Novel Magnetic Properties of AlSb/InAs/AlSb Quantum Wells

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At the nano-scale the physical properties of nanoparticles do not necessarily follow the rules of Newtonian physics. For this reason, the behavior of these nano-scale particles must be studied. In this project, we studied the electric properties of AlSb/InAs/AlSb quantum wells, including a phenomenon called the “Rashba” effect. We used this effect to predict a new mechanism that produces a finite magnetic moment. To understand the more complicated processes involved in charged finite quantum wells, we began with a basic study of the fundamental properties of two-dimensional infinite and finite quantum wells. We then applied our knowledge in a comparison of those properties with the more realistic properties of charged finite AlSb/InAs/AlSb quantum wells. Electron behavior in charged finite quantum wells was studied for two cases. In the first case, doping one side of the well and creating an asymmetric well produced a Rashba spin-splitting effect with the electrons in motion and induced a magnetic field. This effect was seen as each electron within a pair moved in opposite directions of either parallel or anti-parallel to the magnetic field. One electron would have a higher energy than the actual sub band energy level and the other would have a lower energy until they switched. Under the same circumstances, but with an applied magnetic field, the Zeeman spin-splitting effect would be seen with the electrons not in motion. This effect was seen in a very similar way except that the electrons did not switch energy levels. The second case observed was with a symmetric well in which an external magnetic field was applied. However, in this case, the Rashba spin-splitting among electrons in motion induces a Zeeman-like spin-splitting effect in which the electrons to not switch energy levels. The next stage of the project included a series of detailed calculations and simulations via c programming that resulted in finite values for the spin-splitting energies of electrons within these latter wells. Our resulting calculations demonstrated that the g-factor produced by this Rashba spin-splitting effect was greatly enhanced in comparison with typical semiconductors. Given the two ways of manipulating the spin of electrons, our project demonstrates that the Rashba effect, which is typically used in manipulating spin with an electric field, may also be used in manipulating spin with a magnetic field. In this case, it produces much greater results, as shown by the g-factor, than usual semiconductors.

NOVEL MAGNETIC PROPERTIES OF ALSB/INAS/ALSB QUANTUM WELLS

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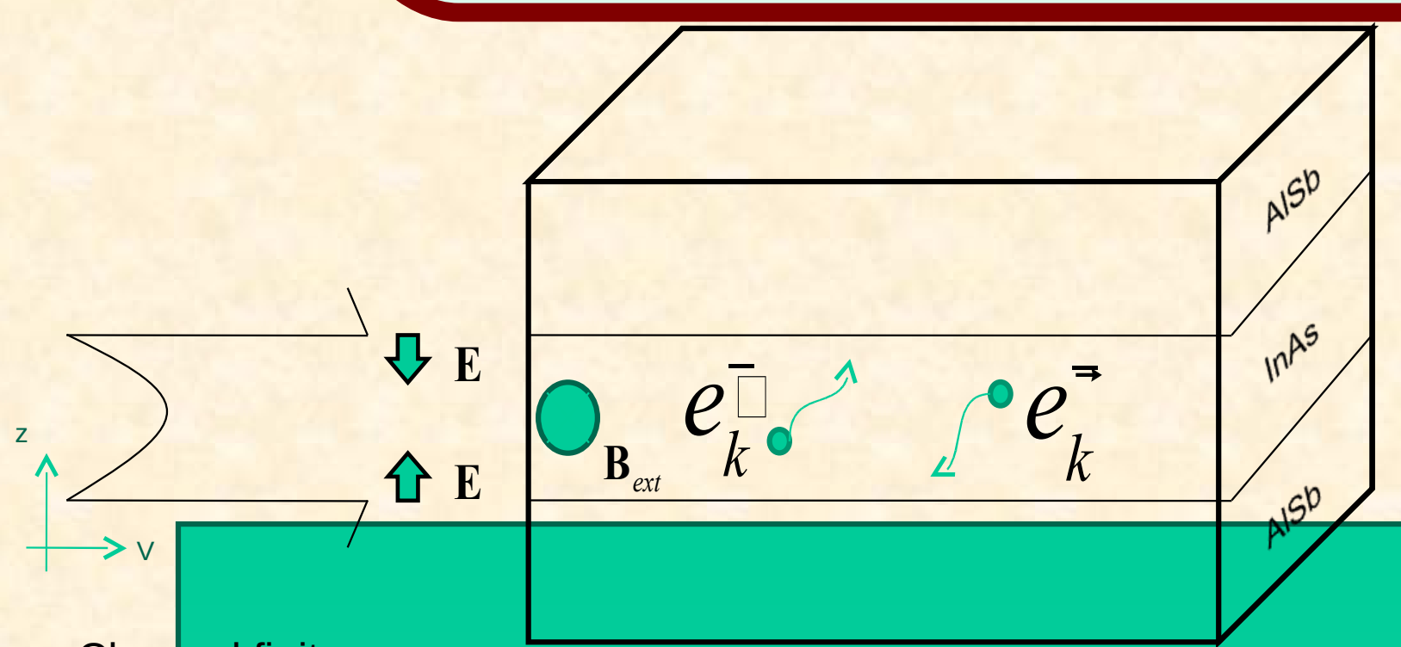
Project Ideas and Goals



Charged finite quantum well

AlSb/InAs/AlSb sample

Introduction

- The field of Spintronics depends upon the control of electron spin. Through study of the Rashba effect we hope to learn more about spin-orbit interaction and eventually increase the capacity to control spin.

Purpose

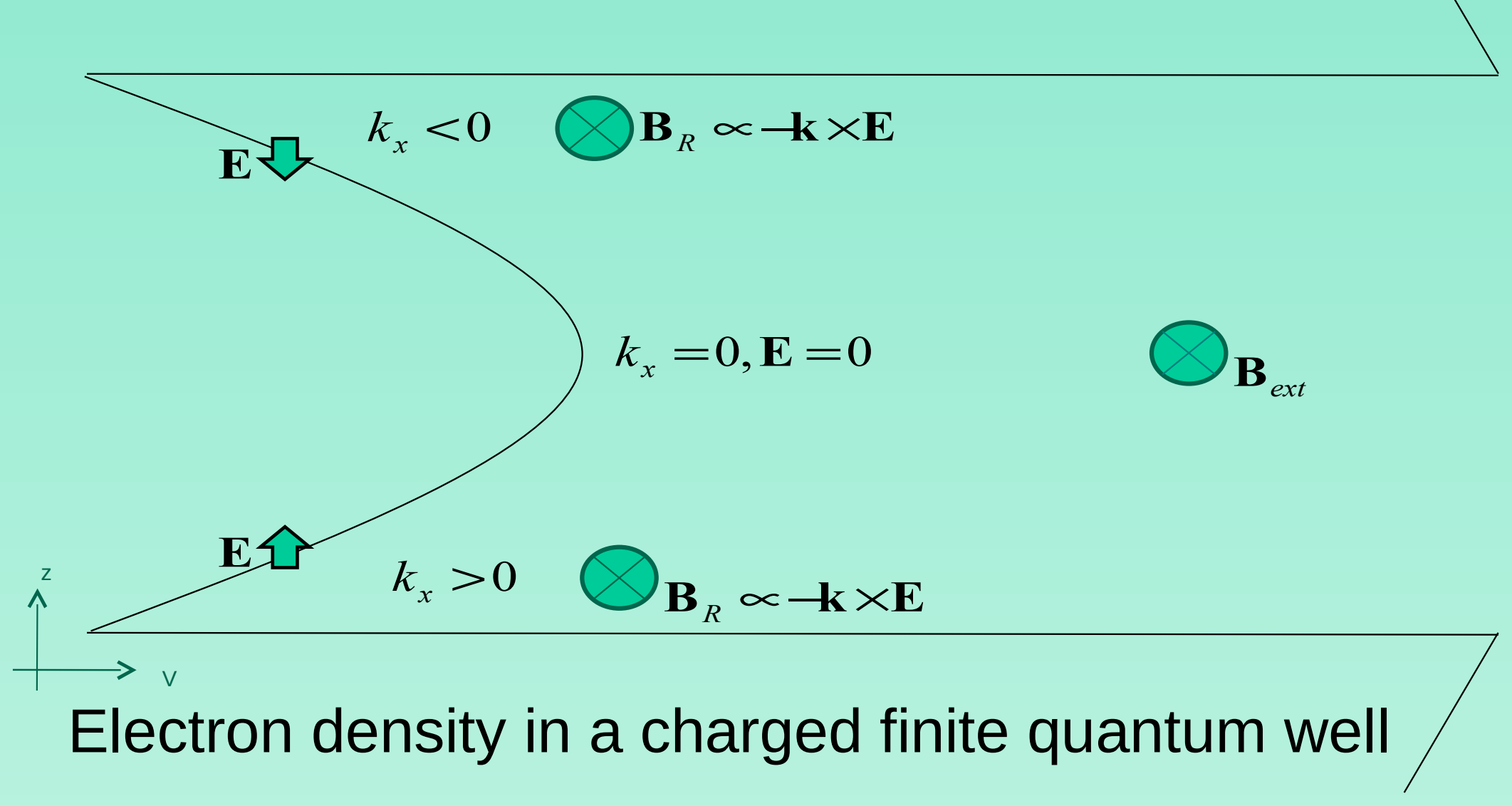
- To examine this "Zeeman-like" spin-splitting effect quantitatively as a function of the external magnetic field.

Details

- InAs/AlSb samples demonstrate strong Rashba effects, thus we used AlSb/InAs/AlSb charged quantum wells (40nm thick) to determine the characteristics of the "Rashba" spin-splitting effect.
- After a magnetic field is applied perpendicular to both the electric field and momentum, a Lorentz force results among the moving electrons sending them either up or down.
- The Lorentz force is described by:

$$\mathbf{F} = -e\left(\mathbf{v}\times\mathbf{B}_{ext}\right)$$

- The resulting electron density in the charged finite quantum well follows the pattern shown in the image below, where at the center, the electric field is equal to zero.



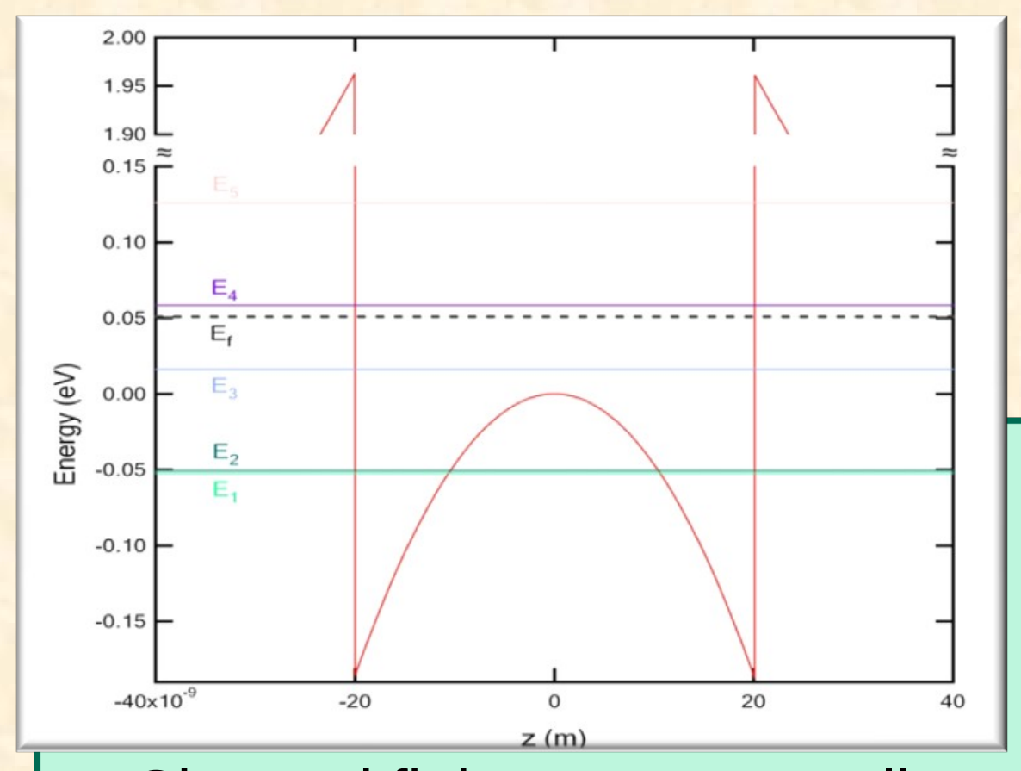
Electron density in a charged finite quantum well

- As a result of the Lorentz force, electrons experience an induced Rashba-magnetic field:

$$\mathbf{B}_R \propto -\mathbf{k}\times\mathbf{E}$$

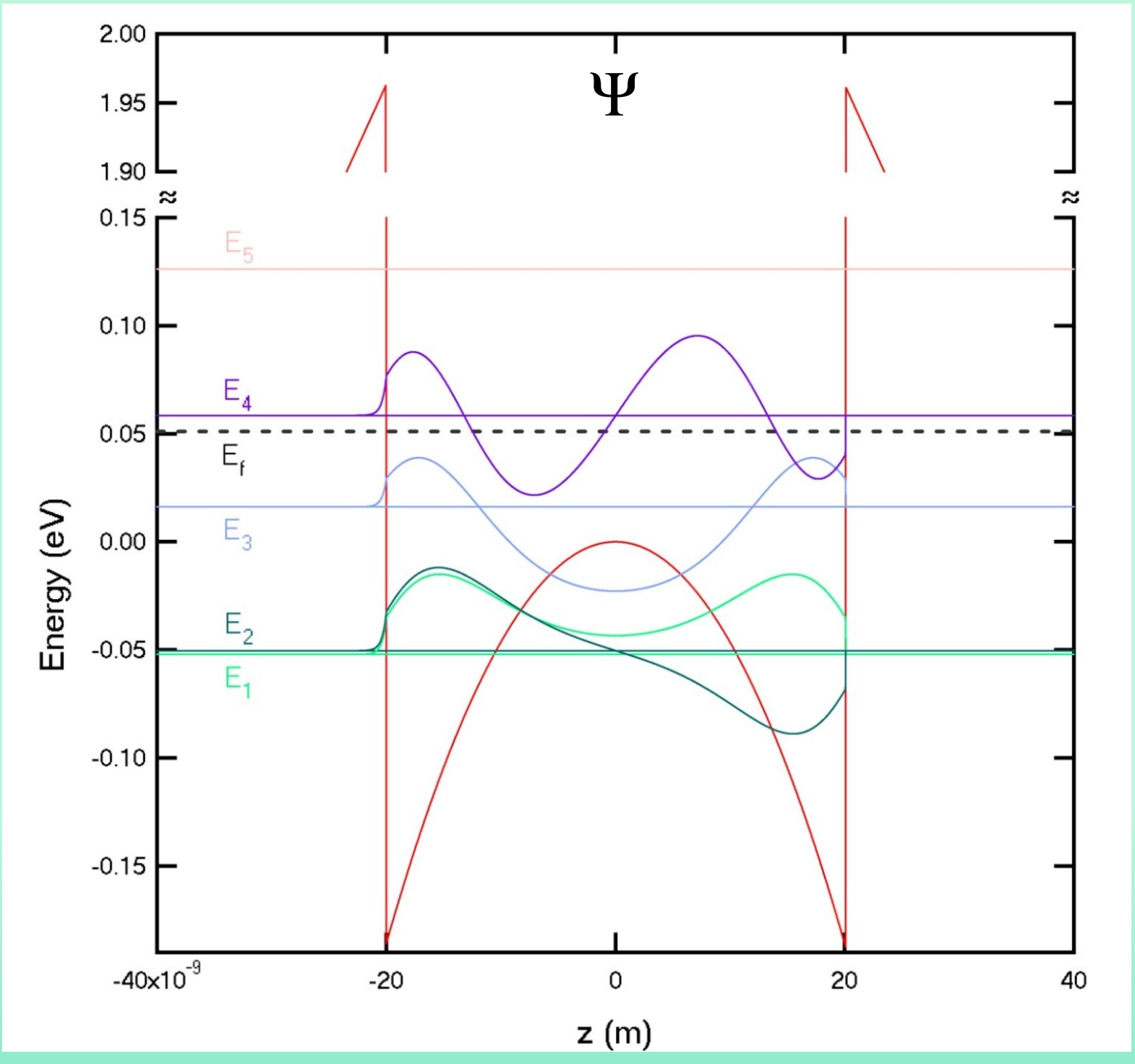
- The resulting spin-splitting among the moving electrons (the Rashba spin-splitting) resembles the Zeeman spin-splitting.

Observations and Calculations



Charged finite quantum well

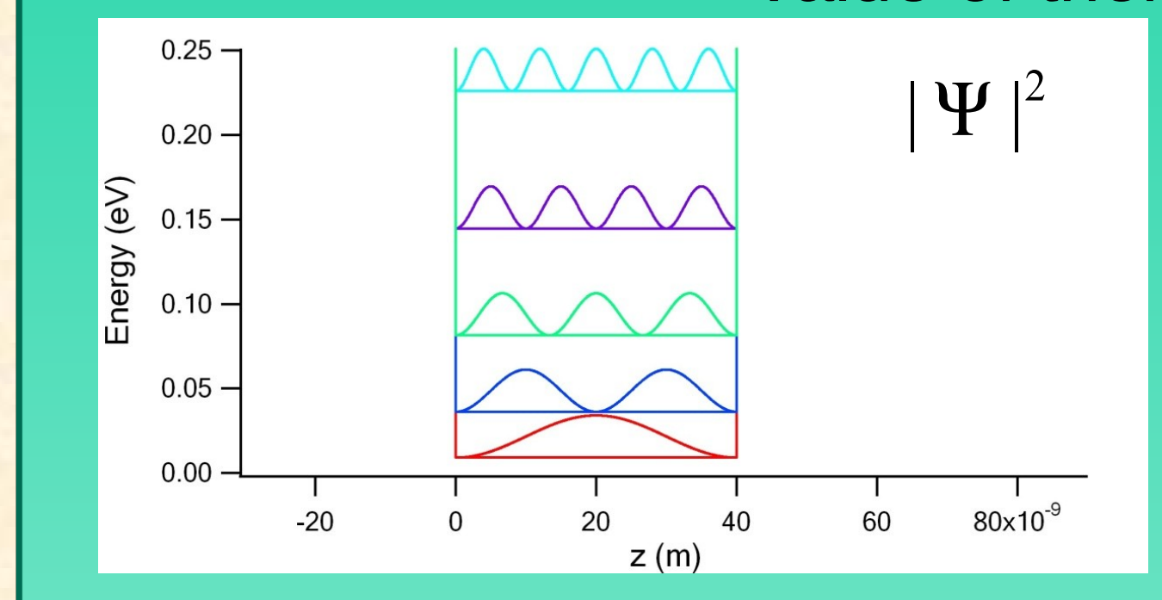
- Wave functions for charged finite quantum wells are not perfect sinusoidal functions, making them unique.



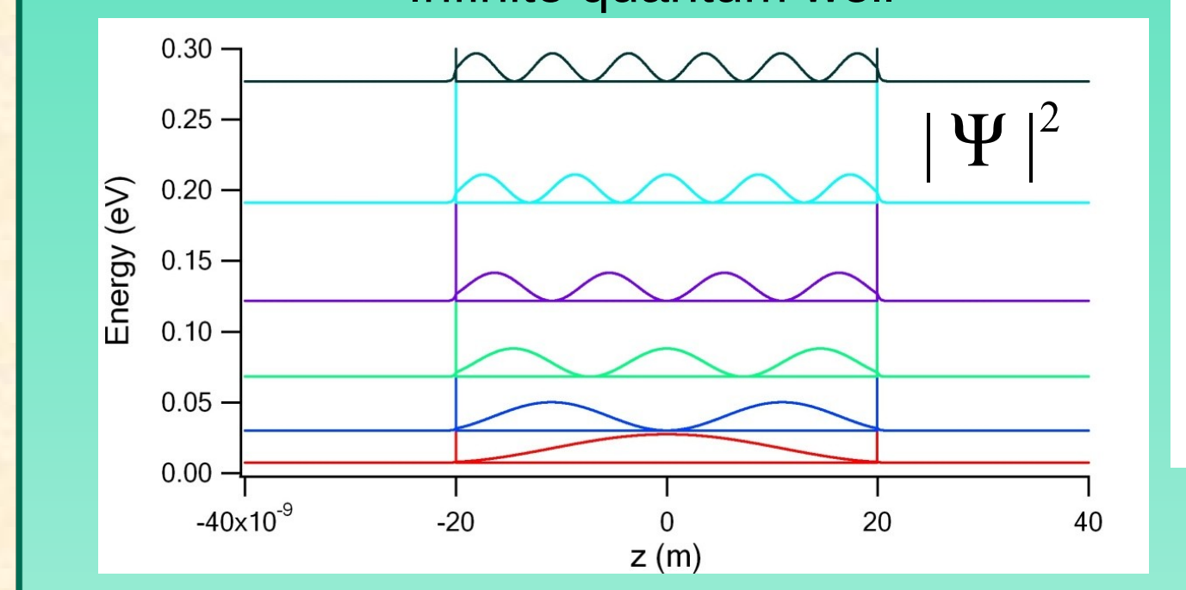
Charged finite quantum well with wave functions

- The square of the absolute value of the wave functions ($|\Psi|^2$) displays the probable density distribution of electrons within the quantum well.
- Compared to typical infinite or finite quantum wells, we noticed that $|\Psi|^2$ in charged finite wells shows a unique behavior near the center of the well.
- In particular, the first sub-band behaves much like the second sub-band.

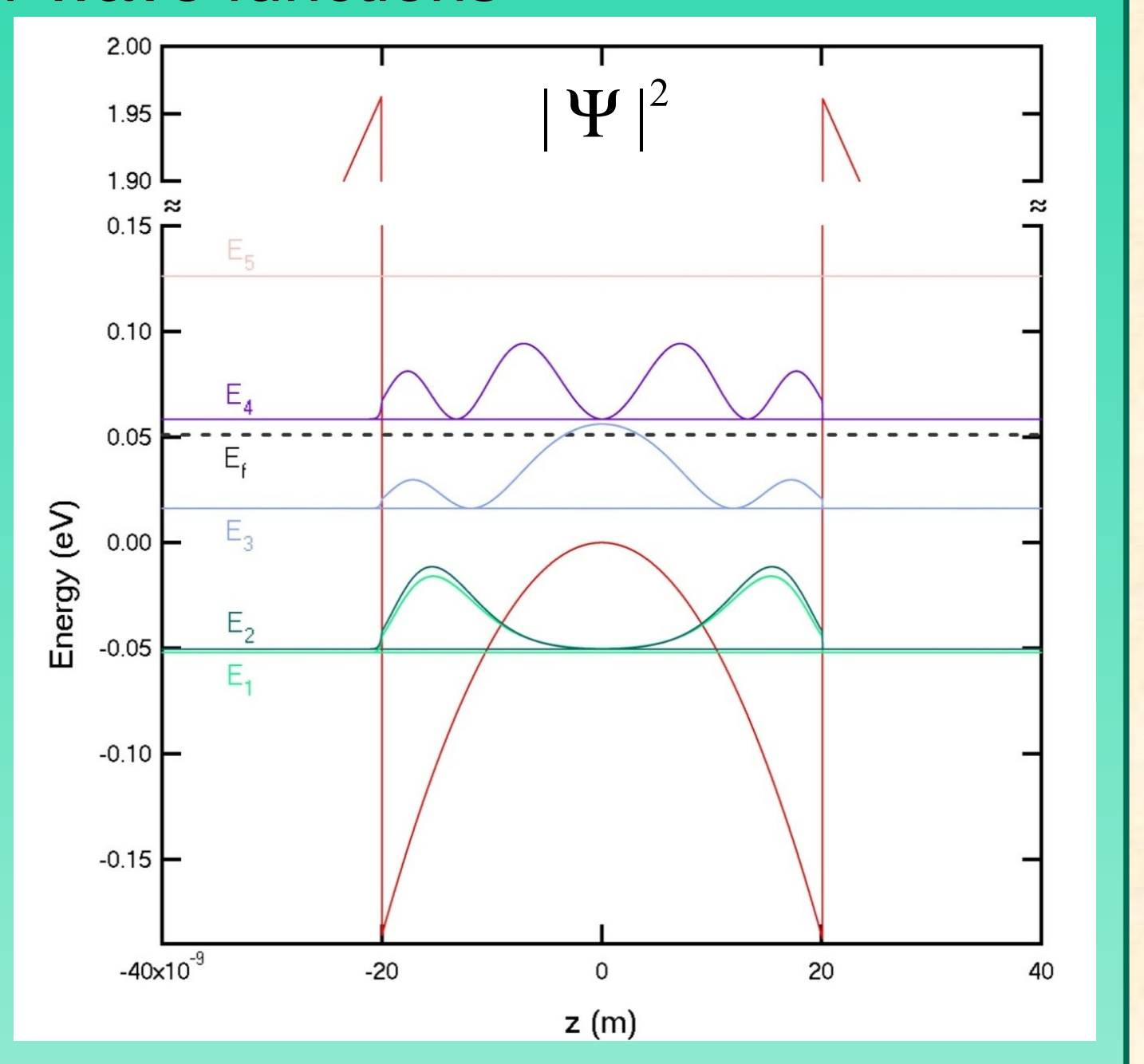
40nm quantum wells with the square of the absolute value of their wave functions



Infinite quantum well



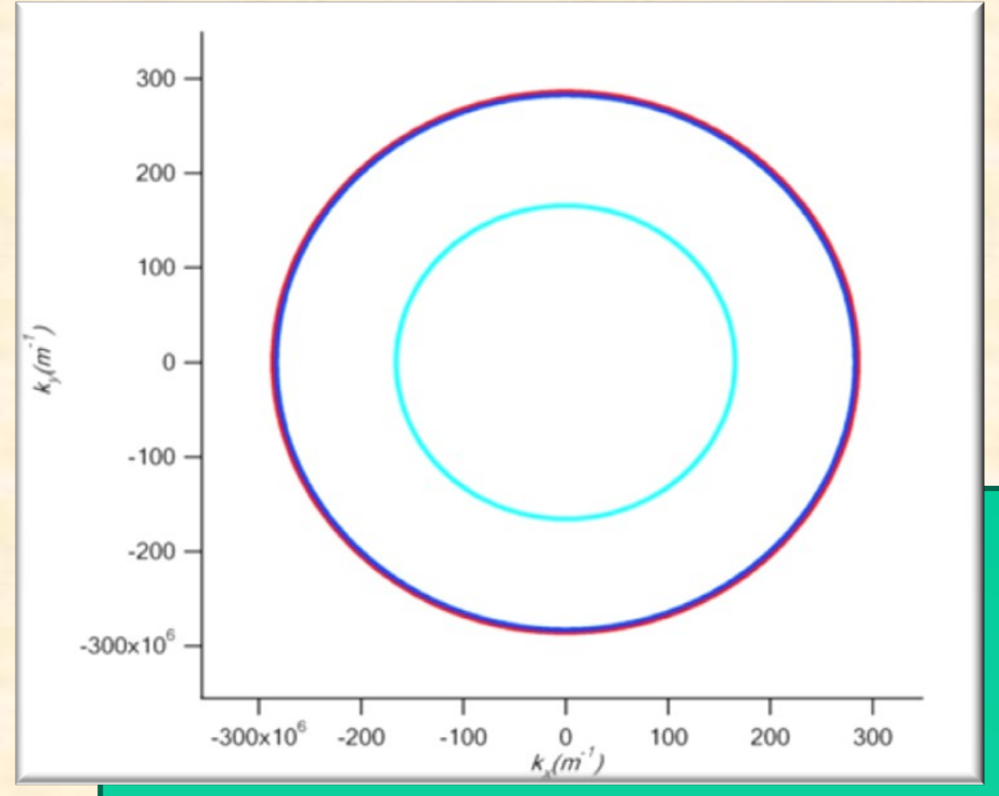
Finite quantum well



Charged finite quantum well

- We studied how the carrier density (Ns) changes with the external magnetic field for a given Fermi energy.
- We calculated spin splitting energies for each sub-band under various magnetic fields.

Results

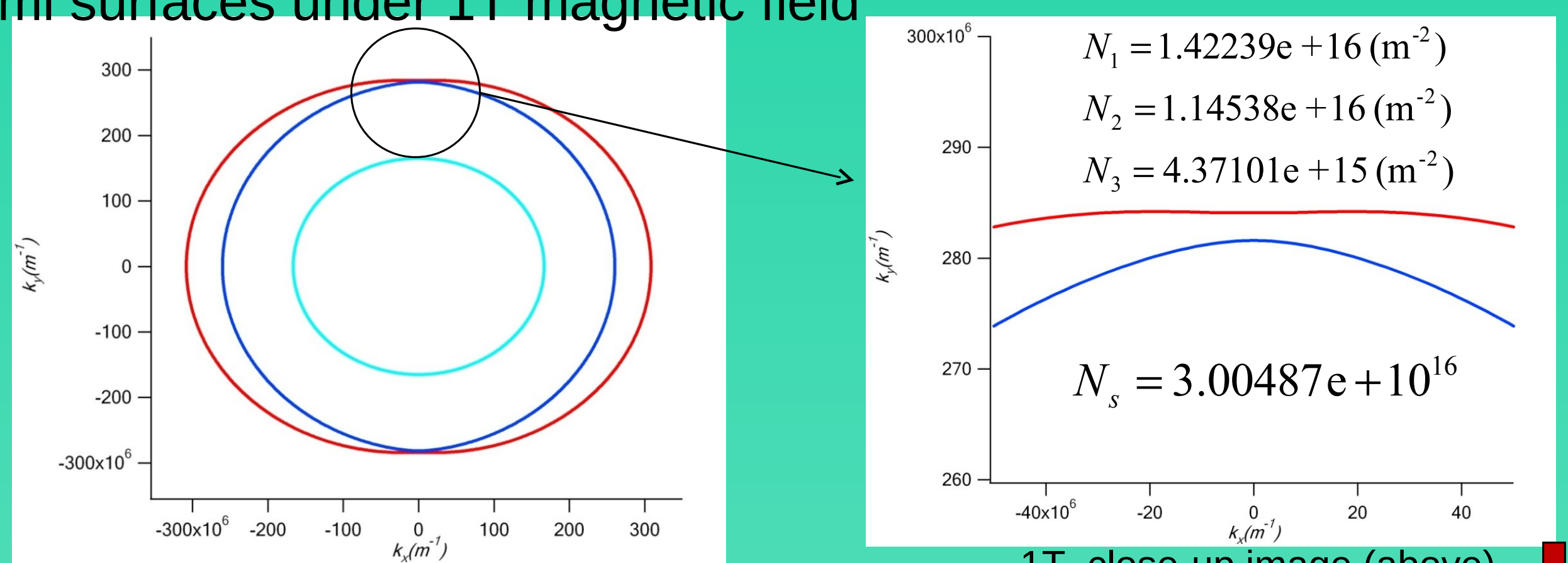


Fermi surfaces under no magnetic field

Densities: $N_1 = 1.29238\text{e}+16\,(\text{m}^{-2})$, $N_2 = 1.27079\text{e}+16\,(\text{m}^{-2})$, $N_3 = 4.36801\text{e}+15\,(\text{m}^{-2})$ } $N_s = 2.99998\text{e}+10^{16}$

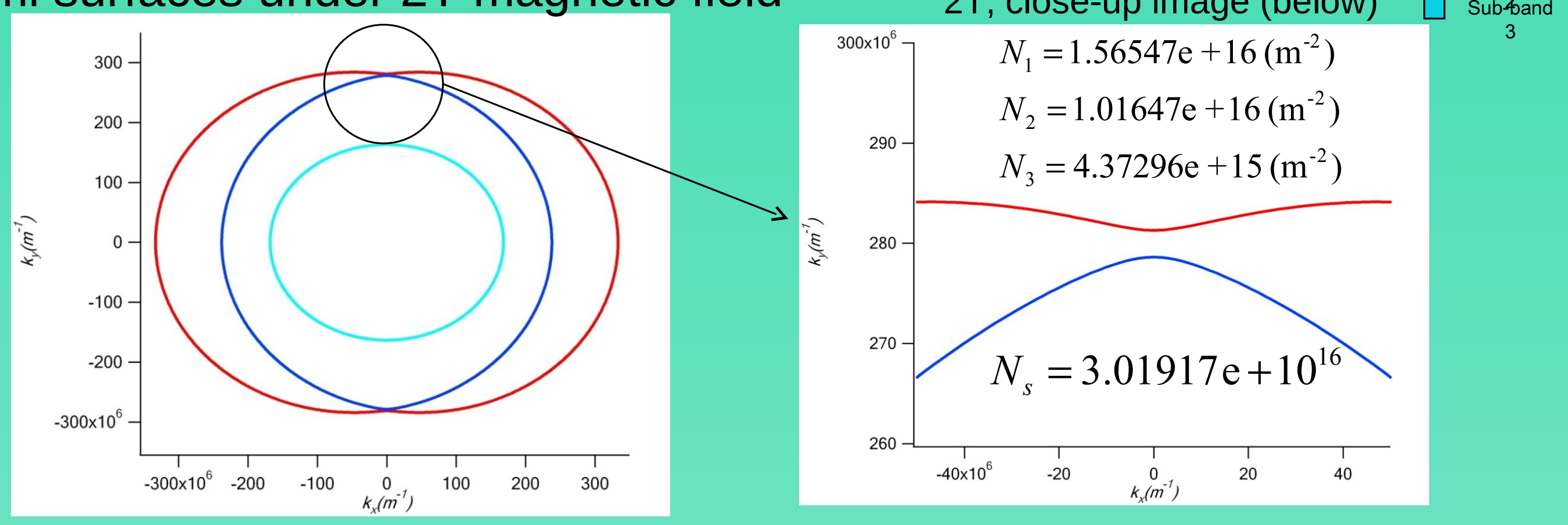
- The graph of the Fermi surfaces under no applied magnetic field has 3 concentric circles.
- Under large applied magnetic fields, the shape of the surfaces became contorted. The surfaces still remained distinct. The densities remained relatively the same (approx. $N_s = 3.0\text{e}+10^{16}$). Thus, Fermi energies did not need to be adjusted for calculations under small magnetic fields since total carrier density was assumed to be the same.

Fermi surfaces under 1T magnetic field

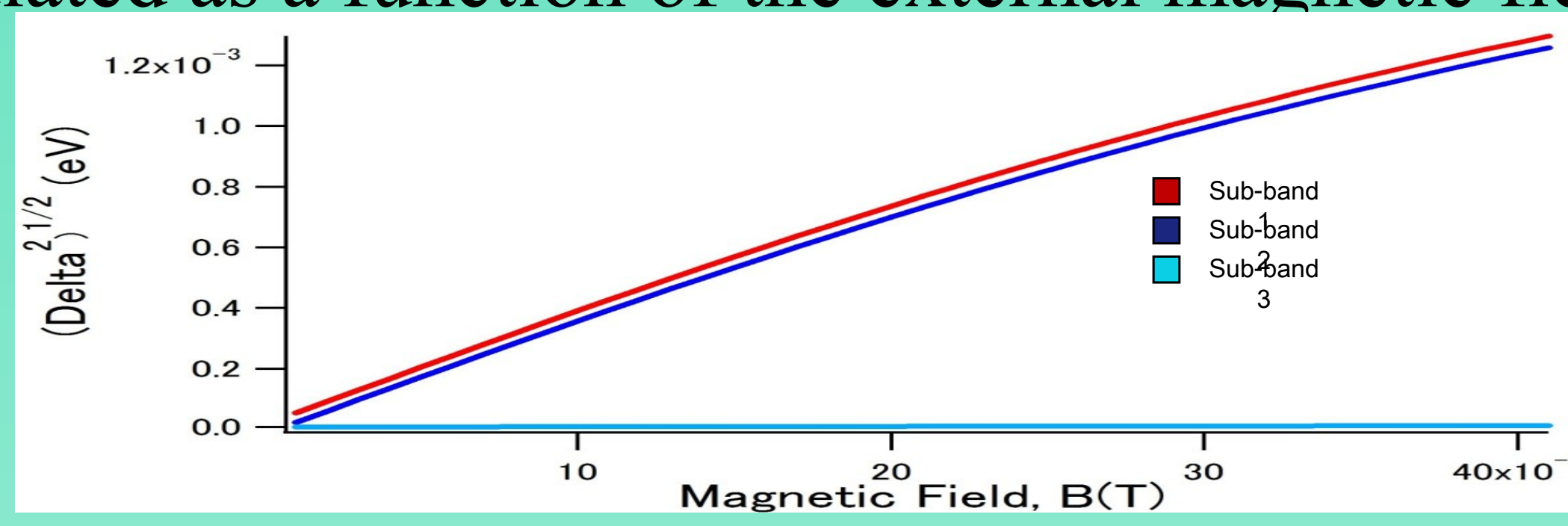


1T, close-up image (above)
2T, close-up image (below)

Fermi surfaces under 2T magnetic field

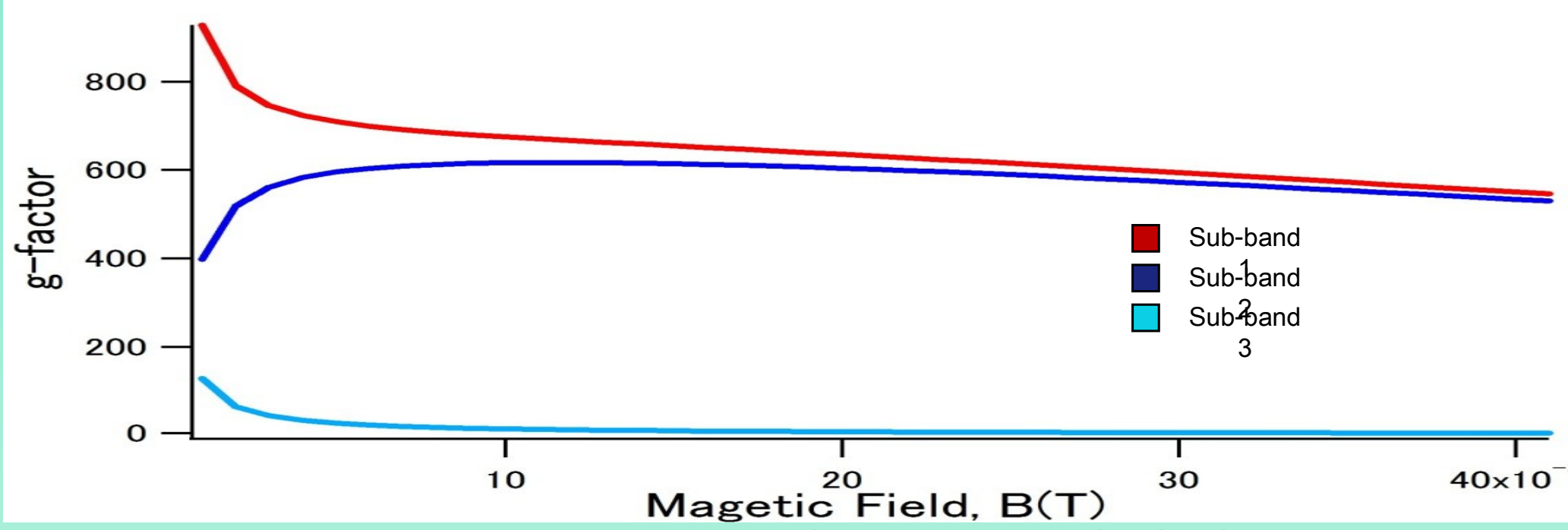


- Spin-splitting energy (Δ), induced by the Rashba effect, is calculated as a function of the external magnetic field.



Spin-splitting energy as a function of magnetic field

- The delta values were converted to g-factor values according to: $\Delta = \frac{1}{2} g\mu_B \mathbf{B}$



g-factor as a function of magnetic field

- The resulting g-factor values are highly enhanced (approx. 600) from typical bulk semiconductor values (|g| < 50).

Conclusion

- The Rashba effect in symmetric charged finite quantum wells was shown to produce measureable magnetic moments. Although paramagnets are usually too small to measure, the results of these simulations show, with large g-factor values, that the Rashba effect allows for the magnetic moment to be directly measured. Such measurements will facilitate future control of spin in the field of Spintronics.
- Objectives for future research are simulating g-factor values for wells of different magnitudes and testing the results of this research through physical experimentation.

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This research was conducted as a result of collaboration between Hokkaido University and the NanoJapan Program, a summer study abroad program sponsored by the National Science Foundation and Rice University.

National Science Foundation

SUMMER NANOTECHNOLOGY STUDY PROGRAM JAPAN

NanoJapan 2008
Rice University
Houston, Texas