INVESTIGATION OF AMORPHOUS THIN FILMS USING ELECTRICALLY DETECTED MAGNETIC RESONANCE

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ABSTRACT

Amorphous thin films play an important role in the electronics industry due to their low fabrication cost and their many current and potential applications. In order to gain a better understanding of the electronic properties of these materials, low-field electrically detected magnetic resonance was used to observe changes in spin-dependent trap-assisted tunneling in films of amorphous hydrogenated boron, amorphous hydrogenated carbon, and diamond-like carbon. The resulting measurements indicate the presence of mid-band gap trap states that facilitate conduction in the films via spin-dependent variable range hopping. Furthermore, the similarity in voltage-dependence of the magnetic resonance and near zero-field magnetoresistance responses provides strong evidence for a common physical origin driving both processes.
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Chapter 1

Introduction

Motivation

Certain amorphous films are currently of great interest due to their relatively low fabrication cost and their many existing and potential applications. Spin-based quantum computing is one of the foremost of these potential applications. A greater understanding of the electronic properties of these films will pave the way for them to be utilized in more sophisticated and useful device structures.

Problem Statement

In order for the amorphous thin films discussed in this thesis to be implemented effectively in complicated devices, it is important to understand their electronic properties well. Electrically detected magnetic resonance (EDMR) is a valuable tool for this purpose because it allows for the observation of spin-based electronic behavior while a device is in use. Using EDMR, this work investigated the electronic properties of thin films of amorphous hydrogenated boron, amorphous hydrogenated carbon, and diamond-like carbon. These films are excellent for studying with EDMR because their amorphous nature provides an abundance of defects, which increase the spin-dependent recombination (SDR) and spin-dependent trap-assisted tunneling (SDTAT) currents through the devices. Moreover, the simplicity of the device structures allows for simple models.
By utilizing EDMR to study these devices, this thesis aims to analyze the magnetic resonance and near zero-field magnetoresistance responses under different biasing conditions to gain insight into the nature of the defects present. Furthermore, a greater understanding of the spin-dependent variable range hopping responsible for these responses is developed by considering the interaction of singlet and triplet states at defect sites. Thus, by carefully observing and analyzing changes in the spin-dependent current through these relatively simple devices, this thesis endeavors to improve the understanding of these amorphous materials.
Chapter 2

Literature Review

In order to develop fully the discussions later in this thesis, it is necessary first to review the scientific literature on the topics discussed herein. This literature review consists of three main sections. The first section discusses the theory used to explain electronic conduction in materials of interest; the second gives a brief introduction to the principles of electron paramagnetic resonance; the third introduces the concept of electrically detected magnetic resonance and discusses some of its potential applications.

Electronic Conduction in Solids

One of the most important material properties when considering devices is the electrical conductivity, typically denoted by ‘$\sigma$’. This property describes a material’s ability to carry an electrical current, as defined by Ohm’s Law:

$$J = \sigma E$$  \hspace{1cm} (1)

In Equation 1, $J$ represents the current density vector and $E$ is the electric field vector. While this relation can describe electrical conductivity macroscopically, the full microscopic description is significantly more complicated, as it considers the transport of individual electrons and holes through a material.
Since all of the materials studied in this thesis are amorphous, conduction through crystalline materials is not as relevant as through non-crystalline materials. A microscopic description of conduction in the non-crystalline materials discussed in this thesis was developed by Sir Neville Mott [1, 2], who proposed that charge carriers tunnel from one impurity site to the next by “thermally activated hopping” [3]. This hopping, also known as “variable range hopping” (VRH), is especially prevalent in some non-crystalline materials. In these materials, conduction is dominated by tunneling between defects. Thus, in the amorphous materials considered in this thesis, the abundance of defects and absence of long-range order suggest that VRH is the dominant conduction process. Furthermore, VRH is highly temperature dependent [2], resulting in the following expression for electrical conductivity in non-crystalline materials:

$$\sigma = A \exp(-B/T^\eta)$$  \hspace{1cm} (2)

In Equation 2, A, B, and \( \eta \) are constants, while T represents temperature in Kelvin. In Mott’s original formulation, \( \eta \) took on a value of \( \frac{1}{4} \) [3]. However, it was later proposed by Efros and Shklovskii [4] that when the Coulombic interactions between the electron and hole are considered, there arises a “Coulomb gap” in the density of states near the Fermi level. This gap directly affects the electrical conductivity, resulting in a value of \( \frac{1}{2} \) for \( \eta \), in contradiction to the value of \( \frac{1}{4} \) originally proposed by Mott. In their formulation, however, Efros and Shklovskii assumed that the localization radius is small compared with the distance between the electron and hole. This assumption allows for easier calculation of the particle wavefunctions by implying there is no overlap between them. However, as Mott later showed, this assumption limits the applicability of the \( \eta = \frac{1}{2} \) model to lightly doped semiconductors [5]. As the concentration of dopants increases, the localization radius approximation breaks down and the value of \( \eta \) begins to approach \( \frac{1}{4} \) [2].
While the precise values of the constants in the Mott equation for electrical conductivity are not of great importance to this thesis, it is essential to note the importance of temperature and charge carrier concentration (which has been absorbed into B). Moreover, impurity sites play a significant role in the measurement techniques used in this research, so a thorough understanding of VRH is vital, as it is the primary mechanism of electrical conduction in the amorphous materials studied herein.

Electron Paramagnetic Resonance

One of the most effective tools for probing the electronic structure of materials is electron paramagnetic resonance (EPR). This technique allows for the detection of paramagnetic sites, which are formed when a material possesses unpaired electrons. Some examples of paramagnetic sites are free radicals, dangling bonds due to crystalline defects, and certain elements with unfilled electron orbitals. Due to the ubiquity of such systems, the applications of EPR are extensive [6]. Moreover, EPR is an important technique in that it allows for direct observation of a multitude of quantum mechanical effects that are not otherwise very readily observable.

In its most basic form, EPR is fairly intuitive and easy to grasp. Every electron has an intrinsic magnetic dipole moment due to its spin. However, when electrons are paired, as they are in chemical bonds and core electron orbitals, the Pauli Exclusion Principle dictates that their spins be antiparallel. This results in a net magnetic dipole moment of zero [6]. However, when electrons remain unpaired (as in the paramagnetic cases mentioned above), there is a nonzero net magnetic
dipole moment. Under an applied magnetic field, in the simplest possible case, this dipole has an energy defined \[ E = g_e \beta_e m_s B_0 \] (3)

where \( g_e \) is a constant known as the Landé g-factor for a free electron, \( \beta_e \) is a constant known as the Bohr magneton, \( B_0 \) is the applied magnetic field, and \( m_s \) is the spin projection quantum number, which takes on values \( m_s = \pm \frac{1}{2} \). Thus, due to the two possible values of \( m_s \), there arises a splitting in energy levels \( \Delta E \), as depicted in Figure 1 [7].

![Figure 1: Energy Splitting for an Electron in an External Magnetic Field](image)

Furthermore, by supplying a quantum of energy equal to the difference in energy levels, it is possible to induce a transition between states [6]. This is achieved by using monochromatic radiation with frequency \( \nu \), the “resonant frequency” of the system. The energy of these photons
is given by the Planck-Einstein relation, \( E = h\nu \), where \( h \) is Planck’s constant. Thus, resonance is achieved when the following condition is met:

\[
h\nu = \Delta E = g_e\beta_e B_0 \quad (4)
\]

Equation 4 is known as the resonance condition; it represents the simplest possible case of magnetic resonance. Additionally, an electron’s surroundings can lead to spin-orbit coupling and a nuclear hyperfine interaction, which slightly alter the resonance condition. However, these corrections are typically small.

In practice, EPR is achieved by placing a sample inside a resonant cavity, which allows the monochromatic radiation to enter through an iris [6]. The cavity is designed to fit an integer number of wavelengths of the radiation, thus setting up standing waves within the cavity. By carefully positioning the sample in the cavity and tuning the frequency of the radiation, it is possible to have the sample coincident with a node of the standing wave, greatly increasing the energy density and therefore increasing the chances of resonant absorption [6].

In order to satisfy the rightmost side of the resonance condition, the resonant cavity is placed inside a magnetic field. This field is typically generated by Helmholtz coils, which provide a remarkably uniform \( B_0 \), thereby ensuring the resonance condition is the same throughout the entire sample. In order to obtain an EPR spectrum, the frequency \( \nu \) of the radiation is typically held constant and the magnetic field is swept through a range centered on the expected resonance value for \( B_0 \). The absorption of the radiation is measured by monitoring the reflected output of the cavity, which should decrease as the field passes through resonance. It should also be noted that it is possible to
obtain an EPR spectrum by holding $B_0$ fixed while sweeping $\nu$, but this method is less common due to the difficulty of obtaining sources with large frequency ranges and the comparative ease of varying the magnetic field with Helmholtz coils [6].

Although the spectrum from an EPR experiment should naturally be an absorption spectrum (since the absorption of radiation is the quantity being measured), by convention, the first derivative of this spectrum is plotted because this is the form of the raw data when a lock-in amplifier is used to reduce noise. Moreover, the first derivative allows for easier identification of more subtle features. Figure 2 depicts the absorption and first derivative plots for a typical EPR spectrum obtained from weak pitch (coal tar in KCl), which is used to calibrate EPR spectrometers.

Figure 2: Typical Absorption and First Derivative EPR Spectra
While this discussion of EPR covers only the most basic principles, as indicated previously, there are a great many often-subtle effects that can reveal a wealth of information about the paramagnetic defects within a sample. For example, the g-factor in the resonance condition is affected by an electron’s immediate surroundings, and small variations in the value of this factor (such as those caused by spin-orbit coupling) can give insight into material properties. However, this overview is sufficient to introduce the next section, which is the focus of the research conducted for this thesis.

**Electrically Detected Magnetic Resonance**

In general, EPR is effective for analyzing materials in bulk. However, in order to study defects within micro- and nano-scale devices, the phenomenon of magnetic resonance can be utilized differently. EDMR is a technique that monitors the changes in conductivity in an electronic device when the resonance condition is met [8]. Essentially, while EPR measures the changes in absorption of electromagnetic radiation by a sample, EDMR measures the changes in current through a device.

Most EDMR studies in the literature utilize SDR, which affects the recombination current, as described by Kaplan, Solomon, and Mott [9]. Their model proposes that electrons and holes become bound in either a singlet or a triplet state. In the singlet state, recombination is allowed and leads to a recombination event, but recombination is forbidden in the triplet state [9]. Thus, triplet states have a longer mean lifetime and therefore a greater steady-state population. However, when the resonance condition is met, electrons can absorb energy and flip their orientations,
causing previously disallowed recombinations to occur: this process results in a measureable change in current through the device. Although this model was originally formulated quasi-classically, it was later confirmed [8, 10] with a full quantum mechanical treatment.

In the materials studied for this thesis, however, the change in current observed with EDMR is the result of spin-dependent trap-assisted tunneling (SDTAT). In the metal-insulator-semiconductor (MIS) devices studied, electrons tunnel from the metal into the conduction band of the semiconductor via trap states in the insulator [11]. This process is depicted in Figure 3. However, due to the Pauli Exclusion Principle, an electron can only tunnel into a trap state that has a spin antiparallel to the electron’s own spin (the singlet state). As discussed previously, in magnetic resonance, the net absorption of energy causes spins to flip, allowing electrons to tunnel to traps that were previously forbidden. This results in more electrons reaching the semiconductor’s conduction band, and therefore a larger current. Since SDTAT is responsible for conduction through the insulator, a measureable increase in current occurs during resonance.

![Figure 3: Diagram of SDTAT Conduction](image.png)
Due to the fact that the resonance condition has two variables (\(v\) and \(B_0\)), it is possible to detect resonance for virtually any magnetic field value, provided that a suitable source can be found to provide the necessary energy at frequency \(v\). While traditionally, EDMR has been performed at frequencies of around 9 GHz, this requires a significant outlay for costly equipment to produce the necessary magnetic field, which has to be stronger than 3 kG. It has been shown [12] that magnetic resonance can be detected at much lower fields (20-200 G) by using relatively inexpensive Helmholtz coils and a solenoid driven at a radio frequency (RF) to provide the electromagnetic field necessary to satisfy the left-hand-side of the resonance condition. At such low values of \(B_0\), however, the precision is generally not sufficient to determine g-values accurately [12]; this represents one of the few trade-offs that comes with the low cost of the low-field EDMR system.

When taking resonance measurements at such low magnetic fields, in addition to finding a change in current when the resonance condition is met, a change in current is also observed as the magnetic field is swept through zero Gauss. This zero-field magnetoresistance (MR) is entirely separate from the resonance effect because it can be observed even when no RF electromagnetic field is provided to induce unpaired electrons to flip [13]. This effect can be considered a result of a relative increase in the number of singlet states compared to triplet states, due to singlet-triplet mixing near zero field. This mixing leads to an augmented recombination current or trap-assisted tunneling current. As zero applied field is approached, the total magnetic field electrons experience becomes dominated by the local environment because the externally applied field \(B_0\) drops out of the vector sum of contributing magnetic fields. Since singlet states and triplet states are defined based on an electron’s orientation relative to the total magnetic field, at zero applied field, free electrons transition into states based on the random magnetic fields produced by their local
surroundings, causing a net change in the singlet-to-triplet ratio [14, 15]. This, in turn, causes a change in the SDTAT current as these newly created singlet pairs undergo previously disallowed transitions.

Following the same convention as in EPR, the first derivative is typically plotted in an EDMR spectrum. Figure 4 depicts an EDMR spectrum with well-defined resonance peaks at ± 53.5 G and a zero-field MR response centered on 0 G. This spectrum is from a device that had previously been irradiated, likely creating many paramagnetic sites, and increasing the strength of the signals as a result.

![Figure 4: EDMR Spectrum with Resonance and Zero-field MR Peaks](image)
As with the previous discussion of EPR, there are far more subtleties in EDMR than can be considered here, which have the power to reveal even more details about the properties of samples. The small peaks in Figure 3 at around \( \pm 26 \) G are examples of such subtleties: they are known as “half-field” responses [16], but the underlying physics behind them is beyond the scope of this thesis. However, even just with the basic principles of EDMR, it is possible to extract a great deal of physical understanding from a spectrum.
Chapter 3

Experimental Setup & Procedure

This chapter first describes the experimental apparatus used throughout the research, as well as specifics about the samples and their preparation. Later, the procedure used to gather the data is described. While this chapter contains no specific results or data, procedural specifications are essential so that the results discussed in the following chapter can potentially be replicated.

Experimental Apparatus

For this thesis, the data was gathered using a low-field EDMR spectrometer. The spectrometer apparatus consists of several important parts, which are depicted in Figure 5. The computer (Figure 5A) functions as an interface to the other equipment, with LabVIEW implemented to control the magnetic field, modulation amplitude, and other variable aspects of the system. Additionally, LabVIEW logs all of the EDMR data taken, writing them to tab delimited files after every magnetic field sweep. These files can then be read by programs such as Microsoft Excel or MATLAB. The relatively large magnetic field $B_0$ is generated by the Helmholtz coils (Figure 5D), which are powerful enough to produce fields of up to approximately 115 G. In addition to the main magnetic field, a smaller, oscillating magnetic is generated by a set of coils known as the “modulation coils”. (The vector sum of these two fields is $B_0$.) The signal for these coils is amplified by a simple audio amplifier (Figure 5B). Finally, an RF generator (Figure 5C) produces a signal that drives a small wire coil around the sample, supplying the electromagnetic energy at frequency $\nu$ required to meet
the resonance condition. These components create the conditions necessary for a magnetic resonance response.

In addition to the components used to induce magnetic resonance, there are a few more that are necessary to make useful measurements of the sample’s response. With multiple different sources contributing to the local magnetic field (Helmholtz coils, modulation coils, and Earth’s magnetic field), it is not possible to accurately determine the total local magnetic field simply by measuring the currents through the coils. Therefore, a Gaussmeter (Figure 5E) is used to measure the exact magnetic field with a Hall Effect probe placed in close proximity to the sample. The magnetic field data is used to determine the center field value and width of signals on EDMR spectra accurately, as well as to control the current through the Helmholtz coils dynamically using a proportional-
integral (PI) scheme. Finally, two preamplifiers (Figure 5F) are used to bias the device, filter the output from the device, and measure both the unfiltered current and the change in current as the magnetic field is swept through resonance and zero-field. Even with these relatively simple components, it is possible to measure atomic-level physical phenomena using low-field EDMR.

**Sample Preparation**

Three different thin film materials were investigated: amorphous hydrogenated boron (a-B:H), amorphous hydrogenated carbon (a-C:H), and diamond-like carbon (DLC). All three materials are amorphous insulators, deposited on single-crystal silicon, and capped with titanium. Thus, each device has an MIS structure. The insulating layers of a-B:H, a-C:H, and DLC were 0.5 μm, 1 μm, and 0.5 μm in thickness, respectively.

In order to prepare these devices for use in the EDMR apparatus described in the previous section, they are first separated from the larger wafers on which they were fabricated using a diamond scribe. Then, the silicon substrate is adhered to a “T” (a printed circuit board designed to hold samples) using electrically conductive paint and a wire bonder is used to contact the titanium. An example of one of these T’s is depicted in Figure 6. The T is designed to be long so that the sample can be placed at the center of the Helmholtz coils, where the magnetic field is strongest. The T utilizes a USB connection to facilitate easy connection with other equipment and to allow for the use of up to four terminals on more complicated devices, although the samples used in this research only require two.
ΔI/I Measurement

While a single EDMR spectrum can reveal a wealth of information about a device, in order to compare multiple different spectra, it can be useful to condense each one into a single value. Doing this allows one to plot the general “size” of a signal versus some other variable, such as gate bias or time. A good way to quantify this idea of a signal’s “size” is by calculating ΔI/I, or the change in current over the course of a magnetic field sweep divided by the total current through the device under non-resonance conditions.

ΔI is simply the EDMR amplitude (recall that this apparatus measures the change in spin-dependent current). Normalizing it with the total current I through the device under normal conditions helps to sort out changes in current that arise from extraneous sources. For example, one such extraneous source could be a small change in room temperature; as discussed in Chapter 2, conductivity in non-crystalline materials is highly temperature dependent, so an increase in the room temperature would increase ΔI during resonance, but it would also increase I under non-resonance conditions. Thus, the value of ΔI/I would be much less affected by this fluctuation than either ΔI or I alone. This consistency makes ΔI/I a particularly reliable and informative quantity.
One consideration that had to be made, however, is that the value of $I$ needs to be measured without any filtering taking place. For this reason, a second preamplifier had to be added to the EDMR apparatus, whereas previously only one had been necessary. This second preamplifier serves to filter the output signal, while the first biases the device and provides the gain. Thus, two different channels are fed into the computer and written into the data files by LabVIEW as EDMR amplitude and unfiltered current. This allows for easy calculation of $\Delta I/I$ by dividing the peak-to-peak amplitude of the EDMR signal by the unfiltered current, yielding a single value per spectrum. In this experiment, $\Delta I/I$ was recorded under gate biases varying from -5 V to +5 V, resulting in a quantitative description of EDMR response as a function of voltage.
Chapter 4

Results & Discussion

This chapter presents the findings of the research conducted. Different sections consider the results from each material individually and then a final section considers what more can be gleaned from a comparison of all of the materials tested.

Amorphous Hydrogenated Boron

The EDMR spectrum for a-B:H is depicted in Figure 7. The spectrum displayed was recorded under a gate bias of -2.5 V because such biasing conditions were previously determined to yield an exceptionally noiseless signal. When analyzing this EDMR spectrum, perhaps the most salient feature is that there is a massively wide zero-field MR response, which has a linewidth (the peak-to-peak width of the signal, denoted ‘a’ in Figure 7) of approximately 100 G. This large linewidth extends all the way out to where the magnetic resonance peaks occur at ± 53.5 G, causing the resonance response to “ride” on the zero-field response.

In fact, by analyzing the dependence of ΔI/I on voltage (shown in Figure 8), it can be clearly seen that the largest responses for both zero-field MR and magnetic resonance occur only under negative gate bias. In fact, practically no relative change in current associated with SDTAT is observed in the positive gate bias regime. This asymmetry with respect to bias polarity strongly
points to the existence of a mid-gap trap state that facilitates SDTAT under negative bias, but is made inaccessible by the shifting of the metal Fermi energy associated with positive bias [13].

Figure 7: EDMR Spectrum for Amorphous Hydrogenated Boron

Figure 8: ΔI/I versus Gate Bias for Amorphous Hydrogenated Boron
Finally, it is notable in a-B:H that the magnitude of $\Delta I/I$ is nearly the same for both the zero-field MR and resonance responses under all biasing conditions. ($\Delta I/I$ values for resonance and zero-field never vary by more than 0.021\% for any given gate bias.) As it will be shown in the following sections, this does not occur in either of the other materials, which in general exhibit smaller $\Delta I/I$ for resonance than for zero-field MR responses.

**Amorphous Hydrogenated Carbon**

The EDMR spectrum obtained for a-C:H is more typical than the one for a-B:H discussed in the previous section. As shown in Figure 9, the peak-to-peak amplitude of the zero-field MR signal is approximately 2.5 times larger than that of the resonance peaks ($b \approx 2.5c$). Moreover, with a linewidth of approximately 20 G, the zero-field response does not overlap with the resonance responses to the extent that occurs in a-B:H. The spectrum depicted in Figure 9 was obtained under a gate bias of +3 V because those conditions resulted in a very large signal-to-noise ratio.

**Figure 9: EDMR Spectrum for Amorphous Hydrogenated Carbon**
While a-C:H also exhibits an asymmetry with respect to bias polarity, the difference is not as stark as in the case of a-B:H. Figure 10 shows that it is possible to obtain a signal under both positive and negative bias, but positive biases in general yield a greater relative change in current. Moreover, there are notable increases in ΔI/I around -2 V and -3.5 V which likely correspond to trap states in the band gap that allow increased tunneling to take place when the metal Fermi energy aligns with them, increasing the overall SDTAT current. At high positive voltages, ΔI/I begins to decrease as a result of increasing current through the device, thereby making the relative change in current smaller.

Consistent with the spectrum in Figure 9, a disparity is observed between the magnitude of the relative change in current for the zero-field MR and resonance responses. In both the EDMR spectrum and the plot of ΔI/I, the zero-field MR response is approximately 2.5 times greater in

![Figure 10: ΔI/I versus Gate Bias for Amorphous Hydrogenated Carbon](image-url)
amplitude than the resonance responses at any given voltage, in perfect agreement with the observed size of the peaks in the spectrum above.

**Diamond-like Carbon**

When considering the crystal structure and chemical composition of DLC, it becomes rapidly apparent just how similar this material is to a-C:H: both are amorphous films predominantly composed of carbon. As such, while slightly different types of defects are likely to be present in each, one would expect their electronic properties to be largely similar. This intuitive argument turns out to be true, leading to many similarities in the measurements taken using EDMR. The EDMR spectrum for DLC is plotted in Figure 11, and it can be seen that the line shape is qualitatively very similar to that of a-C:H. One notable difference is that the zero-field MR response (d) is only about 1.6 times larger on average than the resonance peaks (e), in contrast to the difference of 2.5 times observed in a-C:H.

![Figure 11: EDMR Spectrum for Diamond-like Carbon](image)
As with a-B:H and a-C:H, there is a notable asymmetry in both the resonance and zero-field responses with respect to polarity. The data for Figure 11 was recorded under a gate bias of +1.5 V because, as can be seen in Figure 12, negative biases do not yield appreciable signals in this sample. Furthermore, ΔI/I clearly peaks at +1.5 V, indicating that under such a bias, there is a large increase in SDTAT. A possible mechanism for this is a mid-band gap trap state in the DLC that allows for tunneling when it becomes aligned with the metal Fermi energy as a result of the applied bias [13]. Under greater positive biases, the total current through the device increases exponentially, effectively extinguishing the value of ΔI/I.

![Figure 12: ΔI/I versus Gate Bias for Diamond-like Carbon](image)

It can be seen from both Figure 11 and Figure 12 that the resonance response in DLC is only about two-thirds as strong as the zero-field MR response. This is similar to the case with a-C:H, which also exhibits a larger zero-field MR response. Such parallels likely follow from the compositional similarities between a-C:H and DLC, as discussed previously.
Comparative Discussion

Of the three materials investigated in this thesis, a-B:H is, without question, at greatest variance with the others. While the similar chemical and crystallographic compositions of a-C:H and DLC impart them similar electronic properties, a-B:H behaves very differently. Both a-C:H and DLC exhibit their largest zero-field MR and resonance responses in the positive bias regime, peaking at +1.5 V and then trailing off at higher positive voltages. However, a-B:H shows virtually no SDTAT under positive bias and maintains a fairly constant value for ΔI/I in the negative bias regime, which seems to be largely independent of the bias magnitude. For ease of comparison, ΔI/I is plotted against the gate bias voltage for all three samples in Figure 13.

Figure 13: Combined Plot of ΔI/I for All Three Samples
When ΔI/I values for all three samples are plotted in the same figure, the disparity in the signal magnitudes becomes especially apparent. While a-B:H and DLC both have a maximum ΔI/I of approximately 0.2%, a-C:H has its maximum nearly an order of magnitude larger at around 1.8%. A plausible explanation for this difference would be that a-C:H likely has a greater density of trap states, which lead to a greater rate of SDTAT when the resonance condition is met or when there is a mixing of singlet and triplet states near zero-field. However, due to the compositional similarities between a-C:H and DLC, along with the fact that the largest peak of ΔI/I occurs at +1.5 V for both materials, it is likely the same type of defect facilitates SDTAT in both. Moreover, it is possible that the defects causing increases in ΔI/I at -2 V and -3.5 V in a-C:H may also exist in DLC, but the exceptionally weak signal that DLC exhibits under negative bias bars such a possibility from being investigated by the means adopted for this thesis.

While the ΔI/I peaks that are present for a-C:H and DLC provide insight into the defects that are present in both materials, the seeming lack of peaks exhibited by a-B:H can also reveal some information about the defect structure. Since a spike in ΔI/I would be expected any time the metal Fermi energy aligns with a trap in the a-B:H band gap [13], it can be deduced that no major defects are present in high concentration in this range. However, since there is a slight bump around -3.5 V, it is possible that this corresponds to a defect present in relatively low concentration. Thus, by analyzing the reasons ΔI/I peaks or remains constant, it is possible to develop a much better understanding of a material’s electronic structure.

Furthermore, it should be noted that in all three materials, the shape of the ΔI/I plot is the same for both zero-field MR and magnetic resonance responses. While the magnitudes vary, all peaks,
troughs, and other features occur at the same voltages in both responses for each material. This correlation provides very strong evidence that both phenomena share a single physical origin. Since the magnetic resonance response is the result of spin-dependent VRH, the zero-field MR must also arise from the same mode of conduction. Whereas the peak in spin-dependent current during resonance is a result of resonance-induced transitions from the triplet state to the singlet state, the zero-field MR response is caused by the mixing of triplet states and singlet states. From the evidence provided by the virtually identical ΔI/I line shapes, it can be seen that these triplet to singlet transitions utilize the same trap states to affect the observed changes in tunneling current.
Chapter 5

Conclusion

Spin-dependent processes play an important role in electronics, and understanding how they occur in different materials is crucial for the advancement of device technology. In this thesis, EDMR was used to observe the spin-dependent current changes in amorphous thin films corresponding to magnetic resonance and near zero-field MR. These observations give insight into the nature of the defects in each material and the conditions under which the defects are electronically active. Moreover, consideration of the similarities between resonance and zero-field MR responses in the three materials leads to the conclusion that both phenomena have a common physical origin. Through careful analysis of the data, a greater understanding of these amorphous films has been developed, which will hopefully lead to their utilization for advanced applications in the years to come.
REFERENCES

Academic Vita
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Education

The Pennsylvania State University – University Park, PA
- BS with Honors in Engineering Science – May, 2017
- Minor in Physics
- Dean’s List: Fa13, Sp14, Fa14, Sp15, Fa15, Fa16

The University of New South Wales – Sydney, NSW, Australia
- Exchange Student – Spring, 2016

Research Experience

(7/2016 – present) Undergraduate Researcher – Dr. Patrick M. Lenahan Group
The Pennsylvania State University
- Use electrically detected magnetic resonance (EDMR) to probe spin-dependent recombination centers in various semiconductor devices
- Characterize defect populations in materials using electron paramagnetic resonance (EPR)

The Pennsylvania State University
- Investigation of the magnetoresistive and spin-dependent electronic properties of amorphous thin films using EDMR

(2/2016 – 6/2016) Undergraduate Researcher – Dr. Dane R. McCamey Group
The University of New South Wales
- Designed an organic light-emitting diode (OLED) structure based on the small molecule Alq3
- Developed a procedure for the fabrication of OLEDs using thermal deposition
- Characterized the electrical and optoelectronic properties of the resulting devices

Other Work Experience

(Summer 2015) Prosthesis Designer – Ortopedická Protetika Frýdekk-Místek
(Frýdekk-Místek, Czech Republic)
- Designed a 3-D printable, functional transradial forearm prosthesis
- Collaborated with silicon artists to make the design compatible with a silicon “skin”, rendering the final product virtually indistinguishable from a real forearm

Honors and Awards
- Schreyer Honors Scholar, The Pennsylvania State University
- William & Wyllis Leonhard Engineering Scholar
- Penn State University Provost Scholar
- Jean Kearns McNitt Scholarship in Engineering Science
- Penn State University President’s Freshman Award
- Eagle Scout, Boy Scouts of America