

PHY 312: Advanced Lab  
PHOTOELECTRIC EFFECT

### 1 Background

A photon of frequency  $\nu$  carries energy  $h\nu$ , where  $h$  is Planck’s constant. If such a photon strikes an electron inside a metallic conductor, it can knock the electron out of the metal. Once liberated, the free electron has an energy  $h\nu - W$ , where  $W$  is the binding energy which formerly kept it inside the metal, the “work function” of the metal. This explanation of the photoelectric effect was given by Einstein [1, 2] and was (after Planck’s description of black body radiation) the second big step away from classical physics.

This experiment has some subtleties, which make it more difficult to perform than you might expect from its straightforward theoretical explanation. One significant deviation from ideal behavior is the presence of “contact potentials” in the circuit. For many purposes we can consider metals as lattices of positively charged ions producing a potential “well” that is partly filled by a “sea” of freely moving electrons. Overall, of course, the metal is neutral in charge. The electrons have an energy distribution, which extends from the bottom of the well through a conduction band of well-defined width, as shown in Fig. 1. The energy required to lift an electron from the top of the band just out of the well is the work function  $W$ . Thermal effects tend to blur the top of the band.

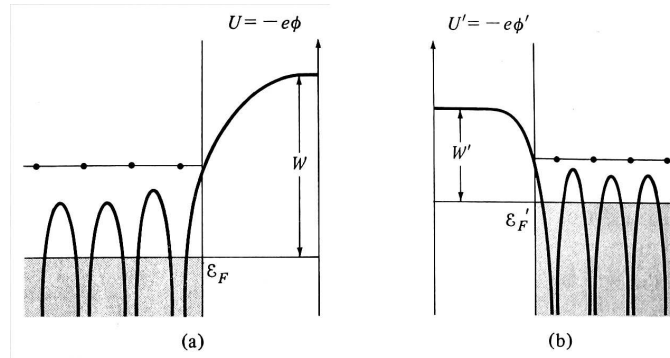


Figure 1: (a) The potential energy of an electron  $U = -e\phi$ , where  $\phi$  is the electrostatic potential, for a metal with work function  $W$  and Fermi energy  $\mathcal{E}_F$ . (b) A similar plot for a second metal with work function  $W'$  and Fermi energy  $\mathcal{E}'_F$ . (Figure from [9])

Now suppose we join two pieces of different metal together, where metal A has the higher work function, i.e.,  $W > W'$ . At the instant of contact, the electrons in B are at higher energy (lower potential) than the electrons in A, and hence some rush into A (remember, a conductor can have no electric field inside

it). This behavior, however, leaves B with an excess of positive charge, thereby lowering its potential until the electron “seas” in A and B (that is, the tops of the conduction bands) are at the same level, Fig. 2. The net result of connecting two wires of different metal is that there exists an electrostatic potential difference between the two free ends of the wire. This potential difference is equal to  $(W - W')/e$ , where  $e$  is the electron charge. The potential difference can amount to as much as several volts and acts much like a battery hidden in the point of contact.

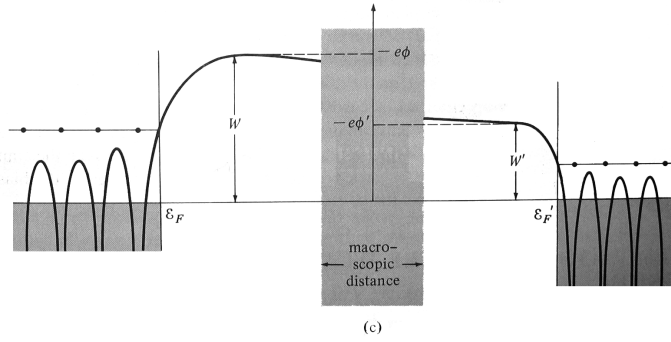


Figure 2: (c) The two metals have been joined together, so that charge can pass freely from the one to the other. The only result is to introduce small amounts of net surface charge in each metal, sufficient to shift uniformly the level structures in (a) and (b) (Fig. 1) so as to bring the two Fermi levels into coincidence. (Figure from [9])

## 2 Experimental set-up

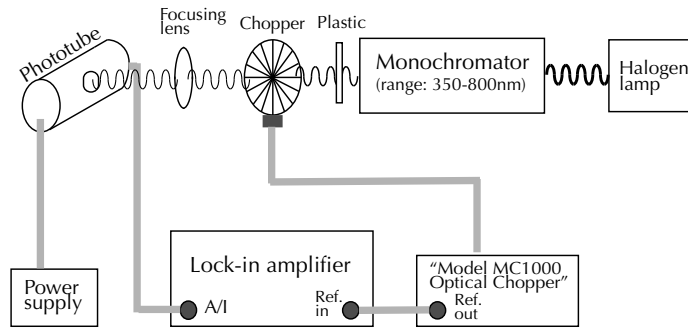


Figure 3: Schematic drawing of the apparatus.

The light source for this experiment is a halogen lamp, which can be approximated as a black body with maximum intensity around  $\lambda = 550\text{nm}$ . Light from

the lamp passes through a grating monochromator, which can be adjusted to emit a beam of light at any wavelength from 350-700nm (and its higher energy harmonics - if you don't know why, remind yourself how a diffraction grating works). The light then passes through a chopper that is connected to a lock-in amplifier so that the photocurrent produced by the light will have a known frequency that can be distinguished from background noise. The light is then focused on an evacuated commercial phototube.

The phototube contains a potassium photo-cathode and a loop of platinum wire for the anode. Potassium is used because of its low work function and platinum because of its high work function and high melting point. (What does this tell you about the contact potential generated between the anode and cathode when you connect the wires?) Work this out in your pre-lab preparations.

The electrons are ejected from the potassium cathode and collected on the platinum anode after being accelerated through a potential difference made up of the contact potential and an externally applied voltage. The photocurrent is measured using the lock-in amplifier, which can measure very small currents (nano-amps in this case) by locking into the frequency of the chopper.

By varying the applied voltage, you can forward and reverse bias the circuit and eventually force the current to zero by making the anode sufficiently negative with respect to the cathode. The value  $V_0$  for which the photocurrent vanishes is such that the kinetic energy of an electron when it reaches the anode is zero. Therefore:

$$h\nu - W = eV_0. \quad (1)$$

Prove in your lab preparation that if  $V_0$  in this equation is the reverse bias that you apply, then  $W$  is the work function of the anode (not the cathode!).

### 3 Procedure

1. Check that all the equipment is properly connected as shown in Fig 3.
2. Be sure the "Optical Chopper MC1000" has the correct blade-number setting; this is the number of blades on the chopper disk (should be 10 for this lab: the MC1000 should read "B -10").
3. Align the optics: turn on the halogen lamp, and adjust the monochromator to give an easily visible beam. Adjust the positions of the focusing lens and the phototube so that the beam is focused on the center of the cathode plate within the phototube. No part of the beam should hit the anode ring; you may use wire tape to cover parts of the phototube opening.
4. Set the monochromator to 350nm. Turn on the chopper, the lock-in amplifier, and the power supply. You will need to take measurements at bias voltages from around -3V to +15V; increments should vary from around 0.2V (near zero) to 1V (over 10V). To obtain negative voltages, connect the two-headed banana plug from the phototube with the ground plug connected to the "+" of the power supply (the ground plug is indicated

with a protrusion on one side); to obtain positive voltages, flip the ground to “-”. Record the photocurrent at each voltage; this is the quantity displayed on Channel One of the lock-in amplifier. Channel Two displays the relative phase between the actual signal (from the phototube) and the reference signal (from the chopper); its value is unimportant as long as it remains constant during your measurements.

5. Repeat the previous step for all wavelengths from 350nm to 700nm, in increments of 25nm.

## 4 Data analysis

Plot the photocurrent as a function of the applied voltage for several different wavelengths. You will see that the photocurrent always approaches its final value asymptotically and that this final value is not always zero, especially if you didn’t do the optics very well (why?). But in order to find the stopping voltage, you need to estimate where the photocurrent goes to zero. Most undergraduate lab manuals would have you simply approximate the current near the cutoff voltage with a linear fit [4, 5]. But from your data you should be able to see that the current-voltage data is *not* linear, and by making a linear approximation we lose sight of some of the underlying physics.

The shape of the photoelectric curve will depend on the band structure of the cathode and also on the geometry of the anode/cathode configuration. Indeed, it is possible (not using this apparatus though!) to make detailed mappings of the band structure by illuminating a sample with photons and noting the energy of the electrons emitted as a function of solid angle. This is the basis for a field known as photoemission spectroscopy [10].

In this case, we will make only a first order correction to the linear approximation. We assume that the conduction band of potassium can be approximated as a free electron gas (this is a reasonable approximation for most good conductors because the ‘sea of electrons’ in the conduction band is not significantly perturbed by the nuclei). Fig. 4 shows an energy diagram for a one-dimensional conduction band; we set the energy to be zero at the bottom of the conduction band.  $E_F$  stands for the Fermi energy of the free electron gas and is equivalent to the bandwidth.

In 3 dimensions, the density of states of a free electron gas is:

$$D(E) = \frac{V}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{3/2} E^{1/2}. \quad (2)$$

In order to determine how many electron states can be reached at a given photon energy for a given reverse bias, we simply integrate the density of states from the lowest possible energy level that can be photoexcited to the Fermi energy  $E_F$ . The photocurrent should be directly proportional to the number of states that can be photoexcited. You should be able to work this out to derive an

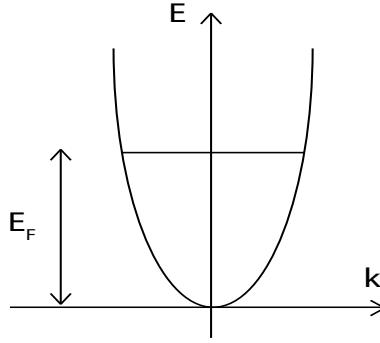


Figure 4: A 1-D conduction band for a free electron gas; the Fermi energy  $E_F$  equals the bandwidth.

equation for the current of the form:

$$I = A \left( B^{3/2} - (V - C)^{3/2} \right), \quad (3)$$

where  $B$  should correspond to  $E_F$ . Note that in this equation  $V$  is the reverse bias, ie. it is the negative of the applied voltage.

You can use the above equation to fit your data near the cutoff voltage. You may notice, however, that the values of the fit parameter  $B$  obtained at different wavelengths vary quite widely. This indicates that there is much more going on than this fit is not taking into account. What important factors are missing in the above derivation?

## References

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