ABSTRACT

ANDREEV REFLECTION STUDIES IN GaMnAs/Nb MICRO-STRUCTURES

by Hussein Abu Jeib

Andreev reflection spectroscopy can be used for estimating the spin polarization for ferromagnetic materials. We used the Circular Transfer Line Method (CTLM) to measure the Andreev reflection effect at the GaMnAs / superconductor interface and to extract GaMnAs spin polarization. In this work I will present a systematic analysis of the Andreev reflection curves for GaMnAs/Nb, using both modeling and experimental data analyses. The relationship between ballistic and diffusive transport was considered. New selective mixed transport state between ballistic and diffusive is suggested. Furthermore, we found a strong effect of short, low temperature annealing on the Andreev spectra. From we concluded that, the surface states play a major role at these compound semiconductor interfaces. Some of conductance curves showed unexpected sharp dips in the conductance. The new transport suggested state is able to explain the presence of the unexpected dips by the previous theory.
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Chapter 1: Introduction

Many studies are concerned with measuring the spin polarization of ferromagnetic materials, especially semiconductor materials. Such studies are important since there is an array of applications and some basic science phenomena that depend on the spin polarization, injection, transport and detection in different materials [5]. One of the most important applications of spin polarization is its major role in the electronics industry, especially in spintronics [6], such as in read heads in modern hard drives and in the fabrication of modern transistors for random access memory chips [7]. Several techniques are being used to measure and estimate the spin polarization such as the positron spin spectroscopy [8], spin-resolved photoemission spectroscopy, tunneling magnetoresistance (TMR) [9], giant magnetoresistance (GMR) and Andreev Reflection. The Andreev Reflection technique has advantages over the other techniques due to the simplicity of the fabrication steps, having no restrictions on the sample geometry, and having the ability to perform the measurements without applying a magnetic field [10]. Andreev Reflection spectroscopy has already been used to measure the spin polarization in a varied range of materials such as the transition metal elements, metallic alloys of transition metals, half-metals and ferromagnetic semiconductors [11].

One attractive material, that has been getting significant interest in polarization research studies is Gallium Manganese Arsenide. GaMnAs is a dilute magnetic semiconductor, summing up two main important branches of condensed matter, semiconductors and magnetism. It is prepared using low-temperature molecular beam epitaxy, where GaAs is doped with the transition metal ions Mn$^{2+}$. The doped Mn atoms provide two properties: they act as acceptor atoms, making the material a p-type semiconductor, and provide a magnetic moment [12]. Still the Mn ions can act as donors if they are interstitial instead of substitutional [13]. The substitutional Mn ions are the ones that replace Ga atoms and reside on their lattice site, while interstitial ions are the ones that settle in between lattice sites and do not replace a host Ga atom. Interstitial ions act as donors, which remove the holes provided by the substitutional manganese. They also couple antiferromagnetically to substitutional manganese, reducing the magnetic moment. Due to that, interstitial Mn ions are undesired. This can be improved by low temperature annealing, where the interstitial ions leave the lattice to surface due to the thermal energy [14].
A material with these properties, Ferromagnetic and semiconductor, is a promising candidate for many applications, especially spintronics devices. Since it exhibit hysteric ferromagnetic behavior giving it memory that can be used in storage devices. It can also be used in gate able ferromagnetism, where an electric field is used to control the ferromagnetic properties. Another application is spin injection. This is where the high spin polarization inherent to these magnetic materials is used to transfer spin polarized carriers into a non-magnetic material.

In Chapter 2 of this thesis, the theoretical basis of spin polarization, Andreev reflection phenomenon and the theoretical model used to extrapolate the spin polarization are introduced. Moreover, the main used Andreev reflection geometries are clarified, concentrating on the problems these geometries faces. In chapter 3, we talk about our experimental setup starting with explaining the geometry we use, the circular transfer line method (CTLM) technique, and how this geometry can be used to get rid of the extra resistance, and keep just the wanted contact resistance in our measurement. Also samples fabrication process is mentioned by details. In Chapter 4, the main experimental results from the conductance and resistance curves are discussed and explained, concentrating on the presence of the un-expected dips in conductance, and the large effect of short low temperature annealing. In Chapter 5, we introduce the theoretical modeling and the producing of theoretical conductance curves depending on theoretical modeling both ballistic and diffusive regime, and we suggest a new selective mixed transport state between ballistic and diffusive. Finally the main conclusions are given in chapter 6.
Chapter 2: Theory

Before explaining the Andreev reflection phenomenon, first the definition and concept of spin polarization should be clarified. Spin polarization is often assumed to be similar to magnetization in being self-evident. Magnetization is determined by the difference between the total spin-up and spin-down electron magnetic moment [15]. This is not the case for spin polarization. Moreover, spin polarization can be different for different experimental techniques and even details. In addition, usually the spin polarization is measured for nonlinear complicated systems that can have many interfaces with different Fermi surfaces, and may also depend on the orientation of the transport measurement. In general the spin polarization measurements probe the spin of moving carriers, which makes it depend on the orientation of the crystal to the transport current, especially for isentropic materials, and make it also depends on all kind of scattering and reflections that happen at the interfaces.

Andreev reflection spectroscopy depends on the measurement of the change in the flow of electrons from a normal metal to a superconductor, when varying the electron energy. Within the superconducting energy gap, the current through the interface depends on whether a majority-spin electron can or cannot find another electron with the opposite spin direction to pair with it as a Cooper pair in order to go through the interface. Conduction electrons in a superconductor travel as Cooper pairs, where each pair has one electron with spin-up and one with spin-down, with a total spin of zero. No quasi-particle states (i.e. individual electron states with either spin up or down) are allowed inside the superconductor. So an incident electron with energy less than the superconducting energy gap moving towards the interface can’t enter the superconductor, for a large distance, as a quasi-particle, since it is a forbidden state. The only way for the incident electron with energy less than the superconductor energy gap to enter the superconductor is by forming a Cooper pair at the interface with an electron with the opposite spin from the Fermi level [16] of the normal conductor at the interface. As a result of Cooper pair formation, a hole with the opposite spin will form moving with the opposite group velocity and the inverse direction of the incident electron.

So, in general, the polarization will define the total number of electrons that will go through the interface at a given applied potential difference, which means defining the current and the resistance. So if we let a current flow through the interface, and just study the change in interface
resistance with the change of the electron energy, then the polarization can be extracted from that measurement. For a perfect interface between a superconductor and a ferromagnet, the conductance at zero bias voltage is given by

\[ G(0) = 2G_n[1 - P] \]  

(1)

Where \( P \) is the polarization, \( G_n \) is the conductance when the applied voltage is larger than the superconducting energy gap and \( G(0) \) is the conductance at zero bias voltage [17]. The conductance gets suppressed for a low density of the minority spin electrons (i.e. large polarization) as shown in Fig. 2.1. So we can use the correlation between the suppression of Andreev reflection at the interface and the conductance to find the polarization of ferromagnetic materials, like GaMnAs [18][19][20].

![Normalized conductance curves for different values of spin polarization and a clean interface.](image)

**Fig. 2.1.** Normalized conductance curves for different values of spin polarization and a clean interface. Every curve is uniquely determined by the value of the spin polarization \( P \) [1].

### 2.1 The Modified Blonder-Tinkham Klapwijk Model (mBTK):

To find the spin polarization of a thin film using Andreev reflection, the conductance curves of the interface should be analyzed using the modified Blonder-Tinkham Klapwijk Model (mBTK) model [13]. In general not all the carrier in a semiconductor/superconductor interface will go
through Andreev reflection, some of them will get reflected normally like what happens in the case of Schottky barrier. The amount of normally scattered carriers are measured by the elastic scattering factor $Z$. In general, if the electrons have energy less than the superconducting energy gap, they will have two probabilities, either normally reflected with probability $B$ proportional to $Z$ or Andreev reflected with probability $C$. The mBTK model finds both of the probabilities $C$ and $B$ as function of $Z$ and the electron energy $E$ [21].

$$B(E) = \frac{Z^2(1+Z^2)|1-\mu^2|}{|1+Z^2(1-\mu^2)|}$$

(2)

$$C(E) = \frac{\mu^2}{|1+Z^2(1-\mu^2)|}$$

(3)

Where $\mu$ is the relative incident energy of electron to superconductor Fermi level. The BTK model was modified to include the polarization when having a ferromagnetic/superconductor interface, as an additional fitting parameter for the conductance curve. The current in the mBTK model is divided polarized and un-polarized current, where the un-polarized current need no modification in the equation since it is the same as the case of normal metal/superconductor interface, and the conductance is given by [21]:

$$G_n = \int_{-\infty}^{\infty} \frac{df(E-vt)}{dv} [1 + C_n(E,Z) - B_n(E,Z)] dE$$

(4)

Where $C_n$ and $B_n$ represents the Andreev reflection and the normal reflection probabilities for un-polarized current, respectively.

In case of polarized current it will behave as a half metal, where all the electrons considered to have the same spin, therefore there is no Andreev phenomenon in this case, since there is no cooper pairs formation probability. The conductance is given by:

$$G_p = \int_{-\infty}^{\infty} \frac{df(E-vt)}{dv} [1 + C_p(E,Z) - B_p(E,Z)] dE$$

(5)

Where $C_p$ and $B_p$ represents the Andreev reflection and the normal reflection probabilities for un-polarized current, respectively. And the total conductance at the interface is given by:

$$G(v)=(1-P)G_n(v)+P G_p(v)$$

(6)
With more calculations processed, and considering both the conductance in the ballistic and the diffusive regime, the mBTK model gives the total interface current in different regimes for energies less and more of the superconducting energy gaps as shown in table 1 [22].

<table>
<thead>
<tr>
<th></th>
<th>$eV \leq \Delta$</th>
<th>$eV &gt; \Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ballistic nonmagnetic</strong></td>
<td>$\frac{2(1 + \beta^2)}{\beta^2 + (1 + 2\Delta^2)^2}$</td>
<td>$\frac{2\beta}{1 + \beta + 2\Delta}$</td>
</tr>
<tr>
<td><strong>Ballistic half-metallic</strong></td>
<td>0</td>
<td>$\frac{4\beta}{(1 + \beta)^2 + 4\Delta^2}$</td>
</tr>
<tr>
<td><strong>Diffusive nonmagnetic</strong></td>
<td>$\frac{(1 + \beta^2) \text{Im}[F(-i\beta) - F(i\beta)]}{2\beta}$</td>
<td>$\beta F(\beta)$</td>
</tr>
<tr>
<td><strong>Diffusive half-metallic</strong></td>
<td>0</td>
<td>$\beta F(1 + \beta^2/2 - 1)$</td>
</tr>
</tbody>
</table>

### 2.2 Main Geometries used to Measure Polarization using Andreev Reflection

There are two main geometries used to study the spin polarization of ferromagnets by AR technique. They are the planar Andreev reflection [23] and the point contact Andreev reflection (PCAR) [17][20][3][24] geometries. Both techniques suffer from multiple problems, especially with high-resistivity ferromagnetic materials.

The planar geometry usually has two layers; ferromagnet/superconductor that might be patterned into microstructures or left un-patterned. The measurements of conductance between a ferromagnet and a superconductor is carried out using the four-probe technique, where two contacts are attached to the back of the conducting substrate, and the two others at the top of the superconductor, as shown in Fig. 2.2. This geometry didn’t give reproducible results for the spin polarization of GaMnAs, for example J.G. Braden et.al (2001), [23][2] were only able to get somewhat sensible AR spectra from one of several superconducting material types on GaMnAs. Also the results from this geometry
suffered from difficulties in extracting the actual interface resistance from the measured total resistance of a typical structure.

**Fig. 2.2.** (a) A schematic of the (Ga, Mn) As heterostucture and the contact scheme. (b) Normalized conductance spectrum of a Ga0: 95Mn0:05As=Ga junction exhibiting high transparency and spin polarization. [2]

The second main used geometry is the Point Contact Andreev Reflection (PCAR), which is the most popular measurement geometry. A fine, superconducting tip is used to establish contact with the surface of the material being measured as Shown in **Fig.2.3.** The conductance is then measured, as a function of the applied voltage, between the ferromagnet and the superconducting tip using a quazi-four-probe technique. This geometry suffers from a similar problem as the previous one, but with a larger effect since the total unwanted additional resistance is larger due to the small size of the tip at the contact, which increases the total measured resistance. In addition to that, the surface of the material is not protected with other layers above it, which can make it prone to oxidation. The oxide layer might cause significant spin flipping, because it is usually amorphous and complex in stoichiometry. This is especially problematic in the case of GaMnAs since MnO oxide is an antiferromagnet and potentially causes too much spin flipping at that dirty interface.
In general, Andreev reflection-based measurements of spin polarization of highly resistive ferromagnets, like ferromagnetic semiconductors, are problematic and have so far given conflicting results that are hard to understand properly [3]. One major source of error is the large spreading resistance that results from the resistive material being characterized. Therefore, in this research the circular transfer line method CTLM is used to remove the extra spreading resistance and extract the contact resistance from the total resistance accurately.
Chapter 3: Experimental Methodology

The circular transfer line method (CTLM) technique is used in this study in order to evaluate the contact resistance of the metal/superconductor interface. Current flow in this technique exhibits cylindrical symmetry, which makes data analysis straightforward. This makes extracting the Andreev resistance at the interface readily possible. Furthermore, there is no need to pattern the bottom ferromagnetic film and a single photolithography and metal deposition step is used to fabricate the structures, thus significantly simplifying the fabrication process [25].

The samples are made by depositing a layer of Nb on the GaMnAs leaving circular opening rings on the Nb layer with inner radius of 200 µm or 300 µm. The gap width (i.e. ring width) is varied and can be 4, 6, 8, 10, 15, 20, 40 or 80 µm as shown in Fig. 3.1. Then the resistances across the circular rings (i.e. between the inner Nb circles and the outside Nb) are measured using the four probe technique. A constant-amplitude AC signal from a Lock-in amplifier is used to measure the voltage across the feature, while another variable-amplitude DC voltage is applied across the same feature. Four-probe technique and a nano-Voltmeter are used to measure the change of DC voltage across the sample. Changing the DC voltage affects the resistance of the sample and thus the AC voltage across the sample, due to the Andreev effect. So, the AC signal is used to measure the differential resistance or conductance with high accuracy, and the applied voltage is measured using the DC nano-Voltmeter. LabView software is used to get the resistance curves as functions of voltage as shown in Fig. 5. The measurements are done while the samples are in liquid helium at a temperature of 4.2K to insure that the Nb is superconducting, since it is superconductor at temperatures below 9.2K. Measurements were also taken at room temperature of about 294 K to compare the results when Nb is a superconductor and when it is not.
There was two ways to produce the resistance curves, and to find the resistance of the samples, first by knowing the applied DC- current and the voltage across the sample from the DC nano-Voltmeter, the differential resistance can be calculated from these values, and the curves were generated. But these curves showed low resolution and accuracy especially at the turning points. The second way, is depending on the changing in the readings of the AC-Voltmeter of the lock-in, the AC signal is used to measure the differential resistance or conductance with high accuracy. Main reason for the high accuracy is the high frequency of 13.77 K Hz. The interface of the lab view program and the block diagram can be seen in **Fig.3.2**.
Fig. 3.2. A block diagram and the interface of the lab view program used in our transport measurement. The program gives the I-V characteristic curve and the resistivity curve as a function of voltage using two different ways: from the AC signal, and from the DC signal.
Sample Fabrication

The CTLM geometry needs one lithography step to pattern the circular Nb features on the GaMnAs. Different samples have been studied from the same wafer of GaMnAs but with different Interface surface properties depending on the existence of native oxide on the interface between Nb and GaMnAs. The native oxide layer was left in place when depositing Nb on some of the samples, while it was stripped off using an HCl acid etchant, and with ion milling using Ar atoms directly before the deposition of Nb.

The steps of the fabrication process of the GaMnAs/Nb microstructures start with GaMnAs films of thickness 44 nm. These samples are grown using molecular beam epitaxy (MBE) by the group of Prof. Jacek Furdyna in the Physics Department at the University of Notre Dame. Prior to photolithography and Nb deposition, one sample was annealed 24 hours at 180°C and another for 5 days at the same temperature. Every 24 hours, samples were cooled down and etched by HCl then placed back on the hot plate for annealing. The etching process removes the native oxide film on the surface, thus allowing Mn atoms that are not in the correct crystal site to move to the surface and be oxidized. This leads to a significantly cleaner GaMnAs crystal that has a higher Curie temperature and a lower resistivity. At the end of the annealing and etching, the sample is cleaned with water and acetone to remove any surface contaminations before the photolithography.

The GaMnAs sample is then placed in the center of the photoresist spinner, and secured by applying a vacuum, and then one droplet of the lift-off resist LOR is dispensed on the sample. After that the sample is spun in two steps, the first step lasts 10 seconds and runs at a speed of 500 RPM, and the second step lasts for 40 seconds at a speed of 3000 RPM. This lets the LOR spread over the whole surface uniformly forming a thin film. The sample is then baked on a hot plate for 10 min at 150°C in order to remove the solvent and harden the LOR. After that the S1813 photoresist is spun over the LOR layer using the photoresist spinner in two steps, just as for the LOR, then the sample is baked at 105°C for 1 min.

After preparing the bilayer photo-resists, the sample is exposed to light so it is transferred to the mask aligner and exposed to ultraviolet light through the mask for 6 seconds. The photoresist that gets exposed to light becomes weaker and is removed by developing the samples using the chemical developer CD26 (or Tetramethylammonium hydroxide) for 40 seconds. The sample is then rinsed with water and dried with nitrogen gas.
After that, samples are etched with HCl acid for 2 min to remove the oxide layer and are then immediately loaded into a metal deposition Vacuum chamber. The sample surfaces are then cleaned one last time using the ion milling technique to make sure that any remaining traces of oxide are removed and that we have a clean surface. About 70nm of Nb are then deposited on both samples using the sputtering gun. Finally the metal is ‘lifted-off” by dissolving the resist in acetone. This leaves the circular discs of Nb, which are separated from surrounding Nb by circular gaps as shown in Fig. 3.1.
Chapter 4: Results and Discussion

4.1 Preliminary Results

Samples with the native oxide layer left intact between the GaMnAS and the Nb layers were already studied by Diana Dahliah [4]. The native oxide was deliberately left in order to see the effect of the oxide barrier on AR and also to make the samples comparable with the Point Contact Andreev Reflection technique (PCAR), where the ferromagnetic thin film is not protected with another layer. The resistance of each feature was measured both at room temperature and at 4.2K. The differential resistance for each feature is drawn as a function of voltage, as shown in Fig. 4.1. As can be seen from the figure, the resistance at 4.2K is not constant under the change of voltage. Instead, it has a sharp peak around V=0, which means there is an energy barrier that prevents the electrons from passing unless they have a sufficient energy.

To determine whether the peak in resistance that we see in Fig. 5 is from the Andreev reflection or not, we measured the resistance at room temperature where the Nb layer is not a superconductor anymore. The results are shown in Fig. 4.1 as well. Looking at the figure, one can see that we got similar results at room temperature to what we got previously at 4.2 K, but with a shallower, more rounded peak. The first conclusion from Fig. 5 is that the change in resistance with voltage cannot be due to Andreev reflection, since Andreev reflection requires having a superconducting material in contact with a non-superconductor in order to happen. The second conclusion is that the variation of resistance with applied voltage is due to the presence of a Schottky barrier at the interface: Looking at the shape of the I-V characteristic slope, the only explanation for this shape is the presence of a Schottky barrier, since this curve is identical to the well-known Schottky characteristic curves. The fact that the resistance peak becomes shallower at room temperature also makes sense, since the electrons have more thermal energy to pass over the energy barrier at the interface. The third conclusion is that close inspection of the data of Fig. 5 taken at 4.2K shows no extra features other than the Schottky-like curve. So, most likely, there is no Andreev reflection effect observed even at 4.2K: The Schottky barrier seems to suppress the probability of AR.
Fig. 4.1: A), C) and E) Represent the resistance as a function of voltage at 4.2K for the circular features with diameter 600 μm, and gap width of 10 μm, 15 μm and 40 μm, respectively. B), D) and F) show the resistance as a function of voltage at room temperature for the circular features with diameter 600 μm, and gap width of 10 μm, 15 μm and 40 μm, respectively [4].
4.2 GaMnAs/Nb Samples with Clean Interface:

The GaMnAs/Nb samples with the clean interface (i.e. native oxide film removed chemically by immersion in hydrochloric acid) were studied in the same way as the previous samples (with the native oxide left intact). Fig. 4.2 shows the room temperature current-voltage and resistance-voltage curves for the samples with the oxide chemically removed from the interface. As it is clear from the figure the measurements of all features have shown linear (I-V) curves and constant (i.e. not changing) resistance with the varied range of voltage. This means that there is no Schottky barrier or any other energy barrier at room temperature. Comparing this with the voltage-dependent resistance of the samples with a native oxide film at the interface, it is clear that the Schottky behavior is due to the presence of the native oxide at the interface between Nb and GaMnAs. It should be made clear, though, that a Schottky barrier can exist even at very clean interfaces between metals (or superconductors) and semiconductors, like GaMnAs, especially at low doping densities in the semiconductor.

Figure 4.3 shows the resistance versus voltage in the GaMnAs/Nb clean interface samples measured at 4.2K, where Nb is a superconductor. The most striking feature is that some of the samples showed large spikes in the resistance. As is clear from the figure, the resistance is not constant anymore and we get a non-Ohmic behavior. The resistance curves have two large spikes that are symmetric around the zero voltage point, and the resistance between the spikes is different from that outside the spikes. Comparing these results with the BTK model shows that this result is similar to what is expected from Andreev reflection effect, since there is a difference in resistance inside the superconducting gap and outside of it. Thus the results can be explained to be due to the presence of Andreev reflection. The sharp spikes in the differential resistance seem to be occurring at the superconducting energy gap, since the resistance inside these spikes is different from that outside of them.
Fig. 4.2: A.1, B.1, C.1 and D.1 represents the I-V characteristic curves for the circular features with radius of 300μm, and gap width of 8, 10, 15 and 10μm respectively as a function of voltage. A.2, B.2, C.2 and D.2 are the differential resistance for the same features respectively. All the measurements were done at room temperature for GaMnAs/Nb for as grown sample.
Fig. 4.3. The resistance as a function of voltage for chosen samples at different stages of annealing. Andreev reflection effect is evident in the figure as well as pairs of large, symmetric, unexpected thin spikes around the origin.
To make it easier to compare with the BTK theoretical model the conductance curves are found in the Fig. 4.4. The similarity with the theoretical model is clear, but there are two main differences: First the superconducting energy gap is larger than the superconducting energy gap of Nb, which is 1.4 mV. The reason is that the measured resistance is the total resistance of the contact resistance plus the resistance of the GaMnAs bulk, so the applied voltage is actually divided between the bulk and the interface. Only a fraction of the total voltage will actually appear across the interface. The main strength of our CTLM technique is that it enables us to separate the bulk and interface contributions to the total resistance by using the straight line fit, which will be explained later in this section.

The second difference is the presence of the dips in the conductivity curves, which do not exist at all in the theoretical model. Even though such dips in conductance are present in many AR curves in the literature [26][27][28][29][30][31], they are not accounted for in any way by standard, well-accepted models in the field, and only a handful of publications ever attempted to explain their presence. The standard BTK model actually predicts peaks, rather than dips, in the conductance at highly non-transparent (i.e. resistive) interfaces, as is expected for the GaMnAs/Nb interface.

One explanation offered in the literature for the dips in conductance is the presence of inter-granular Josephson tunneling [29], which happens in the case of using a polycrystalline superconductor. Cooper pairs can tunnel from one grain to another without breaking down to quasi-particles. If the energy of the electrons reaches the superconducting energy gap, then the tunneling is no longer necessary because most Cooper pairs break at that voltage, which gives a large increase in resistance leading to form the dips in the conductance curves [27].
Fig. 4.4. Conductance as a function of voltage for chosen samples at different stages of annealing, which showed large unexpected thin dips that are symmetric around the origin.
Proximity effect [30] is another proposed potential explanation for the phenomenon. In this case the Cooper pairs diffuse into the metal from the superconductor for some distance without breaking down, making a week superconductor layer inside the semiconductor with lower energy barrier. The electrons with energy less than the new lower barrier can pass over it as Cooper pairs, and if their energy increases to a value more than the new barrier and less than the original one, the electrons go through the new weak superconductor barrier as quasi particles but then get reflected at the interface since their energy is less than the original barrier (i.e. The superconducting energy gap). Yet, if their energy is higher than the original barrier, then they will pass through it as well, which increases the resistance at that interval, forming the dips in resistance. But the fact that GaMnAs acts as a pair breaker [31], reduces the probability that the superconducting proximity effects play a major rule in the origin of these dips.

Both of the previous mentioned effects happen around the Critical Current, where the superconductor becomes a normal metal. The Critical current itself is used as an explanation for the dips in conductance[26][27]. When the transmitted current through the interface reaches the critical current value of the superconductor, the resistivity of the superconductor increases rapidly from zero to the normal value. This leads to a sudden increase in the resistance, thus forming the dips in the deferential conductance curve. But then the question remains: why are the dips displayed by some AR results and not all of them. There should be a more specific reason to explain the presence of the dips in conductance.

The most plausible explanation thus far seems to have been the presence of strongly diffusive scattering. Sheet et al [27] showed that when the superconducting sharp tip in a PCAR measurement was pressed strongly into the non-superconducting film, strong dips were observed in conductance. These dips were shown to become weaker as the tip is withdrawn slightly and to disappear when the tip is only gently pressed against the film such that the contact is very small and the transport is in the ballistic regime. This explanation provides a stronger argument about the origin of the dips because the presence or absence of the sharp dips seems to be independent of the grain structures of the superconducting material. But still in our samples we were able to get the dips in some features, but the presence of this dips were strongly affected by low temperature short annealing, which means that the presence of dips in our case can depend on the grain size of both the superconductor and the ferromagnetic materials , and on the interface between them.
Our samples have a huge contact area compared to PCAR measurements and the transport across the Nb/GaMnAs is expected to be well into the diffusive transport regime. This makes it difficult to justify the emergence of the sharp dips in conductance only under certain conditions, while they disappear with gentle annealing. Annealing at 180°C for only 30 minutes is unlikely to change the interface significantly by causing strong intermixing, for example. One explanation for these dips can be related to the surface states. Surface states are known to play an important role at compound semiconductor interfaces [32][33].

Another major result of these figures, is an estimate of the spin polarization at the interface. Since the conductance inside the gap is larger than that outside of it, the polarization for this interface is expected to be less than 50%.

Since annealing is known to improve or ‘heal’ the interface by affecting the surface states at the metal/semiconductor contact[34], we repeatedly annealed the samples at low temperature (180°C), for 30 minutes at a time, and measured the AR each time. The main goal was to see if this will change the conductance curves we got and the presence of the spikes in the resistance curves (i.e. dips in the conductance curves).

In this study we used three different set of samples. They differ depending on the amount of annealing the GaMnAs samples get before the deposition of the Nb Superconducting layer. First sample was left without any annealing before Nb deposition, the second one was annealed for a continuous 5 days at 180°C, the third one was annealed at the same temperature for 24 hours. The process of annealing effects the interstitial Mn ions, it is accepted that with annealing the ions will get energy enough to make them reach to the surface of the sample, and then by the chemical etching process this ions will be removed.

4.2.1 GaMnAs/Nb As Grown Sample (no pre-deposition annealing):

Fig. 4.5. Shows the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 6 μm (600-6 feature) at different annealing stages. These measurements were taken before annealing, after 30 min annealing, one day after, two days after, after second 30 min annealing, and two days after that. Every time the sample is annealed, there is a change in the conductance curve, in the ‘apparent’ superconducting gap width and height and in the presence of dips in conductance. It is clear that before any annealing there was no presence for Andreev
reflection phenomenon. But after the first annealing the effect is clear with higher conductance inside the energy gap than outside it, and with small dips in conductance at the edges of the superconducting critical voltage value. The figure also shows that just waiting without any annealing can affect the shape of the conductance curve, which means the sample is in a sensitive state. After the second annealing the curve lost its shape, but waiting for two days was enough for it to retain its shape.

**Fig. 4.6.** The normalized conductance curves for the as grown sample with diameter of 600μm and gap width of 8μm (600–8) at different annealing processes.
Fig. 4.6. Shows the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 8 μm (600-8 feature) at different annealing stages. These measurements were taken before annealing, after 30 min annealing, one day after, two days after, after second 30 min annealing, and five days after that. Every time the sample is annealed, there is a change in the conductance curve, in the ‘apparent’ superconducting gap width and height and in the presence of dips in conductance. It is clear that before any annealing there was no presence for Andreev reflection phenomenon. But after the first annealing the effect is clear with higher conductance inside the energy gap than outside it, and with small dips in conductance at the edges of the superconducting critical voltage value. The figure also shows that just waiting without any annealing give minor changes to the curve specially increases the maximum value of normalized conductance. After the second annealing the effect was lost, even waiting did not make any changes after that.

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**Fig. 4.6.** The normalized conductance curves for the as grown sample with diameter of 600μm and gap width of 8μm (600–8) at different annealing processes.
Fig. 4.7. Shows the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 10 μm (600-10 feature) at different annealing stages. These measurements were taken after 30 min annealing, one day after, two days after, after second 30 min annealing, two days and five days after that. It is clear that after the first 30 min annealing there was a presence of Andreev reflection phenomenon, since the conductance inside the gap is different from outside it. By waiting we can see the creation of dips at the edges of the gap, the farther the wait the larger the dips. But after the second annealing the effect almost disappeared. The figure also shows that just waiting without any annealing after that a very different curve shape was created with large main peak and to main dips at the edge of the gap which is narrow in this case. But with more time the peak value decrease and the gap become wider again.

Fig. 4.7. The normalized conductance curves for the as grown sample with diameter of 600μm and gap width of 10μm (600–10) at different annealing processes.
The previous three figures support the proposal that the presence of the dips in conductance is likely due to surface states, or at least get affected by it, since they are easily altered by gentle annealing. Moreover, this sample is showing low polarization, but with annealing the polarization changes, which means that the polarization we measure is directly dependent on the status of the interface itself, and not on the bulk of the GaMnAs alone.

4.2.2 GaMnAs/Nb Annealed for 5 days sample (pre-deposition annealing):

Fig. 4.8. Shows the resistance and the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 6 μm (600-6 feature) at different annealing stages. These measurements were taken before annealing, after 30 min annealing, after 60 min third annealing, after 60 min fourth annealing, two days and 55 days after that. As can be seen from part a) of the figure, every time the sample is annealed, the total amount of resistance shifts. After the first annealing the resistance increased, but after the third annealing the resistance dropped down to a value less than the original one and remains there after that. From part b) of the figure it is clear how the conductance curve shape changes significantly after each stage of annealing or even waiting without annealing. There is change in the ‘apparent’ superconducting gap width and height and in the presence of dips in conductance. It is clear that before any annealing there was a large main peak in conductance, but with annealing the main peak is disappearing. There was dips in conductance at the edges of the superconducting critical voltage value in all the stages except for the measurement after 55 days of the fourth annealing, largest dips were created in the measurement of 2 days after the fourth annealing.
Fig. 4.8. a) The resistance curves and b) the normalized conductance curves, for the 5 days annealed sample with diameter of 600μm and gap width of 6μm (600–6) at different annealing processes.

Fig. 4.9. Shows the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 10 μm (600-10 feature) at different annealing stages. These measurements were taken before annealing, after 30 min annealing, one day after 30 min second annealing, two days after that and after 60 min fourth annealing. As can be seen from the figure, every time the sample is annealed, the normalized conductance curve changes. Originally without any annealing the curve is showing increasing in conductance inside the superconducting energy gap, but there is a main dip inside the main peak, and there is two other dips at the edge of the gap. After the first annealing all the dips disappeared and the value of the maximum conductance became lower, but with waiting for one and two days the shape start to recover its original shape but without the two dips at the edges, and the effect of the fourth annealing is similar to the first one.
Fig. 4.9. The normalized conductance curves for the 5 days annealed sample with diameter of 600μm and gap width of 10μm (600–10) at different annealing processes.

Fig. 4.10. Shows the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 20 μm (600-20 feature) at different annealing stages. These measurements were taken before annealing, after 30 min annealing, after second 30 min annealing, one day after, two days after, after third 60 min annealing and fourth 60 min annealing. Every time the sample is annealed, there is a change in the conductance curve, in the ‘apparent’ superconducting gap width and depth and in the presence of spikes in resistance, which are dips in the case of conductance. To be able to see the shapes of the curves more clearly, the total resistance curves are shown in Fig. 4.11. As can be seen from the figure there is a significant change in the total resistance after each stage. Both Fig. 4.10. and Fig. 4.11. supports the proposal that the presence of the dips in conductance is likely due to surface states, since they are easily altered by gentle annealing. Moreover, this particular sample is showing low polarization, but with annealing
the polarization changes, which means that the polarization we measure is directly dependent on the status of the interface itself, and not on the bulk of the GaMnAs alone.

**Fig. 4. 10.** The normalized conductance curves for the 5 day sample with diameter of 600μm and gap width of 20 μm (600–20) at different annealing processes.
4.2.2 GaMnAs/Nb Annealed for 1 days sample (pre-deposition annealing):

The results of this sample is similar to what we got from the previous two samples, different complicated conductance and resistance curves that has peaks and dips with different height and depth, all that are very sensitive to any annealing process, and change with annealing and time. Examples of the resultant curves can be seen in Fig. 4.12. and Fig. 4.13.

Fig. 4.12. Shows the resistance and the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 10 μm (600-10 feature) at different annealing stages.
And Fig. 4.13. Shows the resistance and the normalized conductance curves for the circular feature with a diameter of 600 μm and gap width of 15 μm (600-15 feature) at different annealing stages.

As concluded from the previous samples, this results also support the proposal that the surface states play a big role in the resultant conductance curves, and that the surface states are very sensitive in this samples, since they are easily altered by gentle annealing.

Fig. 4.12. The normalized conductance curves for the 1 day annealed sample with diameter of 600μm and gap width of 10 μm (600–10) at different annealing processes.
Fig. 4.13. a) The resistance curves and b) the normalized conductance curves, for the 1 days annealed sample with diameter of 600μm and gap width of 15μm (600–15) at different annealing processes.

The main advantage of using the CTLM technique is eliminating the spreading resistance and any extra bulk-related resistance contribution to Andreev reflection. The way to do that is through the straight line fit where the resistance is plotted as a function of the GaMnAs gap width of each feature. Since the contact resistance due to Andreev reflection does not depend on the width of the gap or ring formed in the Nb structures, the Y-intercept of the straight line fit will give the contact resistance directly. That is the case when all the features on the same sample display consistent behavior. But sometimes some features show Schottky behavior while other features on the same piece of GaMnAs show Andreev reflection, making it hard to get a good straight line. Fig. 4.14.A shows the resistance versus the feature gap width at 4.2k under several stages of annealing. As can be seen from the figure, all the samples form a straight line, except for the feature with the width of 20 μm. This sample showed an unexpected increase of resistance after 30 min annealing, as
well as one day and two days after the first 30 minutes anneal, where it did not fall on the expected straight line fit.

![Graphs showing resistance versus feature gap width under several stages of annealing at A) 4.2K and B) room temperature.](image)

**Fig. 4.14.** The resistance versus the feature gap width under several stages of annealing at A) 4.2K and B) room temperature.

When the measurement was done again at room temperature as shown in **Fig. 4.14.B**, the same feature did not show increases in resistance, and was mostly fitted with the expected line. Since this effect happened only at 4.2K where Nb is superconductor, this suggests that the superconductivity plays a major role in it. **Fig. 4.15.** Shows the resistance curves at different annealing stages for the feature with the diameter of 600 μm and gap width of 20 μm that showed the unexpected increase in resistance in the previous figure. As can be seen from the figure, most of the resistance curves are showing no effect on them except for the three curves with the highest resistance, namely the curve of after 30 min annealing, one day and two days after. Those graphs show a strong Andreev reflection effect that fits with the theoretical model. Another thing to notice is that the effect was present after the first stage of the 30min annealing, and stayed until the next annealing, where the effect disappeared after that. This means that there is a special recipe of annealing that gives the best interface quality and gives rise to a large spin polarization at the interface. This in turn supports the previous conclusion that surface states are playing the major role in the resistance and conductance curves, since the surface states are easily altered by annealing.
Fig. 4. 15. The resistance curves for the sample with diameter of 600μm and gap width of 20μm (600 – 20) after different annealing steps.

Fig. 4. 16. gives a closer look at the three resistance curves that showed Andreev Reflection effect. As it’s clear from the figure there is one main large peak at zero bias, and two small wide, shallow dips symmetric around the peak, which presents a typical Andreev Reflection effect for the case of high polarization, mainly because the resistance inside the gap is larger than outside of it. In this case no spikes are observed on resistance (i.e. dips in conductance). We also noticed that there is an increase in the total resistance with time without any annealing. And from the normalized conductance curves we also notice that, the curve become shallower with time, with smaller peak and dips. One reason can be the effect of the large change in temperature from room temperature to 4.2K at every measurement (i.e. temperature cycling).
Fig. 4. a) The total resistance curves b) normalized conductance curves, for the sample with diameter of 600μm and gap width of 20 μm (600–20) at different annealing processes, after 30 min annealing, one day after and two days after.

Figure 17 shows the resistance and the conductance curves after removing the extra resistance, and getting the contact interface resistance alone using the straight line fit results, as can be seen of the figure the resistance now is lower also the width of the superconducting energy gap is smaller, and it is close to the known value for Nb.

In General the GaMnAs/Nb samples showed complex and rich conductance and resistance curves. Some of these curves agree well with the theoretical model of Andreev Reflection and others displayed Andreev reflection with the presence of unexpected spikes on conductance. Gentle annealing changes the measured polarization, which means that the polarization we get is directly dependent on the status of the interface itself, and not on the bulk of the GaMnAs alone, in other words surface states plays the major role in the resultant measured polarization.
Fig. 4. a) The contact resistance curves b) normalized conductance curves, for the sample with diameter of 600μm and gap width of 20 μm (600–20) at different annealing processes, after 30 min annealing, one day after and two days after.
Chapter 5: Modeling and fitting

Due to the various complicated shapes of conductance curves we got from the experimental data, and the large numbers of variables control the resultant shapes, and to understand the theory better. There was a large tendency to produce theoretical conductance curves, under different varies controlled parameters values. This chapter is introducing the theoretical modeling and the producing of theoretical conductance curves depending on the main m-BTK model equations in both ballistic and diffusive regime shown in table1.

The comprehensive analysis of the data is nontrivial, compared with the easiness of getting and measuring the data itself. Multiple parameters play different roles in the resultant conductance curves that should be determined through the analysis. This include the type of contact either ballistic or diffusive, and the superconducting energy gap, the transparency of the barrier itself, not forgetting the spreading and extra resistance. All of these parameters and variables will affect the extracted value of polarization.

One of the most important and confusing parameters mentioned above is the strength of the barrier or the normal reflection factor. If the normal reflection is considered as an Andreev effect, then it will give the wrong extracted value of polarization. Because of that, just comparing the value of conductance inside the superconducting energy gap with the conductance outside it, cannot indicate the polarization, unless for special ideal case of pure fully transparent ballistic contact with no normal reflection, as the curves shown on Fig.1 in the theory chapter.

Using the Excel software, I was able to prepare a modeling simulation program. This program is able to produce theoretical conductance curves with any chosen parameters values of voltage range, intervals, superconducting energy gap, the elastic scattering parameter Z, polarization percentage, and the contact type either ballistic or diffusive. Also a mixed state of both the ballistic and diffusive regimes with controlled percentages is an available option. Even you can choose specific parts of the voltage range to be different than other parts in terms of the transportation regime used to get the curve, this option is used mainly at the transition state in the curve between superconducting state to normal conductance, for different values of voltage. The interface of the Excel program, with the function code can be seen in Fig.5.1.
First a column for the voltage was created increasing the voltage very row by a constant interval value, then using the equations from table 1, the conductance for each conductance regime was calculated in separate column. Then using the IF Statement function, the conductance inside and outside the superconducting energy gap was created in single column for each regime. After that new column for the mixed conductance states were produced by mixing the different regime column by the percentages defined, and another column was created for the interval mixed regime, where the summation of percentages was added inside the parts of the IF statement. All the equations used where from table one exactly as they are, except for one equation, the equation for the diffusive regime when the energy is less than the superconducting energy gap. An identity was used, since Excel cannot find the inverse hyperbolic cosine of an imaginary number, I used:

$$\cosh^{-1} x = \ln(x + \sqrt{x^2 - 1})$$

Through the next paragraphs one of the most important characteristic I’m going to concentrate on, and will try to produce, is the dips in the conductance curves. As demonstrated previously in the results, dips in the conductance curves are present in many of our measurements, instead of peaks as expected in the theory, and as mentioned before such dips in conductance are present in many AR curves in the literature [26][27][28][29][30][31], but still they are not accounted for in any way by standard, well-accepted models in the field, and only a handful of publications ever attempted to explain their presence. We will get these dips directly through the theory equations.
Fig. 5. The Excel program interface showing the function code, the different produced curves and also the controllable variables which are polarization, interval, Z factor, percentage of ballistic total, percentage of diffusive total, percentage of ballistic inside, outside, the percentage of diffusive inside and.
Fig. 5.2. Theoretical normalized conductance $G(V)/G_n$ versus V curves for different values of elastic scattering parameter $Z$. a) from G. Strijkers et al [30] b) reproduced using our program.

Before starting showing the theoretical curves in the different cases first I want to reproduce some theoretical curves that are already published in articles, and compare between them, and see if they are the same. Fig. 5.2 represent a comparison between the theoretical normalized conductance curves that G. Strijkers et al [30] produced and what we were able to produce using our software, it is clear that they match perfectly. Other comparison can be seen in Fig. 5.3 with the theoretical conductance curve of G. Woods et al [10]. A very critical point in the simulated curves is the resolution of your curves, in other words the number of the theoretical data points presented in the curves, and the interval between each point and the next one, this concept is crucial at the transition point between the superconducting state and the normal conductance state, and can affect the maximum values the peaks and dips can reach. In the following curves the interval used was 0.02 mV, with 50 points for each 1 mV.
First will start the simulation process in the ballistic regime, since it is the most used one in literature. In fact many research groups use only the ballistic theoretical model for analysis, with no control over the transport regime for their contact [22]. Fig. 5.4. shows Andreev conductance theoretical curves in the Ballistic regime with different parameters. In a), b) and c) of the figure, the polarization is fitted at constant polarization of 0%, 60% and 100% respectively, with changing values of elastic scattering parameter $Z$. As seen from the figure the larger the value of $Z$, the larger the peak in conductance at the edge of the superconducting energy gap. Also the lower the values of the conductance inside the gap. So in general, larger values of $Z$ lead to an increase in the peak, and deviation of the straight line shape of the bottom of the conductance inside the gap to a parabolic shape with main minimum point. The only exception is in the case of part c), because the conductance is already zero and cannot be lower. Comparing the three figures a), b) and c) together, one can notice that the peak of conductance is larger in the case of lower polarization for the same value of $Z$. 

Fig. 5.3. Theoretical normalized conductance curves in the ballistic regime. a) from G. Woods et al [10] b) reproduced using our program.
The last result can be emphasized more by looking at the rest of the curves in the same figure. In d), e) and f) of the figure, the elastic scattering parameter kept constant with the values 0.0, 0.35 and 0.7 respectively, with changing values of polarization. As seen from the curves the polarization affects the curves by shifting the value of conductance inside the gap, in an inverse manner. Also the larger the value of polarization the smaller the peak in conductance, same as we noticed from the first part of the figure.

Still none of the 51 theoretical conductance curves showed in ballistic regime, with the large range of conductance and Z showed dips in conductance, the curves just showed peaks, as expected, which means the ballistic contacts cannot explain our experimental curves with dips in conductance.
Fig. 5.4. Represents Andreev conductance theoretical curves in the 100% Ballistic regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength Z. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
The process of producing the theoretical conductance curves is repeated again but in the 100% diffusive regime. Fig. 5.5. shows Andreev conductance theoretical curves in the diffusive regime with different parameters. In General, the presence of peaks, and also dips is clear in this figure. In a), b) and c) of the figure, the conductance is shown at constant polarization of 0%, 60% and 100% respectively, with changing values of elastic scattering parameter $Z$. As seen from the figure, the larger the value of $Z$, the larger the peak in conductance at the edge of the superconducting energy gap. By contrast with the dips, the larger $Z$ the smaller the resultant dips. Also the lower the values of the conductance inside the gap. So in general, larger values of $Z$ lead to an increase on the peak height, lower conductance inside the gaps, and smaller dips. Unless in the case of part c), the conductance drop to zero and cannot be lower, so no dips. Comparing the three figures a), b) and c) together, one can notice that the peak of conductance and the dips are larger, in the case of lower polarization for the same value of $Z$.

The last result can be emphasized more by looking at the rest of the curves in the same figure. In d), e) and f) of the figure, the elastic scattering parameter kept constant with the values 0.0, 0.35 and 0.7 respectively, with changing values of polarization. As seen from the curves the polarization affects the curves by shifting the value of conductance inside the gap, in an inversely relation. Also the larger the value of polarization the smaller the peak in conductance, same as we noticed from the first part of the figure.

In the case of the pure diffusive there is dips in the conductance curves, but the peaks are still present and more dominate in the curves. With smaller $Z$ the dips get larger and the peaks get smaller, which means that smaller $Z$ is the way to get curves with dips without peaks or with the smallest peaks. By contrast, both the peaks and dips change the same way with polarization, inversely proportional. But in all of the diffusive curves the peaks will still be present, and the dips cannot form alone without peaks.
Fig. 5. Represents Andreev conductance theoretical curves in the 100% Diffusive regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
In both the pure ballistic and the pure diffusive regime, the dips cannot result without the presence of the peaks. Comparing the curves in Fig.5.4 and Fig.5.5, it can be concluded, that the peaks in the ballistic regime are smaller than in the diffusive. The next step is to consider both of the transport mechanisms where happening together at the same contact, which is the intermediate case. Since the diffusive regime is the mechanism that produces the dips in conductance, first will start with larger percentage of diffusive than ballistic.

Fig.5.6 shows Andreev conductance theoretical curves in the 25% Ballistic and 75% Diffusive mixed state regime with different parameters. In General, the presence of peaks, and also dips is clear in this figure. In a), b) and c) of the figure, the polarization is fitted at constant polarization of 0%, 60% and 100% respectively, with changing values of elastic scattering parameter Z. As seen from the figure the larger the value of Z, the larger the peak in conductance at the edge of the superconducting energy gap. By contrast with the dips, the larger Z the smaller the resultant dips. Also the lower the values of the conductance inside the gap. In d), e) and f) of the figure, the elastic scattering parameter Z kept constant with the values 0.0, 0.35 and 0.7 respectively, with changing values of polarization. As seen from the curves the polarization is affecting the curves by shifting the value of conductance inside the gap, in an inversely relation. Also the smaller the value of polarization the larger the peak in conductance, same as we noticed from the first part of the figure.

Those results are similar to the results of the pure diffusive regime but with slightly smaller peaks, and dips. Follows are Fig.5.7 with 50% Ballistic and 50% Diffusive mixed state regime, and Fig.5.8 with 70% Ballistic and 75% Diffusive mixed state regime, they also give similar results, but the larger the ballistic regime percentage the smaller the peaks and dips, in Fig.5.8 the dips disappeared from most of the curves, and the remaining once are very weak, and the peaks still there but with small values.
Fig. 5. 6. Represents Andreev conductance theoretical curves in the 25% Ballistic and 75% Diffusive mixed state regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
Fig. 5. Represents Andreev conductance theoretical curves in the 50% Ballistic and 50% Diffusive mixed state regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
Fig. 5. 8. Represents Andreev conductance theoretical curves in the 75% Ballistic and 25% Diffusive mixed state regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
The analysis of the conductance curves, depend on several parameters. To be able to analysis the curves, they should show two ranges, and the transition between them. The conductance in the superconducting state, and the conductance in the normal state, when the electrons are given energy larger than the superconducting energy, which makes the superconductor a normal metal. Since the conductance curve under the range of voltage changes the transportation mechanism from superconducting state, where Andreev effect can happens, to normal state where there is no more cooper pair electrons, it can be suggested that also the transport regime itself can pass through critical point and change from one type to the other, like from ballistic to diffusive, or the opposite.

In the next two figures, the conductance transport mechanism inside the superconducting energy gap was chosen different than the one outside it. Fig.5.9. shows Andreev conductance theoretical curves in the 100% Ballistic and 0% Diffusive when $V > \Delta$ and 0% Ballistic and 100% Diffusive when $V < \Delta$, mixed state regime with different parameters. In a), b) and c) of the figure, the polarization is fitted at constant polarization of 0%, 60% and 100% respectively, with changing values of elastic scattering parameter $Z$. As seen from the figure the larger the value of $Z$, the larger the peak in conductance at the edge of the superconducting energy gap. Also the lower the values of the conductance inside the gap. So in general, larger values of $Z$ leads to increase on the peak.

In d), e) and f) of the figure, the elastic scattering parameter kept constant with the values 0.0, 0.35 and 0.7 respectively, with changing values of polarization. As seen from the curves the polarization is affecting the curves by shifting the value of conductance inside the gap, in an inversely relation. Also the larger the value of polarization the smaller the peak in the conductance.

No existence for dips in this curves, as expected since the regime inside the gap is ballistic, and the concluded results of this curves are similar to the results of the totally ballistic curves, but in this case the peaks reach higher values.
Fig. 5. Represents Andreev conductance theoretical curves in the 100% Ballistic and 0% Diffusive when $V > \Delta$ and 0% Ballistic and 100% Diffusive when $V < \Delta$, mixed state regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
Trying the opposite way, by switching the regimes. **Fig.5.10.** shows Andreev conductance theoretical curves in the 0% Ballistic and 100% Diffusive when \( V > \Delta \) and 100% Ballistic and 0% Diffusive when \( V < \Delta \), mixed state regime with different parameters. In a), b) and c) of the figure, the polarization is fitted at constant polarization of 0%, 60% and 100% respectively, with changing values of elastic scattering parameter \( Z \). As seen from the figure the larger the value of \( Z \), the larger the peak in conductance at the edge of the superconducting energy gap. By contrast with the dips, the larger \( Z \) the smaller the resultant dips. Also the lower the values of the conductance inside the gap. In d), e) and f) of the figure, \( Z \) kept constant with the values 0.0, 0.35 and 0.7 respectively, with changing values of polarization. As seen from the curves the polarization is affecting the curves by shifting the value of conductance inside the gap, in an inversely relation. Also the larger the value of polarization the smaller the peak in conductance.

In General, decreasing \( Z \) cause increase in dips and decrease in peaks. Decreasing the polarization increases both Peaks and dips. These results are not different from the pure diffusive, except the peaks here are smaller, and even disappeared in some cases. As **Fig.5.10.** c) shows for the case of \( Z = 0.0 \) and 0.2, the peaks disappear, and the dips are maximum as shown in the subfigure. **Fig.5.11.** shows the conductance curves with \( Z \) equal zero, for three different polarization, as clear in the figure the larger the polarization the smaller the peak, and it is not existed in the case of 80% polarization, just the dips alone can be seen. Curves with this properties fits the experimental conductance curves having dips shown earlier in the thesis. This new idea of the specific Mixed state regime of ballistic and diffusive depending on the range of the voltage running, in other words in the superconductivity state, seems promising. It make since, when try to explain it physically. When the electrons does not have enough energy to overcome a tunnel
Fig. 5. 10. Represents Andreev conductance theoretical curves in the 0% Ballistic and 100% Diffusive when $V > \Delta$ and 100% Ballistic and 0% Diffusive when $V < \Delta$, mixed state regime with different variables. a), b) and c) are produced at constant polarization of 0%, 60% and 100% respectively, with changing values of barrier strength $Z$. e), f) and g) are produced at constant barrier strength of 0, 0.35 and 0.7 respectively, with changing values of polarization.
contact, the only regime available for them is the diffusive regime, but when they have larger energy, the probability of tunneling will increase due to the presence of sufficient energy, which increase the probability of the ballistic regime, of course this scenario highly depends on the surface states of the contact, meaning there is two ways for the electron to go through, and the electron prefer way depends on their energy.

**Fig. 5.** Represents Andreev conductance theoretical curves in the 0% Ballistic and 100% Diffusive when $V > \Delta$ and 100% Ballistic and 0% Diffusive when $V < \Delta$, mixed state regime with $Z=0$ for all. a) $P=40\%$, b) $P=60\%$ and c) $P=80\%$. 


Chapter 6: Conclusions

In this research the CTLM technique was used to study the interface of GaMnAs/Nb and its polarization. The preparation of the samples plays a major role in the properties of the interface. The interface fabrication is a controlled process in this technique. The samples were annealed at low temperature for short periods of time many times and measured in between. There was a dramatic change in the resultant resistance/conductance curves after each annealing stage. Some curves showed unexpected sharp dips in conductance, other showed nice Andreev reflection curves with high polarization. Due to the large change in the curves derived by annealing processes, surface states are suggested to play the major role for the resultant curves and a main role at compound semiconductor interfaces. The polarization of the interface can be quite different from the semiconductor material bulk except in the case of clean interface. The dips on conductance curve were explained using the theoretical modeling, modeling and experimental data analyses. The relationship between ballistic and diffusive transport was considered. New selective mixed transport state between ballistic and diffusive was suggested, and it was able to explain the presence of the dips in conductance.
References


