

TOWARDS A QUANTUM DATA REGISTER IN A QUANTUM WELL SUPERLATTICE

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A Multiple Quantum Well (MQW) consists of alternating layers of two types of semiconductors with different band gaps that create a step potential for electrons that are excited into the conduction band. Applying an electric field to the MQW causes a slant in the potential that removes the degeneracy of the energy levels of electrons in each well and thus creates the Wannier-Stark ladder. The Wannier-Stark states have corresponding frequencies of absorption, which can be measured using Fourier Transform Infrared (FT-IR) and pump-probe spectroscopy techniques. By performing pulse shaping on an excitation laser, it is possible to generate an electron in an arbitrary superposition state. In vision of using this coherent electron wavepacket for storing and processing quantum information, so called wavepacket quantum data register, we have investigated the optical response of a Gallium Arsenide MQW in order to better understand the features of the Wannier-Stark states.

1 Introduction

Throughout the history of computing, computational power and memory densities have been doubling periodically according to Moore's Law. However, soon the transistors that make up CPUs and memory units will be constructed out of a single atom, and the current methods of progress will be blocked. At that point, if Moore's Law is to be upheld, a fundamentally new technology will have to step in. It is likely that full-fledged quantum computers will not be available as early as this point. Therefore, it is desirable to investigate alternate technologies that store information in multiple-bit-per-atom densities. ^a

A Quantum Register is a device that stores information in the quantum state of a system, which enables it to transcend the single-bit-per-atom barrier.¹ Our research is an investigation into the use of Multiple Quantum Wells (MQW) as Quantum Registers. A MQW is superlattice consisting of alternating layers of two types of semiconductors that have different band gaps.^{2,3} An electron in the conduction band will see this as a periodic step potential and will be mostly confined to the layers with lower potential. The use of quantum registers requires the acquisition of engineering techniques involving quantum wavefunctions, decoherence, and entanglement rather than materials properties and fabrication.

2 Implementation

In a semiconductor, electrons are not normally in the conduction band, but they can be excited using optical radiation to form exciton pairs, which consist of an electron that was excited into the conduction band and a hole that the electron

^a Not to be confused with quantum information - there is only one kind of information, the term "quantum information" refers to information that cannot be extracted classically.

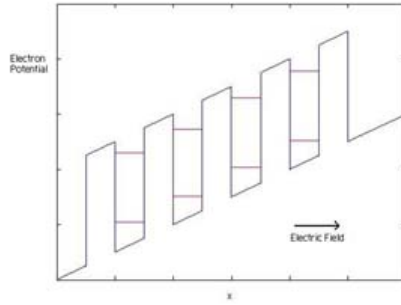


Figure 1: Slanted Multiple Quantum Well Potential

leaves behind in the valence band. After the creation of an exciton from a photon, if the photon had more energy than required, the excess energy will be released as a phonon (heat). Normally, the ground state energies in each well are degenerate. However, if an electric field is applied across the layers of the MQW, the degeneracy is lost and the potential appears as a slanted step function (See Figure 1). In this case, when a photon has more energy than is required to excite an electron, the excess energy can be used to cause the electron to jump to a neighboring well with a higher potential from the electric field. Similarly, if the photon has less energy than necessary, it can still form an exciton as long as the electron subsequently jumps to a well with a lower ground state potential.^b

The energies corresponding to the excitation and subsequent movement of electrons create the Wannier-Stark ladder of energies. When a subpicosecond duration laser pulse is used to form excitons, the time uncertainty is small enough that the uncertainty principle requires a significant spread in energy. This spread is large enough to lead to jumps through at least two wells above and below the origin of excitation. By passing the beam through frequency-specific filters, it is possible to take a partial measurement of the energy of the beam, which partially collapses the wavefunction and gives some control over which Wannier-Stark states can be achieved. This process of filtering known as pulse shaping can be used to select a desired combination of allowed energies, which then becomes a quantum mechanical superposition of the corresponding Wannier-Stark states when the beam is absorbed by the MQW. Pulse-shaping is also used to control the phase of the light at each frequency by selectively passing frequencies through media with different indices of refraction, which causes a delay and shift in the phase of the wavefront. An actual pulse-shaping device uses a diffraction grating to segregate the different component frequencies of the incoming beam and then passes this Fourier transform through a liquid crystal display to filter out the specified frequencies. After filtering, the modified Fourier transform is passed through another diffraction grating to reconstruct a combined wave. The pulse-shaped beam is used to store information in the phase of the wavefunction of an exciton, which allows for very large amounts of classical information to be stored without the need for large numbers of atoms.

By introducing a second wavefunction with known phase to interfere with the first, we can effectively measure the phase of the quantum wavefunction by reading the amplitudes that result from constructive and destructive interference. The amplitude of the wavefunction can be used directly for information storage, but the use of phase is important in quantum computing, so using phase in this experiment

^b The second energy level in a given well is much higher than the ground state energy in a neighboring well with the fields that we apply, so we neglect higher energy levels.

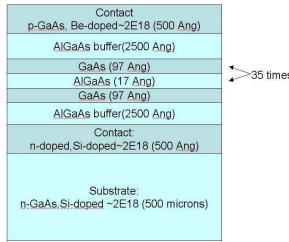


Figure 2: Structure of Quantum Well Sample

is more beneficial due to the gain in engineering skills that can be applied later.

The second pulse, which acts as a retrieval pulse, effectively converts the phase information into amplitude information. Initially, all the amplitudes for the Wannier-Stark states are equal, but the phases are different. When the wavefunction of the second pulse is superimposed on the wavefunction produced by the storage pulse, an interference pattern emerges. The locations of constructive and destructive interference are determined by the phases of the two pulses, so depending on the original phase of the storage pulse, there will be peaks and valleys of amplitude in the interference pattern, which can then be measured. In a quantum register, the amplitude information would then be read out to a classical system. There is also the further possibility that the amplitude information could be entangled with another quantum system in order to construct a quantum computer. An embedded quantum dot is a possible quantum system that is under consideration.

3 Experiment

If the quantum register is to be used as data storage in a classical computer, then there must be a way to readout the classical bits from the quantum wavefunction amplitudes after the retrieval pulse has been applied. One way of doing this is with electro-reflectance measurements that shine light on the quantum register and measure which frequencies are reflected back.^c If a frequency is reflected back that is normally an absorbed frequency, then the corresponding state must already be excited. This may seem difficult since it seems that degenerate jumps would cause false readings, but in fact this is not a problem. Any two jumps going across the same number of wells require the same amount of energy regardless of the initial well since the applied electric field is linear. This means that a jump from well 1 to well 3 is degenerate with a jump from well 2 to well 4. It turns out that when a photon causes one such jump, it actually causes a superposition of all such degenerate jumps, so there are no independent degeneracies to cause confusion since they all happen together. Furthermore, there are no isolated regions of the MQW that can interfere with measurements simply because the storage beam is spread over an area larger than the sample. In practical applications, it is likely that the storage beam would address compartmentalized regions of the surface, which means that it could face readout issues resulting from interference from neighboring regions. However, by making the readout beam small enough and tight enough, it should be possible to ensure that only the desired region is being measured.

Our experiment used a Gallium Arsenide (GaAs) based Multiple Quantum Well. It consists of 35 bilayers of 97 Angstrom GaAs and 17 Angstrom $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ (See Figure 2).⁴ The alternating layers form a potential step function for an electron.

^c Due to the fact that the decoherence time is on the order of picoseconds, an ultrafast pulse would have to be used.

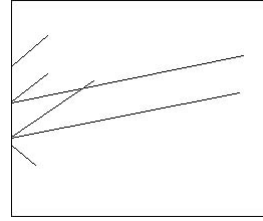
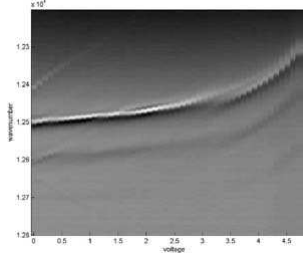
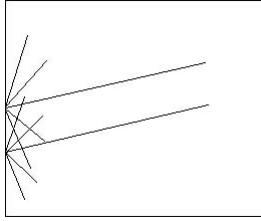


Figure 3: Theoretical Bands

Figure 4: FTIR Data

Figure 5: Observed Bands

The goal of the experiment was to find bands of frequencies corresponding to the Wannier-Stark states under varying bias voltages. These bands were expected to skew apart with increasing bias voltage because the energy required to jump to neighboring wells would increase in absolute value with the slope of the slanted potential. Having more bands that are visible in the data means that the quality of the data is better and the prospects of using the device as a quantum register are better.

Our experiment concentrated on two forms of measurement: Pump-probe time resolved spectroscopy and Fourier Transform Infrared Spectroscopy. Both techniques use optics to determine the energy levels within the sample. We performed reflection studies, but transmission studies are the next step.

Pump-probe time resolved spectroscopy uses a laser pulse to excite the sample and the quickly send in a probe laser pulse to determine the state of the sample very shortly after the excitation. By repeating this process many times and varying the delay between the pump and probe pulses, a time-resolved picture of the post-excitation evolution can be developed. The Fourier Transform Infrared technique uses an apparatus that shines white light on the sample and performs a Fourier transform on the reflected light and displays the result on a computer. To carry out this experiment, the MQW samples were glued to small metallic sample holder plates using GE varnish and thin wires were attached to the surface of the samples using silver paste to act as electrodes for the bias voltage. The sample holders were then inserted into a cryostat. The cryostat was placed in the sample chamber of a Bruker IFS66 Fourier Transform Infrared (FTIR) analyzer. The cryostat and FTIR chamber were both evacuated and liquid helium was used to bring the cryostat down to about 4K. The data taking and computer processing routine was then run 51 times with a manual 0.1 Volt change in the bias voltage between each run. The bias voltage ranged from 0.0V to 5.0V, which may have exceeded the breakdown voltage of the MQW sample. The output of these runs is shown in figure 4.

4 Discussion and Results

The plots resulting from the FTIR experiment did not yield as many branches as we had hoped. Further tweaking may have yielded better results. There is also the possibility that the samples degraded over time since the results seemed to get worse. Still, the effects that were expected did show up in the data. Multiple bands were visible, and they diverged with increasing bias voltage. The two primary bands correspond to light-hole and heavy-hole transitions in the semiconductor. Each band is expected to have branches diverging with increasing applied voltage. Only one or two branches can be seen coming from each band, which correspond

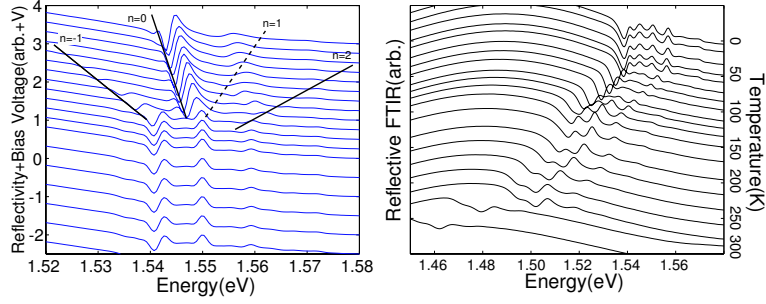


Figure 6: The left figure shows the bias voltage dependence of the Wannier-Stark energy separation lines. The lines drawn represent the bands of frequencies that correspond to exciton formation to neighboring layers. The right figure shows the temperature dependence of exciton energy lines where below 50K phonon transitions are suppressed and the exciton transitions are clearly resolved.

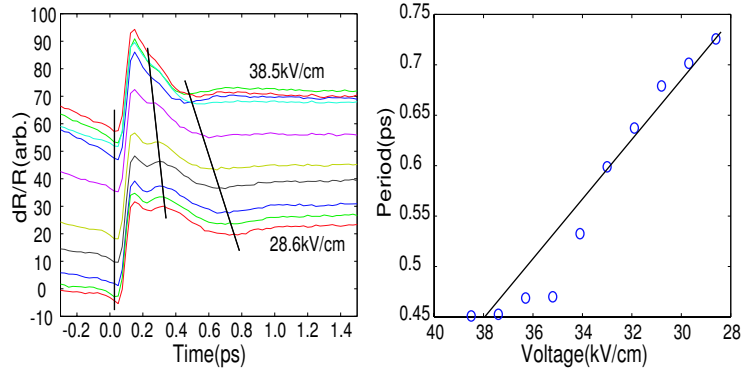


Figure 7: The time-resolved pump probe experiment revealed the coherent charge oscillations in Wannier-Stark energy ladders. The bias voltage was adjusted to induce near 10 meV multiple energy separations, which induces charge oscillation with a frequency of 2THz. The figure on the right shows the linear relation between the bias voltage and the oscillation frequency, as is consistent with Ref[5].

to excitation and a jump to a neighboring well. There is no evidence for electrons jumping two wells over since this would be seen as another branch with twice the slope. There is also a point where two branches intersect and cause some interference. This data has been taken before in other ways, but this is the first time that FTIR has been used.

Multiple Quantum Wells also have other interesting capabilities relating to their optical properties. Bell Labs recognized this with their creation of quantum well modulators (<http://www.bell-labs.com/project/oevlsi/tutorial/>) that control the transmission of light through a MQW. One goal is to use a transparent semiconductor to create a clear window that can turn into a mirror by applying an electric field. A quantum well could be used to contain conduction band electrons and prevent them from recombining with holes in another well even in the absence of a field. The conduction band electrons would absorb photons, converting them into kinetic energy, and then reemit the same photon since they are not in a bound state. A reverse field could then be applied to spill the conduction band electrons back into their original wells where they can recombine with the holes they left behind. If this worked, both the mirror state and the clear state could be stable without any electric field, making the whole process very energy efficient. Quantum Well technology has already shown that it has applications for modern technology. Quantum Well lasers are already being used in commercial devices. The future possibility of quantum registers and electrooptic materials brings more promise to the study of Multiple Quantum Wells.

5 Acknowledgments

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6 References

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