Single electron transport and entanglement induced by surface acoustic waves versus free ballistic propagation in coupled quantum wires

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Surface acoustic waves (SAW) have proved to be a valuable mean to control single-electron dynamics in nano-devices [1]. In this work we study the coherent propagation of electrons in quantum wires driven by SAW, as a part of a feasibility study on a coupled quantum wires device, able to realize the basic operations needed for quantum computing. Such a system has already been proposed and studied by the group of the authors in the case of free electron propagation [2]. The new idea now pursued is that the results obtained should be significantly improved by using SAW. Three main advantages can be identified: 1) two or more electrons can be injected simultaneously in different wires, 2) since the electron wavefunction is embedded in a "moving quantum dot" formed by the minimum of the SAW and the wire barriers, its natural spread is not present during the propagation, 3) the electron in the SAW minimum could be more immune to the decohering effects of phonons.

In order to study the evolution of the electron wavefunction in presence of the time-dependent SAW potential, we perform two types of time-dependent simulations.

Single-particle/two-dimensions. In the first case, shown in Fig. 1, the 2D single-electron wavefunction in wire 1 is split by means of a coupling window in two parts. At a following time a second coupling windows produces a complete transfer of the electron in wire 2 (Fig.1A). A given phase shift can be induced by introducing a low potential barrier (with suitably calibrated height and length) between the windows, along one of the wires, thus avoiding the transfer of the electron in wire 2 (Fig. 1B).

Two one-dimensional particles. In the second case the phase shift induced by a Coulomb coupler [2] is analyzed. This Coulomb coupler constitutes a basic element for the realization of quantum logic gates, since it allows to induce a given phase change on a specific component of the two-electron wavefunction [3], thus implementing the fundamental two-qubit gate (the one producing qubits entanglement) in the propose architecture. For its correct operation such phase change has to produce a π rotation in the qubit. The introduction of SAW has allowed to obtain a rotation of $0.99\ \pi$, while for the free electron propagation case the best result achieved was $0.79\ \pi$ (the time evolution of the square modulus of the two-particle wavefunction is shown, for the two above cases, in Fig. 2). The reason that prevents from reaching the exact value of the rotation angle is the formation of another, unwanted, kind of entanglement between the position of the electrons along the direction of propagation. The confinement determined by the SAW potential is able to limit such entanglement to 0.025, that is significantly lower then the value of 0.13 produced in the case of the free propagation.

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A full journal publication of this work will be published in the Journal of Computational Electronics.

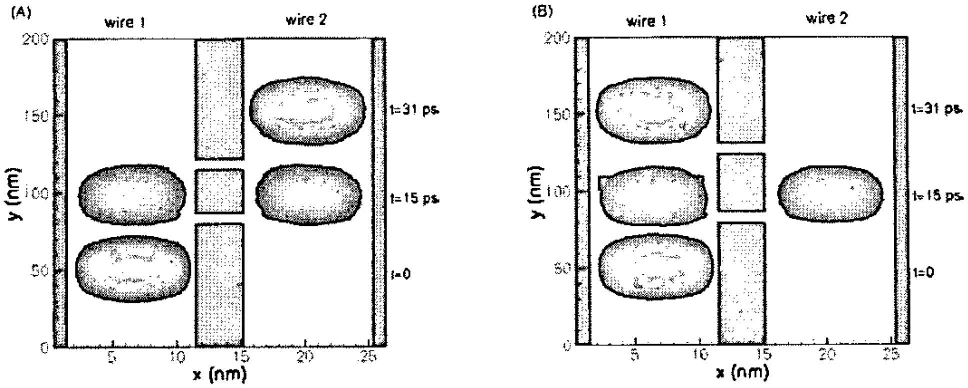

Fig. 1. Square modulus, a three time steps, of the wavefunction of an electron injected and driven by a SAW in a double wire device with two coupling windows. The geometrical parameters are chosen in order to obtain a complete transfer of the electron from wire 1 to wire 2 (A). The introduction of a suitable delaying potential barrier shifts the energy levels of the "moving dot" (see text) and inhibits the transfer. Note the difference in the scales of *x* and *y* axes.

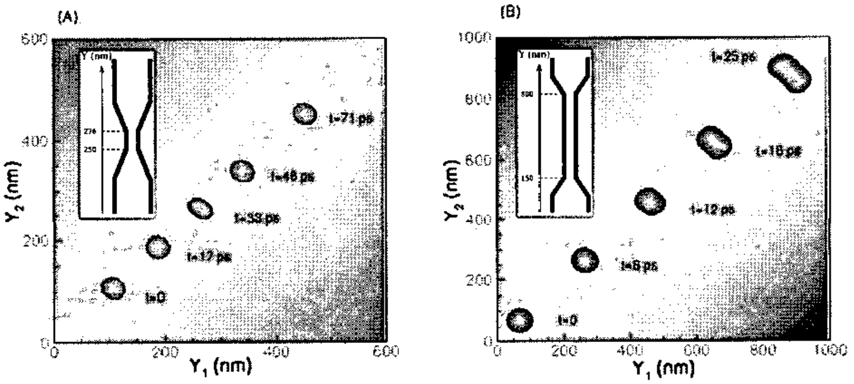

Fig. 2. Square modulus, at different time steps, of the wavefunction of an electron propagating along a Coulomb coupler realized with the wires geometries sketched in the insets. . White region represents the two-particles potential.The two cases that maximize the qubit rotation (see text), with (A) and without (B) SAW, are shown. The presence of the SAW reduces the y-position entanglement along the wire direction with respect to the free electron propagation case. This is revealed by the final shape of the wavefunction, that is "less separable" (in the y_1 and y_2 variables) in case (B) with respect to case (A).

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