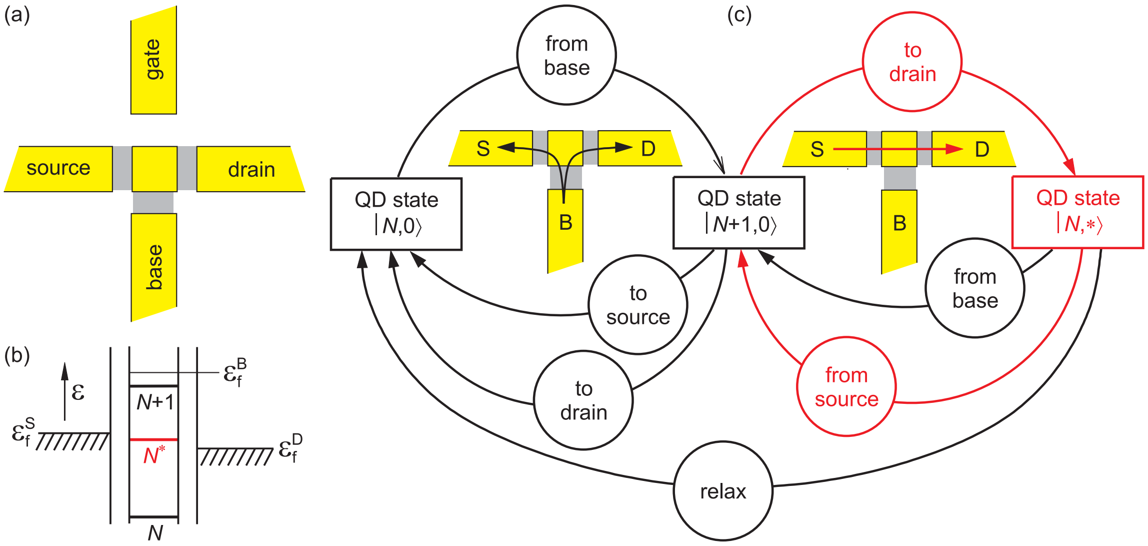

Figure 75: (a) Arrangement of a quantum dot with three leads – source, drain and base. For the bias condition depicted in the energy scheme (b), the single-electron tunneling dynamics between three quantum dot states – the N-electron ground state $|N,0\rangle$, the (N+1)-electron ground state $|N{+}1,0\rangle$, the N-electron excited state $|N,*\rangle$ – is sketched in (c). The half-circles with arrows indicate the direction for the QD state change by single-electron tunneling from or to the respective lead. The left circles describe single-electron tunneling from the base to source/drain, the red circle at the right side single-electron tunneling from source to drain, enabled by a single-electron charging process into the quantum dot from the base lead.

Shifting the threshold level for charging the island with N+1 electrons between the Fermi levels of source and drain, the number of electrons on the island can fluctuate between N and N+1, i.e. single-electron tunneling takes place. Shifting this level below both Fermi levels, the electron transport is blocked, the electron number on the island is fixed to N+1 (regime of Coulomb blockade). Shifting the electrostatic potential further, the behavior repeats, however for increased electron number on the island. Therefore, as a function of the applied gate voltage, a periodic modulation of the conductance is observable – denoted as Coulomb blockade oscillations. Such a single-electron transistor is an electrostatically controlled device, where for a respective device design even voltage gain is achievable.

If the Fermi wavelength of the conduction electrons is comparable to the spatial dimensions of the island, a discrete single-particle spectrum is expected for the electrons confined on the island. Such an island is denoted as ‘artificial atom’ or quantum dot. However, due to the mesoscopic size, the electron-electron interaction is usually the dominant energy scale so that single-electron tunneling processes have to be described in terms of transitions between many-electron states of N and N+1 electrons confined in the quantum dot. In this language, the threshold levels, depicted in Fig. 74(b), indicate the energy difference between the ground state energies of N and N+1 electrons, and their energetical distances usually vary with increasing N. Transitions to excited states of either the N or N+1 electron system appear as additional energy levels in such energy schemes, however are only usable for single-electron transport if at least this level and the respective threshold level lie between the Fermi levels of source and drain. Transitions to excited states can therefore only be accessed at larger source-drain voltage.

By adding a third lead (base) to the quantum dot (Fig. 75(a)), the situation becomes different: Lifting the Fermi level of the base lead above the threshold level for N+1 electrons (Fig. 75(b)), the quantum dot is charged from the base and in the next step discharged by one electron towards the source or drain lead. The quantum dot undergoes a transition from the N-electron ground state $|N,0\rangle$ to the (N+1) electron ground state $|N{+}1,0\rangle$ and vice versa (Fig. 75(c)). Under stationary bias condition, this charging/discharging cycle repeats and leads to a stationary current carried by single-electron tunneling from the base lead to source/drain – a trivial process. However, with discharging the quantum dot to drain (the lead with lowest Fermi level), the electron system in the quantum dot might end up in an excited state $|N,*\rangle$ of N electrons, i.e. a hole-like (single-particle) or collective excitation. Using this access energy, it requires less energy for adding an electron to the island.

If the energy level for the transition between $|N,*\rangle$ and $|N{+}1,0\rangle$ lies in between the Fermi levels of source and drain, an electron from source is able to enter before a relaxation from the excited state $|N,*\rangle$ into the ground state $|N,0\rangle$ occurs. Being now in the state $|N{+}1,0\rangle$, an electron can leave the quantum dot to source, leaving the dot in the excited state $|N,*\rangle$. If the transition between $|N{+}1,0\rangle$ and $|N,*\rangle$ is used now several times for single-electron tunneling events (red circle in Fig. 75(c)) before the ground state $|N,0\rangle$ of N electrons is reached, a single charging event from the base lead has induced several single-electron tunneling events between source and drain. In such a case, the source-drain current exceeds the base current which has enabled the source-drain current.

Modeling the dynamics of this single-electron tunneling device by rate equations shows that – besides a suppression of relaxation from the excited state – the tunneling rates between quantum dot and leads have to fulfill certain requirements which can be summarized basically in the following way: Firstly, discharging the quantum dot into the excited state $|N,*\rangle$ via drain (red path from $|N{+}1,0\rangle$ in Fig. 75(c)) has to have a higher rate than discharging the dot into the ground state $|N,0\rangle$ via source or drain (black pathes from $|N{+}1,0\rangle$ in Fig. 75(c)). Secondly, charging the dot from $|N,*\rangle$ via the base lead has to have a lower probability than charging the dot via the source lead. Such conditions can only be expected for a quantum dot with few electrons where the different tunnel couplings of individual quantum states with the leads are resolvable.

To test our new concept of operating a single-electron transistor dynamically, we have fabricated quantum dots with three leads. The samples are based on a GaAs/AlGaAs heterostructure containing a two-dimensional electron system 50 nm below the surface. The heterostructure was grown in the MBE Service Group of the Institute. A mesa structure was etched and metal alloyed in certain regions of the mesa to contact the two-dimensional electron system. By using electron-beam lithography and a metal lift-off process, structured metal electrodes were deposit on the heterostructure surface. A scanning electron microscope (SEM) image of this split-gate structure is shown in Fig. 76(a).

At temperatures below 0.1 K, negative voltages are applied to the gate electrodes dividing the two-dimensional electron system into the quantum dot, connected by tunneling barriers to three separate 2DES regions acting as leads – denoted in the figure as source, drain and base. Since in such quantum dot systems, the confining potential and the exact number of electrons is usually unknown, we have chosen a pragmatic approach: By tuning systematically the Fermi levels of source, drain and the base lead with respect to each other, tuning the electrostatic potential of the quantum dot by a near-by gate electrode, and measuring under all these bias conditions the dc currents in all three leads, we could well characterize our quantum dot system and could indeed find current gain for certain electron numbers. An example is shown in Fig. 76(b). At zero base voltage, the quantum dot is energetically in the Coulomb blockade regime and the observed current from source to drain can only be due to correlated electron tunneling, not single-electron tunneling.

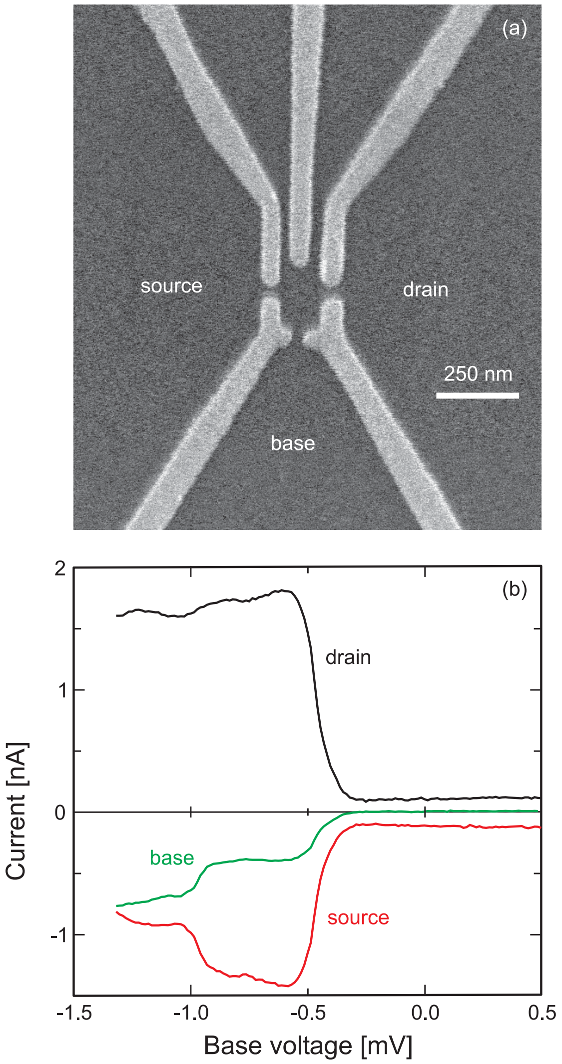

Figure 76: (a) Split-gate structure used to define a quantum dot with three leads in a two-dimensional electron system. (b) Drain, source and base current as a function of the base voltage for a small source-drain voltage (the shift of the electrostatic potential of the quantum dot by the base voltage is compensated by a gate voltage change). Positive current means a net electron flow out of the quantum dot into the respective lead.

Lowering the base voltage to about –0.4 mV, the base current increases in an almost step-like manner, indicating that single-electron tunneling from the base via the quantum dot to source and drain became possible. At the same time, the source and drain currents are increased. However, the signs of the currents indicate that a net electron flow occurs from the source into the quantum dot (and not vice versa) and from the quantum dot to the drain lead. A source-drain current is induced by a base current, – most important, the source current exceeds about four times the base current. For even more negative base voltage, further excited states become involved, changing the single-electron tunneling dynamics.

In summary, we could demonstrate a type of operation for a single-electron transistor, where in the Coulomb blockade regime of the two-lead dot a source-drain current is induced by single-electron recharging events from a third, the base lead. The induced source-drain current exceeds the base current which can only work if certain conditions for the tunneling rates using ground and excited states are fulfilled. The dynamics was described here for the case of charging the quantum dot from the base lead. However, a similar dynamics is obtained for discharging the quantum dot to the base lead. A more detailed and systematic investigations might tell us more about the many-body wavefunctions, selection rules for recharging the quantum dot and relaxation of the electron system within the quantum dot.