

ELECTRONIC PROPERTIES OF A QUASI TWO-DIMENSIONAL SYSTEM (EP2DS) aka Quantum Oscillations

Phys 2010 – Brown University – March 13, 2009

Purpose

The purpose of this laboratory is to learn about and observe certain properties of a two-dimensional system. The system to be used is the inversion layer of a silicon MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor). By making conductance measurements in a magnetic field, Landau levels can be observed whose properties can be used, in conjunction with other information, to verify the two-dimensionality of the inversion layer and to derive some of the physical parameters of the MOSFET.

Theory

In this section it will be shown how one can obtain a two-dimensional electron gas in a silicon MOSFET, that distinct energy levels (Landau levels) due to quantization in the plane of the device can be produced and detected when a magnetic field is applied, and how certain information is revealed by the properties of these levels.

A MOSFET is a commonly used type of transistor. A typical cross-section is sketched in Fig. 1.

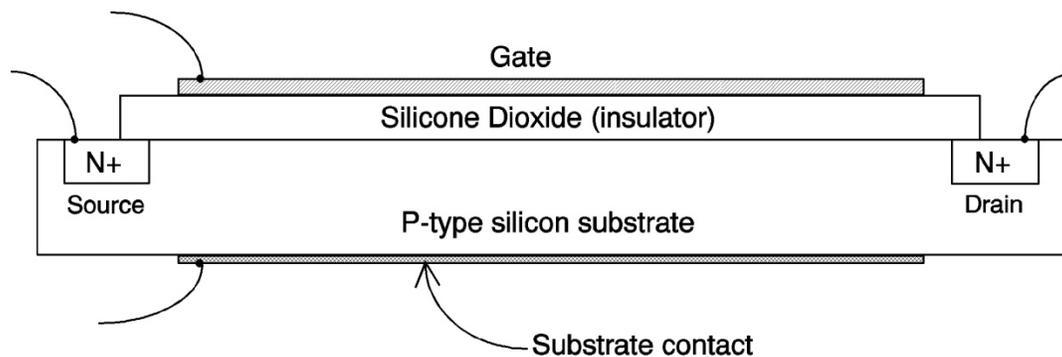


Figure 1. Cross-section of a typical MOSFET with p-type substrate.

The gate is a conducting sheet. It is insulated from the substrate and source and drain contacts by the oxide layer, so a voltage can be applied to the gate relative to the source. Almost no current flows through the oxide, but the gate voltage can induce a change in

the ability of the semiconductor to conduct electrical current between the source and drain. In silicon MOSFET, the insulating layer is made of silicon dioxide, which has a dielectric constant of about 3.7 to 3.8 and is usually of the order of 10^3 \AA thick. The silicon substrate has a dielectric constant of about 11.7. The physics behind the response of the semiconductor to the gate voltage is described below.

Solid materials have their electrons in relatively wide energy bands instead of the narrow levels typical of atoms. A band that is either completely full or completely empty cannot conduct electrical current. Pure semiconductors at $T = 0^\circ \text{ K}$ (or in the ground state) are different from other materials (i.e., metals or insulators) in that the electrons completely fill one band, called the valence band, but have another band, called the conduction band, whose bottom edge is separated by only a few tenths to a couple of electron volts from the top of the valence band.

A semiconductor can also be doped with small amounts of impurity atoms that have a different atomic number from the host material. One type of impurity is called an acceptor. An acceptor's lowest energy condition has balanced charge, but it takes a relatively small amount of energy to add another electron, so the acceptor levels appear slightly above the valence band edge in an energy diagram. A donor is an impurity that can easily give up an electron so a donor level is slightly below the conduction band edge. A semiconductor with more acceptors than donors is called a p-type semiconductor, while the opposite is called an n-type semiconductor, see Fig. 2.

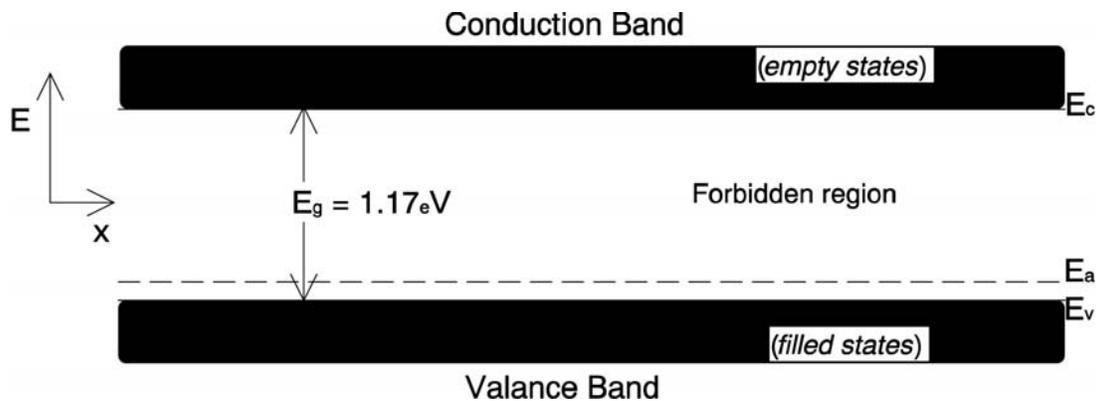


Figure 2. Energy bands in p-type silicon. The shaded regions correspond to areas with states. Only those states below E_F (E_a) will be filled at $T=0$.

The Fermi level is defined as the energy E_F at which, for $T = 0$, all states with $E < E_F$ are filled while all states with $E > E_F$ are empty. For p-type semiconductors, the Fermi level is near the valence band edge. As soon as $T > 0$, some acceptor levels will be filled, that is, negatively charged.

It is also possible to force all of the existing states upward or downward by applying a voltage. This can create interesting situations because the Fermi level remains in its original position if equilibrium is reached, implying that previously full states can become empty and vice versa.

Now, we can consider the application of a positive voltage (with respect to the source) to the gate of a MOSFET with a p-type substrate. Since the energies which are relevant are the electron energies, a positive voltage forces the electron energy levels in the gate downwards. Qualitatively, one can see that the acceptor levels in the substrate will also be drawn downwards, causing those acceptor sites below the Fermi energy to become negatively charged. The amount of band bending can be determined by using Poisson's equation:

$$\nabla^2 \phi = -\frac{\rho}{\epsilon}$$

where ϕ is the electrical potential, ρ is the charge density, and ϵ is the dielectric constant. In the region over which bands are bent, $\rho = eN_a$ where e is the charge on an electron and N_a is the density of acceptor levels. Since these charges screen the gate charges, the band bending must tend to zero as one moves away from the oxide-semiconductor interface. The volume in which the acceptor levels bend below the Fermi level and are charged is called the depletion layer, see Fig. 3.

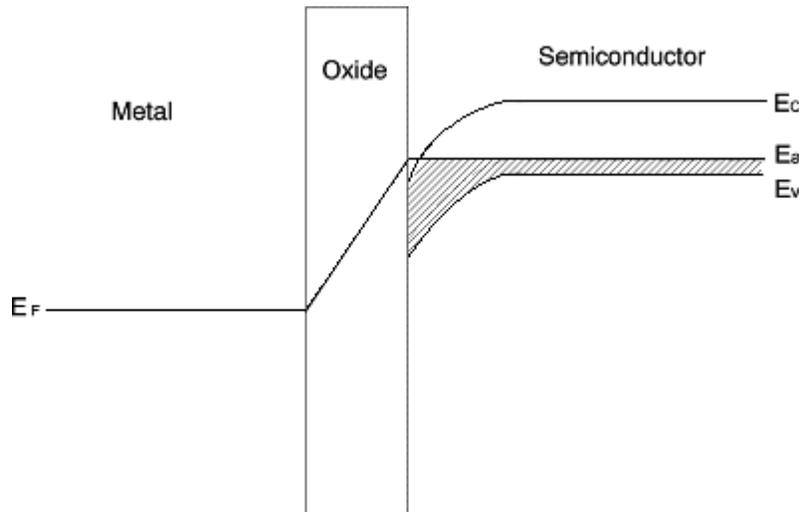


Figure 3. Energy bands in a MOSFET with an applied gate voltage sufficient to form an inversion layer. Occupied states are shaded. $E_F = E_a$ far from the oxide-semiconductor interface.

In this experiment we are concerned with the situation where the band bending is great enough to draw the conduction band edge below the Fermi level. This causes electrons to populate the conduction band in a narrow layer, called an inversion layer because electrons are normally the minority carriers in p-type materials. The electrons are free to move in the x and y directions (parallel to the interface) but are constrained in the z direction by the oxide and the upward sloping conduction band edge. One can easily calculate the gate voltage at which the inversion layer should form, given the relevant parameters of the MOSFET, by using Poisson's equation and the continuity of the electric displacement at the oxide-substrate interface.

Gauss's law states that the electric field F is given by

$$F = \frac{4\pi}{\epsilon} \int \rho d^3r$$

Inside the depletion layer before the inversion layer forms $\epsilon = 11.7$ and $\rho = eN_a$ at low temperatures. If ℓ_d is the end of the depletion layer and the origin is the oxide-semiconductor interface, then

$$F(z) = \frac{4\pi}{\epsilon} eN_a(\ell_d - z)$$

Since $F(z) = -\nabla\phi(z)$, the turn-on potential, or threshold potential, of the inversion layer is given by

$$\int_0^{\ell_d} \nabla\phi(z) dz = \phi(0) - \phi(\ell_d) = \frac{4\pi}{\epsilon} \int_0^{\ell_d} N_a(\ell_d - z) dz = \frac{-e}{\epsilon} N_a \frac{4\pi\ell_d^2}{z},$$

or

$$\phi(0) = \frac{2\pi e N_a}{\epsilon} \ell_d^2$$

where $\phi(\ell_d = 0)$ is a boundary condition. In a semiconductor, though, $\phi(0)$ is just $(E_i - E_v)/e$ where E_i is the conduction band edge with E_v is the valence band edge. In silicon $(E_i - E_v) \sim 1.17$ eV. This finally yields the depletion width ℓ_d .

If the conduction band edge just barely dips below E_F , then to a good approximation the electrons in the conduction band see a linear well in the z direction with an infinite barrier at $z = 0$. The quantum mechanical energy levels can be determined by using Airy functions, or approximately by the W K B method or one can obtain a rough idea from use of Heisenberg uncertainty principle. The uncertainty principle,

$$\Delta z \Delta p_z \approx h,$$

where Δz is the uncertainty in the z coordinate and Δp_z the uncertainty in the momentum. This can be used to approximate the energy level separations by letting Δz and Δp_z be the classical variations of a particle in such a well. Then

$$eF\Delta z \approx \Delta E \quad \text{and} \quad \Delta E \approx \frac{\Delta p_z^2}{2m_z^*},$$

where F is the electric field on the substrate side of the interface, ΔE is the energy level separation, and m_z^* is the effective electron mass in the z direction. Combining these two equations yields:

$$\Delta E \approx \frac{(ehF)^{2/3}}{(2m_z^*)^{1/3}}.$$

Mention was made above of an effective mass. It is an approximate way to account for the fact that electrons in the periodic lattice of a crystal behave differently from free electrons when fields are applied. In silicon, each electron near the bottom of the conduction band has an effective mass in one principal direction of $m_\ell = 0.92 m_e$ and an effective mass in the other two principal directions of $m_t = 0.19 m_e$.

There is a six-fold degeneracy corresponding to minima in the conduction band for each of the positive and negative principal cubic axes of the crystal. For directions other than the principal ones, the three principal effective masses can be assembled into a tensor and rotated in accordance with tensor algebra.

Electrons' constant energy levels in a solid can be drawn in K-space (crystal momentum space). For silicon, the conduction band minima occur along the principal axes of the crystal. The energy of an electron near any of these minima can be expressed by

$$E = E_0 + \frac{\hbar^2}{2} \left(\frac{k_1^2}{m_1^*} + \frac{k_2^2}{m_2^*} + \frac{k_3^2}{m_3^*} \right),$$

where the indices indicate the principal axes, with one subscript indicating the longitudinal mass and the other two the transverse masses. In the samples to be used in this laboratory the principal axes will coincide with the geometry of the device such that one principal axis is normal to the plane of the gate. One can then draw a constant energy surface in K-space (see Fig. 4).

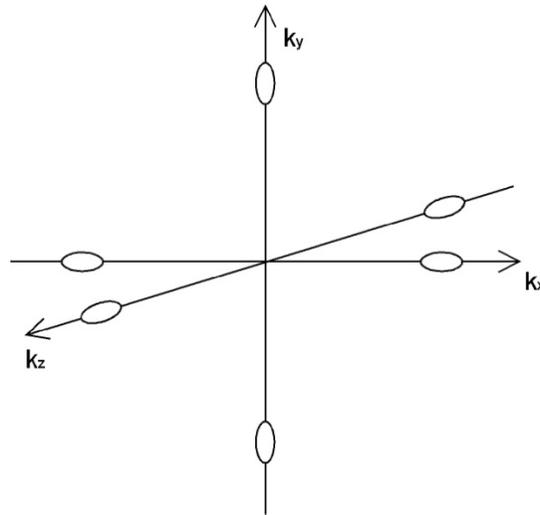


Figure 4. Constant energy surfaces for silicon plotted in crystal momentum space.

The long axis of each ellipsoid coincides with the direction corresponding to the large longitudinal mass m_ℓ , while the two short axes correspond to the transverse mass m_t . The six ellipsoids correspond to the six-fold degeneracy mentioned earlier.

We can now reconsider the potential well in the z-direction, whose first energy level is given by:

$$\Delta E < \frac{(ehF)^{2/3}}{(2m_z^*)^{1/3}}.$$

For four of the ellipsoids, $m_z = m_t$ while for two of them $m_z = m_\ell$. The two longitudinal masses will have a lower ground state energy. This energy band is called the first electric

sub-band, and is the only one which we will consider. Note that the six-fold degeneracy has been lifted, so that there is now only a two-fold degeneracy.

Question: For a doping level of $N_a=10^{15}$ atoms/cm³, what is the energy difference between the first electric sub-band and the conduction band edge at the oxide interface when there are no carriers in the inversion layer?

The above calculation shows that motion in the z -direction is quantized and limited to a few tens of an atomic radius, but motion in the x and y directions is affected only by the edges of the sample, by the periodic crystal potential, and by the presence of miscellaneous scattering mechanisms which will be briefly mentioned later. The crystal potential is accounted for by the effective mass m_t , so except for scattering, the electrons are free to move in the x and y directions. This can be seen by considering the time-independent Schrödinger equation and separating out the motion in the z -direction.

If electrons are free to move in a solid, it is conventional to consider solutions that satisfy the Born-von Karman boundary conditions $\psi(x + L, y, z) = \psi(x, y, z)$, etc., and that are normalized so that $\psi(\vec{r}) = \frac{1}{\sqrt{L^d}} e^{i\vec{k}\cdot\vec{r}}$ where d is the dimensionality of the system and L is a linear dimension (see Ashcroft and Mermin, pp. 32-35). After separating out the z -component, the T. I. Schrödinger equation is just:

$$\frac{\hbar^2}{2m} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \psi_r = \epsilon \psi_r.$$

The solutions are $\frac{1}{\sqrt{A}} e^{i\vec{k}\cdot\vec{r}}$ where A is the area of the MOSFET, $k_i = \frac{2\pi n}{L_i}$ ($i = x, y$) and n

is any integer such that $|n| \leq \frac{L}{2a}$, where a is the lattice spacing.

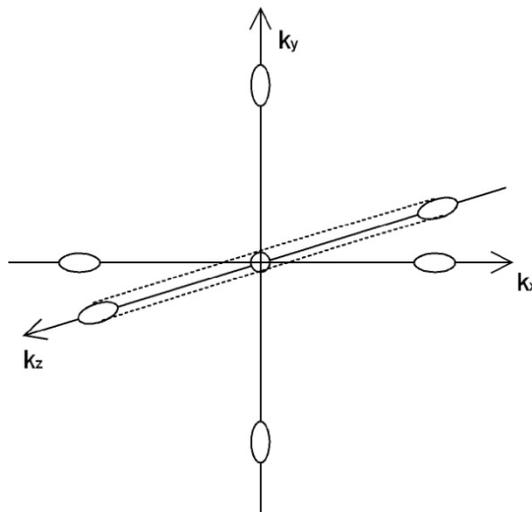


Figure 5. The Fermi circle for the lowest energy sub-band in a (100) silicon MOSFET inversion layer. It is obtained by projecting the k_z ellipsoids onto the $k_x - k_y$ plane.

It is useful to introduce the concept of the Fermi momentum, which is just the momentum corresponding to the Fermi energy. Note that this is a vector quantity. In our MOSFET, a graph of the Fermi level in the k_x, k_y plane is just a circle; at low temperatures (i.e. $k_B T \ll \frac{\hbar^2 k_F^2}{2m_t}$) almost all levels below k_F will be filled and almost all levels above k_F are empty, see Fig. 5.

It is useful to change slightly our point of view. When the gate voltage is increased and induces an inversion layer, the Fermi level stays constant as the edge of the conduction band moves downwards. What we are really interested in, though, is the difference between the most energetic electron's energy and the ground state of the potential well formed by the conduction band edge and the oxide interface. Thus, we may speak of the Fermi level's “ ϕ rising” when actually the conduction band edge, and so the ground state of the well, is falling.

The number of electrons in the inversion layer for $kT \ll E_F - E_0$, where E_0 is the ground state energy of the well, is just the number of states below the Fermi level. In order to relate this quantity to our experimental situation where we can change the gate voltage, or energy, we make use of the density of states:

$$N(E_F) = \int_{E_0}^{E_F} D(E) dE,$$

or, since $E_F = \hbar^2 k_F^2 / 2m^*$, the density of states per unit energy per unit area is $D(E) = m / \pi \hbar^2$, see Fig. 6. and note that $\Delta n_s = \frac{\Delta N}{A} = D(E)$

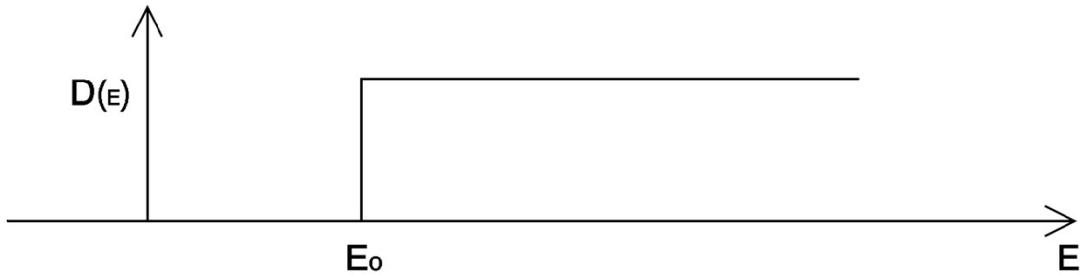


Figure 6. Density of states vs. energy.

Once the inversion layer is formed, the relationship between the gate voltage and the electron density, n_s , is given by the formula for a parallel plate capacitor:

$$Q = n_s A e = C(V_G - V_t)$$

where $C = \epsilon_{\text{oxide}} A / t$, n_s is the number of electrons per unit area, V_G is the gate voltage, and V_t is the threshold voltage at which the inversion layer begins to form. This gives a very simple relationship between $V_G - V_t$ and $E_F - E_0$:

$$n_s = \frac{C}{Ae} (V_G - V_t) = \int_{E_0}^{E_F} \frac{m^*}{\pi \hbar^2} dE = \frac{m^*}{\pi \hbar^2} (E_F - E_0)$$

In all of the above expressions we have left out the various degeneracies of the system. There is a two-fold degeneracy due to the two ellipsoids, or valleys, and there is also degeneracy due to spin. In all of the above expressions $D(E)$ must be multiplied by four, the total degeneracy. m^* is the effective mass of the electron, which is $\sim 1.1 m_e$ in Si.

Experimental setup

We can now discuss the experimental measurements.

The samples have one of the three shapes in the lateral direction (see Fig. 7): a rectangle with contacts (n^+ regions) at each end only, a rectangle with end contacts and pairs of side contacts for measuring the three independent components of the magneto-resistivity tensor; and a Corbino disk (with cylindrical symmetry), with interior and full exterior contacts useful for measuring the longitudinal component of the conductivity tensor directly.

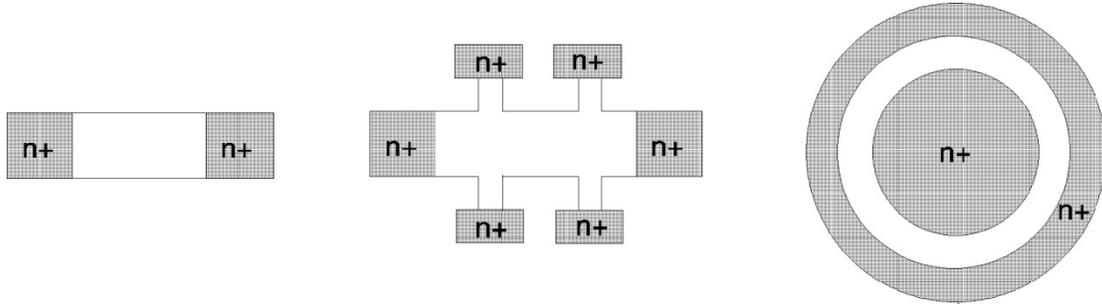


Figure 7. Geometry of the samples.

The conductance between the source and drain can be measured with the circuit shown in Fig. 8. The conductivity σ is related to the conductance by the factor L/W for rectangular samples, where L is the distance from source to drain and W is the width, by the equation $\sigma = W / RL$ (where $1/R$ is the conductance), and is defined by the equation $\vec{J} = \sigma \vec{F}$ where \vec{J} is the current flux and \vec{F} is the electric field in the x-y plane. We can then say that $\sigma = n_s e \mu$; where μ , the mobility of the electrons, is equal to $e \tau / m$, where τ is the mean time between collisions.

The measured conductivity should be limited by the n^+ source and drain contacts only to a negligible degree because the n^+ regions have a very high number of conducting electrons and hence a much higher conductivity than the inversion layer. Therefore we

usually use the “two terminal” measurement configuration shown in Fig. 8. A typical graph of σ vs. gate voltage is shown in Fig. 9. If the mobility were constant, the graph would simply be a straight line rising from the V_G axis, reflecting the linearly increasing n_s . The largest features are easily explained. The intersection of the curve with the V_G axis is not abrupt because lattice defects and oxide impurities interact with the electrons, causing the collision rate $1/\tau$ to be relatively large. As more electrons are added, the collision rate per electron approaches a lower, more constant value due to screening. Then the curve approaches the linear form predicted by our theory. At still higher voltages the well in the z-direction becomes steeper, causing the electrons to collide more often with any surface defects. Thus the slope tapers off eventually.

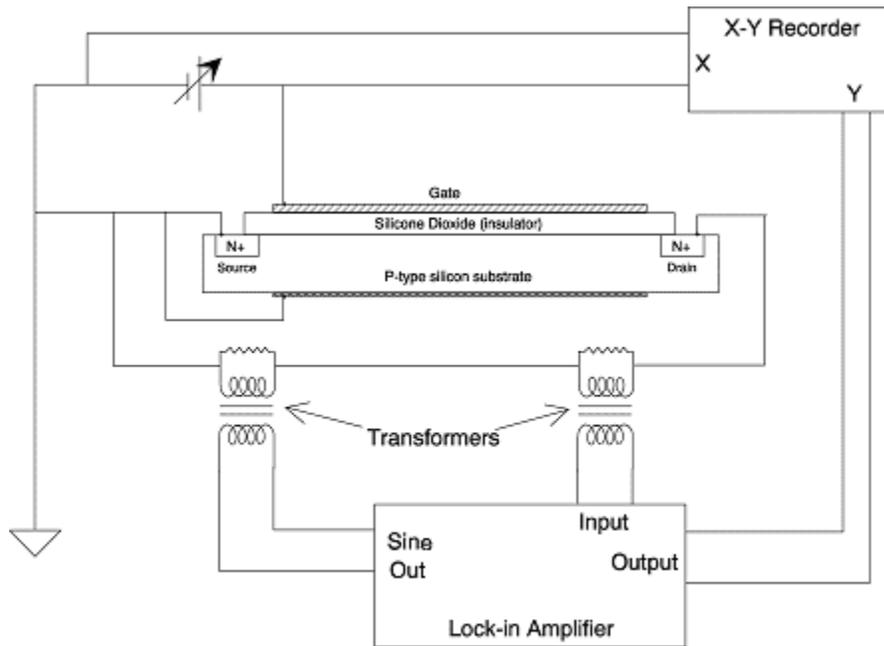


Figure 8. Circuit for measuring conductance. The reference signal results in an emf being produced on the MOSFET side of the reference transformer. This emf causes a current to flow, which is dependent upon the resistance of the sample. This current drives the signal transformer which in turn drives the input of the lock-in. Note: the reference and signal transformers are interchangeable. Note the Reference Signal Out label is incorrect – use the SINE OUT at the back of the Lock-in which generates a ~100 mV rms sine wave. The symbol (top left) – variable voltage is actually a Signal Generator – suggest you use a triangle wave which goes from 0 to 6 V and 0.01 Hz sweep rate.

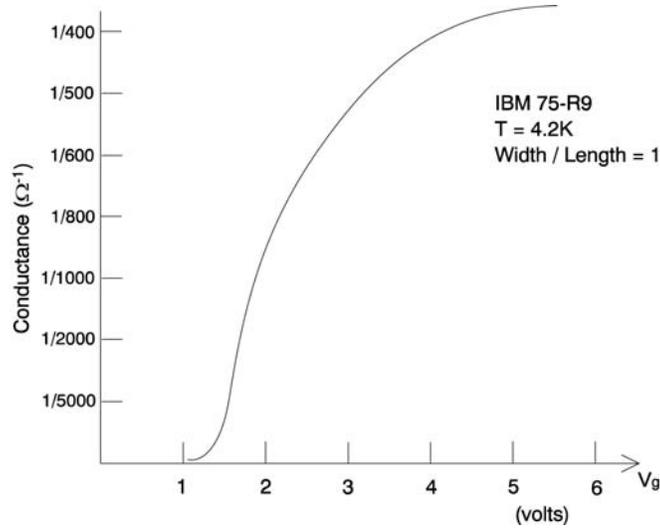


Figure 9. Conductance vs gate voltage V_g curve.

Landau levels

Landau levels are discrete energy eigenstates that are the result of applying a magnetic field to a system of conducting electrons. It can be said that the electrons will move in orbits perpendicular to the magnetic field in such a way that angular momentum is quantized. Using more basic arguments (see Landau and Lifshitz, Quantum Mechanics, vol. 3, p. 456), the energy eigenvalues can be determined.

For the range of magnetic fields and temperatures to be used in this laboratory, it has been shown that the conductivity in the x-y plane is approximated by

$$\sigma_{xx} \sim \frac{2\pi^2 k_B T}{\hbar \omega_c} \frac{\cos\left(\frac{2\pi n_s}{nL}\right)}{\sinh\left(\frac{2\pi^2 k_B T}{\hbar \omega_c}\right)} + f(n_s),$$

where n_s is the density of electrons/unit area, nL , which is proportional to the magnetic field, is the degeneracy of each Landau level and $f(n_s)$ is a smooth function of n_s .

Equipment

WARNING: READ ENTIRE FOLLOWING TEXT, INCLUDING PROCEDURES, BEFORE OPERATING EQUIPMENT

The equipment to be used consists of the MOSFET and measurement apparatus, a superconducting magnet, its power supply and controls, and the liquid helium Dewar. The experiment must be done at liquid helium temperatures primarily so that $\omega_c \tau \geq 1$, for an electron in the MOSFET inversion layer, or in other words so that scattering does not broaden the Landau levels too much. It is also necessary to keep the superconducting

magnet cold, but it is possible to do the experiment with a much larger conventional magnet outside of the dewar. See the TA for instructions on handling the MOSFET. **It is physically and electrically fragile.**

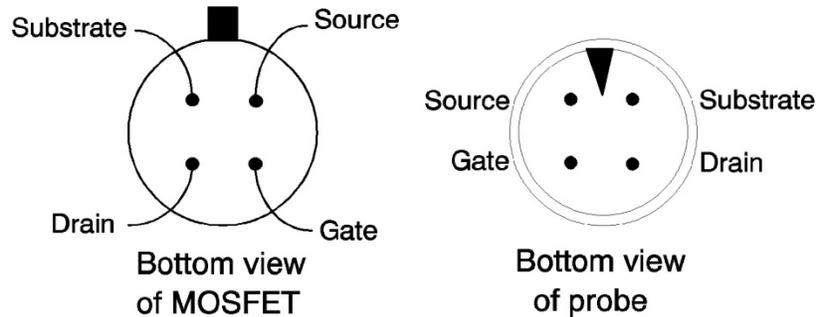


Figure 10. MOSFET and probe pin-out.

Magnet

The magnet system is composed of four major elements: (1) the superconducting magnet, (2) the power supply, (3) the controller for the power supply, and (4) the persistent switch. The magnet is rated for 60 kilogauss at 34.5 amperes at liquid helium temperatures. **Under no circumstances should any current be run through the magnet if it is not at helium temperatures.** The controller allows one to ramp the current from the power supply with arbitrary rates and limits. The persistent switch allows one to turn off the power supply once the desired current is reached by creating a superconducting short circuit between the magnet leads. **The magnet can only be run at liquid helium temperatures, and the power supply must always be run with the controller.**

The steps for ramping the magnet up and down are as follows:

CAUTION: READ ENTIRE SET OF INSTRUCTIONS BEFORE STARTING!

Ramping up

1. Check the liquid helium level. The magnet should not be operated if the level is lower than 15 cm.
2. Check electrical connections.
3. Set the Ramp control switch on the controller (Model 60) to DOWN.
4. Turn the controller on and allow it to warm up for about 15 minutes.
5. Turn the H.P. power supply on and then the persistent switch heater (Model 30).

6. Adjust the current limit on the controller until the desired operating value is displayed. Do not exceed 34.5 Amps! Always use the value displayed as the true preset programmer value. Do not use the reading on the 10-turn dial.
7. Set the Current Monitor selector switch to display Ramp Rate and set the Ramp Control switch to PAUSE. Now rotate the Rate Adjust Potentiometer until the desired ramp rate is displayed on the Current Monitor. The display is calibrated in Amps/second. Always use the displayed value for the true Ramp Rate and not that found on the 10-turn dial. Return the Ramp Control switch to the DOWN position.
8. Set the Current Monitor selector switch to display Power Supply Current. The display should indicate zero or some slightly negative value.
9. After the persistent switch heater has been on for at least one minute, set the Ramp Control switch to the UP position and watch the Current Monitor display. It should indicate a ramp of the current at the preset rate until the current limit is reached.
10. If you do not want to leave the magnet at a constant field simply continue to sweep up and down to the desired magnetic fields. (CAUTION: Any changes in the current limit etc. are to be made only when the current is zero.)

Persistent mode

If you want to leave the magnet at a constant field in the persistent mode do the following:

1. When the current reaches the desired limit record its value.
2. Turn the persistent switch off, then pause for at least one minute.
3. Set the Lamp Control switch to DOWN.
4. When the current is zero turn the power supply off.

Terminating persistent mode operation

1. Turn the power supply on.
2. Ramp the current up to exactly the same value as is in the magnet.
3. Turn the persistent switch on and wait for one minute.

Turning off

1. Ramp the current down to zero.

2. Turn the persistent switch off.
3. Turn the power supply off.

Note: The Ramp Rate should not exceed 1Amp/sec.

It is extremely important that these steps are carried out in the order presented - failure to do so will not only damage the equipment but may be dangerous.

Helium Dewar

For most of the low temperature measurements the Cryomagnetic's "Superconducting Magnet/Dewar System" will be used. The dewar in this system is a vapor shielded liquid helium cryostat. See instructions for the magnetic/dewar system that are supplied with this lab. The student must be closely supervised when filling this Dewar with cryogenes.

Measurement apparatus

Two circuits are to be used. One is for conductance measurements and the other is for transconductance measurements, to be described later. The two circuits are shown in Figures 8 and 11. See your TA for the correct voltage and current levels to use. The transformers and small voltage supplies will be provided.

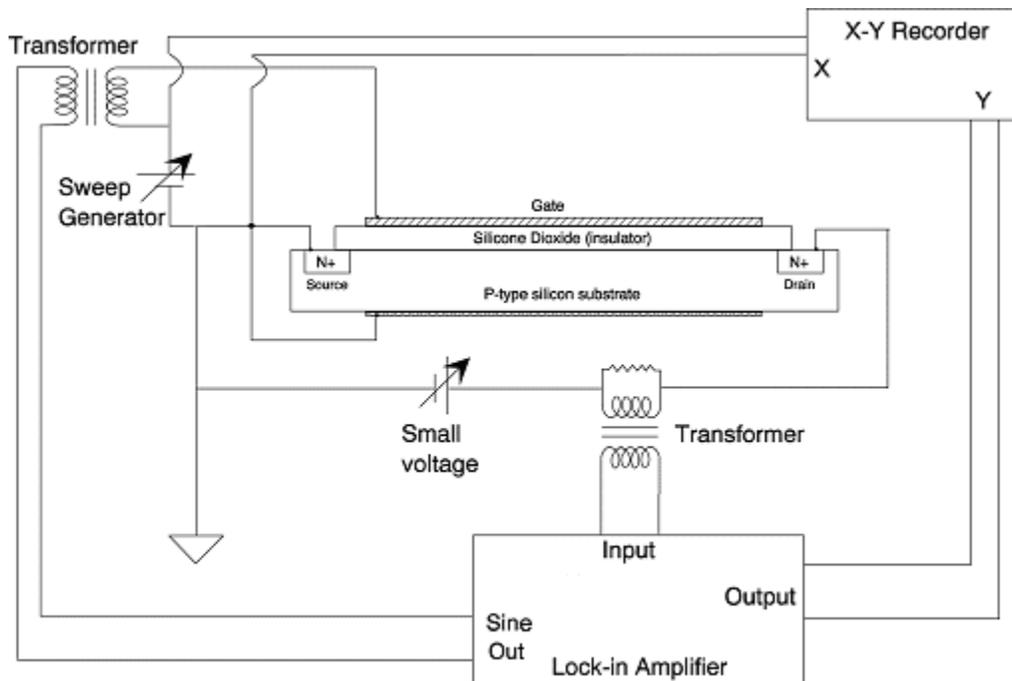


Figure 11. Circuit for measuring transconductance.

The lock-in amplifier in these circuits is basically an AC voltmeter that is selective with respect to a desired frequency and phase - other parts of the signal are filtered out. The output of the lock-in can be read from an analog scale on the front panel or tied directly into one channel of an x-y recorder.

Procedures

A TA MUST BE PRESENT WHEN CRYOGENS ARE BEING TRANSFERRED

First, set up the conductance measuring circuit shown in Fig. 8. Then, obtain a conductance curve at 300 K, 77 K (liquid nitrogen temperature), and 4.2 K (liquid He temperature). Each curve should be calibrated by inserting a decade resistance box in place of the MOSFET and measuring a few inverse resistances.

Set up a transconductance measuring circuit as shown in Fig. 11. The transconductance gives an approximation of the derivative of the conductance curve, as the modulation of the gate voltage (Δx) gives rise to a change in the conductance (Δy) that yields the measured signal. The transconductance is useful because it generally accentuates small, sharp structures by giving a larger signal. Take transconductance curves at room temperature, 300 K, 77 K, and 4.2 K. One definition of the threshold voltage is the value of the V_G intercept of the almost linear, rapidly rising section in transconductance curves taken at 77 K.

Question: Why do measurements at different temperatures yield apparently different values of the threshold voltage?

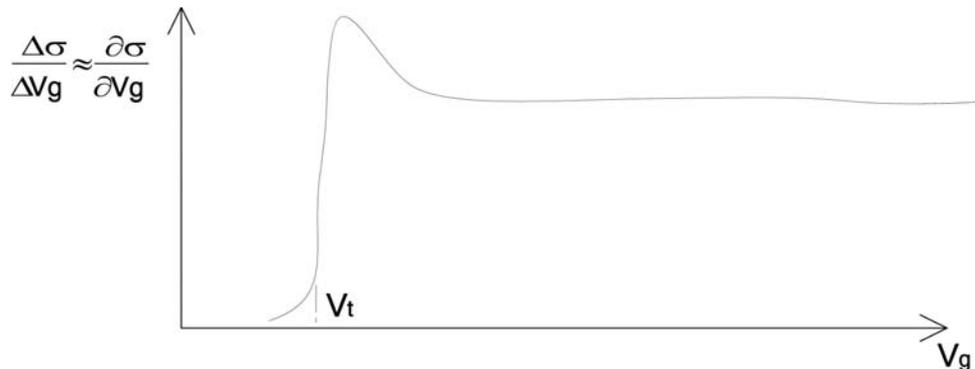


Figure 12. Transconductance curve.

Now locate the MOSFET in the middle of the magnet with the z-axis parallel to the magnet's cylindrical axis and immerse both in liquid helium. Take a transconductance curve at the magnet's maximum rated field. From the signal obtain the thickness of the sample's oxide layer by using the relation:

$$4(\Delta n_s)e = \frac{\epsilon_{ox}}{t_{ox}}(V_n - V_{n-1})$$

where Δn_s is the calculated degeneracy (using theory) of the level and $V_n - V_{n-1}$ is the voltage difference between levels. Use a plot to average easily over many oscillations.

Change the magnetic field and take another transconductance curve. By verifying the result for t_{ox} , the fact that the degeneracy of each level is proportional to the field can be proven.

Then, taking into account the 90° phase change between conductance and transconductance, plot the minima on a graph showing the index of each minimum versus gate voltage.

Two straight, or nearly straight, lines should result. If one could be sure as to the index of the first observed level, then V_t could be calculated precisely. Unfortunately, localization of carriers can wipe out the first level or two, so, in order to remove any ambiguity, it is necessary to do one more field measurement.

Fix V_G at a reasonably high value and vary H, and make a plot of $\frac{d\sigma}{dV_G}$ vs. $\frac{1}{H}$. From this plot it is possible to find the location of the first level by extrapolating the curve to the $\frac{1}{H=0}$ axis. Then one can compare some other level with the earlier runs to find the threshold voltage unambiguously. Why is that so?

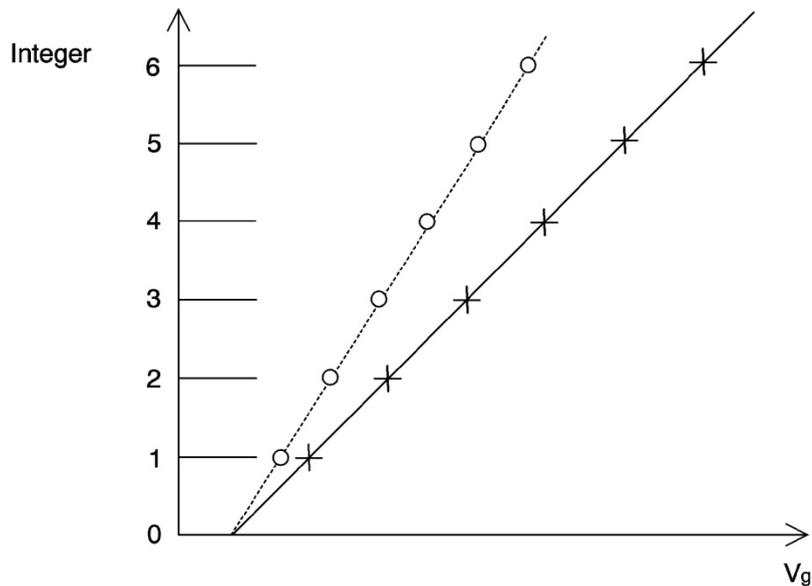


Figure 13. Transconductance minima versus gate voltage.

Finally, by comparing the values of n_s in the runs taken with a magnetic field applied and comparing it to the conductance curves, one can obtain values for the mobility from

the equation $\sigma = n_s e \mu$. Give the mobilities at three different voltages and temperatures. From the equation $\mu = e \tau / m^*$, where m^* is the effective mass, one can also get a value for the mean time between collisions τ .

One can apply the results of a number of transconductance runs with a magnetic field at different temperatures to find an experimental value for m . One may then measure the amplitude of the oscillations at a fixed gate voltage as a function of H to obtain τ .

It is also possible to find the doping level N_a as follows. Fix the magnetic field H and vary the gate voltage V_G while fixing the substrate voltage V_s (see the TA) at successively different values. By observing the shifts of the oscillations, one can use Gauss's law and the change in the number of electrons in the inversion layer to determine N_a . The equation relating these is:

$$\delta n_s \sim N_a^{1/2} \left((E_g + V_{s1})^{1/2} - (E_g + V_{s2})^{1/2} \right),$$

where E_g is the potential of the inversion layer with no substrate bias (a negative voltage in a p-type sample relative to the inversion layer), and δn_s is the change in the number of electrons in the inversion layer.

References

1. S. M. Sze, *Physics of Semiconductor Devices*, New York: Wiley-Interscience, 1969, p. 505.
2. N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, New York: Holt, Rinehart and Winston, 1976, Chapters 1, 2, 14.
3. L.D. Landau and E.M. Lifshitz, *Quantum Mechanics*, 3rd Edition, Oxford, Pergamon Press, 1977, p. 456.
4. T. Ando, A. B. Fowler and F. Stern, *Electronic Properties of Two-Dimensional Systems*, Rev. of Mod. Phys. **54** (1982) 2.

Some Recipes and corrections for Quantum Oscillation

By Yunhe Xie (Added by Gaitskell 25Sep2003)

The first thing I want to say is that there are some small mistakes in the circuit diagrams.

In the measurement circuits both for conductance and for transconductance, shown in Fig. 8 and Fig. 11, the "reference signal out" in LOCK-IN AMPLIFIER" should be the "SINE OUTPUT" channel.

Second, in the circuit for transconductance measurement, we also need to apply a second DC supply on the gate, except the shown small voltage. Since the signal from the function generator is chosen to be triangle, changing from "-" to "+", we need shift it to be positive over all the process. So a second DC supply is needed in this circuit. It can be added into the circuit in this way that it's connected with the function generator in series.

Third, during the progress, we should pay more attention on the transconductance part, which is the biggest goal of our experiment. In this part, there're several "recipes" we can use.

The gate voltage should be high enough for us to observe the oscillations. It can be realized by using high output of function generator, and also high enough DC voltage. Usually, the output of the function generator is around 17V, and the value of DC supply is 10-15V. But be sure not apply too high voltage on the MOSFET, otherwise it'll be damaged. Another thing on this DC voltage you should pay attention to is the connection with function generator, which is pretty tricky. But now, you can turn to Mike for help.

The most difficult thing is the measurement of transconductance oscillations in the external magnetic field. Here we should care mostly about the value of the small voltage. In principle, the transconductance curve is the derivative of the conductance curve. Experimentally, this can be achieved by modulating the gate voltage with a small DC voltage. But the range of this small voltage is very critical, because the oscillation effect will be wiped by the quick decrease if we apply a high DC value. On the other hand, it neither can be too small, which also wipes the oscillation away. Usually it can be set in the order of 10 mV. You can observe its effect directly and clearly by changing the value of small voltage. Since the exact value of small voltage can't be directly read out from the supply's panel, a voltage meter can be used to tell the accurate voltage.

When working with the superconducting magnetic, we should go through the process step by step under the instruction on the manual. Be sure to know what you're going to do, and what you should take care of.

When transferring the liquid Nitrogen and liquid helium, do follow the safety instructions. And the first time, Dean should be there, though after that it may not necessary. Before you do the transferring, try to figure out the proper time schedule, because you have to wait two hours before you pour the liquid helium into the Dewar. And after that, you should do your work as soon as possible, because the Helium almost can last 8 hours, and the decrease will be faster later than the beginning moment. The Nitrogen can last almost the same long period. So I suggest that be sure that you're familiar with the circuit and its connection. You'd better practice to make it easier for you to change correctly between different measurement circuits, before you get the transferring done.

There's something about the calibration on the manual. If you have enough time, I suggest you do it, 'cause it's truly interesting and helpful for your understanding. And by doing this, you can do more data analysis, which was a pity for me. During this step, there're two things you should pay attention to. One is to reset all the parameters of the instruments JUST THE SAME as the setting you want to calibrate. The parameters mean the sweeping frequency, voltage, etc. except the temperature. The calibration circuit is just the conductance circuit, except replacing the MOSFET by the decay box. The other thing is that you should figure out the calibration model you use, which unfortunately I didn't get the chance to do.

During the whole experiment, you find that the sweeping frequency should kind of slow, which can bring you better image on the screen. Another thing about the Lock-in Amplifier is the reference frequency you input. Be sure not to use the multiple of 60 Hz, which will give you wrong information, especially in oscillation part. The following is some parameters we used when we did this experiment.

Function generator: 10-17V, high output, ramp shape (triangle), 0.010 Hz. The frequency can be chosen slower, which brings better, more accurate shape, with the cost of time.

DC supply: 10-15V. Actually it depends on how high you use from Function generator.

Small voltage: 33 mV. You can try around the order of 10mV.

Lock-in Amplifier: Time:300mw, sensitivity: 500uV, reference frequency; 280Hz.

Long integral time smoothes the curve shape, and reference frequency is better if you choose like 150Hz, 210Hz, etc.

Oscilloscope (X-Y recorder): X-Y mode.

Magnet system: highest current is 34.5Amps. The field vs. current ratio is in the operation manual, whose value is 1737 Gauss/Amps.