Photoconductive Sensors

Fritz Schuermeyer, Thad Pickenpaugh

Published online on: 03 Feb 2014
43 Photoconductive Sensors

43.1 Introduction ................................................................. 43-1
43.2 Detector Performance Parameters ..................................... 43-3
  Responsivity • Noise • Detector Sensitivity
43.3 Preparation and Performance of Photoconductive Detectors ........... 43-5
  Cadmium Sulfide • Lead Sulfide • Lead Selenide • Indium Antimonide • Mercury Cadmium Telluride • Extrinsic
  Germanium and Silicon • Gallium Arsenide/Aluminum Gallium Arsenide QWIP
43.4 Instrumentation ............................................................... 43-8
References ............................................................................. 43-8

43.1 Introduction

Photoconduction has been observed, studied, and applied for more than 100 years. In the year 1873, W. Smith [1] noticed that the resistance of a selenium resistor depended on illumination by light. Since that time, photoconduction has been an important tool used to evaluate material properties, to study semiconductor device characteristics, and to convert optical into electric signals. The Radio Corporation of America (RCA) was a leader in the study and development of photoconductivity and of photoconductive devices. Richard H. Bube of RCA Laboratories wrote the classic book Photoconductivity in Solids [2] in 1960. Today, photoconducting devices are used to generate very fast electric pulses using laser pulses with subpicosecond rise and fall times [3]. For optoelectronic communications, photoconducting devices allow operation in the gigabit per second range.

Photoconductive devices normally have two terminals. Illumination of a photoconductive device changes its resistance. Conventional techniques are used to measure the resistance of the photoconductor. Frequently, small changes in conductivity need to be observed in the study of material or device characteristics. Also, in the measurement of light intensities of faint objects, one encounters small photoconductive signals.

Only solid photoconductors, such as Si, PbS, PbSe, and mercury–cadmium–telluride (HgCdTe), will be treated here. Photoconduction has been observed in amorphous, polycrystalline, and single-crystalline materials. During the last decade, major improvements in material growth have occurred that directly translate in better device performance such as sensitivity and stability. Growth techniques such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) allow the growth of single-crystal layers with an accuracy of the lattice constant. Artificially structured materials can be fabricated with these growth techniques for use in novel photoconducting devices.

Absorption of light in semiconductors can free charge carriers that contribute to the conduction process. Figure 43.1 presents the band diagram for a direct bandgap semiconductor where the excitation
processes are indicated. Excitation process (a) is a band-to-band transition. The photon energy for this excitation has to exceed the bandgap of the semiconductor. The absorption constant is larger for this process than for any of the other processes shown in this figure. Typical semiconductors used for electronic applications have bandgaps in excess of 1 eV, corresponding to light in the near-infrared (IR) region. Special semiconductors have been developed with narrower bandgaps to provide absorption in the mid- and long-wavelength IR regions. Indium antimonide (InSb) and HgCdTe semiconductors provide photosensitivity in the 4 and 10 μm wavelength range, respectively. The photogenerated carriers increase the electron and hole densities in the conduction and valence bands, respectively, which leads to an increase in conductivity [4]. For the simplified case with one type of carrier dominating, the conductivity $\sigma$ is given by

$$\sigma = ne\mu$$  \hspace{1cm} (43.1)

where
- $n$ is the density of free carriers
- $e$ is the charge
- $\mu$ is the mobility

Absorption of light results in a change in free-carrier density and a corresponding change in conductivity $\Delta\sigma$:

$$\Delta\sigma = \Delta ne\mu + \Delta\mu$$  \hspace{1cm} (43.2)

$\Delta\sigma$ is the definition for photoconductivity. In Equation 43.2, one assumes that due to the photon absorption, the density of carriers changes. Also, the mobility of the carriers changes due to the modified free-carrier density. The latter effect is very small except for special band transitions, as with InSb at very low temperatures.
Figure 43.1 indicates that other excitation processes exist. For example, bound electrons can be excited into the conduction band. This process can lead to persistent photoconductivity. In this example, the trapped holes have a long lifetime while the electrons move freely due to the applied electric field. Charge neutrality requires that the electrons collected at the anode be replenished by electrons supplied by the cathode. This effect leads to an amplification of the photogenerated charge (i.e., more than one electron is collected at the anode of the photoconducting device per absorbed photon). On the other hand, the storage times are long, in the millisecond range. Hence, photoconductive devices with large amplification factor have a slow signal response.

Small bandgap semiconductors, such as HgCdTe and InSb, are difficult to manufacture. Thus, artificially structured layers of commonly used materials are being developed to replace these. Spatial modulation of doping has been proposed by Esaki and Tsu [5] to achieve a lattice containing a superlattice of n-doped and undoped, and p-doped and undoped layers (n-I-p-I). Due to the energy configuration of this structure, the effective bandgap is less than that of the undoped material. The effective bandgap depends on the thickness of the layers and their doping concentrations. The quantum-well IR photodetector (QWIP) [6] is another approach to obtain photoconductivity in the far-IR wavelength range. In this structure, energy wells exist in the conduction band of the material heterostructure due to the energy band discontinuities. Subbands form in the superlattice and electrons in these wells are confined due to the heterobars. IR photons can excite electrons from their confined states to the continuum, which leads to an increase in conductivity.

While it is possible to use noncontact methods to measure the conductivity in a material, electric contacts are commonly placed onto the structure during the device fabrication process. Typically, ohmic contacts are formed to fabricate metal–semiconductor–metal (MSM) structures (Figure 43.2). These contacts control the Fermi level in the material structure and provide carriers to retain charge neutrality.

### 43.2 Detector Performance Parameters

#### 43.2.1 Responsivity

Variations in photon flux density incident on a photoconductor interact with the material to change the conductivity. These changes produce a signal voltage that is proportional to the input photon flux density. The detector area \( A \) collects flux contributing to the signal. \( J_s \) is the integrated power density over a spectral interval. Responsivity \( (R_v) \) is the ratio of the rms signal voltage (or current) to the rms signal power and is expressed in units of volts per watt. It is expressed as amps per watt for current responsivity:

\[
R_v = \frac{V_s}{AJ_s}
\]  

(43.3)

\( V_s \) is normally linear with photon flux for low levels but can saturate under high flux conditions. One should ensure operation in the linear range for radiometric and photometric instrumentation.

#### 43.2.2 Noise

The performance of a visible or IR instrument is ultimately limited when the signal-to-noise ratio equals one (SNR = 1). Noise from the instrument’s signal processing should be less than the noise from the detector in the ideal case. This means reducing this noise within the restrictions of signal processing design limitations. These may include cost, size, and input power. The detector noise should be minimized.

Johnson noise is the limiting noise in all conductors [7]. It is frequency independent and independent of the current going through the device. Johnson noise is defined in Equation 43.4, where \( k \) is the
FIGURE 43.2 (a) Absolute spectral response of photoconductive detectors with the operating temperatures in K in parentheses: CdS visible and Pb salt IR detectors; (b) Absolute spectral response of photoconductive detectors with the operating temperatures in K in parentheses: III–V and II–VI intrinsic photoconductors plus a III–V QWIP detector; (c) Absolute spectral response of photoconductive detectors with the operating temperatures in K in parentheses: long-wavelength extrinsic Ge and Si photoconductors.
Boltzmann constant ($1.38 \times 10^{-23}$ J/K), $T$ is the detector temperature (K), $R$ is the resistance (Ω), and $\Delta f$ is the amplifier bandwidth (Hz):

$$V_i = \sqrt{4kTR\Delta f} \quad (43.4)$$

Another type of noise known as $1/f$ noise ($V_i$) is present in all semiconductor detectors that carry current. The spectrum of this noise varies as $1/f^n$, with $n$ approximately 0.5 [8].

Noise due to fluctuation in generation and recombination of charge carriers [9] varies linearly with current. Noise may be caused by the random arrival of photons from the background (photon noise), fluctuation in the density of charge carriers caused by lattice vibration ($g-r$ noise), by interaction with traps, or between bands.

Excess noise from the amplifier or signal processing ($V_{\text{amp}}$) can also limit photoconductive detector performance.

These uncorrelated noises add in quadrature, giving the total noise ($V_N$):

$$V_N^2 = V_i^2 + V_{g-r}^2 + V_{\text{amp}}^2 \quad (43.5)$$

The total noise may be given in units of $V\sqrt{\text{Hz}}$. It may also be integrated over some frequency range to provide volts rms. Photoconductive detectors of en have a $g-r$ noise independent of frequency from dc to 100 kHz.

### 43.2.3 Detector Sensitivity

Minimum detectable signal power, that is, noise-equivalent power (NEP) is a convenient means to express detector sensitivity. NEP is expressed in units of watts or $W\sqrt{\text{Hz}}$:

$$\text{NEP} = \frac{V_N}{R_V} \quad (43.6)$$

The reciprocal of NEP, the detectivity $D$, is frequently used. In attempting to make possible comparison among detectors, detectivity can be normalized to an electronic bandwidth of 1 Hz and a detector area of 1 cm². $D$ yields the highly useful parameter specified for detectivity or $D^*$ (pronounced “dee-star”) [10]:

$$D^* = \frac{R_V}{V_N} \sqrt{(A\Delta f)} \quad (43.7)$$

The units of $D^*$ are cm·Hz$^{1/2}$/W, sometimes simplified to “Jones.”

Detectivity is based on evidence that noise varies as the square root of the electronic bandwidth and $D$ varies inversely as the square root of the detector area. $D$ is relationship may not hold closely over a wide range of device sizes and bandwidths. Comparison of device performance is most meaningful among devices having similar sizes and measured under similar conditions, including operating temperature, chopping frequency/scanning rate, and detector field of view.

### 43.3 Preparation and Performance of Photoconductive Detectors

#### 43.3.1 Cadmium Sulfide

CdS is normally prepared by vapor deposition or sintering a layer of high-purity CdS powder on a ceramic substrate [11]. It has the largest change in resistance with illumination of any photoconductor. The peak response of this intrinsic detector is at 0.5 μm. Its spectral response is similar to that of the human eye and operates without cooling.
43.3.2 Lead Sulfide

PbS was among the earliest IR detector material investigated. Cashman was one of the earliest researchers in the United States [12]. It is intrinsic detector material is prepared by deposition of polycrystalline thin films by vacuum sublimation or chemical deposition from a solution. The spectral response extends to approximately 3 μm. PbS operates over the temperature range from 77 K to room temperature. The frequency response slows considerably at the lowest temperatures. The spectral response extends to somewhat longer wavelengths with cooling.

43.3.3 Lead Selenide

PbSe is an intrinsic detector that operates over the temperature range from 77 K to room temperature. Its spectral response extends to longer wavelengths with cooling. Preparation of PbSe is by sublimation or chemical deposition. Noise in PbSe detectors follows a 1/f spectrum.

43.3.4 Indium Antimonide

InSb is prepared by melting together stoichiometric quantities of indium and antimony. It operates over the range from 77 K to room temperature. The higher performance and ease of operation with signal processing electronics lead photovoltaic InSb detectors to be much more widely used than photoconductive.

43.3.5 Mercury Cadmium Telluride

HgCdTe is a versatile intrinsic material for IR detectors. CdTe and HgTe are combined to form the alloy semiconductor Hg1-x·Cd1-xTe. For the alloy with x = 0.2, the bandgap is approximately 0.1 eV, providing a long-wavelength cutoff of 12.4 μm. HgCdTe was initially grown into bulk crystals by solid-state crystallization (also called quench and anneal). Currently, thin-film growth techniques of liquid-phase epitaxy (LPE), MOVCD, and MBE are preferred to obtain larger, more uniform wafers. By appropriately choosing the alloy composition, photoconductive HgCdTe detectors are possible over the 2–20 μm range. CdZnTe wafers permit lattice-matched surfaces for HgCdTe thin-film growth. Operating temperatures can range from 77 K to room temperature, with the lower temperatures necessary for the longer wavelength devices.

43.3.6 Extrinsic Germanium and Silicon

The photoresponse of an extrinsic detector occurs when a photon interacts with an impurity added to a host semiconductor material. With an intrinsic material, the photoresponse is from the interaction with the basic material.

For the extrinsic detector, incident photons may produce free electron-bound hole pairs or bound electron-free hole pairs. The extrinsic detector's spectral response is achieved using an impurity (or doping element). Intrinsic detection occurs with a detector having the necessary bandgap width for the desired spectral response.

Extrinsic detectors require lower temperatures than do intrinsic and QWIPs, but have the advantage of longer wavelength response.

Ge and Si are zone refined to achieve high purity by making multiple passes of a narrow molten zone from one end to the other of an ingot of the material. Unwanted impurities can be reduced to levels of 10²⁵–10³⁴/m³ [13]. Growth of single crystals is by the Czochralski approach of bringing an oriented seed crystal in contact with the melt and withdrawing it slowly while it is rotated or by applying the horizontal zone refining approach, whereby an oriented seed crystal is melted onto the end of a polycrystalline ingot. A molten zone is started at the meeting of the ingot and seed and moved slowly down the ingot, growing it into a single crystal. An inert atmosphere is required to prevent oxidation.
### TABLE 43.1  Photoconductive Detectors

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutoff Wavelength (μm)</th>
<th>Temperature (K)</th>
<th>Responsivity (V/W)</th>
<th>D (cm Hz$^{1/2}$/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>0.7</td>
<td>300</td>
<td>$1 \times 10^5$</td>
<td>$1 \times 10^{13}$</td>
</tr>
<tr>
<td>PbS</td>
<td>3</td>
<td>300</td>
<td>$5 \times 10^4$–$1 \times 10^5$</td>
<td>$1.5 \times 10^{11}$–$3.3 \times 10^{12}$</td>
</tr>
<tr>
<td>PbSe</td>
<td>5.8</td>
<td>77–300</td>
<td>$1 \times 10^5$–$1 \times 10^6$</td>
<td>$2 \times 10^{10}$–$7 \times 10^8$</td>
</tr>
<tr>
<td>InSb</td>
<td>7</td>
<td>300</td>
<td>5</td>
<td>$4 \times 10^8$</td>
</tr>
<tr>
<td>HgCdTe</td>
<td>5</td>
<td>150–220</td>
<td>$1 \times 10^2$–$2 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>Ge/Hg</td>
<td>12</td>
<td>65–100</td>
<td>$1 \times 10^2$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td>Ge/Cd</td>
<td>13</td>
<td>4–25</td>
<td>$8 \times 10^2$</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>Ge/Cu</td>
<td>24</td>
<td>20–30</td>
<td>$5 \times 10^2$</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>GaAs/AlGaAs (QWIP)</td>
<td>33</td>
<td>77</td>
<td>$5 \times 10^2$</td>
<td>$3 \times 10^{10}$</td>
</tr>
</tbody>
</table>


---

**FIGURE 43.3** Energy diagram for a MSM detector.

Hg, Cd, Cu, and Zn are impurities for doping Ge detectors; Ga and As are dopants for Si detectors. See Table 43.1 and Figure 43.3.

### 43.3.7 Gallium Arsenide/Aluminum Gallium Arsenide QWIP

QWIP technology uses a quantum-well structure to provide intraband (intersubband) transitions to achieve an effective long-wavelength response in a wide bandgap material. Quantum wells are used to provide states within the conduction or valence bands. Since $hν$ of the desired spectral region is less than the bandgap of the host material, the quantum wells must be doped. Quantum-well structures are designed to permit photoexcited carriers to depart the structure and be accumulated as signal (photocurrent). The QWIP detector is generally comparable to extrinsic photoconductive detectors [16,17], in that both have lower than desirable quantum efficiency. GaAs/AlGaAs QWIPs have the advantage of higher operating temperatures than extrinsic detectors.
43.4 Instrumentation

The Stanford Research Systems SR 570 low-noise current preamplifier can be used to amplify the current flowing through a photoconductive device. It is preamplifier can be programmed to apply a voltage to the terminals of the photoconducting device. Its output voltage is proportional to the device current. Frequently, the IR radiation or visible light is chopped and the ac component of the device current is detected using lock-in-amplifier techniques. This approach allows the study of very small changes in device conduction. The Stanford Research Systems SR 570 and the EG&G Instruments Model 651 are examples of a lock-in amplifier and a mechanical radiation/light chopper, respectively.

References