Quantum Effects in Nano-Devices: Measuring a Single Quantum System

Quantum nano-structures are likely to become primary components of future electronic devices. Presently the majority of these structures, such as nano-mechanical resonators, semiconductor quantum dots, single electron transistors, and similar low dimensional structures, exist as prototypes in research laboratories or just being contemplated. Practical realization of quantum devices faces a number of challenges. Besides apparent difficulties with device fabrication, which typically requires micro– to nanometer scale resolution, there are numerous fundamental problems. These problems include phase relaxation (decoherence) that erodes operation of a quantum device as well as the problems of control, such as manipulation and measurement of the quantum states in a device. However, the benefits from the successful implementation of these devices can be enormous and have to do with the fact that, in their operation, the quantum devices utilize the fundamental properties of nature that do not have direct analogs in classical physics.

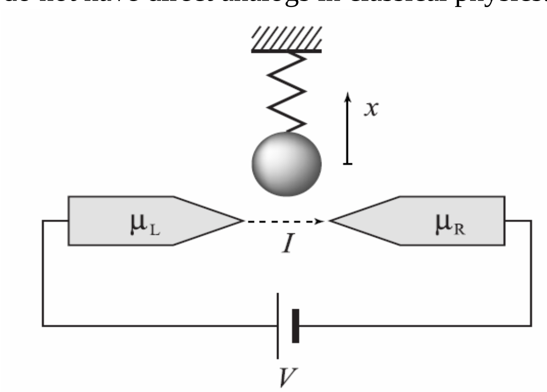

Figure 1: *Example of a Nano-Electro-Mechanical system: nano-mechanical resonator or a localized phonon mode coupled to a non-equilibrium tunnel current. The current measures the mechanical state of the resonator.*

These properties are quantum coherence, i.e., a possibility for a quantum system to occupy several states simultaneously, and quantum correlations, also known as entanglement. It is these two features of quantum physics that open a number of new technological possibilities, ranging from spintronics that relies on electronic spin rather than charge as an information carrier to quantum information processing, which promises a new era in computer science.

My work on quantum nano-devices focuses on theoretical aspects of (i) quantum control and measurement; (ii) coherence/ decoherence; (iii) transport through quantum nano-devices; (iv) quantum computing.

Recently my colleagues and I proposed a novel approach to detection of a *single spin magnetic resonance signal*. In particular, we studied resonant tunneling in single electron traps in a Field Effect Transistor (FET) under the conditions of Electron Spin Resonance. This system has a promising application as a candidate for the implementation of quantum information processing. We have demonstrated that under the appropriate conditions, the resistivity of the FET conduction channel develops a peak that can be associated with coherent transitions between the occupied and unoccupied trap states due to the applied rf-field. Experiments carried out by the group of H. -W. Jiang and E. Yablonovitch at UCLA demonstrated that electron spins in the traps can be efficiently manipulated by the applied rf-fields [1].

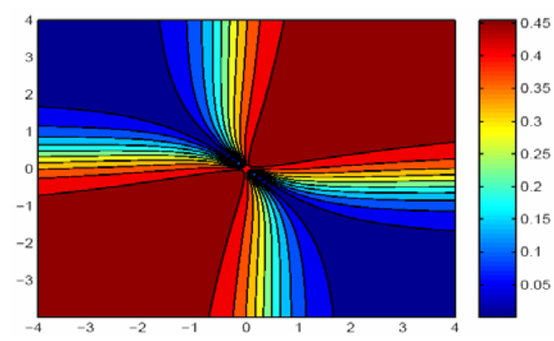

Figure 2: *Sensitivity of a single electron transistor measuring mechanical vibrations of a micromechanical resonator as a function of chemical potentials in the leads of the transistor (vertical and horizontal axes).*

Another possibility to test quantum mechanical properties of a single quantum system is via quantum transport and quantum noise in nano-electro-mechanical systems. These are a new generation of hybrid devices that involve a mechanical degree of freedom, such as a localized vibrational mode (an optical phonon mode or a micro-mechanical resonator) coupled to an electric circuit (a point contact, etc.), e.g. Fig. 1. The electrical circuit provides a readout of the state of the vibrational mode as well as an excitation mechanism for the imbedded vibrational mode. Such devices have novel electronic functionalities, such as strongly non-linear DC current response, generation of AC signals, negative differential conductivity, switching, and hysteretic behavior.

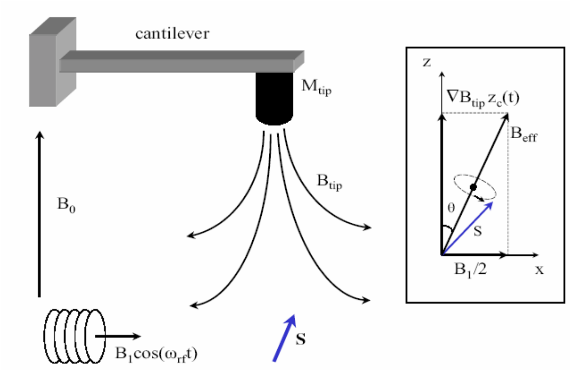

Figure 3: *Schematics of Magntic Resonance Force Microscopy experiment. A magnetic nano-particle is attached to a tip of micromechanical cantilever. The cantilever is used to excite and to detect spins the resonant layer. The inset shows dynamics of a spin in the resonant layer.*

The system involving a Single Electron Transistor (SET) as an electrical probe has recently been fabricated at the Laboratory for Physical Sciences (Maryland) in the group of K. Schwab. The preliminary experiments have shown that the system can operate as an ultra-sensitive displacement detector due to the resonant nature of tunneling in the SET. Based on fully quantum-mechanical description of the system [2], we have determined the limits on sensitivity of the system and identified the regimes in which the most efficient detection of the resonator displacement is possible (Fig. 2).

Magnetic Resonance Force Microscopy (MRFM) is a newly emerging technique that allows for ultrahigh sensitivity magnetic resonance measurements. One of the bottlenecks in the further advancement of the technique had been an increased spin relaxation/decoherence due to the proximity of the magnetic tip. We have identified the main mechanisms of spin relaxation in MRFM and proposed a scheme for an efficient magnetic noise reduction [3]. This scheme has been recently implemented in MRFM experiments by Dr. D. Rugar and collaborators at IBM, who demonstrated a reliable evidence of single paramagnetic spin measurement with MRFM.

Localized electron states in 2D heterostructures (such as quantum dots) provide another possibility for measurement and manipulation by a state of a single quantum system. Particularly the physics of quantum relaxation (decoherence) in these systems is of interest as they are currently being considered as bits for quantum information processing (qubits). We studied indirect interaction between the nuclear spins in a 2D heterostructure as a scheme for controlled coupling between spin-qubits and coherent effects in resonant STM tunneling through paramagnetic impurities as a possibility for single spin measurement [4].

References:

1. *A Scheme for Electrical Detection of Spin Resonance Signal from a Single Electron Trap*, I. Martin, D. Mozyrsky, and H. W. Jiang, Physical Review Letters **90**, 018301 (2003).
2. *Quantum Limited Sensitivity of SET-Based Displacement Detectors*, D. Mozyrsky, I. Martin, and M. B. Hastings, Physical Review Letters **92**, 018303 (2004).
3. *Theory of Spin Relaxation in Magnetic Resonance Force Microscopy*, D. Mozyrsky, I. Martin, D. Pelekhov, and P. C. Hammel, Appied Physics Letters **82**, 1278 (2003).
4. *Indirect interaction of Solid-State Qubits via Two-Dimensional Electron Gas*, D. Mozyrsky, V. Privman and M. L. Glasser, Physical Review Letters **86**, 5112 (2001).

Contact Information: Dima Mozyrsky - Center for Nonlinear Studies and Condensed Matter & Thermal Physics, MS-B258 Los Alamos National Laboratory, Los Alamos, NM 87545 Phone: (505) 667-9657; e-mail: mozyrsky@cnls.lanl.gov