All electrical control of quantum gates for single heavy hole spin qubits in the presence of nuclear spins

P. Szumniak and S. Bednarek

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science,
al. Mickiewicza 30, 30-059 Kraków, Poland

Recently the spin state of the hole emerged as an alternative and very promising candidate for the realization of a qubit in semiconductor solid state systems. Its main advantage over the electron spin is the fact that the hole is less sensitive to the interaction with the nuclear spin of the surrounding material. Since the hole is described by a p-type orbital in many semiconductors, its wave function vanishes at the nuclear site and thus the contact hyperfine interaction between hole spin and nuclear spin is canceled. Even though holes still experience interaction with nuclear spins with dipolar character, it is about ten times weaker than the contact interaction for electrons [1, 2, 3]. Consequently, the coherence time of the spin state of the hole is longer than for the electron spin. The coherence time also depends on the heavy hole (HH)-light hole (LH) mixing. For pure HH states, the coherence time of the hole reaches its maximum because the interaction between hole spin and nuclear spins has an Ising type character [1, 2].

We propose a set of the nanodevices [4] which can act as Pauli X, Y , Z quantum gates and as a gate that acts similar as a Hadamard gate (i.e. it creates a balanced superposition of basis states but with an additional phase factor) on the heavy hole spin qubit. The proposed devices exploit the self-focusing effect of the hole wave function[5] which allows for guiding the hole along a given path in the form of a stable soliton-like wave packet[6]. Thanks to the presence of the Dresselhaus spin orbit coupling, the motion of the hole along a certain direction is equivalent to the application of an effective magnetic field which induces in turn a coherent rotation of the heavy hole spin[7]. The hole motion and consequently the quantum logic operation is initialized and controlled only by weak static voltages applied to the electrodes which cover the nanodevice.

In our calculations the interaction between hole spin and nuclear spin bath of the CdTe host material is considered within the quasi static approximation (QSA)[8] - hole spin experiences effective random nuclear magnetic field with non-homogeneous Gaussian distribution[2]. Such an interaction leads to a dephasing of the hole spin qubit (i.e. decay of the Rabi oscillations). The effect of the valence band mixing as well as an influence of the width of the nuclear spin distribution on the hole spin dynamic will be discussed.

[1] J. Fischer, W. A. Coish, D. V. Bulaev, and D. Loss, Phys. Rev. B **78**, 155329 (2008).
[2] C. Testelin, F. Bernardot, B. Eble, and M. Chamarro, Phys. Rev. B **79**, 195440 (2009).
[3] E. A. Chekhovich, A. B. Krysa, M. S. Skolnick, and A. I. Tartakovskii, Phys. Rev. Lett. **106**, 027402 (2011).
[4] P. Szumniak, S. Bednarek, S. Pawłowski, and B. Partoens, ArXiv (2013).
[5] S. Bednarek, B. Szafran, and K. Lis, Phys. Rev. B **72**, 075319 (2005).
[6] S. Bednarek, B. Szafran, R. J. Dudek, and K. Lis , Phys. Rev. Lett. **100**, 126805 (2008).
[7] P. Szumniak, S. Bednarek, B. Partoens, and F. M. Peeters, Phys. Rev. Lett. **109**, 107201 (2012).
[8] I. A. Merkulov, Al. L. Efros, and M. Rosen Phys. Rev. B **65**, 205309 (2002).