Negative Magnetocapacitance in Schottky barriers

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August 2007

Abstract

Schottky barriers have been found to exhibit negative magnetocapacitance. This is shown in the research on n-type silicon doped gallium arsenide Schottky devices. These Schottky devices consist of a gold electrode and an ohmic contact, both of which were deposited in a vacuum deposition system.

Introduction

Schottky devices are very useful in electronics. Since they are diodes, they act like a one-way valve in a circuit. Although widely used and studied, the sensitivity of Schottky devices to externally applied magnetic fields has not been studied.

In our early measurements we have seen negative magnetocapacitance in silicon Schottky and silicon MOS devices. This motivated us to look at gallium arsenide Schottky devices to determine the relation between Schottky barrier height and magnetic field. To do this, gallium arsenide Schottky devices were made and measured.

Fabrication of the Sample

Initially, commercially available gallium arsenide “Ted Pella” wafers are much too large and are therefore cut for experimental use. This process is done on a clean surface using a diamond pen. To eliminate the stray pieces of gallium arsenide that may stick to the samples’

surface by static forces, we immediately move the samples to sample boxes. After the gallium arsenide samples are cut, they are cleaned to remove impurities on the surface such as dust, oil, and chemicals. We used acetone, isopropanol, and methanol to clean them. Acetone is used to remove dust and break van der Waals forces. We use isopropanol because it is a good chemical to clean the oil off the sample. Lastly, we use methanol because it has a high vapor pressure and therefore the sample can be blown dry with pressurized nitrogen gas to leave the sample dry with no chemical residue. The samples are sonicated for 5 minutes in each chemical, acetone first followed by isopropanol, finishing with methanol. We have used the sonication based cleaning procedure because it enables uniform cleaning. In this experiment we used a Branson 1210 Sonicator.

Metallic layers are deposited on the cleaned gallium arsenide sample on both the top and backside. We deposited gold on the topside to make an electrode. This electrode creates a Schottky barrier between the gold metal and the gallium arsenide semiconductor. It is important that this gold deposition be made on the polished side, referred to here as the top, because it is ideal to have a Schottky barrier between two smooth surfaces. On the back, or rough side, four layers of metals are deposited to make an ohmic contact. All the depositions are made in the Miller system, a vacuum deposition system (see appendix A for more information about the Miller system).

For the top gold electrode, a shadow mask is used to create eight capacitors. However, for the backside, metal is deposited without a mask. For the backside, a multiple-source vacuum system, the Miller system, is used to deposit palladium, germanium, titanium, and gold without breaking the vacuum. See figure 1. We chose this recipe of metals after determining it had the lowest contact resistance among trial recipes.

Figure 1. Diagram of sample after topside and backside depositions

We deposit palladium onto the gallium arsenide because it is "sticky" and holds well to the gallium arsenide. Next, we deposit the germanium and titanium because they make a strong alloy together with palladium. We finish with depositing gold on the titanium to keep titanium from oxidizing, which it would if exposed to oxygen.

To evaporate the metals we run a current of 50-150 amps through our Miller system, varying the current depending on the melting point of the material we are depositing. We place all of our materials to be deposited in individual tungsten boats, which have a high melting point. When the current runs through our system, we use a pre-programmed Inficon deposition monitor to adjust to the specific growth rate and keep track of the thickness of deposition. For the backside we grow 200 angstroms of palladium, 400 angstroms of germanium, 400 angstroms of titanium, and 1500 angstroms of gold at a rate of 5 to 10 counts per second.

After the metals are deposited on the backside, the sample is annealed in a Rapid Thermal Annealing Oven (RTA), which is described in appendix B. The annealing temperature and time found to give the best results varies depending on the doping levels in the gallium arsenide. For our silicon doping level of 9×10^{16} cm^{-3}, the best recipe is 400 degrees Celsius for 15 seconds.

Once the sample is annealed and the gold is deposited on the polished side to form a Schottky barrier, contacts are made. These are very thin gold wires with small loops that are secured to the sample with graphite paint. We make one contact to the backside and contacts to two gold electrodes. Ideally, one contact is made to a small electrode and one to a large

electrode. We use gold wires because they have low resistance and high conductivity, an important property for the wires used to test the sample during measurements. In addition, the graphite paint is used because it is conductive and holds well at low temperatures.

Measurements

Two different instruments take measurements: the physical properties measurement system (PPMS) and the HP4248 capacitance bridge. (See appendix C for PPMS).

We place the sample in a capacitance stick, a special rod that positions the sample at the bottom of the PPMS and connect it through cables to the HP4248 capacitance bridge. The sample's gold wire contacts are connected to leads inside the capacitance stick with indium. This setup enables us to take specific measurements of the sample through the HP4248 capacitance bridge. The direct cable connection is much more accurate because it reduces the series resistance. Once the capacitance stick is placed in the PPMS, the sample chamber is sealed and the system is purged, which readies the system for measurements.

We then hook up a computer, with the program LabView, to the capacitance bridge, and therefore the PPMS. LabView follows a sequence of programmed functions, which enable the accurate settings of temperature, magnetic field, and frequency. These settings, combined with precise data collection, provide useful information for analysis.

During measurements, we must watch the PPMS to make sure that the LabView program is functioning correctly and recording the data. In addition, when looking over the LabView program, it is important to be mindful of the number of data points, waiting times, and starting magnetic fields and temperatures.

When we finish collecting our data, we set the temperature to 300 K and the magnetic

field to 0 T. When these settings are stable we vent the system and carefully remove the capacitance stick with our sample.

Findings and Interpretations

We measured capacitance with increasing temperature to determine the physical processes taking place in the system with different dopings and to determine at what specific temperatures we should measure the capacitance with increasing magnetic fields.

Figure 2 shows no dramatic difference in slope at any point, so it makes very little difference for 9 x 10^{16} cm^{-3} silicon doped n-type gallium arsenide which temperatures are chosen for more data collection. Yet, needing specific points, we chose to measure capacitance with applied perpendicular magnetic field for the temperatures 10K, 30K, 40K, 50K, 60K, and 70 K, as is seen in figure 3. However, understanding that this many points were not needed, we chose 10K, 30K, 50K, and 70 K to measure capacitance as a function of applied parallel magnetic field.

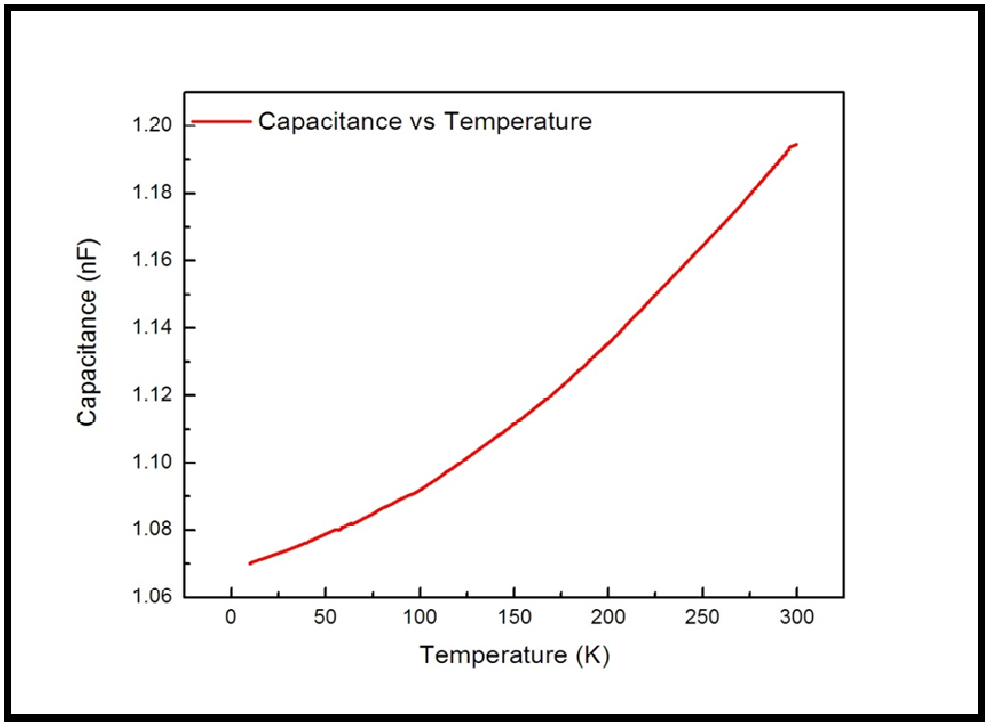


Figure 2. Capacitance vs. temperature for 9 x 10^{16} cm^{-3} n- type gallium arsenide (Si doped). As seen, there is no freeze out taking place, but for 3x $10^{16}cm^{-3}$, we have observed a sharp decrease at approximately 70 K (see figure 5)

As depicted in figures 3 and 4, negative magnetocapacitance was found after measuring capacitance at the selected temperatures for increasing magnetic fields. However, no directional dependence was found, as the difference between these two graphs, and hence between applied parallel and perpendicular fields, is negligible. It is interesting to note the lack of directional dependence because directional dependence was found in measurements for silicon.

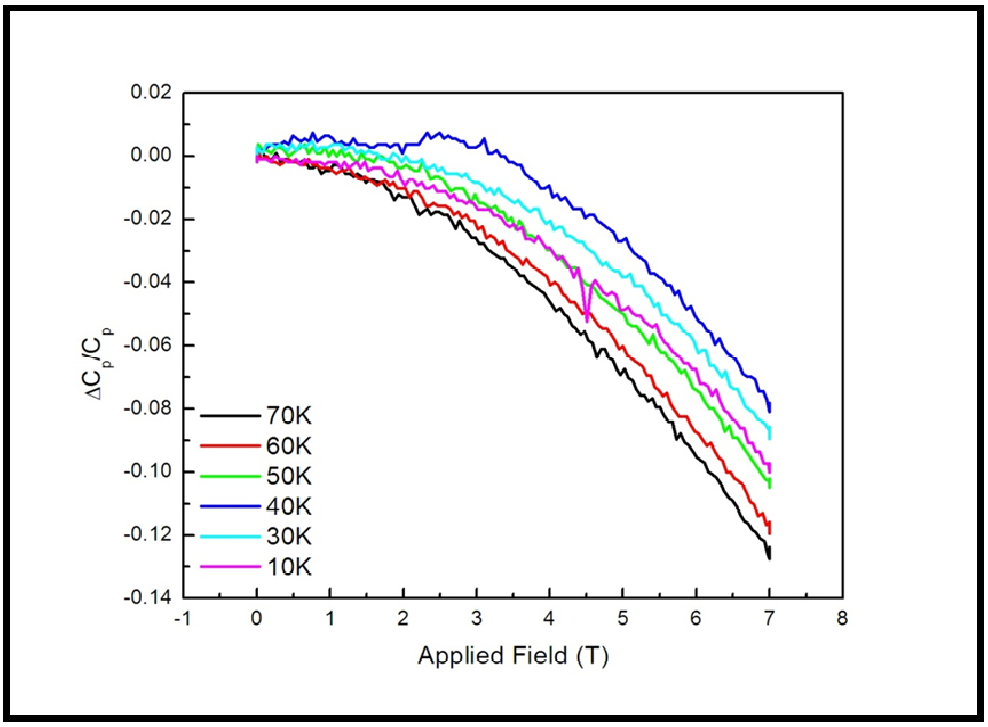


Figure 3. Capacitance vs. magnetic field applied perpendicular to gallium arsenide 9 x 10^{16} cm^{-3} sample.

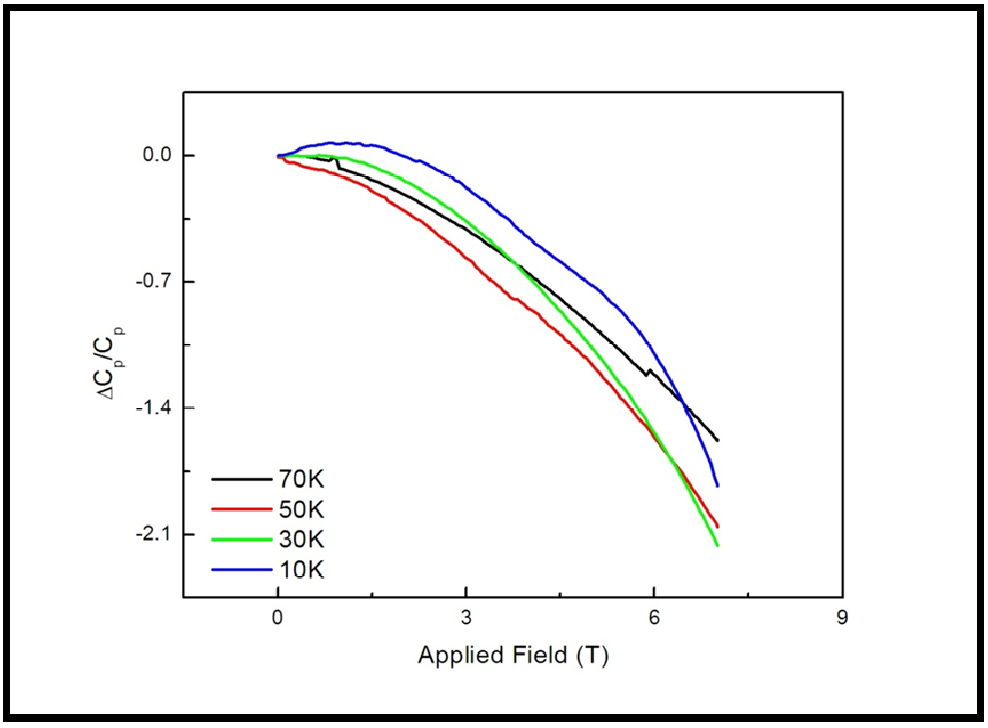


Figure 4. Capacitance vs. magnetic field applied parallel to gallium arsenide 9 x 10^{16} cm^{-3} sample.

The same measurements were done on 3 x 10^{16} cm^{-3} silicon doped n-type gallium arsenide. Again, the capacitance was measured with increasing temperature, see figure 5. However, this time it was important to carefully select the specific temperatures of 20K, 30K, 40K, 50K, 70K, 100K, 150K, 200K, and 300K since freeze-out is seen. Freeze-out is the region of the graph that dramatically decreases with a different slope.

Freeze-out occurs when the temperature gets to be so low that the electrons drop to their lowest energy state and no electrons from the donor state are elevated to the conduction band. To help visualize what this means see figure 6, where E_c is the energy of the conduction band, E_F is the Fermi energy, E_d is the energy of the donor electron, and E_V is the energy of the valence band.

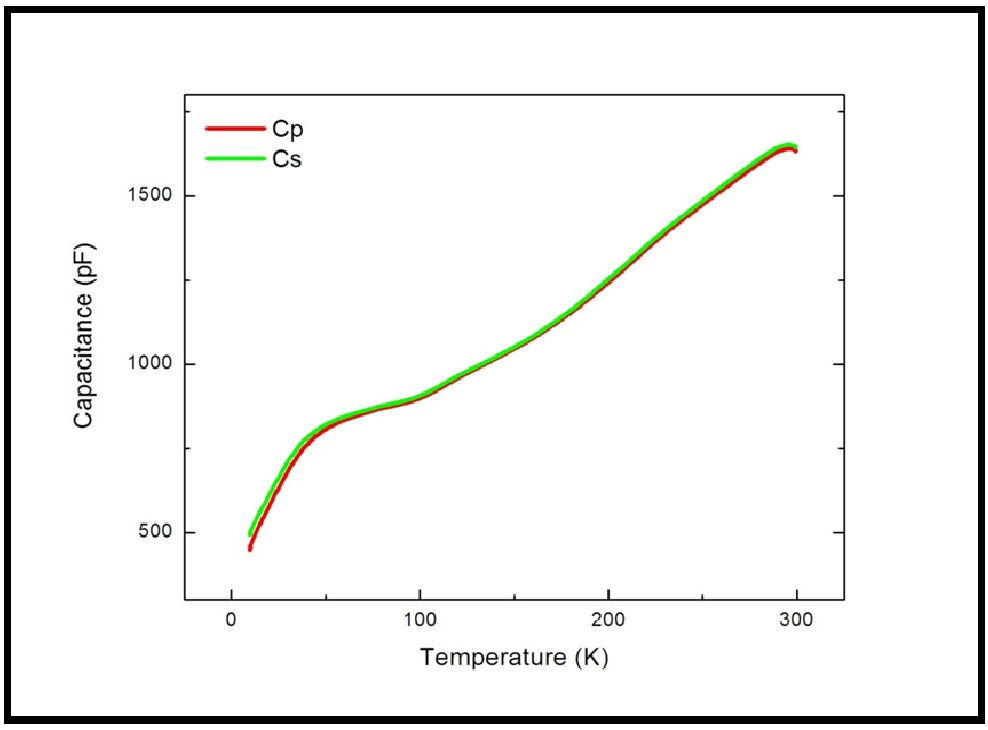


Figure 5. Capacitance vs. temperature for n-type gallium arsenide 3 x 10^{16} cm^{-3} (silicon doped) sample. (Freeze out visible beginning at 70K).

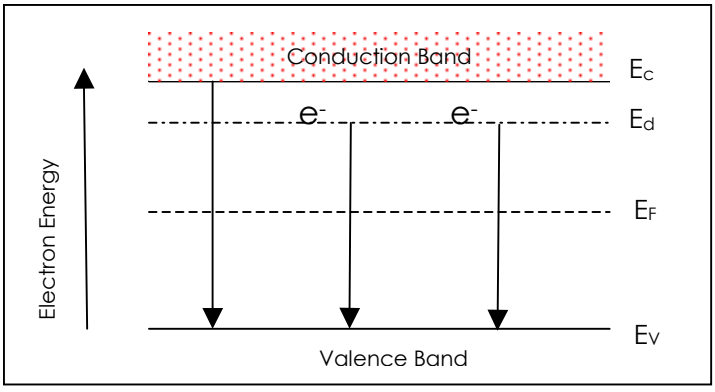


Figure 6. Energy-band diagram at low temperatures for n-type gallium arsenide

For n-type 3 x 10^{16} cm^{-3} silicon doped gallium arsenide, again we see negative magnetocapacitance for both parallel and perpendicular applied magnetic fields (figures 7 and 8 respectfully). Additionally, it does not show directional dependence for n-type 3 x 10^{16} cm^{-3} silicon doped gallium arsenide.

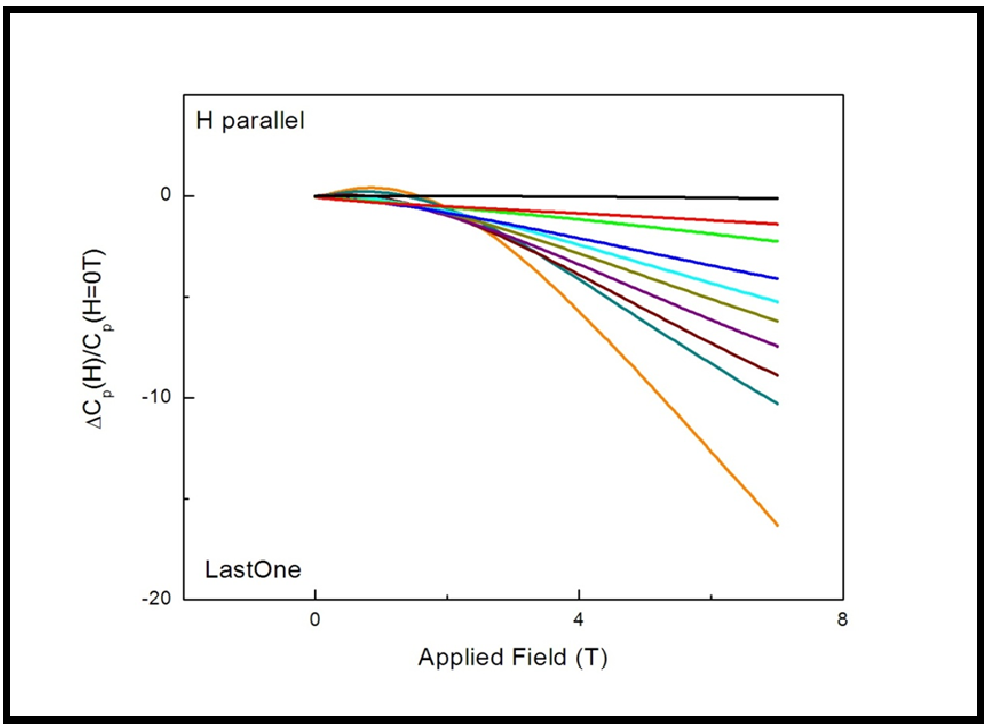


Figure 7. Capacitance vs. magnetic field applied parallel n-type gallium arsenide 3 x 10^{16} cm^{-3} (silicon doped) sample.

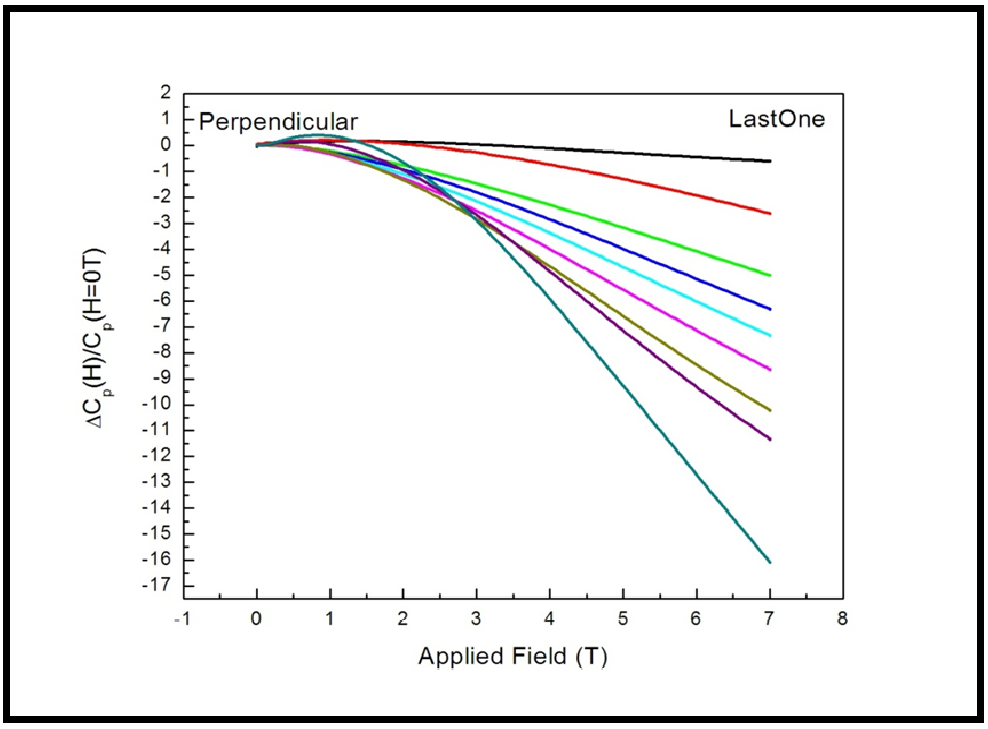


Figure 8. Capacitance vs. magnetic field applied perpendicular to n-type gallium arsenide 3 x 10^{16} cm^{-3} (silicon doped) sample.

Conclusion

Samples of n-type 9 x 10^{16} cm^{-3} and 3 x 10^{16} cm^{-3} silicon doped gallium arsenide were prepared and Schottky barriers and ohmic contacts were deposited in the Miller system. Prior to deposition of the gold for the Schottky barrier, samples were annealed with a recipe chosen after trial and error. When the samples were measured using PPMS with the HP 4248 capacitance bridge they showed negative magnetocapacitance, with no magnetic field directional dependence. In literature, the capacitance of Schottky barriers is independent of magnetic field. However, this experiment shows that this may need to be reconsidered. A new understanding of the relation between Schottky barriers and magnetic fields could have a large impact on computer circuitry.

Acknowledgements

These two projects were made possible by the REU program at the University of Florida, organized by Dr. Kevin Ingersent with the help of Kristin Nichola, and funded through The National Science Foundation. I would like to thank Dr. Hebard and his laboratory for inviting me to work with them for the 10 weeks. A special thank you goes to Sefaattin Tongay for his all his hard work, endless guidance, support, and sense of humor.

Appendices

A. Miller System

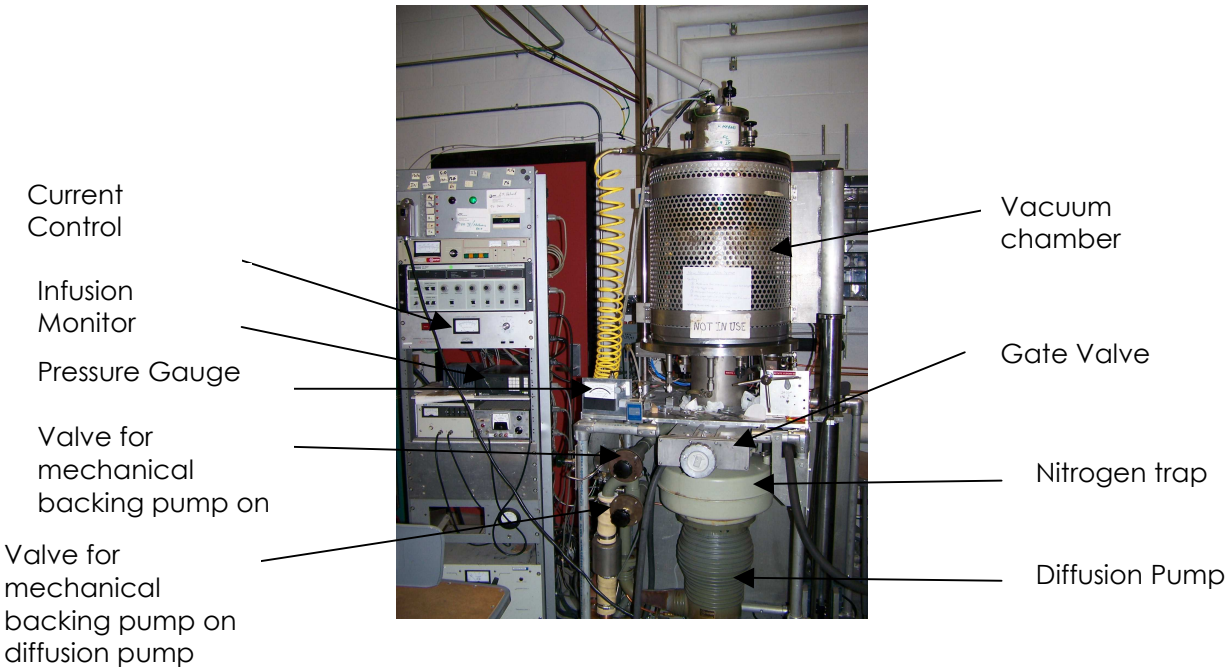
The Miller system is a vacuum deposition system. The Miller system consists of a vacuum chamber, gate valve, nitrogen trap, diffusion pump, mechanical pump, and three other valves. To begin using the Miller system, fill the nitrogen trap with nitrogen from a dewar. When filled the temperature is approximately 60 K. At the same time the vacuum chamber can be vented by opening the N_2 gas valve. It is important to note that at this time the mechanical pump is working on the diffusion pump, not on the vacuum chamber. Once the nitrogen trap is filled, the nitrogen should be turned off immediately. The vacuum chamber can be opened when the chamber is at atmospheric pressure, which will be signaled by the green light as well as the

vacuum chamber pressure gauge. However, the N_2 should remain on while the vacuum chamber is opened, since this maintains a clean system. At this point the sample, which should be fastened to a puck, can be secured inside the vacuum chamber. The readymade target or targets (since one to six targets may be used without breaking the vacuum) of the desired metal are placed in the lower part of the vacuum chamber and fastened in their allotted locations. When this is done, the vacuum chamber is lowered and the N_2 gas turned off.

Subsequently, the mechanical pump is used to pump down the vacuum chamber. This is done by closing the valve for the mechanical pump on the diffusion pump and opening the valve on the vacuum chamber. Once the vacuum chamber is pumped down to approximately 50 millitorr, the mechanical pump is switched from working on the vacuum chamber to working on the diffusion pump. Then the gate valve is carefully opened. It is important to keep roughing and frontline pressures below 100 millitorr. When the gate valve is fully opened, the ion gun is turned on to measure the pressure. The diffusion pump then pumps down to a pressure of about 10^{-7} torr.

With a pressure of about 10^{-7} torr, the system is ready for deposition. The specific metal density and z-factor values are programmed in the Inficon monitor. The Inficon deposition monitor is connected to a crystal inside the chamber for accurate readings regarding the thin-film growth rate and the grown thickness. It is important to face the sample down and turn on the puck rotator at this point for a uniform deposition on the sample. Deposition is made after gradually increasing a current from 0 amps up to a desired ampere for a specific rate of evaporation. When the desired rate is reached and stable, the shutter connecting the upper and lower portions of the vacuum chamber is opened and deposition is made.

After evaporating the metal, the current is turned off. Immediately the ion gun is shut off and the gate valve is closed. Then the system is left to cool off for approximately 10 minutes. Once the system is cooled, the N_2 gas is turned on to vent the system. The vented system can be opened to retrieve the sample once the vacuum chamber has reached atmospheric pressure.



B. Rapid Thermal Annealing Oven (RTA)

The Rapid Thermal Annealing Oven (RTA) consists of a chamber and a controller. The chamber is lined above and below the glass tube oven with tungsten halogen lamps. In this case, the RTA is used to make the backside contact layers of metal uniform electrically and structurally. This eliminates resistance due to the interfaces between the layers. To use the RTA the two water lines must first be turned on. Then the water chiller compressor is turned on. After this the N_2 gas line is opened. To check that it is hooked up well to the RTA, open the N_2 gas valve attached to the pyro tubes. Following this, turn the RTA on and carefully pull the tray out. Place the sample on the thermocouple, which is on top of the quartz tray. Cover the sample with a glass sheet. This acts as a barrier in case the sample has some impurity on it. After

carefully closing the tray adjust the N_2 gas flow. Then it is important to edit the running recipe for the RTA. With the edited recipe execute the recipe. After the recipe has run, wait for it to cool to about 60 degrees Celsius.

C. Physical Properties Measurement System (PPMS)

The Physical Properties Measurement System (PPMS) consists of an empty center core for the sample surrounded by a liquid H_4 dewar, jacketed by a liquid N_2 dewar. The system can be set manually or remotely through LabView for ranging temperatures and magnetic fields. The PPMS is capable of setting temperatures from 1.8 Kelvin to 300 Kelvin with magnetic fields from 0 to 7 teslas.