Ph.D Projects – New Quantum Phenomena in Semiconductor Nanostructures

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The objective of our work is to investigate new quantum phenomena in tailor made semiconductor structures and devices which illustrate new effects in physics which we can exploit in future quantum technologies such as quantum information and quantum computation. This work involves the manipulation and measurement of electron wavefunctions in systems of restricted dimensionality and observation of effects down to the single electron level. In order to achieve these ends semiconductor layers are obtained from growth centres and Ph.D students become expert at fabricating advanced devices using a variety of etching and lithography procedures.

Consequently the projects result in Ph.D’s acquiring considerable knowledge of quantum processes and quantum information and also semiconductor processing technology, this is of considerable importance if they seek an eventual career in the semiconductor or IT industries.

A system which forms a basic building block of quantum physics is a narrow channel, (a quantum wire), formed within a high mobility two-dimensional electron gas. By applying different voltages to patterned gates, made with high-resolution electron beam lithography, the electron gas can be “electrostatically confined” and turned into any particular shape. The electronic properties of one, (quantum wire), and zero dimensional, (quantum dot), systems are of importance and there will be a number of Ph.D projects aimed at investigations using these unique structures. It is intended to form integrated quantum circuits which combine different quantum effects for new functions, this follows the philosophy that “complexity brings new rules of physics”.

When a quantum wire is sufficiently short that electrons move through ballistically, that is without scattering, the conductance takes on quantised values in units of $\frac{2e^2}{h}$, the factor of 2 arises from spin and can be removed by a magnetic field. This is an example of quantum transport and analysis of its dependence allows one to investigate quantised levels and their behaviour. The standard level behaviour is that of the “particle in the box” of elementary quantum mechanics, however when the electron-electron interaction is dominant the normal level sequence is reversed so that wavefunctions which allow the electrons to be apart now become the ground state. This behaviour of “quasiparticles in the box” is radically different to that of “particles in the box”.

Specific available projects are listed below.

1. Investigate the formation of a Wigner Lattice, in which the electron-electron repulsion forces the electrons into a regular array in order to minimise energy, as a one dimensional system is converted into two dimensions. This will be investigated using double layers of electrons to enhance their mutual repulsion.

2. Investigate the role of spin alignment when this can be manipulated by application of voltages as the electrons travel through the sample. The transmission of spin information and its readout will be of importance.

3. Create a spin lattice in which the electrons are trapped or localised and the lowest spin direction can be controlled and will be a function of spatial location. A number of new effects are expected in this unusual situation.
4. Establish a, so called, many-body localised state in which the lattice vibrations, phonons, are frozen out and the electrons form a collective system in which they all move together. In this case the electron system is no longer in thermal equilibrium with the ambient temperature and a range of new transport phenomena are predicted.

5. Design and investigate systems which create electron entanglement. Here electrons can be described by a single wavefunction and so their properties are linked. For example flipping the momentum of one will change the momentum of another as the total momentum must be unchanged. A number of schemes for making quantum computers are based on this idea.

6. The development of electron pumps in which single electrons can be injected into quantum circuits one at a time. This may lead to a highly accurate measurement of electron charge and new schemes of quantum based manipulation of information and data.