Coulomb-Blockade directional coupler

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A tunable directional coupler based on Coulomb Blockade effect is presented. Two electron waveguides are coupled by a quantum dot to an injector waveguide. Electron confinement is obtained by surface Schottky gates on single GaAs/AlGaAs heterojunction. Magneto-electrical measurements down to 350 mK are presented and large transconductance oscillations are reported on both outputs up to 4.2 K. Experimental results are interpreted in terms of Coulomb Blockade effect and the relevance of the present design strategy for the implementation of an electronic multiplexer is underlined.

PACS numbers: 73.23.Ad, 73.23.Hk, 73.63.Nm

Controlled directional injection of electrons from one electronic waveguide to another is being intensively investigated owing to its importance in wavelength multiplexing and in telecommunication routing devices. While photonic multiplexers represent a mature technology, electronic steering devices are still at their infancy.

Pioneering designs were demonstrated exploiting a field-effect tunable barrier between two semiconductor waveguides [1, 2, 3, 4, 5], implementing a Y-branch switch or switching the electrons by means of electric side-gates [6, 7, 8]. An electronic device based on two electron waveguides coupled by an open interaction window rather than a tunneling barrier was also proposed [9, 10, 11] and realized [12], but so far no switching behavior was demonstrated in this configuration.

In this Letter we describe a scheme where the coupling element between two semiconductor waveguides is a single quantum dot (QD) and Coulomb blockade (CB) governs electron routing. We shall demonstrate that in the classic configuration with two electron waveguides mixing at an open ballistic window a QD can be induced – with appropriate biasing conditions and geometry – and employed as a gate-controlled coupling element between the two waveguides.

Figure 1(a) shows a scanning electron microscope (SEM) picture of the device. Schottky gates are labeled $g_1$ through $g_4$. Letters $A$ to $D$ represent the Ohmic contacts (not shown); (b) differential conductance in the collector B (through the QD) and (c) corresponding conductance in the collector C. Inset: “symmetric dot” conductance in function of $V_{g_3}$.

FIG. 1: (a) SEM picture of the coupled-waveguide device. Schottky gates are labelled as $g_1$ through $g_4$. Letters A to D represent the Ohmic contacts (not shown); (b) differential conductance in the collector B (through the QD) and (c) corresponding conductance in the collector C. Inset: "symmetric dot" conductance in function of $V_{g_3}$.

by a DC voltage ($V_{g_2}, V_{g_3}, V_{g_4}$, respectively), while gate $g_1$ (biased $V_{g_1}$) was employed as a plunger gate. A drain-source AC voltage ($V_{DS}=100$ $\mu$V) was applied at the input waveguide (Ohmic contact D in Fig. 1).

The AC current flowing through outputs B and C was measured by two current preamplifiers and phase-locked techniques. A lower AC excitation of 20 $\mu$V was also

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used to test that the device was in the linear regime also at the lowest temperatures.

FIG. 2: Schematic of our device. QD indicates the quantum-dot location (black circle). Black regions represent the metal gates while gray areas show the regions depleted by the applied bias.

Panels (B) and (C) in Fig. 1 show the differential conductance measurements relative to collectors B and C respectively when an AC bias is applied to contact D. The Ohmic-contact A was left floating. Biasing $V_{g2}$, $V_{g3}$, and $V_{g4}$ at -0.65 V, high-contrast oscillations in the output current appear on both collector waveguides at 350 mK as a function of $V_{g1}$ in the range from -1.24 V to -1.1 V. One of the outputs (Fig. 1, C) displays a 5%-wide current modulation while the other collector (Fig. 1, B) shows a 100%-wide current modulation oscillation in the output current.

This behavior can be explained taking into account the formation of a QD in the CB regime in the region indicated by the black disk in the schematic sketch shown in Fig. 2. The QD presence in that position was verified in all cool-downs, and a specific characterization of each waveguide was performed in order to exclude the presence of unintentional dots in the input or output channels. By symmetrically reversing the bias configuration of gate electrodes a dot symmetrically located in the opposite of the coupling region could be induced. This dot was indeed observed when contact B was employed as emitter and A and D as collector waveguides (A, D). In the case of the device shown here it yielded a lower contrast in conductance measurements (see inset in Fig. 2B). We attribute this behavior to a different coupling regime to the reservoir, probably related to the tunnel barrier of the output channel.

The CB-oscillation pattern obtained by measuring the current from contacts B and C showed a π phase shift, excluding the possibility that the QD extends to the whole central region and demonstrating the switching behavior of our device.

FIG. 3: Conductance behavior of the QD at finite bias(a) and in magnetic field parallel to the 2DEG(b). $T = 350$ mK. In a simple model of an ungated 2D disk-shaped QD the total capacitance is given by $C_{TOT} = 4\epsilon_0\epsilon_r D$, where $D$ is the QD diameter, and $\epsilon_r=12.5$ is the dielectric constant of GaAs. From the measured value of $C_{TOT}=100$ aF we derive a dot diameter of $D = 0.23 \mu m$, in good agreement with the geometry of our device. From this diameter and the charge density of electrons in the original 2DEG, we estimate that there are ~100 electrons in the dot under the operating conditions of Fig. 3(a).

The mean periodicity of the Coulomb oscillations reported in Fig. 1 $\Delta V_{g1} = e/C_{g1}=9.4$ mV corresponds to a gate capacitance of $C_{g1}=17$ aF giving, therefore, $\eta=C_{g1}/C_{TOT} = 0.17$ as “lever arm” value between the applied gate voltage and the change in the total energy of the island. The period $\Delta V_{g1}$ remains almost constant changing $V_{g1}$ down to the pinch-off and no contribution related to discrete energy levels of the dot is observed. In any case, the pinch-off in our device is determined by that relative to the output channel QD-B, so no information about the occupation number of the dot is directly available through these measurements.

More information about the QD position can be extracted by comparing CB oscillations as a function of
$V_{g1}$ at different voltages applied to the remaining gates. We observed an increase of $C_{g1}$ from 16.3 aF to 19 aF while decreasing $V_{g2}$, $V_{g3}$ and $V_{g4}$ from -0.6 V to -0.8 V, indicating that electrons in the dot are pushed toward $g1$ when the other gates are biased with increasingly negative voltages.

Measurements in parallel magnetic field $B_\parallel$ (Fig. 3(b)) show a common shift of the CB peaks that is caused by the coupling between the magnetic field itself and the transverse components of electron wave functions in the dot and in the leads (diamagnetic shift)\cite{16, 17}. By plotting the peak spacing in order to eliminate common peak motion with magnetic field and to minimize the presence of switching noise, a strong fluctuation in the data is observed (data not shown). The peak spacing does not follow a clear linear behavior with the magnetic field as $g\mu_B B_\parallel/\eta$ (where $g$ is the Landé factor for bulk GaAs, $\mu_B$ the Bohr magneton and $\eta$ the lever arm value) as expected on the basis of Zeeman splitting of the dot levels. This irregular behavior has been already observed in gate-depleted QDs in the "weak-coupling" regime\cite{18, 19}: the QD is indeed weakly coupled to drain and source and CB peaks typically have a height lower than 0.1 e$^2$/h (see Fig. 4(b)) and an irregular pattern of the peak spacing in function of the magnetic field is reported.

Finally, the temperature behavior of our device (see Fig. 4) shows that the effect is still present up to 4.2 K, consistently with the CB charging energy $U_{CB}$ previously found.

We wish to point out an advantage intrinsic to this scheme with respect to quantum devices based on coherence effects: as for the case of single electron transistors\cite{20, 21}, appropriate geometries and materials can lead to higher and even room-temperature operation of such CB-based directional coupler. Available transconductance values are very high. In fact at low temperatures switching voltages are in the mV range and at least one order of magnitude lower than those required in Y-branch devices (operated both in the so-called "external side-gate"\cite{7} and in "internal ballistic" switching mode\cite{8}). This leads to measured normalized-transconductance values as high as $I^{-1}dI/dV_{g1} \sim 1500$ V$^{-1}$ for collector B in the present implementation. This characteristic is of interest in terms of low power consumption for high miniaturization and large scale integration.

In conclusion, a directional coupler device based on CB was demonstrated. Its differential-conductance characterization as a function of magnetic field and temperature was presented. In the CB regime this device behaves like a current switch in one collector output and as a current modulator in the opposite one. The same basic scheme can be employed to design logic functions or, employing a series of our device, a CB-based electronic multiplexer.

Fruitful discussions with S. de Franceschi and M. Governale are gratefully acknowledged. This work was supported in part by the European Research and Training Network COLLECT (Project HPRN-CT-2002-00291). Work at NEST-INFM was supported in part by MIUR under FIRB contract RBNE01FSWY, and work at Cavendish Laboratory by EPSRC.

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