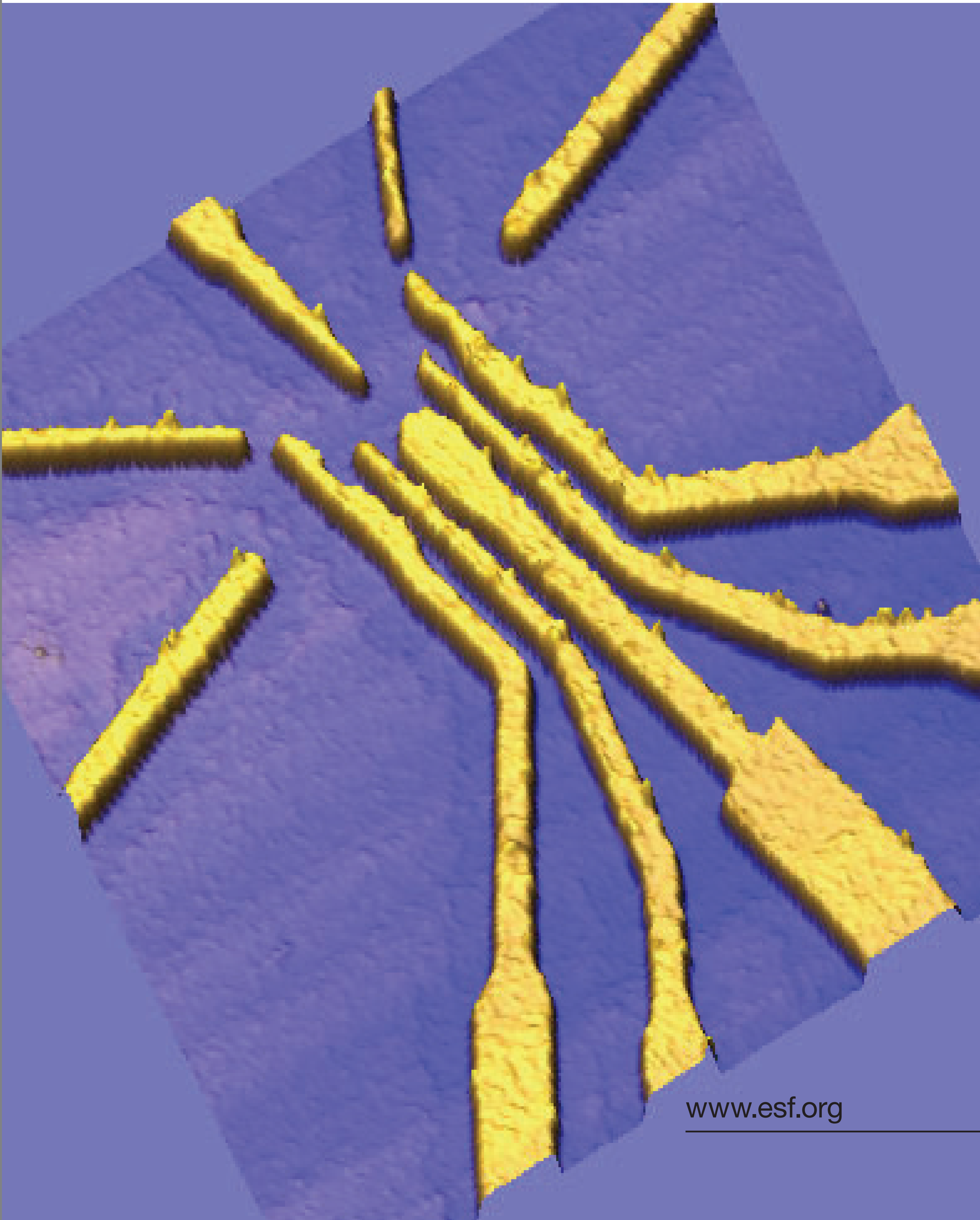
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

RESEARCH NETWORKING PROGRAMME

QUANTUM SPIN COHERENCE AND ELECTRONICS (QSpiCE)

Standing Committee for Physical and Engineering Sciences (PESC)



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Cover picture:
AFM image of a lateral double quantum dot
(Quantum Transport group, TU Delft)

Summary

A physical realisation of quantum information processing requires the use of technologies resting on coherent quantum transport and correlation phenomena. Due to the relatively weak coupling of spin with electric fluctuations of the environment, the spin degree of freedom appears as an ideal candidate for quantum information applications. With the ESF Research Networking Programme QSpiCE, we plan to investigate quantum spin-dependent effects and transport in nanoscale structures such as semiconducting nanowires, carbon nanotubes, quantum dots and graphene nanoribbons. QSpiCE aims to improve the manipulation and the control of the electron or hole spin in nanostructures and to analyse and harness the various mechanisms leading to relaxation and decoherence of spin in nanoscale objects. QSpiCE should help to strengthen networking between the leading European groups in the field and thus increase their influence in this important and popular field of modern condensed matter physics.

Introduction

The scientific activity of QSpiCE is focused on a systematic investigation of spin-related quantum transport phenomena in nanostructures. This includes semiconductors, carbon nanotubes and also more recently developed materials like graphene. QSpiCE aims to identify the relevant physics underlying coherent spin transport and control in such low-dimensional systems, seeking new microscopic schemes for quantum information processing such as manipulating the electron spin via correlation effects, engineered spin-orbit coupling, g-factor control, or by means of optical methods.

Electronics and spin-based quantum computing in the solid state have become strongly interconnected fields where fundamental issues related to the spin dynamics of electrons in semiconductors or in organic compounds are of interest. The main objective of the ESF Research Networking Programme QSpiCE is to investigate the coherent manipulation and control of electron or hole spin in nanostructures, the study of the spin relaxation and decoherence in nanoscale objects, the analysis of important spin effects in electron transport and, finally, opto-spintronics (the manipulation of the electron/hole spin via photons).

QSpiCE will provide interdisciplinary training for both theorists and experimentalists in the field of quantum spintronics. The activities of the programme include the organisation and support of research conferences, workshops and schools for young scientists together with a visitor programme for short (short visit grants) and long visits (exchange grants).

The running period of the ESF QSpiCE Research Networking Programme is five years, from June 2009 to June 2014.

Scientific Goals

Most of the current semiconductor technology is based on the control of the electron charge. Only recently, it has been proposed that electron spin could be used as a new control variable. Yet the combination of spin current and quantum physics has not so far been much developed. In particular, the control of electron spins in phase coherent set-ups offers immense opportunities for novel devices, like spin-based transistors, single electron spin valves or spin based quantum computers. In this new field – which can be termed ‘quantum spintronics’ – the individual electron spin becomes a central object. For instance, full control of an elementary quantum two-level system leads to proposals for quantum-based information processing in the solid state. In this context, the electron spin appears to be a promising candidate for such a qubit, owing to its relatively long coherence times in a solid state environment.

The main objectives of the QSpiCE programme are to investigate coherent quantum spin effects in nanoscopic systems. Along the lines of the main objectives, the proposed research will be focused on the following four topics:

A. Manipulation and control of electron or hole spin in nanostructures

One first challenge aims at studying, improving and comparing complementary techniques for inducing electron spin coherent rotations: electron spin resonance via micro-wave electric fields or via micro-wave magnetic fields. These operations should be performed faster than the spin decoherence rate in order to observe Rabi oscillations.

Part of this programme will also be turned in parallel toward the manipulation of coherent hole spin using electric fields by taking advantage of the strong spin-orbit coupling and therefore offering one way to circumvent restrictions dictated by selection rules.

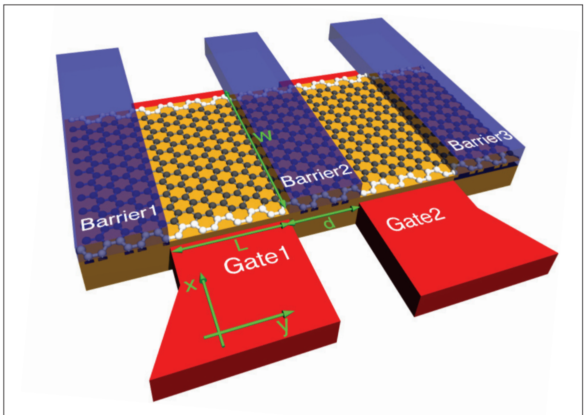

Figure 1. Schematic of a graphene-based double quantum dot (after B. Trauzettel, D.V. Bulaev, D. Loss and G. Burkard, *Nature Physics*, 2007)

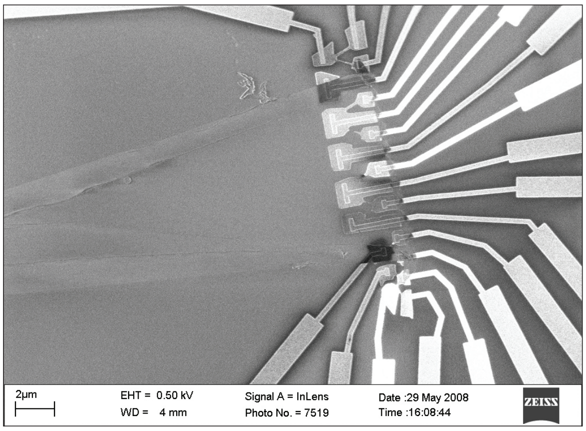

Figure 2. Image of a graphene nanoribbon (Low Temperature Laboratory, Helsinki University of Technology)

Another goal is to address the coherent coupling and entanglement between two spins in order to perform two-qubit operations. They can be realised via Heisenberg exchange interaction between two electron spins in adjacent dots using an all-electrical control scheme. Two-qubit operations are essential for universal quantum computing.

B. Relaxation and decoherence of electronic spin in nanoscale objects

We would like to understand better the different mechanisms leading to spin relaxation and decoherence in nanostructures. Of central interest is the decoherence of the electron or hole spin due to the hyperfine interaction with the surrounding nuclear spins. One goal is to control the Overhauser field that the nuclei generate at the position of the electron or hole. A possible approach is to narrow the nuclear spin distribution by performing measurements on the electron spin. Another interesting approach to narrow this nuclear spin distribution is to polarise them. A recent proposal suggests that this may be achieved by going to a low enough temperature, below which the nuclear spins embedded in the electron liquid may be ferromagnetically ordered. Such theoretical prediction has first to be checked experimentally and refined before it can be used for quantum information purposes.

Another important goal of the programme will be to understand better the spin relaxation mechanism and therefore the spin currents in carbon-based nanostructures such as carbon nanotubes and graphene which are very promising materials for spin-based quantum computing.

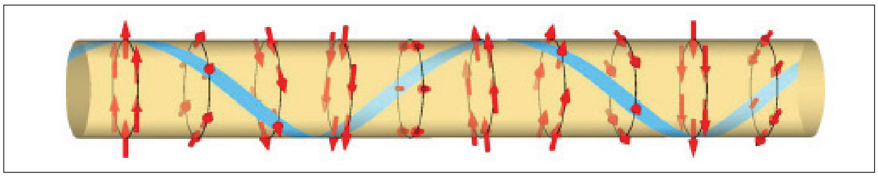

Figure 3. Illustration of the helical nuclear magnetism of a carbon nanotube (after B. Braunecker, P. Simon and D. Loss, *Phys. Rev.* B, 2009)

C. Spin effects in electronic transport

We plan to study spin-related effects via transport through nanostructures. When a nanostructure is embedded between two superconductors, the Josephson current turns out to be very sensitive to the magnetic properties of the nano object. This property could also be used to access the spin dynamics of the nanostructure via some interferometry or directly via the ac Josephson effect. This is presently a very active and promising area of research that we plan to investigate in close collaboration between theory and experiments. On the more theoretical side, we note that while the equilibrium properties of a quantum dot with a net spin are rather well understood, its non-equilibrium properties are however poorly understood and constitute a major challenge which may unlock our understanding of strongly correlated non-equilibrium phenomena.

Spin-related effects also play a prominent role in systems with strong spin-orbit interactions. Our focus is to analyse various spin-related phenomena in systems such as the magneto-electrical effect, the electric-dipole-induced spin resonance in extended and confined systems, the control of single confined spins, the Zitterbewegung effect, the spin-Hall effect and the spin physics in the recently discovered topological insulators.

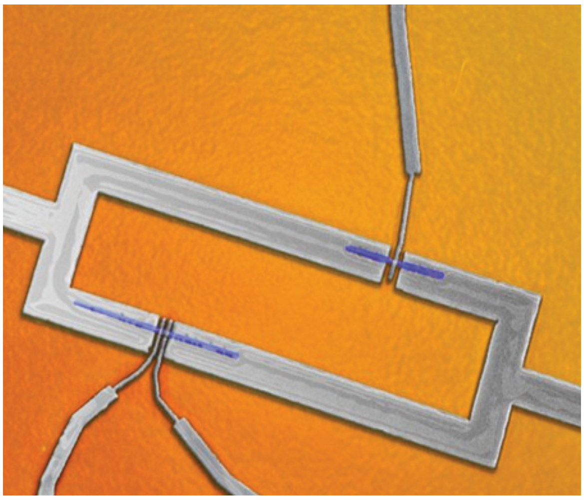

Figure 4. Image of a superconducting nanowire device (Quantum Transport group, TU Delft)

D. Opto-spintronics

We are aiming to design a system in which localised electron or hole spins in quantum dots and flying qubits (such as the polarisation of photons) can be integrated in a single device such that state transfer from localised to flying qubits and vice versa is easily realisable. From the theoretical side, we would like to understand better the different sources of decoherence in these combined systems where very little is known at the moment. From the experimental side, it is challenging to combine nanoelectronics at dilution fridge temperatures with optics. Nevertheless, the functionality of such a device would be superior to other (all electronic based) realisations of the coupling of localised to flying qubits.

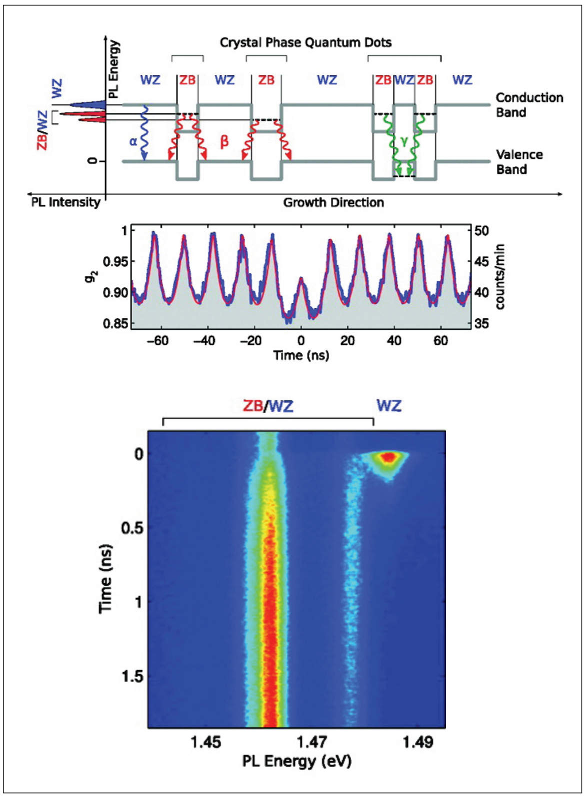

Figure 5. Photoluminescence measurements in crystal phase quantum dots (after N. Akopian, G. Patriarche, L. Liu, J.-C. Harmand and V. Zwiller, *Nano Letters*, 2010)

Activities

Research conferences/summer schools

QSpiCE will organise a summer school in year 2 and a big research conference in year 4 of the funding period. Furthermore, QSpiCE will co-sponsor conferences/schools whenever the scientific aims of the programme are positively influenced by the corresponding activity. This will, for instance, be done for the school on *Spin-based quantum information processing* in Konstanz, Germany in August 2010.

Workshops

It is planned to organise three QSpiCE workshops over the duration of the programme. The first workshop of this series will take place in Acquafredda di Maratea, Italy in October 2010. Additionally, workshops related to the scientific aims of the programme will be co-sponsored. This, will, for instance, be done for a workshop on *The physics of micro and nano scale systems* in Lund, Sweden in June 2010.

Short visit grants

Short visit grants facilitate visits between scientists involved in the QSpiCE programme. Visits for a duration of up to 15 days are funded based on the scientific excellence of the proposal.

Exchange grants

QSpiCE exchange grants aim at promoting exchange visits lasting from 15 days to up to six months.

Website

All applications need to be submitted to the ESF using online application forms that can be found on the QSpiCE website: www.esf.org/qspice.

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For the latest information on this Research Networking Programme consult the QSpiCE website:
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