BME 194: Applied Circuits Lab 6: FET and phototransistor

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1 Design Goal

For this lab, we are making a toy that produces sounds that can be modified by the amount of light falling on a phototransistor. In order for the toy to be as annoying to adults as possible, we want it to be loud and high pitched (note: this is not a realistic marketing goal!).

Constraint: we'd like to re-use the hysteresis oscillator board that was designed for the capacitance touch sensor, so that we don't need to design a new sound-generation circuit. We'd also like to connect to the board using just the 4 off-board connections brought out to the screw terminals, and not have to do any soldering or unsoldering of the components on the board.

Concept: let the phototransistor change how fast the capacitor charges. In bright light, the capacitor should not cross one of the thresholds (being always low or always high). In darkness, the oscillator should run normally, and in shadow, the oscillator should change its frequency based on the amount of light.

2 Background

Phototransistor

A phototransistor is a two-terminal device whose current is proportional to the illuminance of transistor. It can be thought of as a photodiode combined with an amplifying transistor. [4] The schematics in Figure 1 show all three terminals, but the base of phototransistor is not connected to anything.

> *A phototransistor has an n-p-n or a p-n-p structure, and is usually operated in a floating-base connection with the collector junction reverse biased and the emitter junction forward biased. The photoexcited carriers in the base cause the forward bias of the emitter junction to increase, resulting in current amplification by ordinary transistor action.* [2]

The "floating-base" results in the base having a voltage intermediate between the collector and the emitter. A *forward* bias on a PN junction has a positive voltage on the p-doped semiconductor relative to the n-doped semiconductor.

The phototransistor we have in our kits (WP3DP3BT) is an NPN silicon transistor [1], which means that the emitter and collector are n-doped silicon and the base is p-doped silicon. In order to have the forward and reverse biases of the floating base correct, we need to have the base be more positive than the emitter (forward bias) and

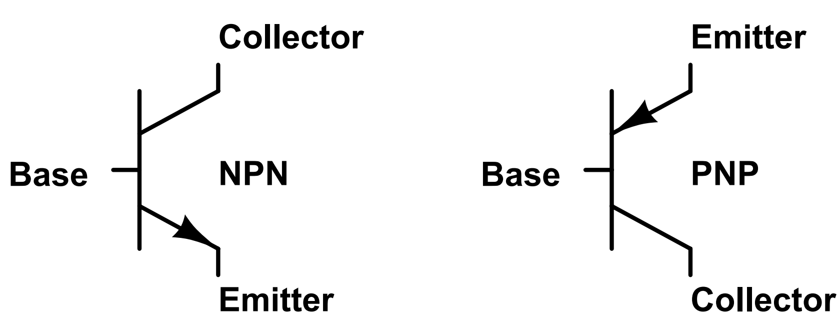

Figure 1: The symbols for bipolar transistors have an arrow marking the direction of conventional current flow (from positive to negative) on the emitter terminal. Current flowing in that direction between the base and emitter cause a larger current (β times as much) in the same direction between collector and emitter. In a phototransistor, the base current results from carriers being excited by photons differently on each side of the junctions.

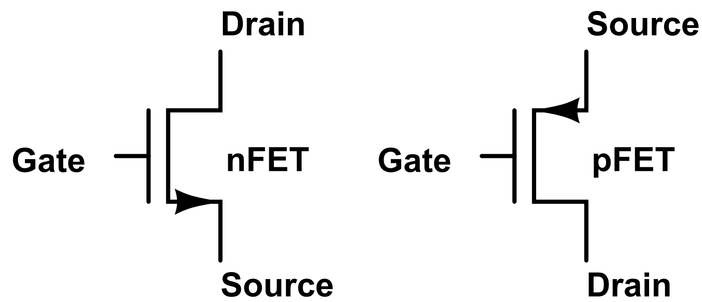

Figure 2: This set of symbols for field-effect transistors have an arrow marking the direction of conventional current flow (from positive to negative) on the source terminal. There are other conventions for drawing FETs: if no arrows are given, an nFET is intended, and either of the non-gate terminals may be the source and the other a drain depending on the voltage (non-power FETs in VLSI chips are often symmetrical this way). If there are no arrows, but there is a small circle on the gate (an inversion bubble), a pFET is intended. There are also more complicated symbols that show a fourth "bulk" terminal, connected to the source. (In VLSI chips, the bulk terminal is the substrate or a large "well" on the chip, and may not be connected to either the source or the drain.) (See the Wikipedia article on MOSFETs [3].)

less positive than the collector (reverse bias). That means that we want the collector wire to be connected to a more positive voltage than the emitter wire.

The phototransistor has maximum sensitivity in the infrared (around a wavelength of 940nm), which is typical for silicon photodiodes and phototransistors. [5] The data sheet gives the dark current (which is very small) and the on current (for bright light).

Field-effect transistor

We have two power FETs in our kit, an 18 amp nFET (NTD5867NL-1G) and a 12 amp pFET (NTD2955-1G). Both are three-terminal devices, in which the voltage between the gate and the source controls the current between the drain and the source. The majority carriers in an FET move from the source to the drain. So in an nFET, with n-doping and electrons as the majority carriers, the source is connected to a more negative voltage than the drain. In a pFET, with p-doping and holes as the majority carriers, the source is connected to a more positive voltage than the drain.

The gate of an FET is essentially one plate of a capacitor (as suggested by the schematic symbol), so there is no DC current into or out of the gate. The voltage on the gate controls the behavior of the transistor. The drain voltage minus the source voltage is written V_{DS}, and is positive for nFETs, negative for pFETs. The gate voltage minus the source voltage is written V_{GS}, and is the controlling voltage for the transistor.

In an nFET, if the gate-to-source voltage is larger than some threshold ($V_{GS} >> V_{th}$), then the nFET is turned on and can conduct a large current from drain to source with little voltage drop (low on-resistance). If the gate-to-source voltage is much less than the threshold ($V_{GS} << V_{th}$), the nFET conducts very little (high off-resistance). The threshold voltage is dependent on the doping and geometry of the transistor, as well as its temperature, but is typically somewhere around $2V$ for power nFETs. If $V_{GS} \approx 0$, the transistor is off. If $V_{GS} \approx 5V$ the transistor is on.

In a pFET, if the gate-to-source voltage is smaller than some threshold ($V_{GS} << V_{th}$), then the pFET is turned on and can conduct a large current from drain to source with little voltage drop (low on-resistance). If the gate-to-source voltage is much more the threshold ($V_{GS} >> V_{th}$), the pFET conducts very little (high off-resistance). The threshold is typically around $-3V$ for power pFETs. If $V_{GS} \approx 0$, the transistor is off. If $V_{GS} \approx -5V$ the transistor is on.

When V_{GS} is near V_{th}, an FET is partially turned on. It is possible to use an FET as a voltage-to-current amplifier (this is what is done in electret microphones, for example), but the power FETs have large changes in their threshold voltages with temperature, and so are difficult to bias to get consistent behavior. Also, the power dissipated in the FET (which heats it up) is much larger in this intermediate region than it is for a fully off or fully on transistor.

Because the FETs can conduct high currents with little voltage drop, and because self-heating is minimized if they are fully-on or fully-off, they are often used as switches. That is how we will use them in this lab, turning the loudspeaker on and off.

3 Pre-lab assignment

TURN IN A COPY OF THIS PRE-LAB ON WEDNESDAY BEFORE THE LAB—KEEP A COPY FOR YOURSELF.

Think about the hysteresis oscillator board as a module for a design. It has 4 off-board connections: power, ground, cap (the input to the Schmitt trigger), and out (the output from the Schmitt trigger). There are $\binom{4}{2} = 6$ pairs of points that you could connect a two-terminal device to the board. Some of the connections would be a really bad idea (like shorting +5V and GND). Use your mental model of how the hysteresis oscillator works to predict the effect of each of the following single-part additions to the circuit. Make a short note in each of the boxes (or make your own table in your lab notebook) with your predictions.

Long calculations are not the point of this lab. I want you to reason approximately about parallel resistances and capacitances, and what happens to the charging and discharging of the capacitor in various situations.

You don't need to do precise calculations—rough approximations are fine. What you are interested in are things like "output stuck high", "output stuck low", "oscillates $f \approx 100kHz$", "$f \approx 1kHz$", "power supply shorted", … . Start by describing the behavior of the oscillator board with no connections other than the power supply.

device	GND–5V	GND–out	5V–out	GND–in	5v–in	in–out
wire						
1kΩ resistor						
10kΩ resistor						
100kΩ resistor						
1MΩ resistor						
5.6MΩ resistor						
100 pF capacitor						
1000 pF capacitor						
0.01 μF capacitor						

The oscillator from the capacitance-touch-sensor lab has too high a frequency for people to hear (at least as most students designed it). Do any of the additions you looked at bring the frequency into the audio range?

Of the connections above that do something interesting, what combinations might be worth trying?

Look up the data sheets for the phototransistor and FETs in your parts kit.

phototransistor Find the dark current and on current for the phototransistor. If you have 2.5V across the phototransistor, what are the equivalent resistances? Which of the 12 ways (6 pairs of points, 2 orientations) that you can add the phototransistor to the hysteresis oscillator circuit will result in it being always biased the right way ($V_{CE} \geq 0$)?

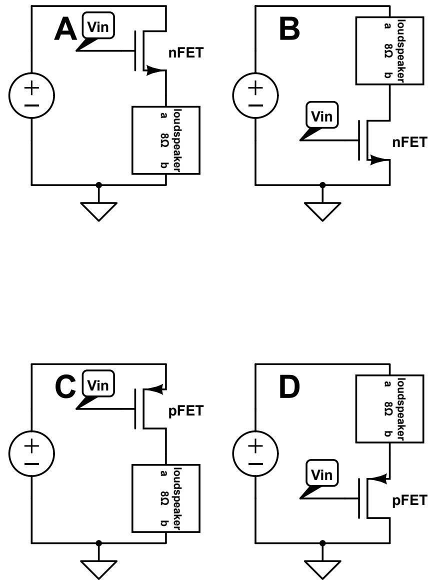

Figure 3: Various ways to arrange an FET and a loudspeaker in series to control the loudspeaker.

Which of those would would affect the behavior of the oscillator as the light on the phototransistor changed? What would the oscillator do in the dark? in bright light? Would any of them result in the oscillator not oscillating at some light levels, but oscillating ok at other light levels? What would happen at intermediate light levels? Note: there are multiple ways to achieve this.

How would the effect be changed if you replaced the phototransistor with a phototransistor in series with a resistor?

FETs Find the threshold voltage, the on resistance, and the off current (the drain-to-source current when the gate is at 0v) for each of the FETs. What is the equivalent off resistance for the off current on the spec sheet, if you have $V_{DS} = 5V$ for an nFET or $V_{DS} = -5V$ for a pFET?

Plot the power that would be dissipated in the FET and the power that would be delivered to the loudspeaker as a function of the effective resistance of the FET, assuming a 5V power supply and and a constant 8Ω resistance for the loudspeaker, with the FET and the loudspeaker in series as in any of the circuits in Figure 3. Remember that power is voltage times current, and you can use the voltage divider rule to figure out the voltage. You may want to use a log scale for the resistance axis.

Figure out, based on what the oscillator will do when it is not oscillating, which circuit(s) from Figure 3 would result in the loudspeaker have no current when the oscillator is not oscillating. (As in many engineering problems, there are multiple solutions depending on what assumptions you make—especially since there were multiple ways to turn off the oscillator, with different effects.)

4 Parts, tools, and equipment needed

Parts for this lab from kit:

- phototransistor
- nFET or pFET (depending on student design)
- hysteresis board, with soldered circuit
- 10W 8Ω loudspeaker
- breadboard
- header pins (for connecting breadboard to loudspeaker)

- miscellaneous resistors and capacitors

Tools for this lab:

- strippers
- wire cutters

Equipment in lab:

- bench power supply (any 5V supply will do, as long as it can deliver enough power for the loud speaker)
- oscilloscope (for viewing waveforms)
- multimeter (for debugging)

5 Procedures

Try it and see: oscillator

I'm not going to answer questions of the form "is this right?" or "what would happen if?" unless there is a safety issue. You all know how to limit the current and voltage on the power supplies—limit it to 20mA and 5v and you should be able to do everything except power the speaker with no trouble. What current limit would you need if you were planning to drive an 8Ω speaker with a 5V signal?

Go through the table of predictions you made about how the oscillator board would behave with various additions to the circuit. Try them and see if your predictions are correct. Use the oscilloscope to look at the output—you may also want to try using the frequency meter to look at the frequency of the oscillation. If the observed behavior is way different from what you expect, revise your mental model of the circuit until you can explain all the behavior.

Keep careful notes!

Try it and see: phototransistor

Measure the current through the phototransistor with about 2.5V across it in the ambient light of the lab. What happens to the current as you shadow the phototransistor? What are the highest and lowest currents you get in the lab? How do these compare to the specs for dark current and very bright light?

How could you use that change in current to change the behavior of the oscillator? Do it! Does it do what you expected? If not, revise your mental model and try again. Does it do something interesting that you didn't expect? Keep careful notes!

You can add other components in series or parallel with the phototransistor or between other pairs of nodes to vary the behavior. Make predictions about what effect various combinations of additions will make, then try them and see.

What further changes do you need to make to the oscillator (without changing the board) to make its output be potentially interesting to send to a loudspeaker?

What might you need to change if this circuit were to be used in full sunlight?

Try it and see: FET

Hook up the speaker and the FET in the configuration you chose (not hooking it up to the oscillator yet). Measure the voltage across the speaker and the current through the speaker you change the gate voltage on the FET. Since we are using the FET as a switch, you only need to measure with gate voltages of 0v and 5V, though you can try setting up a circuit like we used for the microphone lab if you want to characterize the circuit better.

Try it and see: all together

Hook up the phototransistor, the oscillator, and the FET+speaker circuit so that you can control the sound that comes out the loudspeaker.

6 Demo and writeup

Demonstrate your oscillator doing something audibly interesting with control by shadowing the phototransistor.

7 Design Hints

This is a tinkering lab—the point is to try lots of things, keep careful notes, and build a robust mental model of what should happen when you do different things to a simple circuit.

References

[1] Kingbright. Phototransistor wp3dp3bt datasheet. http://www.kingbrightusa.com/images/catalog/SPEC/wp3dp3bt

[2] Toyosaka Moriizumi and Kiyoshi Takahashi. Theoretical analysis of heterojunction phototransistors. *IEEE Transactions on Electron Devices*, ED-19(2):152–159, February 1972.

[3] Wikipedia. Mosfet. http://en.wikipedia.org/wiki/MOSFET#Circuit_symbols, February 4 2013.

[4] Wikipedia. Photodiode. http://en.wikipedia.org/wiki/Photodiode, February 4 2013.

[5] Wikipedia. Response silicon photodiode. http://en.wikipedia.org/wiki/File:Response_silicon_photodiode.svg, February 4 2013.