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14. ABSTRACT

Theoretical work established a quantum framework in which to address atom analogs of electronic devices and circuits. Initial focus was on isolated elements, particularly atom diodes and atom transistors. Two theoretical approaches addressed different device strategies, one based on double and triple potential wells, the other based on periodic structures that are analogous to semiconductor materials. The first approach is suited to implementations using ultracold atom chip technology, whereas the second is amenable to optical lattice experiments. Both approaches established the presence of atom flux gain in a simple transistor configuration. Further theoretical work developed an open quantum systems approach to simple yet complete circuits. This work provides the analytical tools for treating more complex atomtronic circuits. Corresponding experimental work focused on building an atom chip based Bose-Einstein Condensation (BEC) system for carrying out atom transistor experiments. Chip development demonstrated technology for fabricating structures having nanowires suspended across a substrate groove to avoid the deleterious impact of Van der Waals forces. This work established the foundation of atomtronics and the possibility of experimentally demonstrating such circuits in the near future.

15. SUBJECT TERMS

atomic physics, ultracold matter, atomtronics, Bose-Einstein Condensation, atom chips

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Final Report

FA9550-07-1-0083

Atomtronics: Research in Ultracold Atom Semiconductor Device Analogs

Dana Z. Anderson, PI

Atomtronics refers to ultracold atom analogs of electronic devices and circuits. The interest in this new field of endeavor arises largely from the access and ability to control the quantum behavior of atoms, in contrast to electrons in electronic circuits, which propagate as classical particles. Worked performed under this grant established a theoretical foundation for the analysis of the quantum behavior of ultracold atom diodes and transistors, as well as elementary circuits employing those devices. These two devices are the quintessential building blocks of the vast majority of non-trivial electronic circuits; thus they can be expected to play a pivotal role in atomtronic circuits. Moreover, as fundamentally nonlinear elements, they capture some of the most challenging aspects of moving from a classical to a quantum context for circuit analysis and synthesis: The question of *how* to construct a given quantum circuit remains an open one, and certainly the utility of quantum circuits is only beginning to be understood.

Work performed under this grant established (theoretically) atom diode and atom transistor behavior while in parallel we began an experimental program with long-term goals to carry out a demonstration of ultracold atom based devices. The key characteristic of a diode is that it permits current flow for only one sign of an applied potential difference. Translated to the atom domain, an atomtronic diode permits flow of an atom flux for one sign of an applied chemical potential difference, but not for the other. The transistor is a particularly powerful device, in which a large atom flux is controlled by a much weaker atom flux or chemical potential.

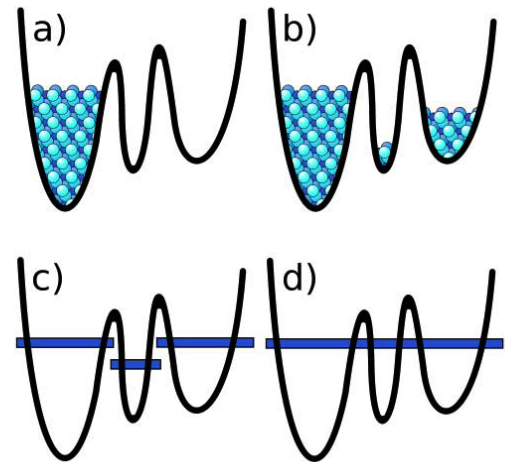

Figure 1. The geometry of a BEC transistor. When the number of atoms in the middle well is small, tunneling from the left into the right well is negligible a. This is due to the fact that the chemical potential of the middle well does not match that of the two other wells c. Placing atoms in the middle well increases the chemical potential due to interatomic interactions d and enables tunneling then atoms tunnel from the left into the right well. This happens because atom-atom interactions increase the energy of the middle guide b.

Theory Accomplishments

We took two theoretical approaches to atom device physics with complementary aspects. On the one hand, we modeled the diode and transistor in terms of double- and triple-well potentials as shown in Figure 1. This approach is amenable to atom chip implementation because the individual wells can be formed using simple wire structures. The second approach more closely resembles semiconductor electronic materials, using one-dimensional periodic potentials to produce desired atom conductivity properties. N-type and P-type doped semiconductor material analogs are shown in Figure 2. This second approach is suited to implementation with optical lattices. The first work on these two approaches appear in references [1] and [2], respectively. Reference [1] in particular, verified that a triple-well system can exhibit substantial gain under appropriate circumstances (see Figure 3) and has guided our experimental work. The first theoretical treatments of lattice based semiconductor analogs for a portion of the Ph.D. dissertation thesis of B. T. Seaman [3].

While the first theoretical works demonstrated the basic nonlinear behavior that is desired from these key elements, the description of a *circuit* is another matter. In particular, a circuit primarily describes a *non-equilibrium* system. Such systems are typically non-trivial to cast in a quantum formalism. Figure 4 shows a conceptually simple electronic diode circuit and its lattice-based atom analog. The question arises, even in this simplest of systems, what quantum-consistent treatment can address a continuous current flowing through the diode. A continuous current, it turns out, requires a dissipative mechanism. We have developed a model in which the battery terminals are represented by reservoirs, i.e., open quantum systems [4]. This technique has been borrowed from quantum optics where spontaneous emission into the vacuum serves as a dissipative mechanism.

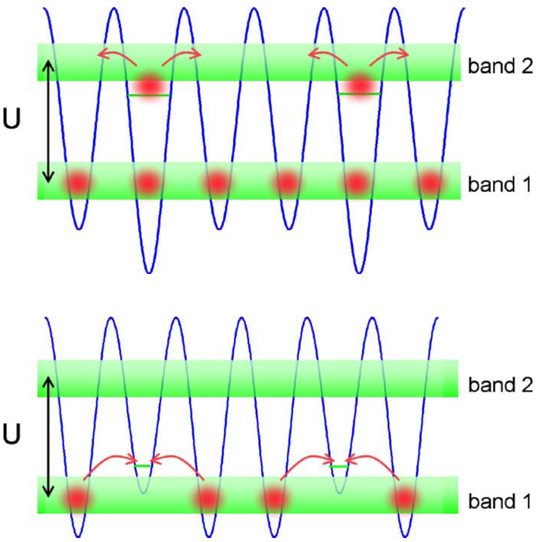

Figure 2. Upper: Schematics of an *N*-doped lattice. The donor sites feature a level right below the first empty many-body band. An atom which occupies this level can easily be excited and move throughout the lattice. Lower: Schematics of a *P*-doped lattice. Acceptor sites have a level right above the highest full band. Atoms can easily be excited into this level and allow for a

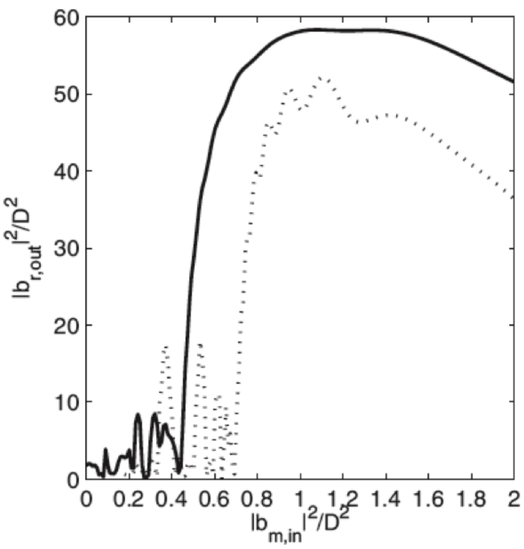

Figure 3. Number of atoms at the output well as a function of the number of atoms in the middle (gate) well for two different circuit conditions. This curve establishes that the

A diode is a device which blocks current given a reverse bias across its terminals, and conducts current with a forward bias. The open quantum systems approach has lead to an insightful picture of diode behavior using level diagram associated with the double well potential for forward and reverse bias.

This picture is illustrated in Figure 5. Each level picture depicts the three lowest unoccupied energy levels of the triple well system. The vertical direction represents energy. The energy placement of the various level diagram sets indicate the energy corresponding to the occupancy of the levels; In general, a greater number of particles present in the two wells increases the system energy. In the forward bias case, sooner or later the system evolves to a cyclic state in which atoms are transported across the diode from the left to right reservoir. In the reverse-based case the system evolves to a “dead end” in which atom flux across the well comes to a halt. Transistor as well as diode behavior are discussed in [4] and [5].

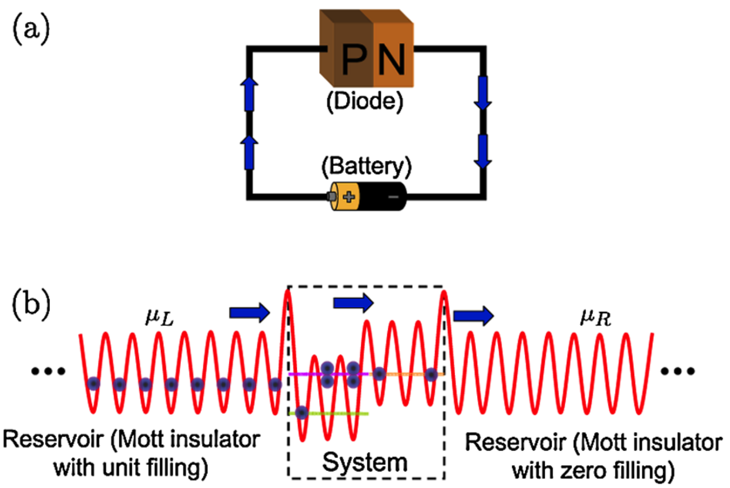

Figure 4. (a) An electronic circuit with a battery, resistive wires, and a p-n junction diode in the forward bias and (b) the atomtronic equivalent. The left reservoir has chemical potential μ_L and unit filling and supplies atoms that flow through the system (dashed box) to the right reservoir, with chemical potential μ_R and zero filling. The weak system-reservoir coupling is ensured by large tunneling barriers at each interface.

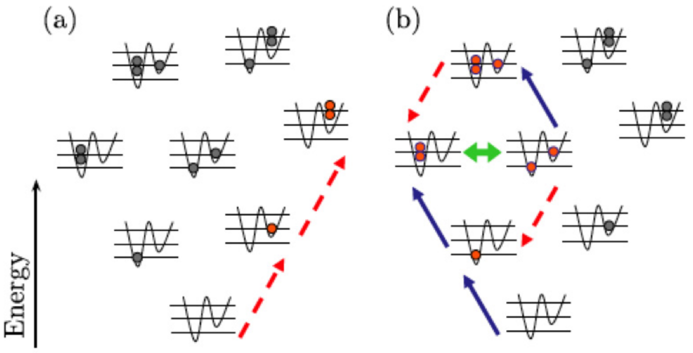

Figure 5. Dynamical path of an initially empty two-well lattice system. The vertical axis corresponds to the energy of the system’s quantum states. The solid (blue) and dashed (red) arrows indicate the transfer of atoms from the left and right reservoirs, respectively. (a) Reverse bias (low left-hand chemical potential and high right-hand chemical potential). Here the system evolves into the $|0,2\rangle$ dark state where it becomes trapped. (b) Forward bias (high left-hand chemical potential and low right-hand chemical potential). The resonance between $|2,0\rangle$ and $|1,1\rangle$ states, shown by the double-headed (green) arrow, allows the resonant transport of atoms across the lattice.

Experimental Accomplishments

Experimental progress under the grant heavily leveraged work done under the DARPA gBECi program. Progress attributed to this work was primarily toward the development of specific atom chip structures that could be used to carry out transistor experiments, and toward the construction of an atom-chip based Bose-Einstein Condensation (BEC) system for carrying out future experiments.

Transistor experiments based on magnetic-field generated trapping potentials require very small (300 nm) conductors suspended over a dielectric support structure. The suspension minimizes the impact of nearby surfaces, which otherwise subject ultracold atoms to Van der Waals forces, which can overwhelm the intended magnetic forces. The electron micrograph of Figure 6 shows a pair of 300 nm wide copper wires that are suspended over a 40 micron wide groove in a silicon substrate. This represents a rather substantial effort to develop a suspended nanowire technology compatible with our vacuum processing requirements, in which vacuum elements (including the chip) are subject to temperatures in the range of 300 - 400 °C.

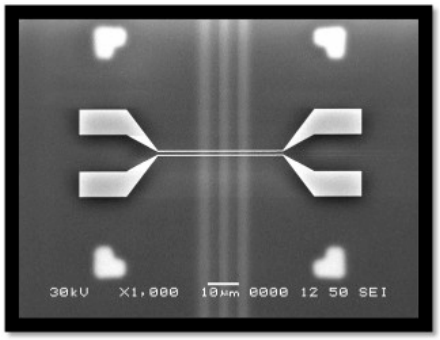

Figure 6. Electron micrograph of a pair of 300 nm wide wires suspended over a groove within a silicon substrate. Visible are an additional pair of (vertical) wires lying at the

While work on the transistor chip technology was underway, we constructed a BEC system using our conventional atom chip design. This system was operational shortly before the end of the grant period.

In the final year of the project we came to realize that nanowire technology needed considerable advancement before being useable in atom transistor experiments. At the same time, chip development is an costly research effort in itself. Thus we have since turned our attention to a hybrid approach in which atoms are trapped magnetically in our usual way, but then subject to an additional *optical* potential to obtain the desired diode and transistor well structures. This work is currently under way and is the subject of future work.

Epilog

This work was carried out by four senior physicists (D.Z. Anderson, PI, experimental physicist, M. J. Holland, co-PI, theoretical physicist, J. Cooper, theoretical physicist, and A.A. Zozulya, theorist at WPI) five graduate students (B. Seaman and R. Pepino, theorists, J. Stickney, theorist at WPI, Evan Salim, experimentalist, and Rick Ho-Chung mechanical engineer) as well as about 5 undergraduate students and one postdoc, Merit Kramer. Partial support for these researchers was also derived from the National Science Foundation.

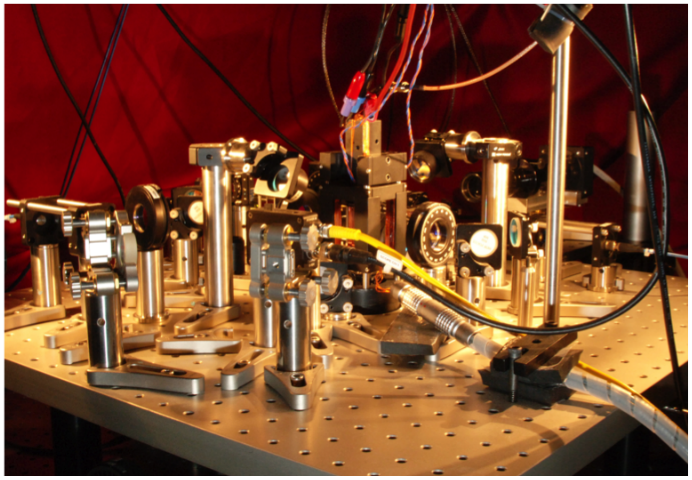

Figure 7. Atom chip BEC system designed for future transistor experiments.

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