NIRT: Next Generation Atom Chips for Quantum Information Technology

NSF NIRT Grant 0200742
PIs: **N. P. Bigelow** *(Physics and Astronomy)*, **M. Feldman** *(Electrical and Computer Engineering)* **and C. R. Stroud** *(Institute of Optics)*
The University of Rochester

Introduction and Objectives

In modern solid-state electronics, electrons move inside submicron scale semiconductor and metallic structures that are together are organized into a single, integrated and miniature electronic system or circuit – the chip. To control the motion of the electrons, carefully tailored potentials are applied to the circuit, and the motion of the electrons and their various interactions cause the desired electrical performance. In a recent wave of experiments, researchers in have demonstrated that it is possible to control the motion of laser cooled atoms suspended above a nanofabricated charged and current carrying structures dubbed the "atom chip" [1]. With further advancement in atom chip technology, it may eventually be possible to achieve the same level of control over neutral atoms as we currently have over electrons and over photons. Atom chips hold the promise to open a new field of coherent matter-wave nano-devices for application to quantum information and quantum computation. The motivation of our NIRT is that these nano-devices hold the promise to accomplish for quantum computing and information processing what integrated circuits have done for modern day computers. We are evolving the concept of the atom chip well beyond the current "first demonstration" level. We take an interdisciplinary approach to atom chip development to provide an atom chip technology suitable for the complex challenges of quantum information processing. Specifically: (1) we are developing atom chips based on superconducting nano-structures, (2) we are developing atom chip based techniques for creation and manipulation of atoms in Rydberg states and of polar molecules and (3) we will apply atom chip created Bose-Einstein condensates (BECs) to create and study mesoscopic entanglement. Each of these goals is linked to key technologies for extensible quantum computation with application to fundamental physics.

Harnessing the atom

The basis of the atom chip concept is that electric, magnetic and laser fields can be used together to manipulate the motion of an atom (i.e. to control its external coordinates) as well as to control its (internal) quantum state. Although these concepts have been known since the first developments of the quantum view of the atom in the early 1900s, it was only when the powerful techniques of laser cooling were developed in the late 1980s and 1990s that control of the external coordinates of the atom became possible. Until recently, research involving ultra cold atoms has relied on suspending the atoms in free space where the interplay of various external fields are used to manipulate and to probe the sample. Cold atoms prepared in such an apparatus have been used to realize important technological devices such as record-breaking atomic clocks [Fertig`00] and deBroglie wave gyroscopes [2]. While the above techniques focus on affecting the external motion of atoms – the atomic deBroglie wavepackets – the last decade has witnessed stunning advancements in our abilities to control the internal states of atoms. Using the tools of Quantum Optics, researchers have been able to literally sculpt the electronic wavefunction in so-called Rydberg states of atoms into wavepackets of their choosing [3]. In essence, what research has been shown is that it is possible to tailor the electronic wave function of the atom [4] that coherently interfere to create the overall desired state.

Quantum Information and Computation

Quantum computation is an entirely new form of information processing. The recent explosion of activity in quantum information has centered around the idea that a quantum system with a given set of states, or "levels", can be viewed as the quantum equivalent of bits called "qubits". A "qubit," codes information not just as "1" and "0" but also as coherent superpositions of the "1" and "0" states of a quantum mechanical two state system. This provides possibilities far beyond the capabilities of classical computation, and many important potential applications for qubit systems have been and continue to be discovered. The interaction of these qubits (particularly including effects of interference and entanglement) can form the basis for logical gates that form a non-classical system of logic. When collections of these gates are assembled into larger systems, they can form networks capable of processing registers of qubits encoded with data. What has made this possibility particularly attractive is that processing can occur in a uniquely parallel manner that allows interesting and important problems to be solved more efficiently than can be achieved using any known classical approach.

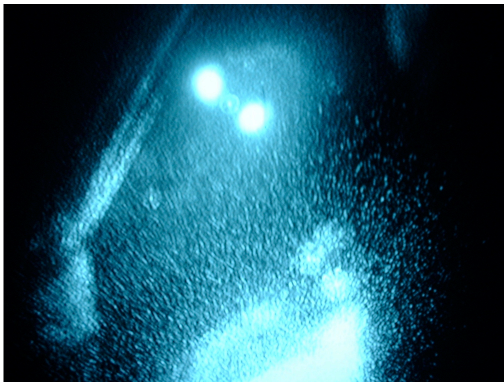
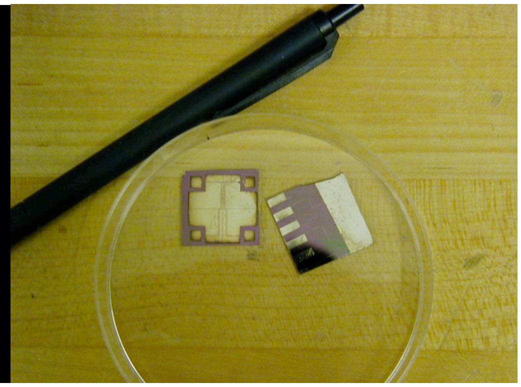
Experimental work towards quantum computation is increasing. The earliest demonstrations of qubit logical interactions were drawn from atomic and optical physics. And to date, the most successful physical realizations of quantum bits and gates has been achieved at NIST using trapped atomic ions as the essential quantum element [5and refs therein]. In these experiments, as in all other systems explored to date, one of the most fundamental challenges is to scale the system to a size that is large enough to make it useful; that is to realize an extensible quantum information system. Ideally, such a system must be completely isolated from its environment, yet be available for interaction and manipulation. The need for isolation derives from the fact that interaction of a quantum system with its "environment" leads to decoherence – to loss of entanglement and to the loss of quantum interference [5]. The conclusion is that the particular choice of a system best suited to quantum information technology is one of the most significant issues for the realization of scalable, robust quantum information technologies. Our effort to combine the atom chip, superconducting technology and Rydberg atom control is intended to address this need.

Research Accomplishments

Since its inception in the Fall of 2002, this NIRT team has focused on building the toolbox for the advanced atom-chip devices. Specifically: (1) realization of tools suitable for creating polar atomic/molecular species on an atom chip and (2) micro fabrication of atom chip structures. Both of these efforts offer significant collaborative opportunities.

Research Accomplishments: I. Realization of a hetero-nuclear surface MOT

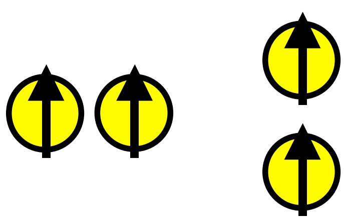
We have realized the first (that we know of) heteronuclear surface MOT. In these experiments a mixture vapor of approximately 10^7 Rb atoms and 10^7 Cs atoms are trapped at the surface of a atom chip / mirror. This project was a first step for (1) controlled cold molecule formation on-chip and (2) fast evaporative creation of an Rb BEC in the presence of the Cs background vapor. In the photo below the cloud (bright spot) to the left is the surface MOT whereas the "cloud" to the right is its reflected fluorescence as seen in the mirrored surface. Using magnetic trim coils we have already demonstrated the ability to scan the mixture cloud over the mirror's surface and to control the distance of the cloud from the mirror.

Research Accomplishments: II. Fabrication of UR Atom Chips

The first generation atom chip fabricated in the Rochester clean room / fabrication facility. On the above right is a simple atom chip with a double-Z trap fabricated using small gold wires deposited on a silicon wafer. Structures are ~100μm wide and ~5μm thick silver. An important point of collaboration with other NIRT investigators would be the fabrication with thicker, larger aspect ration structures. Significant effort is being dedicated to use of finite element methods to calculate accurate magnetic and electric field distributions from more complex current distributions.

Research Accomplishments: II. Fabrication of UR Atom Chips



Anisotropy of the dipole-dipole interaction and the internal quantum structure of the molecules allow important quantum informatics technologies [6]

Large polarizabilites of simple heteronuclear diatomic molecules makes them ideal physical qubits for quantum information. We have demonstrated the first creation of cold, ground-state heteronuclear molecules – NaCs.

The above work has been or is being published in Physical Review Letters and Physical Review.

References (10 point font)

For further information about this project email **nbig@lle.rochester.edu**

[1] R. Folman, P. Krüger, D. Cassettari, B. Hessmo, T. Maier, and J. Schmiedmayer, "Controlling Cold Atoms using Nanofabricated Surfaces: Atom Chips," Phys. Rev. Lett. 84, 4749 (2000).
[2] T. Gustavson, P. Bouyer, and M. Kasevich, "Precision rotation measurements with an atom interferometer gyroscope," Phys. Rev. Lett. 78, 2046 (1997).
[3] M.W. Noel and C.R. Stroud, Jr. “Shaping an atomic electron wave packet,” Optics Express **1**, 176 (1997).
[4] C.A. Sackett, D. Kielpinski, B.E. King, C. Langer, V. Meyer, C.J. Myatt, M. Rowe, Q.A. Turchette, W.M. Itano, D.J. Wineland, and C. Monroe, "Experimental entanglement of four particles," Nature 404, 256 (2000).