Injection of a single electron from static to moving quantum dots

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Received 14 January 2016, revised 22 March 2016
Accepted for publication 24 March 2016
Published 18 April 2016

Abstract
We study the injection mechanism of a single electron from a static quantum dot into a moving quantum dot. The moving quantum dots are created with surface acoustic waves (SAWs) in a long depleted channel. We demonstrate that the injection process is characterized by an activation law with a threshold that depends on the SAW amplitude and on the dot-channel potential gradient. By sufficiently increasing the SAW modulation amplitude, we can reach a regime where the transfer has unity probability and is potentially adiabatic. This study points to the relevant regime to use moving dots in quantum information protocols.

Keywords: quantum dots, single electron, surface acoustic wave, electronic transport, moving quantum dots

(Some figures may appear in colour only in the online journal)

The ability to displace a single electron on a chip controllably and on demand is an important prerequisite for the realization of electronic circuits at the single electron level. It opens the route to interconnect nodes of a spin-based quantum nano-processor [1–4] or to perform quantum optics experiments with itinerant electrons [5–8]. The recent demonstration of fast and on-demand transfer of a single electron is a first step towards this goal [9, 10]. These experiments are performed in AlGaAs/GaAs heterostructures containing a two-dimensional electron gas (2DEG), where an electron travels confined in a moving quantum dot. The moving quantum dots are created in a depleted one-dimensional channel by exciting a surface acoustic wave (SAW) [11]. Due to the piezoelectric properties of AlGaAs, the SAW induces a traveling periodic electrostatic potential. When it adds up to the channel potential, it produces the moving quantum dots that can confine and transfer electrons. Such moving quantum dots have already been used to transfer an ensemble of electrons and preserve their spin coherence over distances approaching 100 μm [12, 13]. To reach the on-demand single electron transfer regime, an electron is initially isolated in an electrostatic quantum dot, located next to the channel entrance, and is then transferred to a moving quantum dot [9]. In order to use such a tool in quantum information protocols, it is essential to understand the mechanism responsible for the injection of the electron from the static into a moving quantum dot.

In this paper, we experimentally investigate the injection process from the static to a moving quantum dot. More specifically, we analyzed the influence of two relevant parameters: the SAW modulation amplitude and the gate-induced electrostatic potential defining the source static quantum dot and the channel [14, 15]. The injection of the electron to a moving quantum dot occurs only when the potential gradient induced by the SAW periodic potential overcomes the largest
gradient of the static potential. The calibration of the SAW modulation amplitude \[^9\text{], and the analysis of the electron injection probability allow us to precisely estimate the value of the static potential gradient for a given gate configuration. This value is used to identify the injection process mechanism. In addition, it is possible to trigger the electron injection for a nanosecond with a unity efficiency. We show that this fast injection technique is compatible with an adiabatic injection in which the electron remains in the ground state of the trapping potential.

The sample used in this work is shown in figure 1. It is fabricated on a GaAs/AlGaAs heterostructure that hosts a 2DEG 100 nm below the surface, of \(1.35 \times 10^{11} \text{cm}^{-2}\) density and \(1.5 \times 10^{6} \text{cm}^{-2} \text{s}^{-1}\) mobility. It is constituted of two laterally defined quantum dots, the source and the reception dots, connected together with a 4 \(\mu\text{m}\) long depleted channel. An interdigitated transducer (IDT) is placed 2 mm to the left of the gate structure in order to generate a SAW. It counts 70 pairs of 70 \(\mu\text{m}\) long fingers with a 1 \(\mu\text{m}\) wavelength. When a radiofrequency (RF) excitation of amplitude \(A_{\text{SAW}}\) is applied on the IDT, it resonantly excites a SAW at 2.6323 GHz. Transport measurements through the left (right) quantum dot allowed us to characterize the energy needed for an electron to enter the dot, called the charging energy \(E_{\text{c}}\), and the single-particle orbital energy splitting \(400 \mu\text{eV}\). The charge state of the quantum dots is monitored thanks to the adjacent quantum point contacts (QPCs), typically DC-biased with 300 \(\mu\text{eV}\). The sample is anchored to the mixing chamber of a dilution fridge operating at a base temperature of 50 mK.

The experimental sequence that we perform to transfer the electron between the two static quantum dots was initially presented in \[^9\text{]. The source dot is isolated from the lead allowing us to trap the electron 5 \(\text{eV}\) above the Fermi energy. We then add a 10 \(\mu\text{s}\) voltage pulse to \(V_{\text{b}}\) and \(V_{\text{c}}\). It is characterized by a voltage displacement \((\delta V_{L}, \delta V_{R})\) that we call the sending pulse. As a result, the potential gradient between the channel and the source dot is further reduced during the sending pulse. A few hundred nanosecond RF-excitation is applied on the IDT to generate a SAW modulation within the duration of the sending pulse, ensuring the electron transfer. The presence/absence of the electron can be inferred in both the source dot and the reception dot via charge measurements \[^9\text{,16\text{].}

To study the influence of the dot potential on the injection process from the source to the moving dots, we vary \((\delta V_{L}, \delta V_{R})\) and probe the charge present in the source dot after the sending pulse (see figures 2(a)–(c)). Without SAW modulation (figure 2(a)), the electron remains in the isolated
dot (white region) except for the sending pulses with the most positive \( \delta V_L \) and the most negative \( \delta V_g \) (top left red region): the dot isolation is no longer sufficient and the electron is lost to the neighbor reservoir. With SAW modulation (figure 2(b), (c)), a new region where the electron leaves the source dot, called the transfer region, is present for the most negative \( \delta V_L \) and \( \delta V_g \) (bottom left corner). It corresponds to the process where the electron has been injected in a SAW moving quantum dot and leaves the source dot. A confirmation of these two regions’ labeling is obtained by analyzing the correlation between the electron leaving the source dot (figure 2(c)) and arriving in the reception dot (initially empty) after the transfer sequence (figure 2(d)). An electron is indeed detected in the reception dot after the transfer only for the sending pulses corresponding to the transfer region.

The sending pulse amplitude has to be more negative than a certain threshold on \( \delta V_L \), \( \delta V_g \) (see figure 2(b), (c)), defined by the limit \( (\delta V_L, \delta V_g)_T \), that separates the transfer region and the region where the electron remains in the source dot. In the following, we analyze the behavior of the transfer for \( \delta V_g = 0 \). We find that the transfer is activated only below a certain threshold \( \delta V_L \), that linearly depends on \( \Delta_{SAW} \) (see figure 2(e)). Indeed, for a larger \( \Delta_{SAW} \), the potential gradient imposed by the SAW modulation overcomes more easily the one resulting from the gate voltages. It results in a wider range of gate voltages where the injection of the electron to a moving quantum dot is possible. This demonstrates the dependence of the two important parameters for the electron transfer: the potential gradient induced by the SAW, and the static dot potential. We conclude that the electron transfer is activated above a threshold defined by two interdependent parameters \( \Delta_T \) and \( V_T \).

This model has to be refined by taking into account the risetime of the SAW modulation that is due to the finite bandwidth of the IDT. To investigate precisely this aspect, we set the sending pulse parameters \( (\delta V_L, \delta V_g) \) to \((0 \text{ V}, -0.55 \text{ V})\) and varied both \( \Delta_{SAW} \) and the RF-excitation duration \( \tau_{SAW} \). The resulting probability to emit the electron is represented in figure 2(f). The injection of the electron to a moving quantum dot occurs only when \( \Delta_{SAW} \) reaches the amplitude threshold \( \Delta_T \). As expected from the risetime of the SAW modulation, a shorter \( \tau_{SAW} \) is needed to reach \( \Delta_T \) when \( \Delta_{SAW} \) is increased. A fit of the data is performed assuming an activation law (see inset of figure 2(f)). It enables us to deduce the risetime of the SAW modulation (about 65 ns) and the value of \( \Delta_T \) (about 1 V). From the relation between \( \delta V_L \) and \( \Delta_{SAW} \), obtained from figure 2(e), and the gate lever arm \((\approx 20 \text{ mV meV}^{-1})\), we estimate that \( \Delta_T \) corresponds to a SAW-induced potential gradient seen by the electron \( \Delta_{V_{SAW}} \approx 30 \text{ meV nm}^{-1} \). As explained earlier, it also corresponds to the dot-channel potential gradient in the specific gate configuration of figure 2(f).

To have a better insight into the injection process, we sketched the time-dependent potential seen by the electron in the presence of the SAW excitation (see figure 3). At a fixed potential gradient induced by the gate voltages \( \Delta V_g \), the transfer process depends on \( \Delta V_{SAW} \). For \( \Delta V_{SAW} \) lower than \( \Delta V_g \) (figure 3(a)), shallow SAW moving dots are created and a thin tunneling barrier separates them from the source dot. As a consequence, a process where the electron can tunnel back to the source dot after being caught is likely to happen [14, 15]. Considering the \( 30 \text{ meV nm}^{-1} \) dot-channel potential gradient previously estimated, the energy detuning between the source and the moving quantum dots in the tunneling-back configuration is expected to be larger than the orbital energy splitting of the source dot. Therefore, the tunneling-back events will certainly result in the excitation of higher orbital states of the source dot, and consequently the injection process will be non-adiabatic in this situation. For \( \Delta V_{SAW} \) bigger than \( \Delta V_g \) (figure 3(b)), the tunnel barrier becomes too thick and no tunneling-back process is possible. In this situation, the injection process is expected to be adiabatic and happens when the source and the moving quantum dot are overlapping.

Therefore, under the experimental conditions of figure 2(f), we infer that the injection process is certainly stochastic and, according to the previous discussion, non-adiabatic. One can notice on figure 2(f) that the electron is expelled from the dot after at least a few tens of nanoseconds corresponding to the time needed for \( \Delta_{SAW} \) to reach \( \Delta_T \). The electron experiences the excitation of a few hundred moving quantum dots before being transferred with most of it at \( \Delta_{SAW} \) below \( \Delta_T \), in a configuration similar to figure 3(a). The emission probability reaches unity only because the electron has the possibility to be injected in a considerable number of

**Figure 3.** Time evolution of the dot potential for two different amplitudes of SAW excitation. The time increases going from top to bottom traces and the time difference between two consecutive traces is 70 ps. The potential gradient \( \Delta V_g \) induced by the gate voltages is the same in (a) and (b). (a) The potential gradient induced by the SAW excitation \( \Delta V_{SAW} \) is comparable to \( \Delta V_g \) and shallow moving quantum dots are defined. Tunneling back of the electron to the source dot is possible (see orange arrows), leading to a stochastic injection procedure. In (b) \( \Delta V_{SAW} \) is larger than \( \Delta V_g \) and deeper moving quantum dots are defined.
SAW periods. It also results in the exploration of the excited states of the source dot and in a non-adiabatic injection process. To be able to probe the adiabatic limit, it is therefore necessary to characterize the electron transfer at a constant SAW modulation amplitude and for a time as short as possible.

To this end, a modified transfer sequence was used for the injection of a single electron. $\tau_{\text{SAW}}$ was reduced to its minimum duration allowed by the SAW risetime, and we added to $V_i$ a 1 ns pulse synchronized with the SAW modulation [9]. This gate pulse is used to rapidly change the potential gradient between the dot and the channel. Practically, the dot potential is tuned to a point P (see figure 2(c)) where the potential gradient is too large for the SAW to transfer the electron into a moving quantum dot. The system is tuned to point T (see figure 2(c)) only for the 1 ns pulse, where the dot-channel potential gradient is reduced. As a consequence, the electron is expected to be transported by the SAW only during the nanosecond pulse. This technique allows us to probe the injection process only for two periods of the SAW excitation and more importantly at constant $A_{\text{SAW}}$.

Figure 4(a) shows the injection counts as a function of the delay $\Delta t_i$ between the SAW burst and the nanosecond pulse applied to the gate. For $A_{\text{SAW}} = 1.78$ V, the injection probability reaches almost unity for a delay close to $\Delta t_{\text{max}} = 765$ ns. This delay is explained by the finite SAW velocity of about 2867 m s$^{-1}$ [17] and the distance between the IDT and the sending dot. Before and after $\Delta t_{\text{max}}$, $A_{\text{SAW}}$ is not high enough to ensure a unity transfer process and the electron can be back-scattered to the source dot. An exponential RC rising/falling time law for $A_{\text{SAW}}$, due to the finite risetime of the SAW excitation, explains qualitatively the asymmetric shape of the emission probability as a function of $\Delta t_i$. $\Delta t_{\text{max}}$ therefore corresponds to the end of the SAW excitation burst, when the amplitude is maximal. For $A_{\text{SAW}} = 1.5$ V, the injection probability follows the same shape with a lower success rate. When the SAW excitation is lengthened from 58 to 70 ns at 1.5 V, the maximum SAW amplitude reached at the dot is increased (due to the SAW modulation risetime), and therefore the emission probability reaches higher values.

Figure 4(b) shows the evolution of the maximum emission probability at $\tau_{\text{SAW}} = 70$ ns and $\Delta t_{\text{max}} = 770$ ns as a function of the SAW amplitude. As previously demonstrated, the SAW amplitude needs to reach a threshold to be able to catch the electron and the injection process shows an activation law with respect to the SAW amplitude. At high SAW amplitude, the injection process has a probability close to unity, and is expected to be adiabatic (figure 3(b)). Figure 4(c) shows the evolution of the maximum emission probability at $\Delta t_{\text{max}}$ as a function of the nanosecond pulse amplitude for two different points P from which the nanosecond pulse is applied. Similar to the results presented in figure 2(f) for the SAW amplitude, we obtain a threshold behavior in the gate voltage. It is worth noting that no broadening of the distribution is observed when the electron is buried deeper into the source dot. This is consistent with the electron staying in the ground state of the source dot potential during the injection process.

In conclusion, we have studied the injection process of a single electron from a static quantum dot into a SAW-induced moving quantum dot. For a specific dot-channel potential gradient at the injection position, the injection probability can be tuned from zero to one by varying the SAW amplitude, pointing to a probabilistic process. At sufficiently large SAW amplitude, only one period of the SAW modulation is required to transfer the electron. In this regime, the injection process is expected to be adiabatic, with the electron remaining, at any time, in the ground orbital state of the trapping potential. Such a regime will be relevant to reduce errors in quantum protocols where single electrons are transferred in moving quantum dots.

Acknowledgments

We acknowledge technical support from the ‘Poles’ of the Institut Néel as well as from Pierre Perrier. MY acknowledges financial support by JSPS, Grant-in-Aid for Scientific Research A (No. 26247050) and Grant-in-Aid for Challenging Exploratory Research (No. 25610070). ST financial support by JSPS, Grant-in-Aid for Scientific Research (No.
26220710, MEXT KAKENHI ‘Quantum Cybernetics,’ MEXT project for Developing Innovation Systems, and JST Strategic International Cooperative. AL and ADW acknowledge DFG via TRR160, the support of the BMBF Q.com-H 16KIS0109, Mercur Pr-2013-0001 and the DFH/UFACDFA-05-06. ST acknowledges financial support from the European Unions Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 654603. BB acknowledges financial support from ‘Fondation Nanosciences.’ TM acknowledges financial support from ERC ‘QSPINMOTION.’

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