Molecular Electronics

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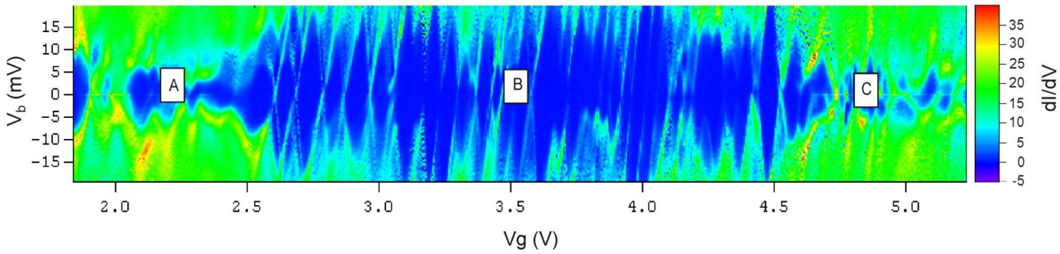
Goal - The goal of our work is to fabricate, characterize and learn how to control the quantum electronic properties of nanoscale particles and molecules.

Approach - Our approach is based on carbon nanotubes and trapped particles. Electronic transport measurements combined with imaging, and probing using atomic force microscopy are used to characterize and manipulate the nanoscale devices.

Electronic Coherence and Quantum Dots in Carbon Nanotubes

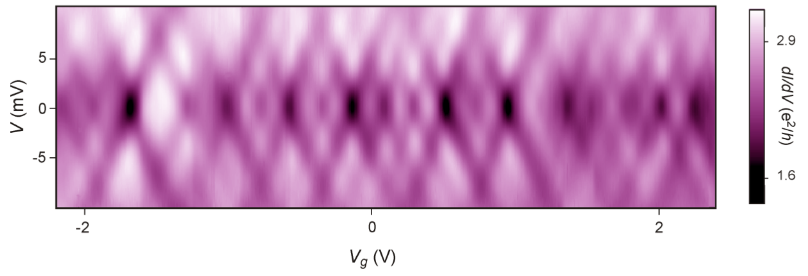
Bockrath et al. (2001) have shown the existence of naturally occurring resonant scattering centers in nominally "clean" carbon nanotubes. The resonant aspect of the scattering is demonstrated by using a scanned AFM tip to locally shift the chemical potential at the defect scattering state, and shows up in a scan image as a ring centered on the defect. In a sample with *two* defects of similar sensitivity, a quantum dot can be formed between the two scatterers. This is dramatically demonstrated by the existence of the Coulomb blockade as shown in the figure.

Differential conductance as a function of gate and bias voltage (T = 4 K)



Bozovic et al. (2001) have used an AFM tip to mechanically bend nanotubes sufficiently to form local kinks, where desired. For sufficiently sharp bends, a localized resonant scattering center, similar to those studied in Bockrath et al. (2000), is created. Scanned gate measurements show that the scattering centers were created by the kink formation. By creating two kinks only ~50 nm apart, a quantum dot was formed with Coulomb gap as large as ~40 meV which showed discrete charging effects up to ~100 K.

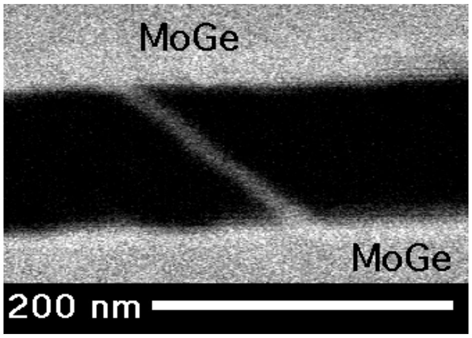
Liang et al. (2001) have demonstrated coherence of electron waves in (nominally defect-free) carbon nanotubes over distances of at least 0.5 μm by showing clear-cut Fabry-Perot interference patterns in a 2D plot of differential conductance vs. V and V_g, shown below. This graphically demonstrated the "electronic waveguide" property of nanotubes, so that the quantum dots described above between two scattering centers are analogous to the resonant cavities set up in electromagnetic waveguides between irises which partially reflect the e-m waves. The scattering is well described by a scattering matrix, which is 4x4 in this case because of the two modes of propagation in each direction in a metallic nanotube. The persistence of phase coherence of the electron waves over micron dimensions will be essential for quantum computing applications.



Self-Assembled Chains of Nanoparticles

It has been suggested that one dimensional arrays of small metallic islands weakly coupled by tunneling could have transport properties useful in constructing memories based on single-electron tunneling. For operation at or near room temperature, one needs structures so small that they would be very difficult to fabricate. On the other hand, sufficiently small *particles* can be readily produced by various means. Bezryadin et al. (1999) showed that electrostatic forces cause chains of nanoparticles to assemble between electrodes patterned at the relatively easy 1 μm scale. Because of the cumulative effect of many particles in series, these devices have threshold voltages ~0.25 V, much larger than the charging energy of an individual grain, without any impossible fabrication demands.

Superconducting Nanowires



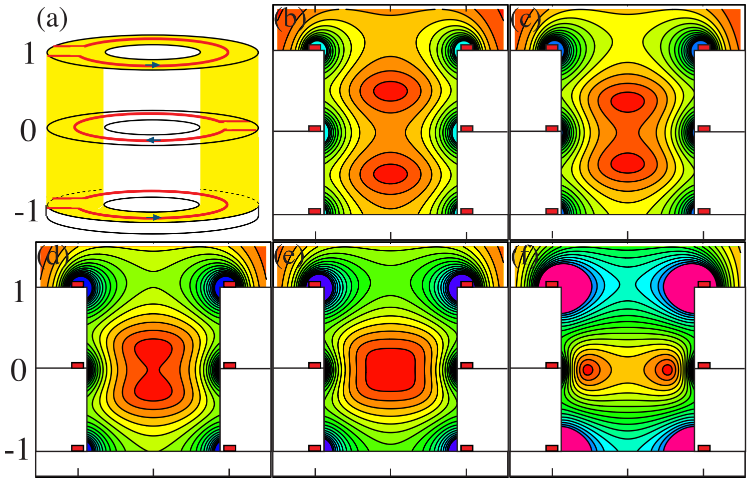
Theoretically, superconductivity (like all forms of long-range disorder) should be impossible in a strictly one-dimensional system. But quasi-one-dimensional systems like narrow filaments are well-known to show superconductivity. This raises the question of what is the actual limit on how thin a wire can be, while still showing superconductivity in the sense of a useful degree of resistance reduction. In addition to its conceptual interest, this question also arises as a limitation of the miniaturization of possible future superconductivity-based computers, whether quantum or classical. We have developed a technique for fabricating wires in the 5 to 10 nm diameter range by sputtering amorphous MoGe onto a carbon nanotube. Our early work (Bezryadin et al. 2000) was confined to wires of ~100 to 150 nm length. For these samples, those with normal resistance below the quantum resistance 6.5 kohm showed superconductivity, those with higher resistance did not. In later work on wires of length up to 500 nm, we have found evidence that the resistance per unit length (or equivalently the wire cross section) is a more general criterion. Numerically, a diameter of ~6 nm seems to be the breakpoint. Certain theories had predicted a critical diameter of ~10 nm, but there is as yet no theoretical consensus. It seems fairly likely that the criterion will turn out to be total resistance for short wires and resistance/length for long wires; the crossover length may be ~100 nm. But much more experimental and theoretical work will be required to sort this out in a definitive way.

Micro-Electromagnet Traps for Neutral and Charged Particles

Nanoscale particles and cold atoms create interesting possibilities for quantum electronics and quantum information processing. Techniques are needed to trap, guide, and manipulate particles on short length scales, and to integrate many such devices into "chips". We have designed and constructed mirrors, channels, traps, and more complex structures to control nanoscale particles by using micro-electromagnets. A micro-electromagnet is a conductor, patterned using lithography and clean room techniques, which creates magnetic fields that interact with the particle's magnetic moment. Using sapphire as a substrate to conduct away excess heat, we have achieved current densities ~10^8 A/cm^2 and magnetic fields > 0.1 T near the conductors. It is also possible to trap charged particles like electrons by using a small charged ring located in an external magnetic field. Micro-electromagnets have controlled cold atoms in a range of experiments, including the demonstration of a atom guide (Dekker *et al.* 2000) which channels cold atoms above a substrate.

We have developed methods to make three-dimensional micro-electromagnets by using multiple metal and insulator layers which are individually patterned lithographically (Drndic *et al.* 2001).

Possible devices include a microtrap, a tunable coupled double trap (shown above), and a trap on top of a mirror for particle cooling and control. We have also fabricated and tested structures to move magnetic nanoparticles in controlled ways. These include a two layer matrix of wires which can move nanoparticles in controlled paths and rotate small objects by controlling which wires carry current. These microelectromagnet devices may find applications in areas ranging from atom control, to controlled assembly of nanoparticles, to quantum information processing.



Micro-electromagnet double trap for magnetic particles. Changing the currents couples the two together, then forms a toroidal trap.

References

RESONANT ELECTRON SCATTERING BY DEFECTS IN SINGLE-WALL NANOTUBES, M. Bockrath, W. Liang, D. Bozovic, J. H. Hafner, C.M. Lieber, M. Tinkham and H. Park, *Science* **291**, 283 (2001).

ELECTRONIC PROPERTIES OF MECHANICALLY-INDUCED DEFECTS IN SINGLE-WALLED CARBON NANOTUBES, D. Bozovic, M. Bockrath, W. Liang, H. Park, J. Hafner, C.M. Lieber and M. Tinkham, *Appl. Phys. Lett.*, submitted (2001).

FABRY-PEROT INTERFERENCE IN A NANOTUBE ELECTRON WAVEGUIDE, W. Liang, M. Bockrath, D. Bozovic, J. Hafner, M. Tinkham and H. Park, *Nature*, submitted (2001).

QUANTUM SUPRESSION OF SUPERCONDUCTIVITY IN ULTRATHIN WIRES, A. Bezryadin, C.N. Lau and M. Tinkham, *Nature* **404**, 971 (2000).

SELF-ASSEMBLED CHAINS OF GRAPHITIZED CARBON NANOPARTICLES, A. Bezryadin, R.M. Westervelt and M. Tinkham, *Appl. Phys. Lett.* **74**, 2699 (1999).

EVOLUTION OF CONDUCTING STATES IN ELECTRORHEOLOGICAL LIQUIDS, A. Bezryadin, R.M. Westervelt and M. Tinkham, *Phys. Rev.* E**59**, 6896 (1999).

GUIDING NEUTRAL ATOMS ON A CHIP, ,N.H. Dekker, C.S. Lee, V. Lorent, J.HY. Thywissen, M. Drndic, S.P. Smith, R.M. Westervelt and M. Prentiss, *Phys. Rev. Lett.* **84**, 1124 (2000).

THREE-DIMENSIONAL MICRO-ELECTROMAGNET TRAPS FOR NEUTRAL AND CHARGED PARTICLES, M. Drndic, C.S. Lee, and R.M. Westervelt, *Phys. Rev.* B, in press (2001).