# ELECTRONICS NOTEBOOK

## More on How to Detect Ultraviolet, Visible Light and Infrared

By Forrest M. Mims III

**This is the second** of two columns on the detection of ultraviolet, visible and infrared radiation. Last month, I described various kinds of thermal detectors for these wavelengths of the electromagnetic spectrum. This month, we'll be looking at the most important kinds of photodetectors.

### Photodetectors

Thermal detectors detect light indirectly by the temperature increase that is produced when the detector is illuminated. Photodetectors detect light directly by the photoelectric effect. Therefore, most photodetectors are more sensitive and have faster response times than most thermal detectors.

There are three major classes of photodetectors: photoemissive, photovoltaic and photoconductive. Photoemissive detectors include phototubes and photomultiplier tubes. Photovoltaic and photoconductive detectors are semiconductor devices. While semiconductor detectors are by far the most common, you should be aware of the basic operating principles of photoemissive detectors.

### Photoemissive Detectors

If you know what a phototube or photomultiplier tube is, then you know what a photoemissive detector is. These detectors consist of an evacuated or gas-filled glass envelope that contains a light-sensitive *photocathode* and an electron-collecting anode. The photocathode is a metal electrode that is coated with a thin layer of material that emits electrons when it is exposed to light.

Two common photocathode materials for the visible spectrum are silver-oxygen-cesium and cesium-antimony. Cesium-telluride and other materials are used for detection of ultraviolet energy.

Some of the more commonly used photocathode materials have been assigned "S" numbers for convenient identification. Figure 1 is a graph that shows the sensitivities of several important S surfaces across the ultraviolet, visible-light and near-infrared spectra.

The simplest phototube detectors have only two electrodes—a photocathode and an anode. A phototube can be made by coating a wire electrode with a photocathode material and enclosing the wire, along with a similar uncoated wire, in a thin glass tube. Larger photocathodes are usually used since they provide more light-collection area. For example, the photocathode of the miniature phototube shown in Fig. 2 is formed by coating the inside half of a cylinder with cesium-telluride. This particular drawing of a phototube is of a Hamamatsu (P.O. Box 6910, Bridgewater, NJ 08807-0910) Model R1826 that I am using to measure the ultraviolet radiation from the sun.

Photomultiplier tubes provide hundreds of times more sensitivity than do ordinary phototubes. The photomultiplier tube, or PMT, contains a series of electrodes called "dynodes." Each dynode is maintained at a potential that is slightly greater than that on the previous dynode. Light stimulates the photocathode of the PMT to release electrons, which strike the first dynode.

In a process called "secondary emission," the dynode emits about five electrons for each one it collects. The secondary electrons strike the second dynode, and the multiplication process is repeated. Since a typical PMT has as many as 10 dynodes, eventually hundreds or even thousands of electrons for each original electron strike the anode of the tube.

Photomultipliers are so sensitive that they can detect the arrival of a single photon. But this sensitivity comes at the price of high operating voltage, which is typically 1,000 to 2,500 volts. And since each dynode requires a different voltage, a low-current voltage divider made from a string of resistors is required. Finally, for

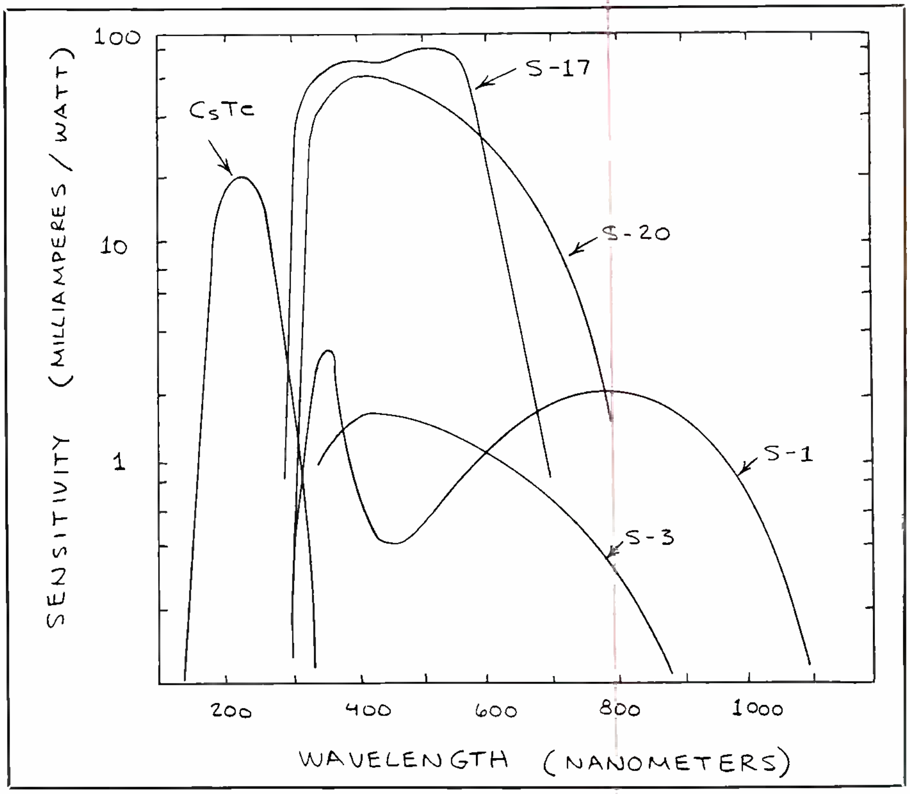

*Fig. 1. Spectral responses of several photoemissive surfaces.*

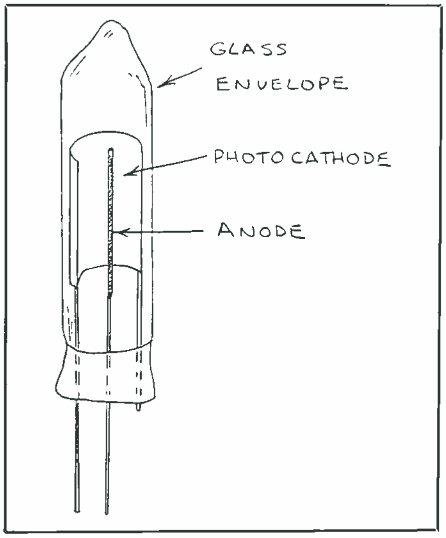

*Fig. 2. Internal details of Hamamatsu R1826 ultraviolet phototube.*

ultra-low noise operation, the PMT should be cooled.

## Photoemissive Detector Applications

Semiconductor photodetectors have taken over in many applications where photoemissive detectors were once used. Nevertheless, phototubes and PMTs still have important uses. The various spectral sensitivities that are available make phototubes and PMTs especially useful for detecting specific bands of light.

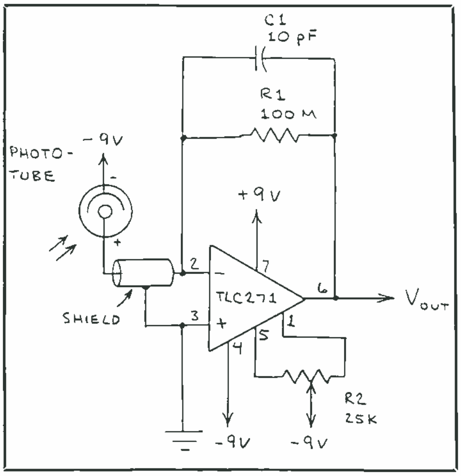

*Fig. 3. Schematic diagram of a high-gain phototube amplifier.*

As an example of the above, ultra-sensitive photodiodes are much more sensitive to red light than to ultraviolet radiation. This poses a difficult problem because interference filters designed to pass UV wavelengths tend to also pass some red light as well. This can be solved by using a phototube or PMT with a cesium-telluride photocathode that responds to only ultraviolet wavelengths.

PMTs are especially useful for detecting very-low light levels. That's why both amateur and professional astronomers use them to measure the light coming from faint stars. PMTs are also used to detect the flashes of light produced when radiation passes through certain plastics and crystals.

## Experimenting With Photoemissive Detectors

Shown in Fig. 3 is the schematic diagram of a circuit I've used to enable the R1826 phototube described above to detect ultraviolet energy from the sky and sun. The TLC271 CMOS op amp provides the extremely high input impedance required for this circuit to perform properly. However, you can substitute any other CMOS or FET-input op amp for the TLC271, making any pin changes that might be needed. Use a shielded cable between the phototube and op amp if the distance between the two exceeds several inches.

In the Fig. 3 circuit, *R2* controls the offset voltage in the circuit. The output can go to a digital voltmeter or, perhaps, a comparator that switches when the light on the phototube exceeds or drops below a preset threshold.

This circuit has plenty of gain. Its output is at a level of about 1 volt or so when the tube is exposed to blue sky on a clear day. The tube should *not* be exposed to direct sunlight. Otherwise, its performance and sensitivity may suffer degradation. Instead, first place the tube behind a UV filter, such as Schott UG-11 glass.

You can further reduce the intensity of direct sunlight with a diffuser made from quartz, silica or some material that is transparent to ultraviolet wavelengths. One or both surfaces of the diffuser should be ground to a rough finish.

You will also want to consider a photomultiplier tube if your application calls for detection of the light from a faint star, a firefly or a crystal that flashes when it is exposed to radioactivity. There are many kinds of PMTs available, each with a specific set of power-supply requirements.

Shown in Fig. 4 is a generalized connection diagram for a typical PMT. This circuit shows the voltage divider that delivers progressively greater voltages to the dynodes in the PMT. It is important that you use good wiring practices and properly insulated sockets when using PMTs. Manufacturers of photomultiplier tubes can supply specific connection and circuit information for their PMTs.

## Semiconductor Photodetectors

The most common detectors of ultraviolet, visible-light and infrared radiation

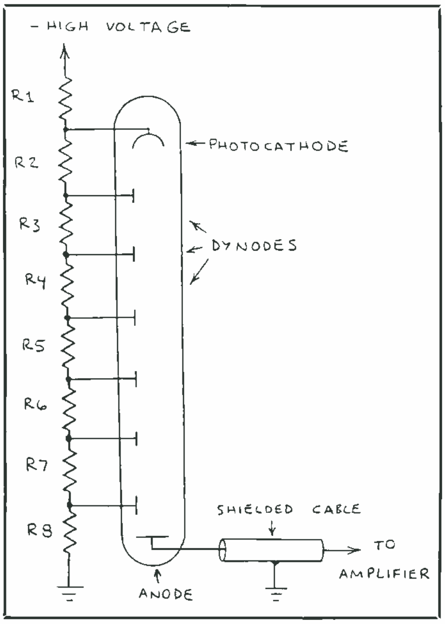

*Fig. 4. Generalized connection circuit for a photomultiplier tube.*

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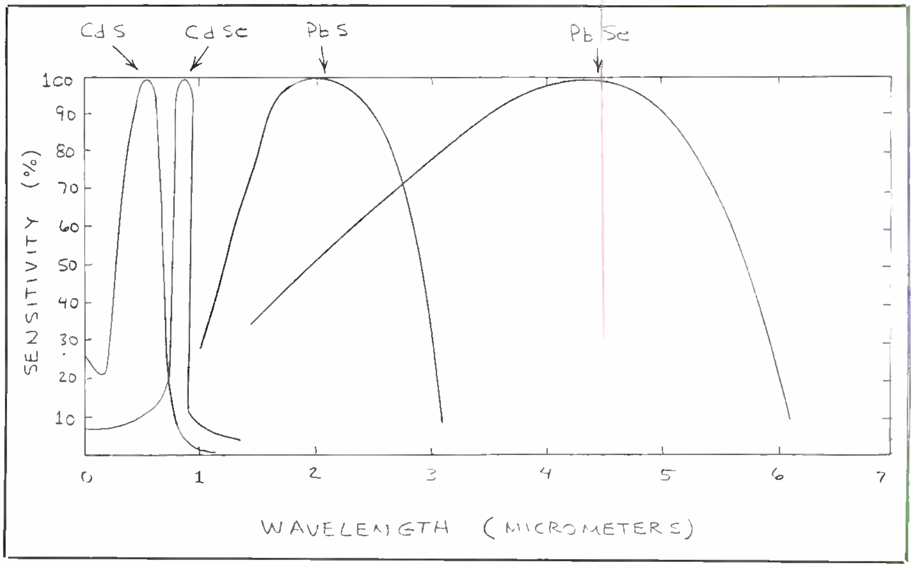

Fig. 5. Spectral sensitivites of several photoresistors.

are semiconductor photodetectors. These can be pn-junction devices like photodiodes and phototransistors, or they can be bulk devices like photoresistors. In either case, semiconductor photodetectors are physically smaller and more durable than photoemissive detectors.

- *Photoresistors.* Photoresistors are also known as light-dependent resistors (LDRs) and photocells (PCs). Since their resistance varies with the intensity of the light they intercept, photoresistors are "photoconductive" detectors. The resistance of a photoresistor is much higher when the device is dark than when it is being illuminated.

Photoresistors are made by applying electrodes to a thin film of photoresistive material. The electrodes are usually applied in a spiral or zig-zag pattern to increase the exposure of light-sensitive material.

The most common light-sensitive materials used in photoresistors are cadmium-sulfide (CdS) and cadmium-selenide (CdSe). The peak spectral response of some formulations of CdS closely matches that of the human eye—in the 550-to-555-nanometer range. The peak spectral response of CdSe ranges from 720 to 780 nanometers in the far red portion of the visible spectrum.

Lead-sulfide (PbS) and lead-selenide (PbSe) are used to make infrared-sensitive photoresistors. Cooling these detectors greatly increases their sensitivity. Figure 5 compares the spectral sensitivities of some of the most important photoresistor materials.

Photoresistors are easy to use and ex-

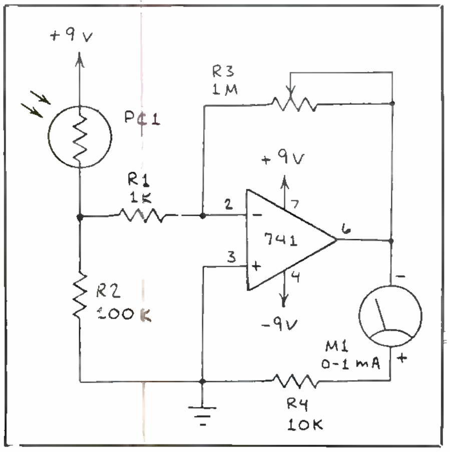

Fig. 6. Circuit details of a photoresistive light meter with gain stage.

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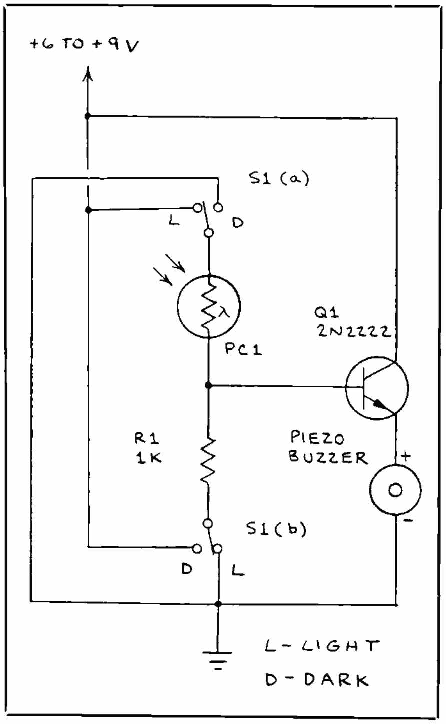

*Fig. 7. Schematic diagram of a light/dark buzzer circuit.*

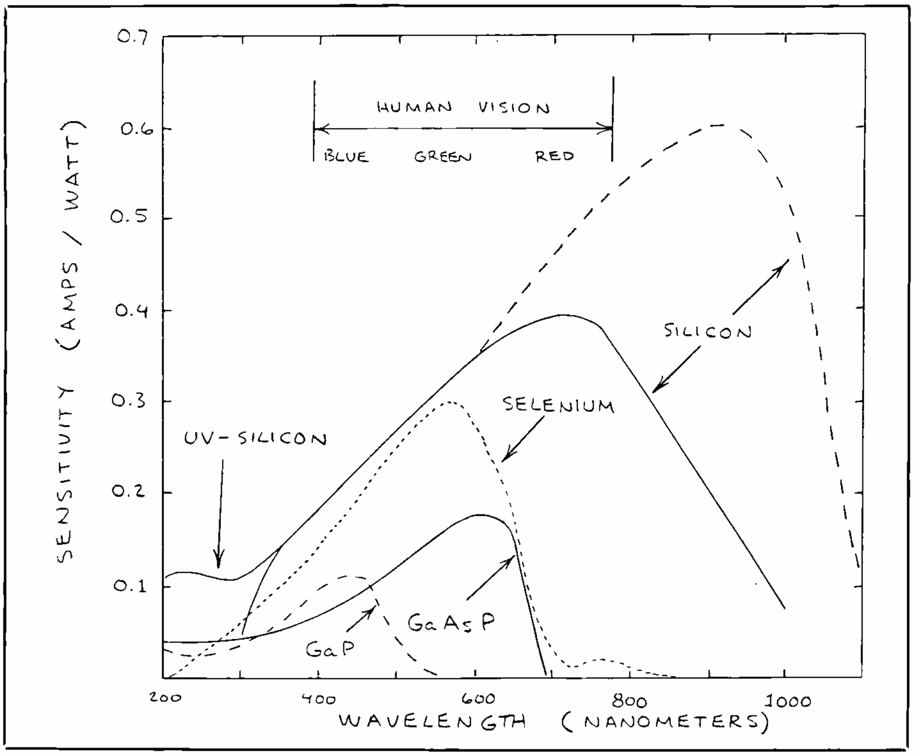

*Fig. 8. Spectral responses of several photodiode materials.*

ceptionally sensitive to light. However, their response time is much slower than that of junction semiconductor detectors. Also, photoresistors are subject to the "light history effect" in which the resistance of the device is dependent for a time upon the previous light level received by the detector.

You can make a sensitive light meter by connecting a photoresistor in series with a battery and milliammeter, as shown in Fig. 6. This circuit also shows how to increase the sensitivity of such a meter by adding a single op-amp gain stage. While the 741 op amp shown in the Fig. 6 schematic diagram will work, better-quality op amps with less offset voltage will work even better. A good choice is the OP-07 op amp.

Shown in Fig. 7 is the schematic diagram of a simple circuit that doubles as both a light and a dark detector. The circuit can be used to wake you when the sun comes up or warn you when your refrigerator door is ajar.

If you would like to know more about photoresistors, I refer you to my September 1988 "Electronics Notebook" column, in which I described these and several other applications. I also discussed in that column the operation of CdS and CdSe photoresistors in some detail.

- *Pn-Junction Detectors.* Virtually any semiconductor pn junction is sensitive to visible or infrared radiation. Bell Laboratories found this out when they encapsulated some of their early transistors in transparent plastic. Even light-emitting diodes can be used as light detectors.

Many kinds of semiconductor photodetectors are in common use, and many others have been developed by research laboratories. Some of them have a very small active surface area to make them suitable for detecting very fast optical pulses. Others are divided into two halves or four quadrants for use in position-sensing applications.

Position-sensitive detectors can also be made from single detector elements. These use what is called the "lateral effect" to detect the position of a light spot on the surface of the detector.

The spectral sensitivities of various pn-junction photodetectors are dependent on the semiconductor material from which they are manufactured. Figure 8 shows the spectral sensitivities of some of the semiconductor materials used to make junction photodetectors. Of course, silicon is the most common photodetector material currently in use.

The peak spectral response of silicon matches the peak emission wavelength of several kinds of light-emitting diodes. For applications in which infrared sensitivity is not desired, filters can be placed in front of a silicon detector, or a gallium-phosphide (GaP) photodiode can be used for ultraviolet and visible-blue wavelengths. Gallium-arsenide-phosphide (GaAsP) can be used for the UV through visible red wavelengths.

Any semiconductor pn-junction photodetector is, by definition, a photodiode. Therefore, even silicon photocells are photodiodes. The most important characteristic of photodiodes is that they produce an output current that is linear with respect to the light that strikes their active surfaces. Depending on the semiconductor material from which the photodiode is manufactured, linearity can range from around four to as many as ten decades of light-intensity variation.

Pn-junction detectors can be used in either a photovoltaic or photoconductive mode. Self-generating photodetectors, such as silicon photodiodes and solar cells, are commonly used in the photovoltaic mode. The detector is simply connected directly to the input of an operational amplifier, as shown in Fig. 9. The op amp then functions as a current-to-voltage (also known as transimpedance or transresistance) amplifier that boosts the detector's photocurrent.

Figure 10 shows two ways in which a junction detector can be connected in the photoconductive mode. In both methods, the detector connects to an external current source in the reverse direction. Light striking the active surface of the detector increases the current flow (photocurrent, or $I_p$) through the device.

The voltage-amplifier connection transforms the photocurrent into a voltage that is then amplified. In the current-amplifier (transresistance or transimpedance) mode, the photocurrent is boosted by an op amp and connected to a voltage-to-current amplifier.

The voltage-amplifier connection provides a convenient way of increasing the photodiode's sensitivity. Simply increase the resistance of load resistor $R_L$ to increase sensitivity. The down side of this is that the resistor contributes noise and a bias current is required. Also, the response speed of the circuit is inversely proportional to the resistance of the series resistor. In other words, increasing the sensitivity by increasing the resistance of the load resistor slows down response time. This happens because $R_L$ determines the time required for the internal capacitance of the photodiode to be discharged.

The transresistance or transimpedance arrangement has no load resistor to contribute noise or slow down response time.

The avalanche photodiode is the solid-state analog of the photomultiplier tube. These photodiodes are designed to be operated at a relatively high reverse-bias voltage that is just below the breakdown or avalanche potential of the diode. Incoming photons generate free electrons that permit a much greater current to flow than in a conventional photodiode. Gains of up to several hundred are possible.

While avalanche photodiodes provide exceptionally high sensitivity, they require a carefully regulated high-voltage power supply. They are also expensive.

Now that we've covered some photodiode basics, let's look at those photodetectors that are most important to electronics experimenters.

- *Selenium Cells.* selenium cells are large-area photodiodes with several important advantages and features. Their spectral response closely matches that of the human eye, they can be used as low-power solar photovoltaic cells, and they have good sensitivity in the blue and near-ultraviolet regions of the spectrum. It's easy to make selenium cells in various shapes and with holes. They can even be made in the shape of a cylinder.

These advantages and features have for many years made selenium cells the most important light detectors available. Perhaps their most important use was as detectors in light meters used by photographers and illumination engineers. These light meters consisted of a self-gen-

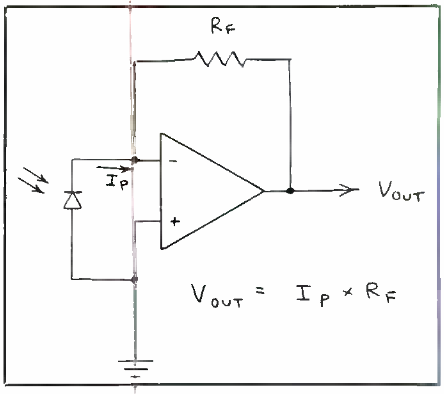

*Fig. 9. Circuit details of photovoltaic operation of a photodiode.*

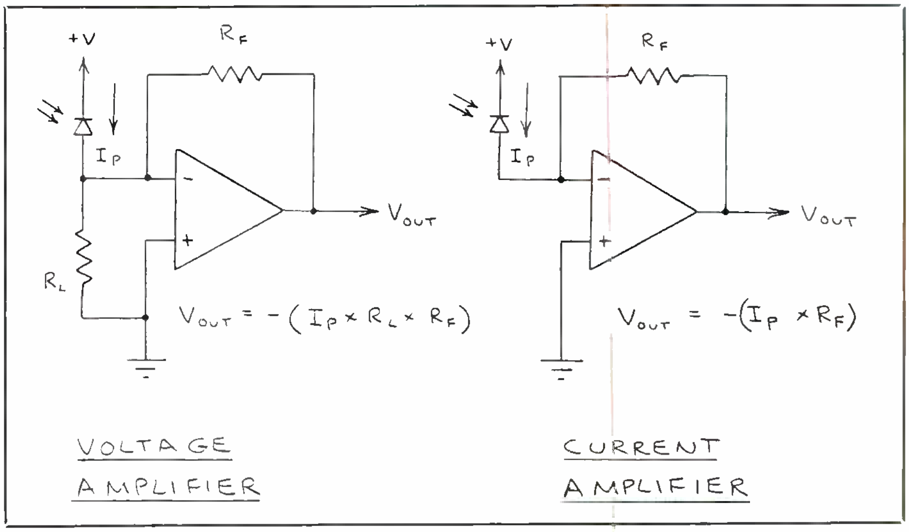

*Fig. 10. Details of photoconductive operation of a photodiode.*

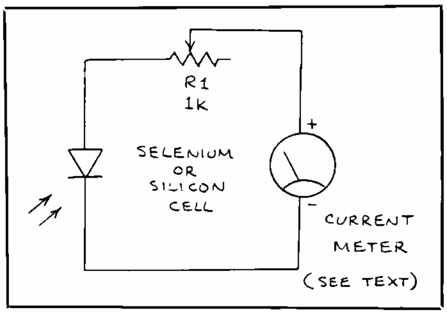

*Fig. 11. Schematic diagram for a self-powered light meter.*

erating selenium cell connected across a microameter. Another common use for selenium cells was in light-activated relay applications.

From the late 1950s to the mid-1960s, International Rectifier sold its famous B2M selenium "sun battery" for $2.50. During those years, silicon solar cells cost at least $20. Therefore, a B2M played a major role in introducing many experimenters around the world, including yours truly, to solar-powered projects.

Today, selenium solar cells have been replaced almost entirely by silicon photodiodes. One of the few remaining manufacturers of selenium cells is EG&G Vactec (10900 Page Blvd., St. Louis, MO 63132). Sometimes, selenium cells are available on the surplus market.

- *Silicon Solar Cells.* Silicon solar cells can convert into electricity up to 10 percent or more of the light that strikes them. The forward voltage of a silicon solar cell is around 0.6 volt. Current output varies linearly with light exposure. In full sunlight, a 1-square-inch cell can deliver as much as 100 milliamperes of current. Large circular cells will deliver a full ampere or more.

While silicon solar cells are generally considered to be "sun batteries," they also make highly effective light sensors. Their main advantage as sensors is their large active-surface area. This means that they can detect very-low light levels without the use of a light-collecting reflector or lens.

Aside from recharging batteries on a homemade xenon strobe light I take on bicycle trips, my favorite applications for solar cells are as detectors for lightwave communication receivers and lightning detection. Their large surface area gives silicon solar cells too much capacitance for them to detect fast-risetime pulses.

Shown in Fig. 11 is the schematic diagram of a simple but effective light meter that you can make with a selenium cell or a silicon solar cell and a microammmeter. A silicon cell provides considerably more sensitivity in this application, while a selenium cell provides a spectral response that resembles that of the human eye.

If the Fig. 11 meter is too sensitive, you can place a light-limiting aperture over the detector. Alternatively, you can insert a current-limiting potentiometer between the detector element and meter movement.

You can make a simple light-powered, light-activated relay by connecting a series-array of selenium cells or silicon solar cells to a low-voltage relay. You'll have to experiment to determine how many cells of either type are needed to energize the relay. For example, a 5-volt dc relay will require approximately 10 silicon solar cells. The cells must be able to deliver sufficient current to actuate the relay, of course.

Small-area silicon photodiodes are ideal for use as detectors in lightwave communication systems. Figure 12 shows a basic circuit you can use to receive an intensity- or pulse-modulated visible or near-infrared signal. Note that *C1* is included in the circuit so that only the fluctuating (ac) signal and not the steady (dc) background is not amplified.

You can greatly increase the receiving range of the Fig. 12 circuit by placing the detector behind a lens. The circuit will work much better in daylight if you use a filter that passes only the wavelength of the signal. Interference filters work best, but they're expensive. A cheap substitute for near-infrared wavelengths is developed color film. Photodiodes encapsulated in infrared-transmitting plastic are another good choice.

Photodiodes are well-suited for use in sensitive light meters, and radiometers. The schematic diagram shown in Fig. 13 is for the circuit of a radiometer that will detect very-low light levels. Virtually any photodiode can be used in this circuit, including a solar cell. Many different operational amplifiers can be used, too. For best results, though, be sure to use an op amp that has a high input impedance, such as the OP-07. CMOS op amps might

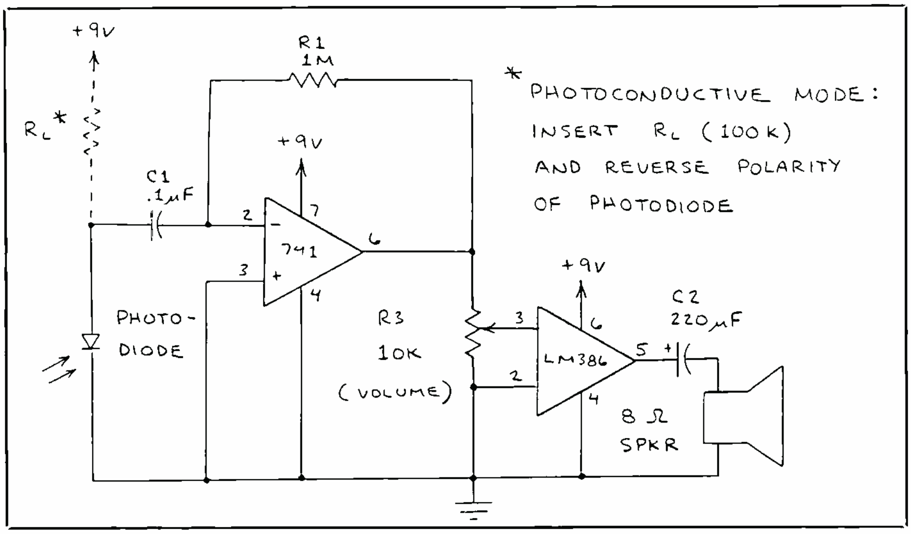

*Fig. 12. Schematic diagram of a photoreceiver for audio-frequency signals.*

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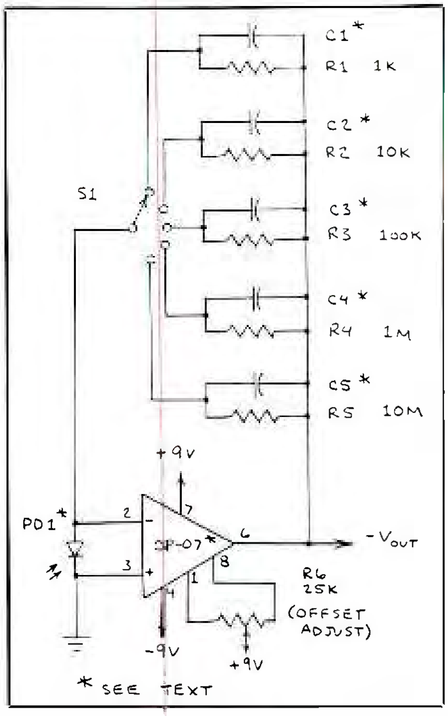

*Fig. 13. Schematic diagram of a photodiode radiometer with range control.*

work even better. If necessary, be sure to modify the pin connection scheme to the offset adjust.

Capacitors *C1* through *C5* serve as feedback elements that keep the response of the circuit uniform across the frequency-response (f) range of the op amp. The value of feedback capacitance needed is calculated using the formula $1/(2\pi \times f \times R_f)$. These capacitors can be eliminated if steady-state light sources are being measured.

- *Phototransistors.* A phototransistor is a transistor in which the base region has been enlarged. Light striking the base region has the same effect as a current applied to the base of a standard transistor. When the transistor is dark, only a small leakage current flows between the collector and emitter. When light strikes the base area, a collector current flows. The level of collector current that flows depends on the the intensity of the light and the current gain of the transistor.

Photodarlingtons are phototransistors that include an integral output transistor stage connected in a Darlington configuration. This arrangement provides more current gain and, hence, much greater sensitivity than a phototransistor alone.

Because of their inherent gain, phototransistors do not provide the same degree of linear response as photodiodes. When the detected light exceeds a certain level, the transistor simply saturates, or switches fully on. This means that phototransistors usually cannot be used in daylight because they will be "swamped out" by ambient light long before they detect any signal you aim at them.

Phototransistors are easy to use and provide a very simple approach to many optoelectronics applications. In Fig.

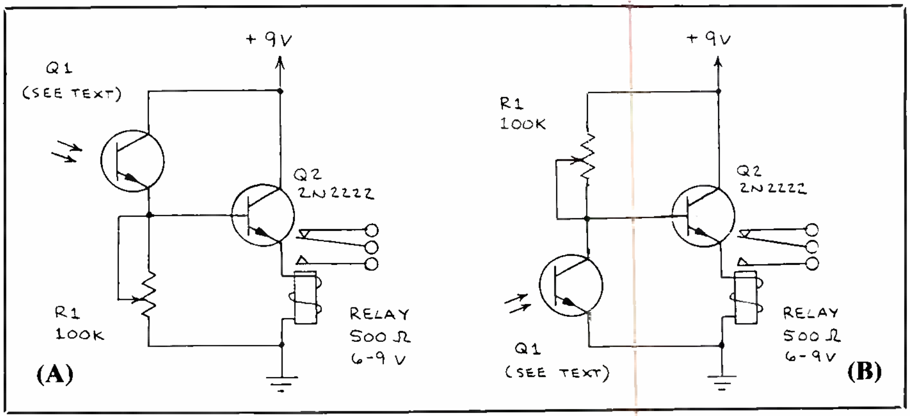

*Fig. 14. Light-activated (A) and dark-activated (B) phototransistor relay circuits.*

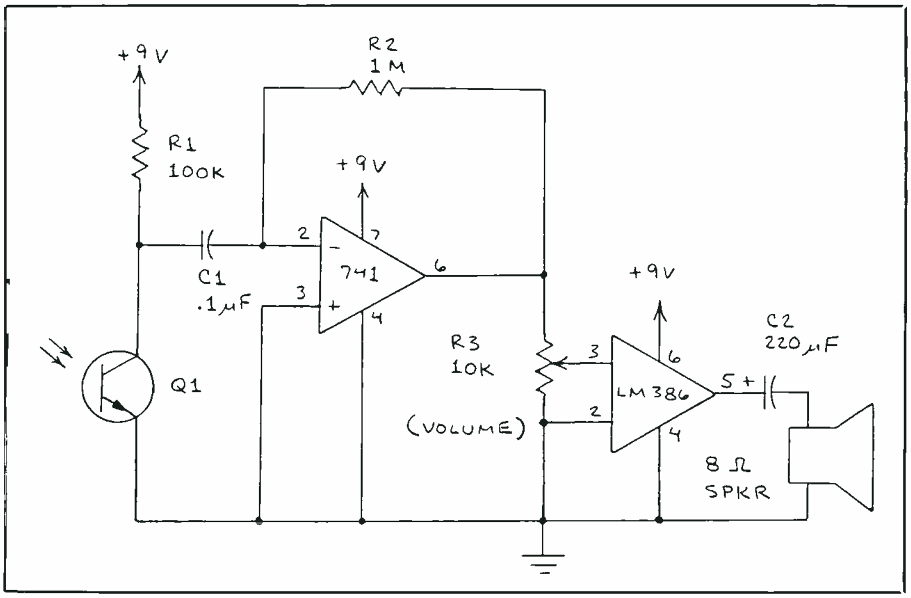

*Fig. 15. Schematic diagram of a phototransistor receiver circuit for audio signals.*

14(A), for example, a simple light-activated relay is made up of only four components. The sensitivity of the circuit is controlled by *R1*. Figure 14(B) shows how the position of the phototransistor and *R1* in Fig. 14(A) can be reversed to make up a dark-activated relay.

Any npn phototransistor should work well in either Fig. 14 circuit. If either circuit triggers erratically or prematurely, the phototransistor is probably receiving ambient light. In this event, either remove the external light source or place a piece of black heat-shrinkable tubing over the phototransistor to form a collimator.

Shown in Fig. 15 is the schematic diagram of a simple phototransistor receiver circuit you can assemble and use to detect a modulated light beam. This circuit is well-suited for use with many different kinds of audio-frequency lightwave-communication systems.

When experimenting with these and other phototransistor circuits, you may notice that the phototransistor is more sensitive to the signal it is supposed to detect when the phototransistor receives a small amount of ambient illumination. I noticed this many years ago when I was testing a portable lightwave receiver set up 1,000 feet away from a transmitter. While checking the receiver with a small penlight, the volume of the signal emitted from the receiver's speaker suddenly increased in amplitude. Depending on where I pointed the penlight, it was possible to increase the output signal by several times.

You might want to experiment with this technique of increasing the sensitivity of phototransistors that don't have a base lead. You can alter the gain of phototransistors with a base lead by using traditional biasing techniques.

## *Going Further*

Even though I've devoted two columns to discussing the devices and techniques for detecting ultraviolet, visible-light and infrared radiation, there's much that I haven't touched upon. If you want to find out more about the general subject of light detectors, visit a good technical library. Many books on optoelectronics include detailed chapters on various kinds of detectors.

If you want more information about circuits for various kinds of light detectors, there's no better source than the brochures and data sheets published by the manufacturers of the detectors. Particularly good brochures are published by EG&G (25 Congress St., Salem, MA 01970); United Detector Technology (12525 Chadron Ave., Hawthorne, CA 90250); Centronic, Inc. (1829-B DeHaviland Dr., Newbury Park, CA 91320-1702); Silicon Detector Corp. (855 Lawrence Dr., Newbury Park, CA 91320); and both Hamamatsu and EG&G Vactec (addresses given earlier).

Finally, I included an elementary introduction to light detectors in my *Engineer's Mini-Notebook: Optoelectronics* (Radio Shack, 1986). I've also included considerable information about detecting light in *The Forrest Mims Circuit Scrapbook* (McGraw-Hill, 1983) and *Forrest Mims' Circuit Scrapbook II* (Howard W. Sams, 1987). ME