

Research Proposals

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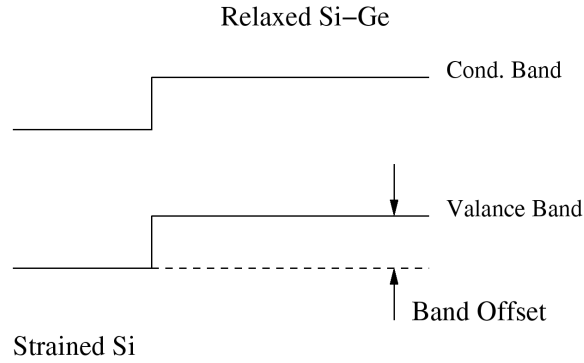
1 Imaging electrons in SiGe - strained Si structures

SiGe is a very technologically important material: it is increasingly likely that it will form the basis for the future of high speed transistors devices. While GaAs currently dominates this market, it has become apparent that on chip integration of GaAs with standard silicon CMOS is not practical. SiGe offers a high mobility conduction channel, comparable to GaAs structures, that offers a route towards large scale integration of high speed circuits with standard CMOS technology.

The basic band structure of a strained Si - SiGe structure is shown in figure 1. The idea is that the strain in the Si layer due to the lattice mismatch with the relaxed SiGe layer causes an offset in the bandgap. This is referred to as a Type II band alignment. Electrons fall out of the SiGe into the Si layer and form a quantum well. Mobility can be greatly enhanced if the donor ions are moved away from the interface by using modulation doping, where a spacer layer is inserted between the donors and the Si layer.

So why are we interested in this material? One important reason is that we have one of the top growers of SiGe structures, E. Fitzgerald, in house on the fifth floor of our building. Such close connection allows us to have much more input and interaction with the growth process. From a physicist's perspective, SiGe structures are an interesting medium in which to study electron dynamics:

1. High mobility, clean 2DEG quantum wells are possible in this material using modulation doping. This was clearly demonstrated by K. Ismail et. al. in APL 66 (1077), where clean fractional quantum hall states were seen in a sample with a mobility of $5 \times 10^5 \text{ cm}^2 \text{ V} / \text{s}$. The clean signal seen was comparable to that seen in GaAs samples with mobilities of 1×10^6 .



Type II Band Alignment

Figure 1: The behaviour of the conduction band edge in a Si - SiGe interface.

2. There is the possibility of growing these samples with 2DEGs very close ($\sim 30 \text{ \AA}$) to the surface. The advantage here over GaAs is that the surface of silicon behaves like a traditional dielectric (see Davis "The physics of low dimensional semiconductor devices", 1998 (Cambridge Press: Cambridge UK)). In GaAs, there are metallic states that are found at the surface that have a large density of states, and whose energy lies in the band gap. Whenever you build a GaAs heterostructure, electrons fall out of the bulk and into these surface states: the net result is that the fermi energy is always pinned to the surface state level. This places limitations on the type of heterostructure you can make in GaAs: in particular, the 2DEG well can not be too close to the surface to prevent these surface states from depleting the quantum well. In SiGe, there are no surface states, leaving much more flexibility in designing heterostructures.

3. SiGe has a very large g-factor, around 1.98, comparable to the g-factor of free electrons. This is in contrast to GaAs, where spin-orbit coupling in the conduction band gives the electrons in the quantum well a g-factor of close to zero. What this means is that the spins of electrons in SiGe couple much more strongly to magnetic fields. Essentially, the electrons have a larger effective spin: this simple fact suggests that any successful device involving spin dependent transport will likely be made in SiGe structures, not GaAs. This large g-factor, along with low spin relaxation rates, has propted some theorists to suggest that SiGe is an ideal platform for constructing a quantum computing device, and even to propose a device strutures (PRA 62 012306 (2000)). SiGe is simply a more interesting material in which to study eletron spin

effects.

Using SiGe, it may also be possible to extend our experiments to include tunnelling measurements of the 2DEG density of states. This would be possible if we are able to put the dopants below the quantum well and move the 2DEG close to the surface. This would allow us to non-invasively study the density of states at the fermi level using our capacitance probe, and also to probe excited states that lie above the fermi level using tunnelling.

2 Imaging charge distributions in CdSe dot arrays

CdSe dots are nanoparticles of CdSe semiconductor whose size is small enough that the electrons in the conduction band form quantized levels, as in a traditional lithographic quantum dot. One of the important features of these materials is that the energy level spacing in the dot is in the optical range. Furthermore, this level spacing is tunable, naturally leading to the suggestion that these could be used to make a device similar to traditional photodiodes, but with a continuously tunable wavelength.

One of the limitations right now is that it is very difficult to pass current through the dots. This is believed to be related to the thick tunnelling barriers between the dots, although the coulomb repulsion that appears as you start to charge the dots is also thought to be important. The physics of transport in these structures is being actively researched by members of the condensed matter theory group here at MIT.

Measurements carried out by Nicole Morgan here at MIT show that charging of these dot arrays involves very long time relaxations of the current, over a period of several hours. There is evidence that the charge may only be accumulating in a small layer near the edges of the sample.

Imaging this charging using our capacitance microscope would be a relatively simple experiment, and would provide valuable insight into how current flows in these structures. Understanding transport in these arrays will allow us to determine how to use electrical excitations to stimulate light emission.

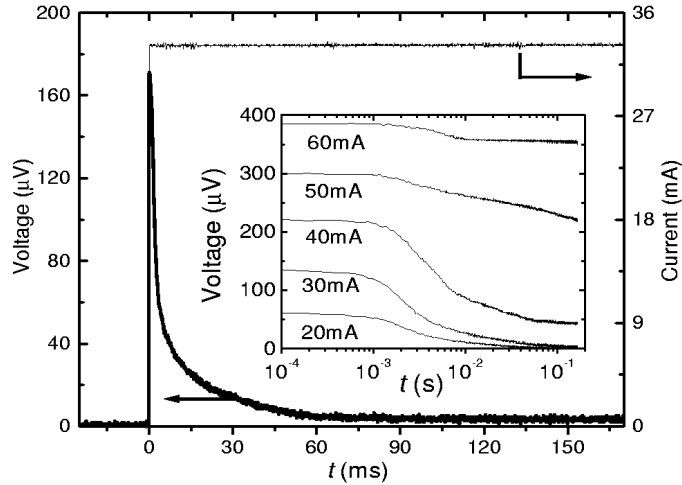


Figure 2: Voltage relaxation curves in a NbSe₂ single crystal. From E. Andrei et al., *cond-mat/9904141*.

3 Imaging vortex relaxations in NbSe₂

In type II superconductors, those used in all of the superconducting magnet systems made today, resistance present in the presence of magnetic fields below the second critical field is due to the motion of “vortices” in the material. Magnetic fields and superconductivity cannot coexist in a material. In type II superconductors, magnetic flux is allowed to pass through the material by enclosing the magnetic field line in a small tube of material that has become non superconducting. This way, superconductivity can be preserved, while allowing flux to penetrate through the material. However, if these vortices are free to move, this will lead to a resistance when you pass a current through the superconductor. If the material heats too much and exceeds the critical temperature, the whole wire can become a normal metal, dissipating an enormous amount of heat if there is a large current in the superconductor at the time.

Recently, E. Andrei has been studying the details of vortex flow in NbSe₂, a type II superconductor. They have developed a technique for precisely controlling vortex flow using current pulses (PRL 86 2431). The idea is that you first prepare the vortices in a disordered metastable state, where they are pinned to lattice defects in the crystal. By applying current pulses, you can drive the vortices into motion and watch how they relax: an example of this is shown in figure 2. For small currents, the vortices relax back into a pinned state, and the voltage goes to zero at long times. With larger

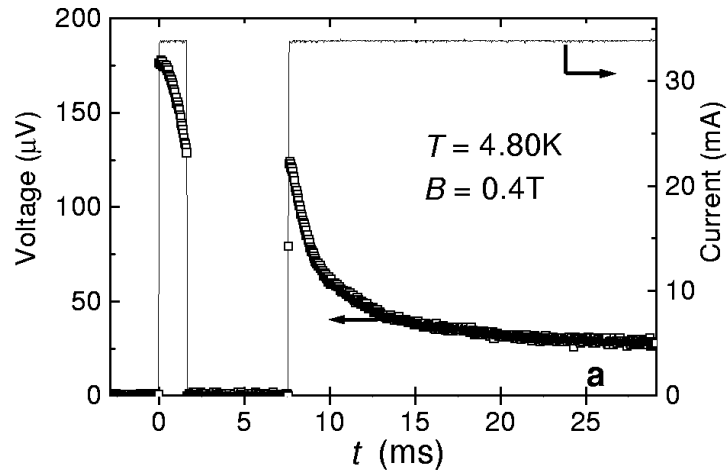


Figure 3: Using a current pulse to “turn on” and “turn off” the vortex lattice relaxation. From E. Andrei et al., cond-mat/9904141.

currents, you can completely unpin the vortices: the system develops an equilibrium resistance, associated with steady state flow of vortices.

This current pulse technique can also be used to freeze the relaxtions by stepping the current back to zero. This is shown in figure 3. You can actually stop the relaxation by turning off the current, wait a long period of time, turn the current back on, and the relaxtion will continue from where it left off. The idea is that we will be ablt to use this to “pause” the relaxtion so that we can image the vortex positions using our microscope. By stepping through the relaxation in this way, we can image the motion of the vortices as they relax, and watch what is happening microscopically to the vortices as the system relaxes.