SAW-driven single-electron quantum devices with optical readout of the spin

1. Introduction

The aim of the Fellowship was to develop a method of emitting and detecting polarised photons of light from quantum dots at temperatures less than 1°C above absolute zero. Quantum dots are "boxes" that can contain one or more electrons, and the dots here are special, in that they are formed and driven across a piece of gallium arsenide (GaAs) material by a surface acoustic wave (SAW). This is a moving strain wave that causes the potential energy to oscillate along with the strain. Electrons residing in a layer just below the surface are caught in the minima of this potential and can be carried along, even being dragged up a potential hill from an n-type region of electrons to a p-type region of holes. Each electron should then recombine with a hole to give out a photon of light.

Such a single-photon source will be useful in its own right, in quantum cryptography (sending an encrypted message or key with the ability to know if anyone is eavesdropping) and eventually in quantum computing (where the ability of quantum particles to be in more than one state at a time could give a vast speed improvement for complex calculations). In addition, the ability to polarise each photon based on the spin-polarisation of the emitting electron will offer extra capability in quantum cryptography, and provides a method of reading out the result of a quantum computation performed with electrons in quantum dots.

While developing such devices, it is vital to be able to work at extremely low temperatures close to absolute zero (–273°C or 0 Kelvin). Getting light out of a cryostat that provides such low temperatures is a difficult task, so it was necessary to design and build a low-temperature, scanning microscope connected to an optical fibre to get the light out. This was a major part of the work in this two-year Fellowship. In addition, ways of making the samples themselves had to be developed. Regions of electrons and holes (missing electrons that behave like positively-charged electrons) have to be produced on the same piece of material. This makes it impossible to dope the whole piece of material uniformly to provide the charges. A technique for inducing the charges by metal "gates" on the surface has been refined and shown to work in these samples. There will be a large potential slope up which the SAW has to drag the electrons. The SAW potential therefore needs to be as large as possible. We have shown that, by depositing a crystalline layer of zinc oxide (ZnO) on the surface, the potential can be increased by a factor of up to 20. This is a very significant achievement, and it required much optimisation of the crystal growth parameters. As a spin-off result, this type of high-quality ZnO layer is now being developed for use in other applications such as biological sensors.

The various aspects of the work will be described in more detail in the subsequent sections.

2. SAW-driven quantum dots in a lateral n-p junction

In conjunction with two PhD students, whom the Fellow trained in fabrication and measurement, techniques for reliably inducing regions of electrons and holes in undoped GaAs wafers have been developed, though not yet on the same piece of material. We have shown that the mobility (a measure of how little scattering the electrons undergo) is very high in these samples (>7,000,000 cm^2/Vs) due to the absence of scattering from the dopants. The fabrication of ohmic contacts to these undoped GaAs wafers is non-trivial, as the inducing gates have to overlap the contacts without the high voltage difference causing a leakage current. n-type contacts for electrons are working well, but further work is needed on the p-type contacts for holes to increase the yield, but they are now useable.

Once both types of contact were shown to work, a mask for optical patterning of the wafer was designed that would allow electrons and holes to be induced close together on the same chip, with all the required connections for gates and contacts, and transducers to produce SAWs. This has just been completed, and the students will carry on the task of making a lateral induced n-p junction using this mask and then electronbeam lithography to fabricate the smallest features.

In order to increase the strength of the potential wave produced by the SAW, we decided to deposit a layer of ZnO on the surface of the GaAs. Such a layer is only strongly piezoelectric when its crystal quality is very high. We developed a collaboration with a group in a neighbouring department (the Centre for Advanced Photonics and Electronics, CAPE), where ZnO could be sputtered on to a sample. We optimized the sputtering on GaAs substrates by many experiments with different conditions, checking the quality with X-ray diffraction, until it was possible to make high-quality crystals even with the substrate at room temperature rather than close to 300°C. We have fabricated pairs of SAW transducers on ZnO/GaAs structures and characterised the fundamental and higher-order (guided) acoustic modes and calculated the piezoelectric enhancement at the depth where the electrons and holes will be. An improvement by a factor of about 20 has been shown in transmission between the two transducers, and this should give a similar enhancement of the SAW potential experienced by the electrons. This will make it much easier to drag electrons up the potential slope in the depletion region between the electron and hole regions.

This ZnO deposition technique has already led to the development at CAPE of thin-film bulk acoustic resonators (FBAR) on ZnO/Si for sensing applications.

3. A cryogenic scanning optical microscope

In order to detect photon emission from a SAW device, we have designed and built a scanning optical microscope at the bottom of a narrow sample probe that is inserted into a cryostat operating at 0.3K. This is a state-of-the-art instrument that will be of great use in the future, both for SAW devices and other types of quantum-optical devices and nanostructures. The whole microscope has to fit into the 40mm bore of the cryostat. It consists of one or two micro-lenses in a titanium (Ti) housing to focus the collected light on to an optical fibre. It is attached to three commercial piezoelectric transducers to position the whole assembly, which in turn is surrounded by a titanium frame that holds the sample and its attached rigid coaxial high-frequency cables beneath it. Room-temperature optics has been set up to measure the light at the top of the fibre and to align the micro-lenses before final assembly. The planning and mechanical design and CAD drawings took a long time, with many manufacturers being approached to discuss and source suitable optical components. The Ti parts were machined in our workshop by a highly-skilled technician, and we polished the fibre connections, made a vacuum feed-through for the fibre and modified the 2.5m-long sample probe to accommodate the microscope. The whole assembly is very nearly ready to be tested and calibrated. This will be carried out by the PhD students who have been shadowing this work in order to learn the techniques.

4. Additional results and collaborations

Our development of the method of making high-quality ZnO films led to our collaborators at CAPE using them in other applications such as biological sensors, and a number of papers and conference presentations have resulted from this. In addition, we have made a few more measurements on SAW-driven charge transport through 1D constrictions in 2D electron gas in an AlGaN/GaN heterostructure, finishing off work started as a short Researcher Exchange Award from the British Council in 2009. This was presented at EP2DS-19 in the USA in 2011. We have also collaborated with the ISOM-UPM in Madrid, Spain on high-frequency SAW resonators in AlN/diamond, giving advice and ideas, and a paper is due to appear shortly.

5. Impact

The long-term impact of this project will be in furthering the host institution's work towards making a single-photon source, with applications in quantum cryptography and quantum computing as described in the introduction. However, the cryogenic microscope may turn out to have many more uses in the future in measuring polarised photon emission from a variety of novel devices. The detailed design will be made available to other interested research groups (it is not sufficiently novel to be patentable). The spin-off from the work on ZnO films may have unexpected impact on a short timescale, given that the collaborators are already using them for biosensors, which is a growth area that may have important applications in healthcare.

These are all highly satisfactory outcomes for a two-year project funding just one person.