Solid States Spins for Quantum Computation in Indium Phosphide

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Abstract

Indium Phosphide (InP) is host to a spin system that is a candidate qubit in the quest for quantum information processing. In order to use InP the spin needs to be able to be controlled via optical pumping. A series of tests was done to see if one could optically pump InP. There seemed to be some amount of optical pumping but more research will be required to confirm this result.

1) Introduction:

Over the past few years there has been an increased interest in quantum information processing (QIP). QIP has possible uses in computer security (the factoring of products of large prime numbers), the simulation of large quantum systems, and secure communication. This has led for the search for a good qubit. Some of the options for qubits include photons, trapped ions and semi-conductor impurities. This summer we started looking at the III-V semiconductor indium phosphide, which is host to a prospective qubit.

Quantum Information Processing:

A qubit is similar to the classical computer bit, however, it is made of a linear combination of +½ and -½ spins. In order for a candidate quantum computer to be acceptable it needs to pass the DiVincenzo Criteria: 1) the system needs to be scalable with well characterized qubits, 2) the qubits states need to be initialized to a standard state, 3) the decoherence time needs to be long compared to computation time, 4) there needs to be a universal set of quantum gates, and 5) the qubits need to be able to be measured [1].

InP is host to a spin system which is a prospective qubit. To test whether this is a good candidate for quantum computing, it needs to pass the above qualifications. With this prospective qubit, optical pumping would be used to control the spin. For optical pumping to occur, the spin-flip time would need to be long compared to the time it takes to excite and relax the spins into the desired state. I joined a project to investigate the possibility to optically pump InP. If optical pumping occurs this would then allow the relaxation time to be measured to see if it was long compared to computation time.

Excitons:

Excitons are created when a hole in a semi-conductor binds to an electron and they form a hydrogenic state. In this case the electron is excited from the valence band into the conduction band and then binds with the hole it created to form an exciton. At liquid He temperatures the exciton can bind to a donor

impurity that has a single valence electron, creating a donor bound exciton (Figure 1) [2]. They also can remain as free excitons that are not bound to any atom but are free to move about the lattice.

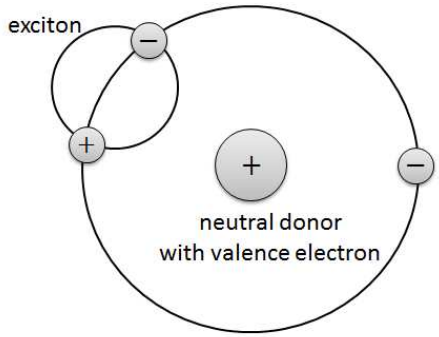

Figure 1: Donor Bound Exciton

Optical Pumping:

The energy levels of the donor bound exciton (D^0X) and the neutral donor (D^0) in the absence of a magnetic field is a two energy level system (Figure 2). The excited state has quadruple degeneracy while the ground state is doubly degenerate.

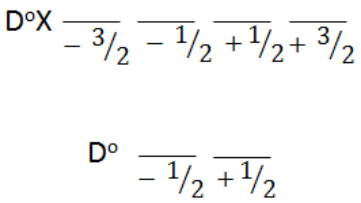

Figure 2: Energy Levels for a Neutral Donor (D^0) and a Donor Bound Exciton (D^0X)

The allowed transitions between the states are within the same energy level (the blue and green arrows) a ± 1 spin; between the energy levels (the red arrows) it is either ± 1 spin or no change in spin.

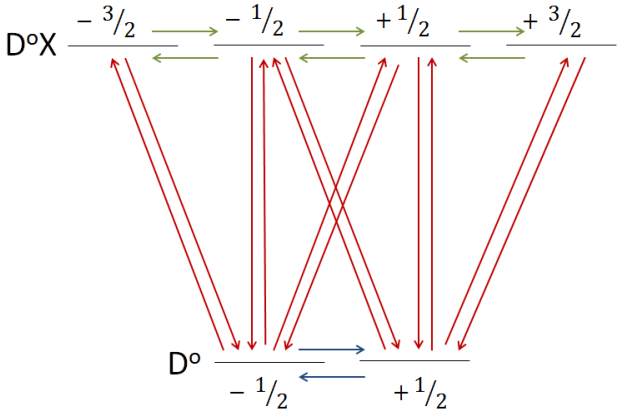

Figure 3: The allowed transitions for a D^0X and D^0 system

When an electron is excited in to the excitonic ground state by right handed circularly polarized light (+1 spin) if it is initially in the -1/2 state it is excited to the +1/2 state and similarly if it is in the +1/2 state it is excited into the +3/2 state. The +3/2 state can only relax to the +1/2 state because of selection rules, while an electron in the +1/2 state can relax into either the +1/2 state or the -1/2 state. This means that ideally it is possible to eventually have nearly all the electrons in the +1/2 state (conversely -1/2 state if left handed circularly polarized light is used). This process is optical pumping.

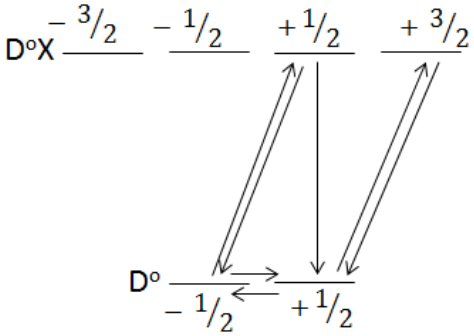

Figure 4: Optical Pumping of D^0 and D^0X system

The reason that this does not necessarily happen is there can be spin flipping that restores previous states. If the time that it takes to spin flip is long in comparison to the time it takes for the electron to get excited and relax, then optical pumping can occur. If spin relaxation time is short in comparison then the -1/2 state is repopulated as it is depopulated and no optical pumping occurs. Another transition that can occur that would prevent optical pumping is that there can be a transition between the excited states. If the transition time is long compared to the excitation and relaxation time, then we can ignore it because the spins will have relaxed by the time they could have transitioned to another of the higher level states. If not than this can prevent optical pumping from occurring.

Some of the D^0X excited states relax into the first excited state of the neutral donor, known

as the Two Electron Satellite state (TES) (Figure 5).

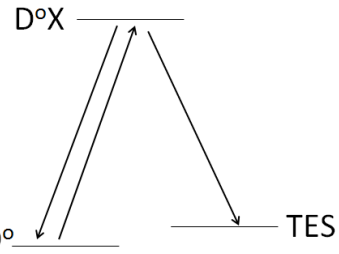

Figure 5: TES levels

Optical pumping can also occur in this state, and this is the region of focus when looking at the effect of polarization angle on photoluminescence intensity.

Material:

The material being studied is indium phosphide (InP). It is a III-IV semi-conductor. It contains donors that can bind excitons at low temperatures

2) Experiment

The optical table was set up for the initial cool-down in a similar fashion to Figure 6, but lacking the power stabilizer and preceding linear polarizer. The polarization optics were able to be taken in and out of the setup. The power meter was placed after the exciting polarization optics so that the power used to excite was measured rather than the initial power. The laser light was collimated and irises were used to make certain that it was parallel to the table. The laser that was used was a Matisse Ti:Sapphire. This allowed us to adjust the wavelength of the laser so that both above band and resonant excitation could be used. I made an aluminum sample holder that screwed into the sample holder for the cryostat. It was made to contain one of the InP chips. For data collection the sample was cooled to about 5 K using liquid helium, with the sample being inside of an immersion cryostat. The laser was then shone on the sample. Measurements were taken while varying the power, the polarization optics, and the wavelength of the excitation laser. The photoluminescence was collected and sent to an Andor Spectrometer. All of this was done in the absence of magnetic field.

For the second cool-down experiment, several changes were made to the optics table as in the diagram below. One of these changes was the insertion of the power stabilizer because the power from the laser fluctuated in the first experiment. The linear polarizers were placed on flip mounts so that they would still be aligned with the beam when taken in and out of the set up. I made another sample holder that could fit more than one sample and had a large space for the sample so as not to strain it. Otherwise the procedure was the same as stated above.

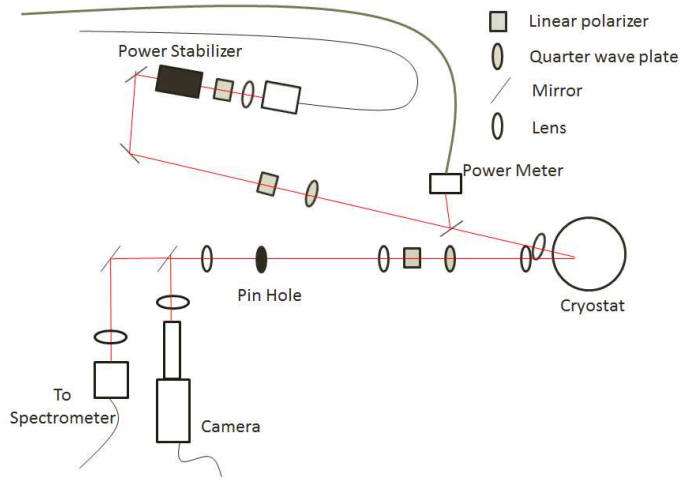

Figure 6: Set up of the optical table

3) Results

Strained Sample:

The first time we cooled down we noticed that there were five main peaks in the spectrum, occurring at 1.41638 eV, 1.41651 eV, 1.41669 eV, 1.41686 eV, and 1.41704 eV (see Figure 7).

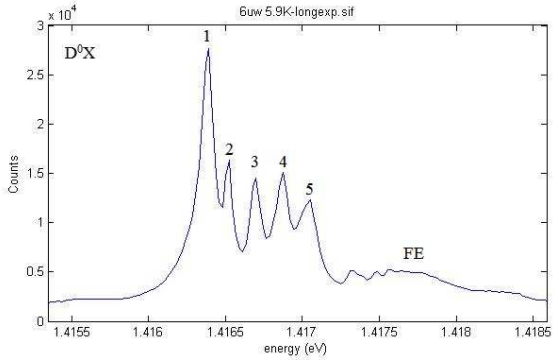

Figure 7: Sample Spectra of Strained Sample

This was unexpected because in the literature there are three major peaks in that region at zero field [3]. However we found a paper that showed five peaks, with two of the

major peaks splitting because of strain in the sample (Figure 8). This is what we believe occurred in our sample, since we did not observe it again when the same sample was cooled a second time. The stress was caused because the sample holder was slightly too small for the sample and so the sample was compressed when it was placed in the sample holder. This caused the first and second lines to split. This was because the first and second lines are fourfold degenerate, while the third line is doubly degenerate [3].

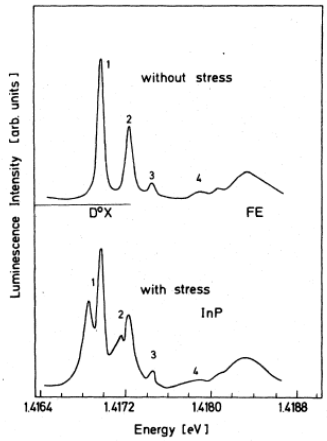

Figure 8: Spectra of Strained Sample from the literature [3]

In literature there are two extra lines that are attributed to strain within the sample. One difference between the splitting that we observed and the splitting in the literature is that other than the major peak the peaks seem to be about the same height while in the literature there was a clear difference between the heights of the peaks

Unstrained Sample:

During the second cool down, with the larger sample holder, the sample was no longer strained. This time only three major peaks were observed, which was expected and agrees with the literature. The photoluminescence spectra looked like the following one. With three main sharper peaks corresponding to the donor bound excitons recombining and coming down to the neutral donor state, there also is the free exciton visible as a low broad bump at a higher energy

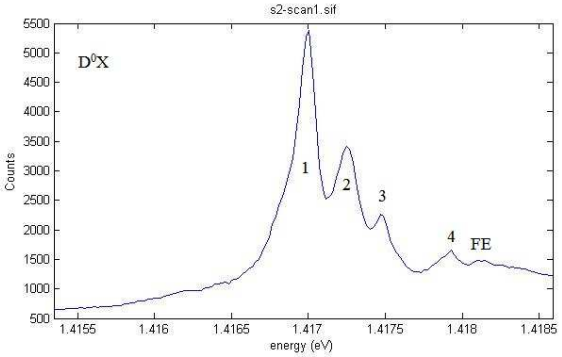

Figure 9: Sample spectra of unstrained sample

The peaks measured were at the following energies:

Table 1: Energetic positions of the D^0X lines and the distance from the lines to the first D^0X line.

D^0X line	Energetic position (eV)	Energetic distance to $(D^0X)_1$ line (meV)
1	1.41699	…
2	1.41724	0.25
3	1.41746	0.47
4	1.41792	0.93
FE	1.41812	1.13

These energies are similar to the values listed in Ruhle, just slightly higher in energy. For example the line 1 is at 1.41692 eV [3]. The energetic distances are also similar but on average slightly smaller. The distance between lines 1 and 2 is 0.273 meV in Ruhle [3], but only 0.25 meV in the sample measured.

There was not much in the TES spectra but it looked like:

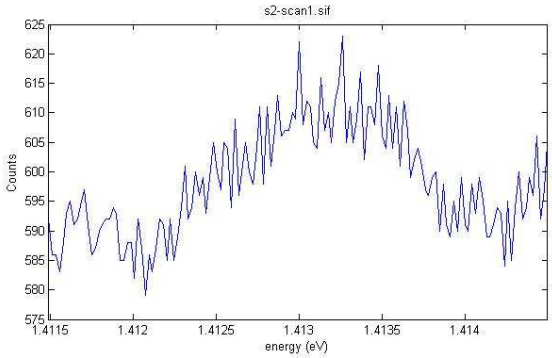

Figure 10: TES Spectra

When we excited the sample with varying polarizations at angles of 0°, 45°, 90°, 10°, 5°, 120°, 135°, 180°, 225°, 270°, and 315° at a temperature of 4.5 K and powers ranging from

62-91 μW, the intensities of the peaks within the TES region looked like:

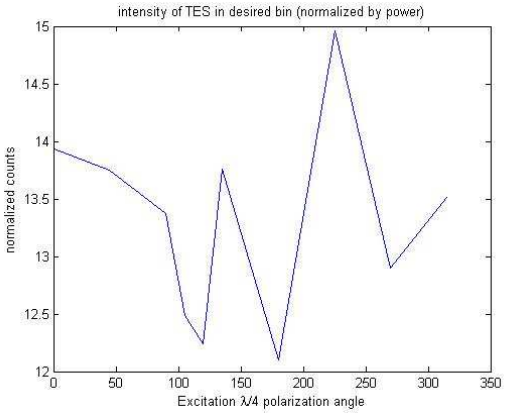

Figure 11: TES intensity vs. excitation polarization angle

Since there was a range of powers for the excitation, the number of counts was normalized by dividing by the power that was used to excite them. This was to compensate for the effect that power had on intensity. Looking at Figure 11, there seems to be some dependence on polarization angle. We would expect for the intensity to be highest if we were optically pumping with circularly polarized light because then the all of the emitted light would be circularly polarized and we would be able to collect most of it, while if it is not all circularly polarized then we would expect there to be pi polarized that was emitted. However, the pi polarized light would not be collected since it is emitted in a different direction from where we collect. Thus we would expect that the more circularly polarized light, the more counts we would see. We expect to see the circularly polarized light to occur at angles of 45°, 135°, 225° and 315°. These are ± 45° off of the axis of linear polarization. These predicted maxima were mainly where maxima were observed in Figure 11, however, they are not all the same strength and 45° does not appear to be a maximum, while 0° is. The difference in height could be partially due to power differences. The start of the graph at 0° does coincide with a maximum power of 91 μW. However, this is does not explain why the peak at 225° is so tall, since it was excited at 68 μW while 45° was excited at 75.5 μW and 315° and 74 μW, both of which were excited at a higher power than the 225° peak. So the power fluctuation could have some effect. Another possible area where error could arise is that the region in the spectra that we look for intensity is the TES region which is very noisy, since there is not much relaxation into the TES state. A longer integration time could help lessen the noise in this region.

4) Conclusion:

There seemed to be some dependence on the polarization of the excitation. The dependence does not necessarily mean that optical pumping occurs, however it does not rule it out as a possibility either. This means that we cannot discard the spin system within indium phosphide as a potential qubit, but further work is required.

5) Future Work

More measurements should be done on angle dependence with the excitation power being held constant. There are also two more InP samples that can be investigated. The strain on the sample also can be investigated. If there is a confirmation of optical pumping, then the relaxation time in the ground state needs to be measured to see if the impurities InP hosts are a viable candidate for a qubit.

6) References:

[1] D.P. DiVincenzo. arXiv:quant-ph/0002077 (2000)

[2] K.M.C. Fu, W. Yeo, S. Clark, C. Santori, C. Stanley, M.C. Holland, Y. Yamamoto, PRB 74, 121304 (2006).

[3] W. Ruhle, W. Klingenstein, PRB 18, 7011 (1978).

7) Acknowledgments:

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