ELECTRONICS NOTEBOOK

Experimenting With Photoresistors

By Forrest M. Mims III

The variety of light-sensitive electronic components available to today's designer and experimenter is truly astounding. Such components include photodiodes, phototransistors, photomultiplier tubes, light-sensitive SCRs, photoFETs, solar cells and various kinds of solid-state image sensors. Many kinds of thermal sensors designed primarily to detect infrared radiation can also detect visible light. Even light-emitting diodes (LEDs) and laser diodes can function as light detectors as well as generators.

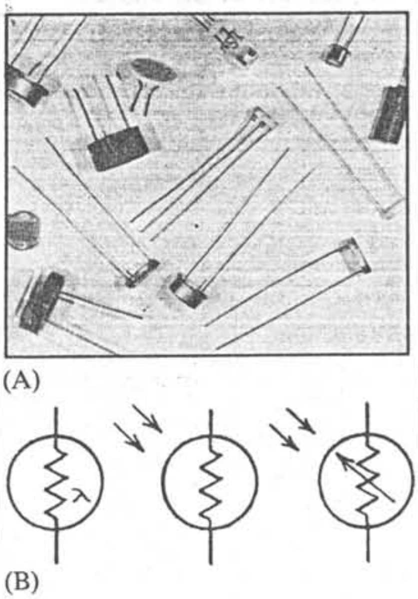
With many detectors from which to choose, it is easy to overlook the lowly photoresistor. While photoresistors have notoriously low response times and suffer from the "light history" effect, they are among the most sensitive light sensors around. For this reason alone, they are well suited for use in many light-sensing applications. Photoresistors are also characterized by a narrower spectral response than are most other light sensors, which makes it possible for them to be used in a number of unique applications.

It is important for the well-rounded circuit designer and experimenter to be fully aware of the characteristics and operating requirements of the various kinds of light-sensitive components now available. Therefore, before we get into a description of the principles of photoresistors in detail, let's briefly review the various families of light-sensitive devices in general.

The Families

Besides photoresistors, the two most important classes of light-sensitive devices are classified as photoemissive detectors and junction photodiodes.

Photoemissive devices are electron tubes that incorporate a light-sensitive photocathode that emits electrons when struck by photons (light energy). The emitted electrons are collected by an anode electrode to form a photocurrent that is proportional to the intensity of the light that caused them to be emitted from the photocathode. Vidicons, image converters and image intensifiers are special types of photoemissive detectors.



(A) (B)

Fig. 1. Assorted photoresistors from author's shop (A) and common photoresistor schematic symbols (B).

The single biggest drawback of photoemissive detectors is their requirement for an evacuated envelope. When the envelope is glass, which is usually the case, the photoemissive device is quite fragile. Another drawback is that photoemissive detectors require a higher operating voltage than do most kinds of solid-state detectors. On the plus side, photoemissive devices known as photomultiplier tubes that incorporate a series of internal stages are among the most sensitive of all light detectors.

Semiconductor junction photodetectors make up a broad class of solid-state light sensors that include photovoltaic, photoconductive and avalanche photodiodes. Though most junction photodetectors are made from silicon, many other semiconductor materials are also used, including germanium, gallium-arsenide, indium-arsenide and others.

Photovoltaic photodiodes are pn junctions that generate a photocurrent when struck by photons. Many kinds of photodiodes can be used in the photovoltaic mode. Silicon solar cells are photovoltaic detectors. An important advantage of photovoltaic photodiodes is their exceptionally low dark current, which is the unwanted current that flows when a device is in total darkness.

Photoconductive operation of a photodiode is usually implemented by reverse biasing the device with an external current. When photons illuminate the photodiode's light-sensitive junction region, the diode permits a current to flow that is proportional to the flux of the incident photons. Photodiodes operated in the photoconductive mode are very sensitive and have very fast response time. However, they do have a higher dark current than do photovoltaic photodiodes.

Avalanche photodiodes have a high reverse breakdown voltage. They are designed to be reverse-biased at just below their breakdown potential.

Photons striking the photodiode stimulate a disproportionate flow of electrons, thus giving avalanche photodiodes a sensitivity that rivals that of photomultiplier tubes. The chief drawback of avalanche photodiodes is the requirement for the high reverse voltage. The requirement is made even more difficult by the temperature dependence of the diode's breakdown voltage. Therefore, for optimum performance over a wide range of temperatures, the power supply that provides the reverse bias must be temperature regulated.

Photoresistors

Also called photocells and light-dependent resistors, photoresistors are by far the simplest of light detectors. Though they are solid-state devices, they do not possess a pn junction. Instead, they are considered to be "bulk-effect" light sensors.

Shown in Fig. 1 are an assortment of photoresistors taken from my electronics shop and the most common photoresistor schematic symbols.

A typical photoresistor is fabricated by applying electrodes to a film of light-sensitive material. Often, the electrodes are applied in a zig-zag or spiral pattern to increase the exposure area of the material.

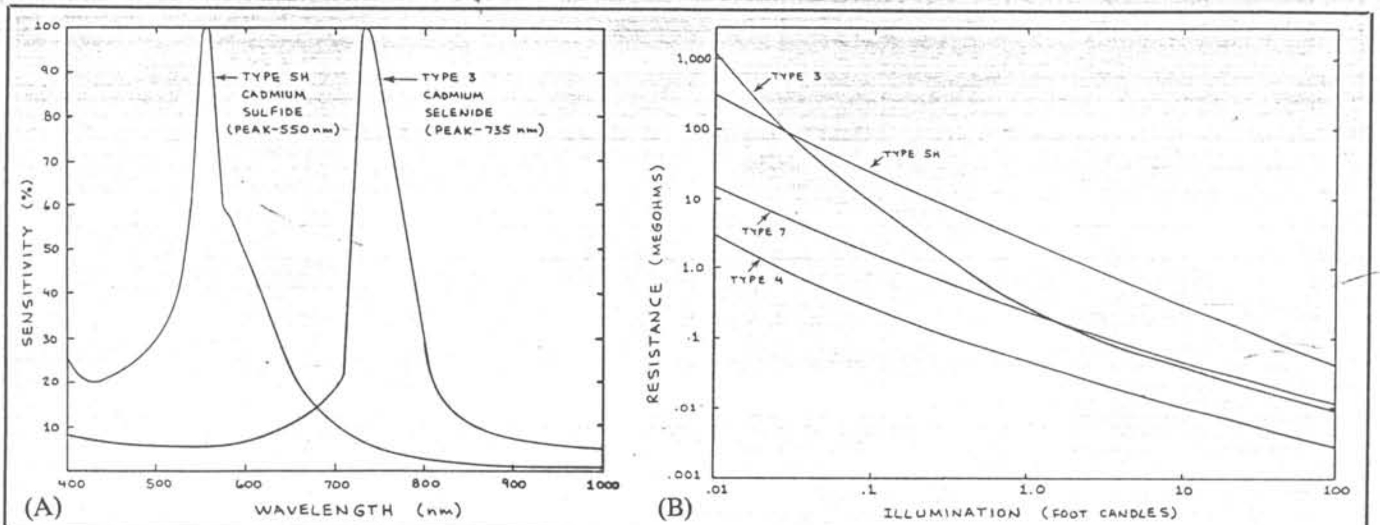


Fig. 2. Spectral sensitivity of representative cadmium-sulfide (CdS) and cadmium-selenide (CdSe) photoresistors (A) and resistance-versus-illumination plots of several photoresistor materials (B).

When a photoresistor is in total darkness, it has a very high electrical resistance. When light strikes it, though, its resistance decreases, often dramatically.

The *resistance ratio* is a figure of merit for the resistance change a photoresistor undergoes after an illuminating source is switched off. The resistance ratio can be specified in many ways, but the most common is the ratio of the resistance when the photoresistor is illuminated by 2 foot-candles (fc) to the resistance in total darkness within 5 seconds of switching off the light source. Therefore, a photoresistor that has a resistance of 2,000 ohms at 2 fc and a resistance of 800,000 ohms in total darkness has a resistance ratio of 2,000:800,000, or 1:400.

The level of light produced by a candle at a distance of 1 foot is known as 1 fc. A 25-watt tungsten lamp has an intensity of about 19 candle power, a 60-watt tungsten lamp about 60 candle power.

The response of photoresistors to a square pulse of light is much slower than that of photodiodes. While a silicon photodiode may have rise and fall times measured in nanoseconds, a photoresistor often has rise and fall (decay) times measured in milliseconds or even several *tenths* of a second.

Another drawback of photoresistors is

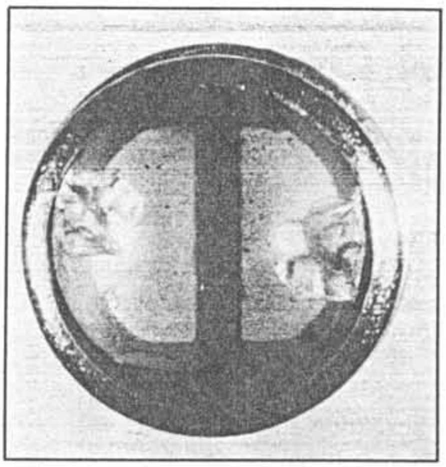


Fig. 3. Light-sensitive region of a CdS photoresistor in a TO-18 transistor can.

the *light history effect*. The resistance a photoresistor assumes on being illuminated by light depends in part on the previous level of light received by the device. The magnitude and direction of the effect depends on many factors, including the duration of the previous light exposure and the current exposure.

Photoresistors are specified to have a certain resistance when illuminated at a specified level of light. This resistance is sometimes called the *equilibrium resistance*. If a photoresistor that has been stored in a light-tight container is removed from its container and exposed to light, its resistance will at first be lower than the equilibrium value. Gradually, however, the resistance will reach the specified equilibrium value.

Now consider the case of a photoresistor that has been stored on a shelf illumináted by the morning sun. If this photoresistor is moved out of the sunlight and its resistance is measured at the much lower light level at which the equilibrium value is specified, its resistance will at first be higher than the equilibrium value. Gradually, its resistance will fall to the equilibrium value.

Photoresistor Materials

The two most common light-sensitive substances used to make photoresistors are cadmium-sulfide (CdS) and cadmium-selenide (CdSe). The spectral sensitivity of these two materials differs substantially.

Peak spectral response of the various formulations of CdS range from about 500 to 620 nanometers (nm). The peak response of Type 9 CdS is 550 nm, the same as that of the human eye. Some CdS formulations have an exceptionally narrow spectral width. For example, the spectral bandwidth of Type 2 CdS at the −3-dB points (50 percent) is about 50 nm. The spectral bandwidth of Type 5H CdS at the −3-dB points is about 40 nm.

The peak spectral response of the various formulations of CdSe range from about 720 to 780 nm. Therefore, CdSe affords reasonably good near-infrared sensitivity. For example, Type 3 CdSe has a peak sensitivity of 735 nm. At the 880-nm wavelength of high-power AlGaAs near-infrared emitting diodes, the sensitivity is 20 percent of the peak value. At the 940-nm wavelength of high-power GaAs:Si near-infrared emitters, the sensitivity is 10 percent of the peak value.

Spectral bandwidth of CdSe photoresistors is wider than that of most CdS devices. For example, the spectral bandwidth of Type 3 CdSe at the −3-dB points is about 95 nm. The spectral bandwidth of Type 4 CdSe at the −3-dB points is about 140 nm.

Though they will not be described here because they aren't designed to detect visible light, it's important to note that lead-sulfide (PbS) and lead-selenide (PbSe) are also used to make photoresistors. These materials provide infrared sensors that have peak spectral responses of a few micrometers.

Figure 2(A) graphically compares the spectral sensitivities of Type 5H CdS and Type 3 CdSe. The most striking aspect of this graphic representation is the substantial spacing between the peaks of the two response curves. This makes possible some interesting applications, some of which will be discussed later.

Figure 2(B) compares the resistances of several common photoresistive materials as a function of illumination. Types 5H and 7 are CdS and Types 3 and 4 are CdSe. The scales of both axes in Fig. 2(B) are logarithmic due to the exceptionally broad dynamic ranges and vast differences in sensitivity of both these photoresistive materials.

As noted above, the various formulations of both CdS and CdSe have different peak spectral responses and other characteristics. Clairex Electronics (560 S. Third Ave., Mt. Vernon, NY 10550), a major manufacturer of photoresistors, has published specifications and data about the most common formulations. The following information is extracted from Clairex's publications:

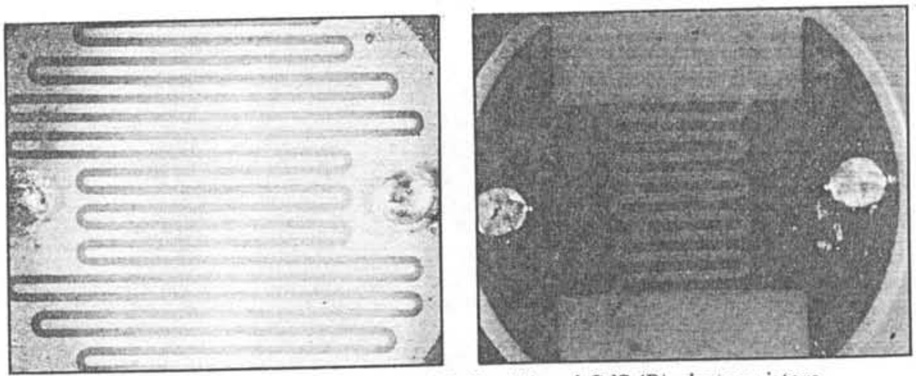


Fig. 4. Light-sensitive regions of CdSe (A) and CdS (B) photoresistors.

Cadmium-Sulfide Photoresistors

- *Type 5*—Peak spectral response of 550 nm closely matches that of the human eye. Minimum resistance ratio of 1:1,000. Very stable with less light-history effect than other formulations.
- *Type 5H*—Like Type 5, peak spectral response is 555 nm. Minimum resistance ratio of 1:1,000. Considerably faster rise time than most other materials, including Type 5.
- *Type 7*—Peak spectral response of 615 nm. Minimum resistance ratio of 1:300. Moderate rise time.
- *Type 7H*—Peak spectral response of 620 nm. Minimum resistance ratio of 1:1,000. Fast decay time.
- *Type 9*—Peak spectral response of 550 nm. Minimum resistance ratio of 1:1,000. According to Clairex, this is the most stable of photoresistive materials. It also has the lowest light-history effect.

Cadmium-Selenide Photoresistors

- *Type 3*—Peak spectral response of 735 nm. Minimum resistance ratio of 1:10,000 is much higher than that of any CdS material. Faster response time than most materials.
- *Type 4*—Peak spectral response of 690 nm. Minimum resistance ratio of 1:400. Lowest resistance of any photoresistor.

Photoresistor Fabrication

Photoresistors are much easier to make than junction photodiodes. Typically, a layer of CdS or CdSe is deposited on a ceramic substrate. A metal electrode pattern is then evaporated onto the light-sensitive region. Several different patterns are used, including simple bars and

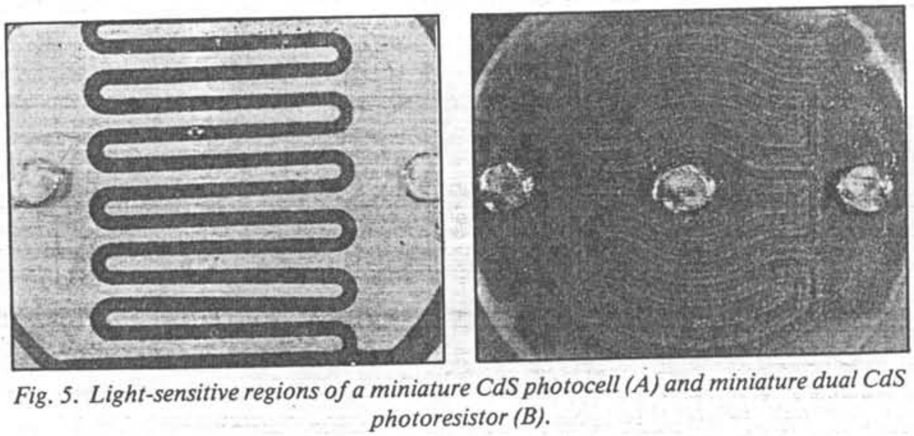


Fig. 5. Light-sensitive regions of a miniature CdS photocell (A) and miniature dual CdS photoresistor (B).

interleaved combs and spirals.

In some applications, the electrode pattern can be important. For example, a system in which a distant light source is imaged onto the light-sensitive surface by means of a lens might work best with a photoresistor that has a simple bar-shaped active region. On the other hand, non-critical applications that require maximum sensitivity without use of a lens work best with zig-zag or spiral electrodes that expose much more light-sensitive material than does a simple bar.

Maximum voltage rating of a photoresistor is in part determined by the spacing of its electrodes. The maximum voltage rating is specified when the photoresistor is dark because this is when the maximum voltage ordinarily appears across the device.

Figure 5 is a macrophotograph of the light-sensitive region of a photoresistor installed in a TO-18 transistor header. The light-sensitive region is the dark bar in the center of the header. The electrodes are the two semicircular shapes on either side of the bar. The two amorphous shapes on either electrode are conductive ink used to make electrical contact to the device's external wire terminals.

Shown in Fig. 4 are the active regions of two photoresistors with interleaved electrodes. In both cases, the light-sensitive material is the dark zig-zag pattern. The device shown in (A) is interesting because it makes maximum use of available space to expose more of the light-sensitive material. Less of the light-sensitive material in (B) is exposed because the spacing between the electrodes is slightly wider. This often indicates a higher maximum operating voltage for the particular device.

Figure 5 shows the light-sensitive regions of two miniature photoresistors. Note that the electrodes of the device shown in (A) are darker than the light-sensitive material.

The device shown in Fig. 5(B) is a dual photoresistor. The center terminal is connected to an electrode that snakes its way between the interleaved electrodes connected to the two outer terminals. Dual photoresistors have several specialized applications, including detection of motion.

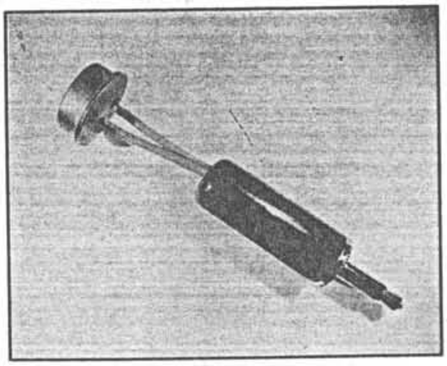


Fig. 6. Photoresistor soldered to miniature phone plug eases connections during experimenting.

Applications

Photoresistors have dozens of practical applications. Unlike photodiodes, they are not polarity-sensitive, so they can be powered by either ac or dc sources and their leads can be connected in either direction. Furthermore, many photoresistors can be operated at much higher voltages than most photodiodes and phototransistors.

For many years, photoresistors have been used in various kinds of light meters. While they have exceptional sensitivity and dynamic range, their lack of linearity over the entire range of their response is a major drawback.

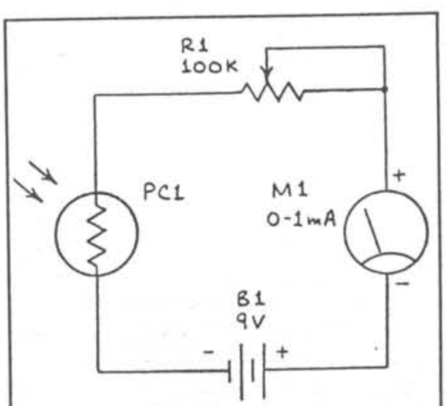


Fig. 7. A simple photoresistor light meter.

Many households are equipped with light-sensitive night lights that are controlled by photoresistors. Street lights and other kinds of indoor lighting are also switched on and off by simple photoresistor circuits.

Photoresistors can be used to make simple break-beam detection systems. Such systems are used to detect objects on a production line and to detect a person entering a store or approaching an electrically-activated door.

Various kinds of light and dark warning systems can be designed around photoresistors. A refrigerator door-open alarm, for instance, can be designed to sound a warning tone a predetermined time after the door has been opened.

Dual-element photoresistors can be used to make motion detectors. In a typical application, a single lens images a distant scene onto both halves of a dual-element photoresistor. The two halves of the photoresistor are connected to a differential circuit that ignores variations in the ambient light as long as the light level in each half of the photoresistor is equal. Should an object in the field of view of one photoresistor move or a new object enter the field of view of one half of the photoresistor, the resistance of that half will change. When this occurs, the circuit outputs a signal that ultimately causes an audible or/and visible alarm to actuate.

Photoresistors were once commonly used for electronic exposure control of cameras. The light-history effect, however, makes photoresistors much less satisfactory than photodiodes for this application. Therefore, most modern cameras use photodiodes for exposure control.

Many kinds of optical isolators (so-called "optoisolators") can be produced by pairing a photoresistor with a light source. Various kinds of light sources can be used, including LEDs and both tungsten and neon lamps. In a typical application, a very small current applied to a LED can produce sufficient light energy to lower the resistance of a photoresistor to the point where it can directly actuate a heavy-duty relay. This application

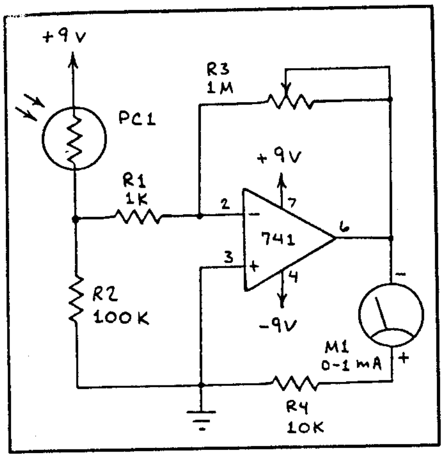


Fig. 8. A photoresistor light meter with a gain stage.

permits a tiny control current to switch a much larger current.

It's important to keep in mind that photoresistors can be exchanged for both fixed resistors and potentiometers to give light sensitivity to many kinds of circuits. For example, a photoresistor can be directly substituted for the frequency control potentiometer in a tone generator to form a light-sensitive generator. Similarly, a photoresistor can be substituted for the potentiometer that controls the gain of an amplifier to provide a light-sensitive volume control.

Some Circuits

In this section, we'll discuss several simple photoresistor circuits. In each of these circuits, the photoresistor is designated *PC1*, which identifies it as photocell 1. Many different CdS and CdSe photoresistors can be used in the circuits, some of which will function best with photoresistors selected for a particular resistance range or high light-to-dark resistance ratio.

If you plan to experiment with various kinds of photoresistors, you might want to solder several different devices to miniature phone plugs, as shown in Fig. 6. This will allow you to use a single photoresistor in different circuits. It will also permit you to use different kinds of photoresistors in the same circuit.

You can enhance operation of the circuits by installing the photoresistor in one end of a hollow tube that will then function as a collimator that gives the photoresistor a highly directional feature. You can also place various filters and apertures in front of the photoresistor or the tube in which it is installed. Finally, you can attach an optical fiber to a photoresistor to provide a remote-detection capability. The end of the fiber can be cemented directly to the photoresistor or be attached temporarily with clay, wax or any of the various compounds designed to hold pictures to walls.

• *Simple Light Meter.* Shown in Fig. 7 is the schematic diagram of an ultra-simple but surprisingly sensitive photoresistor light meter. Potentiometer *R1* controls the meter's sensitivity. If you wish greater sensitivity from this circuit, you can use a 0-to-50-microampere meter movement for *M1*.

Photoresistor *PC1* can be any CdS or CdSe device. For greatest sensitivity, select a device that has a high light-to-dark resistance ratio.

Since this circuit is very sensitive, you must use care to avoid forcefully "peg-

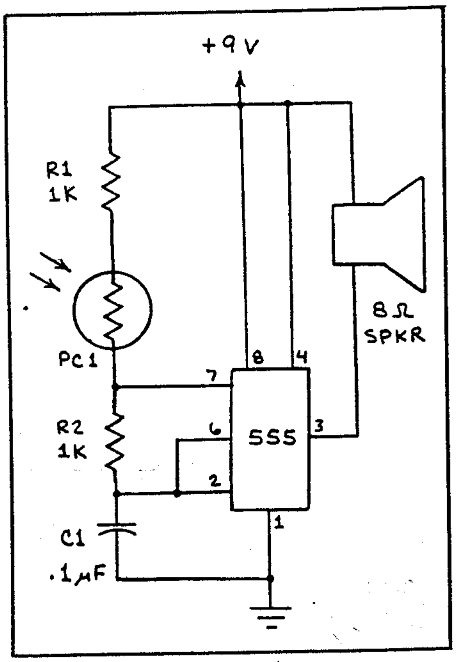


Fig. 9. A light-dependent oscillator built around a 555 timer IC.

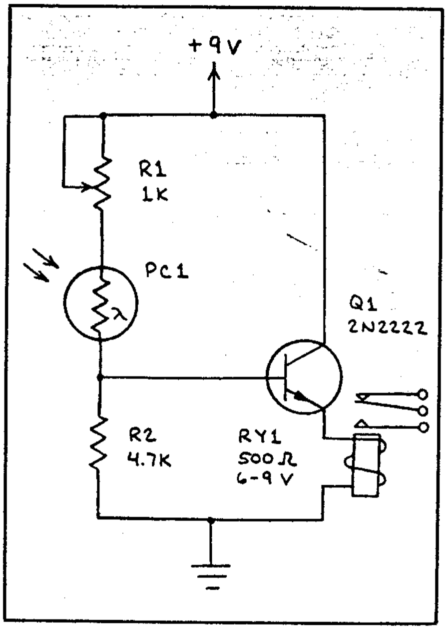


Fig. 10. A light-activated relay.

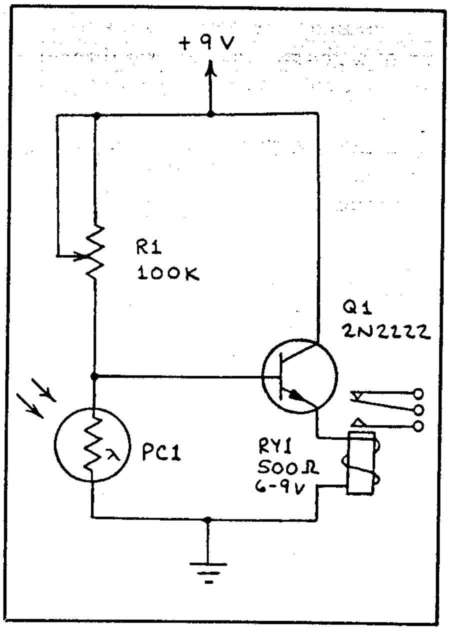


Fig. 11. A dark-activated relay.

ging" the meter's pointer. Therefore, always make certain that *R1* is set for minimum sensitivity (maximum resistance) before applying power to the circuit.

• *Advanced Light Meter.* Considerably more sensitivity to light can be obtained with the circuit shown in Fig. 8. Indeed, at its most-sensitive setting, the circuit is difficult to use because the light level required to read the meter may itself be bright enough to forcefully peg the meter's pointer!

As with the Fig. 7 circuit, many different photoresistors can be used in the Fig. 8 circuit. A high light-to-dark resistance ratio will provide best results.

Since this circuit is so sensitive, always make sure the *R3* is set to its lowest value before applying power. Also, always increase *R3*'s resistance gradually to avoid pegging the meter's pointer.

• *Light-Dependent Oscillator.* The frequency of virtually any oscillator can be changed in response to light by including a photoresistor in the RC portion of the circuit. How this can be accomplished with a simple audio-frequency oscillator made from a 555 timer chip is illustrated in Fig. 9. Many different photoresistors can be used for *PC1*. Increase the capacitance of *C1* to reduce the tone frequency, or decrease the capacitor's value to increase the frequency.

If the sound from the speaker is too loud, insert a resistor between the speaker and pin 3 of the 555 timer. Try a few hundred ohms, or use a 1,000-ohm potentiometer that can be adjusted to give a comfortable sound level.

• *Light-Activated Relay.* Many kinds of light-activated relays can be made using photoresistors. Some relays can be driven by nothing more than a photoresistor and a power supply. However, a gain stage provides greater sensitivity. For example, Fig. 10 shows a straightforward light-activated relay that uses a single transistor to increase sensitivity. Relay *RY1* is a Radio Shack Cat. No. 275-004 device. Potentiometer *R1* controls sensitivity.

• Light-activated relays are used to sound a warning when a door has been left ajar and to detect objects and people passing by.

• *Dark-Activated Relay.* The Fig. 11 circuit is the opposite of the previous circuit. When *PC1* is illuminated in this circuit, the relay is *not* actuated. Only when the light level on *PC1* falls below a certain point, determined by the setting of *R1*, does the relay energize. This circuit can be used to activate a light at dusk and to switch it off at dawn.

• *Light/Dark-Activated Buzzer.* The circuit shown in Fig. 12 controls a piezoelectric buzzer. A dpdt switch is used for *S1*. When *S1* is in position "L" (light), the buzzer sounds when *PC1* is exposed to light. Setting *S1* to "D" (dark) causes the buzzer to sound in darkness.

This circuit has many of the same applications as the previous two circuits. Its advantage is that it is self-contained and requires no external warning device. It can also be used to control a relay.

• *Dark-Activated LED Flasher.* A simple way to actuate a flasher LED with a photoresistor is shown in Fig. 13. This simple circuit makes a handy warning light for a darkroom. The flasher LED installs near the outside of the darkroom's door. The remainder of the circuit installs anywhere else inside the darkroom. With this setup, the flashing LED warns outsiders that the lights in the darkroom have been extinguished. For this application to be practical, it is necessary to install an on/off switch inside

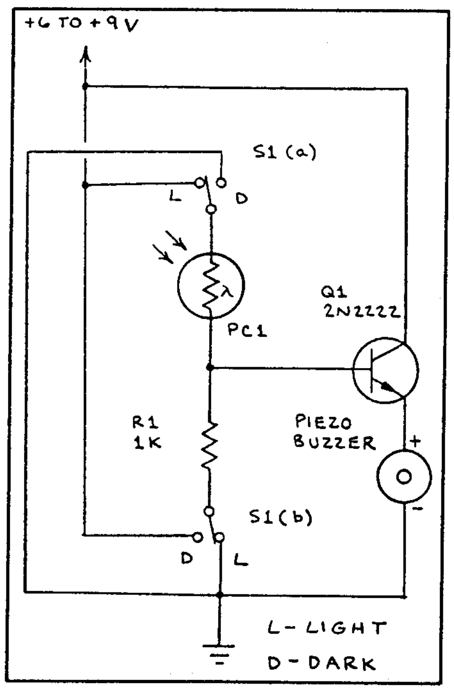


Fig. 12. A light/dark-activated relay.

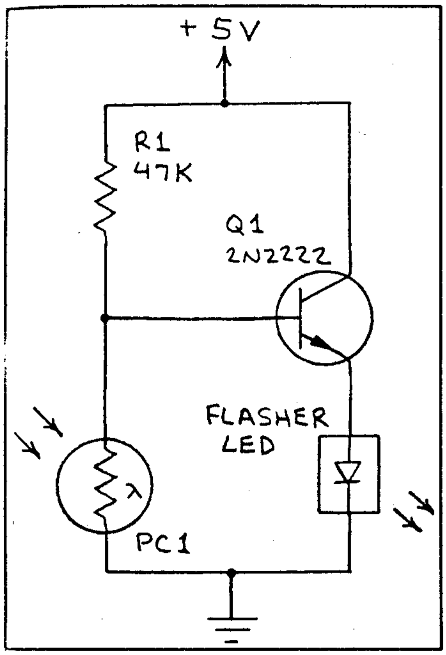


Fig. 13. A dark-activated LED flasher for darkroom warning use.

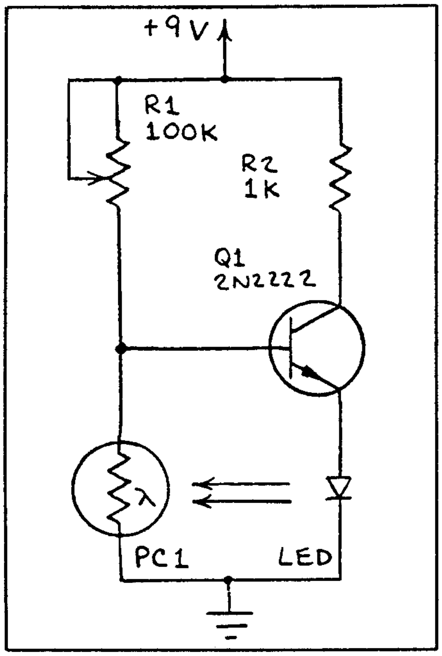


Fig. 14. A photoresistor optical feedback circuit.

the darkroom to disable the circuit when the darkroom is not in use.

• *Photoresistor Optical Feedback.* If your home is equipped with a photoresistor-controlled night light, you have probably noticed that the light will flicker when an object is placed near it at night. This occurs when some of the unit's light is reflected back to the photoresistor, thereby switching the device off. When the light switches off, the resistance of the photoresistor increases and causes the light to switch on again, and the cycle repeats.

This phenomenon, which is a form of optical feedback, can be used to regulate the brightness of a light source, such as a LED or miniature incandescent light. Shown in Fig. 14 is a simple circuit that does just this.

Assume the circuit is in darkness. The resistance of *PC1* will be high and *Q1* will be conducting. This allows current to flow through the LED. If the LED is positioned so that some of its light strikes *PC1*, the photoresistor's resistance will be lowered. In turn, this reduces the current flowing through *Q1*, thereby reducing the brightness of the LED. Therefore, the circuit functions as a current regulator.

Potentiometer *R1* is adjusted for optimum circuit operation. The LED's brightness is determined by the placement of the LED relative to the sensitive surface of *PC1*. When the two are closely spaced, the LED will be dim; when father apart, the LED will be brighter. Reflective objects placed near the LED will increase the light falling on *PC1*, thus reducing the light from the LED.

Since the light from the LED responds almost instantaneously to changes in the LED's forward current, the LED does not flicker. Instead, its brightness changes just as if it were connected to a potentiometer that controlled its forward current.

Going Further

The circuits described here are merely representative of what can be accomplished with the help of a common photoresistor. For additional ideas, see my *Engineer's Mini-Notebook: Optoelectronics Circuits* (Siliconcepts, 1986), a Radio Shack book. I have also included a number of photoresistor circuits or circuits suitable for use with photoresistors in *The Forrest Mims Circuit Scrapbook* (McGraw-Hill, 1983) and *Forrest Mims' Circuit Scrapbook II* (Howard W. Sams, 1987).

Many other possibilities exist. For example, you might wish to design a circuit that uses photoresistors that have different spectral responses to detect objects that have different coloring.

In any event, be sure to experiment with all kinds of photoresistors. Most published circuits specify CdS photoresistors that have high light-to-dark resistance ratios. You may discover that other kinds of photoresistors will function as well or better in a particular circuit you have in mind. **ME**