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.

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].

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.

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.

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.

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

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].

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