Proposed Study of Spin Currents in Metallic Nano-Structures

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A dissertation submitted for the partial fulfilment of BS-MS dual degree in Science

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April, 2015

Certificate of Examination

This is to certify that the dissertation titled **Proposed Study of Spin Currents in Metallic Nano-Structures** submitted by **Mr. Aaveg Aggarwal** (Reg. No. MS10101) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. Sanjeev Kumar | Dr. Ramandeep Johal | Dr. Ananth Venkatesan

(Supervisor)

Dated: April 22, 2015

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Ananth Venkatesan at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Aaveg Aggarwal

(Candidate)

Dated: April 22, 2015

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Ananth Venkatesan

(Supervisor)

Acknowledgement

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Aaveg Aggarwal

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Abstract

Charge transport of electrons in mesoscopic systems display a variety of interesting quantum effects. Universal Conductance Fluctuations (UCF) is one such effect where sweeping a magnetic field when measuring the resistance of a sub-micron metallic wire, noise like fluctuations are seen. But the fluctuations are reproducible when the field is swept back and forth. This unique magnetic finger-print is due to scattering from impurities when phase coherence of electrons are comparable to device sizes. Spintronics is an emerging field where the spin of the electron is used to process or transmit data like the charge in conventional electronics. A pure spin current without charge transport is central to not only spintronics but also to realize novel effects related to spin in nano-scale devices. In this proposal we do some experimental ground work to make metallic nano-structures. The classic Johnson-Silsbee non-local geometry will be used to generate and detect spin currents. The main motive is to look for effects similar to UCF but in spin currents. Separating charge UCF from spins will be one major challenge. The main work involves perfecting the lithography to make metallic devices on sapphire. Sapphire was chosen due to its high thermal conductivity at low temperatures which is needed to cool the devices efficiently. A host of other work needed to start the measurements like cryogenic filters for noise coldfingers and sample holders are being designed in this work.

This dissertation opens with a brief introduction on the physical concepts governing the experiment, extensively explains the device fabrication procedure in the second chapter and the proposed setup in the third. The dissertation closes with a brief description of the major equipments in the appendix.

Chapter 1

Introduction

In the year 1921, two physicists named Otto Stern and Walther Gerlach [2], carried out an experiment with silver atoms and discovered a strange property of electrons, which was later termed as ***Spin***. The spin is an additional degree of freedom that a quantum particle like electron possesses. This can be thought of as an arrow that points in a direction. Just like other degrees of freedom, the spin is also quantised which means that the arrow can now point in only specific directions. Electrons turn out to be spin half particles which means that the electron can have two possible orientations i.e. spin up or spin down.

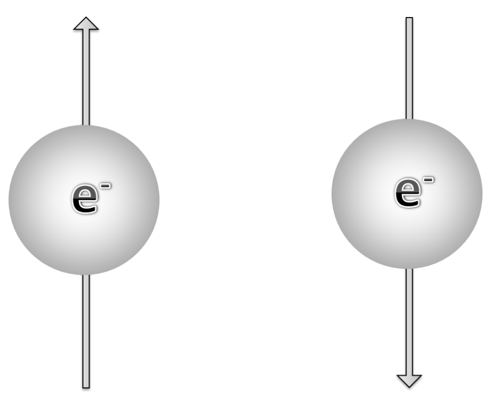


Figure 1.1: The two possible orientations of an electron.

Because of the spin, the electrons behave as tiny magnets (with two possible orientations) and this property of electrons can be exploited to create more sensitive and powerful devices. This thought process has led us to a new and very active field of research, that has the potential of changing the future of electronic devices i.e. ***Spintronics***.

1.1 Generation of Pure Spin Currents

Most of the spin devices are based on *spin currents*, which basically means a transfer of spin angular momentum without a net transfer of charge. One approach to generate a pure spin current is to have a ferromagnet as a spin injector [3]. The ferromagnet injects polarised electrons in the system because electrons which tunnel through ferromagnet junction retain their polarisation. The same ferromagnet can also be used a a detector. As shown in Fig.1.2 the ferromagnet in the second loop selectively allows polarised electrons to pass through it and develops a voltage in the second loop.[3] discusses more on this.

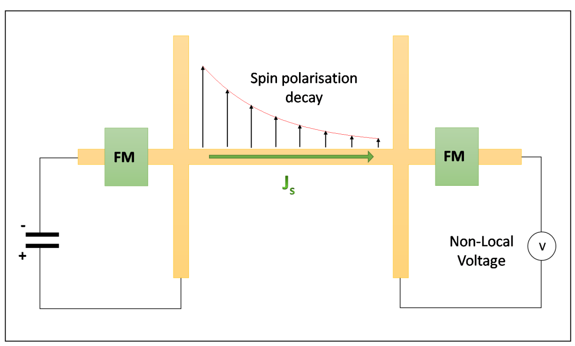


Figure 1.2: Schematic based on [3] to show the generation and detection of Spin currents using ferromagnets.

A second approach is called the ***Spin Hall Effect (SHE)***. It refers to the accumulation of spin in the direction perpendicular to the direction of flow of the charge. This phenomenon occurs due to intrinsic spin orbit interactions and spin dependent scattering and therefore does not require a ferromagnet. As shown in Fig.1.3 J_C represents charge current and J_S refers to the spin current. It can be seen that the spin current is generated in the direction perpendicular to the direction of charge current. To detect this spin current we can use the inverse relation called ***Inverse Spin Hall Effect (ISHE)*** which suggests that a spin current will lead to accumulation of electric charge in the perpendicular direction. This charge accumulation due to spin current can easily be detected using a voltmeter. Fig.1.3 shows a schematic of this approach.

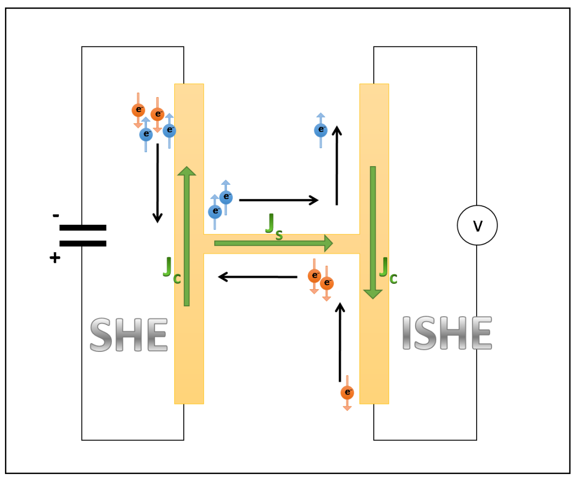


Figure 1.3: Schematic based on Spin Hall Effect and Inverse Spin Hall Effect for the generation and detection of Spin currents.

Fig.1.2 and fig.1.3 shows how spin currents lead to a non-local detection of voltage. It is also interesting to notice that this non-local voltage generation violates the Kirchhoff's law.

Another important concept that we need to know is Universal Conductance Fluctuations (UCF), as our experiment involve measurements of UCF on nano-wires made of Gold and Gold-Palladium alloy.

1.2 Universal Conductance Fluctuations (UCF)

In a solid medium when the material is cooled to ultra-low temperatures, the defects in the material gets frozen. The electrons are primarily scattered by these defects in the structure of the solid. These defects can be viewed as the centres of electron scattering which in a small conductor can be coherently tuned by a magnetic field. The magnetic field can change the electron orbits around these centres which can change the overall conductance of the material. Therefore, the conductance of the material depends on these scattering centres/defects and the magnetic field strength. The conductance of the material fluctuates and these fluctuations are of the order of $\frac{e^2}{h}$ and hence the name. Fig.1.4 shows a typical conductance vs Magnetic field graph which is taken from, [1]

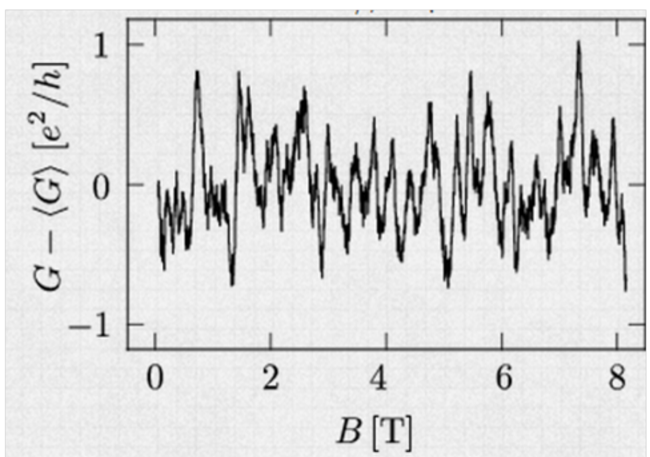


Figure 1.4: Fluctuations as a function of perpendicular magnetic field of the conductance of a 310 nm long and 25 nm wide Au wire at 10 mK. The trace appears random, but is completely reproducible from one measurement to the next. [1]

The interesting thing about fig.1.4 is that it looks like complete noise with no information content but that is not true. For many years it was thought of as noise but later it was found that this random looking data can be reproduced. Since these fluctuations occur because of the defects in the solid and since these defects are frozen at low temperatures, we would get the same pattern no matter how many times the data is recorded. Therefore, the plot of conductance versus Magnetic Field forms a signature of the sample. The signature changes if the sample is heated to temperatures $> 4K$ and cooled back again. This happens because the defects move as the temperature gets higher.

Chapter 2

Fabrication Process

We will be using the devices fabricated in the nano-fabrication facility at IISER Mohali for taking the measurements. In this chapter I will go through all the steps for fabricating a sample and side by side mention any precautions that needs to be taken.

The goal of the whole exercise is to fabricate a circuit over a wafer/substrate which has contact pads for connecting external instruments.

2.1 Cleaning

The wafer is thoroughly cleaned before starting the fabrication process. The cleaning process has three steps:

- **Acetone Cleaning**: The wafer is dipped for 20-30 minutes in acetone in ultrasonic bath.
- **Ethyl Lactate Cleaning**: After cleaning in acetone, the wafer is cleaned in Ethyl Lactate again for about 30 minutes in ultrasonic bath.
- **Iso-propanol Cleaning**: The wafer is thoroughly washed with Iso-propanol (IPA)

to get rid of any residue of Ethyl Lactate or Acetone. The wafer is then blow dried with Nitrogen.

2.2 Coating

Once we have a clean wafer to work on, we begin the process by coating ***LOR*** followed by Polymethyl Methacrylate (***PMMA***) on the wafer. The coating is done with help of a spin coater. For our samples, we used 100nm of PMMA and 300nm of LOR.

LOR is a proprietary product of Microchem and is available in two types - A series and B series. We use LOR A series as it has a lower rate of dissolution and hence easier to handle.

The advantage of using two layers is that we can get finer structures using this method.

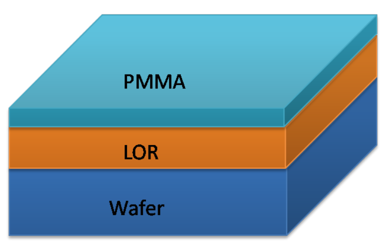


Figure 2.1: Bi-layer coating of LOR and PMMA on the substrate

2.3 Pattern Writing

2.3.1 Exposure

The coated wafer is then exposed to e-beam for writing the desired pattern. We have a Xenos pattern generator that works with the JEOL SEM. The generator comes with a software (Exposure Control Program) where we can write the instructions and also visualise the patterns before running the exposure. Since, PMMA is sensitive to electron beam, the places where the surface is exposed becomes loose and can be dissolved. Electron beam leaves LOR unaffected.

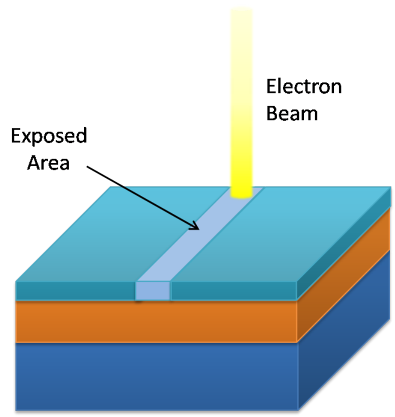


Figure 2.2: PMMA layer is exposed with electron beam

2.3.2 Processing PMMA

The solution used for dissolving the exposed PMMA is chosen depending on the type of pattern. We used the following two solutions:

- **IPA + Water** : Though IPA and Water both independently cannot dissolve PMMA but a mixture of these is a very strong dissolver. We use the ratio of IPA:Water to be 2:1 by volume. The sample is kept in the mixture for 15 seconds. This solution gives very sharp patterns and is recommended for structures below 100nm. The solution should be thoroughly mixed in ultrasound for about 30 minutes before use. Also, the timing should be carefully followed.

- **IPA + MIBK** : (MIBK stands for Methyl Isobutyl Ketone) We use the ratio of IPA:MIBK to be 2:1 by volume. This solution dissolves PMMA at a much smaller rate and we keep the sample in the solution for 2 minutes. It is recommended for patterns greater than 200. Though this does not give as sharp the edges as IPA + Water gives, but it is recommended for the ease of its use.

2.3.3 Processing LOR

The wafer is then dipped in 0.26N Tetramethylammonium hydroxide (TMAH) for about 30 seconds. After taking the wafer out, flush the wafer with excess DI water and then blow dry with nitrogen. This should create an undercut in the LOR as shown the the diagram below.

(a) Exposed area is removed

(b) Undercut in LOR

Figure 2.3: The device after LOR undercut

The following images were taken during a practice session with an optical microscope. These images will show show the fabrication process actually looks like. The device that we are trying to make is just a random pattern.

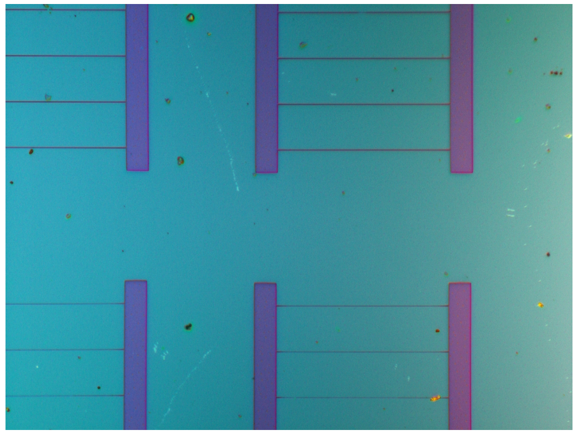


Figure 2.4: Pattern in PMMA. Violet colour of PMMA is also visible.

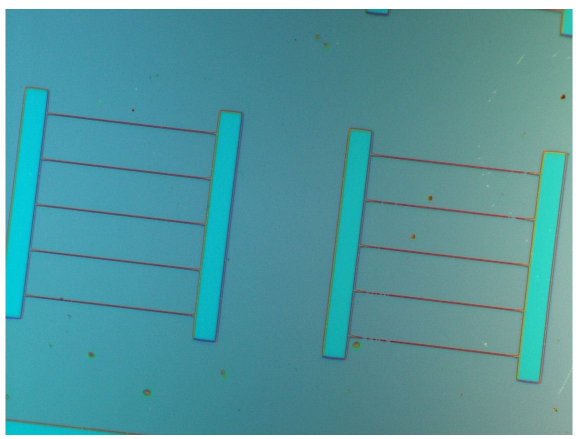


Figure 2.5: Double edges indicates that there is an undercut in the LOR. Also the colour of LOR has disappeared.

2.4 Evaporation

The above procedure will give us a stencil for the pattern to be made. The next step is to coat the wafer with the desired material. The material is thermally evaporated in a vacuum chamber to avoid any contamination. The following image gives a rough idea of how the sample looks like after the completion of this step.

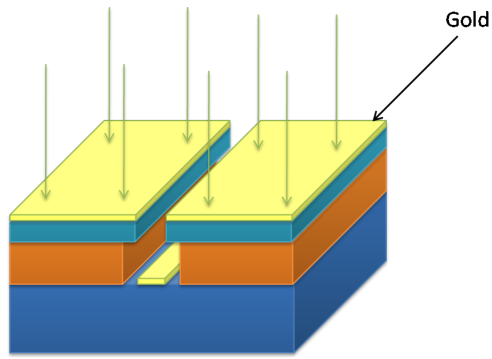


Figure 2.6: Device after Evaporation

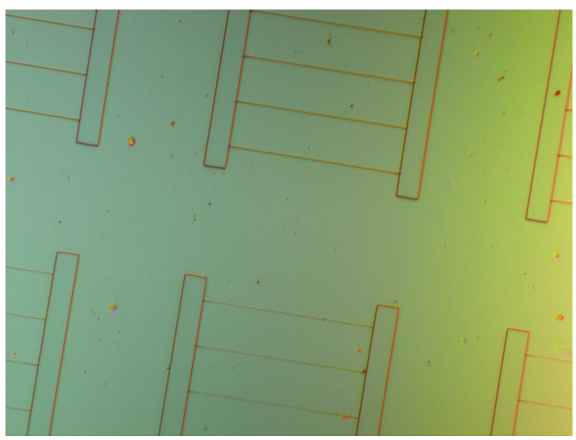


Figure 2.7: Germanium metal is coated on the patterns.

2.5 Lift-Off

This is the final step of the process after which we should get our samples ready for testing. In this process the bottom most layer i.e. LOR is removed with NMP. This leaves us with the pattern on the wafer.

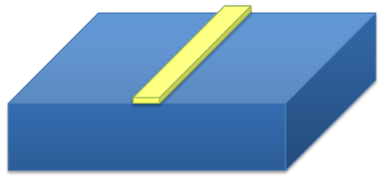


Figure 2.8: The final product of the fabrication process

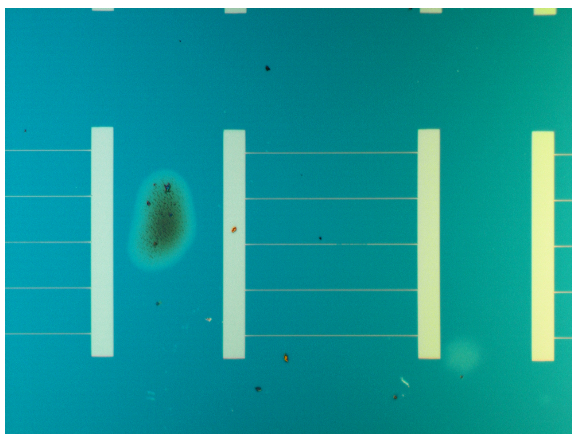


Figure 2.9: This is how the pattern looks like after the lift off. (Some unwanted residue is also present)

2.6 Non-Conducting Substrate/Wafer

The described process works absolutely fine for wafers that are electrically conducting. However if the wafer is non-conducting, the electrons will start accumulating on the surface during the e-beam lithography step. As a result, the electron beam gets deflected and the patterns become distorted. To solve this problem a layer of metal is used in the middle i.e. between LOR and PMMA. We used germanium as the discharge layer.

This brings us to yet another problem, which is to get past the germanium layer. For this, we use ***Plasma Etching***.

2.7 Plasma Etching

This is a technique where a plasma of a gas is used to etch a material in a high vacuum chamber. It is also known as dry etching. In our case we have to etch through the germanium layer and then the LOR layer. The process can also be used to clean substrate surface with oxygen plasma. Fig.2.10 taken from [5] can help understand the etching process.

There is an inlet and an outlet for the gas to be circulated at a specific pressure. The electrodes create enough potential to generate a plasma which then accelerates and strikes the target. The plasma of specific gases react with the respective targets and leads to etching of the target.

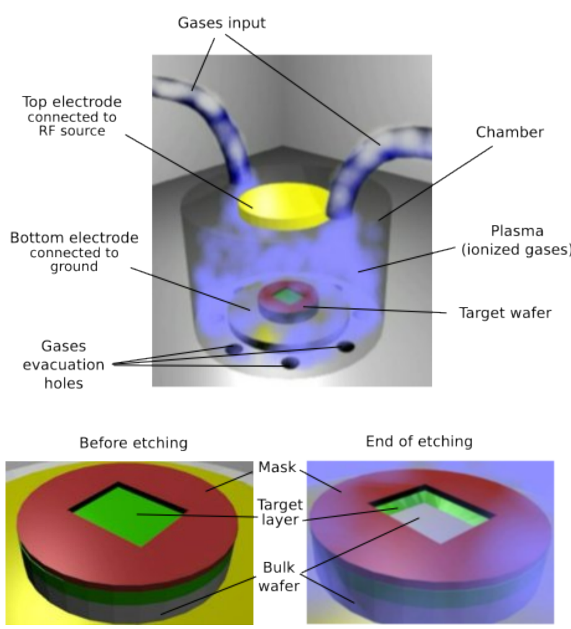


Figure 2.10: A schematic of a plasma etcher by [5]

Chapter 3

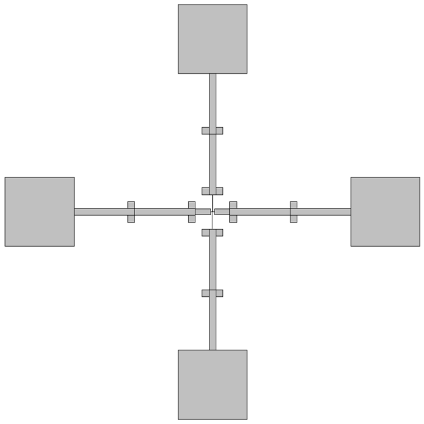
Proposed Experimental Setup

This chapter will give all the details regarding the designing and planning of the experiment. I will start with the design of the sample/device that is to be tested.

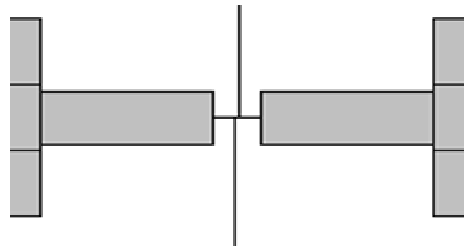
3.1 Device

Our device consists of a combination of both the schemes of spin injection and detection as discussed in the introductory chapter. The device has several probes to measure the voltage developed due to ISHE along the wire. The design below is the actual design of the sample on the ECP-program (lithography software) by Xenos.

We will take measurements on two materials which are gold and gold-palladium alloy and the ferromagnets that we will use are either permalloy or cobalt. The images below show how the trial device turned out to be.



(a) ECP drawing for the prototype sample



(b) Magnified center of the device

Figure 3.1: The drawing for the first device made

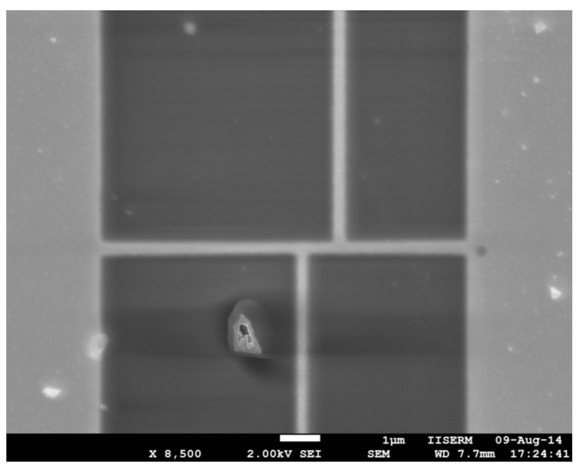


Figure 3.2: The SEM image of the device

After the prototype sample shown in the images we tried to use sapphire as the substrate. Since sapphire is a very good thermal conductor therefore it will easily cool the device. The gold wires on sapphire looks something like this:

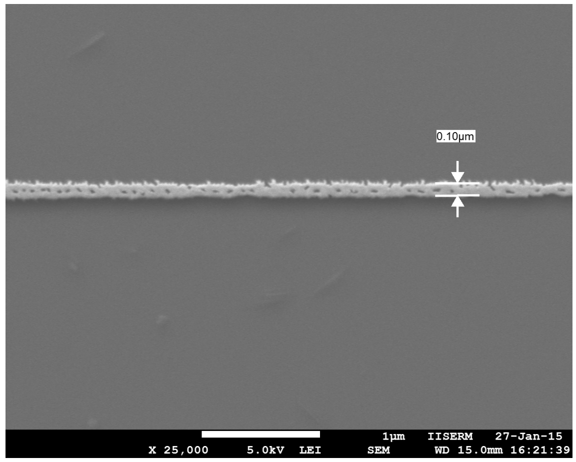


Figure 3.3: SEM image for a 100nm wide and 30nm thick gold wire on sapphire.

3.2 Sample Holder

These devices sit on a sample holder which has been designed on eagle software. The carrier has been designed to maximise cooling by having copper pour on both side of the PCB. The sample sits in the center of the PCB and we have made through holes in the center which will directly cool the sample.

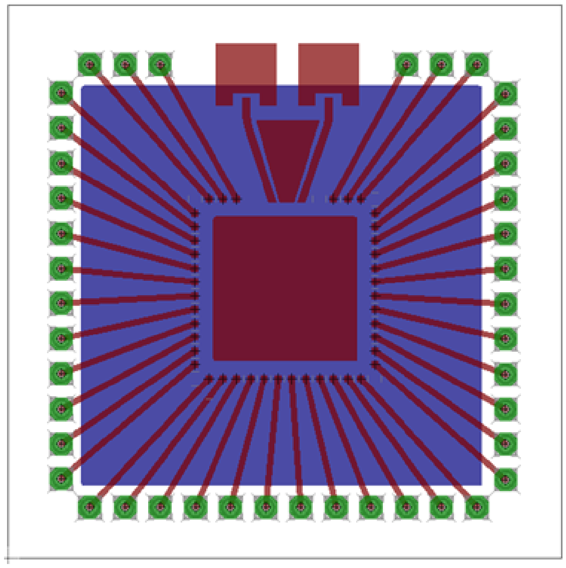


Figure 3.4: Eagle drawing of the chip-holder PCB

3.3 Filter and Wiring

We will be using twisted pairs for the measurements as it significantly reduces the noise due to external magnetic fields. The idea behind using a twisted pair is that the noise generated due to magnetic fields will cancel each other on the same wire. Fig. 3.5 by [8] helps visualise the concept better.

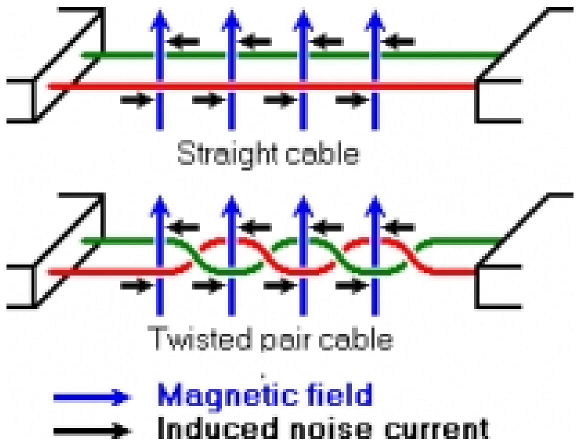


Figure 3.5: Concept of twisted pair by [8]

To reduce the noise in the measurements, we will pass our signals through a filter. We will be creating a transmission line filter with the help of copper tape. Fig. 3.6 shows the lumped circuit model for a transmission line low pass filter.

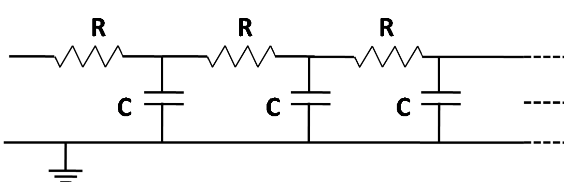


Figure 3.6: Lumped circuit model for a transmission line low pass filter

The circuit can be realised by sticking a copper tape on the twisted pair and grounding it. This will create a capacitive coupling to the tape(ground) and this will act as a low pass filter. [11]

3.4 Cold Finger

The physics we are trying to understand can only be seen at ultra low temperatures. We will be using our dilution refrigerator to cool the sample down to a temperature range of about 10 millikelvins. Such low temperatures can only be achieved by choosing the material of the cold finger and the can suitably. Therefore, we have chosen annealed oxygen free high conductivity (OFHC) copper. The designs of the can and the cold finger have been made in Solidworks, which is a 3D CAD software.

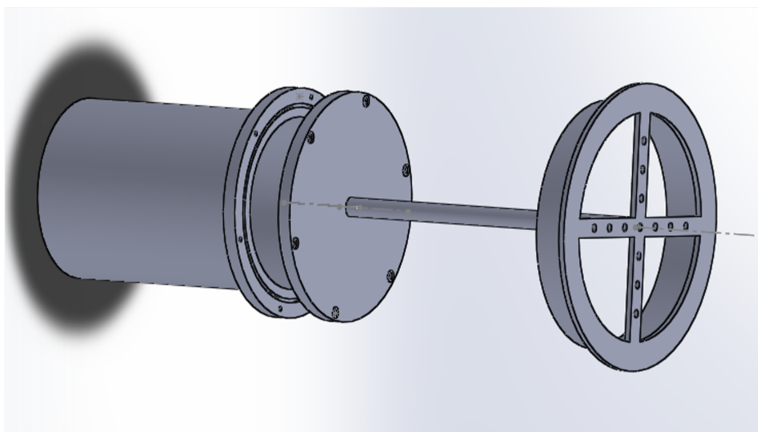


Figure 3.7: Eagle drawing of the chip-holder PCB

3.5 Dilution Refrigerator

A dilution refrigerator that is used for cooling to very low temperatures typically below 300mK. At present it is the only instrument that can provide cooling below 300mK. It is not possible to go below such temperatures using conventional ways, therefore dilution refrigerator uses a very smart technique. It uses two isotopes of He i.e. ^3He and ^4He. At low temperatures ^3He and ^4He undergoes spontaneous phase separation and the enthalpy change cools the system even further. There are other methods which can be used to reach even lower temperatures such as nuclear demagnetization but it will not be discussed here.

We have an Oxford dilution refrigerator installed in our lab which will be used to cool the samples.

Appendices

Appendix A

The images for all the equipments used in fabrication of a device are shown below:

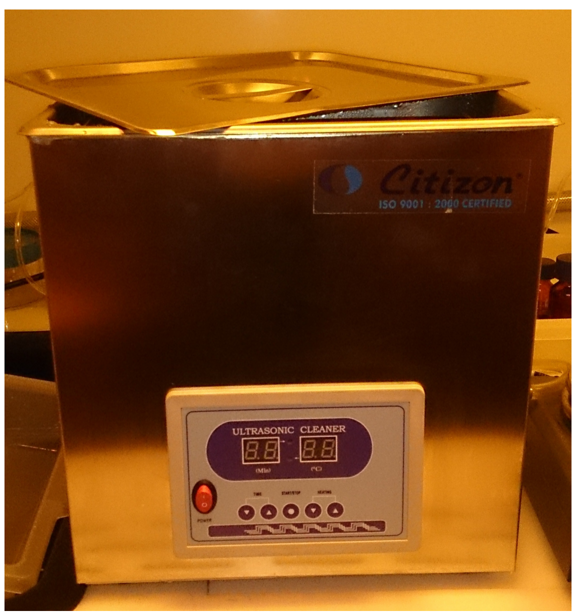


Figure A.1: Ultrasound Bath: This is used for cleaning the substrate.

Figure A.2: Spin coater: This is used for coating substrate with LOR and PMMA.

Figure A.3: Hot plate: This is used for baking LOR and PMMA after coating.

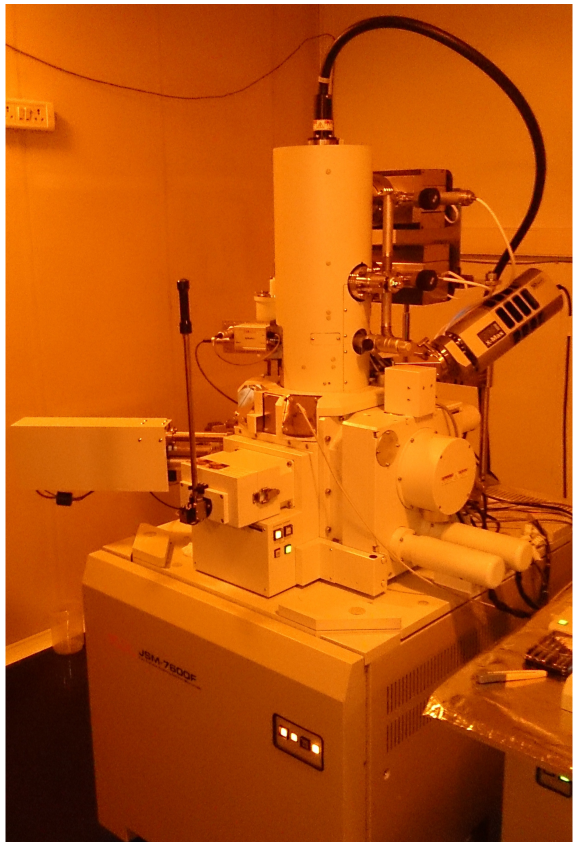


Figure A.4: SEM with lithography unit: This is used for writing on the PMMA and also imaging the device.

Figure A.5: Evaporation unit: This is used for evaporating different metals. This unit also has sputtering option

Figure A.6: Plasma Etcher: This is used for etching metals with the help of plasma.

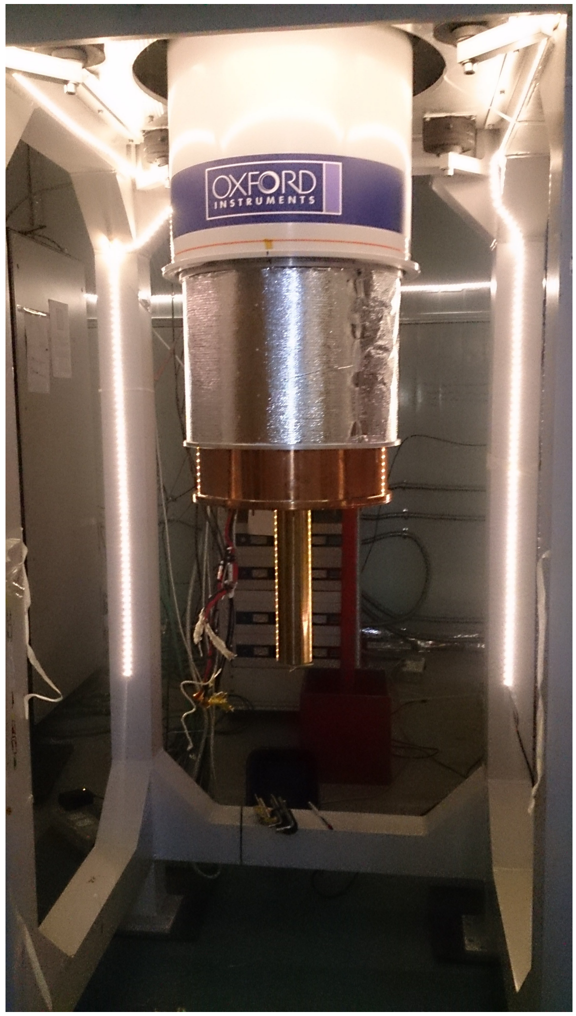


Figure A.7: Dilution refrigerator: This is used for cooling down the device.

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