Nanodevice for High Precision Readout of Electron Spin

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Abstract

In this paper we propose and simulate operation of a nanodevice, which enables the electron spin accumulation and very precise read-out of its final value. We exploit the dependence of the electron trajectory on its spin state due to the spin-orbit coupling in order to distinguish between different spin orientations.

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].

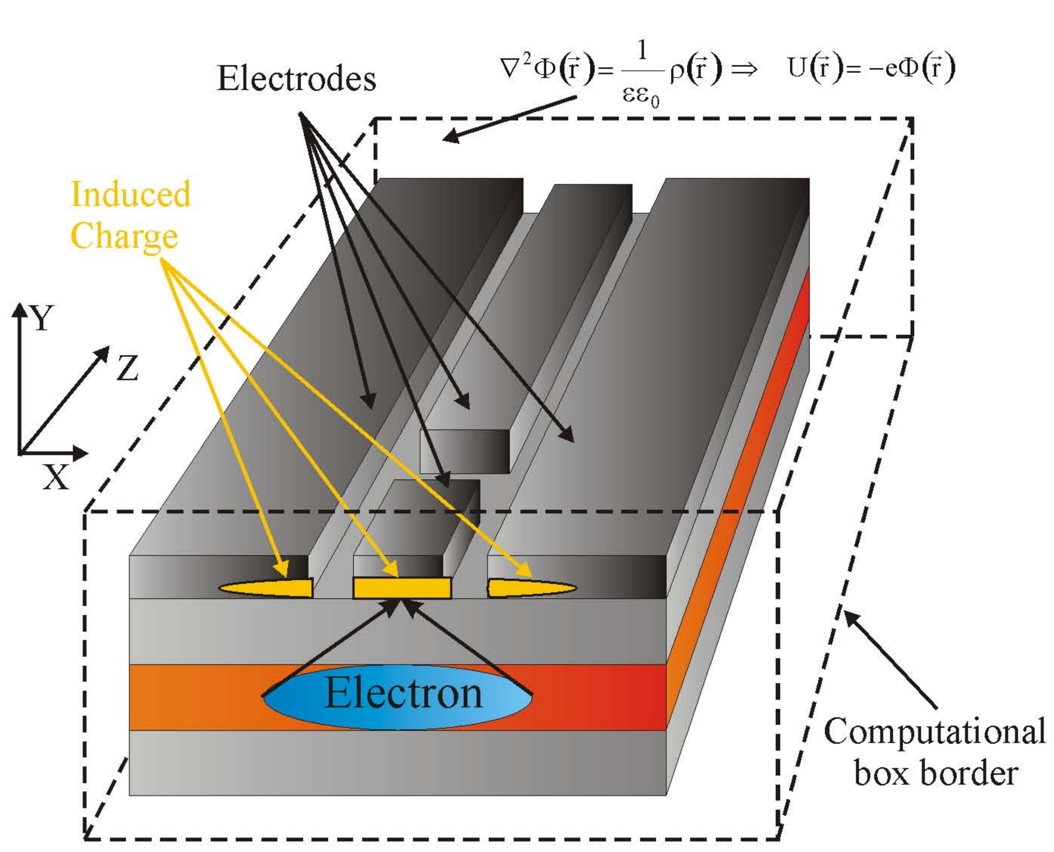

Fig. 1. Cross-section of the nanodevice. Self-focusing effect.

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).

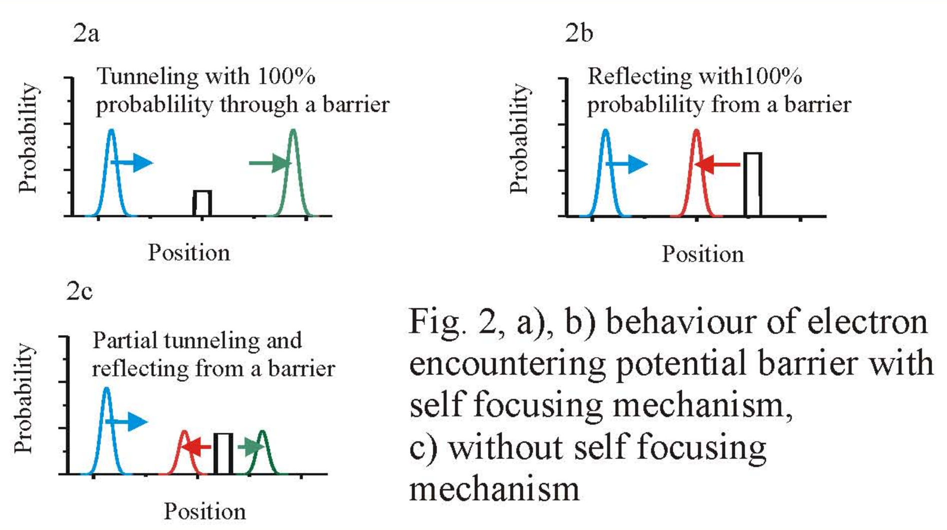

Fig. 2, a), b) behaviour of electron encountering potential barrier with self focusing mechanism, c) without self focusing mechanism

The self-focused electron 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 a trajectory controllers [2]. The gates with cut corners are used in order to turn the electron into the desired direction (Fig. 3).

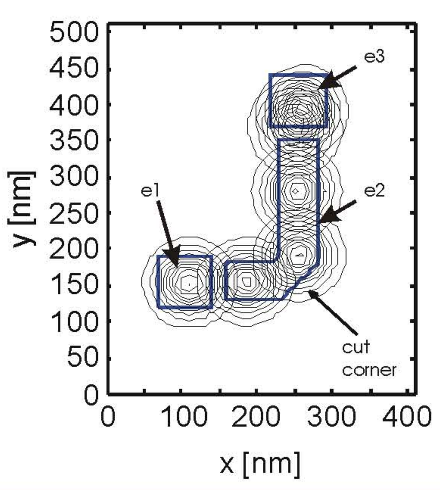

Fig. 3 Transport of the elctron from under electrode e1 under e3 through e2. The cut corner of t e2 forces the electron to turn left.

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.

Operation on electron spin state

Exploiting the spin-orbit coupling, one can perform any operation on electron spin state.

As an example we bring forward the nanodevice described in our previous papers [3, 4] shown in Fig. 4a which could serve as a NOT gate.

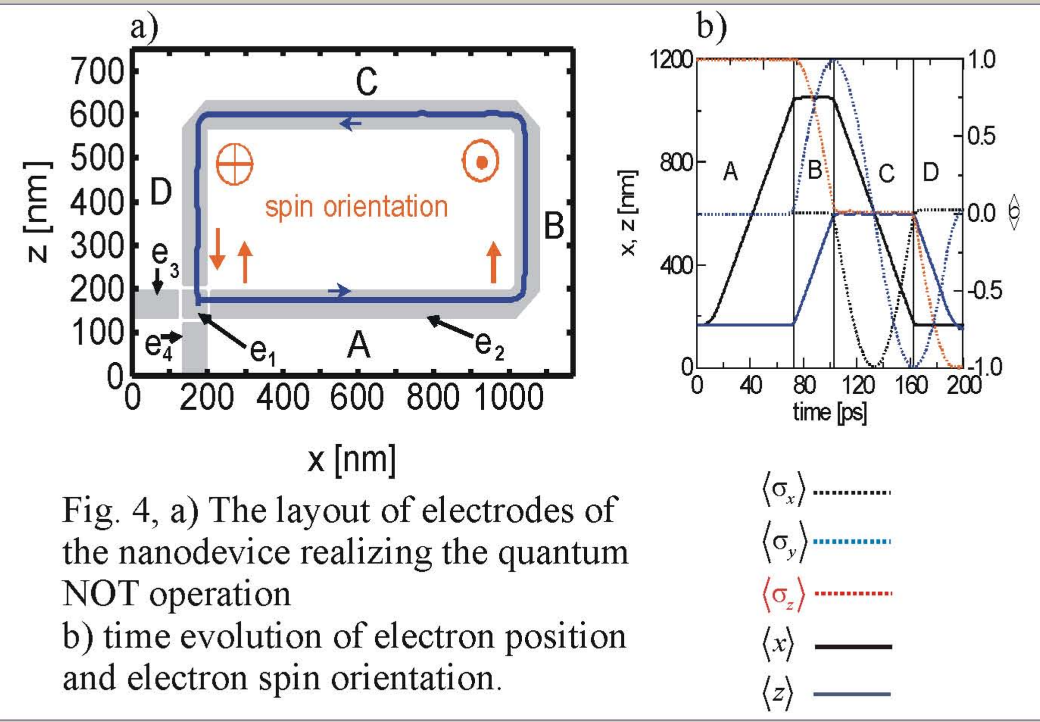

Fig. 4, a) The layout of electrodes of the nanodevice realizing the quantum NOT operation
b) time evolution of electron position and electron spin orientation.

Applying adequate voltages on electrodes e1, e2, e3 and e4 it is possible to bind an electron under e1.

Next it can be set in ballistic motion in trajectory determined by e2 by decreasing the potential on e3 and e1. Electron wave function preserves its shape due to self-focusing mechanism and it finally returns under e1 where it can be trapped again As a result the electron is set back into its initial position while its spin rotated by the spin-orbit coupling is set to opposite value (Fig. 4b).

Electron spin read-out

Here we propose a nanodevice which enables electron spin set up and read out necessary in quantum computing. We use the influence of the spin-orbit interaction on the electron trajectory in order to distinguish particles with different spin.

In Fig. 5. we present the simulated motion of an electron in various initial spin states in the presence of the Dresselhaus coupling.

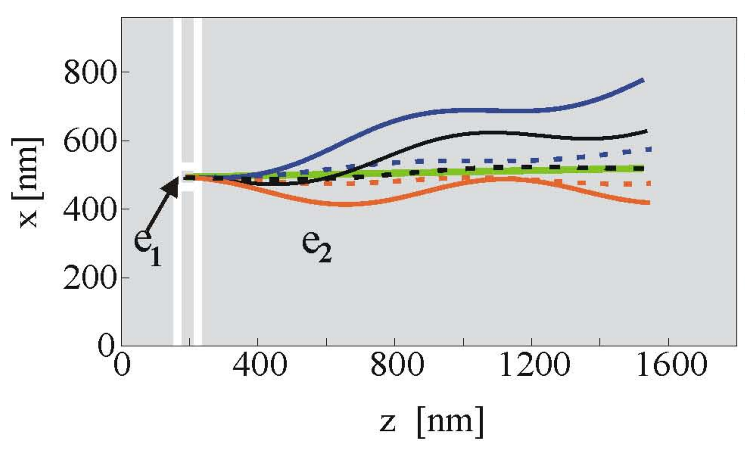

Fig.5. Electron trajectories for different initial spin states in presence of the Dresselhaus interaction.

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 which is shown in Fig. 6. In our simulation the electron was initially bound under e1. By setting adequate voltages on the electrodes it is forced to move parallel to the e3 in the beginning. Any shift in the motion direction will result in the electron being intercepted by e4 or e5. As can be seen in Fig. 6, only the electrons with spin parallel or anti parallel to the z axis go straight under e3.

The final goal is to distinguish electron with spin parallel to "z" axis from once with spin anti-parallel. We have proposed two nanodevices. In first proposal (Fig. 6.) electron is carried into a magnetic semiconductor layer containing Mn^{2+} ions (marked with vertical lines).

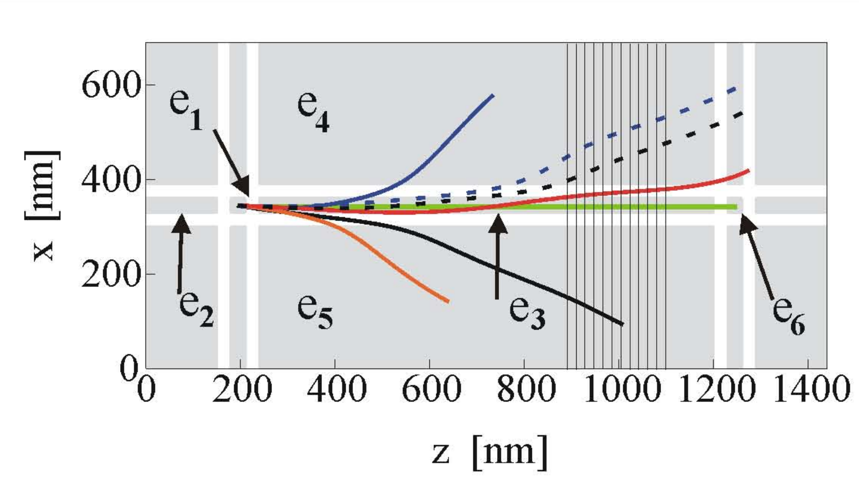

Fig. 6. The layout of electrodes in a nanodevice filtering-out electrons in spin state having any x or y component.
The trajectories of electrons with different spins are marked as in Fig. 2. Spin up electron passes through the semimagnetic area (marked with vertical lines) and spin down electron reflects from it.

Depending on spin orientation electron can penetrate the magnetic layer or reflect from it. This behavior is due to interaction between electron spin and Mn^{2+} ions spins. This device can perform electron spin read out and set up. A disadvantage of this solution is the necessity of using an external magnetic field to polarize Mn^{2+} ions.

In alternative approach (Fig. 7) the direction of electron motion which was initially parallel to "z" axis is altered by about 90^0 in "x" direction by electrode with appropriate geometry. Due to spin-orbit (Dresselhaus) interaction the initially spin up electron is captured by upper (e6) electrode and spin down electron is trapped under lower (e7) one. In this approach application of magnetic field is not necessary. However the original electron spin state is destroyed in last step of the measurement process. Such a nanodevice is able to perform only read-out of an electron spin.

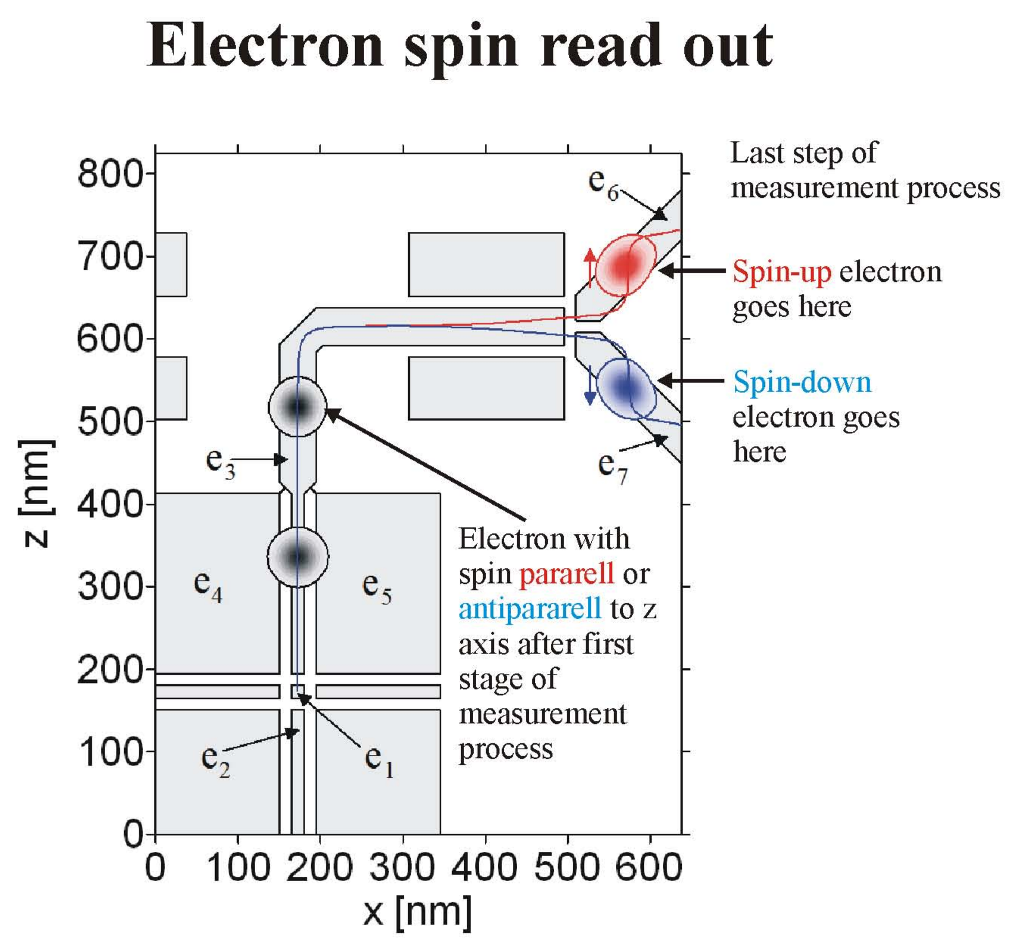

Fig. 7 The nanodevice in which the initial electron spin orientation is measured without applying external magnetic field.

Conclusion

- **We put forward and simulated the operating of two alternate nanodevices based on the induced quantum dots and wires, which could be used both to spin accumulation and to perform an 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 microwaves.**

Acknowledgements

This work was supported by the Grant No. N N202 128337 from the Ministry of Science and Higher Education, as well as by the "Krakow Interdisciplinary PhD-Project in Nanoscience and Advances Nanostructures" operated within Foundation for polish Science MPD Programme co-financed by European Regional Development Fund.

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