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Fast and efficient single electron transfer between distant quantum dots

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Lateral quantum dots are a promising system for quantum information processing devices. The required basic manipulations of a single electron spin have indeed been demonstrated. However, a stringent requirement is the ability to transfer quantum information from place to place within one sample. In this work, we explore and demonstrate the possibility to transfer a single electron between two distant quantum dots in a fast and reliable manner. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795528]

I. INTRODUCTION

Lateral quantum dots have seen tremendous improvements over the past years and allow to manipulate a single electron or its spin quantum coherently.[1–5] In addition, double dots—i.e., two dots lithographied close to each other—offer the possibility to make two electrons interact with each other in a controlled manner. These tools can hence be seen as new building blocks for electronic devices based on single electrons, whether in classical manner or for a quantum computer. However, in both cases, a major ingredient is missing in the previous list: the possibility to transfer the information, that is the transfer of a single electron from one quantum dot towards another distant one in keeping the electron isolated in the structure. In the following, we show that this missing ingredient has been realised thanks to surface-acoustic-wave assisted transport. In the context of quantum computing, displaced electrons can play the role of photons in superconducting qubits and allow to mediate the interaction between distant qubits.

II. SAMPLE DESCRIPTION

The structure used for this work is a GaAs/AlGaAs heterostructure that hosts a 2D electron gas (2DEG) at 95 nm below the surface, with a mobility $1.5 \times 10^6\,\mathrm{cm}^2/\mathrm{Vs}$ and density $-1.35 \times 10^{11}\,\mathrm{cm}^{-2}$ at 4 K. The device was realised by standard optical and electron-beam lithography, e-beam metal deposition, and lift-off techniques. A mesa was defined by wet etching using a solution based on sulfuric acid and oxygenated water. The sample is presented in Fig. 1 and is composed of two lateral quantum dots that will serve as a source and receiver of electrons. They are linked by two long gates that allow to fully deplete the 2DEG between the two quantum dots. This is a stringent requirement in order to avoid receiving an electron previously trapped in the 1D-channel defined when no electron is in the source dot. Furthermore, in the view of realizing a quantum computer based on the spin of the electron, it is necessary that the injected electron is the one which is received in the detector since its spin will carry information. It directly follows that we need electrometers in order to determine in a single shot manner the charge state of the quantum dots. This role will be assumed by Quantum Point Contacts (QPCs) juxtaposed to the quantum dots. It has been shown that such devices allow to detect a change of charge of a single electron in a nearby quantum dot.[6–8] The QPCs were typically biased with 300 μeV. They allowed to establish the stability diagrams shown in Figure 1, which show that the single electron regime is reached for each dot.[9] A further tool is needed: If one electron is simply "pushed" into the 1D-channel, it will stay blocked on irregularities of the potential. It is thus necessary to assist it on its journey. This help is brought by Surface Acoustic Waves (SAWs), which will drag the electron along the wafer. SAWs are generated by a 30-nm-thick TiAu InterDigitated Transducer (IDT) thanks to the piezoelectricity of GaAs. It is composed of 70 pairs of fingers, 60 μm in length. The spatial periodicity of the design is $\lambda \simeq 1\,\mu$m. When polarised with an electrical voltage of frequency $f = 3$ GHz, it generates an acoustic wave located within λ to the surface. Since the material is piezoelectric, this SAW is accompanied by a sinusoidal electrical potential that can drag electrons in the 2DEG.[10] More recent work has shown that when a QPC or 1D-channel is irradiated by such a SAW, it can drag a current through the sample, quantized in units of $e \times f$, where e is the electron charge.[11] This implies that each minimum of the acoustic wave can be loaded by exactly 0, 1, 2, … electrons. The combination of a SAW and a 1D-channel thus mimics a quantum dot,[12] that is moving in the 2DEG at a speed of 3000 m/s, hence the name of dynamical quantum dot (DyQD). We can hence use one of these DyQDs to transport one electron from one side of the sample to the other through the 1D-channel.

III. EFFICIENT TRANSFER OF A SINGLE ELECTRON

Since the 1D-channel is pinched off, its potential floor is higher in energy than the Fermi level of the reservoirs. We

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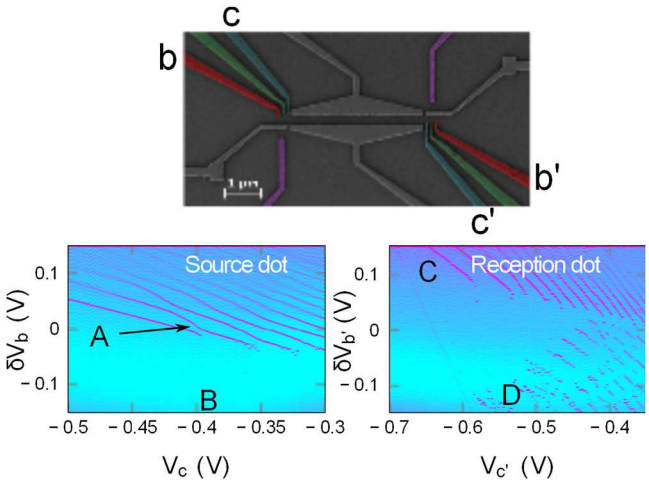

FIG. 1. Top: False colors SEM image of the sample used. Bottom: Stability diagrams of both dots. The zero electron region is reached in the bottom-left corner of the two diagrams.

will then need to push the electrons higher in energy if we want them to be able to reach the 1D-channel (see Fig. 2). Figure 2 shows QPC traces resulting from a gate sequence that loads one electron (in the $n = 1$ region of the dot's stability diagram, Fig. 1, A) and then pushes it high in energy into a metastable position[13] (into the $n = 0$ region, Fig. 1, B). We can clearly see two levels for the QPC trace: The dot is loaded with 0 or 1 electron. If loaded with one electron on arrival at the metastable point, it leaves the dot after a stochastic time. If averaged, we recover an exponential decay towards 0 electron with a characteristic time around 600 ms, characteristic of the tunneling back to the reservoir. The same experiment can be repeated, but now a burst of acoustic wave is generated 100 ms after the dot is set in the metastable position. The results indicate (data not shown here) that the electron gets out of the quantum dot with a high probability. In order to check that the electron is indeed transported through the 1D-channel and is not simply kicked back into the reservoir,[13] we will set up the second quantum dot to try and catch the electron.

The reception quantum dot is thus polarized deep in the metastable region (point D in Figure 1). This configuration allows to get a high and thick barrier between the reservoir and the dot: the electron will indeed be pushed by the SAW, we hence need this barrier high enough to block it. Once the electron is caught, the dot is polarized at point C to empty it and reset the experiment. The overall sequence is hence as follows: (1) the injection dot is loaded, (2) the reception dot is emptied and set in reception position, (3) the injection dot is set in the metastable position, (4) the charge states are checked for 50 ms, (5) a burst of SAW is generated, and (6) the (new) charge states are measured for 50 ms. The resulting single shot traces observed experimentally are presented in Figure 3. Statistics are accumulated for 10 001 repetitions in different loading situations in the source dot. This analysis allows to completely characterize the transfer process and shows that it is indeed the electron that is loaded in the injection dot that actually arrives in the reception dot with a high efficiency: 95% for the injection and 92% for the reception.[14] This high efficiency and reliability have been confirmed in a simultaneous work by McNeil and co-authors.[15]

IV. NANOSECOND TRIGGERED ELECTRON TRANSFER

An important parameter for the use of this system in a quantum computer resides in the ability to trigger every

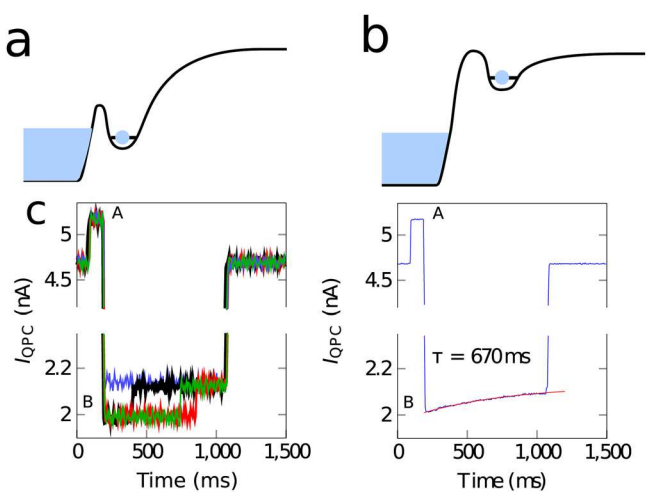

FIG. 2. Schematic view of the electrical potential of the injection dot at load point (a) and at the metastable point (b). (c) Time traces of the injection QPC for the gate sequence describe where an electron is first injected in the dot (position A) and then brought in the metastable position B above the Fermi energy where the electron tunnels out of the dot with timescale approaching 1 s. The loading event (at A) is not resolved, since faster than our measuring electronics. The traces around 4.6 nA correspond to a rest position of the voltage sources.

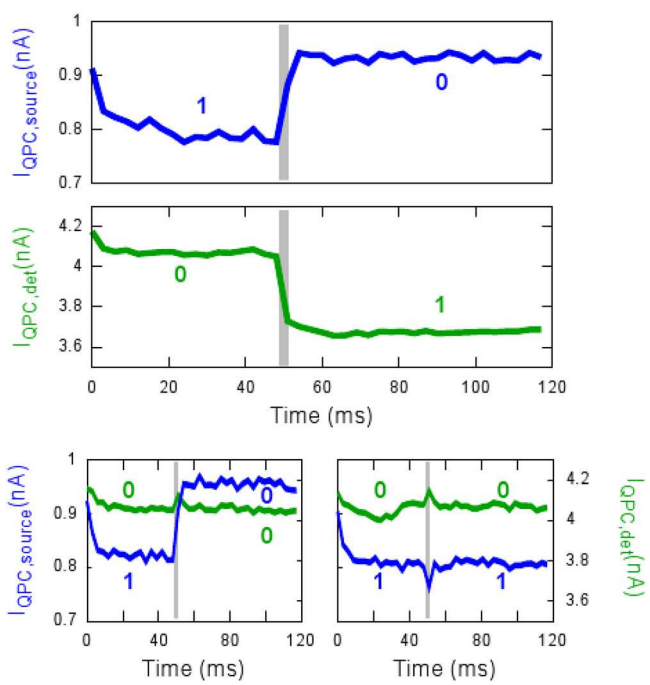

FIG. 3. Upper part: Single shot QPC response as a function of the time recorded during the transfer procedure. The grey line represents the instant at which we apply the microwave burst. For the source dot, the signal jumps from the one-electron conductance to the zero-electron conductance. For the reception dot, the opposite takes place. Lower part: Experimental single shot traces where an error is happening during the transfer. Left: The electron did not reach the reception dot. Right: The electron was not sent during the procedure.

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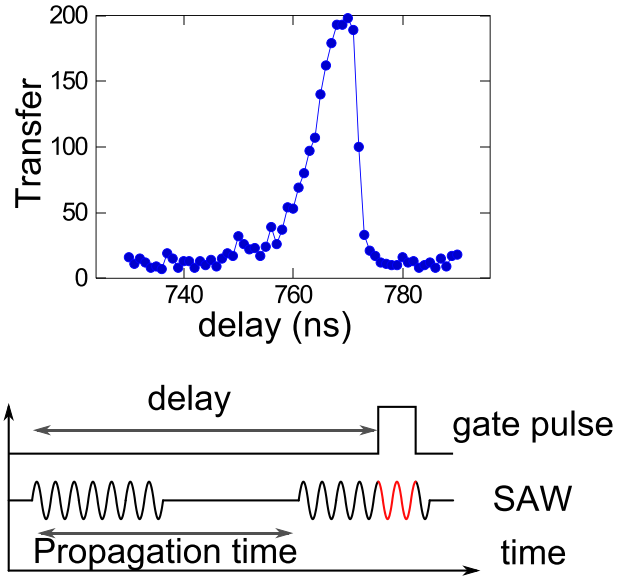

FIG. 4. Evolution of the transfer success number as a function of the delay between the SAW generation and the 1-ns pulse on V_C, out of 200 repetitions. The SAW duration is 65 ns. Lower panel: Timing schematic of the experiment. The time of flight is the time needed for the SAW to travel from the IDT to the centre of the sample—around 2 mm.

operation faster than the coherence time of a single electron spin. If spin echo sequences can raise this time up to 200 μs, the "bare" coherence time is typically around 10 ns.[2,16–18] We thus need to trigger the transfer on this timescale. However, the experiments already presented here used a SAW burst of 65 ns, which is the limit imposed by the bandwidth of the IDT. The idea to get triggering at the nanosecond timescale is first to bury the electron deeper in the emission dot so that the SAW excitation is not enough to inject the electron into the moving quantum dots. Second, the addition of a voltage pulse on gate c (see Figure 1) during 1 ns allows to bring back the electron in a situation where it is more sensitive to SAW excitation and allows to turn back on the injection probability (while conserving the good transfer efficiency). The corresponding transfer probabilities are presented in Figure 4, where the delay between the generation of the SAW burst and the ns-gate is varied.

This shows that the injection can indeed be triggered within 1 ns and the limit to go lower should only be technological (a faster pulse generator with the same amplitude should allow the same result on faster time scales).

V. CONCLUSION

In conclusion, we have demonstrated a fast and efficient transfer method for a single electron between two distant quantum dots. Further investigations on the spin of the transported electrons are to be realized to fully characterize the abilities of this system.

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