A Proposed Fluxtronic Capacitor

VIVEK SINGH

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

Indian Institute of Science Education and Research Mohali

April 2017

Dedicated to my parents and Maharaj Ji

Certificate of Examination

This is to certify that the dissertation titled **A Proposed Fluxtronic Capacitor** submitted by **Vivek Singh** (Reg. No. MS11067) for the partial fulfillment 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.

Prof. Sudeshna Sinha   Dr. Sanjeev Kumar   Dr.Ananth Venkatesan

(Supervisor)

Dated: April 21, 2017

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 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.

Vivek Singh

(Candidate)

Dated: April 21, 2017

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

Dr.Ananth Venkatesan

(Supervisor)

Acknowledgment

I would like to thank my MS thesis guide Dr. Ananth Venkatesan, who gave me an opportunity for a project in his ULTP lab and for his unending guidance and support. I thank him for being extremely understanding and believing in me despite the difficulties I faced in my course work. I am thankful to IISER Mohali and DST nano mission for funding. A big thanks to Prof. Sudeshna Sinha and Prof. Kapil Hari Paranjape for mentally and academically supporting me during my first year when I was not feeling good in IISER Mohali and was planning to drop BS-MS program due to some personal reasons. I am very much inspired towards physics by the people of IISER Mohali, especially physics faculty and physics Phd students who help me gain a better understanding in physics. Words will never be enough to thank my Mom and Dad for their love, and for always supporting me financially and mentally. I express my deepest gratitude to my younger brother Sudeep who always helped and loved me like an elder brother. I would like to acknowledge my elder brother Rahul and my sister in law Aboli for never allowing me to feel alone in any condition of my life.And thanks to my cousin brother and cousin sisters for their love. Unexplainable thanks to my Spiritual Master 'Sant Rajinder Singh Ji Maharaj, who continues to support me internally and externally. A big thanks to Shyam and Shalender for helping me a lot in my project despite their own hectic schedule and workload. I would like to thank Inderjit (lab engineer), Soumyadip (Phd), Dr. Minaxi (Post-doc), Jasleen (Phd), Guratinder (Phd, Switzerland), Dr. Sheesram (First Phd-student from ULTP lab), Ushma (project student), Akumani (MS), Aaveg (Phd in Chicago, USA). Now a very special thanks to my best friend Anooja with whom I talked and fought a lot on many topics (academically and socially) during my MS. And now thanks to two very important people, Deepak and Neha, for providing me their spiritual as well as social company, and for keeping me positive and motivated all the time. I thank my old but gold friends Tarun, Sachin, Vikhyatand Vyom. A joyful thanks to my few nice friends, Nisha (Phd, IISERM), Sumit (Phd, IISERM), Smriti (Phd, IISERM), Anita (Phd, IISERM) and Hemanshu (past MS), who treated me as family and with whom I celebrated and enjoyed numerous occasions both inside and outside IISERM. Now I would like to thank few more nice people of IISER Mohali with whom I wish I could have spent more time during my MS - Kishor (Phd in NUS,Singapore), Manvendra (Phd, IISERM), Gyanendra(MS), Hari(MS), Abhinav Kala(Phd in TIFR), Ravi(MS) and Deepti(MS). I express my sincere thanks to Harbansh Uncle and his family for loving and treating me as if I were his grandson.I thank IISER Mohali staff (both administration and academic) for their cooperation with me during my BS-MS program

So my life is full of gems and all these gems help me every time and this time in graduating from IISER Mohali in May 2017. And last but not the least, I thank the land of Punjab for providing me such a beautiful place, loving culture and great vegetarian food.

List of Figures

Abstract

The Byers and Yang theorem predicts that multiply connected system like a superconductor that encloses flux is known to show flux periodicity in the partition function. As a result the free energy and all thermodynamic properties exhibited by the system show flux periodicity in-terms of the elementary flux quanta (ϕ_0 = h/e), where e = 2e in superconductors. The most common physical quantity measured in this context is the thermodynamic magnetization. One can assume other thermodynamic properties also exhibit the same flux periodicity. A capacitor that is charged and discharged adiabatically is also a thermodynamic system. We propose a capacitor with holes on a superconducting electrode would exhibit a flux dependent capacitance. We present some basic nano fabrication recipes to fabricate capacitor with micron and sub-micron holes. Other than simply demonstrating another interesting thermodynamic quantity one can also foresee the role of charge flux duality playing a role in these measurements. We discuss a sample fabrication process and a bridge measurement setup to implement this scheme.

Contents

Chapter 1

Introduction and Theory

"When we get to the very, very small world say circuits of seven atoms we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, quantized magnetic flux, quantized spins, etc."

Richard P. Feynman

What is Mesoscopic Physics??

Mesoscopic (word coined by Van Kampen in 1981) physics is a very young branch of science which started 28 year ago. This field deals with the study of systems of sizes ranging between macroscopic and microscopic. This study is not only to understand the macroscopic limit but also for molecules in bulk. Many exciting phenomena are being measured these days by experimentalist at the mesoscopic scale .This field has proven many theories in statistical and quantum physics. These are often considered with thermodynamic limit ($n = \frac{\Omega}{N}$, where, N is number of particle and Ω is volume) to get bulk properties of matter.

The ideas of nanoscience and nanotechnology started with a talk "Theres Plenty of Room at the Bottom" by physicist Richard Feynman at American Physical Society at the California Institute of Technology on Dec 29, 1959. Nanoscience and nanotechnology give us the ability to see and to control individual atoms and molecules. Everything on earth is made up of atoms -the food we eat, the clothes we wear, the buildings and houses we live in, and our own bodies. If something is hidden from our eyes, does not mean that it is not present now. So there is a lot of information hidden inside the nano world but due to some limitations of our instruments and natural laws we cant see and experience it through our sensors today, but scientists and engineers continue to work on it.

1.1 Superconductivity

1.1.1 Zero Resistance:

The phenomenon of superconductivity is always exciting, for both scientific fundamental interests and applications. In the year 1911, Kamerlingh Onnes observed that the resistance of mercury dropped suddenly to an infinitely small value when cooled to below 4.2 K. The phenomenon which shows the complete disappearance of the resistance below critical temperature, TC, called as superconductivity. Cooling below TC is considered to cause a phase transition in the specimen from normal state to superconducting state.Superconducting state is a phase of superconducting material in some conditions when resistance inside the superconducting material is completely ‘zero. For example, once a current is produced in superconducting ring maintained at sufficient at low temperature then current persist in loop wont decay. This state maintains current in loop due to zero electrical resistance, no scattering and no heating. The temperature at which resistivity vanishes is called critical temperature, Tc, and the external magnetic field above which superconductivity vanishes is called critical magnetic field H_C of superconductors (SC) as shown in the figure 1.1 and figure 1.2.

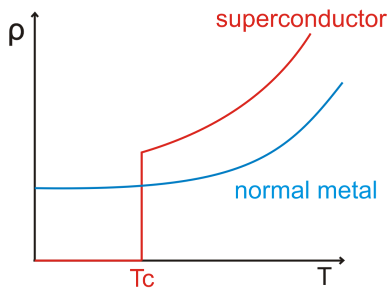

Figure 1.1: Resistivity becomes zero at T_c in superconducting material [1].

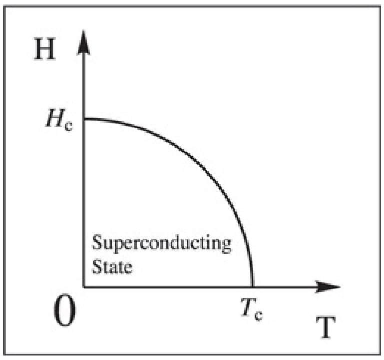

Figure 1.2: Region of superconductivity under limitation of magnetic field and temperature [2].

1.1.2 Meissner Effect

In the beginning the superconductors were simple metals like mercury (Hg), lead (Pb), bismuth (Bi) etc. at very low temperatures of liquid helium range. Two fundamental properties of superconductivity are, complete disappearance of the electrical resistance below T_C, indeed, the current in a closed superconducting circuit can circulate forever without damping and another fundamental property that was discovered in 1933, Meissner effect (perfect diamagnetism), the expulsion of magnetic flux when the applied field is below the H_C, termed as critical magnetic field. Both these properties have been exploited for various practical applications. It was later discovered that superconductivity could be destroyed (i.e. electrical resistance restored) if a sufficiently strong magnetic field were applied, and consequently it was found that a metal in the superconducting state has very amazing magnetic properties, quite unlike those known at ordinary temperatures. Several metallic elements and alloys show superconductivity and semiconductors like Si, Ge, Se and Te become superconductors under high pressure at low temperatures. Theoretical explanation of Meissner effect comes from London equation.

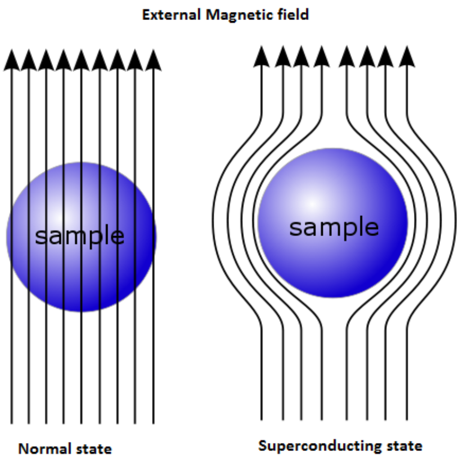

Figure 1.3: Meissner effect in Superconductors [3].

1.1.3 London Equations

Electrodynamics properties were studied by London brothers (F. and H. London) on the basis of two-fluid model in 1935. Electrodynamic properties are very useful in practical sense. The electrical conductivity in the normal state of most of metal follows Ohms law.

$$j = \sigma E \tag{1.1}$$

Where, j is current density, σ is charge density and E is electric field. So we need to modify the above equation in order to describe conductivity and Meissner effect in superconductors. They assume that there are both normal and super electrons in superconducting state. So, the modified current density is

$$j = j_n + j_s \tag{1.2}$$

$$j = en_n v_n + en_s v_s \tag{1.3}$$

Now, equation of motion for super electron in electric field E,

$$F = qE \tag{1.4}$$

$$F = ma \tag{1.5}$$

$$eE = m\frac{dv_s}{dt} \tag{1.6}$$

And current density,

$$j_s = -nev_s \tag{1.7}$$

$$\frac{dj_s}{dt} = -n_s\frac{dv_s}{dt} \tag{1.8}$$

$$\frac{dv_s}{dt} = \frac{-e}{m}E \tag{1.9}$$

$$\frac{dj_s}{dt} = -n_s e(\frac{-e}{m}E) \tag{1.10}$$

So,

$$\frac{dj_s}{dt} = \frac{ne^2}{m}E \tag{1.11}$$

Where, v_s and v_n is the velocities of super electron and normal electrons respectively. The above equation is London first equation. So, in superconductors, only super electrons respond in the presence of electric field. The normal electrons do not respond to the electric field. By Maxwells equation -

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1.12}$$

First London equation -

$$\frac{dj_s}{dt} = \frac{ne^2}{m}E \tag{1.13}$$

Taking curl -

$$\nabla \times (\frac{dj_s}{dt}) = \nabla \times \frac{ne^2}{m}E \tag{1.14}$$

$$\frac{d\nabla \times j_s}{dt} = \frac{ne^2}{m}(\nabla x E) = \frac{ne^2}{m}(-\frac{dB}{dt}) \tag{1.15}$$

We know that

$$B = \mu_0 H \tag{1.16}$$

$$\int d(\nabla \times j_s) = \int \frac{ne^2\mu_0}{m}\frac{dH}{dt}dt \tag{1.17}$$

So,

$$\nabla \times j_s = (\frac{ne^2\mu_0}{m})[-H + H_0] \tag{1.18}$$

For Meissner effect, $H_0 = 0$,

$$\nabla \times j_s = \frac{-ne^2\mu_0}{m}H \tag{1.19}$$

This theory gives us some idea about superconducting state but still cannot explain superconductivity from quantum mechanical point of view. So, we move towards a very famous theory on superconductors.

1.1.4 Type-I and Type-II Superconductors

For many years it was thought that all superconductors behaved according to basically similar pattern. However, it has been realized now that there are two kinds of superconductors, namely, Type-I and Type-II. Most of those elements which are superconductors exhibits Type-I superconductivity, whereas alloys generally exhibits Type-II superconductivity. Both Type-I and Type-II superconductors have many properties in common but show considerable differences in their magnetic behavior. Moreover, the allotropic forms of Bi are superconducting with different transition temperatures which imply that superconductivity may depend on the crystal structure. This should not be shocking since the electronic band structure varies with the crystal structure. Notably, none of the ferromagnetic materials such as Fe, Co, Ni displays the superconductivity because the strong magnetic field inside these materials is believed to be the cause, as strong magnetic fields are known to suppress the superconductivity. Figure 1.4 is displaying the magnetization behavior of Type-I and Type-II superconductors.

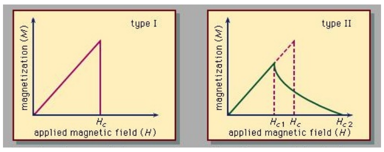

Figure 1.4: Magnetization versus magnetic field plots for Type-I and Type-II superconductor [4]

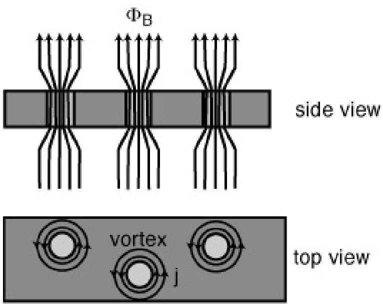

Figure 1.5: Vortex formation in presence of magnetic field [5].

Type-II superconductors are characterized by the formation ofmagnetic vortices when a strong magnetic field is applied on it (and the flux passing through it gets quantized) as show in figure 5. This behavior occurs above certain critical field strength, Hc1.The number of vortices increases with increase in external magnetic field strength. At some highercritical field Hc2, superconductivity is destroyed. Type-II superconductors do not show complete Meissner effect

1.1.5 Bardeen Cooper Schrieffer (BCS) Theory

The microscopic theory of superconductivity, popularly known as BCS theory, was proposed in 1957, by Bardeen, Cooper and Schrieffer. The important clue to BCS theory came from the isotope effect, Cooper modernized the Frohlichs idea of electron-phonon interaction into the philosophy of electron-phonon-electron interaction, known as Cooper pairs. The BCS theory demonstrated that superconductivity results from the paring of charge carriers which leads to the formation of a coherent wave function depicting all of the Cooper pairs. The superconductivity of conventional (T_C¡ 20 K) or low TC superconductors and their properties are well explained by the microscopic BCS theory. The concept of two basic length scales i.e. coherence length, ξ, and magnetic penetration depth, λ, associated with the superconductivity was the outcome of the microscopic BCS theory and Ginzburg Landau (GL) theory. The coherence length is a measure of characteristic length of the range of order parameter in superconducting state whereas the penetration depth is the measure of the depth of penetration of surface currents within the superconductor. The classification of superconductors into two types was made on the basis of thermodynamics of these materials and the existence of two characteristics length scales. When $\xi \gg \lambda$, the surface energy is positive, the class of material is called Type-I superconductors and when $\xi \ll \lambda$, the surface energy is negative, the class of material is called Type-II superconductors. The Hamiltonian for this pair is explained by second-quantized field operator.

$$H = \frac{1}{2m}(\frac{h}{2mi}\nabla - eA)^2 + u(r) - \mu \tag{1.20}$$

1.2 Aharonov-Bohm (AB) Effect

AB-effect is other version of Youngs Double Slit experiment which tells the particle-wave duality in subatomic particle on the basis of quantum mechanics. This also shows the constructive and destructive interference of two electron wave in the presence of an external field due to which charges experience force and results in a phase shift. Vector potential A plays a hidden role here which causes the force on the electrons.
So, the moment gets modified by vector potential of magnetic field -

$$p \rightarrow p - e\overrightarrow{A} \tag{1.21}$$

Phase difference between two waves -

$$\phi 1 - \phi 2 = \frac{e}{h} \oint \overrightarrow{A}.\overleftarrow{dl} = \frac{e}{h} \int \overleftarrow{B}.\overleftarrow{ds} = \frac{2\pi\phi}{\phi_0} \tag{1.22}$$

The AB effect is given in the figure 1.6.

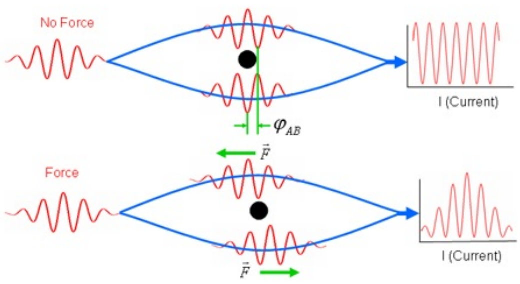

Figure 1.6: Aharonov-Bohm effect when the magnetic field is ON and OFF [6]

1.3 Flux Quantization

When a charged particle moves in a field free space that surrounds another region, where trapped magnetic flux ϕ, then on completing a closed loop by the particles wave function, then it will gain an additional phase factor $e^{\frac{2\pi i e\phi}{hc}}$. But the condition for the wave function of a superconductor is that it must be single valued at any point in space. This can only be true when the magnetic flux ϕ is quantized [9]. We need,

$$\frac{2\pi e\phi}{hc} = 2\pi n \tag{1.23}$$

Where, n=-2,-1,0,1,2.

This quantization of the magnetic flux is observed in Type-I and Type-II superconductors. BCS theory is developed due to a special correlation between cooper pairs (pairs of electrons in a special pattern) that behave in a coherent way over the whole body of the superconductor. Type I superconductor shows Meissner effect, excludes all magnetic flux lines from its interior. If there is a hole in Type-I and Type-II superconductors, then flux can be trapped in this hole which are created artificially or generated by high magnetic field. The trapped magnetic flux must be quantized if their size is not too big (less than some micron size hole). It has been proven experimentally that the trapped flux is quantized (units of $\phi = \frac{2\pi hc}{4\pi e}$). So, this result tell us that the charges are correlated in SC are in pairs of 2e.

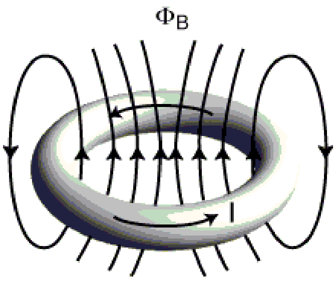

Figure 1.7: Magnetic field gets quantized when passing through a SC ring and pass flux quanta [7].

1.4 N. Byers and C. N. Yang Theorem

N. Byers and C. N. Yang [Byers 61] published a theoretical paper on 'quantized magnetic flux in superconducting cylinders' in 1961. They consider multiple connected macroscopic superconducting rings or cylinders and show that energy level is periodic in the presence of magnetic flux ϕ of a superconducting cylinder as shown in figure 8.If potential in Hamiltonian of SC is real then complex conjugate of potential will show energy levels are even function of ϕ, eigen value equation. So the partition function of the system is an even periodic function of with period (ch/e), (where, c is velocity of light, $\phi = ch/e$) multiple of integer)

$$\frac{\partial lnZ}{\partial \phi} = 0 \tag{1.24}$$

So, in the presence of magnetic field a very small persistent current or body current around cylinder will be induced (where TC is critical temperature of SC),

$$I = KTc\frac{\partial lnZ}{\partial \phi} \tag{1.25}$$

This current came from the derivative of free energy F with respect to flux ϕ,
where, $F = -kTlnZ$
So according to the Meissner effect, $I = 0$, current should be zero inside the superconductor, thus the equilibrium states are given by the maxima and minima on plot (N-1lnZ verses ϕ). The maxima of lnZ as function of will show the superconducting state.

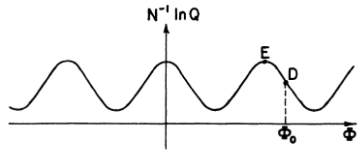

Figure 1.8: Partition function of superconductors showing periodicity with flux [Byers 61].

In microscopic picture, they calculated the energy of electron that has non-interacting spin between two concentric cylinders. According to BSC theory of superconductor 'pair correlation' form between two cylinders will show oscillation in free partition function with ϕ. They extrapolated the curve between maxima and they calculated the parabola equation for macroscopic object (ring).
Then they got a nice estimation of body current from the plot.

$$I = -Nfc\frac{e^2}{mc^2}\phi\frac{1}{(4\pi^2 r^2)} \tag{1.26}$$

Where f = fraction of electrons that are paired in SC state and N = number of particles odd or even.

So, variation in energy levels of electrons in superconductors with flux ϕ, even when there is no magnetic field, will show same effect as experimentally proposed by Aharonov and Bohm (called Aharonov-Bohm effect) in 1959.

1.5 Estimated Current for Superconducting Rings

N. Byers and C. N. Yang predicted body current or persistence current for a superconducting ring of micron or submicron size, more detail are given in the book by Heikkila [Heikkilä 13].

$$I = -\frac{\partial F}{\partial \phi} \tag{1.27}$$

$$I = -2 \sum_{n;E_n<EF} \frac{\partial E_n}{\partial \phi} \tag{1.28}$$

$$I = -2\frac{he}{4\pi^2 mr^2} \sum_n (n - \frac{\phi}{2\phi_{0]}}) \tag{1.29}$$

At low temperature and electron coherence behavior in superconductors, we take the ballistic limit (no other interactions) .So, the current value

$$I = \frac{he}{4\pi^2 mr^2}(n_{max}) \tag{1.30}$$

$$I = \frac{e}{2\pi r}\sqrt{\frac{2E}{m} = \frac{ev}{2\pi r}} \tag{1.31}$$

So, for radius, r= 500nm ring, current will be 50 nano ampere.

Thus the current from all the rings will be the root mean square current $I^{2(}1/2)$ and it increases as a square root mean of the number of rings N [Heikkilä 13].
The mean current per ring

$$< I >= \frac{< I^2 >^{1/2}}{N} \tag{1.32}$$

1.6 Thermodynamic equation for charge store on gate (capacitor) of Field Effective Transistor (FET)

A. Widom and T. D. Clark [Widom 82] gave two theorems for charge store in FET. The suggested equation telling that we can measure Hall impedance non-invasively, that mean, we can measure such device by without using hall prove measurement technique.
Gate capacitance (differential) -

$$C = (\frac{\partial Q}{\partial V})_{T,\phi} \tag{1.33}$$

vacuum impedance (R) is,

$$R = \frac{4\pi}{c} \tag{1.34}$$

$$\frac{R}{Z} = 4\pi(\frac{\partial Q}{\partial V})_{T,V} \tag{1.35}$$

Landau magnetic levels,

$$Q = \frac{2e^2\phi n}{hc} \tag{1.36}$$

$$\frac{R}{Z} = \frac{8e^2 n}{hc} \tag{1.37}$$

$$(\frac{\partial C}{\partial \phi})_{T,V} = 4\pi(\frac{\partial \frac{R}{Z}}{\partial V})_{T,\phi} \tag{1.38}$$

So, above equation tell about the change in capacitance by changing flux. Impedance of FET can be measure:

$$Z = n_2 \frac{\phi_0}{cen_1} \tag{1.39}$$

Where, n_1= number of electron flow, n_2 = number of flux quanta and ϕ_0= h/(2e) $\approx$ 2.067833831(13)1015 Waber. In case of superconductors e = 2e.

Chapter 2

Fabrication of device

After reading the title of this chapter the question that comes to mind is how to make a nano or micro electronic-device to measure the physical quantities in lab. In order to make a device of nano scale one needs to be careful about purity of material. So we need an area such as a clean room where the atmosphere has to be dust free. There are control protocols designed by scientists and engineers which include clean room suits, latex gloves, and highly purified ventilation systems in clean room. The thin film is grown on a base and then we have to cut the film according to the desired geometry of our device. In this fabrication, our aim is to fabricate two parallel plate capacitors having sub micron holes on one capacitor for bridge measurement. All the fabrication procedures are carried out in the clean room (class 10,000).

2.1 Desired geometry of device

Why do we need to choose such type of geometry for the device? It is because many properties such as impedance depend upon the geometry. So we have to careful about it. Geometry should be very comfortable to work with on chip processing and electrical contacts should be easily fixed on it. In this case we gave three contacts to the whole device, one contact was common at the upper plate of capacitor and two separate contacts to lower plate. All those geometry is command based in e-beam lithography. And we use a command based platform to draw any desired geometry. The software required to draw any shape for devices was provided in the lithography unit. See figure 2.1.

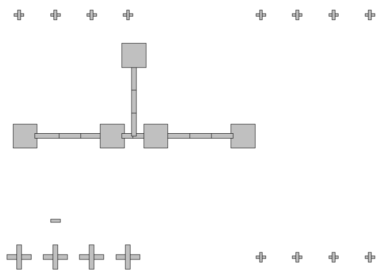

Figure 2.1: Desire geometry for the device with global markers, two parallel-plate capacitors.

2.2 Selection of substrate

Most of the substrates are single crystals and non-conductors. In this fabrication we used silicon nitride as device substrate. Mostly silicon nitride layers are used as dielectric material and can act as hard mask. Low pressure chemical vapor deposition (LPCVD) and plasma enhanced chemical vapor deposition (PECVD) method are used to deposit this nitride layer on silicon. This layer provides low electrical conductivity, high thermal stability and good coverage of edges.

2.3 Cleaning of wafer

Cleaning of wafer is a very important and basic step in fabrication. If the wafer is not cleaned properly, it could contain small micron or nano size impurities (organic or inorganic). This impurity could leave a huge impact on many parameters like resistance or could even destroy the structure of device. All these processing is done inside clean room.

So, how do we clean the wafer in lab? First we place the wafer inside acetone under ultrasonic cleaning for 10 minutes. Ultrasonic cleaning helps to remove the particles which are strongly bound to the wafer by electrostatic force. So an ultra sonic wave boom hits the particles and remove them from wafer without damaging the wafer itself. Then shift the wafer (with the help of tweezers) inside IPA (isopropyl alcohol). Then keep this in ultra sonic cleaning for 10 min at 30 C. Then remove the wafer from IPA and blow dry with nitrogen gas and place wafer(first put wafer on glass plate wrapped with aluminum foil) on hot plate at 180 C for 5 min so that wafer can dry completely.

2.4 LOR coating

Lift off resist (LOR) chemical is used to remove all the material from the wafer after the evaporator. This coating is applied by using the spin coater at r.p.m. (5000) for (40 second) time. This gives us approximately 200nm thick layer on wafer. This thickness varies for different chemicals at these parameters of spin coater. See figure 2.2.

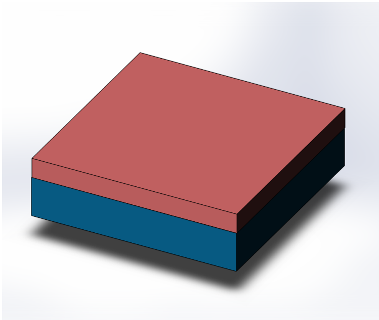

Figure 2.2: Spin coating of LOR on substrate.

2.5 PMMA coating

Poly methyl methacrylate is used to develop the pattern under the exposure of electron beam. This is a transparent liquid and can be coated on the film with the help of spin coater with certain parameters of rpm and total time. This chemical is very sensitive to the electron beam and when electron beam falls on it, its bonds weaken and can easily be removed by developing chemicals. See figure 2.3.

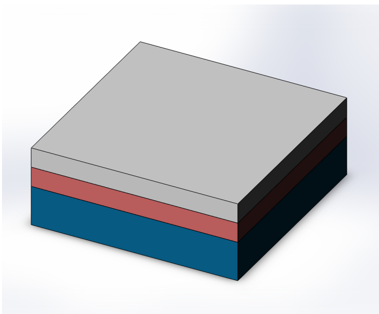

Figure 2.3: Spin coating of PMMA on LOR.

2.6 Electron-beam lithography

This is a most important and sophisticated technique for nano scale devices. Through this technique we can reach up to 10nm beams of thin film. But it is very hard to optimize the method because for each lithography, we need to perform field calibration for staging and focusing the beam. In our lab we use XENOS software to make patterns using e-beam lithography. Lithography technique is installed inside the FESEM (field emission scanning electron microscope). See figure 2.4.

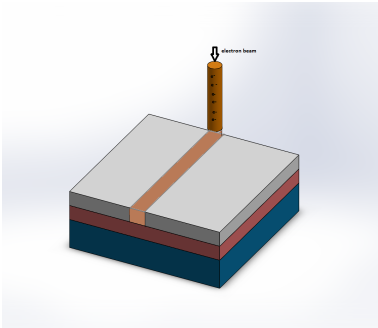

Figure 2.4: Electron beam exposure on PMMA.

2.7 Developing pattern

Methyl isobutyl ketone (MIBK) with IPA in the ratio of 1: 2 for 2 min. is used to develop the pattern after exposure. Then the wafer is placed in IPA and afterwards, blow dried with nitrogen gas. And we can see the developed pattern under optical microscope. Then we developed LOR by dipping in tetramethylammonium hydroxide (TMAH) chemical for 12 second. See figure 2.5.

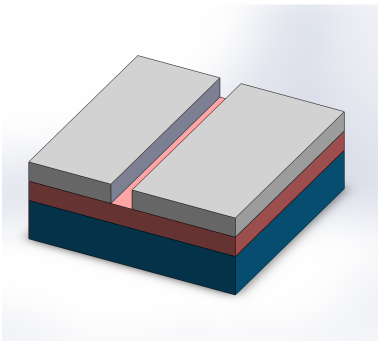

Figure 2.5: Pattern formation after being developed with PMMA

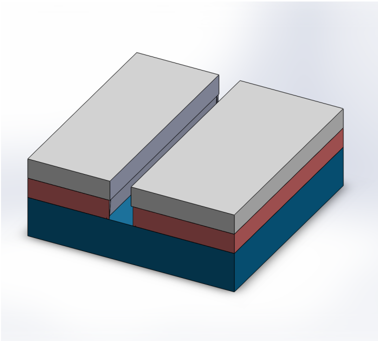

Figure 2.6: LOR Under cut

2.8 Thin film deposition

After developing the LOR, we move to next step of deposition of material. The deposition of thin film of gold and niobium is done by thermal evaporator and e-gun evaporator (see appendix). We deposited lower plate of gold which is done by thermal evaporator. Thickness of lower plate is 50nm.Then we deposited germanium (50nm) as dielectric on gold plate by thermal evaporator. Then we evaporate niobium with the help of e-gun evaporator. Niobium is the top plate of capacitor and has a thickness of 60nm. See figure 2.7.

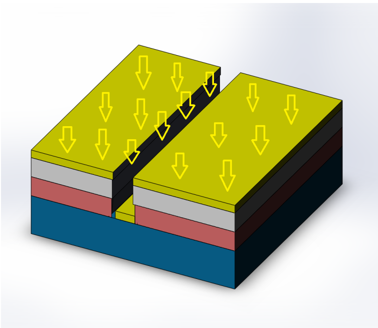

Figure 2.7: Evaporation of metal on substrate

2.9 Lift Off

After every evaporation we have to lift off the rest of material from the wafer. So we have to lift off LOR because all the extra material is deposited and coated on the LOR. This is done by the PG-remover or N-Methyl-2-pyrrolidone (NMP) chemicals. See figure 2.8.

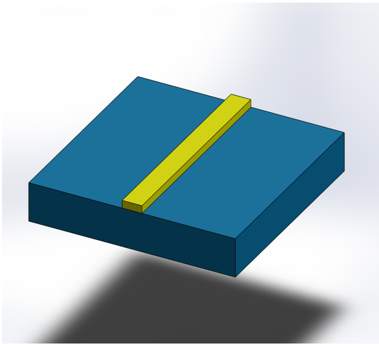

Figure 2.8: After liftoff the resist is the only desire geometry left on the substrate.

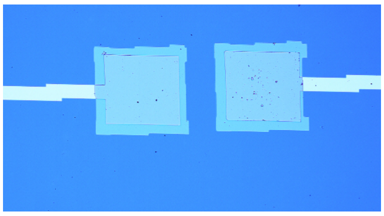

Figure 2.9: Germanium as dielectric evaporated on the gold pads.

2.10 Alignment of plates

Alignments of plates and dielectric are very important steps of fabrication procedure. So we make sixteen markers in first writing. Each marker is of gold (50nm). Geometry of markers is like plus sign. With the help of markers, we align our device components in each lithography. Pattern of markers is given in figure 2.10.

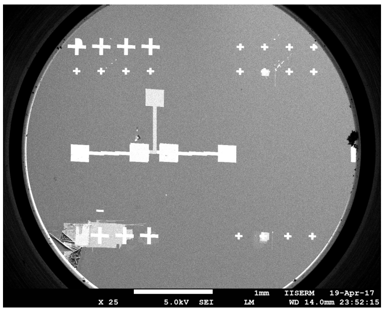

Figure 2.10: SEM image of mark design on the chip for alignment.

2.11 Creation of holes on thin film

We need to make sub-micron size holes on one top plate of the device. So we spin coat PMMA on niobium film for testing. Then we test sub micron hole of different diameter with varying doses of electron beam. Then we develop PMMA and LOR. PMMA works as a mask on plate in this plasma etching process. We etch niobium film with SF6 gas. We try to make dots of very small diameter (50nm), but we were not able to develop it due constraints on the focus of the electron beam. We create holes of 150nm to 450nm diameter by varying doses of electron beam along the y-axis from (100 to 350) micro coulomb per centimeter square. For dots, dosage varies from 25 to 100 femto coulomb. So we try ZEP 2.4 (resist) on device for making holes. Then we develop it on the ZED (normality 50). Then we etch niobium by plasma etching and remove the rest of resist by ZDMAC. We get nice circular holes of diameter 350nm - 450nm at a dose of (250 -350) micro coulomb per centimeter square. See figure 2.11 and figure 2.12.

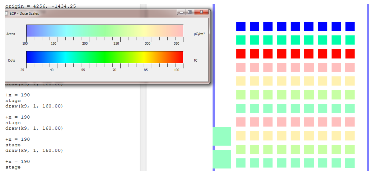

Figure 2.11: Lithography software program for dose testing for submicron holes.

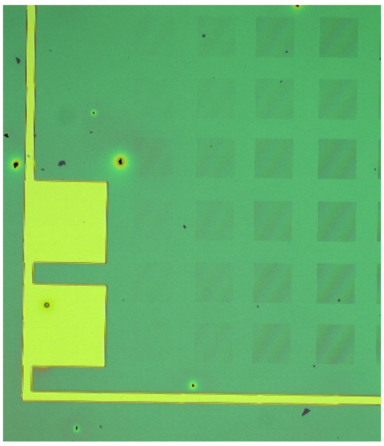

Figure 2.12: Optical images of hole on PMMA.

2.12 Plasma etching or dry etching

Plasma etching is a very popular technique these days in industries as well as for research. It is used to etch the thin film with the plasma of various gases. This process is very similar to sputtering or magnetron sputtering. We need to etch niobium thin film in our fabrication. Niobium etching is done using SF_6 gas, which reacts with niobium and forms niobium tetra and hexafluoride under high vacuum. SSF_6 plasma produces blue light.

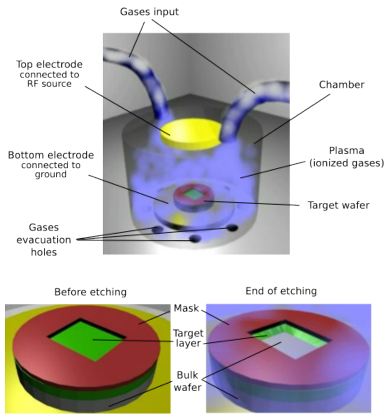

Figure 2.13: SF6 plasma inside plasma etching machine.

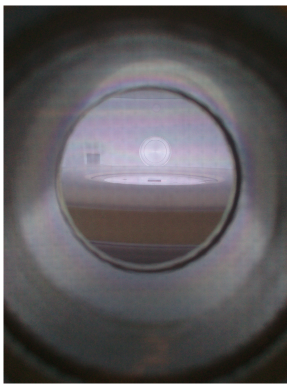

Figure 2.14: SF6 plasma inside plasma etching machine.

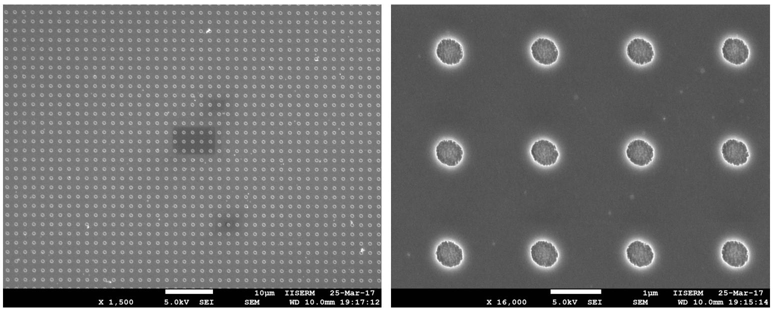

Figure 2.15: Submicron holes (435nm) array on Nb plate.

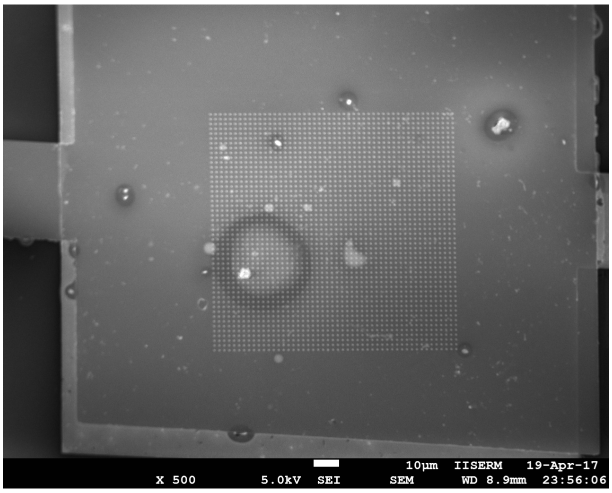

Figure 2.16: SEM image of etched holes on the niobium plate (2500 holes).

Chapter 3

Proposed Experimental Setup

This chapter will tell you about the device and proposed experimental setup. Our device is very sensitive to parasitic capacitance (wire capacitance). So, we will discuss more about capacitance, how to measure it and what we might get from measuring capacitance of device.

3.1 Device

The device is fabricated with four lithography writings. There are three contacts on the device. Two contacts are of evaporated gold, including lower plate. One common contact on the top plate is of evaporated niobium superconductor. See figure 3.1. Geometry of this device has been so designed because we proposed our measurement by bridge capacitance measurement. I will discuss the measurement in the next section.
Why this device is named fluxtronic capacitor?

The top plate is made up of a superconductor (Niobium, Nb, Type II superconductor). When device is cooled below the critical temperature, Tc, 9.3 K, using dilution fridge (oxford

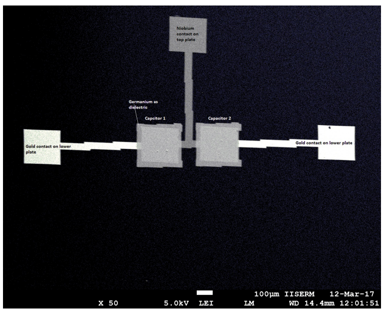

Figure 3.1: SEM image of device before holes creation.

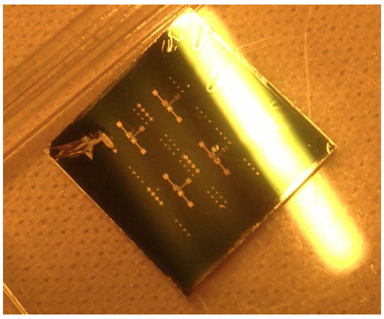

Figure 3.2: Devices on the silicon nitride wafer.

instrument, minimum cooling temperature ≈ 0.010 kelvin), it prevents magnetic field from penetrating inside due to Meissner effect. But this is only valid for Type I superconductors (because there is no vortex formation in presence of magnetic field). But in our case we took niobium which is Type II superconductor. We choose niobium because we can sweep magnetic field strength from (100-500) mT and vortex formation in Niobium occurs within this magnetic field range (vortex form in between H_{c1} and H_{c2}). Niobium also has a relatively high T_c. So we created some holes to see the effect because we would like to observe the capacitance periodicity by sweeping magnetic field. When magnetic field is applied perpendicular to the sample, induced current flows on the surface of the ring or hole. This induced current allows only integer flux quanta ϕ due to AharonovBohm effect. Due to cooper pair formation, electron wave will interfere across the hole and force applies by vector potential will the periodicity in capacitance.
So the lower gold plate will receive the charge due to the AC potential difference across plates. Gold is used due to its good electrical conductivity. By measuring capacitance we can find the trapped magnetic flux, which is quantized.
So the lower gold plate will receive the charge due to the AC potential difference across plates. Gold is used due to its good electrical conductivity. By measuring capacitance we can find the trapped magnetic flux.
This experiment is very sensitive to the magnetic field, so we need proper shielding for our instruments.

3.2 How Can We Measure an Unknown Small Capacitance of Submicron size Device?

Basically we are interested in measuring the 'differential capacitance($C = \frac{\partial V}{\partial Q}$) (with change of flux) of our device. This device capacitance comes in the range of pico and femto farads. We have tried some methods to measure capacitance [10]. Capacitor does not allow DC current pass through it. This measurement is very sensitive to parasitic capacitance. The signal is very weak in our case. So we can use preamplifier. Wires like coaxial or BNC and twisted pair cable capacitance also comes in the range of pico farad.

3.3 Bridge Measurement

It is a very popular method to measure any unknown impedance. Potential across the bridge is always zero, which is a condition for balanced bridge. This bridge method for measuring capacitance is also known as Schering Bridge. So our aim is to balance the bridge by changing the value of trimmer resistors and trimmer capacitors.

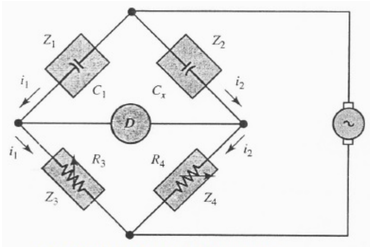

Figure 3.3: .
]Common bridge method for measuring unknown resistance or capacitance [8].

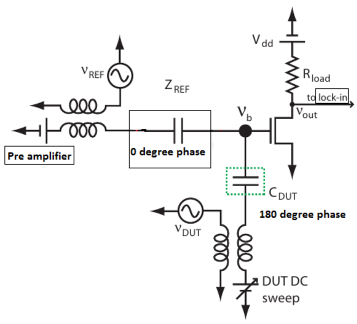

Figure 3.4: Modified bridge measurement technique with a preamplifier and lock-in setup [Hazeghi 11].

3.4 Table of capacitance of different wires

Sl.No.	Wire	Capacitance
1	BNC cables	2-10pF/m
2	Twisted pair	50-100pF/m

3.5 Wiring, Contacts and Sample Holder

We are trying to reduce the extra capacitance from our device by choosing the wiring very careful. The circuit should be properly grounded, so that extra charge cannot go to the signal. Contacts should also be properly fixed because they can also generate stray capacitance. We need only three contacts to measure the capacitance; this is the simplicity of our device. So we can choose any gold coated or copper coated PCB as sample holder. Contacts can be done by pressing indium wire on the contact pads. For very low signal we can place an amplifier.

3.6 Lock-in Amplifier

This instrument is used to measure very small AC signals which have lots of noise. Lock-in amplifier gives very high precision measurement. Lock-in is a filter of many narrow bandwidth which matches with reference signal, so it can reject many unwanted noise which come with signals. This filter has a very high quality factor approx. in mega. Lock-in can also amplify the signal. For example, nano volt signal can be amplified up to 10 volt. The filtered signal is very narrow band so it can easily be measured .

3.7 Dilution Refrigerator

This instrument (oxford dilution instrument) provides ultra low temperature environment for measuring the device in its superconducting state, at ultra low temperature lab (ULTP) lab. Dilution refrigerator is a very fancy fridge but very complicated to use. It is not easy to go below 0.3 K in a big volume. So, this fridge has special technique which can go below 0.3 K. In this machine two isotopes of helium (3Heand 4He) are used. When we use mixture of these gases then these gases show very different behavior. After mixing they have spontaneous phase separation so the temperature falls very low. And temperature can reach up to 10mK. This temperature is enough to stop much noise in the signal.

3.8 Conclusion

We optimized the recipe to fabricate the device. We created sub micron holes on niobium and aluminum in between the size 250-450 nm. We fabricated the device in which one capacitor has holes while the other capacitor has no holes. Device geometry is design for bridge capacitance measurement. And we were able to measure the unknown capacitance of any lump capacitor (micro farad to pico farad) with the help of bridge measurement technique by using lock-in amplifier.We measured twisted pair and twisted pair cables but lock-in. The recipe of device is reproducible.

Appendix

Images of all instruments that we used in the fabrication of our device are given below:

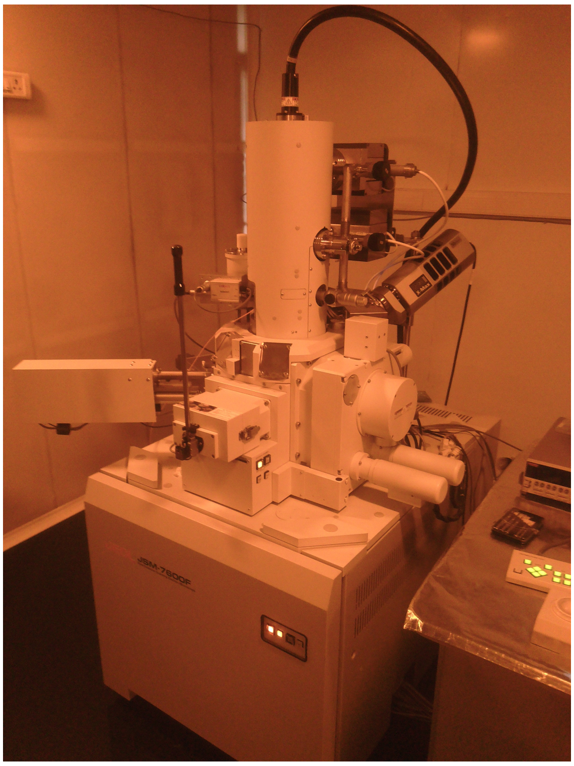

Figure 3.5: Scanning electron microscope (this instrument is used for lithography and imaging the device).

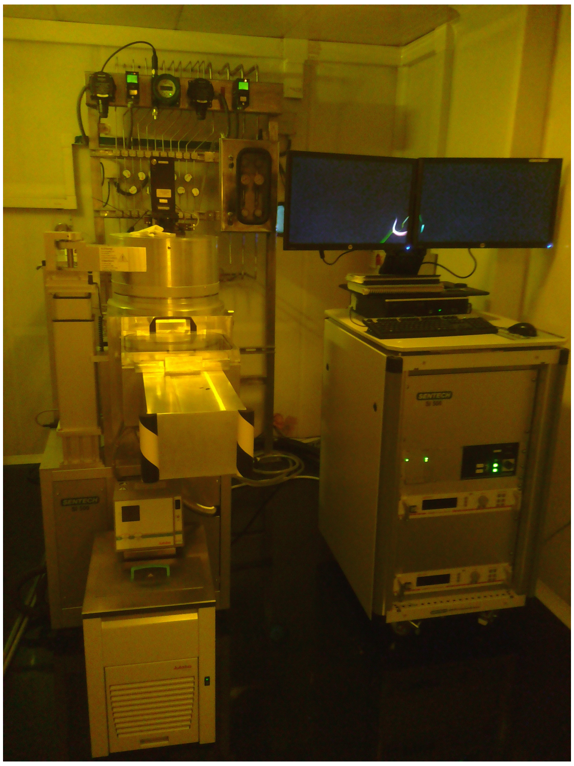

Figure 3.6: Plasma etching machine (this instrument is used to etch the metal or non metal with the help of different gases).

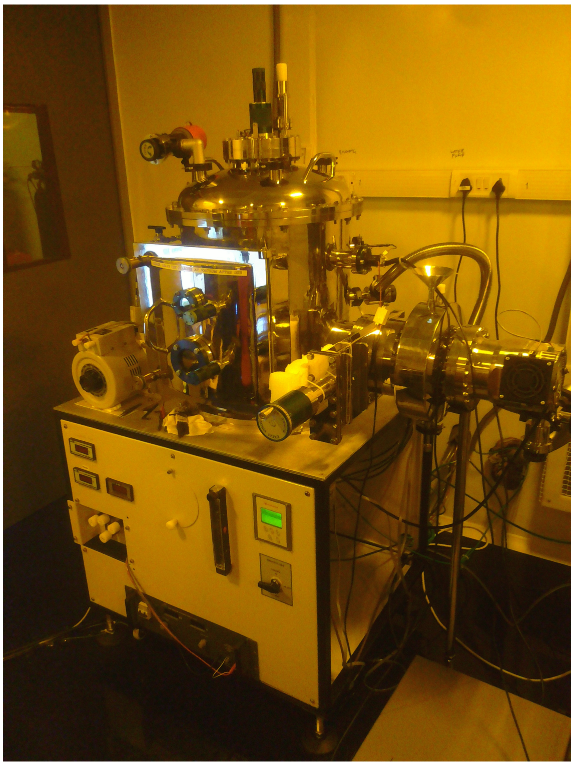

Figure 3.7: Thermal evaporator (this instrument is used for coating the material layer or depositing thin film).

Figure 3.8: E-Gum Evaporator (this instrument is used for depositing thin film, mostly high melting point materials are used)

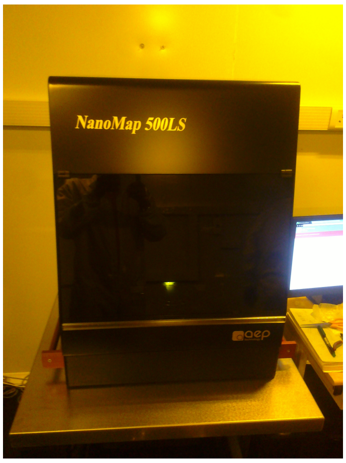

Figure 3.9: Ellipsometer (this instrument is used for measuring the thickness of device)

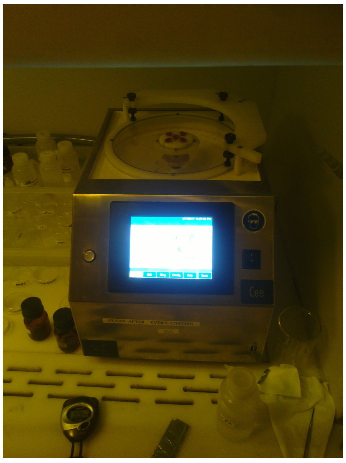

Figure 3.10: Ultra sonic bath (for cleaning the sample)

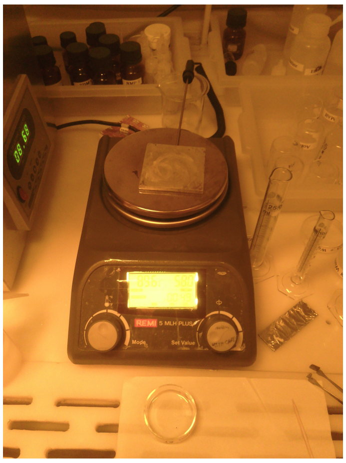

Figure 3.11: Hot Plate (for annealing the sample)

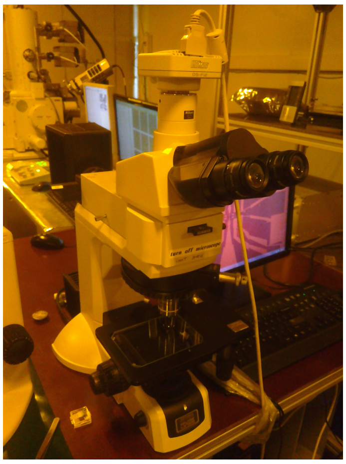

Figure 3.12: Optical microscope (for observing micro structures)

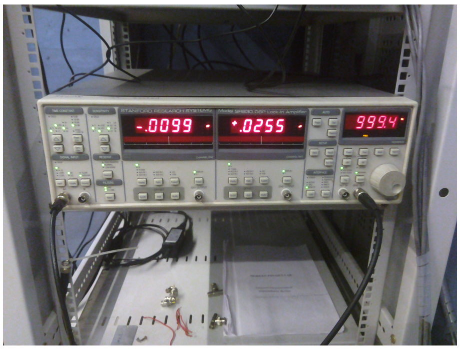

Figure 3.13: Lock-in Amplifier SR830 DSP (used for measurement)

Figure 3.14: Dilution Refrigerator (this instrument is used to cooling the sample)

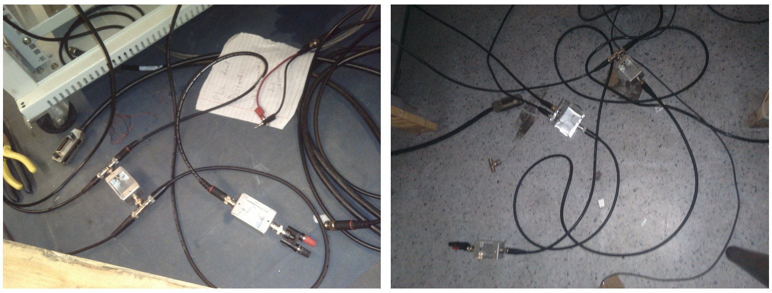

Figure 3.15: BNC cables and BNC male connectors with aluminum shielding box.

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