Lithographic techniques for fabrication of spin injection and detection devices exploiting ferromagnetic semiconducting Gadolinium Nitride

by

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Abstract

This thesis will present a variety of methods for fabricating spin-injection and detection device based on the rare-earth nitrides as ferromagnetic electrodes and copper as a spin diffusion channel on Si/SiO$_2$ substrates. The fabrication of a spin injection device is shown using photolithographic methods in tandem with; Photomask based patterning, Ar-assisted ion milling, Direct laser writing, and Electron beam lithography. This is the first ever work that has used electron beam lithography for patterning rare-earth nitride devices with submicron features, as all previous works have used photolithography. The design, fabrication and testing of devices focuses on achieving high device yield, and reduction of device features. The best method for successfully patterning a rare-earth nitride-based spin injection device down to nm scale involves using electron-beam lithography, but film adhesion issues will have to be solved to produce devices ready for testing.

Devices were characterised and tested using XRD, SEM and a four terminal lateral non-local electrical measurement geometry. Electrical resistance of the various current paths in the device were measured, as well as attempts to measure a fully fabricated device using the four terminal lateral non-local experimental set up. A spin injection and detection device using GdN was fully fabricated and can be easily reproduced. However, the devices were found to be fragile and easily damaged during electrical measurements. Therefore, future work needs to focus on improving the robustness of the device.
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Ehara taku toa i te toa takitahi, engari he toa takitini.
‘My strength is not that of a single warrior but that of many’.

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Glossary

- **AlSil** - Aluminium Silicate. Used for wire bonding electrical connection.
- **Ar** - Argon. Refers to argon gas in this work.
- **BJT** - Bipolar Junction transistor
- **Cr** - Chromium
- **Cu** - Copper
- **De-I** - Deionised water.
- **EBL** - Electron beam lithography
- **ECP** - Electro-chemical potential
- **EDS** - Energy dispersive X-ray spectroscopy
- **FET** - Field-effect transistor
- **FM** - Ferromagnetic material. Typically, a metal.
- **GaN** - Gallium Nitride
- **GdN** - Gadolinium Nitride
- **GE** - GE varnish – commonly used low temperature adhesive.
- **GMR** - Giant magnetoresistance
- **IPA** - Isopropanol alcohol.
- **LNL** - Lateral non-local
- **MBE** - Molecular beam epitaxy
- **MgO** - Magnesium Oxide
- **MIBK** - Methyl isobutyl ketone.
- **MOSFET** - metal-oxide semiconductor field-effect transistor
- **NLSV** - Non-local spin valve
- **NM** - Non-magnetic material. Typically, a metal.
- **PCB** - Printed circuit board
- **PL** - Photolithography
- **PPMS** - Physical Property measurement system
- **Py** - Permalloy. A magnetic alloy made of eighty percent nickel and twenty percent iron
- **RAM** - Random access memory
- **REN** - Rare-earth nitride
- **SEM** - Scanning electron microscope/microscopy
- **Si** - Silicon
- **SiO₂** - Silicon di-oxide. Refers to a 200 nm thick layer on the surface of a silicon substrate
- **UV** - Ultraviolet
- **XRD** - X-ray diffractometry
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Chapter 1

Introduction

Exponential uptake of modern technology by information and energy hungry consumers of developing nations (such as India) will put enormous strain on global data processing infrastructure [1]. Globally, electricity used for data centres alone makes up 3 percent of all electricity consumed [2]. In April 2018, the music video “Despacito” became the first YouTube video to reach five billion views, also burning the same amount of energy as forty thousand American households consume in one year [3]. Electricity generated for data centres is responsible for 2 percent of global greenhouse gas emissions. This is equivalent to the carbon footprint of the global airline sector [4],[5]. Electricity use by data centres could rise to as much as 8 percent of global energy consumption by 2030 [3]. Reducing the energy consumption by data centres will help mitigate our carbon footprint as well as accommodate the growing number of consumers of this technology. Improving the energy efficiency of reading and writing information to memory devices is one way to achieve reduced energy consumption.

The latter half of the twentieth century and the early twenty first century was marked by expeditious improvement in information technology and therefore massive increases in the energy consumed by this technology This advancement is often referred to as Moore’s law [6]. In Gordon E. Moore’s own words, Moore’s law is described as “has come to refer to almost anything related to
the semiconductor industry that when plotted on semi-log paper approximates a straight line [7]. In summary, Moore’s law can be taken to mean that the performance of given electrical components of integrated circuits will improve exponentially at some constant rate. For example, an economically viable transistor density on a microchip will double every two years. This has played an important part in encouraging technological innovation required for satisfying the hunger for more computing power. An example of this is the gate length of a transistor which in the 1970s was on the order of a few micrometres in length [8] compared to as small as 20nm today [9]. One may argue that the intensive downscaling in size of the metal oxide semiconductor field-effect transistor (MOSFET) has reached its limitations after being the cornerstone of advancements by the semiconducting industry [8] due to the physical limitations of fitting electrical components of integrated circuits on a device. Reducing the number of transistors on a device also increases the energy consumed due to current leaking resulting from quantum mechanical tunnelling and the additional Joule heat produced by the desired increase in power density [9]. It is clear that a new approach to further develop this technology is required to satisfy the demand to continuously improve computing devices. One novel approach is to consider exploiting the electron spin as well as, or instead of, its charge, which allows us to address another major concern for global society - energy consumption by data centres.

Due to advancements made by Stuart Parkin [10] and IBM, we have seen the availability of commercial storage media, such as magnetic hard disk drives increase rapidly. Another promising form of memory storage, known as magnetoresistive random access memory (MRAM) enables efficient control of charge transport by exploiting the relative magnetisation directions of two ferromagnetic metals separated by a thin non-magnetic material only a few nanometres thick [11],[12],[13].

A transistor relying on the spin of an electron instead of solely on electron charge is predicted to require less power to operate than a traditional transistor. In a spin transistor, switching between states is controlled via a spin polarised
current and not solely a charge current [14]. The first spin injection transistor was proposed by Datta and Das [15]. Their proposed device is composed of two ferromagnets that act as a source and drain, separated by a non-magnetic conducting channel through which a spin-polarised current could flow. The proposed concept can be simply thought of in terms of an optical device comprised of a light polarizer and analyser set 90° out of phase from each other. In this initial state we expect minimal transmission of light. However, by adding an electro-optical material in between, we can rotate the polarisation of the incoming light by applying an external voltage to the material as seen in Figure 1.1. If the applied voltage is enough to rotate the light polarisation by 90° then total transmission would be achieved.

![Figure 1.1](image-url)

Figure 1.1: (Top) - we see concept of an optical device that exploits the polarisation of light to control transmission of light through the device. (Bottom) - the electronic analogue of the optical device. Adapted from [15].

Since the proposal, both theoretical and experimental contributions have
been made to physically realise this device, such as the manufacture of a basic spin transistor incorporating cobalt as the ferromagnet injector and detector [16][17][18]. However, for a spin injection device to be successful a high spin injection efficiency from the ferromagnet and conduction channel junction must be achieved. Junction materials must have similar conductivities to achieve high efficiency spin injection [19]). Since most modern electronics are semiconductor based it is difficult to achieve high spin injection efficiency when most ferromagnetic materials are metals. Therefore, a material that exhibits ferromagnetism and is semiconducting is desirable.

In this thesis I present the development of a spin injection device based on the four terminal lateral non-local geometry that incorporates rare-earth nitrides (RENs) as the ferromagnetic injector and detector electrodes separated by a non-magnetic copper conduction channel. Some notable RENs are ferromagnetic semiconductors where the conductivities can be tuned a number of orders of magnitude via doping [20]. The RENs form a rock salt structure and are comprised of elements from the lanthanide series with 3- charge and nitrogen with a 3+ charge and have ferromagnetic Curie temperatures as high as 70K.

In the second chapter of this thesis, I will review the required physical understanding of concepts of spin injection and detection in both metallic and semiconducting materials. Most importantly, how one can justify the application of the chosen measurement geometries in this thesis. In chapter three, I will discuss the sample fabrication methods of molecular beam epitaxy (MBE) and physical vapour deposition for sample growth; argon-assisted ion beam etching (also referred to as ”ion milling” or “dry ion etching”), photomask photolithography, electron-beam lithography (EBL) and laser writing in conjunction with photolithography for sample patterning. Chapter Four will be dedicated to results and discussion. Chapter five will summarise the outcomes of this work and provide suggestions for future work.
Chapter 2

Theory

2.1 Introduction to Spintronics

Spin (in the context of this work) is a quantum mechanical property of electrons and can be thought of as the associated magnetic moment of an electron. Spintronics is a subfield of electronics that considers the manipulation of the electron spin or a combination of the electrons charge and spin to read, write, transform, and transfer information. Some envisioned applications of spintronics include transistors, logic devices, and quantum computation [21],[16],[22]. Spintronics often involves controlling the relative magnetisations of two unique magnetic layers to turn on or off the flow of spin polarised electrons in a device. In 1988 Albert Fert and Peter Grünberg discovered the giant magnetoresistive effect (GMR) and were later awarded the Nobel Prize in Physics for this in 2007 [23],[24],[25] (Figure 2.1). They observed that the electrical resistance in any ferromagnetic metal/non-magnetic metal/ferromagnetic metal stack depends on the relative magnetisation of the two ferromagnetic layers [26],[27].
Figure 2.1: A proposed spin valve that exploits the GMR effect. The large arrows in the blue ferromagnetic layers show the magnetisation. The electrons in the orange non-magnetic layer scatter differently depending on their spin orientation. A simple resistor model shows resistance experienced by either spin population. The size of the green resistors relate to the magnitude of resistance experienced by a spin polarised electron depending on its spin orientation. Adapted from [28].

The configuration where adjacent ferromagnetic layers have parallel alignment displayed low resistance, whereas the one with adjacent layers that were anti-aligned displayed high resistance. The magnetic orientation of the layers
can be easily controlled by application of an external field. The different resistance states are related to the amount of scattering experienced by spin polarised electrons in the two different configurations. The probability of this scattering depends on relative direction of the electron spin to the effective magnetic field inside the ferromagnet. If the spin is anti-parallel to the effective magnetic field, there are more states available for electron scattering. This means that the electrical resistance here is larger than if the spin is parallel to the effective field.

A ferromagnet is a material that is magnetically ordered. The magnetic sublattice of a ferromagnet crystal is created by atoms with non-zero magnetic moments. The degree to which electrons scatter off the magnetic sublattice is determined by the relative orientation of the electron moment to that of the moments in the sublattice. Least scattering occurs when the two moments are aligned, whereas the largest amount of scattering occurs when the two moments are anti-aligned [29].

Electron-atom scattering in ferromagnets is governed by how the band that is responsible for that material’s magnetic properties is filled. For example, in Iron, Nickel and Cobalt, the filling of the 3d band determines the magnetic properties of that material. In these materials the density of states at the Fermi level of spin up and spin down electrons is not equal, meaning there are more spin up (or spin down) electrons than spin down (or up). The Fermi level lies within the sp band for majority spin electrons and electron transport is like that in a ferromagnet or non-magnetic conductor, whereas the Fermi level for minority spins lies within the d band as the sp and d band are hybridized. There is a high density of states within the hybridized spd band resulting in strong scattering for those minority-spin down electrons compared to those majority-spin up electrons. Thus, the mean free path of minority spin electrons is much shorter than majority spin electrons.

Spintronics has applications in at least three branches of computer hardware. Information storage on short (Random-access memory) and long (Hard drive) time scales, and performing logic tasks. Most commercially available comput-
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Figure 2.2: Schematic of the density of states in ferromagnetic and non-magnetic metals. 1 shows a non-magnetic layer sandwiched between two ferromagnets with anti-parallel magnetic alignment. Here the arrows depict the orientation of the magnetisation. 2 shows the spins splitting in the density of states where F is the Fermi level. In the ferromagnetic layers there is an imbalance between the two spin populations in the density of states below the Fermi level. Adapted from [30].

ers’ short-term memory uses random-access memory (RAM) based on electron charge. For information to be stored in a state and maintain this state they require to be constantly powered. Capacitors that are used in RAM to store charge are often sensitive to leaks and reduce in performance over time [14]. Spintronics looks to overcome this by storing the information in magnetic domains instead of charge. Unlike the capacitor this does not require a consistent application of power to keep the device running, we need only apply an external field for a defined amount to time to re-orient the magnetic moment as we please. We do not require to always be applying the field to keep the device in a working state, like the principle we observe in GMR. The only time power is needed to be consumed in an MRAM device is when a state needs to be changed or read, unlike its charge based counterpart [14].
2.2 Charge-based Transistors

This project is focused on developing a spin-based transistor. However, it is important to understand the operation of a conventional charge-based transistor beforehand. A transistor is a semiconducting device that is used to either amplify or switch an electronic signal. There are two types of transistors; bipolar junction transistor (BJT) and field-effect transistors (FET) which differ in structure [31]. A BJT is comprised of two adjacent diodes, this is constructed by either sandwiching a thin n-type semiconductor between two p-type semiconductors (pnp) or a thin p-type semiconductor between two n-type semiconductors (npn) as seen in Figure 2.3. n-type semiconductors have more free electrons as charge carriers than an undoped semiconductor, whereas p-type semiconductors have more electron-holes as charge carriers than an undoped semiconductor. The emitter contributes the larger portion of majority charge carrier species and is always forward biased relative to the base such that it can supply this surplus of majority charge carriers to the base. The collector will accumulate most charge carriers provided by the emitter and is always reversed biased with the base. Typically, the emitter is heavily doped, whereas the collector is moderately doped. The base forms two circuits; one with the emitter, which is low resistance due to the forward bias, and one with the collector which is high resistance due to the reverse bias.

![Figure 2.3: A typical NPN bipolar junction. Adapted from [32].](image-url)
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The operation and functions of a BJT is explained as follows. There are two separate currents that flow within the BJT; a small current flow between the base (B) and emitter (E), and a large current that flows between the emitter (E) and collector (C). The larger current is controlled by the small current. By varying the small current, we control how many charge carriers move toward or away from the emitter.

The BJT can be biased in various ways to achieve different modes of operation. This is summarised in Table 2.1:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Emitter Junction (EB)</th>
<th>Collector Junction (CB)</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>Forward-biased</td>
<td>Reverse-biased</td>
<td>Active</td>
</tr>
<tr>
<td>FF</td>
<td>Forward-biased</td>
<td>Forward-biased</td>
<td>Saturation</td>
</tr>
<tr>
<td>RR</td>
<td>Reverse-biased</td>
<td>Reverse-biased</td>
<td>Cut-off</td>
</tr>
<tr>
<td>RF</td>
<td>Reverse-biased</td>
<td>Forward-biased</td>
<td>Inverted</td>
</tr>
</tbody>
</table>

Table 2.1: **FR** – The transistor acts as an amplifier as the collector current depends on the emitter current. **FF** – transistor behaves as a closed switch because the collector current is independent of the emitter current. **RR** – transistor behaves like an open switch which because no carrier current flows to the collector due to no majority charge carriers flowing from emitter to the base. **RF** – A poorly performing inverting transistor due to the collector being less doped than the emitter and unable to supply majority charge carriers to the base.

A FET is comprised of three main components; source (S), drain (D) and gate (G) and sometimes a body (B) or substrate (Figure 2.4). Source and body are often electrically connected so that they share the same source of current. Like
the BJT, the FET has three regions of different doping. The source and drain are connected to regions where the semiconductor is n-doped, whereas the body of the device is a p-doped semiconductor. Typically, both of these regions are made from silicon, but doped with B, Li, P, As, Bu, or Sb for n-type and B, Al, Ga, In for p-type[33].

![Figure 2.4: A typical field-effect transistor. Adapted from [34].](image)

The source provides charge carriers that flow toward the drain. This flow of carriers between the source and drain can be controlled by applying a voltage to the gate. By varying the voltage applied to the gate we can excite two states; one where charge carriers can flow from source to drain, and one where no charge carriers can flow.

The small region between the source and drain is known as the conduction channel. The resistance experienced by charge carriers in this region is controlled by the voltage applied to the gate. If no voltage is applied to the gate, then there will be no current flow between the two n-type regions because there are no charge carriers available between the two n-type regions. If a positive voltage is applied to the gate then an electric field is set up near the gate, this causes electrons to be attracted toward the gate and repels holes away. The
result is a conductive channel that allows charge carriers to flow between the n-type regions. Increasing the applied voltage/potential increases the strength of the electric field and therefore increases the conduction of charge in the channel. Typically, there is a threshold voltage required for charge to flow in the transistor. However, some transistors are fabricated such that conduction is possible when no gate voltage is applied. In this case a negative voltage may be applied to the gate so that the transistor is in state that no charge can flow (is in the off-state).

2.3 Spin-based Transistors

A spin-based transistor does not operate on basic charge flow, but where the spin polarisation of the electrons belonging to that current flow is important. Transistors that are instead based on electron spin injection and detection via ferromagnetic source and drain were first conceived by Datta and Das as early as 1990 [15] (Figure 2.5). Such devices, known as spin transistors, have since been developed and are structurally very similar to a traditional FET. This is very similar to GMR devices as the flow of spin polarized electrons is determined by the relative magnetisation of two unique magnetic layers, whereas in GMR the flow of electrons is controlled by the relative magnetic alignments of two ferromagnetic metals. A basic spin transistor can be thought of as replacing the n-type semiconducting regions of a normal FET seen in Figure 2.4 with ferromagnetic electrodes and replacing the body material with a non-magnetic conducting channel. One such device uses ferromagnetic Cobalt as the source and drain components, thus allowing for the manipulation and detection of spin precession as discussed in the beginning of this section [16].
2.3. SPIN-BASED TRANSISTORS

As described in the previous section, a traditional charged based FET uses a gate to control the flow of charge carriers with uncontrolled spin from source to drain, whereas a spin transistor exploits the flow of a spin polarised current. Spin polarisation can be defined as the degree to which the spin of an electron is oriented in a particular direction (e.g. up or down). This property is present in conduction electrons in a ferromagnetic material [35]. A spin polarised current can be injected into the conduction channel by passing a charge current through a ferromagnet. The ferromagnet has an intrinsic net imbalance of species in the spin population (i.e. there are more spin-up electrons than spin-down, or vice versa). When an un-polarised electron is injected into a ferromagnet, the electron experiences a magnetic precession due to the difference between its spin and the local magnetic moment of the ferromagnet. Over a very short time scale (effectively instantaneous in this work’s consideration) the spin of the electron will align with the local moment. Most electrons that are injected into the conduction channel from the ferromagnet have the same spin orientation and therefore form a spin polarised current near the interface which decreases further away from the interface.

In the non-magnetic material far from the ferromagnetic interface, the den-
sity of spins should be balanced. Therefore, as the spin polarised electrons travel further, the polarisation will decay towards the equilibrium. As the spin polarised electrons travel further into the non-magnetic material away from the interface, the polarisation is expected to decay due to scattering. This can be thought of in terms of the electrochemical potential of the two spin species; near the interface the density of spin species and electrochemical potential of either spin is imbalanced, whereas they are balanced far into the non-magnetic material. The distance over which the change in electrochemical potential occurs can be related to the spin diffusion length [36].

Detection of a spin-polarised current at the second ferromagnetic electrode requires the fabrication of a sufficiently short conduction channel, approximately on the order of the spin diffusion length of the non-magnetic material. If the spin polarisation of the current aligns with that of the second electrode, then the electrons will experience a low resistance. However, if they are anti-aligned then the electrons will experience high resistance. The low and high resistive states can correspond to “on” and “off” states like in the conventional transistor. However, the region where the current flows does not need to depend on having a base-collector current, or a gate voltage applied. Instead it depends on the orientations of the magnetisation in the magnetic injector and detector electrodes.

Spin-based transistors offer some energy saving features. Information encoded in conventional charge-based transistors is hindered by energy limitations when the electron switches energy states [37]. Spin injection transistors exploit the alignment of electron spin, instead of moving charge. This can be achieved by passing a current through the ferromagnet and into the non-magnetic layer, then out of the device in the opposite direction to the conduction channel as seen in Figure 2.10. This means only a spin-current will diffuse along the non-magnetic channel toward the second ferromagnet. Therefore, the power that is dissipated in the conduction channel is zero since $P = I^2R = 0$ and there is no charge current moving through the conduction channel.
2.3. SPIN-BASED TRANSISTORS

The ferromagnetic electrodes will stay aligned regardless of whether the device is on or off (unlike traditional devices). The state of the transistor depends on the alignment of the ferromagnetic electrodes, and only a change in state requires power to switch the magnetisations. Therefore, maintaining the existing device state requires no power. The spin transistor is superior to the charge transistor as we are not required to spend energy overcoming a barrier to perform operations.

The spin of an electron moving through the channel (provided the channel material exhibits spin-orbit coupling) will precess in a transverse electric field, which can be applied via an external magnetic field or gate voltage. The resistance of the transistor is dependent on whether the precessing spins are aligned or anti-aligned as they arrive at the drain electrode. Tuning the precession allows switching between high and low resistance states, analogous to a "0" or "1". The spin precession can be explored by measuring the spin analogue of the Hanle effect. The Hanle effect is the change in alignment of spin polarised current that experiences a transverse electric field to the direction of motion[38](Figure 2.6).
Figure 2.6: The operation of a spin-based transistor exploiting the Hanle effect. The top row shows the device operating when no voltage is applied to the gate. Top left - The magnetisations of both electrodes are aligned parallel, so the device is in the ‘on’ state. Top right - The magnetisations of both electrodes are aligned anti-parallel, so the device is in the ‘off’. The bottom row shows the device when a voltage of 1.4V is applied to the gate. Here, the gate voltage induces an electric field causing the spins to precess as they travel through the conduction channel. Bottom left – Although the magnetisations of the electrodes are parallel, the spins arriving at the detector electrode have are anti-aligned to the local moment. Therefore, the device is in the “off” state. Bottom right – Although the magnetisations of the electrodes are anti-parallel, the spins arriving at the detector electrode have are aligned parallel to the local moment. Therefore, the device is in the “on” state. Adapted from [39].
2.4 Hindrances in the development of a spin transistor

High spin injection efficiency from the ferromagnet to the conduction channel is required for a successful device to be fabricated [40]. A continuous current density across and through the ferromagnet-conduction channel junction is a requirement of efficient spin injection [40]. If the current density is not continuous then charge will build up at the interface, thus hindering the injection of spin polarised carriers. Recall $J = \sigma E$ where $J$ is the current density, $\sigma$ is the conductivity of the material, and $E$ is the applied electric field. For a continuous current density in a constant electric field across both materials, we require that $\sigma$ is the same in both materials.

An estimation of the efficiency of spin injection can be calculate via the spin injection coefficient which is expressed in terms of the ratio conductivity of the two contacting materials. $\gamma \propto \frac{\sigma_{\text{NM}}}{\sigma_{\text{FM}}}$, where $\sigma_{\text{NM}}$ is the conductivity of the non-magnetic material and $\sigma_{\text{FM}}$ is the conductivity of the ferromagnetic injector material. As $\gamma \to 1$, the spin injection efficiency increases. Whereas a small $\gamma$ corresponds to poor spin injection [40].

Fabricating a spin injection device that is integrable with semiconductor components has been challenging thus far. I will show this by constructing an imaginary system where we pick a well known ferromagnet (e.g. Iron) [41] and a well-studied doped semiconductor (e.g. Gallium Nitride) [42]. Some standard resistivities for these materials at room temperature are:

\[
\rho_{\text{Fe}} = 1.0 \times 10^6 \Omega cm \tag{2.1}
\]
\[
\rho_{\text{GaN}} = 0.02 \Omega cm \tag{2.2}
\]

Using $\sigma = \frac{1}{\rho}$, we have

\[
\sigma_{\text{Fe}} = 1.0 \times 10^6 \Omega^{-1} cm^{-1} \tag{2.3}
\]
\[
\sigma_{\text{GaN}} = 50 \times 10^6 \Omega^{-1} cm^{-1} \tag{2.4}
\]
Therefore

\[
\gamma \propto \frac{\sigma_{\text{GaN}}}{\sigma_{\text{Fe}}} = \frac{50 \times 10^6 \Omega^{-1} cm^{-1}}{1.0 \times 10^6 \Omega^{-1} cm^{-1}} = 0.00005 = 0.005\%
\] (2.5)

This clearly shows that one cannot simply use a junction of materials with large differences in conductivity to fabricate a successful spin injection device.

Attempts to overcome this issue have included adding an insulating layer in between to form a tunnelling barrier. The quantum tunnelling mechanism allows for spin injection by using a material that has a higher probability of transmitting one spin species over the other without depending on the two outer layers having a similar conductivity [43]. Adding another layer to the device increases the complexity of the device by adding a further fabrication step, which increases the chances of procedural failure. However, it has been shown that GaOx when sandwiched between iron and semiconducting MgO achieves a magneto resistive change of 92% between the parallel and anti-parallel states [44]. Additionally, MgO has been shown to be a good choice as a tunnel barrier material when placed between iron and semiconducting silicon with injected spin polarisations up to 90% [45].

The obvious solution for this problem is however to choose FM and NM materials with similar conductivities. For this device to be integrable in modern electronics, the conduction channel must at least be a semiconductor, and therefore we must consider a ferromagnetic semiconductor to act as the spin injector material. Such a device has been fabricated with ferromagnetic semiconductor GaMnAs and GaAs conduction channel in the form of a metal-oxide-semiconductor field-effect-transistor (MOSFET) [46]. Changes in magnetoresistance up to 60% were shown as well as the ability to vary the spin polarised current from injector to detector also up to 60%. Unfortunately, the number of materials that exhibit both ferromagnetism and are semiconducting are few. Many are in fact dilute magnetic semiconductors (DMS), which obtain their magnetic and electronic properties through doping and cannot easily be tuned.
2.5 Background about the Rare-earth Nitrides

The lanthanides (Lu through to La, as well as Sc and Y) are known as rare earth elements. One important feature of the lanthanide series is the filling of the $4f$ orbital as the series increases in atomic number.

Electrons in the $4f$ valence orbital are well separated from other orbitals, have high angular moment, and have no node. Therefore, $4f$ electrons are very localised [20].

Rare earths have a valency of three, except Ce which has a valency of four. This means that three electrons are required to bond to N and form a rare-earth nitride. These three electrons per site act as charge carriers.

The rare earth nitrides form the crystal structure of a simple FCC rocksalt, where the central lanthanide atom with a 3+ charge state is surrounded by six nitrogen atoms with a 3- charge state (Figure 2.7). This corresponds to ABAB stacking where each crystal plane is the same as the next-nearest neighbour.
Due to the filling up of the $f$ orbital as we move through the lanthanide series, the materials display interesting magnetic properties. These can range from some materials being intrinsically ferromagnetic, antiferromagnetic, and some paramagnetic [47],[20]. All of the rare-earth nitrides behave paramagnetically at room temperature, whereas GdN has the highest curie temperature of 70K.

Paramagnetic materials are weakly attracted to an externally applied magnetic field, but unlike ferromagnets do not retain this magnetisation after the applied field is removed. This is a result of the orbital and spin moments being oriented such that each atom has a permanent magnetic dipole. However, thermal motion causes the spin of atoms to have random orientations. Therefore, a paramagnetic material does not retain its magnetisation after the external field is removed.

Unlike paramagnetic materials, ferromagnetic materials retain the magnetisation of an applied field after the field has been turned off. Electron orbitals are filled up such that the unpaired electrons will have spin alignments parallel to one another, which is decided by Hund’s rules [48]. Parallel aligned atomic mo-
ments align to create magnetic domains. The bulk material is made up of many domains, that do not necessarily align with each other and could be randomly oriented, causing the bulk material to have either a weak magnetisation or no overall magnetisation at all. Applying an external magnetic field to the material will cause the magnetic domains to re-orient themselves in the direction of the applied field. When the field is turned off, the ferromagnetic material ‘remem-
ers’ its magnetic history and retains its magnetic alignment. This property is called magnetic hysteresis. This alignment will be retained unless acted upon by another applied field or sufficiently heated up such that the thermal motion of electrons causes the randomization of spin alignment.

An advantage of studying the properties of RENs is that they are generally considered to be intrinsic magnetic semiconductors, which means that they can be doped to change their electronic properties independently of their magnetic properties. This is unlike the commonly studied dilute magnetic semiconduc-
tors (DMS) [49],[50] (Figure 2.8).

The electronic properties of the rare-earth nitrides are subject to any nitrogen vacancies in the crystal lattice that may occur during the growth [51]. Therefore, the conductivity of the REN can be adjusted by varying the nitrogen pressure during deposition. At lower nitrogen pressures the number of available ni-
trogen’s is too low to form a stoichiometric 1:1 REN, so some nitrogen lattice sites will have a vacancy instead – leading to a conductive REN or a material that looks electronically like the pure rare-earth metal. A deficiency in nitrogen infers there are more ‘free electrons’ in the valence band, meaning a larger con-
ductivity.

Growing at a higher nitrogen pressures ensures the availability of nitrogen atoms to fill the lattice sites required to achieve close to 1:1 stoichiometry. A REN with high nitrogen content has a lower conductivity than nitrogen de-
cient REN because the available electrons are required to form the triple bond, therefore there are less available free electrons.
The conductivity of GdN can be tuned over six orders of magnitudes via the doping of Mg \cite{51,50,49}. GdN is therefore an ideal candidate to overcome the aforementioned conductivity mismatch problem experienced in previous developments of a spin-based transistor. This is because the conductivity of the GdN can be grown to be similar to that of the non-magnetic conduction channel in a spin transistor such as Cu (a nonmagnetic metal), GaN or Si (both well understood nonmagnetic semiconductors) \cite{52,53}. Therefore I plan to fabricate spin injection and detection electrodes using GdN, which is known to have a high spin polarisation \cite{54}, variable resistivity \cite{51}, and an observed ferromagnetic Curie temperature as high as 70K \cite{55}.

GdN is slightly magnetically anisotropic, meaning there is a directional dependence on how easy it is to magnetize the material along a crystal axis. This results in a typically small coercive field that can be varied between 1mT and 20mT \cite{17}, therefore it is suitable in devices requiring a magnetisation with orientation that can be easily reversed (such as in a spin based transistor).
RENs are extremely sensitive to crystal impurities such as water and oxygen. The latter being an issue both during and after growth [56],[57],[52]. The REN will become RE$_2$O$_3$ when left in atmosphere. Overcoming this issue requires the films to be grown under ultra-high vacuum and protected by a capping layer that is grown on top of the REN. The purity of the REN can be checked by x-ray diffraction. The presence of a REN crystal will be indicated by a sharp peak, whereas in an oxidised sample there will a weak peak (or no peak at all) and a stronger background from the amorphous structure of the rare-earth oxide.

### 2.6 Spin injection and detection

Manipulation of spin-polarised currents from ferromagnetic (FM) to non-magnetic (NM) materials is an important concept in spintronics and this research. Ferromagnetic materials (FM) have an intrinsic magnetic moment because of the net imbalance of the number of up spin-polarised electrons compared with the number of down spin-polarized electrons (Figure 2.9).

![Figure 2.9: Density of states near the Fermi level in a ferromagnetic metal. Adapted from [58].](image-url)
CHAPTER 2. THEORY

One may refer to spin injection as the flow of spin-polarized charge carriers from the FM to the NM. Conversely, if the current flows in the opposite direction as in the previous case. Then one may refer to this as spin extraction, resulting in non-equilibrium spin density in the NM.

Numerous measurement techniques have been used in the investigation and development of spin injection and detection devices such as; local and non-local electrical geometries [59],[60],[61], Kerr microscopy [62],[63], and spectroscopy [64],[65]. In this thesis I will use a non-local measurement geometry incorporating RENs to detect a spin-polarized current. This is the first milestone required to fabricate a working spin transistor.

The non-local geometry has been chosen as the ideal measurement configuration as other electrical measurement techniques (such as two-point magnetoresistive and 4 point local geometry) can be difficult to interpret. This is because it is difficult to separate other signal contributions such as electrode magnetoresistance and local Hall effects from the pure spin current [36]. The non-local geometry removes speculation about other contributions by measuring the change in the electrochemical potential outside and well separated from the path of the applied charge current.

When a current is passed from the ferromagnetic injector electrode into the nonmagnetic conduction channel, many of the electrons conserve the local spin alignment they were attributed in the ferromagnet. The spin-dependant electrochemical potential (ECP) responds to accumulation of spins in the nonmagnetic channel and can be shown as $\Delta \mu = \mu_\uparrow - \mu_\downarrow$, where $\mu_\uparrow$ and $\mu_\downarrow$ represent the ECP of spin up and spin down populations respectively.

Before any current is applied through the bilayer, we expect that the number of electrons in the non-magnetic material that are spin up are equal to the number of spin down electrons, and are therefore equally represented in the spin dependant ECP. When we ‘turn on’ our current through the bilayer, spin polarised electrons are injected to the nonmagnetic metal causing the number
2.6. SPIN INJECTION AND DETECTION

of electrons belonging to one spin population to increase, and the minority spin electrons decrease, i.e. the density of majority spin increases by $+\delta \mu_N$, and the density of minority spin decreases by $-\delta \mu_N$. The total change in the ECP is therefore $2\delta \mu_N$ as a result of the spin splitting [36].

A pure spin current travels from the injector electrode side of the conduction channel to the detector electrode, whereas a spin polarised charge current follows the current path.

In the four terminal lateral non-local geometry, current is applied through one ferromagnetic and non-magnetic material interface and flows out one end of the non-magnetic material. No net charge current flows in the non-magnetic conduction channel between the two ferromagnetic electrodes. However, the spin dependant ECP decays towards zero as you get further away from the interface. This means over a finite distance away from the first electrode, the ECP in the conduction channel is non-zero, meaning there are more of one species than the other spin species. This is the same as a spin current flowing in the channel toward the second electrode, even though there is no charge current. The spin current can be thought of as spin up and spin down electrons moving in opposite direction such that the net charge current is zero, but the net flow of spins is non-zero.

\[
I_{\text{charge}} = I_{\uparrow} + I_{\downarrow} \quad (2.6)
\]

\[
I_{\text{spin}} = I_{\uparrow} - I_{\downarrow} \quad (2.7)
\]

If the number of spin up and spin down electrons is the same, but the direction of travel is opposing, then the charge current is zero, however the spin current is non-zero.

The voltage that is measured across the ferromagnetic detector electrode and the conduction channel in a lateral non-local geometry is described as follows [36].
\[ \frac{V_2}{I} = \pm 2R_N e^{-\frac{L}{x_N}} \prod_{i=1}^{2} \left( \frac{P_J R_i}{1 - P_J^2} + \frac{P_F R_F}{1 - P_F^2} \right) \times \left[ \prod_{i=1}^{2} \left( 1 + \frac{2R_i}{R_N} \frac{1}{1 - P_J^2} + \frac{2R_F}{R_N} \frac{1}{1 - P_F^2} \right) - e^{-\frac{2L}{x_N}} \right]^{-1} \]

Equation (2.8)

Where \( P_J \) is the polarisation of the interfacial current, \( R_N \) and \( R_F \) are the cross-sectional resistances of the non-magnet and ferromagnet, \( p_F \) is the polarisation of the current in the ferromagnet, and \( R_i \) is the resistance through the \( i \)th interface (where \( i \) can take values of either 1 or 2 – this represents the two ferromagnetic electrodes). \( \Pi \) is a Pi function that instructs the reader to multiply the associate terms up to the \( i \)th element. The + and – signs at the front of the right-hand side shows that the measured voltage can be both positive and negative. This depends on the relative magnetic alignment of the two electrodes. If they are parallel then we expect to observe a small resistance as we observe a low resistive state, additionally if they are antiparallel, we expect to observe a high resistive state. Consider the parallel state as being when both ferromagnets have magnetic moments aligned in the same direction, and an antiparallel state being when both ferromagnets have magnetic movements anti-aligned in the same direction (2.6).
2.6. SPIN INJECTION AND DETECTION

Figure 2.10: Birds eye view schematic of the four terminal lateral non-local measurement geometry. Current is applied through the first (injector) ferromagnetic electrode and out through the left side of the conduction channel. Spins of opposite species diffusive along the conduction channel in opposite directions. Any change in voltage is measured between the second (detector) ferromagnet electrode and the conduction channel. $w_N$ is the width of the non-magnetic conduction channel, $w_F$ is the width of the second ferromagnetic electrode, and $L$ is the distance between the centre of each electrode.

The non-local spin signal can be either expressed as a change in resistance or a change in voltage. This is a change in voltage measured between the detector electrode, which is far from the path of the charge current, and the conduction channel. So, the measured voltage is referred to as non-local relative to the charge current location. The spin signal can be thought of as the difference in measured voltage between the parallel and antiparallel states of the ferromagnets (Figure 2.10).

\[ R_s = \frac{V_s}{T} \quad \text{(2.9)} \]

\[ V_s = V_{2P} - V_{2AP} = 2|V_2| \quad \text{(2.10)} \]

For the readers ease I have broken up the expansion of the above equation into two parts, first dealing with the numerator expression in brackets, then the denominator expression.
Expanding the Pi function in the numerator for both $i=1$ and $i=2$ we have:

$$\left(\frac{2|V_2|}{I}\right)_{\text{numerator}} = 4R_N e^{\frac{L}{\lambda N}} \left( \frac{P_J \frac{R_1}{R_N}}{1 - P_j^2} + \frac{p_F \frac{R_F}{R_N}}{1 - p_F^2} \right) \left( \frac{P_J \frac{R_2}{R_N}}{1 - P_j^2} + \frac{p_F \frac{R_F}{R_N}}{1 - p_F^2} \right)$$ (2.11)

For the reader’s ease, I have shown the result that assumes the device contacts lie within the transparent contact regime. The full derivation is shown in the appendix for completeness. It is based on simplified assumptions but is enough to show how the non-local voltage depends on the relative resistances, the conduction channel length and the spin-diffusion length of the channel. We now assume that the device lies within the transparent contact regime. This is where the ECP is continuous between the semiconducting conduction channel and the ferromagnetic electrode such that the interfacial conductance tends towards infinity ($G_i \to \infty$) and that $R_1, R_2 \ll R_N$. As a result, the interfacial current polarisation (defined as $P_J = \frac{|G^\uparrow_i - G^\downarrow_i|}{G_i}$) tends toward 0 ($P_J \to 0$) [36]. Therefore, each term in the brackets with $P_J = 0$ as a numerator disappears, leaving the following expression for the numerator and denominator:

$$R_s = \left(\frac{2|V_2|}{I}\right) = 4R_F \left( \frac{p_F}{1 - p_F^2} \right) \left( e^{\frac{L}{\lambda N}} \right)$$ (2.12)
Chapter 3

Experimental Methods

3.1 Device Fabrication

Fabricating my samples requires two main steps; deposition of the copper conduction channel and contacts, and deposition of the rare-earth nitride ferromagnetic injection and detection electrodes. Patterning of the layers was achieved by using photolithographic techniques using either a photomask or direct laser writing to photoresist. Thin films were deposited by thermal evaporation, and under ultra-high vacuum via thermionic emission for GdN films. Work conducted at the School of Chemical and Physical Sciences at Victoria University of Wellington included photomask photolithography and deposition of all thin films. Electron beam lithography was conducted at the Electrical and Computer Engineering department at the University of Canterbury. Laser writing and the related photolithography was performed at Callaghan Innovation. Each sample has the geometry of 8 available contact pads. 6 contact pads were used, 2 were left unused so that future iterations of the device could include a gate electrode. The design of the contact pads is shown in Figures 3.1 and 3.2.
Figure 3.1: Each sample has 8 available (labelled in orange) contact pads on a 2” wafer. In this design, six pads lead to parts of the inner device, two are left free for future iterations (such as implementation of a gate electrode). Each sample can be cleaved out into a 10mm x 10mm piece from the master wafer shown by red outline.

The six used copper contact pads are all connected to at least one of the GdN ferromagnetic electrodes and/or the copper conduction channel. Contacts were deposited on both 2 inch and 3 inch diameter wafers of Si as shown in Figure 3.1. Some devices were grown on Si wafers with 300nm of SiO$_2$ and others were grown on Si with only the native oxide layer of $\approx$5 nm thickness. Each wafer contains a three by three grid of devices (nine in total) each with a different combination of conduction channel width and GdN ferromagnet electrode spacing. Each row of devices varies by the thickness of the conduction channel - 10,8,3 $\mu$m from top row to bottom. 3 $\mu$m width was chosen as the minimum as this is close to the lower limit of our patterning equipment. Each column of devices varies by the separation of the two GdN electrodes depending on whether the method of fabrication is via electron beam lithography or laser writing.
3.1. DEVICE FABRICATION

Figure 3.2: PL pattern inner device. The conduction channel and four inner Cu pads are connected to the larger Cu pads seen in Figure 3.1. The numbered contacts correspond to the same numbered contact pads in Figure 3.1.

The electrode spacing was chosen so that the distance between them was less than 1 \( \mu \text{m} \), which is approximately 5 times the spin diffusion length of copper at 300 Kelvin (Figure 3.3). As shown in Equation A.3 a spin polarised current that travels diffusively toward the detector electrode from the injector electrode will decay exponentially, and if the electrode spacing is too large no spin current signal will be detected.

The ferromagnetic electrode shape was chosen such that their geometric anisotropies greatly differed, meaning that one of the electrodes will switch in an applied field before the other. The electrode with the pointed ends is expected to flip magnetisation at a smaller applied field than the electrode with the half dumbbell shape due to the geometric shape anisotropy in Figure 3.15.
CHAPTER 3. EXPERIMENTAL METHODS

Figure 3.3: Devices in row; one have 10 $\mu$m, two have 8 $\mu$m, and three has 3 $\mu$m wide conduction channel. Columns a, b, and c have varying electrode spacing dependent on the method of fabrication. For EBL a=800nm, b=400nm, c=200nm. For laser writing a=2.0 $\mu$m, b=1.5 $\mu$m, c=1.0 $\mu$m.

3.1.1 Photolithographic techniques

Microfabrication techniques often include the use of photolithography (sometimes referred to as optical lithography) to produce a pattern on a wafer and/or thin film. Lithography has its origins in ancient Greek where lithos meaning ‘stone’ and graphein meaning ‘to write’ translates to printing on a stone or a metallic flat smooth service. Photolithography requires passing light through a photomask, after which the light interacts with a photosensitive photoresist that is coated onto the substrate. The photomask is a smooth flat glass plate with some regions coated in chrome metal to stop light passing through. One can either let their pattern be designated by chrome areas on their glass plate (light does not pass through the areas of their pattern) or have the entire photomask coated chrome, minus the areas covered by their pattern. These two configurations are known as ‘light field’ and ‘dark field’ masks respectively. Photoresist that has been exposed to UV light is photopolymerized. This causes damage
to the cross linked long chain molecules causing them to be soluble in a photo developer solution, leaving only the areas of the photoresist that were not exposed to UV light.

![Diagram showing the different results when using a dark field mask with a positive or negative photoresist. The mask is considered dark field as the non-pattern areas are non-transparent or ‘dark’. Adapted from [66].](image)

Part of this thesis will evaluate two different methods to fabricate the device; the lift-off method, and the ion milling method.

Previous works by our group have implemented the T-profile (found at the end of this section) recipe plus the lift-off method with some success [67]. In this work I attempt to use both T-profile and image reversal recipe. Since it was unknown how successful the image reversal recipe would be, we had both light and dark field photomasks made at the Electrical and Computer Engineering department University of Canterbury. This allowed me to test both lift-off and ion milling methods with a photolithography recipe that is known to work (Figure 3.4 and Table 3.1).

![Figure 3.5: Schematic showing the photolithographic procedure. A dark field mask (Figure 3.6) will have chrome coating on areas that are intended to not have a film deposited, so glass only areas will allow UV light to pass through. The UV light](image)
CHAPTER 3. EXPERIMENTAL METHODS

### Table 3.1: Sample patterning methods. Each row corresponds to a unique method of fabricating a patterned thin film

<table>
<thead>
<tr>
<th>Mask Field</th>
<th>Lithography recipe</th>
<th>Resulting features</th>
<th>When the Deposition step occurs</th>
<th>Milling step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Field</td>
<td>T-Profile</td>
<td>Photoresist removed from patterned area</td>
<td>Post-development</td>
<td>N/A</td>
</tr>
<tr>
<td>Dark Field</td>
<td>Image-Reversal</td>
<td>Photoresist protects pattern</td>
<td>First step</td>
<td>Final step before lift-off</td>
</tr>
<tr>
<td>Light Field</td>
<td>T-Profile</td>
<td>Photoresist protects pattern</td>
<td>First step</td>
<td>Final step before lift-off</td>
</tr>
<tr>
<td>Light Field</td>
<td>Image-Reversal</td>
<td>Photoresist removed from patterned area</td>
<td>Post-development</td>
<td>N/A</td>
</tr>
</tbody>
</table>

damages the cross-linked chain molecules in the photoresist so that when the resist is removed by the developer, these areas become empty. Only areas that are intended to not have a deposited film will still be covered in photoresist. The film is then deposited over the entire wafer, on top of the photoresist and in the gaps. Post deposition, the wafers are placed in glass trays of acetone which will wash away any photoresist on the wafer, including any film that has been deposited on top of the photoresist. The only thin film remaining will be that which was deposited in the photoresist gaps – which correspond to the non-chrome coated areas of the photo plate.

The lift off procedure described above can be also used with a light field
3.1. DEVICE FABRICATION

Figure 3.5: Schematic of the photolithographic process using either a positive or negative photoresist. The coating step requires spin coating the photoresist onto the wafer. The exposure step then applies UV light through a photomask. The pattern is then developed in a developer solution to produce features. During the transfer process we typically deposit the thin film (or before the coating step if using ion milling). The strip step is also known as lift-off and requires submerging the substrate in acetone for a few hours. Adapted from [68].

mask. In this case, the chrome coated areas on the photo plate are reversed with the transparent glass areas compared to the dark field mask. Following the T-profile recipe will result in the desired pattern being protected by photoresist. This is a suitable way to create a pattern from an already deposited thin film, since, which it allows us to ion mill the entire wafer so that the non-photoresist covered areas are removed. Therefore, I must deposit the thin film before following the photolithography recipe. The first layer in my device is made of patterned copper contacts and conduction channel grown on a 5nm chromium buffer layer.
Figure 3.6: The dark field photomask used to transfer the device pattern to the substrate.

The following is the specific processes used for patterning devices using photolithography.

T-Profile recipe.

1. Place wafer onto spin coater vacuum chuck. Blow wafer with N2 gas to remove any particles on the surface. Residual dust particles will cause 'comets' (streaks in the photoresist) as it self-planarizes during the spinning stage.

2. Spin coat AZ5214E at 4000 rpm for one minute (Figure 3.8).

3. Bake the wafer at 95 degrees Celsius for 1 minute (Figure 3.9).

4. Flash expose the wafer without the photomask to UV light for 0.25s at 9 mWcm$^{-2}$ (Figure 3.7).

5. Bake the wafer at 110 degrees Celsius for 2 minutes.

6. Expose the wafer to UV light through the photomask for 12 seconds at 9 mWcm$^{-2}$.

7. Develop the wafer in 1:4 deionised water and AZ315B developer for 4 minutes (or till developed).
3.1. DEVICE FABRICATION

8. Place wafer in glass tray containing deionised water. Gently swirl the tray so that the water mechanically removes any residual developer mix.

9. Dry the wafer with N₂ gas.

10. Bake the wafer at 110 degrees Celsius for 2 seconds to boil away any residual water.

Image reversal recipe.

1. Place wafer onto spin coater vacuum chuck. Blow wafer with N₂ gas to remove any particles on the surface. Residual dust particles will cause ‘comets’ (streaks in the photoresist) as it self-planarizes during the spinning stage.

2. Spin coat AZ5214E at 4000 rpm for one minute.

3. Bake the wafer at 95 degrees Celsius for 1 minute.

4. Expose the wafer to UV light through the photomask for 6 seconds at 9 mWcm⁻².

5. Bake the wafer at 110 degrees Celsius for 2 minutes.

6. Flood expose the wafer without the photomask to UV light for 30s at 9 mWcm⁻².

7. Develop the wafer in 1:4 deionised water and AZ315B developer for 4 minutes (or till developed).

8. Place wafer in glass tray containing deionised water. Gently swirl the tray so that the water mechanically removes any residual developer mix.

9. Dry the wafer with N₂ gas.

10. Bake the wafer at 110 degrees Celsius for 10 seconds to boil away any residual water.

Post Lithography process:
1. Inspect the pattern features under the microscope.

2. Ratios of device features have been calculated from the photo plate CAD design and can be used as rough guide to determine whether the desired feature sizes have been achieved.

3. If features have not developed properly, then the wafer may be rinsed with Acetone/Isopropanol/Deionised water then dried with N2 gas and baked at 110 degrees Celsius for 10 seconds to boil away any residual water. General notes on the lithographic process enhancement.

General notes:

1. The above T-profile recipe was developed by Dr Leo Browning [69] and the Image Reversal recipe was inherited from PhD student Erica Happe from the Plank group at Victoria University of Wellington.

2. Development time for the T profile recipe was intended to be only 12s. I found that this development time was sufficient for patterning 10mm x 10mm Si pieces, but wafer of 2” and 3” diameter require a longer development time.

3. A device yield of 33% was achieved on average by increasing the development time to approximately 2 minutes. In this case, only the devices with 10 µm conduction channel widths would completely develop.

4. Development time of at least 4 minutes now has a 100% yield of successful devices at 10,8, and 3 µm conduction channel widths.

5. UV exposure was completed by using a Karl Suss MJB3 Mask Aligner.
3.1. DEVICE FABRICATION

Figure 3.7: The Mask aligner used to expose the resist with UV light.

Figure 3.8: The spin coater used to spin on AZ5214E photoresist during the Cu contact fabrication step.
3.1.2 Ar-assisted ion milling for device fabrication

Ion Milling is a form of physical etching where inert atoms (in this case Ar atoms) are accelerated from a source of ionization toward the surface of a substrate. Ultra-high vacuum (typically less than $10^{-7}$ Torr in our case) is required such that the mean free path of the Ar atoms is much larger than the distance from the ionization source and the substrate. (Recall that the mean free path of any particle is the distance travelled by that particle before it collides with another particle such that the direction that particle one is travelling changes).

Accelerated atoms bombard the surface of the substrate, causing surface atoms to be ablated away. One can think of this as a similar process to sand blasting, where the sand particles are instead represented by the argon atoms in our case.
3.1. DEVICE FABRICATION

Fabrication process compared to lift off

Ion milling can be used as an alternative to PL lift-off for the fabrication of the Cu electrodes in our device. Application of ion milling requires the thin film stack of Cr(5nm)/Cu(50nm) to be grown first over the entire wafer substrate. Then the PL recipe is followed such that the photoresist will be covering all the areas of the device that we wish to remain on the substrate (e.g. the Cu conduction channel, outer contact pads, etc). Therefore, this requires either an image reversal PL recipe using the same photomask as the lift-off procedure or; the same PL recipe used for the lift-off procedure but with a field reversed mask (i.e. if dark field mask was used for lift-off then a light field mask should be used for ion milling).

Although we may expect the photoresist (an organic) to be ablated at a faster rate than the metal layers due to having a much lower density. For example the density of room temperature copper is 8.96gcm$^{-3}$, whereas the photoresist used in this work has a density of 1.083gcm$^{-3}$. However, the photoresist layer is sufficiently thick (microns in thickness) compared to the thin film metal coating.
which is sub 100nm. Therefore, any thin film metal not covered in photore sist will be ablated away well before the argon atoms penetrate the photore sist layer.

An INTLVC Nano quest 1 based at Robinson Research Institute shown in Figure 3.10 was used for milling samples. Since the Ion milling system is relatively new, there has not been any characterisation of milling conditions for the materials we are working with. However, milling rates for well characterise materials such as Cu can serve as a guide [70].

Cu deposited samples were milled with a beam voltage of 300V and beam current of 45A for predefined times (30s, 1min, 2min, etc) till the Cu was removed. This could be easily observed by using ones eyes to observe the colour change in the thin film from a typical brown Cu colour to the distinct purple/green colour of the substrate. Table 3.2 shows the conditions that were used for milling all samples:

<table>
<thead>
<tr>
<th>Beam Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission (V)</td>
<td>6-7</td>
</tr>
<tr>
<td>Emission (A)</td>
<td>0.100</td>
</tr>
<tr>
<td>Cathode (A)</td>
<td>12.730-12.780</td>
</tr>
<tr>
<td><strong>Beam (mA)</strong></td>
<td><strong>45</strong></td>
</tr>
<tr>
<td><strong>Beam (V)</strong></td>
<td><strong>200</strong></td>
</tr>
<tr>
<td>Acceleration (mA)</td>
<td>3</td>
</tr>
<tr>
<td>RF Power (W)</td>
<td>87</td>
</tr>
<tr>
<td>Reflected Power (W)</td>
<td>19</td>
</tr>
<tr>
<td>Chamber Pressure (Torr)</td>
<td>$2.32 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>Milling Time (minutes)</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

Table 3.2: Ion milling conditions. Numbers in bold represent parameters we can control

Measuring a consistent electrical resistance through the conduction channel
of each device on the wafer tells us how reliable the ion milling technique is to achieve a consistent standard for devices. For this method to be reliable, each device with a conduction channel that is 10 $\mu$m wide should have similar values of resistance (similarly for devices with 8 $\mu$m and 3 $\mu$m conduction channels). Therefore, we measure the electrical resistance through the conduction channel of each device using a multimeter after the full wafer has been milled. We can then compare the consistency of electrical resistance of each device fabricated via the ion milling method with the consistency of electrical resistances measured on device fabricated using the lift-off method.

**Evaporation of Cu electrodes**

**Photolithography development conditions**

Before electrical contact pads could be deposited, a clean wafer with patterned photore sist is required. Table 3.3 summarises the development conditions needed to achieve clean edge features using the T-profile recipe.

Batch 1 developer was mixed at 4:1 de-ionised water (De-I) water 315B developer during the first set of TB Dev samples (i.e. TB Dev 01-06). So at least a couple months had passed after batch 1 was mixed before it was used for the first set of wafers. The development time had to be varied from wafer to wafer to produce well-defined patterns. To make the development time more consistent a second batch was mixed.

Batch 2 developer was the same mixture as Batch 1, but I topped it up with pure developer (i.e. I added additional developer to the old batch in the glass dish. This meant that the developer to De-I water ratio would be slightly less than 4:1).

Batch 3 was mixed from new developer and De-I water due to concern that the previous batches had reduced in their efficacy over time as a result in the increasing and inconsistent development time. The freshly mixed batch 3 pro-
Table 3.3: Summary of developer batch and development times.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Substrate</th>
<th>Development time</th>
<th>Development batch</th>
<th>Microscope images post PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB Dev 07</td>
<td>Si/Si</td>
<td>3 mins</td>
<td>Batch 1</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 08</td>
<td>Si/SiO2</td>
<td>3 mins 30s</td>
<td>Batch 1</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 15</td>
<td>Si</td>
<td>13 mins</td>
<td>Batch 1</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 09</td>
<td>Si</td>
<td>4 mins 30s</td>
<td>Batch 2</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 16</td>
<td>Si</td>
<td>6 mins 20s</td>
<td>Batch 2</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 10</td>
<td>Si/SiO2</td>
<td>4 mins</td>
<td>Batch 3</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 11</td>
<td>Si</td>
<td>4 mins</td>
<td>Batch 3</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 12</td>
<td>Si/SiO2</td>
<td>4 mins</td>
<td>Batch 3</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 13</td>
<td>Si</td>
<td>4 mins 10s</td>
<td>Batch 3</td>
<td>All good</td>
</tr>
<tr>
<td>TB Dev 14</td>
<td>Si/SiO2</td>
<td>4 mins</td>
<td>Batch 3</td>
<td>Required an additional 1 min development.</td>
</tr>
</tbody>
</table>

duced consistent development times as seen in Table 3.3.

**Cr/Cu contact deposition conditions**

Electrical contacts were deposited in two steps (Table 3.4). Thin film contacts were thermally evaporated using a Angstrom Engineering NEX-DEP 200. Copper was chosen as the non-ferromagnetic material for the conduction channel due to its long spin lifetime when travelling diffusively [71]. Copper is known as a cheap, non-toxic and readily available conductor that is commonly used as contacts in devices. It is known that copper does not adhere well to Si when evaporated directly to the surface, so a buffer layer of Chromium was used to ensure the copper layer did not exfoliate during the lift-off step [67].
### 3.1. DEVICE FABRICATION

<table>
<thead>
<tr>
<th>Deposition number</th>
<th>Sample ID</th>
<th>Nominal film thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition 1</td>
<td>TB Dev 07,08, 09, 10, 11</td>
<td>Cr(5nm)/Cu(50nm)</td>
</tr>
<tr>
<td>Deposition 2</td>
<td>TB Dev 12,13,14,15,16</td>
<td>Cr(5nm)/Cu(60nm)</td>
</tr>
</tbody>
</table>

#### Table 3.4: Summary of Cu contact depositions

<table>
<thead>
<tr>
<th>Deposition number</th>
<th>Base Pressure (Torr)</th>
<th>Material</th>
<th>Power (%)</th>
<th>Pressure (Torr)</th>
<th>Growth Rate (Å/s)</th>
<th>Thickness (kÅ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6E-6</td>
<td>Cr</td>
<td>18.8</td>
<td>(1.9-2.4)E-6</td>
<td>0.04-0.11</td>
<td>0.050</td>
</tr>
<tr>
<td>1</td>
<td>1.6E-6</td>
<td>Cu</td>
<td>22.0</td>
<td>(1.7-6.2)E-6</td>
<td>0.10-0.12</td>
<td>0.508</td>
</tr>
<tr>
<td>2</td>
<td>7.7E-7</td>
<td>Cr</td>
<td>18.6</td>
<td>(5.9-6.6)E-7</td>
<td>0.07-0.10</td>
<td>0.057</td>
</tr>
<tr>
<td>2</td>
<td>7.7E-7</td>
<td>Cu</td>
<td>22.0</td>
<td>(0.8-4.6)E-6</td>
<td>0.09-0.14</td>
<td>0.511</td>
</tr>
</tbody>
</table>

#### Table 3.5: Summary of Cu contact deposition conditions

Each wafer was fixed to the rotator with Kapton tape, which is placed into the evaporator so that the face of the wafer faces the Cr and Cu boats at the bottom of the chamber. We then pump on the evaporator chamber with a turbo pump for at least 18 hours so that a base pressure of at least $1 \times 10^{-5}$ Torr is achieved. If the pressure of the chamber exceeds the value of $1 \times 10^{-5}$ Torr then an interlock will be triggered, and the system will turn off. Ideally, the chamber is loaded the morning of the day before deposition so that it has at least a full day to pump down to $1 \times 10^{-6}$ Torr. Achieving a lower pressure reduces the number of contaminants in the chamber that could end up in trace amounts in
the deposited film. During film growth, the sample stage is rotated so that the deposited film is uniform in thickness across the wafer. The growth conditions are displayed in the table above in table 3.5.

Each device was fully submerged in acetone in a glass dish for at least 3 hours. Some samples required an acetone rinse using a squirter bottle to mechanically remove residual Cu left over from the lift-off when removed from the glass dish. Samples were then submerged and swirled in De-I water in the glass dish. Samples were then rinsed in De-I water using a squirter bottle to mechanically remove any residual Cu and dried with flowing N₂ gas. Finally, samples were placed on a hotplate at 110°C for \(\approx 1\) minute to evaporate any residual De-I water on the wafer.

### 3.1.3 Direct Laser writing

Photolithography using a photomask during the exposure step has a lower limit for features sizes of approximately \(1\) µm. Using a laser to directly write the pattern on the resist is an alternative way to exposing the resist to UV light that has passed through a patterned photomask. In this research I have been able to achieve \(3\) µm feature sizes using a photo plate and mask aligner. Using the direct laser writer we aim to achieve sub \(3\) µm feature sizes.

Laser writing was conducted at Callaghan Innovation using a Microtech Laser-Writer LW405 seen in Figure 3.11, which has a lower limit of \(0.7\) µm feature size. Writing to a 3” wafer takes approximately 15 hours therefore I typically set up the equipment to write overnight. This means that the throughput of using the laser writer to pattern the electrodes is less compared to that of using Electron Beam Lithography and UV Photomask exposure.

UV flood exposure is required for one step in the PL recipe for direct laser writing as well as the T-profile recipe mentioned earlier. Completing some of the PL recipe at Kelburn using the mask aligner then travelling with the sample out to Gracefield was deemed unnecessary as there is another option for UV
3.1. DEVICE FABRICATION

Figure 3.11: Microtech Laserwriter set up at Callaghan Innovation.

flood exposure at Callaghan Innovation. A KLOE UV-KUB 2 seen in Figure 3.12 was used to provide UV to flood expose wafers at a maximum of $40 \text{mWcm}^{-2}$ at 365nm. The intensity output is much larger than the Karl Suss mask aligner used at VUW, therefore the intensity needed to be scaled to $9.0 \text{mW/cm}^{-2}$ or the exposure time decreased. Rather than a using a short burst of high intensity light, scaling the intensity of the light output was chosen as this was more like our earlier PL experiments.

**Recipe for direct laser writing:**

1. Clean wafer by rinsing in Acetone/IPA/De-I water, then dry with $N_2$ and place on hot plate set at least 100 °C to boil off any residual water.

2. Spin coat undiluted AZ5214E photoresist.

3. Speed 500rpm ramp 100rpm/sec for 5sec.

4. Speed 8000rpm ramp 4000rpm/sec for 40 sec.
CHAPTER 3. EXPERIMENTAL METHODS

Figure 3.12: The KLOE UV-KUB 2 UV used for flood exposing the photoresist coated wafers at Callaghan Innovation.

5. Speed 0rpm ramp 4000rpm/sec for 2.0 sec. Achieves 1um thick photore sist.

6. Soft baked at 110 °C on vacuum hotplate for a total of 50 sec. Remove to room temperature.

7. Load wafer into laser writer.

8. Complete alignment of wafer. Three alignment marks with known positions are chosen from the initial Cu contact deposition. These position are (16350 µm,16350 µm), (16350 µm,-16350 µm) or (-16350 µm,16350 µm), and (-16350 µm,-16350 µm) as these correspond to the outer most alignment marks on the wafer (giving the best correction for a rotated wafer or any change in height across the wafer).

9. Expose high resolution images require the following conditions:

10. Lens 5 high res. 1% filter, dimmer 10%, gain (about 1.29mW), D-step 2, overlap set to 0%, height of lens above wafer is approximately 2170 µm. These conditions correspond to an exposure dose of $5.75 \times 10^{-5} \text{mJ} \mu\text{m}^{-2}$. 
11. Reversal bake on vacuum hotplate at 122°C for 2 minutes. Critical step – need to be consistent. Let temperature stabilise with vacuum on before placing wafer on.

12. Flood expose wafer in KLOE UV-KUB 2 at 5.8mW/cm$^{-2}$ for 60sec. This corresponds to approximately 15% of the intensity of the max output of 40mW/cm$^{-2}$.

13. Develop for 60 seconds in fresh AZ726 developer at 21°C. Inspect wafer under optical microscope or SEM.

### 3.1.4 Electron beam lithography

Electron beam lithography (EBL) is a maskless form of lithography that applies a focused beam of electrons to expose any custom shape on electron sensitive resist. EBL can direct write custom shapes and patterns with sub 100nm resolution, unlike PL which is typically limited to 1 $\mu$m size features. However EBL, like PL requires the substrate to be spin-coated with a resist (EBL resist is electron-beam sensitive, whereas PL resist is photo-sensitive), baked at a high temperature for some time, exposed, and developed.

EBL patterning tends to have a much lower throughput than PL as each individual point and/or line in the pattern is exposed by a focused electron beam which may take may hours depending on the complexity of the pattern. PL has a much higher throughput as we can expose the entire resist covered substrate through a mask in one step.

EBL is an interesting technique to use for my research due to the ability to pattern very small features sizes. For example, in Cu at 300K the spin diffusion length is on the order of 100s of nm[71]. Assuming the minimum separation that can be achieved by PL between electrodes is $\approx 1\mu$m, then the polarisation of the diffusive spin current has reduced by $e^{-3.33}$ when they arrive at the second electrode. This is a reduction of the spin polarisation to $\approx 3.5\%$ of the injected value at the interface. Therefore, reducing the distance between electrodes will increase the polarisation of the spin current arriving at the second electrode.
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EBL is a good option for reducing the distance from \( \approx 1\,\mu m \) to a practical limit of sub 100nm.

EBL work was conducted at the University of Canterbury Nanofabrication lab using a RAITH 150 seen in Figure 3.13, which has a resolution lower limit of 50nm, writing field of up to 10 \( \mu m \). Electron beams were produced using field-assisted thermionic emission utilizing the Schottky effect, which occurs when a strong electric field is applied to a heated metal. Thermal electrons are emitted from the metal due to a decrease in the potential barrier caused by the applied electric field.

EBL Recipe.

1. Clean wafer by rinsing in Acetone/IPA/De ionised water, then dry with \( N_2 \) and place on hot plate set at least 100 \( ^\circ C \) to boil off any residual water.

2. Spincoat PMMA (5.6 \% low molecular weight) at 4000rpm for 1 minute.

3. Bake the entire wafer at 170 \( ^\circ \)Celsius for 30 minutes.
3.1. DEVICE FABRICATION

Figure 3.14: Schematic of the mushroom-like shape formed when spincoating a high molecular weight resist on top of a spin coated low molecular weight resist

4. Spincoat PMMA (2.56% high molecular weight) at 4000rpm for 1 minute.

5. Bake the entire wafer at 170 °Celsius for 30 minutes.

6. Load wafer into EBL and expose

7. Develop in 1:3 MIBK:IPA for 30 seconds at 22 °Celsius. Methyl isobutyl ketone (MIBK)

General notes: Spincoating two layers of PMMA of different molecular weights allows to change the shape of the region of exposed PMMA. Spincoating a low molecular weight resist, then a high molecular weight resist will result in a mushroom-like shape as seen in Figure 3.14 with an undercut after the development step.

EBL pattern design

Electrode pattern seen in Figure 3.15 was also designed using Layout Editor (similarly to the photomasks used for PL). Initially, the device aspect ratio was chosen to scale that of successful Cu/Py Non-local spin valves (NLSV) fabricated at Kyoto University. Here, the aspect ratio simply means the ratio between the widths and lengths of features is conserved. However, this was not compatible when patterning the bottom contact layer using PL as the electrodes would not overlap the Cu contact pads if the Kyoto aspect ratio is conserved. Instead, the relative geometry of the two electrodes in the Kyoto design was conserved, but the vertical and horizontal dimensions changed so that the ends
of each electrode overlapped a Cu contact.

![Figure 3.15: Schematic of the device drawn in Layout Editor. Yellow areas show Cu contact pads and green areas show REN electrode areas.](image)

Each electrode was drawn individually so that the gap size between each electrode is \( \text{gap} = (800, 400, 200) \text{nm} \). The size of this gap in a fabricated device was measured by scanning tunneling microscopy (SEM), the closeness of the size to the nominal distance will determine whether the EBL conditions need to be changed in future iterations. Typically, we would consider changing the EBL dose applied before evaluating development time, resist thicknesses, baking temperatures and times.

It is important to note that there is the difference between the physical meaning of the gap size and the length between electrodes as used in the theory section. This is to remind the reader that the \( 'L' \) used in the spin diffusion equations A.3 is taken as the distance between the midpoint of the conduction
channel/electrode interface, not the edge of the electrode (which is how I have defined the electrode gap) in Figure 3.15.

3.2 Device Characterisation

3.2.1 X-ray diffractometry

X-ray diffractometry (XRD) was employed to characterize the crystallographic phases present in the thin films. XRD principles are well understood and a detailed explanation of the important principles can be found in the textbook “Solid State Physics” by Ashcroft and Mermin [48]. XRD was performed at Callaghan Innovation using a Bruker D8 Advance with a cobalt K alpha x-ray source with wavelength 1.789 Å. The samples measured using XRD were un-patterned REN thin films with an area of several cm$^2$ grown on a piece of Si or Sapphire placed in the MBE system during the growth of the spin injection devices. The non-local spin valve devices were not used in XRD due to the ferromagnetic electrode size being too small to accurately place in the path of the emitted x-rays.

1. First, a fast (2θ) sweep is performed from 20 – 110 degrees in increments of 0.5 degrees to estimate the (2θ) peak position of the substrate peak and any film peaks.

2. Once the position of the substrate peak is identified we perform a rocking curve around this peak to calculate any offset between the plane of the film and the emitter and detector arms.

3. The offset is calculated as offset = $\frac{(2\theta)}{2} - \omega$. Where $\omega$ is the measured rocking curve angle. It is added to the tube/emitter angle (which is described in $\omega$ angles) when performing a $\theta/2\theta$ sweep.

Example of an offset calculation: Rock angle (2θ) = (27.325)° (the (2θ) angle that we rock about), max peak angle (2θ) = (12.943)°. ∴ offset = $\frac{27.325}{2} - 12.943 = 0.675$. 
0.675 is then subtracted from the Tube angle ($\theta$) for an offset corrected ($2\theta$) sweep. Therefore, a scan from 20 - 110 degrees would require the Tube angle to be set to $10 - 0.675 = 9.325 \theta$.

### 3.2.2 Optical microscopy

Device features were inspected by optical microscopy at each of the following steps in the photolithography as seen in Figure 3.16: Post-development, Post-deposition, post-lift-off when using the dark field photomask and the lift-off procedure. Post-development, post-milling, post-lift-off when using the light field photomask and the ion milling procedure.

![Figure 3.16: The different stages of lithography.](image)

(Top left) - 3 $\mu$m conduction channel structure: after development of the photoresist (the remaining photoresist is gold coloured). (Top middle) - 3 $\mu$m conduction channel structure: after Cr/Cu deposition. (Top right) - 3 $\mu$m conduction channel structure: after lift-off. The deposited Cr/Cu is gold coloured. (Bottom left) - post-lift-off of a 10 $\mu$m conduction channel device patterned using the light field photomask and T-profile recipe. (Bottom middle) - post-lift-off of an 8 $\mu$m conduction channel device patterned using the light field photomask and T-profile recipe. (Bottom right) - post-lift-off of a 3 $\mu$m conduction channel device patterned using the light field photomask and T-profile recipe.
3.2. DEVICE CHARACTERISATION

3.2.3 Spin injection measurement system

Characterization of the electrical properties of the device is achieved by using the Physical Property Measurement System (PPMS) seen in Figure 3.17, a Quantum Design instrument available at the Robinson Research Institute in Gracefield, Lower Hutt. The PPMS allows us to perform experiments on the device using magnetic fields up to 9 Tesla, and at temperatures between 2K and 400K.

![Figure 3.17: The Quantum Design PPMS used in this work.](image)

Figure 3.17: The Quantum Design PPMS used in this work.

![Figure 3.18: Channel two is shown inside the red box. Channel three is shown inside the orange box. Here the breakout box is configured to measure two-point magnetoresistive measurements through contacts twelve and thirteen. Currently switches twelve and thirteen are in the up position meaning they are connected to a 10k resistor and ground (shown in the green box). Both switches need to be in the down position to connect the device to the PPMS.](image)

Figure 3.18: Channel two is shown inside the red box. Channel three is shown inside the orange box. Here the breakout box is configured to measure two-point magnetoresistive measurements through contacts twelve and thirteen. Currently switches twelve and thirteen are in the up position meaning they are connected to a 10k resistor and ground (shown in the green box). Both switches need to be in the down position to connect the device to the PPMS.

The four terminal lateral non-local (4T LNL) measurement relies on applying a current through one path in the device and measuring a voltage across a
Figure 3.19: (Top) – Keithley 6220 precision current source used to apply current through the device. (Middle and bottom) – Keithley 2182A nanovoltmeters used to measure the change in voltage between two contacts in a device.

different pair of electrical contacts. The measured voltage is outside the path of the current shown in Figure 3.21. A Keithley 6220 precision current source and a Keithley 2182A nanovoltmeter are used to conduct electrical measurements. Additionally, the use of a breakout box allows us to change the electrical connections on the device without having to warm the PPMS chamber to room temperature to remove the sample. The applied current, applied magnetic field, and temperature are all controlled via a LabView program. This setup was developed by a previous student [67].

To make the four terminal lateral non-local measurement (4T LNL) we require the use of a PPMS (Figure 3.17), current source (Figure 3.19), nanovoltmeter (Figure 3.19), breakout box (Figure 3.18), resistor box (Figure 3.20), and a LabView program. The use of a rotator rod allows us to change the angle of the sample relative to the field, providing a full 360 degrees to work with. Although we are mostly interested in applying the field in the plane of the sample, and sometimes field out of plane.
3.2. DEVICE CHARACTERISATION

Figure 3.20: The resistors connected in series to the PPMS. When the switch is set to ‘short’, there is no electrical connection between the device and the PPMS. The switch is then changed to the ‘measure’ position with both variable resistors set to $20k\Omega$ so that any built up potential can dissipate through these. The variable resistors are then slowly tuned down to $0\Omega$ so that there is an electrical path from the PPMS to the device with no additional resistors in between.

A Keithley 6220 precision current source is used to apply current through one of the electrodes and out through the conduction channel. Keithley 2182A nanovoltmeter is used to measure changes in voltage across the second electrode and other end of the conduction channel. This voltage measurement is outside the path of the current applied by the current source.

A breakout box is used to easily change the contact connections the current source and nanovoltmeter without having to warm the PPMS to room temperature in order to reconfigure the electrical contacts. This saves approximately one hour while we are required to wait for the PPMS to warm, then stabilise at room temperature. The resistor box is set up in parallel between the PPMS and the device. The resistor box allows us to dissipate any floating potential energy in the circuit without damaging the device.

A LabView program is used to send commands to the PPMS, current source, and nanovoltmeter, as well as receive information back such as the applied field, field sweep rate, temperature, applied current, measured voltage. The program
allows us to define the number of measurements to be made at each temperature to then be averaged. It is typical to make twenty measurements and average these together to reduce the effect of electrical noise in the measurement. Reducing the electrical noise is important when measuring voltages in the nano and pico amp range, where the noise can be on the same order of magnitude as the measured device response.

Samples were attached to a standard PPMS rotator puck by applying a small amount of GE varnish (used here as an adhesive) to the back of sample – top of puck interface. Electrical connections were made between the contact pads on the sample and the contacts on the PPMS puck using the wire bonder.
3.2. DEVICE CHARACTERISATION

3.2.4 Wire bonding

To make electrical contacts between the device and PPMS, wire bonds were made between the device and small PPMS puck that can be loaded into the PPMS. Before making the wire bonds, the devices are fixed to a PCB puck with a small amount of GE varnish. The sample is then left under a hot visible light lamp for at least 45 minutes to ensure the device is stuck well to the PCB puck. Device contacts are connected to the PCB puck contact pads via bonding wire. The bonding wire used is made of Alsil of 1.25mm diameter. The wire bonder used is the Quikbond based at Robinson Research Institute seen in Figure 3.22. The wire is bonded to the contact pucks by fast mechanical pressure and ultrasonic energy, also known as wedge bonding. This is explained in Figure 3.23. Wire bonds are made to Channel 2 and Channel 3 contact pads on the puck as shown in Figure 3.24, and are allocated 4 contact pads each and correspond to measured voltage or applied current.

Figure 3.22: The Quikbond wedge wire bonder used to bond device to contact puck.

The small dimensions of the devices mean that they are sensitive to damage when being handled, as well as from static shocks. Therefore, the integrity of the
electrical contacts is tested several times while preparing a device for measurement. First, the resistance of each pair of contacts is measured in each possible permutation (i.e. resistance between pad 1 and pad 2, pad 1 and pad 3..., pad 5 and pad 6) on the device using a multimeter. The same method is then repeated but the measurement is taken across the pads on the PCB puck to note if there has been any change in resistance after the wire bonds have been made.

Figure 3.23: Schematic of the wire bonding process. (a) Position of first bond is determined and approached. (b) A combination of mechanical pressure and ultrasonic energy is applied to bond the wire to the contact. (c) Wire bonder head is moved away from the contact leaving the wire bonded to the contact. Steps (d) and (e) identical to (a) and (b), but instead performed to make the second bond. (f) The bond is terminated. Adapted from [72].

The PCB puck with device is then mounted to the rotator rod of the PPMS, which allows us to change the angle of the device relative to the applied magnetic field. This allows us to explore both out of plane and in plane applied field environments.

Once the device is loaded into the PPMS rotator and inserted into the PPMS
3.2. DEVICE CHARACTERISATION

Figure 3.24: A sample that has been stuck to a puck with GE varnish. Contact pads on the device have been wire bonded to several pads on channels two and three. Nothing is bonded to the thermal channel (channel 1).

sample space, a third resistance check is performed on the device through the breakout box connected to the PPMS resistivity channels. Using the breakout box shown in the figure 3.18 we can see which channels correspond to each contact pad on the device. The device current paths are as small as 1 µm in width, therefore care must be taken to avoid ‘burning out’ the channels by passing through a large current density. An upper limit of applied current was set to 15 µA to avoid destroying devices. This corresponds to a current density of $9.09 \times 10^3 \, Acm^{-2}$. This upper limit was chosen because we had destroyed multiple devices at applied currents that exceeded this.

\[
P = I^2R
\]  
\[
P = (1 \times 10^{-6} \mu A)^2 \times (1 \times 10^6 \Omega)
\]  
\[
P = 1 \times 10^{-6} W
\]

Using a handheld multimeter to measure resistances through contact pads applies an unknown current that may destroy a device. An example of a damaged device is shown in Figure 3.25. To overcome this, the multimeter was connected to the resistor box. The current path between the multimeter terminals was short out across a 100 Ω resistor. When the circuit is switched from the ‘short’
position to the ‘measure’ position, the current then passes through a 20 k \( \Omega \) variable resistor which is then connected to the device. Any potential difference between the multimeter plus connected circuit and the device being dissipated through the device causing damage. The variable resistors are then carefully reduced to the minimum resistance converging to zero. Resistance through the device can now be measured safely.

### 3.2.5 LNL measurement - test devices

Devices fabricated at Kyoto University were used as test samples to ensure the lateral non-local measurement set up could detect a spin current. These devices were made with Cu conduction channel and Permalloy ferromagnetic electrodes. Before loading the samples into the PPMS, the electrical resistances through each pathway was measured (Table 3.6 and Figure 3.26). Then these same pathways were measured again after the sample is loaded in the PPMS via the breakout box.

A 15 \( \mu \)A current is applied through the device as a magnetic field is swept between [-1000 Oe, 1000 Oe] at several different low temperatures between [4K,300K]. Each measurement is repeated twenty times and then the mean is taken across all measurements. This is to reduce the effect of noise in measurement. In Figure 3.27 we see clear evidence of the magnetic switching of the two Py electrodes. On the down sweep (red data) we see the first electrode begin to change its magnetisation at -200 Oe and enter the anti-parallel state. The size of the change in measured voltage is approximately -0.058 nV compared to the baseline around 0 nV. Both electrodes enter the parallel state just below -750 Oe as the data returns close to the baseline of 0 nV. Similarly, on the up sweep when the magnetisation
3.2. DEVICE CHARACTERISATION

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Terminal</th>
<th>Resistance measured with multimeter</th>
<th>Resistance measured through breakout box</th>
</tr>
</thead>
<tbody>
<tr>
<td>V+</td>
<td>V-</td>
<td>1.414 k Ω</td>
<td>1.413 k Ω</td>
</tr>
<tr>
<td>V+</td>
<td>I+</td>
<td>0.883 k Ω</td>
<td>0.882 k Ω</td>
</tr>
<tr>
<td>V+</td>
<td>I-</td>
<td>43.3 Ω</td>
<td>46.6 Ω</td>
</tr>
<tr>
<td>V-</td>
<td>I+</td>
<td>2.252 k Ω</td>
<td>2.248 k Ω</td>
</tr>
<tr>
<td>V-</td>
<td>I-</td>
<td>1.414 k Ω</td>
<td>1.413 k Ω</td>
</tr>
<tr>
<td>I+</td>
<td>I-</td>
<td>0.881 k Ω</td>
<td>0.880 k Ω</td>
</tr>
</tbody>
</table>

Table 3.6: Table of measured resistance through the Kyoto device. Measured resistances show that there is negligible change in the sample during the wire bonding and loading stages.

of the second electrode changes at -200 Oe, the size of the change in voltage is approximately -0.048 nV compared to the baseline around 0 nV.

The shape of these transitions is indicative that a spin-current has been measured, and that the experimental set-up can produce good results. Data has been transformed so that the baseline of each set of data sits around 0 nV. This was done by fitting a first order polynomial to regions that are low noise and relatively linear (e.g. the blue curve region between [-900,-250]Oe). The constant term of the polynomial is then used to shift the data to 0 nV so the reader can easily identify the magnitude of the change in voltage when switching occurs.

Future work should include using the same experimental set up to evaluate a lateral non-local device incorporating the RENs as ferromagnetic electrodes. Such a device can now be easily fabricated as shown earlier in this work. I have also shown that the home-made breakout box measurement system and complimentary LabView program is working and it is possible to measure a spin polarised current at the detector electrode of a device.
Figure 3.26: Microscope image of the Kyoto device. Yellow areas are Cu channels, Green areas are the Py electrodes, and the purple background is the Si substrate. Current was applied through one of the ferromagnet electrodes and passed out through one side of the Cu channel. Change in voltage was measured across a secondary electrode and the other side of the Cu channel.
Figure 3.27: LNL measurement on a Kyoto sample. 15 $\mu$A current is applied through the device at 5K. Red data is down sweep where the initial applied field is set to 1000 Oe, then swept to -1000 Oe at 5 Oes $^{-1}$. Similarly, the blue curve represents the up sweep from -1000 Oe to 1000 Oe. The displayed data is the mean of twenty repeated measurements.
Chapter 4

Results and Discussion

Results from this work will be presented similarly to the order of items in the experimental section. First, there will be a presentation of the results of fabricating a lateral non-local geometry incorporating rare-earth nitrides via the methods of photolithography using a mask aligner, Ar-assisted ion milling, direct laser writing, and electron beam lithography. The second stanza will focus on the characterization of these devices and testing of the home-made spin injection and detection system on a GdN spin injection device successfully fabricated using photolithography and direct laser writing.

4.1 Advances in Device Fabrication

The following section is focused on the developments made in the patterning and fabrication of a REN based spin injection device. As discussed in the experimental methods section, several unique methods were employed to find the best way to fabricate this device. These include mask aligner-based photolithography and lift off, Ar—assisted ion milling, direct laser writing in conjunction with photolithography, and EBL. Devices were successfully fabricated using a combination of mask aligner-based photolithography for electrical contacts, and direct laser writing for making GdN based ferromagnetic electrodes. Surprisingly, there was enough time remaining at the end of this project to attempt to measure these devices with our LNL measurement system. Unfortu-
nately, the LNL measurement was not able to successfully be carried out due fragility of these devices as they were damaged by applying too much current through the device contacts. However, consistent devices are now able to be fabricated with improvements made on the previous work by K. Pitman [67] such as small device dimensions and sharp features achieved by laser writing. Additionally, for the first time ever, EBL has been used in the patterning of REN based thin film. Although some work is needed to be done to achieve a working device.

4.1.1 Devices produced by photolithography and lift-off

Each of the 10 \( \mu \text{m} \), 8 \( \mu \text{m} \), and 3 \( \mu \text{m} \) conduction channels were able to consistently be fabricated across each wafer when using the mask aligner. The development time had to be adjusted slightly for each wafer since sticking to the recipe defined time often resulted in under-development (Table 3.3). Therefore, wafers were placed in developer for however long they needed to become fully developed. This could range from three to five minutes. After development, the patterns were viewed under a microscope. If the pattern was underdeveloped, the wafer would then go through an additional development step for thirty to sixty seconds, then inspected under the microscope again.

Conduction Channel resistances

The electrical resistance through the conduction channel of each device was tested throughout the fabrication process to identify if any one step could damage the device (Table 4.1). It should also be noted (not shown here), that as the photolithography process was practiced and refined, the resistance through the conduction channel was smaller in the newest fabricated samples compared to the first fabricated samples. This shows important of obtaining well defined features to ensure good device performance.

Further improvements could be made by reducing the width of conduction channel further down to 1.5 \( \mu \text{m} \). Reducing the feature sizes would mean the contact pad layer would be more compatible with the small distance between
4.1. ADVANCES IN DEVICE FABRICATION

<table>
<thead>
<tr>
<th>Conduction channel width</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm</td>
<td>28.2 ± 2.6</td>
</tr>
<tr>
<td>8 µm</td>
<td>39.6 ± 5.0</td>
</tr>
<tr>
<td>3 µm</td>
<td>52.3 ± 5.0</td>
</tr>
</tbody>
</table>

Table 4.1: Conduction channel resistances for samples fabricated via photomask photolithography.

electrodes that is required to measure a strong presence of a spin polarised current, particularly when considering the hybrid method employing EBL. This would require the manufacture of a new photomask with the new feature sizes designed in layout editor.

4.1.2 Ion milled devices

Applying the ion milling method to fabricate devices has been somewhat successful. In figure 4.1, we see that we can fabricate the Cu contact pad layer using the ion milling method. The ion mill method offers high sample yield as we can mill up to a four-inch wafer in one step. However, it is clear in the left image of Figure 4.1 that the sharpness of features is not as good as the features fabricated using the photomask method. However, the conduction channel here is still well formed. The 8 µm channel forms well, however it is not as sharp as the 8 µm channels fabricated using the photomask method. Additionally, the 3 µm channel does not always form for all samples on the wafer as we can see the conduction channel features in the right image of Figure 4.1 are very thin and rough.

We have seen that using the light field mask with the image reversal mode of the photoresist has not produced continuous and well-formed conduction channels in Figure 4.1. To check the quality of the conduction channel features, resistance is measured through the conduction channel. We can compare the measured resistances here with the resistances measured through devices made with the photomask method. If the measured resistances are close to those mea-
sured in the photomask method, then both methods can be considered good ways to form sharp features. However, if the resistances of samples made via ion milling are much larger than the resistances measured on samples made by the photomask method, then we can attribute this to the poor sharpness of features observed in the microscope images.

Figure 4.1: Cu deposited patterns post ion milling and lift-off. (Left) - 10 µm channel using ion milling and image reversal mode. Gold areas show copper contact pads. (Middle) - 8 µm channel using ion milling and image reversal mode. Gold areas show copper contact pads. (Right) - 3 µm channel using ion milling and image reversal mode. Gold areas show copper contact pads.

Conduction Channel resistances

The following table shows the electrical resistances measured through the conduction channels post ion milling (Tables 4.2 and 4.3):

<table>
<thead>
<tr>
<th>Channel Width (µm)</th>
<th>10 µm</th>
<th>8 µm</th>
<th>3 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>111.5 Ω</td>
<td>280.1 Ω</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>112.8 Ω</td>
<td>347.2 Ω</td>
<td>-</td>
</tr>
<tr>
<td>1c</td>
<td>111.6 Ω</td>
<td>248.1 Ω</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2: Conduction channel resistances for TB Dev 02, which was fabricated using ion milling and lift-off.
4.2. PATTERNING OF SPIN INJECTION AND DETECTION ELECTRODES

<table>
<thead>
<tr>
<th></th>
<th>TB Dev 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm</td>
<td>1a 99.7 Ω</td>
</tr>
<tr>
<td>8 µm</td>
<td>2a 220 Ω</td>
</tr>
<tr>
<td>3 µm</td>
<td>3a 1752.0 Ω</td>
</tr>
</tbody>
</table>

Table 4.3: Conduction channel resistances for TB Dev 03, which was fabricated using ion milling and lift-off.

The resistance of 10 µm wide conduction channels is consistent across either wafer. The mean resistance of 10 µm wide channels in TB Dev 02 is 112.0±0.3 Ω and in TB Dev 03 is 102.0±1.0 Ω. The mean resistance of 8 µm wide channels in TB Dev 02 is 291.8±24.8 Ω and in TB Dev 03 is 203.8±17.6 Ω. Therefore, we can conclude the ion milling method of fabricating our devices can yield 10 µm conduction channels with consistent resistances. However, we cannot claim that the 8 µm and 3 µm channels would produce similar results without further improvement of the image-reversal PL recipe. Future work with ion milling should instead use a dark field photomask with the T-profile PL recipe used in the lift-off method.

4.2 Patterning of Spin injection and detection electrodes

4.2.1 Direct Laser writing

Discussed here is a method of laser writing for patterning the REN electrodes. The goal of this section of research was to optimize the laser written features so that they matched the CAD design shown in the experimental section such that we achieve micron sized features and endeavour to make sub-micron features. This means achieving the desired electrode size, position and separation as well as developing a method for pushing feature size to submicron. All laser written photolithography was conducted on wafers with pre-patterned Cu electrodes.
and conduction channel. In Figure 4.2 we see that areas with pre-patterned Cu tend to have residual photoresist borders around newly patterned features. This is due to a slight over-development of the areas of photoresist around the electrode holes. Due to a longer development time, the photoresist becomes thinner in these areas.

Figure 4.2: Here the pattern is offset from the centre point of the conduction channel due to poor laser writer alignment. Alignment marks used lie at (-16350 µm, 16350 µm), (-16350 µm, -16350 µm), and (16350 µm, 16350 µm), near the outer most large Cu pads. There is evidence of overdeveloped residual photoresist on the outside of the electrode patterns when on top of the Cu areas, but not over the substrate.

Initially it was thought that the outermost alignment marks of pre-patterned Cu should be used as this would create the largest alignment area over which any rotation or tilt in the wafer could be corrected for. Included in the contact pad pattern are small square pads that are used as reference marks so that subsequent patterns can be aligned on top. The outermost alignment marks were positioned at (-25000 µm, 25000 µm), (-25000 µm, -25000 µm), (25000 µm, -25000 µm), and (25000 µm, 25000 µm), where any three points could be chosen to align to. In practice however, it proved difficult to align to these positions within 1 µm as the laser writers stepping motor could only move at a minimum of 1 µm.
4.2. PATTERNING OF SPIN INJECTION AND DETECTION ELECTRODES

Instead it was typical to have an alignment that was less than a micron distance from the desired alignment mark. As shown in Figure 4.2 we see that even submicron misalignment at the outer edges of the wafer meant several micron misalignments for a wafer central device.

Figure 4.3: Optical image of electrode pattern before deposition of GdN taken at 100x magnification. The conduction channel is measured as 8.78 µm slightly wider than the nominal 8 µm width. The distance between electrode is measured as 1.00 µm over the substrate and is expected to be submicron above the conduction channel. Measurement was not taken over the conduction channel due to pixel size limitation.

To overcome this, the writing step was broken into ten independent writing stages. Each of the nine individual devices would be written separately, during which each I would align to marks belonging to each individual device. The tenth writing step used a larger spot size laser to cover the rest of the wafer faster than the small spot size laser used for the fine details. This tenth writing step was later replaced by using a 0.9mm thick stainless-steel shadow mask with 1mm holes at the position of each device to be used during the GdN deposition. Since each writing step takes two hours, replacing one writing step with the shadow mask improved the throughput of device fabrication.
CHAPTER 4. RESULTS AND DISCUSSION

Writing each individual device means that the alignment area required is much smaller. For example, the alignment marks used for device 1a (the top left device on any wafer) have positions (-16350 µm,16350 µm), (-16350 µm,7650 µm), and (7650 µm,7650 µm). This corresponds to a writing area of 8700×8700 µm² compared to alignment across the wafer which has a writing area of 25000×25000 µm², which greatly improves the accuracy of electrode placement. However, this does mean that nine separate alignment steps need to be taken instead of just one.

In summary, three iterations were made to the writing technique:

1. Alignment was made to the outermost reference marks. Resulting in a slightly misaligned patterned.

2. Alignment of each device using its own alignment marks closer to the device compared to marks across the entire wafer.

3. The addition of a shadow mask to speed up the process and replace the final writing step.

In Figure 4.3 we see an optical image of pattern produced by laser writing. Aligning to individual devices improves the alignment and features are within some submicron distance of their desired position as defined in the CAD drawing. Again, we see the areas of over-developed photoresist enveloping the patterned electrodes only on areas where there is Cu present. The electrode shaped areas contain no photoresist and are just holes where the GdN will be deposited and remain after lift-off. There is a wall of photoresist that separates the two electrode holes with thickness of one micron. We see that the width of this wall is smaller when on top of Cu areas compared to the 1 µm reference. This is ideal since a spin current will need to travel less than the nominal 1 µm distance to reach the detector, which implies a larger signal measured.

Future work could include attempting to reduce the thickness of the photoresist wall. It is possible to reduce the 1 µm wall width further by slightly
Figure 4.4: Here we see a pair of lines at the edge of the electrode holes. These pair of lines mean there is an undercut present near the edge of the photoresist. The extra inner line is evidence of an area of photoresist that is thinner than the rest of the outer photoresist.

reducing the exposure power and developing the wafer for slightly longer (images not shown here). In this case, the developer will remove slightly more of the photoresist wall thus reducing the final width. Wall width should be checked by SEM instead of with an optical microscope as we see that we are already reaching the limit for this equipment in Figure 4.3 where the 1 μm gap is already difficult to see.

4.2.2 Electron beam lithography

EBL is a commonly used technique to fabricate spin injection devices, allowing for submicron features typically 100nm to 500nm. Initial EBL patterning was
conducted on a test wafer of Si with SiO₂ top layer of 200nm, and pre-patterned copper contacts. Figure 4.5 shows the electrode pattern post-development. The areas where the REN electrodes will be deposited appear light in colour as they are regions where there is no PMMA left, so the gap between the electrodes is a wall during this step.

Figure 4.5: SEM image of the electrode device area where the nominal electrode separation is 800nm. (Left) - shows the electrodes (outlined in blue) are well separated by a visible straight edge wall of PMMA imaged at 10kV. There is a slight misalignment of the electrodes to Cu contact layer, but there is sufficient overlap between the layers (from which an area can be calculated). (Middle) - shows the width of the PMMA wall between the electrode gap imaged at 5kV. (Right) - shows the width of the PMMA wall between the electrode gap imaged at 10kV.

The EBL pattern is shifted vertically, as seen in Figure 4.5, and it does not sit squarely on top of the bottom copper electrodes, but can still be used as a device as there is some overlap between the bottom Cu contacts and the hole in the PMMA. The overlap should look identical to the pattern designed in Layout editor; however the poor overlap we see here is due to a slight misalignment of
4.2. PATTERNING OF SPIN INJECTION AND DETECTION ELECTRODES

In Figure 4.5 we see that the nominal width of this wall is 800nm, but the SEM measured width is close to 600nm. Similarly, in Figure 4.6, we see the nominal width of the wall is 400nm, but the real width is closer to 200nm. The trend continues in Figure 4.7, where the nominal wall width is 200nm, but the real width is approximately 100nm over the substrate areas with no Cu contacts, but much less (approximately 50nm) when on top of the Cu contact conduction channel.

Figure 4.6: SEM image of the electrode device area where the nominal electrode separation is 400nm. (Left) - shows the electrodes are well separated by a visible straight edge wall of PMMA at 10kV. There is a slight misalignment of the electrodes to Cu contact layer, but there is sufficient overlap between the layers (from which an area can be calculated). (Middle) - shows the upper region of the two well separated electrodes imaged at 10kV. There is a slight ‘rounding’ of the edge of the square electrode, but this is not expected to affect the device performance. (Right) - shows the real width of the PMMA wall between the electrode gap imaged at 10kV.
It is interesting to note that in Figure 4.7 (right), we see the PMMA wall curves laterally and decreases in width as it passes over the Cu conduction channel from the substrate only regions.

Figure 4.7: SEM image of the electrode device area where the nominal electrode separation is 200nm. (Top left) - There is a slight misalignment of the electrodes to Cu contact layer, but there is sufficient overlap between the layers (from which an area can be calculated). (Top right) - shows the PMMA wall between the electrode gap curves as it passes over the Cu conduction channel at 10kV. (Bottom left) - shows the real width of the PMMA wall between the electrode gap decreases as the wall passes over the Cu conduction channel at 10kV. (Bottom right) - the PMMA wall curves at the top and bottom (not shown), so is not straight compared to the wall in Figures 4.5 and 4.6 at 10kV.

Figure 4.8 shows a second EBL pattern where the exposure dose has been increased. Increasing the exposure dose was intended to increase the real wall width such that it was closer to that of the nominal width. In Figure 4.8 we see the that the increased exposure dose has decreased the wall width by approximately 400nm. Similarly, for Figure 4.9, we see the real wall width has also decreased and we now see the curved wall that was observed in Figure
4.2. PATTERNING OF SPIN INJECTION AND DETECTION ELECTRODES

4.7. This shows that below a certain wall width (somewhere below 200nm) for certain high dose exposure, we form this curved wall instead of a straight wall. In Figure 4.9, we observe no wall has formed between the two electrode holes. This confirms that instead we should decrease the exposure dose to achieve wall widths close to the nominal. In conclusion, it is important to apply the correct dose exposure to get the correct wall width. The smaller dose applied in the first set of samples is shown to get closer to the wall width we had expected than the high dose.

Figure 4.8: SEM image of the electrode device area where the nominal electrode separation is 800nm. Here the exposure dose has increased compared to Figure 4.5. There is a slight misalignment of the electrodes to Cu contact layer at 5kV, but there is clear improvement in the alignment compared to Figure 4.5. (Right) shows the PMMA wall between the electrode gap is straight and well formed, but is approximately half the nominal width.

EBL Summary

Using EBL to pattern ferromagnetic electrodes for application in a REN based spin injection device is achievable and very promising. Measuring a larger
Figure 4.9: SEM image of the electrode device area where the nominal electrode separation is 400nm with all images taken at 5kV. (Top Left) - The PMMA wall is curved across the entire device area, but it symmetric on both the top and bottom side of the Cu conduction channel. (Top Right) - shows there is a 500nm variation in the curvature of the PMMA wall on the top side of the Cu conduction channel. (Bottom Left) shows similarly to Figure 4.6 that the width of the PMMA wall decreases as it passes over the Cu conduction channel. (Bottom right) - shows a slight broadening of the PMMA wall near the top of both electrodes.

change in potential using the 4T LNL geometry is achieved by reducing the distance the spins are required to travel diffusively to the next electrode. My work has shown that sub-micron electrode gaps can be achieved by the PL/EBL hybrid method rather easily for spin injection structure patterns.

It is clear from this work that in future work using the PL/EBL hybrid pattern method to produce spin injection devices that the exposure dose will need to be decreased so that the PMMA wall width increases towards the nominal value. However, it is shown that EBL allows us to produce very clean features with even sub 100 nm widths. This is very promising for fabricating devices
4.2. PATTERNING OF SPIN INJECTION AND DETECTION ELECTRODES

Figure 4.10: SEM image of the electrode device area where the nominal electrode separation is 200nm with all images taken at 5kV. (Left) - There is no evidence for a PMMA wall indicating the two electrodes would be in contact with each other if deposited. (Right) - higher magnification confirms there is no PMMA wall present.

with very small distances between electrodes, which is ideal for attempting to measure a strong signal from a spin polarised current in the 4T LNL configuration.

4.2.3 Device Fabrication Summary

In summary, a variety of fabrication methods have been employed to manufacture a four-terminal lateral non-local device based on using rare-earth nitrides as ferromagnetic electrodes. Using photolithography in combination with a mask aligner proved to be a high throughput method for producing consistent patterned thin films. However, this method is limited by the minimum feature size of $\approx 3 \, \mu m$ and it is desirable to reduce the size of these devices to detect a spin polarised current at the detector electrode. Additionally, the mask aligner
method lacks in the ability to rapidly change the design of the pattern as this
requires the re-design and manufacture of a new photomask. 

Incorporating Ar-assisted ion milling for device fabrication proved successful and was only hindered by the lack of quality in early photolithography outcomes. Ion milling is shown to be a fast way to pattern features on a thin film as the milling time is only eight minutes, as well as the ability to mill numerous devices simultaneously across a four-inch wafer. However, this method was not investigated further due to the high success rate of patterns produced using the previously mentioned lift-off method.

The ability to rapidly change one’s device pattern at each iteration is the main advantage of laser writing since it is only required to change the pattern in a CAD software. This means after each device is patterned, improvements can be made without manufacturing a new photomask which can be both costly and time consuming. The laser lens can be chosen to suit the desired feature size, meaning that small detailed features can be written with lens five and larger features can be written with lens three. Thus, reducing the write time of an entire wafer if we were to use just the small lens. It has also been shown that device features can be reduced to at least one micron, which is better than that achieved by the mask aligner. The disadvantage is that alignment of the laser writer to the wafer surface features can be tricky and has a rastering accuracy of \( \approx 1 \, \mu m \). Additionally, the write time for a field of \( \approx 8\text{mm} \times 8\text{mm} \) area is \( \approx \) one hour and forty minutes, which is much larger than the few seconds of exposure required for the mask aligner.

EBL is the method of choice for fabricating sub-micron features for REN based spin injection devices. Additionally, this is the first time ever that EBL has been used to fabricate a REN based spin injection device. The writing time is relatively quick compared to laser writing as we can pattern a full three-inch wafer in an hour. However, work is required to find the ideal exposure dose to achieve the nominal device features sizes. Another hindrance of this method is that the equipment is not readily available at our university, so either travel is
4.3 Device Characterization

Before the REN devices made from the best fabrication technique of photolithography and direct laser writing were tested in the LNL measurement system, some characterization of the device was carried out. This included investigating the crystal structure of the GdN films via x-ray diffractometry and measuring the resistances of the different current paths through the device via a handheld multimeter. As well as investigating the remains of the damaged REN device using SEM and EDS spectral analysis.

4.3.1 X-ray Diffraction

The crystallographic structure of the device was characterised by XRD (Figure 4.11). The film shown in figure 4.11 was grown separately to my devices, however the same growth conditions were used when growing the device as this film. Here, the GdN film was grown to 1.2k Å, at $(6 - 9) \times 10^{-6}$ mbar with a nitrogen flow rate of 1.7 sccm, where the base pressure of the UHV system was $2.0 \times 10^{-8}$ mbar. The labelled GdN peak corresponds to the (111) reflection. The peak position indicates that the GdN is conductive. This is because we expect the lattice constants to be larger when there are more nitrogen vacancies present, compared to a previously grown insulating GdN film that has a small number of nitrogen vacancies [49].

4.3.2 Device testing

Testing of devices fabricate using GdN as the ferromagnetic electrodes is discussed in this section. Electrical testing with a handheld multimeter directly to the pads of the device via the PPMS puck is conducted as well as investigation of device damage using SEM and energy dispersive x-ray spectroscopy (EDS).
Figure 4.11: $\theta-2\theta$ XRD measurement of a GdN film grown on (100) orientated Si/SiO2 substrate. The blue line shows the GdN (111) peak position. The red line shows the peak position of a previously grown insulating GdN film. Each $\ast$ corresponds to a Si substrate peak. The left most silicon peak is a known artefact produced by the XRD system in use. The middle peak is the K- $\beta$ peak of (100) orientated Si, and the right most peak is the K-$\alpha$ peak of (100) orientated Si.

GdN capped with AlN was deposited on the laser written wafers and were then lifted-off in acetone to remove the deposited material from the non-electrode areas. In Figure 4.12 we see the fully fabricated device, ready for measurement using the breakout box and PPMS. Before measuring with the PPMS each device was testing using a multimeter. This was done by measuring the resistance through each combination of device paths as shown in Figure 4.12.

The resistance measured through the conduction channel is consistent with resistances measured through other 8 $\mu$m channels throughout the fabrication process. This tells us that the fabrication process does not damage the Cu channels.
4.3. DEVICE CHARACTERIZATION

Figure 4.12: GdN electrodes in the centre of the device appear as a dark grey/blue areas when Cu is present underneath and are green when on top of the substrate. We see a clear gap between the electrodes as we see only Cu. Each pad is numbered to correspond with each outer contact pad that electrical measurements are taken from.

Very large resistances on the order of mega ohms were measured for current paths through the GdN electrodes (Table 4.4). This could be due to; poor interface between the Cu and GdN contacts burning out during the testing with the multimeter as a result of the high current density through the micron sized features, or the GdN is not as conductive as implied by XRD measurements.

The device was loaded onto the PPMS rod and a lateral non-local measurement was attempted. Unfortunately, the measured data implied that the device was no longer working and likely had an open circuit. Optical images of the device were taken after the resistance was measured to inspect the effect the measurement had on the device as seen in Figure 4.13. The Cu conduction channel
CHAPTER 4. RESULTS AND DISCUSSION

<table>
<thead>
<tr>
<th>Pads measured in device 2c (8 µm conduction channel)</th>
<th>Multimeter Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.481×10^6</td>
</tr>
<tr>
<td>2</td>
<td>36.0</td>
</tr>
<tr>
<td>2</td>
<td>0.536×10^6</td>
</tr>
<tr>
<td>4</td>
<td>0.493×10^6</td>
</tr>
<tr>
<td>4</td>
<td>1.055×10^6</td>
</tr>
<tr>
<td>5</td>
<td>1.088×10^6</td>
</tr>
</tbody>
</table>

Table 4.4: Table of electrical resistances measured through device 2c. Entries that are not included couldn’t be measured. This could be due to the resistance through these paths being too large for the multimeter to measure since measurements through the other GdN electrode is on the order of megaohms.

has burned out and there is no longer a path for current to flow here. There is clear damage to the GdN electrodes also. It isn’t clear if there is any residual GdN on the Cu pads, although we see the outline of where the electrodes should be, they appear a blue/grey colour in areas that the GdN sits directly on top of the substrate. If there are still GdN on the Cu pads, then it must be very thin since we can see the Cu underneath and some colour change that implies there is some interference occurring due to small changes in thickness. The composition of these areas can be checked using the SEMs energy dispersive x-ray spectroscopy ability, that allows the surface composition to be probed as seen in Figures 4.14 and 4.15.

The measured EDS spectra of the optically transparent area of the GdN electrode shows there is still Gd present and a small amount of N and Al. This indicates that although the electrode has broken, GdN is still present, meaning the film is somewhat intact but is very thin (as seen in the optical image).

Future device success will rely on careful consideration for measuring the electrical resistance through these stacks to avoid burning out the features. Since
4.3. DEVICE CHARACTERIZATION

Figure 4.13: A device that has been tested with a multimeter. The multimeter passes an unknown current through the device channel. The resulting current density is too high for the device and the result is the Cu conduction channel burning out, creating an open circuit device. Additionally, the GdN electrodes have been damaged as we see areas of varying colour within the electrode outline. Electrode areas on top of Cu tend to be somewhat transparent and varying thickness due to variety of reflections we see. Electrode areas on top of the substrate appear to be dark unlike the areas on the Cu pads.

The amount of current applied by a multimeter is unknown, it is recommended to control the applied current with a current source that can be finely tuned and completely remove the multimeter testing step. One could start by applying very small currents in the pico-amp and nano-amp range through the GdN electrodes whilst simultaneously measuring the voltage drop, then calculate the resistance. The lateral non-local system we use to measure a spin-current could be set-up to perform this measurement.
Figure 4.14: SEM image of broken sample showing areas where an EDS spectrum was measured. Area six (EDS spectra shown in Figure 4.15) is of most interest as this part of the electrode appeared transparent under an optical microscope.
4.3. DEVICE CHARACTERIZATION

Figure 4.15: The EDS spectra of area six shows strong evidence for the presence of Gd and a small amount of Al (belonging to the cap).
Chapter 5
Conclusions

In this work it was shown that REN based spin injection and detection devices were successfully fabricated. Four unique methods of fabrication were employed and displayed different advantages and disadvantages. These methods included: photolithography using a photomask and mask aligner, Ar-assisted ion milling, direct laser writing, and electron-beam lithography. Using a photomask and mask aligner allows for a high throughput of contact pad fabrication due to the short exposure time. Cr/Cu conduction channels that were fabricated via this method had resistances of \((28.2\pm2.6) \ \Omega\) for 10 \(\mu m\) widths, \((39.6\pm5.0) \ \Omega\) for 8 \(\mu m\) widths, and \((52.3\pm5.0) \ \Omega\) for 3 \(\mu m\) widths. However, if one wants to achieve features of below 3 \(\mu m\) or make quick iterations to the photomask design, this is not the method of choice due to the equipment’s physical limitations and slow turnaround time for photomask fabrication.

Ar-assisted ion milling showed promise for high throughput contact pad manufacture due to short time of eight minutes for the milling to be completed and the potential to mill a four-inch wafer. However, conduction channels fabricated this way had higher resistances and were less consistent than those fabricated with the lift-off plus mask aligner method. The mean resistance of 10 \(\mu m\) wide channels in TB Dev 02 is \(112.0\pm0.3 \ \Omega\) and in TB Dev 03 is \(102.0\pm1.0 \ \Omega\). The mean resistance of 8 \(\mu m\) wide channels in TB Dev 02 is \(291.8\pm24.8 \ \Omega\) and in TB Dev 03 is \(203.8\pm17.6 \ \Omega\). Additionally, the variation in resistances
measured in 3 µm wide channels varied from 314.0 Ω to 9560.0 Ω. The inconsistency and larger resistances were a result of poor lithography in the initial stages of this project, and it is not clear if it related to the milling itself. The promising advances in terms of consistency of clean features using the lift-off plus mask aligner method resulted in the ion milling method being abandoned early. However, I recommend the ion milling method to be pursued in future due to the increase the throughput of device manufacture. Future work with ion milling should instead use a dark field photomask with the T-profile PL recipe used in the lift-off method.

Direct laser writing allows changes to be made to the pattern quickly between successive iterations – a distinct advantage over the photomask method. Additionally, the ability to pattern clean consistent submicron features and ease-of-access of this machine means it was the method of choice for the GdN electrode pattern. The longest writing step was able to be removed by the addition of a shadow mask during the deposition of the GdN, thus improving the throughput significantly. However, the long write time means photomask-based methods may be preferred when the desired final iteration of the pattern has been achieved.

Electron-beam lithography proved to be the method of choice for patterning features on the order of hundreds of nanometres. This is ideal for measuring the largest possible change in voltage due to a spin-polarised current in the four terminal lateral non-local measurement geometry. However, work is required to optimise the exposure dose to achieve the desired nominal feature sizes and it may be difficult to access this equipment due to travel barriers. For the first time ever, EBL was used to pattern a REN based spin injection device as previous devices has only ever used photolithographic methods for fabrication.

The spin injection measurement system was successfully tested and shown to be capable of measuring a spin injection device fabricated at Kyoto University. A change in potential of ≈0.06 nV was measured, where the magnetic switching ≈250 Oe. Excitingly, it was unexpected that time was available near
the end of this work to measure one of REN based devices but unfortunately, they were damaged during the measurement procedure. However, this work has shown that the fabrication of a REN based spin injection device has been achieved and that the experimental setup required to measure a device is in place.
Appendix
Presented here is the full derivation of the spin injection and detection equation, and follows very close to (Takahashi & Maekawa, 2003). Consider a device comprising of a NM metal of width \( w_N \) and thickness \( d_N \) connected to two FM metal electrodes of the same width \( w_F \) and thickness \( d_F \), separated by a distance \( L \). Let’s assume that the magnetisations of both ferromagnets can either be parallel or anti-parallel.

The spin diffusion length of a typical NM metal is on the order of a micron \( \lambda_{Cu} \approx 1\mu m \), and \( \lambda_{Al} \approx 1\mu m \), and is much larger than the spin diffusion length of a typical FM metal, \( \lambda_{Py} \approx 5nm \). Therefore, we can consider \( \lambda_N \ll (d_N, d_F) \ll (w_N, w_F) \ll \lambda_F \).

The electric field \( E \) and the deviation from equilibrium of the gradient of the carrier density \( \delta n_\sigma \) determines the electrical current \( j_\sigma \) in the conduction channel:

\[
 j_\sigma = \sigma_\sigma E - eD_\sigma \nabla \delta n_\sigma \tag{A.1}
\]

Where \( \sigma_\sigma \) is the electrical conductivity and \( D_\sigma \) is the diffusion constant. We can use:

\[
 \delta n_\sigma = N_\sigma \delta \epsilon_\sigma \tag{A.2}
\]

\[
 \sigma_\sigma = e^2 N_\sigma D_\sigma \tag{A.3}
\]

Where \( N_\sigma \) is the density of states in the spin sub-band, and \( \delta \epsilon_\sigma \) is the change in the ECP of carrier from the equilibrium. Therefore:

\[
 j_\sigma = - \left( \frac{\sigma}{e} \right) \nabla \mu_\sigma \tag{A.4}
\]
Where $\mu = \epsilon + e\phi$ is the ECP and $\phi$ is the electric potential.

Now consider the continuity equations for both charge and spin:

\[ \nabla \cdot (j_\uparrow + j_\downarrow) = 0 \text{(charge)} \]  \hspace{1cm} (A.5)

\[ \nabla \cdot (j_\uparrow - j_\downarrow) = -\frac{e\delta n_\uparrow}{\tau_{\uparrow\downarrow}} + \frac{e\delta n_\downarrow}{\tau_{\uparrow\downarrow}} \text{(spin)} \]  \hspace{1cm} (A.6)

Where $\tau_{\sigma\sigma'}$ is the time taken for an electron to scatter from spin state $\sigma$ to $\sigma'$. Putting these equations together, as well as exploiting $\frac{N_\uparrow}{\tau_{\uparrow\downarrow}} = \frac{N_\downarrow}{\tau_{\uparrow\downarrow}}$, we have:

\[ \nabla^2 (\sigma_\uparrow \mu_\uparrow + \sigma_\downarrow \mu_\downarrow) = 0 \]  \hspace{1cm} (A.7)

\[ \nabla^2 (\mu_\uparrow - \mu_\downarrow) = \lambda^{-2} (\mu_\uparrow - \mu_\downarrow) \]  \hspace{1cm} (A.8)

With spin diffusion length $\lambda = \sqrt{D\tau_{sf}}$, where $\tau_{sf}^{-1} = \frac{1}{2} (\tau^{-1}_{\uparrow\downarrow} + \tau^{-1}_{\downarrow\uparrow})$ and $D^{-1} = (N_\uparrow D_\downarrow^{-1} + N_\downarrow D_\uparrow^{-1}) / (N_\uparrow + N_\downarrow)$.

Material parameters in NM are independent of spin, for example: $\sigma_\uparrow^N = \sigma_\downarrow^N = \frac{1}{2} \sigma_N$, $D_\uparrow = D_\downarrow$, etc. Whereas material parameters in FM are dependent on spin, for example: $\sigma_\uparrow^F \neq \sigma_\downarrow^F$, but $\sigma_F = \left(\sigma_\uparrow^F + \sigma_\downarrow^F\right)$, $D_\uparrow \neq D_\downarrow$, etc.

Let the distribution of interfacial current be uniform over the contact area, where the contact area is $A_J = w_F w_N$, and there is a discontinuous drop in the ECP at the interface of junction $i$ where $i = (1, 2)$ and corresponds to the interface at ferromagnet one or ferromagnet two. The drop in the ECP is associated with an interfacial resistance $R_i$. Ignoring any interfacial spin-flip scattering, the interfacial current across the interface becomes:

\[ I_i^\sigma = \left(\frac{G_i^\sigma}{e}\right) \left(\mu_F^\sigma \left(|z=0^+ - \mu_N^\sigma \left(|z=0^-\right)\right)\right) \]  \hspace{1cm} (A.9)
\[ G_i^\sigma = G_i^\uparrow + G_i^\downarrow = R_{i}^{-1} \]

Where \( G_i^\sigma \) is the interfacial conductance.

In the transparent contact regime, the ECPs are continuous \((G_i \to \infty)\). The interfacial charge and spin currents are:

\[ I_i = I_i^\uparrow + I_i^\downarrow \quad (A.10) \]
\[ I_i^s = I_i^\uparrow - I_i^\downarrow \quad (A.11) \]

By applying a current through FM one and through NM away from FM two, no charge current will pass through FM two. i.e. \((I_1 = I)\) and \((I_2 = 0)\). In NM, where \((d_N, w_N) \ll \lambda_N\), \(\mu_N^\sigma\) varies only in \(x\) (along the conduction channel):

\[ \mu_N^\sigma (x) = \bar{\mu}_N + \sigma \delta \mu_N \quad (A.12) \]

Where \(\bar{\mu}_N = -\left(\frac{e}{\sigma_N}\right) x\) for \(x < 0\), \(\bar{\mu}_N = 0\) for \(x > 0\), and \(\delta \mu_N = a_1 e^{-|x|/\lambda_N} + a_2 e^{-|x-L|/\lambda_N}\). \(a_1\) is the shift in the ECP at \(x = 0\) (at the interface of FM one and NM), and \(a_2\) is the feedback shift in the ECP at \(x = L\) (at the interface of FM two and NM). The associated spin current flows along \(x\) according to \(j_s = -\left(\frac{\sigma_N}{e}\right) \nabla \delta \mu_N\).

At junction \(i\), the continuity of the spin current is \(I_i^s = 2 \left(\frac{\sigma_N A_N}{e \lambda_N}\right)\), where \(A_N = w_N d_N\) is the cross-section area of NM. Recall that only a spin current flows in the region \(x > 0\) and no charge current.

Both ferromagnets have thickness and contact dimensions much larger than \(\lambda_F\). Spin splitting \(\mu_F^\sigma\) decays very rapidly moving away from the interface (in the \(z\) direction), and has a solution of the form near the interface \((0 < z \ll \lambda_F)\):

\[ \mu_F^\sigma (z) = \bar{\mu}_F + \sigma b_i \left(\frac{\sigma_F}{\sigma_F^\sigma}\right) e^{-z/\lambda_F} \quad (A.13) \]
Where $\mu_F = -\left(\frac{eI}{eA_J}\right)z + eV_1$ in FM one and $\mu_F = eV_2$ in FM two, $V_1$ and $V_2$ are the voltage drops $(\mu_F - \mu_N)/e$ at the interfaces. Applying the continuity conditions for spin we have:

$$I_s^1 = p_FI - 2\left(\frac{\sigma_F A_J}{e\lambda_F}\right) b_1$$  \hspace{1cm} (A.14)$$

$$I_s^2 = -2\left(\frac{\sigma_F A_J}{e\lambda_F}\right) b_2$$  \hspace{1cm} (A.15)$$

Where the current polarisation of FM one and FM two is $p_F = \left(\sigma_F^+ - \sigma_F^-\right) / \left(\sigma_F^+ + \sigma_F^-\right)$ and $a_i$, $b_i$, and $V_i$ are simply constants determined by the conditions of the charge and spin continuity.

The voltage that is measured across the ferromagnetic detector electrode and the conduction channel in a lateral non-local geometry is described as follows (Yamashita et al., 2002)

$$V_2 = \pm \frac{2R_N e^{-\frac{L}{\lambda_N}}}{I} \left[\prod_{i=1}^{2} \left(1 - P_i^2\right) + \frac{R_F R_N}{2} + \frac{R_F R_N}{2}\right]^{-1}$$

(A.16)

Where $P_J$ is the polarisation of the interfacial current, $R_N$ and $R_F$ are the cross-sectional resistances of the non-magnet and ferromagnet, $p_F$ is the polarisation of the current in the ferromagnet, and $P_i$ is the resistance through the $i$th interface (where $i$ can take values of either 1 or 2 – this represents the two ferromagnetic electrodes). $\Pi$ is a Pi function that instructs the reader to multiply the associate terms up to the $i$th element. The + and – signs at the front of the right-hand side shows that the measured voltage can be both positive and negative. This depends on the relative magnetic alignment of the two electrodes. If they are parallel then we expect to observe a small resistance as we observe a low resistive state, additionally if they are antiparallel, we expect to observe a high resistive state. Consider the parallel state as being when both ferromagnets have magnetic moments aligned in the same direction, and an antiparallel
state being when both ferromagnets have magnetic movements anti-aligned in the same direction.

The non-local spin signal can be either expressed as a change in resistance or a change in voltage. The spin signal can be thought of as the difference in measured voltage between the parallel and antiparallel states.

\[ R_s = \frac{V_s}{I} \quad (A.17) \]

\[ V_s = V_{2P} - V_{2AP} = 2|V_2| \quad (A.18) \]

For the readers ease I have broken up the expansion of the above equation into two parts, first dealing with the numerator expression in brackets, then the dominator expression.

Expanding the Pi function in the numerator for both \( i=1 \) and \( i=2 \) we have:

\[ \left( \frac{2|V_2|}{I} \right)_{\text{numerator}} = 4R_N e^{X_N} \left( \frac{P_J R_{1N}}{1 - P^2_j} + \frac{pF R_F R_{1N}}{1 - p^2_F} \right) \left( \frac{P_J R_{2N}}{1 - P^2_j} + \frac{pF R_F R_{1N}}{1 - p^2_F} \right) \quad (A.19) \]

We now assume that the device lies within the transparent contact regime. This is where the ECP is continuous between the semiconducting conduction channel and the ferromagnetic electrode such that the interfacial conductance tends towards infinity \( (G_i \to \infty) \) and that \( R_1, R_2 \ll R_N \). As a result, the interfacial current polarisation \( (P_J = \frac{|G_i^\uparrow - G_i^\downarrow|}{G_i}) \) tends toward 0 \( (P_J \to 0) \) (Takahashi & Maekawa, 2003). Therefore, each term in the brackets with \( P_J = 0 \) as a numerator disappears, leaving the following expression for the numerator:
\[
\left( \frac{2|V_2|}{I} \right)_{\text{numerator}} = 4R_N e^{\frac{-L}{\lambda N}} \left( \frac{p_F R_F}{R_N} \right)^2
\]  
(A.20)

Now we expand the denominator

\[
\left( \frac{2|V_2|}{I} \right)_{\text{denominator}} = \left(1 + \frac{2 R_1}{1 - p_F^2} + \frac{2 R_2}{1 - p_F^2} \right) \left(1 + \frac{2 R_1}{1 - P_j^2} + \frac{2 R_2}{1 - P_j^2} \right) - e^{-\frac{2L}{\lambda N}}
\]  
(A.21)

Recall that for transparent contacts we have \( P_J \rightarrow 0 \) and \( R_1, R_2 \ll R_N \). Therefore, we can remove the second terms from inside each bracket as \( \frac{R_1}{R_N}, \frac{R_2}{R_N} \rightarrow 0 \). We yield as follows:

\[
\left( \frac{2|V_2|}{I} \right)_{\text{denominator}} = \left(1 + \frac{2 R_F R_N}{1 - p_F^2} \right)^2 e^{-\frac{2L}{\lambda N}}
\]  
(A.22)

\[
\left( \frac{2|V_2|}{I} \right)_{\text{denominator}} = 1 + \frac{4R_F}{R_N (1 - p_F^2)} + \frac{4R_F^2}{R_N^2 (1 - p_F^2)} - e^{-\frac{2L}{\lambda N}}
\]  
(A.23)

If we assume the ferromagnetic material is much more conductive than the channel ( \( R_F \cong 0.01R_N \) ), then the second order term is negligible.

\[
\left( \frac{2|V_2|}{I} \right)_{\text{denominator}} = 1 + \frac{4R_F}{R_N (1 - p_F^2)} - e^{-\frac{2L}{\lambda N}}
\]  
(A.24)

\[
R_s = \left( \frac{2|V_2|}{I} \right) = \frac{4R_F^2}{R_N} \frac{\left( \frac{p_F}{1 - p_F} \right)^2 e^{\frac{-L}{\lambda N}}}{\left(1 + \frac{4R_F}{R_N (1 - p_F^2)} \right) - e^{-\frac{2L}{\lambda N}}}
\]  
(A.25)
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