dr hab. Jerzy Dajka, prof. UŚ
Institute of Physics
University of Silesia

Katowice, 11.08.2013

Review of Ph.D Thesis
Design and computer simulations of the nanodevices to application in quantum computing
by mgr inż. Paweł Szumniak

Quantum computing requires quantum computers. It is a tautology. There are at least few quantum algorithms of spectacular power and unusual properties going far beyond the power of their classical ancestors. Two wide classes consists of search algorithms and the algorithms dedicated to the so called hidden subgroup or discrete logarithm problem. Effective application of such algorithms will result in reevaluation of that what we mean by computationally complex.

Having software one needs hardware to implement theoretical ideas. Research of mgr P. Szumniak and his coworkers, the ideas formulated and developed in the dissertation, is a response to that need. The series of papers forming the dissertation has one main objective: to design realistic device which can serve as a hardware for quantum gates. Due to the essentially quantum character of quantum computing the devices proposed in the dissertation operate in nanoscale.

The dissertation consists of a series of four papers devoted to design and analysis of the properties of a class of nanodevices allowing for effective control of electron spin in semi-conducting materials:

1. P. Szumniak, S. Bednarek, P. Grynkiwicz and B. Szafran, *Nanodevices for high precision readout of electron spin*, Acta Phys. Pol. A 119, 651 (2011)

2. S. Bednarek, P. Szumniak and B. Szafran, *Spin accumulation and spin read out without magnetic field*, Phys. Rev. B 82, 235319 (2010)

3. P. Szumniak, S. Bednarek, B. Partoens and M. F. Peeters, *Spin–orbit mediated manipulation of heavy-hole spin qubits in gated semiconductor nanodevices*, Phys. Rev. Lett. 109, 107201 (2012)

4. P. Szumniak, S. Bednarek, J Pawłowski and B. Partoens, *All–electrical control of quantum gates for single heavy-hole spin qubits*, Phys. Rev. B 87, 195307 (2013)

Additionally the Author of the dissertation provides a well written commentary which bonds together results of his research.

All the four papers has already been published in well recognized scientific journals and has already undergone peer review procedure. I fully agree that all of them should have been published as they contain interesting, new and important results. Instead of an additional 'super–review' of constituents of the thesis I am going to analyze the papers [1-4] *in toto* as an integral object and judge if it is a suitable basis for public defense and awarding PhD degree by the Author.

Let me start with a formal issue: There are coauthors of the papers constituting the thesis. According to the attached declarations of the coauthors mgr P. Szumniak is the main contributor to the work included in his dissertation. That is why the series of papers [1-4] is suitable from formal point of view for his PhD dissertation.

<u>Summary of results</u>

In the dissertation the author presents an interesting class of electrically controllable quantum systems. Their properties are well summarized in the commentary to the dissertation. The author also provides a relation of his results to that previously obtained by some of his coworkers. The ideas included in the dissertation of P. Szumniak are novel and significantly different. They are also novel and in many aspects advantageous in comparison to other proposals known in the scientific literature. However the comparison included in the dissertation is rather qualitative.

There are advantages of the author's proposal indicated in the dissertation. First of all quantum control proposed and presented in the dissertation does not employ magnetic fields but rather relatively weak electric potentials. That is very interesting and important results. This feature is particularly useful and opens new possibilities of controlling single components of relatively large systems of qubits. This ideas result in very interesting proposals of nanodevices applicable for qubit preparation and read–out [1,2] via projective measurement.

Very inventive design of all the considered nanodevices allows to eliminate unwanted types of interactions and in effect to obtain longer coherence times of the pseudospin used to encode qubits. Here the use of heavy holes [3,4] effective decoupled from light holes in Luttinger–Kohn 4D model is particularly interesting and important. Effective manipulating of qubit via spin orbit interaction (of Dresselhaus or Bychov–Rashba type considered in the dissertation) allows to perform single qubit unitary quantum operations with no e.g. microwave control typical for other solid–state qubits often used e.g.

for quantum dots.

Let us notice that the ideas presented in the dissertation satisfy majority of the famous 'DiVincenzo axioms' for quantum computing.

Critical remarks

Studying real time evolution of driven quantum systems is one of difficult problems in quantum dynamics. Such type of evolution is essential for modelling quantum control. As long as the applied modelling remains credible theoretical results agree with the results of forthcoming experiments. In the dissertation, motivated by earlier works indicated in bibliography, the author apply the so called Schrödinger–Poisson method. In simple words: to obtain time evolution of the qubit state one needs to solve self–consistently the Schrödinger equation of the charged pseudospin carrier and the accompanying Poisson equation for the time dependent electric potential, which comes both from externally gate and is induced by moving charged carrier. As the result one obtains quantum dynamics of the mean field type. Such modelling is rather phenomenological. There are several reasons supporting such a modelling presented in the dissertation but none of them seem to be qualitative and fully convincing. An occurrence of possible many body effects is also not discussed. There is also no discussion on the quality and credibility of applied numerical method for the Schrödinger–Poisson calculations. There are several field theoretic methods dedicated to quantum systems out of equilibrium known in non–equilibrium statistical mechanics. Any comparison (even in simplest, trivial examples) of the results obtained via Schrödinger–Poisson method with that going beyond mean field would certainly help to judge credibility of applied approximation. Of course, an experiment would be even better.

Any electromagnetic field is a natural source of noise of various kinds. In other words, except deterministic signal one can expect noisy background. Especially when the signal is weak, as in the case discussed in the dissertation, one can expect relatively significant signal–to–noise ratio. Of course, one can hope that such 'randomization' can be neutralized by suitable error correcting procedure. However the character of this procedure depends on the character of the noise–induced disturbance which in this work is not evaluated. Contrary to the internal, fully quantum mechanical noise, unavoidably affecting transport properties of a qubit, electromagnetic noise in Schrödinger–Poisson approximation could be described by classical stochastic perturbation.

Not all controllable quantum systems are suitable candidates for quantum computing. It seems that the proposal presented in the dissertation fulfils most of the DiVincenzo requirements. Unfortunately, the Author did not consider a very important problem of implementation of two–qubit gates. It is known that quantum algorithms require such gates. It would be interesting to present any predictions concerning this topic in the dissertation.

Conclusions

Despite some general criticism mentioned above the dissertation of mgr Szumniak is very interesting and important. The results contained in the dissertation open new and promising directions for practical implementations of quantum information processing. In particular it is a significant step in development of quantum computation. The results are original and interesting and will encourage other researchers to follow the presented ideas. Thanks to this type of research quantum information processing transcends purely theoretical, or mathematical, physics and becomes promising for practical applications.

The thesis reaches all standards of quality required for PhD thesis. Therefore I recommend mgr P. Szumniak to be admitted to further stages of the procedure of awarding degree of Ph.D in physics.

I also recommend honoring the thesis according to the usual local practice. Due to the highest quality and significance of the results the dissertation is a distinguishing scientific work and should be graded *summa cum laude.*

Jerzy Dajka