Cooper-Pair Decoherence in SNS Hybrid Structures

Sareh Shafiee

Master Thesis
Department of Physics

Umeå University
Umeå, Sweden 2014
Cooper-Pair Decoherence in SNS Hybrid Structures

Sareh Shafiee

Master Thesis
Department of Physic, Umeå University
Department of Microtechnology and Nanoscience, Chalmers University
Umeå, Sweden 2014
Cooper-Pair Decoherence in SNS Hybrid Structures

Abstract

The Laws of quantum mechanics control the behavior of electrons in nanoscale devices and nanostructures. Quantum coherence of electrons can appear in different experiments. In this work we used SNS (Superconductor-Normal-Superconductor) structures in order to experimentally and theoretically study and investigate the effect of quantum decoherence.

We applied Nanofabrication technology to fabricate devices with SNS structure (using Ti-Au-Pd-Au-Pd-Al material in the shape of a sandwich structure). Fabrication has been carried out for devices with different junction lengths and thickness in the Nanofab laboratory (Clean-room) at the department of Microtechnology and Nanoscience, Chalmers University of Technology. Room and low temperature measurements were performed for respective devices and Critical currents measured as function of temperature up to 2.5\(\mu\)A for the shortest length (L=42nm). The result of the measurements were in agreement with what could be expected when using this fabrication system.

We recommended fabrication of samples with longer junction and carrying out measurements at lower temperature down to 10mK.
Acknowledgements

Foremost, I would like to express my sincere gratitude to my supervisor Prof. Leonid Kuzmin for the continuous support of my research at Chalmers University.

Many thanks to Dr. Mikhail Tarasov, Dr Erns Otto, Mr. Sumedh Mahashabdeh and Andrew Semenov for their insightful comments and advice in the experimental and theoretical part of my research; also I am thankful the whole Quantum Device Laboratory group at Chalmers University for providing such productive research environment. My appreciation goes to Nanofab lab and administrative staff as well for helping me all the time. Your ultimate cooperation is highly regarded here.

I would like to express my special thanks to Prof. Bertil Sundqvist and Prof. Michael Bradley for their guidance and cooperation at Umeå University.

Massive credits goes to my parents Shokoh Shafiee, Mohammad Shafiee, for giving birth to me at the first place and supporting me spiritually throughout my life; the best sister I could ever have, Somayeh. You are always my role model. Mahsa, how can I forget your kindness and hospitality from the first moment who I was arrived to Umeå; Thanks for everything.

Above all, special thanks to my dearest husband, Aboozar Zarini. Your tolerance and compassion had been magnificent.

Sareh Shafiee
Umeå, Feb 2014
Contents

1. Introduction
   1.1 Background ...................................................................................................................... 9
   1.2 Motivation.......................................................................................................................... 11
   1.3 Outline for this thesis ....................................................................................................... 12

2. Theory
   2.1 Introduction to superconductivity ...................................................................................... 14
   2.2 Superconductivity in low dimensions .............................................................................. 18
       2.2.1 Superconducting Proximity Effect .............................................................................. 19
       2.2.2 Andreev reflection .................................................................................................. 19
       2.2.3 Josephson Effect ................................................................................................... 21
       2.2.4 Josephson Effect in SNS structure .......................................................................... 21

3. Fabrication procedure
   3.1 General fabrication process ............................................................................................... 24
   3.2 Fabrication process to make sample .............................................................................. 25
       3.2.1 Spin resist .................................................................................................................. 25
       3.2.2 Electron Beam Lithography (EBL) ............................................................................ 26
       3.2.3 Dicing ....................................................................................................................... 27
       3.2.4 Development ........................................................................................................... 27
       3.2.5 Ashing ....................................................................................................................... 28
       3.2.6 Evaporation ............................................................................................................ 28
       3.2.7 lift off ....................................................................................................................... 29
   3.3 Inspection of sample ......................................................................................................... 30
       3.3.1 Optical microscopic inspection ............................................................................... 31
       3.3.2 Scanning Electron Microscopy (SEM) ..................................................................... 31
       3.3.3 Atomic Force Microscopy (AFM) ........................................................................... 33

4. Experimental realization
   4.1 Requirements for experiment ........................................................................................... 35
   4.2 Chip overview .................................................................................................................. 35
   4.3 Realization of experiment ............................................................................................... 36
5. Measurements setup

5.1 Room temperature measurements .............................................................................. 38
5.2 Cryogenic (low temperature) measurements ............................................................... 40
5.3 Cryogenic equipment .................................................................................................. 40
  5.3.1 The Heliox $^3$He refrigerator .................................................................................. 40
  5.3.2 The Heliox sample holder ....................................................................................... 41
5.4 IV Measurements in Current Bias mode ..................................................................... 42

6. Experimental result and analyze

6.1 Fabrication outcome .................................................................................................... 44
  6.1.1 Resistance and material ....................................................................................... 45
  6.1.2 Geometrical consideration .................................................................................... 47
6.2 Experimental result analyzes and data processing ........................................................ 47

7. Conclusion and future prospect ..................................................................................... 53

Bibliography ..................................................................................................................... 55
Appendix A ....................................................................................................................... 57
Appendix B ....................................................................................................................... 59
Appendix C ....................................................................................................................... 65
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Abbreviation/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>Superconductor</td>
</tr>
<tr>
<td>$N$</td>
<td>Normal metal</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$L_\phi$</td>
<td>Decoherence length</td>
</tr>
<tr>
<td>$\tau_\phi$</td>
<td>Decoherence Time</td>
</tr>
<tr>
<td>$D$</td>
<td>Diffusion coefficient</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Temperature length</td>
</tr>
<tr>
<td>$E_{th}$</td>
<td>Thouless energy</td>
</tr>
<tr>
<td>$G$</td>
<td>Andreev conductance</td>
</tr>
<tr>
<td>$I_c$</td>
<td>Critical (Super) Current</td>
</tr>
<tr>
<td>$SC$</td>
<td>Superconductor</td>
</tr>
<tr>
<td>$K$</td>
<td>Kelvin</td>
</tr>
<tr>
<td>$Al$</td>
<td>Aluminum</td>
</tr>
<tr>
<td>$Au$</td>
<td>Gold</td>
</tr>
<tr>
<td>$Pd$</td>
<td>Palladium</td>
</tr>
<tr>
<td>$Ag$</td>
<td>Silver</td>
</tr>
<tr>
<td>$Hg$</td>
<td>Mercury</td>
</tr>
<tr>
<td>$W$</td>
<td>Tungsten</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Wave function</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Density of state</td>
</tr>
<tr>
<td>$T_C$</td>
<td>Critical temperature</td>
</tr>
<tr>
<td>$J_c$</td>
<td>Critical Current density</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Microscopic phase coherence</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Superconducting energy gap</td>
</tr>
<tr>
<td>$\lambda_L$</td>
<td>London Penetration depth</td>
</tr>
<tr>
<td>$\xi_o$</td>
<td>Coherent length</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCS</td>
<td>BCS Theory</td>
</tr>
<tr>
<td>JJ</td>
<td>Josephson Junction</td>
</tr>
<tr>
<td>WL</td>
<td>Weak Localization</td>
</tr>
<tr>
<td>HTS</td>
<td>High Temperature Superconductivity</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopic</td>
</tr>
<tr>
<td>AFM</td>
<td>Atomic Force microscopic</td>
</tr>
<tr>
<td>SPM</td>
<td>Scanning Probe Microscopic</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropanol</td>
</tr>
<tr>
<td>MIBK</td>
<td>Methyl isobutyl ketone, used as solvent</td>
</tr>
<tr>
<td>1165</td>
<td>Microposit and Megaposite photoresist remover</td>
</tr>
<tr>
<td>PTC</td>
<td>Pulsed Tube Cooler</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction and Motivation

Superconductivity is an effect which is characterized by lack of electrical resistivity for a certain material (named superconductor) at quite low temperature, near absolute zero; superconductors show this property while they act as perfect diamagnets above zero temperature. H. K. Onnes in 1911, three years after achieving liquefied Helium, was the first person who discovered the superconductivity effect in mercury.

One of the devices which present this phenomenon is a Josephson Junction (JJ); which is a device with a sandwich structure and consists of two superconductors separated by a weak barrier; this barrier could be an insulator, normal metal or conductor. By going down to enough low temperature (critical temperature, $T_C$) supercurrent flows through the barrier; In fact, the normal metal part also demonstrates superconductivity which has been explained by Andreev reflection. There is phase difference between the order parameters of two superconductors which Josephson in 1962 linked to the applied current and fields across the Josephson junction.

1.1 Background

The study of the behavior of electrons in nano-scale structures based on the laws of Quantum Mechanics is quite important. There are different phenomena such as Weak localization correction, Aharonov-Bohm oscillations of conductance, constant current in metallic rings and many other phenomena which manifest the quantum nature of the current.

Nowadays, dirty normal metal is a well-known structure for studying quantum coherence phenomena. In a normal metal at a very high temperature conductivity is observed; the main contribution to the resistance is scattering by impurities and it’s given by Classical Drude formula. So, at very low temperature there is a lack of interactions but the electrons’ wave functions maintain their coherence; thereby quantum interference remains in most of the samples and two time reversal electron trajectories may interfere. This correction is called weak localization correction (WL) effect and it’s given by diagrams with one Cooperon. A Cooperon is defined as a probability of diffusion from one point to another connected with a pair of time reversed classical trajectories and it’s very sensitive to the presence of time reversal symmetry in the system [1]. For instance, It has been corroborated by experiments
that magnetic field is one of factors which could break down this symmetry and yields cessation of Weak Localization.

All the above physical implications apply for non-interacting electrons but in reality different interactions (e.g. electron-electron interactions, electron-phonon interactions etc.) are present which may considerably modify the quantum behavior of conducting electrons in disordered metals.

By going to low temperature, phonons are effectively frozen out; consequently the only interaction which we are able to study is the electron-electron interaction. This interaction is viewed as fluctuations of electric field produced by fluctuating electrons; so while electrons propagated in the system, they feel and get influenced by fluctuations of electric field and perchance the most prominent consequence of these interactions is decoherence. In fact, the wave functions of these electrons collect all random phases and finally lose their ability to interfere. We can thus introduce a decoherence time ($\tau_\varphi$) which is the time of decay for a Cooperon and a decoherence length $L_\varphi = \sqrt{D\tau_\varphi}$ ($D$ is the diffusion coefficient) which is the finite length in which electrons lose their phase coherence. Only trajectories with length smaller than $L_\varphi$ would be able to contribute to the Cooperon. From a physical perspective, this scale gives information about the system size at which quantum coherent phenomena can be observed [1].

The dependence of decoherence length on temperature is obvious and well-known; $L_\varphi$ and $\tau_\varphi$ generally increase with decreasing temperature ($T \to 0$) and quantum effect becomes more important in this scale. But what particularly happens for the decoherence length when $T \to 0$? There are two possible states, one is increasing $L_\varphi$ without any limitation at $T \to 0$, and in this case it’s possible to observe quantum effects in any conductor by cooling them down to sufficiently low temperature. The other state at $T \to 0$ is saturation of $L_\varphi$ to a finite value $L_\varphi 0$ due to electron-electron interactions.

Great experiments performed at sufficiently low temperature show that $L_\varphi$ and $\tau_\varphi$ do not grow anymore. As far as the problem of WL in disordered normal metals is concerned, electron-electron interactions (present in any realistic structure and not negligible) restrict the decoherence length to be finite at any temperatures including zero. Some experiment have been done for various three dimensional disordered metals which shows this phenomenon [2, 3, 4].

The hybrid superconductor normal metal (SN) structure is another system which can be used for studying the physics of quantum coherence phenomena. It’s well known that a normal metal (N) attached to a superconductor (S) with good electrical contact also obtains superconducting properties [5, 6]. This is called superconductivity
proximity effect and it’s directly related to the phenomenon of Andreev reflection [7]. Indeed, at the NS border a Cooper pair converts to sub gap quasi-particles (electrons) and diffuse into the normal metal while keeping information about the macroscopic phase of the superconducting condensate. Consequently, all of the normal metal could show superconducting properties at low enough temperature and the superconducting coherence expands into the normal metal by the temperature length \( L_T \sim \sqrt{D/T} \) (\( D \) is diffusion coefficient).

The significant advantage of this system is that the quantum coherent effect gives the main contribution to the transport properties and can be measured directly in contrast to the case of normal metal, where the weak localization correction yields only a very small contribution to the system conductance.

1.2 Motivation

A.Semanov, A.Zaikin and L.Kuzmin have addressed the problem of quantum decoherence by electron-electron interactions in NS nanostructures theoretically [1]. They demonstrate penetrate electron-electron interactions cause dephasing of Cooper pairs which penetrate from the superconductor into the diffusive normal metal.

Destruction of macroscopic coherence of electrons penetrating from a superconductor at a typical length scale \( L_\varphi \) is caused by the fluctuating electron magnetic field produced by fluctuating electrons in the disordered normal metal. The decoherence length inflicts substantial limitations on the proximity effects in NS Nano-structures at low temperature \( (T < \frac{D}{L_\varphi^2}) \). In this temperature range, the penetration depth of superconducting correlations into the normal metal is no longer given by \( L_T \); but it’s limited by the temperature independent value \( L_\varphi \) which doesn’t grow when decreasing the temperature to zero [1, 8].

The main focus of this work is to investigate the effect of quantum decoherence in diffusive SNS junctions experimentally.

From previous experiment, it’s known [9] that for a normal layer with thickness (\( W \)) shorter than \( L_T \) some junctions may preserve a large supercurrent that is not exponentially suppressed with \( W \). Since \( L_T \) diverges at quite low temperature, it follows instantly that at zero temperature, one can run a non-vanishing supercurrent even through SNS junctions with very thick normal metal layer. This happens because of macroscopic coherence of the Cooper pairs’ wave functions which penetrate into the normal metal from both superconductors, interfere and establish a coherent state in the whole SNS system. The experiment has been done already and showed this effect clearly besides that the results found were in excellent agreement with theory. The above scenario applies if one can neglect electron-electron
interactions that is provided the corresponding $L_{\Phi}$ remains much larger than both L and $L_T$ [1].

If two conditions are fulfilled, first, a sufficiently low temperature ($L_{\Phi} < L_T$) and second, a sufficiently thick normal metal layer ($L_{\Phi} < W$), macroscopic quantum coherence in the normal layer should be destroyed by the electron-electron interaction and the Josephson critical current should be exponentially suppressed, $I_c \propto e^{-L/L_{\Phi}}$ (even for zero temperature). Since this suppression has not been shown experimentally; in this work I’ll perform the corresponding experiment for investigation of this fundamental problem. For achieving this propose, fabrication of SNS junctions and measurements of the critical current in this system as a function of both length and temperature are planned.

1.3 Outline for this thesis

As mentioned before, this thesis -which is mostly based on experimental work- is trying to achieve suppression of Josephson critical current in the presence of decoherence by measurements on fabricated diffusive SNS junctions with different thicknesses of the normal metal layer.

The rest of the thesis is divided into 6 chapters. In chapter 2 you’ll find a comprehensive overview of the theoretical aspect of this work. The first part of this chapter starts with an explanation of the fundamental definition of Superconductivity and then in the second part, it continues by going more into details of superconductivity at low temperature. Chapter 3 will describe the fabrication process and give a brief description of the devices used. The Experiment realization is covered in chapter 4 where the restrictions, the chip design, and the steps going from design to results are explained. This is followed by a description of the measurement setup both at room temperature and low temperature in chapter 5.

Chapter 6 deals with experimental results and the method of analysis used during this work. The last chapter presents the conclusion and further prospects. The Appendix has further technical information on tools used in the cleanroom.
Chapter 2

Theory

2.1 Introduction to superconductivity:
Reviewing some fundamental properties of materials may seem simple but for having an initial understanding it’s quite beneficial; Materials have different properties such as density, temperature, thermal conductivity, electrical conductivity etc. Electrical conductivity is an interesting property in this case. Materials science divides materials into three groups and labels them Metals, Insulators and Semiconductors. Metals act like a sea of free carriers; able to travel easily and capable of carrying electric current which however decreases with increasing temperatures. Often it’s easier to discuss the electrical resistivity rather than electrical conductivity (these two are inversely proportional to each other). The Insulators are opposite of metals; electrical charge in insulators is fixed and does not flow freely, therefore they have vanishing conductivity. Semiconductors act something between metals and insulator; they have intermediate electrical conductivity compared with metals and insulators. Even it’s possible to say that they behave very much like insulators, but they can be persuaded to conduct electricity by adding impurities.

The story of superconductivity goes back over a hundred years to when H. Kamerlingh-Onnes, in 1911 was the pioneer to find this new property of metals after he reached liquid Helium temperature. By putting mercury in the liquid helium and push a current through it, he obtained a historic result; the demonstration of zero resistance for mercury. Afterwards, he discovered that several metals lost their resistance below a specific temperature which is called the critical temperature \( T_c \) and called them superconductors (Like Al, Ti, Nb …) [5]. All superconductors show a sudden or even gradual a drop of resistance at a particular low temperature (Critical temperature). No resistance or in other word infinite conductivity, implies that if current passed through this material, it could flow forever without any dissipation (although there is a possibility to destroy this property by applying high current or magnetic field) see Fig2.1.
This means that, Mercury wasn’t just a perfect conductor (metal with zero resistance) but also it had a very special quantum mechanical state. The evidence for that was later found by Meissner, who showed that in addition to zero resistance, it also exhibited a perfect diamagnetism. This means an external magnetic field penetrates into the superconductor material only a finite distance (penetration depth); which it is usually small compared to the width of material [10]. However, it’s well known that if the magnetic field is sufficiently strong it will destroy superconductivity in a material. So if a piece of superconductor is placed in a magnetic field, it would generate a screening current such that the magnetic field inside the superconductor will be zero (inside the superconductor, the magnetic field is excluded).

Since the Superconductivity effect was discovered in materials before the physics community predicted the phenomenon, theories were formed to attempt to explain and predict the characteristics of these materials that undergo the phase transition. In 1950, Ginzburg-Landau theory (which was a phenomenological theory) used vibrational principle of quantum mechanics to explain this phenomenon [11, 12, 13]. Afterwards, explanation and results were able to accurately match the experimental results of the time and later were shown to be a specific form of BCS theory.

It is common that it takes a long time to find a scientific explanation for a new discovery, proceeding by many small steps. In this case, it took 40 years before Bardeen-Cooper-Schrieffer (BCS named after J. Bardeen, L.N.Cooper and J.R. Schrieffer) finally in 1957, presented a microscopic theory for superconductivity. This theory relies on the assumption that superconductivity arises when the attractive Cooper pair interaction dominates over the repulsive Columb force. The Cooper pair is a weak electron-electron bound pair mediated by phonon interaction [5].

A description of BCS theory based on quantum mechanics could be a little complicated, so the following five steps try to give a simplified and more understandable explanation. We assume the current is smaller than the critical current ($T_c$); there are some minimal vibrations which belongs to virtual phonons. Second,
while electron travel, they distort the lattice. In fact during the electron’s fast movement through the lattice, attractions between electron and positive charge makes some distortion in the lattice by movement of positive charge toward electron but with a delay. Third, the lattice movement is delayed. Fourth, a positive region is created behind the first electron. Fifth, the second electron is attracted to this positive region and the lattice rebounds back into its original shape and further electron pass them. Consequently the two electrons with opposite spin and negative charge (contrary to the expectation) attract each other and a Cooper pair is formed. This attraction was created by the phonon-electron force under low temperature; lots of Cooper pairs are formed and reformed constantly such that we have many supercurrent carriers (see Fig2.2).

Fig.2.2: Representing the BCS theory structure

There is absolutely no resistance for a Cooper pair which means there is no more collision with the lattice and eventually it becomes a perfect conductance or superconductor.

To sum up, lets define superconductivity as a microscopic quantum effect in which below the critical temperature, a fraction of the electrons are aggregated into a single state that is described by a single wave function $\psi(r) = |\psi|e^{i\phi(r)}$; the significant properties of superconductivity are related to its energy spectrum.

In the Superconductivity state and below $T_c$, the net interaction increases the probability of forming “Cooper pairs”; Cooper pairs are two electrons with opposite momentum and spin which have paired up. In other word they are two virtual bosons and therefore obey Boson-statistics to form a condensate. Besides that they are strongly correlated and form a coherent state with phase ($\phi$). By the formation of a condensate, a superconducting energy gap $2\Delta$ which is (symmetric) around the Fermi level (and contains no density of states for quasi-particles excitation or single electrons) is formed.

The size of gap depends on magnetic field and temperature; by going to temperature less than $T_c$ the size of the gap increases and reaches a maximum value $\Delta(0) \approx 1.76K_BT_c$ ($K_B$ is the Boltzmann constant).
The zero value for electrical resistance in a superconductor occurs because the Cooper pair condensate moves as a coherent quantum mechanical entity and Cooper Pairs encounter no opposition. Atomic lattice vibrations and impurities cannot disrupt Cooper pairs by scattering [14].

Although Cooper pairing or BCS pairing is a quantum effect there is a simplified classical explanation for this pairing. In metals electrons behave as free particles and they repel each other due to identical charges but they also attract the positive ions that make up the rigid lattice of the metal. But this attraction also distorts the ion lattice, moving the ions slightly toward the electron and increasing the positive charge density of the lattice in the vicinity. Then this positive charge can attract other electrons. At long distances this attraction between electrons due to the displaced ions can overcome the electrons repulsion, due to their negative charge, and cause them to pair up. Based on quantum mechanical explanation this effect is due to electron–phonon interactions. In other words, two negatively charged electrons inside a metal, even though they repel each other may also have some attracting interaction between them. This attracting interaction comes from phonon exchange. So one electron is flying and then it emits a phonon, changes the direction while another absorbs that phonon and changes direction. This process of changing the phonon created the correlated state between two electrons which otherwise are traveling independently. So it needs a sufficiently strong electron-phonon interaction in a material to be superconducting; which it is the theoretical idea of Bardeen, Cooper and Schrieffer. In the next part, we try to focus more on superconductivity at low temperature.

Mercury with 4.2 Kelvin critical temperature had been discovered by H.K.Onnes as the first superconducting metal [15]. Afterward, scientists found that superconductors could be divided into two types, type-I and type-II [16]. Type I, contain superconductor pure metals which exhibit a very sharp transition to a superconducting state (zero resistance) at low temperature (see fig2.1), lose their superconductivity easily by placing in external magnetic field (the reason that they also named as soft S) and has been explained by BCS theory. These kinds have coherence length of superconducting electrons much smaller than the penetration depth of magnetic field below critical temperature. They show superconductivity at temperature below 30 K (~243.2 °C). For instance, Mercury and Aluminum are two of thirty pure metals in this group; the electrical resistivity of Al at 20°C is 2.824μΩ-cm, the critical temperature of Al lies just below 1.175˚ Kelvin and the critical magnetic field is 0.01 Tesla. There are many other materials which show superconductivity properties in the same temperature region as Al. Al is available in most laboratories and its cheaper compared to other superconductor metals [5]. There are additional elements which can be coaxied into a superconductive state with the application of high temperature; such as Phosphorus, which has the highest $T_c$ 14-22˚ Kelvin, under extremely high pressure (2.5Mbar).
The type II superconductors lose their superconductivity gradually in an external magnetic field. They obey the Meissner effect but not completely. The penetration depth of a magnetic field in this kind is larger than the coherence length of superconducting electrons [16]. HTS have shown superconductivity at temperature as high as 138 K (−135 °C, at atmospheric pressure) and they are mostly copper-compounds such as Cuprate ($YBa_2Cu_3O_7$) or yttrium barium copper oxide (YBCO). Although low temperature superconductivity is explained by BCS theory, there has been no theory to describe HTS yet [5].

Figure 2.3 tries to show the Meissner effect for two types of superconductivity. As mentioned before at normal temperature, a magnetic field penetrates into a superconductor (S) but at low temperature below $T_c$, magnetic fields don’t penetrate into superconductor anymore. By applying a high external magnetic field to superconductors type one, they lose their superconductor ability abruptly; superconductors of type two lose their superconductivity gradually in this situation but not abruptly.

The intermediate state or vortex state is the state between the lower critical magnetic field ($H_{c1}$) and the higher critical magnetic field ($H_{c2}$).

### 2.2 Superconductivity in low dimensions

Some of the greatest physicists introduced the concept of interface superconductivity over 50 years ago. Physicist at that time wondered whether a quasi two-dimensional (2D) superconductor can actually exist, what are the properties of 2D superconductivity and how does the reduced dimensionality affect the critical temperature ($T_c$). After the discovery of high-temperature superconductors, which are composed of coupled 2D superconducting layers, the interest in reduced dimensionality structures increased.

Scientist proved that interface superconductivity can occur at the junction of two different materials (normal metals, insulators, semiconductors) [5]. Since the study of
Nanoscale superconductivity has been done in the past three decades, it’s obvious that it is important to know how the ground state properties change when one or more of the system dimensions are reduced below the characteristic length scales for a bulk superconductor (such as, coherence length ($\xi_o$) and the London penetration depth ($\lambda_L$)). The superconducting properties for low-dimensional systems often show dramatic changes from those of the bulk. By reducing dimensions, new phenomena which are not seen in bulk superconductors may also be observed. Nanoscale superconductivity has been studied in two-dimensional thin films and one-dimensional nanowires [17 18, 19].

2.2.1 Superconducting Proximity Effect
The proximity effect is the occurrence of superconductivity in non-superconducting materials placed in perfect electrical contact with a superconductor (S). The Proximity effect and superconducting-normal interference have been studied since quantum transport was discovered, it’s because common to combine a superconductor for their properties with another material like semiconductors or a normal metal (a nickname for anything that isn’t superconductor but is metal). In this case, a semiconductor counts as a normal metal, as long as the Fermi level is in the conduction bands somewhere or there are some charge carriers around. Superconductivity thus leaks into the normal metal if we put them together closer than the coherence length.

Superconductivity is a distinct state of matter and therefore it’s separated from other states of the same matter by a phase transition (Superconducting phase transition). So below a certain temperature and below a certain critical field it superconducts (there is a critical magnetic field above which superconductivity does not exist). In most superconductors, critical current ($I_c$), critical temperature ($T_c$) and critical current density ($J_c$) are related to each other [20]. This is a thermodynamic relation so there is a certain energy associated with the superconducting phase and it’s possible to make that phase unfavorable by either adding temperature or magnetic field to the system. When superconductivity is killed, a magnetic field starts to penetrate, so the penetration depth is infinite and the magnetic field does not care any more about the superconductor; by going to low temperature, a magnetic field is expelled but still penetrates some finite length which is small compare to the sample size.

2.2.2 Andreev reflection
Andreev reflection is playing a main role in the proximity effect (at NS junctions) since it provides the primary mechanism for converting single electron states from normal metal states (with energy $\varepsilon > \Delta$) to Cooper pairs in the superconducting condensate and thus establish a current flow between N and S. But electrons with energy $\varepsilon \leq \Delta$, cannot
find any available state to scatter into so there is no current flow in the case of normal scattering. The actual proximity effect is the result of an interaction between Andreev reflection at NS interfaces and long range coherence in the normal metal.

A. F. Andreev noted in 1964 for the first time that particle scattering could occur at interfaces between a superconductor and a normal metal. While he studied heat transport at NS interfaces, he reported that an electron could be reflected from a superconductor in an unusual way [21]. Figure 2.5, shows the differences between normal and Andreev reflection scattering.

So, in Andreev reflection, when an electron from the N part with energy less than $\epsilon < \Delta$ hits the border of NS, it will return to the normal part as a hole (electron with plus charge) and enter into the S part as a Cooper pair while the electron is conserved in normal reflection. In Andreev reflection momentum is conserved but in normal reflection it is not. This means that the incident electron with energy $\epsilon$ and momentum $K_{e1}$ drags another electron from the normal part at energy $-\epsilon$ of opposite momentum $-K_{e2}$ and spin with it, to form a Cooper pair in the superconductor. In other word the incident electron is reflected as a hole or vice versa [22]. Energy and spin are conserved in both normal and Andreev reflection.
2.2.3 Josephson Effect

B. Josephson in 1962 made a significant prediction about current flow in Josephson Junctions (JJ) at zero voltage by electron tunneling. In the initial stage of Josephson effects studies, the primary role was played by tunnel junctions in which two superconducting electrodes were separated by a thin layer of insulator. His prediction was confirmed by experimental work and he was awarded the 1973 Nobel Prize in Physics [5, 23, 24, 25]. Nowadays it’s clear that the Josephson Effect is one of the macroscopic quantum phenomena of superconductivity. In it two strongly superconducting electrodes are connected by a weak link. The weak link can be a normal metal (N) or a short narrow constriction (C). These typical cases are often referred to as S-N-S and S-C-S weak link. The current through a weak contact (between two superconductor electrodes) $I_s$ (supercurrent) is dependent not on the voltage between the electrodes but on the phase difference between the two superconductors, it is a measure of how strongly the phases of the two superconducting electrodes are coupled through the weak link. In the classical case this supercurrent is given by $I_s = I_c \sin \varphi$; $I_c$ is supercurrent amplitude or in other expression critical current and phase ($\varphi$) are related to voltage across the electrode (V) by $\frac{d\varphi}{dt} = \frac{2e}{h} V$ (this came from main principle of quantum mechanics and only fundamental constant).

The $I_c$, essentially depends on geometry, material, temperature and other factors. The geometrical dimension of the weak link is its length or in the other words the dimension of weak link in the direction of current. But in fact the length that is called effective length ($L_{eff}$) played a main role in the process. $L_{eff}$ is the length within which the nonlinear effects in a weak link are localized. In a JJ, the non-superconducting barrier separating the two superconductors must be very thin. For an insulator barrier it has to be of on the order of 30 angstroms thick or less and if the barrier is another metal (non-superconducting), it can be as much as several microns thick.

2.2.4 Josephson Effect in SNS structure

Assume an ideal $S_1NS_2$ structure with phases $+\varphi/2$ and $-\varphi/2$ belonging to $S_1$and$S_2$. The electron energy level in the normal metal consists of phase dependent Andreev bound-state and can carry a finite super-current. The total $I_s$ is given by an aggregate of the contribution and current carrying states which all depend upon the phase difference $\varphi$ between the two superconductors.

For a system in thermal equilibrium, the population probabilities of each state are given by the Fermi-Dirac distribution function. When the phase difference is zero, for each bound state there is another degenerate bound state (time-reversed state) that carries the
same current in the opposite direction and therefore the total current is zero. When the phase difference in the SNS junction is non-zero, the energies of these states are different giving rise to a finite super-current at low temperature.

At high temperature, the thermal population of states with opposite current is almost the same which causes a suppression of $I_S$. This suppression occurs when $K_B T$ is of order of the spacing between states with opposite currents. This picture remains valid in diffusive systems. In this case this spacing is of order of the Thouless energy.

Measurements of the Josephson critical current in SNS junctions shows that the characteristic energy $\frac{eI_c}{G_N}$ at low temperature is of the order of the Thouless energy of the sample and also shows that the Thouless energy is the relevant energy scale in the diffusive metal in proximity with a superconductor. Since the sample length is varied, there is a crossover between the superconducting gap for short junctions ($L < \varepsilon_s$) and the Thouless energy for long junctions ($L < \varepsilon_s$) [26].
Chapter 3

Fabrication procedure
The first cleanroom’s initial plan was created by American physicist W. Whitfield in 1960. Chalmers MC2 Nano Fabrication laboratory with 1240 $m^2$ of cleanroom classified area was started to work in 2001. This Laboratory with micro and nanotechnology facilities produced very good research opportunities. This laboratory is a level 10 cleanroom, which means the number of airborne particles should not be much more than $10/m^3$. Protection cloth, gloves and glasses in addition to observance of the Cleanroom principles, are required in order to protect the fabrication area from dust and any other contamination. The significant reason for such precaution is that the structures fabricated are often in nano-scale size and sensitive, sometimes in the range of 100nm or even less. Hence, even barely visible dust particles could easily ruin important structures during the fabrication process.

Talking about fabrication is simpler than making experimentation; but by going to the fabrication process, doing wet etch, E-beam lithography, metal deposition by evaporation, ashing, measurements and make inspection by SEM or AFM, it is realized how all these steps are to achieve work’s propose.

This chapter is started by some overview of the Cleanroom fabrication process and continues with some fundamental information of sample construction. More information related to this topic may be obtained in e.g. Jaeger’s book [27].

3.1 General fabrication process
To have a more clarified views of the process take a look on Fig 3.1; it gives a full overview of the fabrication method which is used to build a SNS structure.
Generally the beginning point of the process is a silicon wafer (for this work, it is a 3inch wafer) which will serve as substrate and all structures are grown on top of it.

### 3.2 Fabrication process to make sample:

While doing fabrication in nano scale, any tiny contamination or airborne particles are going to play a main role in final result. In this case, although wearing gloves will be helpful but keeping them clean, and avoid touching face (as it’s the only uncovered part of the body) during the fabrication process need specific attention.

In summary, the work will go through the following steps one after the other: spinning resist on the substrate, perform EBL, development, inspect structure by optical microscope, Oxygen plasma ashing, different layer evaporation based on recipe, lift off, make second inspection by optical microscope and in case it is needed doing SEM or AFM.

#### 3.2.1 Spin resist

The starting point in fabrication is to clean the 3inch silicon wafer by acetone; then it will continue by spinning two layers of resist, of which the first one is ‘‘Copolymer’’
resist, spinning with 3000rpm for 1min followed by baking at 160°C for 7min and the second one is ‘‘ZEP 520 1:1’’ resist, spinning with 3000 rpm for 1min followed by baking in 150°C for 7min. The reason of baking the wafer after spinning is to improve the uniformity of the resist and the resolution of the exposure in addition to hardening the resist on wafer. This step is one of the most important critical fabrication steps in terms of sensitivity to dust particles.

Fig 3.2: Fabrication step. It shows the steps of spinning resist which plays a fundamental role to achieve a perfect sample in the final step.

### 3.2.2 Electron Beam Lithography

The desired layout was formed by Electron Beam Lithography (EBL). This method has been used for fabricating microscopic structures with high resolution. The resolution limit in EBL depends on two factors, the first one is the resolution of the resist and for the resist it depends on molecular structure; the second one relies on Coulomb interaction between beam electrons and resist molecules.

When the exposure area is wider than the feature, the surrounding resist is influenced by the electron beam; this is known as the electron beam proximity effect, it leads to variation of exposure between features or even inside them and could merge features together. This effect counts as an important problem for writing small features. Besides, astigmatism and drift affected on the EBL process but compared to the proximity effect, they are easier to correct.

The process of exposure in E-beam lithography and Photolithography is the same; but E-beam lithography used electrons and Photolithography used photons with limited wavelength of the emitted UV light for exposure and making pattern. Photolithography is faster but the wavelength limitation causes a low resolution which is not enough for some microscopic structure. In this structure, high precision for optimal alignment is essential.

After loading a wafer in the EBL system, pumping down to reach low pressure takes some time and makes it possible to enter pattern information to the control unit and do some calibrations such as beam current, pattern area, microscope magnification, frequency of exposure, tuning electron beam, adjustment of electron gun, focusing
electron beam and... . The exposure of the wafer will be start as soon as everything is in operation mode and then the pattern is going to be exposed on the wafer, see Fig 3.3.

Fig 3.3: Fabrication step, showing the EBL

3.2.3 Dicing
Based on sample size, there is a possibility to have a large number of samples on a 3inch wafer. The size of the sample here is 7x7mm, so at least more than 60 sample pattern can be formed on a wafer and after EBL it requires to dice them and sort in a sample box. The dicing step is done with a diamond and dicing tool.

3.2.4 Development
Development will be done after EBL to remove resists and obtain the final layout. Depending on the types of resist, there could be one solvent which affects both layers or two different solvents which affect each layer of resist; in this case the recipe is to immerse the sample in ‘’Hexyl Acetate’’ for 35s followed by drying it and immerse it for 6min 30s in ‘’MIBK/IPA 1:1’’ (MIBK is a kind of solvent, look at definitions).

The solvent is chosen only to dissolve and remove the part of resist which was irradiated by the electron beam and leave the rest of the resist. Compared to the top layer, the bottom layer of resist should react more strongly and this causes an undercut of the edges in this layer, see Fig 3.4.
Fig 3.4: Fabrication step, showing development of structure after EBL

The sample is inspected after development, in order to check the layout and find other visible problem to help avoid working on a sample with initial errors.

3.2.5 Ashing

Even working in a class 10 Cleanroom laboratory (in terms of controlled level of contamination) will not be sufficient to have high accuracy fabrication and definitely extra consideration is required. Oxygen plasma ashing is one of way to remove sample’s organic contamination from airborne, aerosol, gloves or...; It plays an outstanding role to increase the chance of better adherence between metal and sample surface for the next step.

In simple explanation Plasma is a cloud with negative and positive charges and ashing means removing organic contaminations from the surface by a physical or chemical process.

The sample in this work is placed in a chamber of a reactive Ion etching (RIE) tool and an oxygen plasma at 10mTorr pressure and 50W power was created for 10s; by entering Oxygen (O2) to the chamber and increasing the potential difference between plasma and electrodes, the active plasma formed and moved to the surface. Then a reaction on the surface happened (the active plasma desorbed humidity and carbon oxides and other contaminations from the structure). This step was finished by pumping out the reaction products from the chamber. It is anisotropic ashing; hence the sample has different ashing rates in different directions.

3.2.6 Evaporation (Metal Deposition)

One of the prevalent methods of thin-film deposition which is used in nanofabrication is Evaporation. Under vacuum the source metal is evaporated; evaporation in low pressure or vacuum makes it possible for vapor particles to reach the sample (substrate)
directly and condense back to the solid state and accordingly the position of the sample is important. Each evaporator machine has a special sample holder and fixing the sample in the sample holder to carry out angle evaporation needs special consideration.

Angle evaporation or in the other definition, shadow evaporation is a technique to have control over the formation of film in specific parts of chips. This technique makes it possible to evaporate several metal layers and fabricating different structures in chips while all metals can be evaporated in the same vacuum cycle.

Two to eight hours of pumping give quite low pressure; since chemical reactions between metal and air particles could increase the oxidation risk or cause impurities in the film, having a high vacuum and perform evaporation at low pressure is a crucial factor in the fabrication process.

Multilayer evaporation in this work was done in the Lesker machine which is a fully computer controlled tool. By introducing a recipe into the system and follow the software in all steps, the user has the possibility to control the whole system (See Fig 3.5).

3.2.7 Lift off

Lift off is a process for removing metal layers which form on top of the resist mask during the evaporation process. Using different Chemical removers such as Acetone, 1165 or other chemicals used in the nanofabrication laboratory is a usual way for removing resist mask and the metal on top of it. There are some ways to speed up the lift off process, such as preheating the remover solution before putting the sample inside or using Ultrasonic while the sample is inside the remover (these methods applied unless the structure is susceptible).

The undercut emanating from the development of the bottom resist layer, helps to decrease the risk of damaging the metal pattern during lift off.
In this work, lift off was done by using remover 1165 which was heated up to 75°C for 10 minutes, followed by placing the sample in IPA (Isopropyl) for some minutes and washing sample with water (to remove IPA) and as the last step dry the sample and put it in sample box. Because of the sensitivity of the structure, using ultrasonic while sample was in IPA, was not used during lift off (See fig 3.6).

![Diagram of lift off process]

Microscope inspection after lift off is the final step in the fabrication process; beside that different filters in the optical microscope provide multiple ways of inspection.

### 3.3 Inspection of samples

To generate working samples, the success of the entire fabrication process is required; a simple error in one step, leads to an unusable sample for which continued work is just wasting time. For example, if the output features of the lithography do not match with the desired layout (because of errors during the process of using uneven photoresist), the user is going to spend time on a sample which will not show appropriate results in measurements.

Considering the time consuming fabrication process, optical inspection is an important step that will minimize unnecessary work; besides that some errors that are detected can be adjusted by an additional fabrication step.

Optical microscopy, scanning electron microscopy (SEM) and atomic force microscopy (AFM) are proper ways for examining the surface of chips. Because of the destructive effect of Scanning Electron Microscopy (SEM) on the sample, doing this kind of inspection is not recommended before measurements; instead atomic force microscopy can be used.
3.3.1 Optical microscope inspection

There are two types of field (Bright and dark field) in an optical microscope; the principle of imaging in both is the same. The surface materials reflect light of different wavelengths. In this work, the bright field optical microscope was used. This kind of microscope utilizes light perpendicular to the specimen [10].

The resolution and magnification of optical microscopes vary between different models and the one used in this work has a resolution of about 250nm and a maximum magnification of thousands of times; for this range of magnification, it is clear that there is no chance to see the smallest part of the sample with size around 50nm. Anyhow, even the small parts interfere with surrounding materials and this interference can be observed.

An example of an optical microscope picture is presented in figure 3.7. The diagonal lines represent Aluminum or the superconductive part and the horizontal line represents the normal metal part of the structure.

Since optical microscopy is a nondestructive inspection method, there is no limitation for frequently usage [27]. If any error in formation is found with this inspection, this can be connected through fabrication steps or if the sample has uncorrectable errors, the sample can be thrown away.

![Image](image.png)

Fig3.7: Inspection by optical microscope for sample B6-56 after liftoff step. (a) The optical microscope inspection with UV filters. Superconductive parts are shining when using this filter (b) the inner part of the structure; the superconductive parts are shown by an S and the normal part is shown by an N.

3.3.2 Scanning Electron Microscopy

The principle of Scanning Electron Microscopy (SEM) is the same as for Electron Beam Lithography (EBL); In EBL, the sample’s surface is bombarded with electrons with energy between 0.5-40KeV [10]. In SEM, pictures were formed by scanning the surface with incident electrons and detecting secondary electrons. Since surface topography gives precious information about the sample, it has always been an
interesting topic; and this is the reason to use the detection of secondary electrons. In fact secondary electrons were generated when the incident electrons ionize the sample’s atoms. The current’s magnitude depends on the surface material and mainly on the curvature of the surface.

The SEM counts as a destructive inspection method and could destroy the sample; because of this, SEM is never used before measurements [11]. Doing SEM and catch pictures in this way is favorable as it gave information about the sample, errors in fabrication and the answer to the question why the sample was not working properly and why it gave unexpected results in the measurements.

The maximum resolution of the SEM is about 1-2nm corresponding to a magnification of 300 000 times. Seeing that, the resolution is far better than that of the optical microscope, many features on the sample were clearly visible in SEM.

By taking a look at fig 3.8, you see an example of a SEM picture. Even the slightest features of layout can clearly be seen and measured by using the length scale. The shadow evaporation and some errors are clearly visible. Errors will be discussed in chapter 6.

Fig 3.8: SEM Image of sample B-56, with second layout
3.3.3 Atomic Force Microscopy

Atomic Force Microscopy (AFM) is one kind of Scanning Probe Microscopy (SPM) for which the principle of is to scan a small area of the surface by a sharp tip. In AFM, the extremely sharp tip is mounted on the end of a cantilever which is moved by a mechanical scanner over the sample and any variation of the surface height causes a variation of the force of acting on the tip and varies the bending of the cantilever. The bending is measured and recorded in an electronic memory and finally gives a 3D picture of the scanned structure.

While the lateral resolution of an AFM is about 30 nm, the vertical resolution can be up to 0.1 nm. As AFM doesn’t have any destructive influence on the structure, it can be used for studying the structure even before measurements and directly after fabrication.

In the appendix there is a comparison table between SEM and AFM and an explanation in more details.

In Fig 3.9, an example of an image obtained by AFM is presented. Shadow evaporation is visible in this image.

Fig3.9: Inspection by AFM. (a) A 2D image of the structure. (b) A 3D picture of the structure. The superconductive parts are shown by S and the normal part is shown by N.
Chapter 4

Experiment realization

The main requirement for an appropriate realization of an experiment is to recognize its theoretical and practical limits. This chapter starts by a discussion about that and it continues by talking about the proposed solutions which enabled the experiment and a description of the chip setup.

4.1 Requirements for the experiment

For the purpose of achieving a critical current and observing it’s exponentially suppression \((I_c \propto e^{-L/L_\phi})\) described in section 1.2, the experimental system has to contain an electrical circuit with resistance of different lengths. For having superconductivity, the sample should cool below the critical temperature \(T_c\) (in this case, for Aluminum in bulk form the \(T_c = 1.2K\) while in thin film it could be higher \([16]\)). In this work, we also tried to minimize thermal noise while doing the measurements.

The limitations of different fabrication technologies were be described in the fabrication chapter. The smallest parts of the structure are of the order of 42nm, and this gave the limit as to how small the structure could become. As described in section 1.2, there is some limitation in order to keep in \(L < L_\phi\).

Since the main junction has to be fabricated in conducting metal which keeps in its normal state at the experimental temperature, Gold and Silver are two possible choices. Using Aluminum as the superconductive part was the only choice at MC2 Lab.

4.2 Chip overview

Figure 4.1 shows the chip (sample) at different zoom levels for the first and second layouts. It contains a comprehensive view of the entire chip and the central part of the chip. The difference between the first and second layouts is in the design of the central part. In general, the rim of the chip contains 16 contact pads which are numbered clockwise as shown in Fig 4.1 and they are big enough to see with the naked eye. Each contact pad is connected to 16 secondary contacts by thick contact lines; specifically in the second layout, number 15, 16, 1 to 6 secondary contacts are connected to the top part of the main junction line by thin contact lines and number 7 to 14 secondary contacts are connected to the bottom part of the main junction by thin contact lines. The thick connections (with 20\(\mu m\) wide) which leave contact pads to connect to the secondary contacts are shown with green color. Thin contact lines (with 2.1\(\mu m\) width)
are shown with white color. The main junction line with 100\text{nm} width and 16\text{\mu m} length is shown with red color. The ID number which represents the model of chip is also shown at the top of the layout. Three red crosses in three different corners of the chip are used as guide lines during EBL.

4.3 Realization of experiment

In this work, samples were made according to a layout created by Leonid Kuzmin and explained in section 4.2 and fabricated by techniques described in the fabrication chapter.

The angle of shadow evaporation was changed from the first to the second layout; but since the first layout gave errors in measurements which will be described in the result chapter, most experiments were done with the second layout. An additional layer of Pd (Palladium) was inserted in the latest structure to have better adherence between normal and superconductive metal.

Throughout the entire process, samples were screened by using inspection techniques described in section 3.3. Samples were fabricated and measured electrically at room and low temperature according to the process given in the measurement setup chapter. The results of the fabrication and measurement process are provided in the chapter on experimental results and analysis; also in this chapter the resistance of the external wires had been removed from the final resistance.
Fig 4.1: The original AutoCad layout for (a) first layout and (b) second layout
Chapter 5

Measurements setup

After the fabrication steps, the most reliable samples will be chosen for measurements. To check the whole structure and survey the level of performance, a resistance check on the structure is required. The final data can provide information which proves or reforms theory and it’s important to use a proper measurement setup and technique.

In this work, measurements were done in two different setups; at room temperature and in the sub-kelvin regime. While Current-voltage curves were received from both measurement setups an extra measurements was carried out at low temperature (sub-kelvin) measuring the temperature dependence of the current-voltage Curve.

5.1 Room temperature measurement

Since loading a sample in the cryostat for sub-kelvin measurements takes more time and cooling down the cryostat has a significant cost, room temperature measurements are important for choosing promising samples for loading in the cryostat.

The setup for room temperature measurements contains a sample holder with pins which connect to the sample and the whole holder is connected to an amplifier and multiplexer box. It has a sweep generator and an oscilloscope which are all connected to software to display IV curves on a monitor. In this system voltage was measured with the voltmeter and converted into current. Also, by changing the bias resistance the user can control on the current which is applied to the structure during the measurement. Fig5.1 shows a complete view of the measurement setup.
To start the experiment, the sample is mounted in a sample holder which is a copper tube and acts as electrical shield against interference. The sample is placed inside the copper tube and all 16 contact pads on the sample are connected to their own contact pins on the sample holder, see Fig 5.2. Now it is time to connect the sample holder to the measurement box that contains a matrix board. Pins can be placed in the matrix board to create the desired measurement schematic.

Resistance data can be measured in two, three or four point measurement setups but two point measurements represent the common type of measurement setup to begin with.

For measuring voltage and current over the sample, four wires have been used. If the voltage and current are measured over the same two contacts, a two point measurement is performed.

At this point the electric characterization of the metals on the sample gave information which was useful to detect errors such as broken lines or short circuit. For this reason, knowing the resistance of the junctions is the only interesting information and since the IV characteristics are all linear at room temperature this could be found from IV Measurement. So voltage is simply measured over the sample- including all electrodes and cables which are located between the sample and the voltmeter (However some resistance cannot be singled out with this type of measurement). In the measurement system the resistance of each cable is about 100Ohm and for each contacts the desired resistance can be deduced from the layout. Hence, if we find a different resistance this indicates damage somewhere in system. For checking the resistance of a specific part of the structure or find the exact place of damage three point and four point (or Kelvin) measurements are applied. When the pins had one contact in common, it’s called three point measurements and when the pins didn’t have any common contacts it is called four point measurements. Fig 5.3 shows the schematic of the electrical circuit and the simulation of a current-voltage path over the layout.

![Fig 5.3: Electrical circuit and simulation over the layout for different IV measurement setups](image)

Samples which indicated a reasonable resistance and working connections proceeded to cryogenic measurements.
The risk of damage was high while loading and unloading a sample into the measurement setup. Besides that static electricity from the human body could burn connection lines and destroy the sample. To prevent this common problem, the sample and the user should have contact with a ground cable. Another damage that was avoidable with greater precision was the breaking of connection lines by scratches from the tweezers used to hold the sample.

5.2 Cryogenic (low temperature) Measurements

When talking about Cryogenic measurements, the desired temperature which is called base temperature is just below 300mK, more often at 280mK. The resistance of the metals and especially the superconducting metal parts on the sample are then very different from the values at room temperature.

After checking the sample by room temperature measurements, the low temperature characterization begins. In this step, the genuine noise properties of the samples at their operation temperature will be examined [1].

In the whole measurements process two different modes (current bias mode and voltage bias mode) were available and in this work, the current bias mode was used. For some samples, IV measurements at different temperature were done. The electric characterization of the structure determined whether it was comparable with theory or not (see figure 6.5, IV curves of measurements). Moreover, as illustrated in the theory section, the current response to an applied voltage or vice versa has a characteristic behavior for superconducting Josephson Tunnel junctions.

5.3 Cryogenic Equipment

The cryostat is constructed to provide cryogenic temperatures; with various refrigeration methods there is a possibility to reach low temperature. In this work two different types of cryostat were used, the Helium-4 cryostat and an Oxford Helium-3 cryostat. In the first measurements the Oxford Helium-3 was used, this system is based on helium-3 condensation and is able to achieve a base temperature down to 280mK. The second measurements were run in a Helium-4 cryostat designed to achieve temperature less than 30mK; this instrument is located in the laboratory in Nizhniy Novgorod in Russia.

5.3.1 The Heliox ³He refrigerator

The sample holder contains the sample, and is mounted inside a cryogenic refrigerator (also known as Heliox ³He refrigerator or cryostat) for cooling. After closing and sealing the vacuum jacket of the cryostat, the evacuation of air will begin and will be
continued until the pressure has reached around $10^{-5}$ mbar. Now is the time to turn on the main cooling device which is a pulsed tube cooler (PTC).

When operating at low temperature, the He-3 refrigerator has two modes of operation. After initial cooling by the PTC, until the second stage of the PTC has achieved a temperature of around 3.3K, the sorption pump is warmed to release the adsorbed He-3 gas. The temperature will rise initially and subsequently fall again as the gas is again cooled by the second pulsed tube cooler stage. Then the He-3 gas will cool the He-pot with the samples, until a temperature close to that of the second PTC stage is reached. Some of the He-3 gas has liquefied in the pot at this point, to an extent depending on the temperature of the PTC. As final cooling step, the heat switch between the sorb and the PTC is closed so that a strong thermal link is formed in between them. The PTC will cool the sorb to below 4K, which will decrease the vapor pressure of He-3 above the liquid even more, causing further cooling of the sample. When a temperature of around 300mK or below has been achieved, measurements can begin, see Fig 5.4.

Fig 5.4: Image of Cryostat in Quantum device laboratory of Chalmers University

5.3.2 The Heliox sample Holder

The sample holder used in this measurements, had been made as a coil with space for one sample to be placed on one of two flat bobbin’s sides. On upon each sample, a separate part with 16 contact pins for connection to the sample’s contact pads, must be mounted and tightened with screws for every new measurement. The opposite ends of the contact pins are soldered together with wires which are wound into twisted pairs, in
order to decrease the noise. Finally, the twisted pairs have been soldered to connectors matching those of the refrigerator, and insulated with nail polish. Thin wire is wrapped onto the bobbin in 312 turns and insulated with lacquer. The idea is to provide an opportunity of applying a magnetic field to the sample, in order to suppress the critical current in the SIS’ junctions.

5.4 IV Measurements in Current Bias Mode

In current biased mode, the voltage over the structure was measured as function of applied current. The amplifier box, which is connected to the sample, was provided with an input sweep voltage (V). Subsequently, there are two output signals corresponding to current and voltage respectively of the IV characteristics. One of them is labeled the output argument and the other the output function (to distinguish them from each other). In current biased mode, the current through the sample served as the output argument while voltage over the sample was named as the output function. The voltage that acts as output argument from the box in this case is a voltage proportional to the current through the sample and to the bias resistance $R_{bias}$ (which is adjustable during measurement). In order to obtain the actual current which is the argument of the IV-graph, the signal coming to the Irtecon is divided by $R_{bias}$. 
Chapter 6

Experimental result and analysis

In the present chapter, the results and developments in the fabrication method as well as the measurements of on fabricated samples will be provided. The main interest is the model of the Josephson Effect and studying the electrical characterization of this in the SNS structure.

Some steps in the fabrication process were changed with time; the main changes were about the geometry of sample, the materials and the evaporation recipe and the method in the measurements. This section is going to talk about these improvements.

Then it continues by showing how the experiment was corrected and finally presents the outcome of the measurements and provide an analysis based on the theory in chapter2. At the end of this chapter, some suggestion for future experiment are provided.

6.1 Fabrication outcome

In total about 30 fabrications were done for about 35 samples, based on the first and second layouts; information related to these samples are presented in Fig6.2.

The first layout was fabricated in chip size on wafer level (3inch silicon); as shown in Fig6.1, two thin lines are connected to squares, join and then connect to the top side of the main junction; in total this layout contains 8 thin lines connected to the main junction.

The resistances of the junctions have been measured at room and low temperature using two, three or four point measurements, as described in the previous chapter.
The large junctions with around 3\(\mu m\) length have a typical resistance of 250\(\Omega\) and the small junctions with only 0.25\(\mu m\) length have typical resistances of 12\(\Omega\) (the average value of resistance from different experiments); the variety in length is designed for studying critical current for different lengths.

Considering the measurements from the result of the first layout and applying some improvement, a change in design of the layout was made by L. Kuzmin and a second layout was generated. In this second layout, symmetric electrical measurements were considered to improve the chances for successful experiments. Also providing each junction with a specific connection line makes the measurements setup easier to work with for the user (as shown in the figure in section 5.1).

The second layout shown in figure 4.1(b) (in section 4.2) was fabricated in chip size on specific chips. This means that the initial contact pads were fabricated in the first EBL and the second pattern containing the inner structure parts was added in the second EBL. The resistance of each long junction (around 6\(\mu m\) length) and short junction (around 6\(\mu m\) length) were 350\(\Omega\) and 7\(\Omega\) for this layout, respectively (the average value of resistance from different experiments).

To modify the final result of measurements, fabrication recipes were varied from one chip to another. This includes variation in development time, materials and thickness of materials in the evaporation recipe.

### 6.1.1 Resistance and materials

In the first experiment, Pd had been used to improve film adhesion; first between substrate and normal metal and second between normal metal and superconductive metal. In the last processes, Ti was used as first layer as it was regarded to have a better adherence compared to Pd. But still it was difficult to get a critical current for samples with Ti-Au-Pd-Al-Al layers. This could be due to bad contact between different layers which leads to inappropriate Josephson junction fabrication.

To improve the method for observing a critical current and to make a real Josephson junction, we decided to make evaporation in a multilayer or sandwich structure after literature studies and some discussion. In Fig6.2, the list of evaporation recipes that were used in the fabrication is presented.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layout</th>
<th>Materials</th>
<th>Thickness (nm)</th>
<th>Fabrication Error</th>
<th>Measurements (R_{300K})</th>
<th>Measurements (R_{278mK})</th>
<th>SEM/AFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>B6-34</td>
<td>First</td>
<td>Au-Pd-Al</td>
<td>10-4-60</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B6-35</td>
<td></td>
<td></td>
<td>12-4-60</td>
<td></td>
<td>Yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B6-36</td>
<td></td>
<td>Pd-Au-Pd-Al</td>
<td>3-12-48</td>
<td></td>
<td>Yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B6-20</td>
<td></td>
<td>Pd-Al</td>
<td></td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sample</td>
<td>Fabrication Method</td>
<td>Alloys</td>
<td>Sample Range</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------</td>
<td>--------</td>
<td>--------------</td>
<td>---</td>
<td>-----</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>B6-26</td>
<td>Pd-Ag-Pd-Al</td>
<td>3-50-10-100</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-14</td>
<td></td>
<td>3-50-10-100</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-24</td>
<td></td>
<td>3-40-3-110</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-22</td>
<td>Pd-Au-Pd-Al-Al</td>
<td>2-16-2-42-33</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-23</td>
<td></td>
<td>4-16-2-25-42-80</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-32</td>
<td></td>
<td>4-16-8-60-84</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-33</td>
<td></td>
<td>2-8-5-38-50</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-31</td>
<td></td>
<td>2-8-4-32-50</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-21</td>
<td></td>
<td>2-5-3-28-48</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-15</td>
<td></td>
<td>5-30-5-51-81</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-45A</td>
<td>Pd-Ag-Pd-Al-Al</td>
<td>5-30-5-51-81</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-46A</td>
<td></td>
<td>5-30-5-57-81</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-56A</td>
<td>Al-Al-Pd-Au</td>
<td>20-36-5-35</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-43</td>
<td></td>
<td>2-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-54</td>
<td>Pd-Au-Pd-Au-Pd-Al-Al</td>
<td>2-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-44</td>
<td></td>
<td>5-3-10-3-56-70</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B6-55A</td>
<td>Ti-Au-Pd-Au-pd-Al-Al</td>
<td>5-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-56B</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-45B</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-46B</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-45C</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-55B</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-56C</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-51</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>B6-52</td>
<td></td>
<td>3-10-3-10-3-56-70</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Fig 6.2: Information on sample fabrication
The resistance of a junction is dependent on the thickness of the metal and the length of the junction. As Ag is not stable in contact with air, changes in resistance were observed from one measurement to another for the same sample. Because of some non-reproducible measurements and since the reaction could be strong enough in some cases to destroy the sample, the use of this metal was avoided in fabrication.

In section 6.2, more data will be discussed.

### 6.1.2 Geometrical consideration

In figure 6.3 some of the problems in fabrication are shown. Figure 6.3(a) shows a shadow of above and below the main junction which causes a short circuit in the thin line; it is due to overdevelopment in section 3.2.4. Figure 6.3 (b) shows a break in the main line, between junction parts; the reason is not yet known.

Since the structure is sensitive to angle evaporation, using the wrong sample holder resulted in fabrication of an inaccurate structure and further errors in measurement.

![Fig 6.3: Fabrication errors; (a) fabrication error is part of development step, caused by overdeveloping the structure; (b) fabrication errors in evaporation step.](image)

### 6.2 Experimental result analysis and data processing

Measurements were done by using the ‘‘Irtecon’’ subprogram and IV characteristics data were saved as Logfiles on the computer. Each individual Graph has its own data and because measurements for a single junction could be done several times, it’s obvious that the Logfile could contain several measurement data sets for the same junction. There are different ways to read these data for later analysis; one is using the LabView subprogram (which is plotting and makes it possible to plot many graphs from the same Logfile, all at once), Matlab, Origin or Excel.

The Irtecon program had different data presentation options such as I-V, $\frac{dV}{dl}$ - $V$, $\frac{dV}{dl}$ - $I$ and the other modes. In this work, the I-V mode was mostly used.
In the following, since the first layout didn’t give reliable results, the resistance mentioned in section 6.1 is counted as the reported data and this section focuses on the outcome for the second layout. Fabrication of different samples resulted in a variety of room and low temperature resistances. Even two samples with precisely the same fabrication recipe still produced different junction resistances. Measurements (for different samples) at low temperature were done in two different Cryostats; one with the possibility to go down to 278 mK present at the Quantum device laboratory of Chalmers university and the other with the possibility to reach down to 3 mK at Nizhniy Novgorod laboratory in Russia.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material &amp; Thickness(nm)</th>
<th>Junction ID</th>
<th>Length (μm)</th>
<th>$R_{300k}$ (Ω)</th>
<th>$R_{278mk}$ (Ω)</th>
<th>$R_{22mk}$ (Ω)</th>
<th>$I_c$ (µA)</th>
<th>$T_c$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B6-51</td>
<td>Ti-Au-Pd-Au-Pd-Al-Al</td>
<td>A</td>
<td>8.3</td>
<td>442</td>
<td>-</td>
<td>334</td>
<td>340</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(3-10-3-10-3-56-70)</td>
<td>D</td>
<td>0.97</td>
<td>58</td>
<td>-</td>
<td>44</td>
<td>46</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.55</td>
<td>43</td>
<td>-</td>
<td>30</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>0.38</td>
<td>25</td>
<td>-</td>
<td>17</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G</td>
<td>0.275</td>
<td>25</td>
<td>-</td>
<td>16</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.25</td>
<td>18</td>
<td>-</td>
<td>10</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I</td>
<td>0.2</td>
<td>15</td>
<td>-</td>
<td>1</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J</td>
<td>0.169</td>
<td>13</td>
<td>-</td>
<td>0</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>0.11</td>
<td>15</td>
<td>-</td>
<td>1</td>
<td>12</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>0.085</td>
<td>14</td>
<td>-</td>
<td>7</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.085</td>
<td>13</td>
<td>-</td>
<td>0</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>0.042</td>
<td>11</td>
<td>-</td>
<td>0</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>B6-45</td>
<td></td>
<td>I</td>
<td>0.2</td>
<td>15</td>
<td>28</td>
<td>2</td>
<td>25</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>0.085</td>
<td>13</td>
<td>18</td>
<td>1</td>
<td>15</td>
<td>0.3</td>
</tr>
<tr>
<td>B6-56</td>
<td></td>
<td>M</td>
<td>0.085</td>
<td>12</td>
<td>9</td>
<td>1</td>
<td>10</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Fig 6.4: Detailed information on the samples studied

A typical current-voltage characteristic is represented in Fig 6.5 for a structure with good interface contacts and a length of 42 nm. Above the critical temperature (in this case $T_c \approx 1.1 K$) the superconducting electrode lies in its normal state and the IV curve (in dark blue) displays Ohmic behavior with normal state resistance $R_n = 100$. By cooling down the sample and going down to a temperature below $T_c$, the IV curve (in red) displays three distinct conductance regimes [28]. Two linear regimes where the voltage is close to the resistance in the normal state and a zero voltage regime where the sample’s structure switches to a zero resistance state showing Josephson current. IV curves similar to that in Fig 6.5 were found for each successful fabrication (shown in
6.4) that shows critical current, is reproducible and agrees with other experiments made on same structure (SNS) [5, 29, 30]. The differential resistance $\frac{dV}{dI}$ as function of voltage is plotted in Fig6.6 for a junction with length $L=42\text{nm}$. As observed, the resistance significantly decreases from the normal state resistance $R_n$ at $|V| > 2\Delta/e$ to a sub-gap resistance at $|V| < 2\Delta/e$ and exhibits a symmetric resistance peak.

![Fig 6.5: IV characterization of a junction with 42nm length at temperature less than critical temperature and low temperature](image)

![Fig 6.6: The differential resistance as function of voltage for a junction with length 42nm](image)
The normal state resistance was measured as a function of length over different junctions in sample B6-51 using four-point measurements and the results are in Fig. 6.7. Although the experimental result is not completely linear due to noise it’s still valuable, since it is relative to junction’s length.

![Graph showing normal resistance $R_n$ for different length of sample B6-51](image.png)

**Fig 6.7: Normal resistance $R_n$ for different length of sample B6-51**

The correlation between the measured normal state conductance and the critical current can be confirmed by the $I_c R_n$. In Fig. 6.8, $I_c R_n$ as function of temperature for specific junction with shortest length $L=42\text{nm}$, is plotted. For this specific junction with a sharp critical current and zero voltage, we clearly observed the disappearance of the critical current by increasing temperature and in agreement with SNS Josephson junction on theory. This dependence was also observed in other experiments see ref [31, 32].
In the following I have made theoretical calculations based on experimental data which did not fit with theory. There are large deviations of the points from the fitted line of $R_n$ versus length. A rough estimate of the diffusion coefficient by using $D = \frac{V_f l_e}{3}$ (Fermi velocity of gold ($V_f$), mean free path ($l_e$)) gave a result of about $\sim 300 \text{cm}^2/\text{s}$. It corresponds to a mean free path of $\sim 70 \text{nm}$. It means that this sample is inappropriate for the study of physics connected with dephasing. A possible explanation for this could be inaccurate measurement of the normal part or bad contact between the normal part and the superconducting electrodes. Also, in this experiment there was a multilayer structure of Titanium, Gold, and Palladium (although the thickness of Ti and Pd is small) but in the calculation the Fermi velocity of gold ($1.4 \times 10^6 \text{ m/s}$[33]) was assumed. So still we need to be consider suitable values for the next generation of experiment and calculation in this field.

Moreover most of the junctions are so short that their Thouless energies are much larger than the superconducting energy gap, even in the long junction case. In this case one can estimate the value of the critical current at zero temperature as $eI_c = 7.9 \frac{T_c}{R_n}$.

For samples, number 7,8,12 it should be approximately $\sim 34 \mu\text{A}$ which is much larger than the measured current. Possible explanations for this, are bad contacts between the normal metal and the superconductor and/or bad measurements.

Also we’d like to point out that most of the obtained $I_c$ was found in short junctions whose Thouless energies are much larger than the superconducting energy gap and the

Fig 6.8: $I_cR_n$ measured as function of temperature for a junction with $L=42 \text{nm}$
theoretical estimate for $I_c$ was about $\sim 34\mu A$ which is much larger than the experimental result.

The intention of this work was to measure the critical current over long junctions while most of the observed critical current was found in short junctions.

<table>
<thead>
<tr>
<th>Junction ID sample</th>
<th>Length (nm)</th>
<th>R (Ohms)</th>
<th>$I_c$ (µA)</th>
<th>D (cm²/s)</th>
<th>$L_\varphi$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.2</td>
<td>12</td>
<td>0.6</td>
<td>260</td>
<td>1.53E-05</td>
</tr>
<tr>
<td>J</td>
<td>0.17</td>
<td>14</td>
<td>0.5</td>
<td>20</td>
<td>1.18E-06</td>
</tr>
<tr>
<td>K</td>
<td>0.13</td>
<td>10</td>
<td>0.5</td>
<td>169</td>
<td>9.97E-06</td>
</tr>
<tr>
<td>L</td>
<td>0.085</td>
<td>11</td>
<td>0.6</td>
<td>20</td>
<td>1.18E-06</td>
</tr>
<tr>
<td>M</td>
<td>0.085</td>
<td>15</td>
<td>0.6</td>
<td>11</td>
<td>6.52E-07</td>
</tr>
<tr>
<td>N</td>
<td>0.042</td>
<td>12</td>
<td>2.5</td>
<td>7.7993</td>
<td>4.60E-07</td>
</tr>
</tbody>
</table>

Fig 6.9: Calculated data for different junctions in sample B6-51
Chapter 7

Conclusion and future prospects

Hence to date, we have managed to fabricate a large number of non-suspended and suspended samples (of different lengths and thicknesses) and simultaneously we have done measurements at room and low temperature. We started this work by using a single metal as the normal metal part in the structure which did not give successful results in the measurements. Further on, based on different discussions and more article study, we selected a sandwich structure instead of a single metal and this lead us to observe a real critical current at least for one junction in a sample. We investigated the electrical properties of SNS junctions and measured relevant features of the current-voltage characteristic of the Josephson critical current. Although, we could observe a stepwise decrease of the conductance and a critical current before the conductance vanished completely and a change in resistance corresponding to the length there was a non-linearity aspect as well (this means that at zero length there should be zero resistance, and the linear function goes through zero); we assumed that this non-linearity could be due to bad contact between the normal part and the superconducting electrodes.

In this work, we were faced with an inapplicable sample for measurements of decoherence physics. The key problem is the fact that the decoherence length was much longer than the temperature length; and the solution for that is working at lower temperatures and focus the study on longer junctions (the idea is to measure the length dependence of the critical current at different temperatures).

We’d like to add some comments and talk about possible direction for future work in structure design and measurements; Working with a sandwich structure will definitely improve the chance of getting better results in the measurements but still it needs to be examined and explained in a theoretical model. Since the main idea is to do characterization on a long junction, we suggest to work more on the layout to achieve a better design with longer junctions. The last but not the least suggestion is to carry out all low temperature measurements in the Heliox4 cryostat to reach below 10mK which for this work is essential.
Bibliography:

Appendix A

List of Figures:

Fig 2.1: The superconducting critical temperature ($T_c$), is the temperature at which the resistivity of a superconductor drops to zero.

Fig 2.2: Represents the BCS theory structure.

Fig 2.3: Meissner effect in Superconductivity of (a) type I and (b) type II

Fig 2.4: Schematic picture of Andreev reflection at NS interface

Fig 3.1: Fabrication steps overview

Fig 3.2: Fabrication step. The figure shows the spinning of resist which plays a fundamental role to achieve a perfect sample in the final step.

Fig 3.3: Fabrication step, showing the EBL

Fig 3.4: Fabrication step, showing the development of structure after EBL

Fig 3.5: Evaporation through resist mask

Fig 3.6: Lift off process

Fig 3.7: Inspection by optical microscope for sample B6-56 after the liftoff step. (a) Optical microscopy inspection with UV filters. The superconductive parts are shining with this filter (b) the inner part of the structure, the superconductive part is shown with S and the normal part is shown with N.

Fig 3.8: SEM Image by sample B-56, with second layout

Fig 3.9: Inspection of AFM. (a) 2D image of the structure. (b) 3D picture of the structure. The superconductive parts are shown with S and the normal part is shown with N.

Fig 4.1: The original AutoCad layout for (a) first layout and (b) second layout

Fig 5.1: IV measurements in Voltage Bias mode

Fig 5.2: Image of sample holder for room temperature measurements

Fig 5.3: Electrical circuit and simulation of layout for different IV measurement setup

Fig 5.4: Image of the Cryostat in the Quantum device laboratory of Chalmers University

Fig 6.1: Autocad design of first layout

Fig 6.2: Information about sample fabrication

Fig 6.3: Fabrication errors; (a) fabrication error in the development step, caused by overdeveloping structure; (b) fabrication errors in evaporation step.

Fig 6.4: Detailed information about the samples studied.

Fig 6.5: IV characterization of a junction with 85 nm length at room and low temperature

Fig 6.6: The differential resistance as function of voltage for a junction with length 85nm

Fig 6.7: Normal resistance $R_n$ for different lengths of sample B6-51
Fig 6.8: $I_c R_n$ measured as function of temperature for a junction with $L=42$ nm
Fig 6.9: Calculated data for different junctions of sample B6-51
Appendix B

Technical Information:

This part will be presenting the tools which have been used in this work.

A.1 EBL (Electron Beam Lithography) [33]

The JBX-9300FS electron beam lithography system is a spot electron beam type lithography system designed for use in writing patterns having dimensions from nanometers to sub-micrometers. This tool is manufactured by JEOL Company and installed at MC2 Nanofabrication laboratory in 2002.

The system can be characterized as follows:

• The spot beam for electron beam writing is generated by a ZrO/W emitter and a four-stage electron beam focusing lens system.
• Pattern writing is performed by a combination of vector-scan type electron beam positioning and step-and-repeat stage movement.
• Electron-beam scanning speeds up to 25 MHz are available.
• The acceleration voltage can be switched from 50 kV to 100 kV and vice versa.
• Electron-beam scan increments down to 1 nm are available.
• The work stage can mount a wafer up to 300 mm in diameter as the work piece for writing.
• The position of the work stage is controlled by a laser-interferometer positioning system with a resolution of λ/1024 (approximately 0.62 nm).

![Fig A.1: Electron Beam Lithography tool at MC2 Nanofabrication laboratory](image)

A.2 Edward evaporator (Evaporator machine):

This evaporator is designed for high precision angle evaporation. It is equipped with a 4-position resistive evaporation source, and a fully automatic turbo pumping system which gives a base pressure of $< 5 \times 10^{-7}$ mbar. The Maximum sample size used in this tool is 50 mm with tilt stage, but without tilt it is possible to fit up to 6” (152.4 mm)
wafers. An oxygen gas inlet allows for oxidation of Al films. Materials permitted are Al, Au, Ag, Cr, Cu, Ge and Ti.

The main disadvantage of this tool is that the position of the metal source must be changed manually (which is a little tough) and sometimes caused metal to fall down from boats; besides the risk of breaking the boat while increasing the voltage for warming up the metal source (especially for W boat) makes working with this tool a little tricky.

In this tool, W and AlO2 boat have been used for Pd and Al evaporation. Based on the sample’s layout, it was also necessary to use ±45° tilting for Al evaporation.

As in the Edward evaporator the process is mostly manual. It means that by keeping an eye to the boat which carries the target metal and by increasing the power, more current is driven through the electrode which made a complete circle around the boat. The target metal started to melt when the boat warmed up. Once the evaporation rate shows on the screen, it’s the time to open the shutter. The shutter will be closed by the time we reach the desired thickness.

The tricky point in this tool is being careful while increasing power. It happened from time to time that pushing to much current caused a break in the boat and since the pumping down for this tool takes 6 hours, it will be really annoying to face this problem.

Fig A.2: Edwards Evaporator tool at MC2 Nanofabrication laboratory

A.4 Lesker evaporator (Evaporator Machine):

E-beam evaporator with up to 12 materials. This evaporator has a base pressure less than 10e-7 Torr/mbar after 90 minutes pumping down. It has ±45° tilt for samples which need shadow evaporation.

Computer controlling is one advantage and disadvantage for this tool. While it could make it easier to work with this evaporator, there is a possibility of getting errors during the process. Anyway, for multilayer fabrication this is the only tool which works so far.

Based on the software controlling system it’s one of the user friendly tools. After loading a sample, the next step for this tool is to setup a recipe in the software. When
the desired pressure is reached (it takes about 2 hours), evaporation by the running recipes should start. The machine increases current and voltage and heats up the metal source, then the metal begins to evaporate almost uniformly in the chamber and especially on to the shutter; there is sensor in the chamber which is used to determine the rate of evaporation and once the desired rate is reached, the shutter opens and the sample is exposed to the evaporating metal. The desired thickness had been set up in tool software and it automatically closes the shutter when this thickness is reached. In the case of a multi-layer recipe, after finishing the first layer the tool will be ready for running the next recipe and going through the same process. By the end of the process, it needs to wait some minutes for cooling down the source and it continues some more minutes for ventilating the chamber which means increasing the pressure inside chamber to atmosphere pressure and opening the door.

Fig A.3: Lesker#2 Evaporator tool at MC2 Nanofabrication laboratory

A.5 Plasma etches (Plasma etch tool):
This tool is more often used for oxygen stripping and for etching using fluorine type plasma. It has other available process gases such as Ar, CF4, and H2. This tool is fully computer controlled by a recipe which exists in the program. Although it’s a user friendly tool it has disadvantages such as flipping samples upside down while the chamber ventilates.
A.6 SEM (Scanning Electron Microscope):
The ‘‘Zeiss Supra 60 VP’’ Scanning Electron Microscope is an indispensable tool for inspecting nano-structures down to a few nm. The Schottky field emitter offers bright, stable image, and the instrument is very easy to use. The efficiently pumped load-lock can be used for wafers up to 8 inch in size. Work-piece movement over the full range is actuated by X-Y motors controlled by a joystick.
A.7 SPM (Scanning probe microscopy)

Scanning probe microscopes are devices that measure properties of surfaces. They include atomic force microscopes (AFMs) and scanning tunneling microscopes (STMs). In the initial steps, they were used mainly for measuring 3D surface topography. SPMs are the most powerful tools of our time for surface metrology, measuring surface features whose dimensions range from interatomic spacing to a tenth of a millimeter.

The instrument present at the MC2 laboratory is an Atomic force microscope (AFM). The main feature of this device is doing measurements which are performed with a sharp probe operating in the near field (that is, scanning over the surface while maintaining a very close spacing to the surface).

This Microscope (AFM) has an accuracy of about a tenth of nanometer, the same as the SEM; but the technique which is used in this microscope, is to use a cantilever with an extremely sharp tip made from diamond, silicon nitride or carbon nanotube which feels the sample’s surface and scans it. Probing the entire surface of the sample gives a 3-dimensional image.

![Fig A.6: (a) Layout of the environmental Atomic Force Microscope [36] (b) AFM tool at MC2 Nanofabrication laboratory](image)

More information about different microscopes are presented in Fig A.7.
<table>
<thead>
<tr>
<th>Microscope</th>
<th>SEM</th>
<th>AFM</th>
<th>TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>Vacuum</td>
<td>Vacuum, Air, liquid</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Source of radiation for image formation</td>
<td>Electrons</td>
<td>Feeling the surface using mechanical probing</td>
<td>Electrons</td>
</tr>
<tr>
<td>Dimensionality of image</td>
<td>2D</td>
<td>3D</td>
<td>2D</td>
</tr>
<tr>
<td>Utilization</td>
<td>Imaging and characterization the interior structures</td>
<td>Manipulate the molecules in addition to imaging</td>
<td>Imaging and characterization the interior structures</td>
</tr>
<tr>
<td>Time for image</td>
<td>0.1-1 Minute</td>
<td>1-5 Minute</td>
<td>0.1-1 Minute</td>
</tr>
<tr>
<td>Depth of field</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Field of view</td>
<td>1mm</td>
<td>100µm</td>
<td>100nm</td>
</tr>
</tbody>
</table>

*Fig A.7: Comparison between SEM, AFM and TEM (Transmission Electron Microscopy)*
Appendix C

PowerPoint of Presentation:

Outline
- Introduction
- Experimental procedure
- Result, data processing and fabrication outcome
- Conclusion
- Summary and future work suggestion

Superconductivity
- Heike Kamerlingh-Onnes, in 1911
  - Mercury (Hg), Au, Ti, Nb and ...
- 1950 → Superconductivity was showed theoretically
  - Ginzburg-Landau
- 1957 → Introduce microscopic definition for superconductivity
  - By J. Bardeen, L.N. Cooper, J.R. Schrieffer (BCS theory)
  - This theory relies on the assumption that superconductivity increase when the attractive Cooper pair interaction dominates over repulsive Coulomb force.

BCS Theory
- Go Below \( T_c \)
- Electron moving forward in lattice
  - Lattice motion and distortion by delay
  - Attraction of second electron to positive region and lattice returns axis to original place
  - Two electrons with opposite spin absorb each other which is formation of Cooper pair

Types of Superconductivity:
- Low temperature superconductivity
  - Pure metals
  - Distorted by BCS
  - Lose their s properties by placing in magnetic field
  - Show S below 30 K (−243.2°C)
- High temperature superconductivity
  - High Tc, known as high Tc
  - Include hole superconductivity
  - Includes more components
  - Okay Brandon effect but not completely
  - Gradually keep s properties by placing in magnetic field
  - Show S at or high as 123K (−150°C)
  - No theoretical explanation

Josephson Effect
- In 1962 Josephson predicted that tunnel junction consisting of two S, separated by thin insulating barrier should conduct super-current.
  - Experimental verification one year later by Anderson and Rowell.
  - Josephson awarded Nobel prize in 1973
- This means that Electrical current flows between two S materials even when they are separated by a thin insulator.
Andreev Physics

In 1964, Andreev suggest mechanism for charge transport through SNS junctions.

Two problem at the beginning:
- The normal metal length exceeds a length where Cooper pair can tunnel directly.
- Normal metal between two superconductor allows single charge carriers, electrons and holes to exist.

Andreev Suggestion:

Occurrence of superconducting manner in non-superconducting materials placed in perfect electrical contact with superconductor referred to Andreev effect.

Behavior of electron in nano-scale

Governed by Quantum mechanics:

- Manifest itself in different phenomena
- Resistive contact to metal's rings
- Andreev-Beenakker oscillation of resistance
- Weak link effect possible in conductance of normal metal
- Dirty normal metal

Conductivity of metal at low $T$:

Arrive from scattering on impurities given by classical Drude formula:

$$
\sigma = \sigma_0 \frac{e^2}{\pi h} \frac{1}{L}
$$

In realistic situation, there are:

- Electron-electron
- Electron-phonon

Interaction on $t_s$ is significant modify quantum behavior of conducting electrons in disordered metal.

At low temperature, focus on e-e interactions:

Decoherence:

- Electrons wave function stores random phase.
- Loss their ability to interface.
- Cooper pair decay.

Decay in time with new time scale $\tau_D$.

What happen when $\tau_D$:

- $\tau_D$ grows unexhibited.
- $\tau_D$ saturate to finite value $\tau_D = \tau_{in}$.

So system consisting of $N$ and $S$ is good for studying quantum decoherence as function of system parameter.

A. Semenov, A. Zalubin and Liubimov have addressed a problem of quantum decoherence by electron-electron interactions in NS nanostructure theoretically in 2012.

Existence of $\tau$ impose fundamental limitation on perpendicularly effect at low $T$ ($\tau < \tau_D$).

Experimental procedure:

1. Design layout
2. Spin resist
3. E-beam lithography
4. Dipping
5. Development
6. Ashing
7. Evaporation
8. Lift off
9. Sample inspection
10. Measurements
   - Room temperature measurements
   - Cryogenic measurements

Andreev conductance for NS in presence of e-e interactions at low $T$ depends on $\tau_D$.

So if:
- $\tau_D < \tau_T$
- Normal metal layer is long enough $L_n < \xi$

Andreev conductance for NS at low $T$:

Josephson critical current should be exponentially suppressed at $T = 0$.

$$
I_c = \exp(-1/\tau_D)
$$
1. Design Layout
- Symmetrical Junction
- Independent electrodes

2. Spinning Resist
- Copolymer (common for early) / Polyester (for newer)
- ZEP 52011 (common for newer) / Shipley 1130 (for test)

3. E-beam Lithography
   Introduce design on wafer at low pressure

4. Dice

5. Development
   - Methyl Alcohol (common)
   - PEG 400 / IPA 1:1 (novel/novel)

6. Ashing
   - Remove organic contamination
     (By Oxygen plasma for 10s)

7. Metal Evaporation
   - Edwards Evaporator
   - High vacuum / Low pressure

8. Sample Inspection
   - Detect fabrication error
   - Optical Microscope
   - Scanning Electron Microscope (SEM)
   - Atomic Force Microscope (AFM)
10. Measurements

- Room Temperature Measurements
- Low Temperature Measurements

Fabrication outcome and errors:

- Over developing
- Angle evaporation
- Measurements errors

Solutions:

- Keep developing time by second accuracy
- Select right sample holder
- Grounded user and measurements facilities
- Control current flow by bias resistance and start by following small amount of current through junctions.

Experimental Result, fabrication outcome and data processing

- Fabricate more than 40 samples
- Doing Measurements for more than 35 samples
- Data analyzing for 4 samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Room temperature</th>
<th>Length (μm)</th>
<th>Current (μA)</th>
<th>Resistance (μΩ)</th>
<th>Critical Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1A</td>
<td>3.5</td>
<td>12</td>
<td>89</td>
<td>520</td>
</tr>
<tr>
<td>B</td>
<td>2A</td>
<td>4.5</td>
<td>15</td>
<td>89</td>
<td>520</td>
</tr>
<tr>
<td>C</td>
<td>3A</td>
<td>5.5</td>
<td>18</td>
<td>89</td>
<td>520</td>
</tr>
<tr>
<td>D</td>
<td>4A</td>
<td>6.5</td>
<td>19</td>
<td>89</td>
<td>520</td>
</tr>
</tbody>
</table>

Normal resistance $R_n$ versus length for different junctions

- Non-linearity because of having noise while doing measurements
- Changing resistance correspond to length

Normal resistance $R_n$ vs. Critical current $I_c$
Conclusion

- Manage to achieve general properties of SNS junction
- Changing resistance correspond to length but with non-linearity aspect (this means that at zero length there should be zero resistance, and the linear line pass zero), this could be because of bad contact between normal part and superconducting electrodes.
- Estimation of diffusion coefficient by using \( D = \frac{v_f}{2} \) (Fermi velocity of gold \( v_f \)), mean free path \( \lambda(v_f) \) give result about \( \approx 300 \) cm\(^2\)/s. It corresponds to mean free path \( \approx 70 \) nm. It means that this sample is inappropriate for the studying of physics connected with dephasing.
- Most of obtained \( j_c \) belong to short junction which their Thouless energies are much larger than superconducting energy gap
- Theoretical estimation value for \( j_c \) was about \( \approx 36 \) A/m which is much larger than experimental result

Summary and suggestion for future work

- Fabrication non-suspended and suspended samples with different thickness and in different junction length
- Doing room and Low temperature measurements
- Investigation of electrical characterization of SNS Junction
- Achieving critical current for short junctions
- Studying temperature dependence of critical current

Suggestion for future work:

- Try different layout have direct impact on result
- Working with sandwich structure for studying SNS junction will be more effective
- Doing low temperature measurements in Heliox cryostat regarding to reach 10 mk temperature

Acknowledgments:
This project was supported by the Bolometer group of Quantum device Physics laboratory (Chalmers University Technology). Two theorists, A.Zaikin and A.Gomenev supported analyzing the theoretical part and L.Kuzmin and S.Mahashode, were my supervisor in experimental part.