MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering and Computer Science

6.007 – Electromagnetic Energy: From Motors to Lasers
Spring 2011

Lab 5: Quantum Mechanical Tunneling
Tuesday and Wednesday, April 26 and 27, 2011
Due: Friday, May 6, 2011

Introduction

In this lab, we will analyze a piece of material composed of nickel in rubber that exhibits a nonlinear current versus voltage (I-V) relationship due to the dominance of tunneling in the conduction process. We will examine how the tunneling, and therefore resistance, of electrons in the material can be modified by compressing the material. Finally, we'll build a simple resistive touchpad utilizing several pieces of the nickel/rubber compound.

1 Pre-Lab

0. Read this lab document.

1. What do you expect to measure for the resistance of the Quantum Tunneling Composite$^{\text{TM}}$(QTC) pill without any applied pressure? (Just give a range: ohms, kohms, Mohms, Gohms)

2. What will happen to the QTC pill if you apply 5V DC for 5 minutes?

3. Draw a side view of the device that you will make in Section 3.2. Include and label all layers and materials in the drawing. Note: The illustrations provided in Section 3.2 are the top view.

At each lab station you will have:

- (5) 3 mm × 3 mm pieces of nickel/rubber compound (QTC Pills$^{\text{TM}}$made by Peratech, Ltd.).
- (1) ITO-coated glass, 3 in × 1 in .
- (2) 3 in × 1 in microscope slides.
- (4) $\frac{1}{16}$ in ball bearings.
- (1) Multimeter.
- Binder clips.
- Rubber strips.
- Copper tape (extra is available from the TA)
- Alligator clips.

2   Theory

2.1   Tunneling in Everyday Life

Perhaps one of the most puzzling phenomena to see for the first time in quantum mechanics is that of a particle tunneling through a barrier. Classically, there is no explanation for how a particle such as an electron could penetrate a barrier. Only by considering the electron as both a particle and a wave can one obtain a physical model that explains electron tunneling.

Many examples of electron tunneling can be found in everyday life. As mentioned in class, a large part of the heat generated by your laptop is from electrons tunneling through the gates of transistors in modern microprocessors. Figure 1 shows a cross-section of a modern transistor. The single-ended arrow points to the gate oxide of only a few nanometers in thickness. Figure 2 shows the scaling of the gate oxide thickness over the last several generations of MOSFETs.[1]
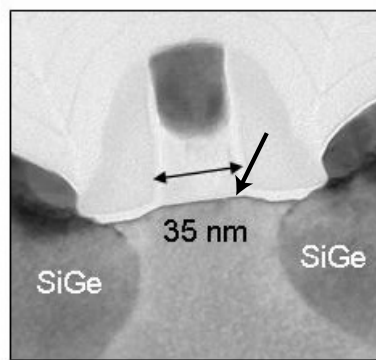

Figure 1: Modern MOSFET with indicated length and gate oxide thickness of only a few nanometers. The single-ended arrow points to the thin gate oxide layer.
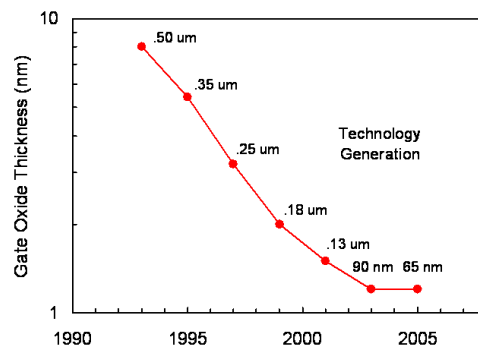

Figure 2: Scaling of MOSFET gate oxide thickness over the last several generations of transistors. The nominal channel length for each generation is indicated.

Source: Bohr, Mark. "A 30 Year Retrospective on Dennard's MOSFET Scaling Paper." " IEEE SSCS Newsletter, Winter 2007, 11-13. Copyright © 2007 IEEE. Used with permission.

An additional everyday example of electron tunneling occurs in flash-based storage, such as in the memory cards for digital cameras and in flash-memory-based MP3 players. Figure 3 shows a schematic of a flash memory device. In flash memory, the discharging of electrons on the floating gate occurs through a tunneling process.

---

[1]From "A 30 Year Retrospective on Dennard's MOSFET Scaling Paper" by Mark Bohr in *Solid-State Circuits*, January 2007.
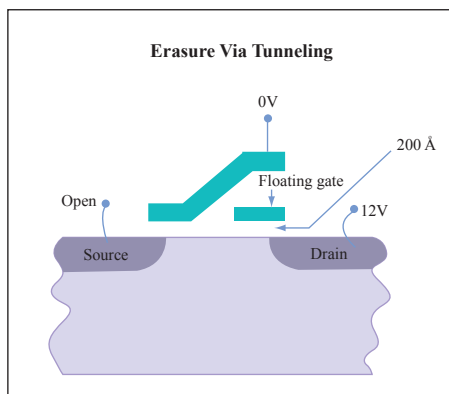
Image by MIT OpenCourseWare.

Figure 3: Flash memory in clearing operation where electrons tunnel from the floating gate.

Finally, one more type of everyday device which exhibits electron tunneling that you've likely encountered are cold-cathode fluorescence light (CCFL) bulbs. You can identify these bulbs by their instant turn-on characteristics (as opposed to the flickering turn-on of traditional fluorescent bulbs). In their first moments of operation, the electrons ejected by the bulbs' cathodes are from a tunneling process.

2.2   Describing Tunneling Current – Fowler-Nordheim Equation

As you'll learn in 6.002 and 6.012, one of the primary means for characterizing electrical devices is to determine the amount of current that flows through the device for a given applied voltage. The plots of current (I) versus voltage (V) that you can generate for various devices are known as *I-V characteristics.* For electron tunneling, also referred to in scientific literature as "field emission," the I-V characteristic can be derived using a the simple barrier tunneling picture that we went over in class. By making some simplifying assumptions, an I-V relationship known as the *Fowler-Nordheim Formula* can be derived.

Consider the system shown in Figure 4. Two regions of metal are separated by an insulting material. The potential energy of each section and how they relate to one another are shown by the sketched levels. Without an applied field (or voltage), the energies of all the levels are flat.
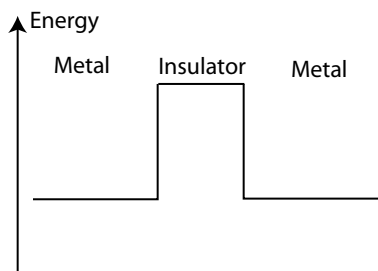

Figure 4: Metal-insulator-metal system with no applied field.

However, when a low field is applied, the metal energy levels shift with respect to one another in energy by the applied potential as shown in Figure 5. Recall that $\Delta U = q\Delta V$, and since we are talking about electrons, $q = -e$, so a material at a higher voltage has electrons with lower potential energy. This difference in energy is dropped linearly over the insulator (corresponding to a constant electric field in the insulator region).

Finally, when a very high electric field is applied, the barrier becomes triangular since the difference in potential energies between the two metals is very high, as shown in Figure 6. This is the system used to derive the Fowler-Nordheim Formula.
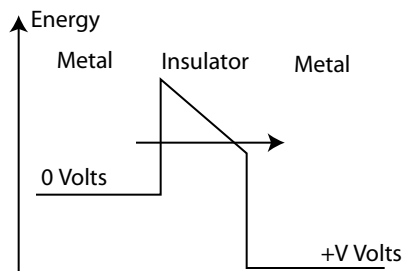
Figure 5: A low applied field causes a small shift in the metal levels with respect to one another, making the barrier between the metals resemble a trapezoid.
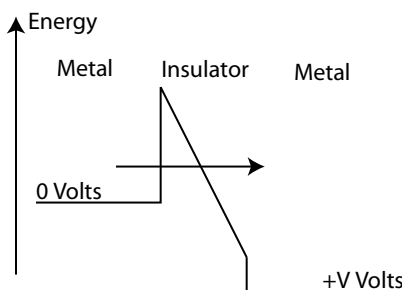

Figure 6: At high applied field, the difference in energies is so high that the potential barrier between the metal regions is triangular.

We won't delve into the derivation of the Fowler-Nordheim Formula here since it relies on a more advanced quantum mechanics tool known as the WKB approximation to model the triangular potential barrier. The WKB approximation is covered in classes like 6.728.

By computing the probability current through an approximation of the barrier as a triangle (making use of the WKB approximation), the formula for current versus voltage is found to be of the form:

$$I = AK_1V^2e^{-K_2/V}$$

where I is the current, A is the cross-sectional area of the material, V is the applied voltage between the metal regions, and K_1 and K_2 are constants that depend on the underlying material properties and the length of the insulator region.

The above is the Fowler-Nordheim Formula. As you can see from the formula above, when tunneling is the dominant conduction mechanism, the I-V characteristic is no longer that of Ohm's law, the linear relation $V = IR$. Instead, the resistance effectively changes as a function of applied voltage. We can define the resistance in this case as

$$R(V_i) = \frac{\partial V}{\partial I}|_{V_i}$$

3 Procedure

The material that we'll be using for this lab is a nickel/rubber compound produced by Peratech (www.peratech.co.uk) known as Quantum Tunneling Composite^{TM}, or QTC. We'll be using QTC Pills, which are squares that are 3 mm on a side and about 1 mm in thickness. The volume concentration of nickel is low enough such that without compression, no current pathways exist through the material (i.e., $R \approx \infty$) since the rubber is not conductive. However, as the material is compressed, the rubber gaps between islands of nickel are made smaller, allowing electrons to start tunneling between islands of nickel. We will first use a mechanical gauge

to measure how the resistance changes with displacement. Then we will measure the I-V characteristics and compare that to the Fowler-Nordheim Formula. Finally, we will use the material to create a touchpad.

3.1 Collecting Diplacement-Resistance Characteristics for a Single Nickel/Rubber Pill

In this section, we will use a high sensitivity displacement gauge to measure the dependence of the resistance as a function of compression.

(1) The measurement station will have a single Nickel/Rubber Pill sandwiched between two piece of glass coated with copper tape. Connect your multimeter to the copper tape with alligator clips. Have your partner press very lightly on the gauge, then press with increasing pressure. Read off the displacement number on the gauge and measure the resistance at the same time. Start with a displacement of 0.1 mm or less. For consistency, do this in a single run, increasing the pressure gradually. Take at least five measurements. In the post-lab you will graph this data in MATLAB.

Displacement (mm)	Resistance (Ω)

3.2 Collecting I-V Characteristics for a Single Nickel/Rubber Pill

In this section, we'll build a setup to collect I-V characteristics from a compressed piece of nickel/rubber composite.

Follow the directions below to build a setup to collect I-V characteristics from a square of QTC.

(1) First, we need to make two electrodes. Take your two glass microscope slides (NOT the ITO-coated slide) and put copper tape on them as shown in Figure 7.
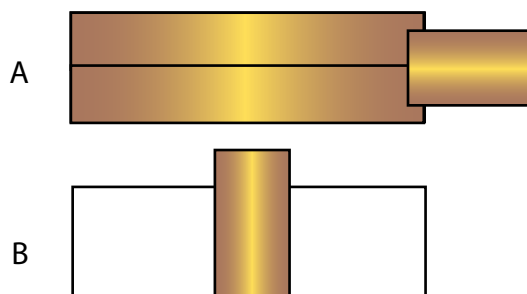

Figure 7: On slide A, coat one surface using two pieces of copper tape, and attach a small piece of copper tape to the coated surface as a contact. On the slide B, put a piece of copper tape in the middle with one edge hanging off as a contact.

(2) Next, place 1 QTC pill on the slide A, as shown in Figure 8, then place rubber strips near the two ends of the slide to act as spacers.

(3) Finally, flip over slide B and align it over slide A such that the copper tape on slide B contacts the top of the middle QTC pill, as shown in Figure 9. Place 4 binder clips in the positions shown by the black rectangles.
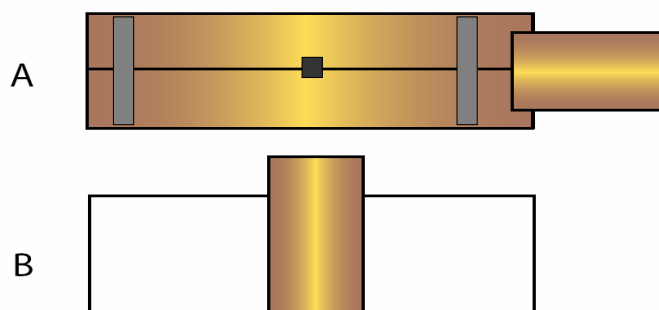
Figure   ubber
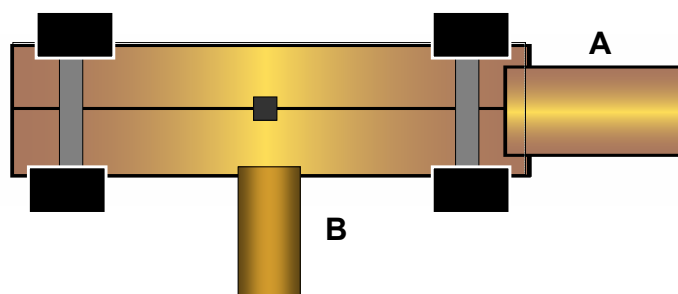strips

Figure 9:   Flip over and place slide B on slide A, making sure that only the middle QTC pill
contacts the copper on both slide A and slide B. Place binder clips in the positions shown.

Now use a power supply and multimeter to measure the I-V characteristics of the QTC pill.

***IMPORTANT: Do not leave a DC voltage across the QTC pill for more than a few
seconds at a time. Current running through the QTC leads to material heating and
eventually destruction of the QTC you are testing. To get accurate measurements, only
place voltage across the QTC temporarily.***

Measure the current by connecting the multimeter in series with the QTC pill setup. To take this
measurement, first set the power supply to the voltage desired with an open circuit, then turn it off.
Now, hook up the power supply to the circuit and flip the power supply on for a few seconds, long
enough to observe the current. Repeat for each voltage desired.

The binder clips are used for biasing the pressure on the middle QTC pill. Adjusting their positions
will change the I-V characteristics of the QTC pill. Pick 3 positions relative to the QTC pill to place
the binder clips (e.g. all clips far away, all clips close, or 2 close and 2 far), and collect three I-V
plots from −5 V to 5 V in increments of 1 V. Note the positions of the binder clips used for each
measurement. You will plot this data in MATLAB for the post-lab exercise.

Voltage (V)	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
Current 1 (A)											
Current 2 (A)											
Current 3 (A)											

3.3   Building a Rudimentary Touchpad

In this part of the lab, we'll build a rudimentary resistance-based touchpad by substituting an indium-tin-oxide (ITO) electrode for one of the copper electrodes. Since ITO is more resistive that copper, we'll be able to pinpoint which nickel/metal compound is being compressed in the structure.

Follow the directions below to make your touchpad. We'll be making a 2×2 touchpad.

(1) Determine which side of the ITO-coated slide has the ITO. Use your multimeter to figure this out. Take a measurement of the resistance across the long direction of the slide, and find the resistance per square, or the sheet resistance. $R_s =$_____ $\frac{\Omega}{sq}$.
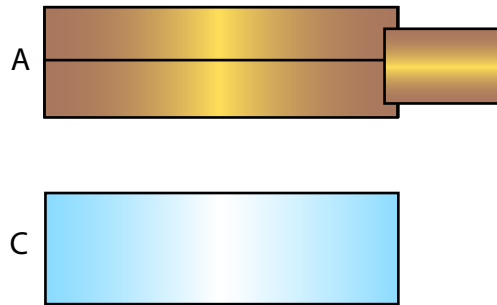

Figure 10:   Use slide A from the previous setup. Determine which side of the ITO-coated slide, slide C, has the ITO using your multimeter.

(2) We'll use slide A from the previous section for our other connection, as shown in Figure 10. Attach copper tape to the ITO side of slide C as shown in Figure 11. Once again we will be using the rubber strips as spacers, but this time the spacing between glass slides will be increased, so we will be using them in piles of four. Pl.
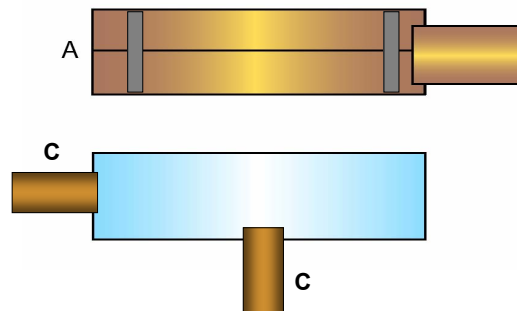

Figure 11:   Attach copper tape to the ITO side of slide C as shown. Place four overlapping strips of rubber on the two ends of slide A as shown.

(3) Using the tip of a pen, gently make indentations on each pill. Using tweezers, place a ball bearing on each pill. Finally, place QTC pills on slide A as shown in Figure 12. Then, flip over and align slide C with slide A as shown in Figure 13. Very carefully, pick up the sandwich of glass slides and make sure you apply enough pressure so that the ball bearings are touching the ITO slide (otherwise they will easily roll off). Fasten tl   'n.
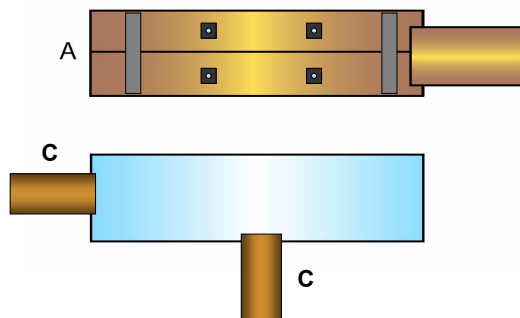
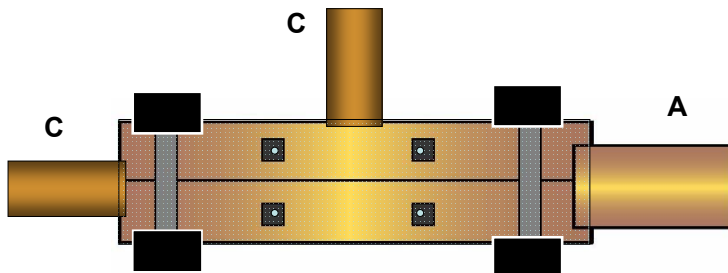

Figure 12:   Place the QTC pills on slide A as shown.

Figure 13:   Flip and align slide C with slide A as shown. Fasten together the two slides using binder clips in the locations shown.

3.3.1   Characterizing your Touchpad

Let's assess the design trade-offs in using this nickel/metal compound for a rudimentary touchpad. To use the device as a touchpad, you'll want to connect one of the leads to the slide A lead. Then, you can use either of the leads on slide C to determine the X and Y positions of your applied pressure. When you use the top lead of slide C, we will call that the resistance between "Pair 1" leads, and when you use the left lead of slide C (as shown in Figure 13), we will call that the resistance between "Pair 2." Take three data points for each pair of terminals: one with no compression, one with compression near the terminal and one far away from the terminal. BE CAREFUL NOT TO COMPRESS SO HARD THAT THE GLASS BREAKS! (this resistance will depend on how hard you compress...use a reasonable force and try to be consistent).

Compression	R of Pair 1 (Ω)	R of Pair 2 (Ω)
None		
Near Terminal		
Far from Terminal		

4   Post-Lab

- **(1 Point)** Pre-lab questions.

- **(2 Points)** Using your data from Section 3.1, plot resistance versus displacement data on a log scale. Your plot should be linear in the logarithmic scale. What is the reason for this?

- **(2 Points)** Make a plot in MATLAB of your I-V characteristics from Section 3.2. You should have three I-V curves; plot them on the same graph. Below the graph, draw or describe what the position of the binder clips were for each of the graphs.

- **(1 Point)** What do you observe happens to the I-V characteristics as applied pressure changes (determine if your pressure was increasing or decreasing by examining the location of your binder clips for each measurement)? Why?

- **(1 Point)** Now let's compare your I-V curve to the Fowler-Nordheim Formula. Using the Fowler-Nordheim Formula, derive the dependence of I on V for large V. Does this corroborate with your data? If not, can you think of any mechanisms that would affect the tunneling current for large voltages?

- **(2 Points)** Using your data from Section 3.3, how would you determine whether the lower right, versus the upper left, of the touchpad was being pressed? What is the effect of adding ball bearings on the way the device operates? Would you make a touchpad using this platform? Please explain.

- **(1 Point)** Lab participation. You should have been checked off in lab.

6.007 Electromagnetic Energy: From Motors to Lasers
Spring 2011