Electron spin read-out in the absence of external magnetic field

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Abstract

In this presentation we bring forward the simulation of work of a nanodevice capable of performing the single electron spin read-out.
The electron's wave wave function is being formed as a stable packet which has the properties of a soliton due to the self-focusing effect. For distinguishing different spin orientation we use the influence of the spin-orbit coupling on electron trajectory.

Induced quantum dots and wires

Let us consider a planar semiconductor heterostructure composed of a quantum well bounded by two barriers. On its surface metal electrodes forming current paths are deposited (Fig. 1). If one places an electron in the quantum well, its charge cloud will induce charge of opposite sign on the surface of the conductor.
The induced charge will attract the trapped particle and the electric field in the quantum well's plane has a component directed into the center of the electron cloud. This leads to self-focusing mechanism that forms the wave function into a stable wave packet of finite size. It can move under the conductor in the xz plane without changing its shape and shows soliton behaviour [1].

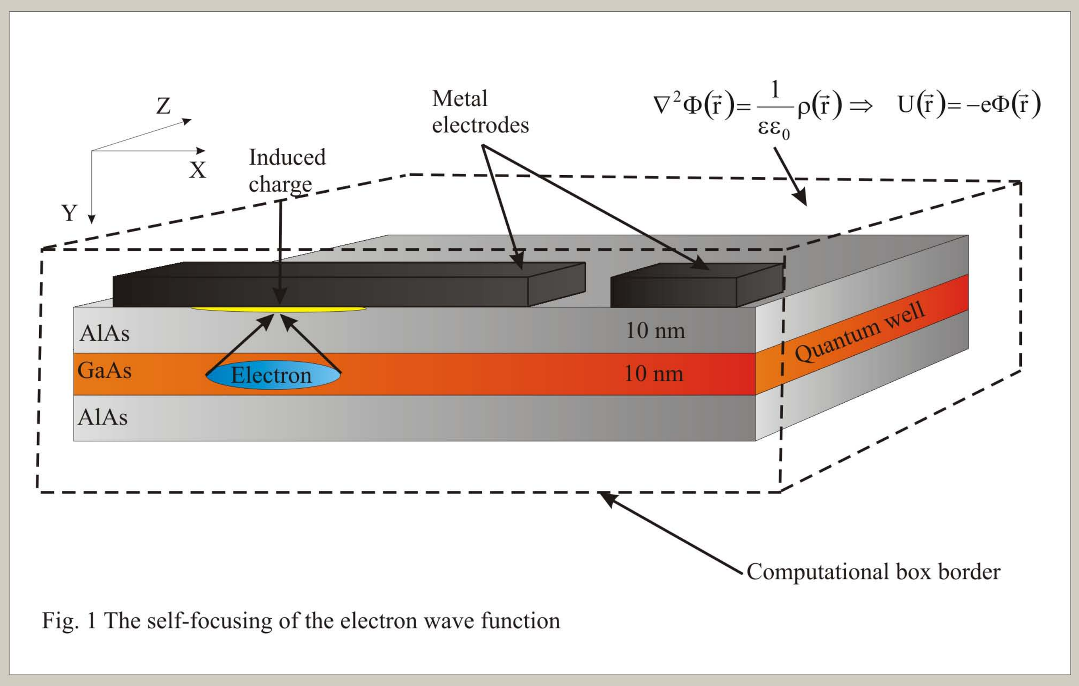

Fig. 1 The self-focusing of the electron wave function

As the result of the self-focusing mechanism (caused by interaction with the induced charge) the electron shows properties unique for a quantum particle. It is able to tunnel through or reflect off a potential barrier with probability 100% (Fig. 2a, 2b). Such behaviour, characteristic for a classical object, is very rare for a quantum one, which usually partially tunnels through and partially reflects from the barrier (Fig. 2c).

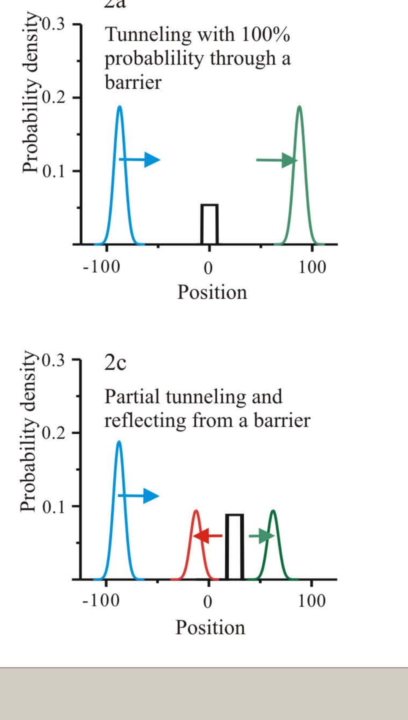

Fig. 2 a), b) behaviour of electron encountering potential barrier with self focusing mechanism, c) without self focusing mechanism

An electron forming a soliton can be transported in a controllable manner to different locations in the nanonstructure by applying low voltages (0.1 mV) to the metal electrodes acting as trajectory controllers [2]. The gates with cut corners are used in order to turn the electron into the desired direction (Fig. 3).

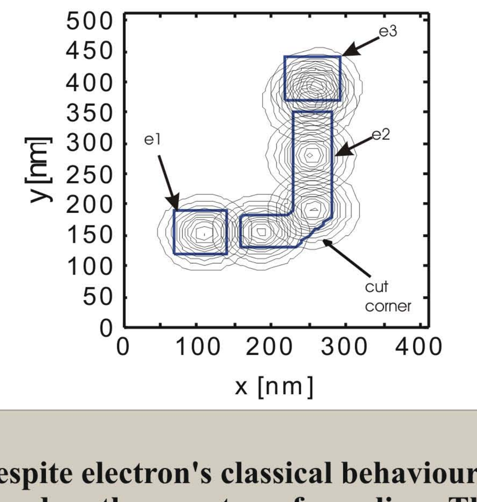

Fig. 3 Transport of the electron from under electrode e1 under e3 through e2. The cut corner of e2 forces the electron to turn left.

Despite electron's classical behaviour in all of our simulations its motion is based on the quantum formalism. The time evolution is given by the iterative solution of the time dependent Schrödinger equation:

$$d\psi = -i\hbar\psi\, dt$$

The potential distribution is being computed at each time step by solution of the Poisson equation in a 3D box containing the entire nanodevice (Fig. 1).

Operation on electron spin state

In a nanostructure in which the spin-orbit coupling is present one can perform any operation on electron spin state, forcing electron to move in a properly chosen closed trajectory. In paper [3] we describe three one qubit quantum gates of fundamental significance in the quantum computing.
As an example we bring forward the nanodevice shown on Fig. 4a which could serve as a NOT gate.

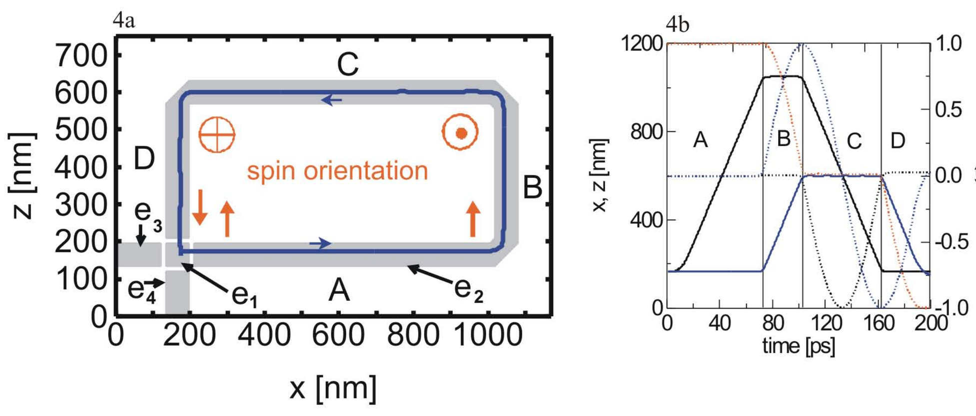

Fig. 4, a) The layout of electrodes of the nanodevice realizing the quantum NOT operation
b) time evolution of electron position and electron spin orientation.

Applying adequate voltages on electrodes e1, e2, e3 and e4 it is possible to obtain a minimum of electron potential energy under e1, which can be used to bind an electron. Decreasing the potential on e3 and e1, one can accelerate the particle and push it under e2. Next it will move balistically and its trajectory is determined by e2. Electron finally returns under e1 where it can be trapped again by decreasing the voltages on electrodes e2 and e4. During motion electron wave function preserves its shape due to self-focusing mechanism, and the spin-orbit coupling rotates the spin by 180 degree. As a result the electron is set back into its initial position while its spin is set to opposite (Fig. 4b).

Electron spin read-out

We propose an another nanodevice based on the spin-orbit coupling. It performs electron spin read-out necessary in quantum computing.
We use influence of the spin-orbit interaction on the electron trajectory in order to distinguish particles with different spin.
On Fig 5 we present the simulated motion of an electron in various initial spin states in the presence of the Dresselhaus coupling.

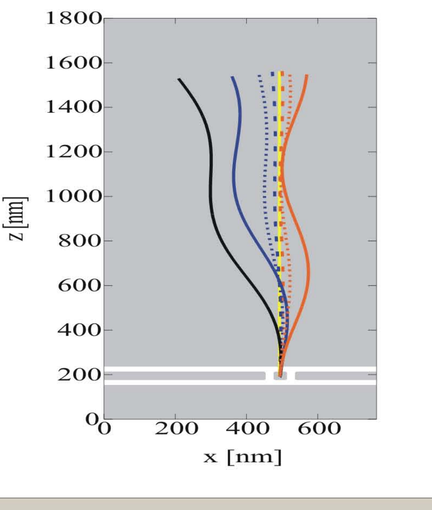

Fig.5

Electron trajectories for different initial spin states in presence of the Dresselhaus interaction.

After setting in motion along the z axis, the electron with spin parallel or anti parallel to the movement direction goes straight. The trajectories in all other cases are curved lines.

We filter out electrons with undesired spins orientation with help of the nanodevice composed of nine electrodes which is shown at Fig 6a.

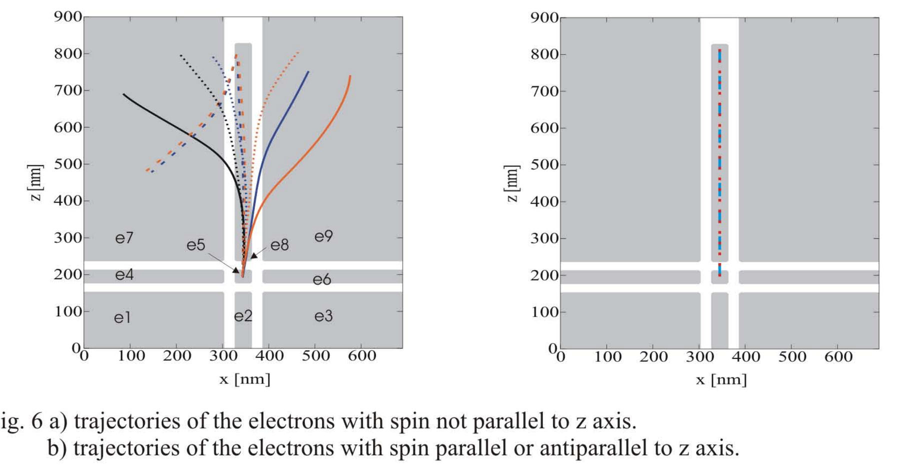

Fig. 6 a) trajectories of the electrons with spin not parallel to z axis.
b) trajectories of the electrons with spin parallel or antiparallel to z axis.

In our simulation the electron was initially bound under e5.
By setting adequate voltages on the electrodes it is forced to move parallel to the e8 in the beginning. Any shift in the motion direction will result in the electron being intercepted by e7 or e9. As can be seen on Fig. 6b, only the electrons with spin parallel or anti parallel to the z axis go along the whole length of the e8, bounce from its edge and return under e5, which makes them well distinguishable from all other.

In order to tell parallel spin from anti parallel one (sz=1, or sz=-1) we use the Rashba coupling, that we turn on when the electron returns under e5, forcing it to turn left for $\langle\sigma_z\rangle = 1$ or right for $\langle\sigma_z\rangle = -1$ (Fig. 7).

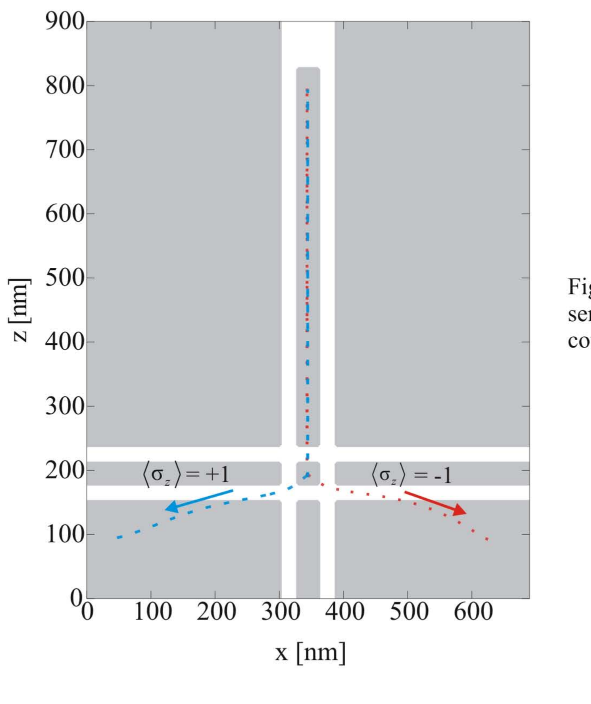

Fig. 7 Final distinction of the spin vector sense due to switching on the Rashba coupling

This way we simulated the spin read-out.
Electrons with $|\langle\sigma_z\rangle|$ not equal 1 were filtered in the first step of the process.
The direction in which the particle turn after switching on the Rashba coupling determines the value of $\langle\sigma_z\rangle = 1$ or $\langle\sigma_z\rangle = -1$.
The read-out has a destructive character as the spin-orbit coupling rotates the spin of electron moving right or left in the xz plane.

Conclusion

- We propose a device based on induced quantum dots and induced quantum wires which enables single electron spin read-out.
- The self-focusing mechanism forces the electron wave function to conserve its shape and to behave like a classical particle, which makes its transport controllable with low voltages applied on properly deposited metal electrodes.
- Our method of distinguishing particles with different spin allows to avoid using external magnetic fields and microwaves.

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References

[1] S. Bednarek, B. Szafran, and K. Lis "Electron soliton in semiconductor nanostructures" Phys. Rev. B72 (2005) 075319
[2] S. Bednarek, B. Szafran, R. J. Dudek, K. Lis „Induced quantum dots and wires: Electron storage and delivery" Phys. Rev. Lett. 100, (2008) 126805,
[3] S. Bednarek, B. Szafran, "Spin rotations induced by an electron running in closed trajectories in gated semiconductor nanodevices" Phys. Rev. Lett. 101, (2008) 216805