Construction and Characteristics of CdS Cells

Photosensitive devices can be divided into photovoltaic devices and photoemissive devices. CdS cells are a type of photoconductive device. They are semiconductor sensors that utilize the photoconductive surface that reduce the resistance. A voltage is applied to both ends of a CdS cell. The change in resistance due to light is output as a current change signal. Despite the small size, the output current per photoconductive surface area is large enough to drive relays directly. For this reason, CdS cells are used in a wide variety of applications.

The following information explains briefly the basic operating principles, fabrication, and structure of CdS cells.

PHOTOCONDUCTIVE EFFECT

Figure 1 is a schematic diagram of a CdS cell and its operation circuit. An electrode is set at each end of the photoconductor. In darkness, the photoconductor resistance is very high. When a voltage is applied, the ammeter shows only a small dark current. This is the CdS photoconductor's characteristic thermal equilibrium current. When light is incident on this photoconductor, a current △ I flows. **Figure 2** shows the current that flows when the amount of light is increased.

Figure 1: CdS Cell Schematic Diagram and Operation Circuit

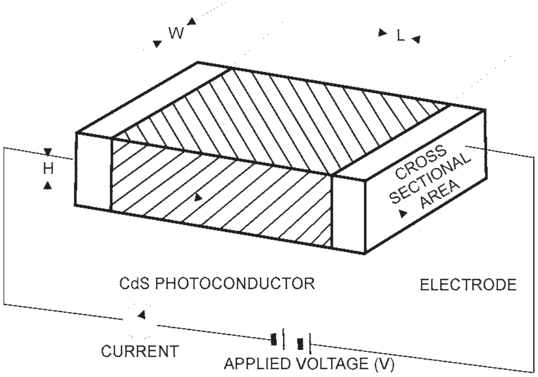
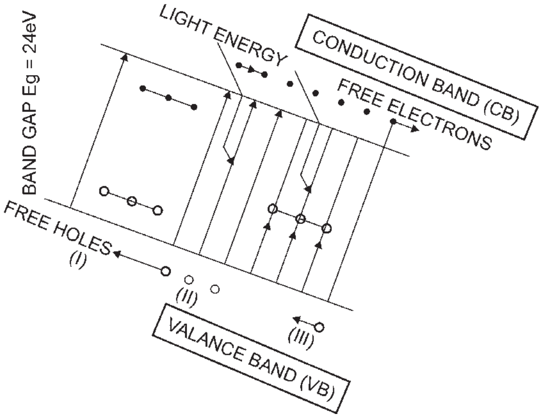


Figure 2: Carrier Generation by Light Excitation



Here are the basic principles of the photoconductive effect.

(I) Directly beneath the conduction band of the CdS crystal is a donor level and there is an acceptor level before the valence band. In darkness, the electrons and holes in each level are almost crammed in place in the crystal and the photoconductor is at high resistance.

(II) When light illuminates the CdS crystal and is absorbed by the crystal, the electrons in the valence band are excited into the conduction band. This creates pairs of free holes in the valence band and free electrons in the conduction band, increasing the conductance.

(III) Furthermore, near the valence band is a separate acceptor level that can capture free electrons only with difficulty, but captures free holes easily. This lowers the recombination probability of the electrons and holes, therefore increasing the number for electrons in the conduction band for N-type conductance.

The increase in conductance in (II) requires that the light energy be greater than the band gap Eg. For Cds with a band gap 2.41 eV, the absorption edge wavelength λ is $\lambda = c/\nu = hc/E_{ph} = 1240/Eg \sim 515$(nm).

Where:

E_{ph}: photon energy ($h\nu$)

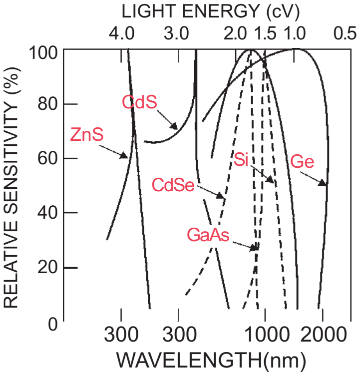
h: Planck's constant

ν: light frequency

c: speed of light

The CdS crystal absorbs light with a wavelength shorter than 15nm transmitted. Therefore, the photoconductor's absorption edge wavelength determines the spectral response characteristic on the long wavelength side. In the actual spectral response characteristic shown in **Figure 3**, the sensitivity of CdS drops at wavelengths shorter than 515nm. This is because at short wavelengths the light is absorbed near the surface of the crystal, increasing the local charge density and inducing electron-hole recombination. Also, there are lattice defects at the crystal surface, which promote the recombination.

Figure 3: Spectral Response Characteristics for CdS and other Photoconductors



Until the carries generated in (II) and (III) recombine, electrons are injected from one electrode and pulled out by the other.

When these carries last longer and they move more, the conductance increases greatly. The conductance $\triangle p$ is given by the following equation:

$$\triangle p = ef\,(\mu n\ \tau n + \mu p\ \tau p)$$

Where μn, μp: free electron, free hole movement (cm/V • sec)

τn, τn: free electron, free hole life (sec)

f: number of generated carriers per second per cubic volume

For a CdS cell, $\mu n\ \tau n >> \mu p\ \tau p$ and conductance by free holes can be ignored. Then it becomes an N type semiconductor. Thus,

$$\triangle p = ef \bullet \mu n\ \tau n$$

Here, the gain G is defined as how many electrons flow between the electrodes due to excitation by one photon in the CdS photoconductor (until the carrier lifespan is over).

$$G = \tau n/t_t$$

Where t_t: transit time between electrodes = $12/V\ \mu n$

I: distance between electrodes

V: voltage applied

Therefore,

$$G = \mu n\ \tau nV/1^2$$

For example, μn = 300 cm2/V • sec, τn = 10-3 sec, 1 = 0.2mm, and 1.2V, then the gain is 900. This means that there is multiplication in the CdS photoconductor and that the CdS is highly sensitive.

The sensitivity of CdS is the change in resistance, i.e., the change in current in response to change in light. As **Figure 1** shows, if the distance between the electrodes is 1 the cross-sectional area of the photoconductor is S, and the voltage applied is V, then from Ohm's law:

$$\triangle I \propto \triangle p \bullet S \bullet V/1 = \triangle p \bullet t \bullet V/1$$

If the conductance $\triangle p$ and the photoconductor thickness t are held constant, then:

$$\triangle I \propto d/1 \rightarrow \text{resistance } \triangle R \propto 1/d$$

This 1/d is an important factor in designing the electrode configuration. In other words, the shorter the distance between the electrodes and the greater the electrode length, the higher the sensitivity and the lower the cell resistance. Thus, the electrode patterns for high-sensitivity CdS cells consist of many zig-zags.

STRUCTURE

CdS cells can be separated by the manufacturing process of the photoconductive layer into three types. These types are the sintered type, the single crystal type and the evaporated type. We use the sintered film fabrication method because it offers high sensitivity areas, a large mass production effect and relatively superior production profitability.

The process for making sintered CdS cell Impurities and a fusing agent for encouraging crystal growth are added to highly pure CdS crystal powder and this mixture is dissolved in water. The resulting solution is applied to CdS ceramic substrate and dried, then it is sintered in a high-temperature oven to form multiple crystals. In this way, a thick layer with the photoconductive effect is formed.

Lead terminals are introduced to the CdS substrate and the CdS is packaged **(Figure 4 and Photo 1 shows an example of the structure of a plastic coated CdS cell).**

Figure 4: Structure of Plastic-Coated CdS Cell

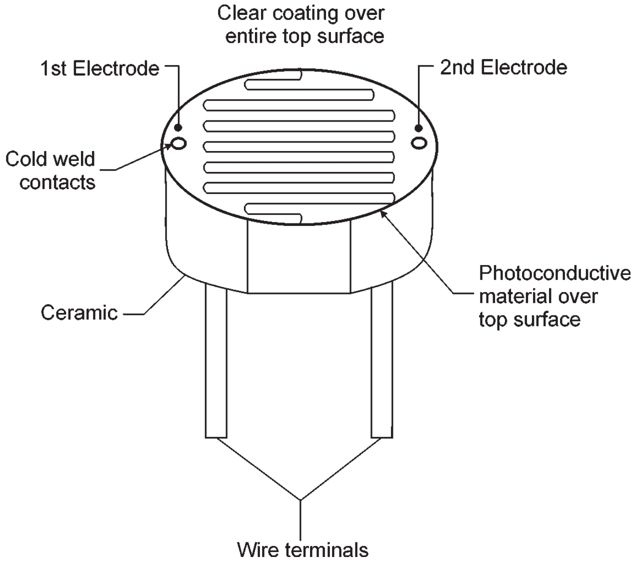
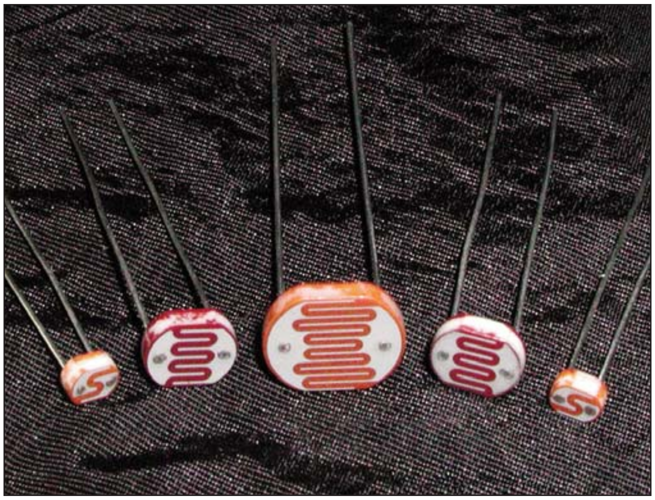


Photo 1: Examples of CdS Cell Configurations



CHARACTERISTICS

In the selection of a suitable CdS cell, the characteristics required by the functions of the circuit in which the CdS cell is to be used are important. There are analog uses such as light measurement and digital uses such as on-off switching. Use in digital circuits such as switching requires a fast response and a high ratio between illuminated resistance and dark resistance. The sensitivity of the slope of resistance vs. illuminance (gamma) and the spectral response are important for measurement of brightness with devices such as illumination and exposure meters. Therefore, understanding the various characteristics of CdS cell presented below is important for selecting the right CdS cell for your application.

MAXIMUM RATINGS

The maximum ratings given are absolute maximum ratings. This means that these are the values which are not to be exceeded even momentarily. Values above the maximum rating may break down the CdS cell and lower it's performance. Take adequate care in circuit design to avoid exceeding the maximum ratings.

Allowable Power Dissipation

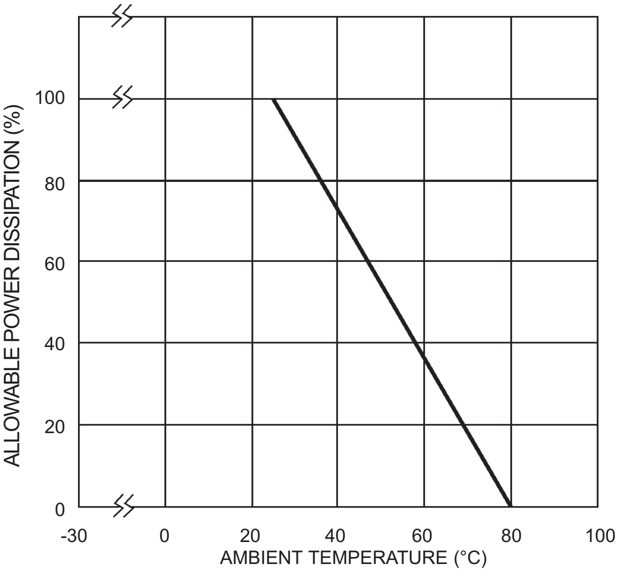
Allowable power dissipation is the limiting value of power consumption of a CdS cell when it is operated in a circuit. If a CdS cell is operated under conditions that cause the allowable power dissipation to be exceeded, deterioration of performance is hastened and the photoconductive surface can be damaged or broken down. This parameter must be held within the ratings in the same manner as are the applied voltage and ambient temperature. Allowable power dissipation applies to total illumination of the photoconductive surface of a CdS cell. When only part of the surface is used, the allowable power dissipation must be reduced in proportion to the illuminated surface area.

The allowable power dissipation figures in this catalog are for a temperature of 25°C. When these CdS cells are used at higher ambient temperature, the power consumption must be reduced, as the derating shown in **Figure 5**. This point must be taken into consideration as well.

Ambient Temperature Range

Unless otherwise specified, the maximum rated ambient temperature range is for CdS cell operation and storage. Operating or storing a CdS cell outside of this temperature range reduces its performance. Never keep or operate CdS cells at temperature exceeding the maximum rating. It is suggested to keep CdS cells at a normal room temperature and humidity before using them.

Figure 5: Allowable Power Dissipation vs. Ambient Temperature



Even within the ambient temperature range, the cell resistance, response, and other characteristics vary somewhat with the temperature, take this into consideration.

Applied Voltage

The maximum applied voltage is the voltage that can be applied between two terminals of a CdS cell. When the CdS cell resistance is at its maximum (the equilibrium dark resistance in total darkness), the voltage that can be applied between the CdS cell terminals is also at its maximum. Never let the applied voltage exceed the maximum rating. If the power consumption increases during CdS cell operation, the rating of allowable power dissipation should take precedence over the applied voltage rating.

SENSITIVITY

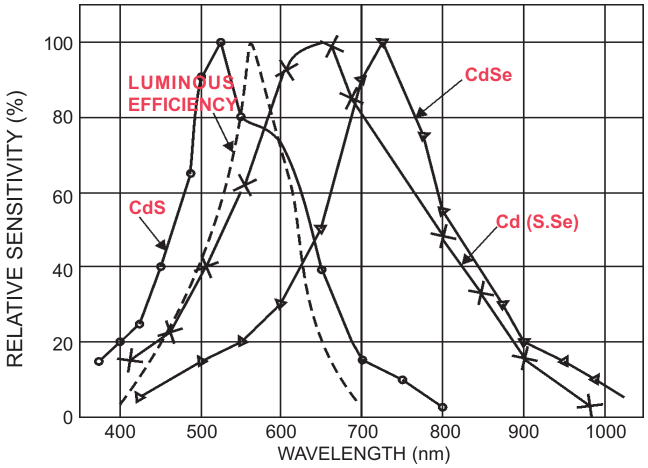
Spectral Response Characteristic

The relative sensitivity of a CdS cell is dependent on the wavelength of the incident light. The sensitivity as a function of wavelength is called the spectral response characteristic. Fundamentally, the maximum sensitivity wavelength (or peak wavelength) for CdS cell is 515nm. By controlling the composition ratio of CdS to CdSe, the maximum sensitivity can be optimized at a wavelength between 515 and 730nm. Photoconductive cells with spectral response close to that of the human eye are available.

Figure 6 shows these relationships. CdS, Cd (S.Se), and CdSe cells are often called “CdS cells”.

By using a CdS cell with a spectral response similar to the human eye, it can be widely and easily be used in applications as sensors substituting for the human eye.

Figure 6: Spectral Response of CdS Cells and Spectral Luminous Efficiency (Human Eye Response)



CdS: cadmium sulfide
Cd(S.Se): cadmium sulfo-selenium
CdSe: cadmium selenide

Expressing Sensitivity

The sensitivity of light sensors expresses the relation between the intensity of the light impinging on the sensitive surface and the resulting output signal. If voltage V is applied across a CdS cell and illuminance E (lux) is shown on it, and signal current IL flow, then:

$$I_L = K \bullet V^{\alpha} E^{\Upsilon}$$

Where K is a constant, α is the voltage index for signal current and can be treated as just about 1. Υ (gamma) is also called the illuminance index for signal current and shows the slope of the signal current vs. illuminance characteristic.

As the above equation shows, the sensitivity can be expressed as the value of the signal current with respect to the incident illuminance, but usually, rather than expressed in the signal current, the sensitivity is expressed in the cell resistance.

REFERENCE

Lux is unit of illuminance, equal to the illuminance on a surface 1 square meter in area on which there is a luminous flux of 1 lumen uniformly distributed. The illuminance is proportional to the square of the distance from the light source. The illuminance E (lux) at a distance D meters from a point light source of luminous intensity I (cd) is obtained from the equation:

$$E\ (\text{lux}) = \frac{I}{D^2}$$

This is based on the standard luminous efficiency, so these are light measurement units for the visible region only.

Table 1: Illuminance Conversion Table

Conversion value	Foot-cadle (Ft-C)	Lux	Photo
Foot-Cadle (Ft-C)	1	0.0929	929
Lux = $1m/m^2$	10.76	1	10.000
Photo	0.00108	0.0001	1

1 foot-0candle

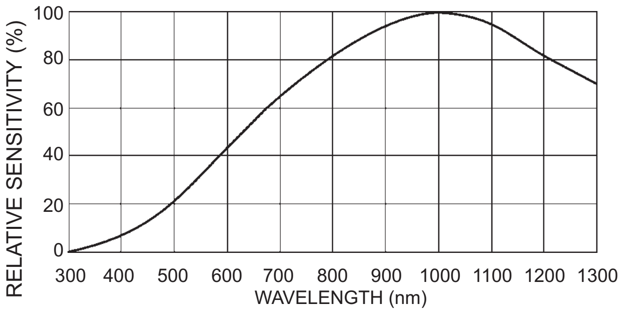
$$E = I/D^2 = 1cd/0.3048^2 = 10.764\ (\text{lux})$$

(1 foot = 0.3048 meter)

The lux is a light measurement unit based on the standard luminous efficiency. Light sensors with spectral response characteristics which are shifted from the standard luminous efficiency show different output signals if the radiant spectral distribution (color temperature) of the light source is different, even if the illuminance is the same. Therefore, when using light sources for light measurement, the radiant spectral distribution characteristic must be specified.

A tungsten lamp with a color temperature of 2856K is used as the standard light source. The color temperature of the tungsten lamp is expressed as the absolute temperature of a black body (a platinum black body furnace). This color temperature is approximately proportional in the visible region to the spectral radiant distribution of the lamp.

Figure 7: Spectral Energy Distribution for 2856K Black Body



ILLUMINANCE VS. RESISTANCE

Figure 8 gives a typical example of graphing the CdS cell resistance as a function of incident illuminance. The slope of this curve, Υ (gamma), varies with the cell type and is important for detecting analog-like light level differences. This is given by the tangent θ of a line connecting two points on the curve. If the illuminated resistances at illuminance Ea (lux) and Ed (lux) are Ra (Ω) and Rb (Ω), then Υ between a and b is expressed by the following equation:

$$\Upsilon^{a}_{b} = \tan\theta = \frac{\triangle I}{\triangle E} = \frac{\log Ia - \log Ib}{\log Ea - \log Eb} = \frac{\log(Ia/Ib)}{\log(Ea/Eb)}$$

(Ia. Ib...the signal current when the CdS is illuminated)

$$= \frac{\triangle R}{\triangle E} = \frac{\log Ra - \log Rb}{\log Ea - \log Eb} = \frac{\log(Ra/Rb)}{\log(Ea/Eb)}$$

Usually, Υ is expressed as $\Upsilon^{100}/_{10}$, the slope between the 100 lux and 10 lux. So the above equation becomes:

$$\Upsilon^{100}/_{10} = \frac{\log(Ra/Rb)}{\log(Ea/Eb)} = \frac{\log(R_{100}/R_{10})}{\log(100/10)} = \log(R_{100}/R_{10})$$

From this relationship, the conversion equation is obtained

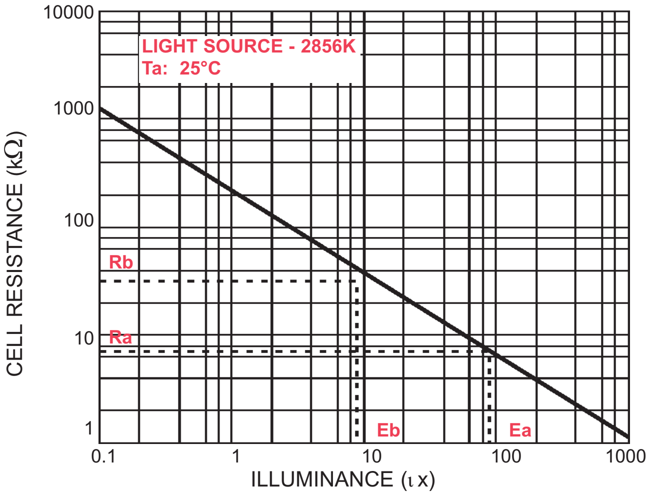
$$Ra = Rbx\ (Ea/Eb) - \Upsilon^{a}_{b}$$

If the slope Υ^{a}_{b} and the illuminated resistance Rb are known, the illuminated resistance for any point between Ea and Eb can be obtained. This relationship gives the equation:

$$Ea = Eb \text{ x } (Ra/Rb)\ 1/\Upsilon^{a}_{b}$$

Given the value of Υ^{a}_{b} and the illuminated resistance Rb at illuminance Eb, the illuminance Ea that will give a illuminated resistance of Ra can be obtained.

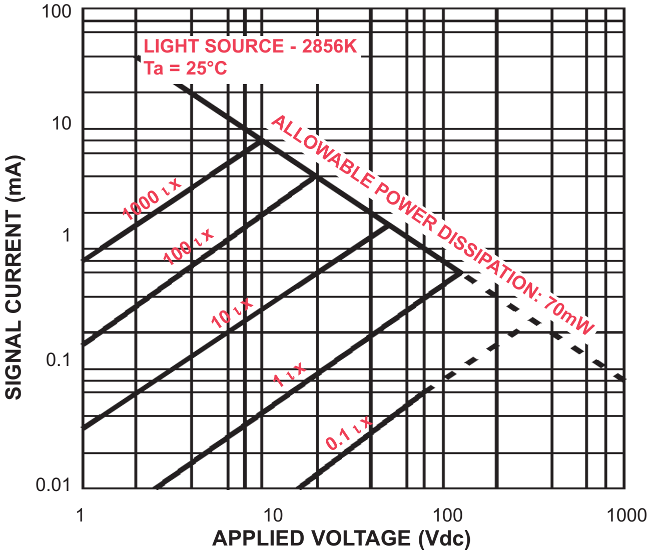
Figure 8: CdS Resistance vs. Illuminance Characteristic Example



SIGNAL CURRENT VS. APPLIED VOLTAGE

Figure 9 shows the signal current vs. applied voltage characteristic for different illuminance levels. This characteristic is nearly linear and holds for applied voltages down to 1V and consumption near the allowable power dissipation. The amount of heat generated by the CdS cell increases, causing a change in cell resistance. Linearity becomes lost, therefore take precautions in system designs.

Figure 9: Signal Current vs. Applied Voltage Characteristic Example



DARK RESISTANCE/DARK CURRENT

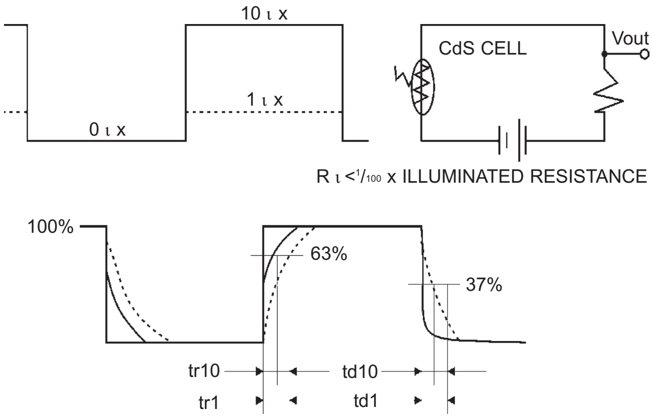
If a CdS cell is left in total darkness for 15 hours and the resistance is measured, the resistance value will be high. This is true dark resistance (equilibrium dark resistance). In practical applications, the CdS cell is used at various light levels. The previous light levels affect the dark resistance, which is called light history effect. Therefore, the dark resistance must be expressed specifying the time allowed after the incident light is removed. In this catalog, the dark resistance is measured 10 seconds after incident light of 10 lux has been cut off. This dark resistance measurement can also be viewed as expressing the response time (fall time) for CdS cells.

RESPONSE SPEED

CdS cells have a certain time delay in responding to incident light. This response speed is an important point in designing detection of rapidly changing light levels and on-off switches.

The response speed is usually expressed as the time required for the illuminated resistance to reach 63% of its saturation value after the cell is illuminated (rise time), and as the time required for the illuminated resistance to fall to 37% of its saturation value after the light is removed (fall time). The rise and fall times listed in this catalog are measured with repetitive intermittent light.

Figure 10: Rise Time and Fall Time



tr10, tr1: Rise Times at 10 ι x and 1 ι x
td10, t1: Fall Times at 10 ι x and 1 ι x

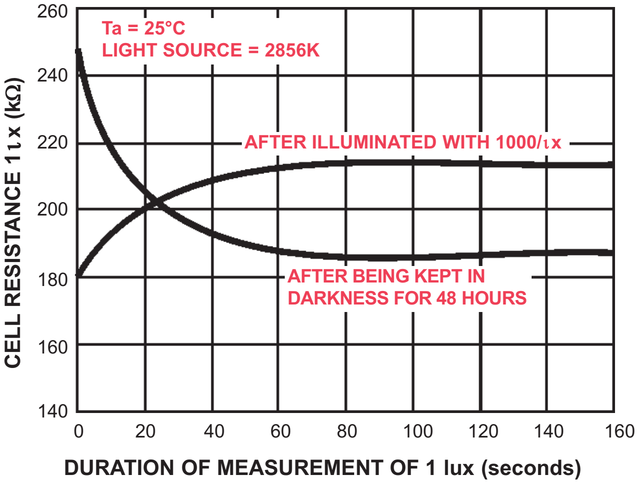
The response speed varies considerably with the light level, the light history condition, the lad resistance, the ambient temperature, and other factors. The higher the incident light level, the faster the response speed. Also, cells kept in darkness exhibit slower response than cells kept at a brighter light level. This effect becomes more distinct as the cell is kept for longer periods at a dark light level. Also, the apparent rise time becomes faster with a larger load resistance, but the fall time shows the contrary effect.

LIGHT HISTORY EFFECT

As described before, the illuminated resistance, dark resistance, and response speed vary with the conditions to which the CdS cell has previously been exposed. This is called the light history effect. In particular, if the CdS cell has been kept in darkness or brightness prior to measurement, this results in a difference in illuminated resistance (i.e. sensitivity). This difference is called the light history error. In general, when a cell is kept in darkness for a long time, its illuminated resistance will be lower compared to a cell kept at a light level. This light history error indicates the initial change in the illuminated resistance from the previous condition of the saturation (recovery) region. This is different from the change in resistance when the CdS cell is kept in operation with the saturated illuminated resistance or 'drift'.

Under the conditions given in **Figure 11**, some cells may show light history errors as large as 50%. This is often seen in CdSe cells with a maximum sensitivity wavelength at near 730nm.

Figure 11: Light History Effect Example

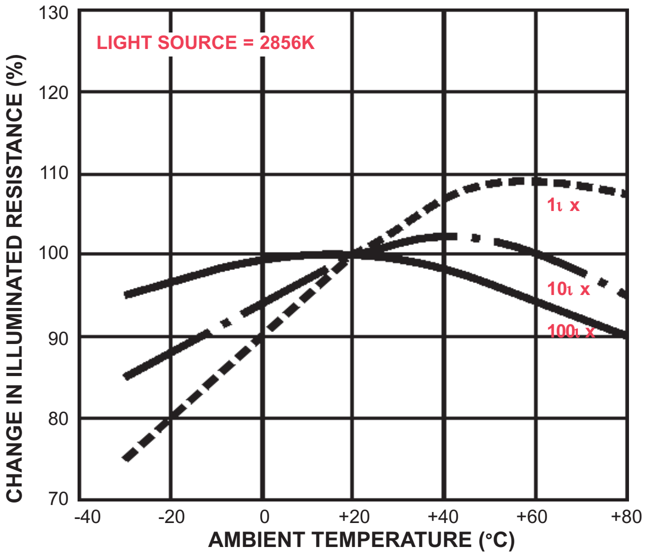


Because CdS cells have this light history effect, particularly when they are used at low illuminance levels (1 lux or less as a general guide), this phenomenon must be considered. In some cases, in order to reduce the light history effect, the CdS cell can be used after being exposed to light for several minutes. All the values listed in this catalog have been measured with the cell left exposed to 100 to 500 lux for 1 to 2 hours before measurement.

TEMPERATURE CHARACTERISTICS

The change in the cell resistance with ambient temperature depends on the light level. In general, the lower the illuminance, the greater the change in resistance with temperature change. Also, the slope of the temperature coefficient (positive or negative) depends on the composition and the fabrication method of the CdS cell.

Figure 12: Temperature Characteristic Examples



OPERATING LIFE

Figure 13 illustrates the change in illuminated resistance (at 10 lux) of CdS cells with operating time, showing slightly increasing curves. If used within the maximum ratings specified in this catalog, the CdS cell recovers from this time change and maintains stable values for quite a long period. Exceeding the maximum ratings can cause deterioration or damage. If this is kept in mind, the life of CdS cells can be expected to be quite long.

Figure 13: Change In Illuminated Resistance vs. Operating Time