

University of Anbar  
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# فيزياء الحالة الصلبة Solid state Physics

المرحلة الرابعة  
الكورس الثاني

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## ➤ Semiconductors Crystals:

Semiconductors are generally classified by their electrical resistivity at room temperature, with values in the range of  $10^{-2}$  to  $10^9$  ohm-cm, and strongly dependent on temperature. At absolute zero a pure, perfect crystal of most semiconductor will be an insulator.

تصنف أشباه الموصلات بشكل عام من خلال مقاومتها الكهربائية في درجة حرارة الغرفة ، بقيم تتراوح في مدى  $10^{-2}$  الى  $10^9$  أوم- سنتيمتر ، وتعتمد بشدة على درجة الحرارة. عند الصفر المطلق ، للبلورة النقية والكاملة لمعظم أشباه الموصلات ستكون عازلاً

Devices based on semiconductors include transistors, switches, diodes, photovoltaic cells, detectors, and thermistors. These may be used as single circuit elements or as components of integrated circuits.

تشمل الأجهزة القائمة على أشباه الموصلات الترانزستورات والمفاتيح والثنائيات والخلايا الكهروضوئية والكاشفات والثرمستورات. يمكن استخدامها كعناصر دائرة مفردة أو كمكونات للدوائر المتكاملة

A highly purified semiconductor exhibits intrinsic conductivity, as distinguished from the impurity conductivity of less pure specimens. In the intrinsic temperature range the electrical properties of a semiconductor are not essentially modified by impurities in the crystal.

يظهر أشباه الموصلات عالية النقاء الموصلية الذاتية ، كما تتميز عن الموصلية النقية للعينات الأقل نقاء. في نطاق درجة الحرارة الجوهرية ، يتم تعديل الخصائص الكهربائية لأشباه الموصلات بشكل أساسي عن طريق الشوائب في البلورة.

The conduction band is empty at absolute zero and is separated by an energy gap  $E_g$  from the filled valence band.

يكون نطاق التوصيل فارغاً عند الصفر المطلق ويفصل بفجوة الطاقة عن نطاق التكافؤ الممتلئ.

The **energy gap** is the difference in energy between the lowest point of the **conduction band** and the highest point of the **valence band**.

The lowest point in the conduction band is called the **conduction band edge**; the highest point in the valence band is called the **valence band edge**.

فجوة الطاقة هي الفرق في الطاقة بين أدنى نقطة في حزمة التوصيل وأعلى نقطة في حزمة التكافؤ. تسمى أقل نقطة في حزمة التوصيل حافة حزمة التوصيل و أعلى نقطة في حزمة التكافؤ تسمى حافة حزمة التكافؤ.

As the temperature is increased, electrons are thermally excited from the valence band to the conduction band. Both the electrons in the conduction band and the unoccupied orbitals or holes left behind in the valence band contribute to the electrical conductivity.

بزيادة درجة الحرارة ، يتم تحفيز الإلكترونات حراريًا من نطاق التكافؤ إلى نطاق التوصيل. تساهم الإلكترونات الموجودة في نطاق التوصيل والمدارات أو الثقوب الشاغرة التي تُركت في نطاق التكافؤ في التوصيل الكهربائي.

### ➤ Band gap:

The intrinsic conductivity and intrinsic carrier concentrations are largely controlled by  $E_g/k_B T$ , the ratio of the band gap to the temperature. When this ratio is large, the concentration of intrinsic carriers will be low, and the conductivity will be low.

يتم التحكم في الموصلية الجوهرية وتراكيز الحاملات الجوهرية إلى حد كبير من خلال نسبة فجوة النطاق إلى درجة الحرارة. عندما تكون هذه النسبة كبيرة ، سيكون تركيز الناقلات الجوهرية منخفضًا ، وستكون الموصلية منخفضة.

Band gaps of representative semiconductors are given in Table 1. The best values of the band gap are obtained by optical absorption.

Crystal	Gap	$E_g$ , eV		Crystal	Gap	$E_g$ , eV	
		0 K	300 K			0 K	300 K
Diamond	<i>i</i>	5.4		SiC(hex)	<i>i</i>	3.0	—
Si	<i>i</i>	1.17	1.11	Tc	<i>d</i>	0.33	—
Ge	<i>i</i>	0.744	0.66	HgTe <sup>a</sup>	<i>d</i>	−0.30	
αSn	<i>d</i>	0.00	0.00	PbS	<i>d</i>	0.286	0.34–0.37
InSb	<i>d</i>	0.23	0.17	PbSe	<i>i</i>	0.165	0.27
InAs	<i>d</i>	0.43	0.36	PbTe	<i>i</i>	0.190	0.29
InP	<i>d</i>	1.42	1.27	CdS	<i>d</i>	2.582	2.42
GaP	<i>i</i>	2.32	2.25	CdSe	<i>d</i>	1.840	1.74
GaAs	<i>d</i>	1.52	1.43	CdTe	<i>d</i>	1.607	1.44
GaSb	<i>d</i>	0.81	0.68	SnTe	<i>d</i>	0.3	0.18
AlSb	<i>i</i>	1.65	1.6	Cu <sub>2</sub> O	<i>d</i>	2.172	—

In a **direct absorption process** the threshold of continuous optical absorption at frequency  $\omega_g$  measures the band gap  $E_g = \hbar\omega_g$  as shown in Figs. 1a and 2a. A photon is absorbed by the crystal with the creation of an electron and a hole.

In the **indirect absorption process** in Figs. 1b and 2b the minimum energy gap of the band structure involves electrons and holes separated by a substantial wavevector  $k_c$ . Here a direct photon transition at the energy of the minimum gap cannot satisfy the requirement of conservation of wavevector, because photon wavevectors are negligible at the energy range of interest. But if a phonon of wavevector  $K$  and frequency  $\Omega$  is created in the process, then we can have

$$k(\text{photon}) = k_c + K = 0 ; \hbar\omega = E_g + \hbar\Omega$$

The phonon energy  $\hbar\Omega$  will generally be much less than  $E_g$

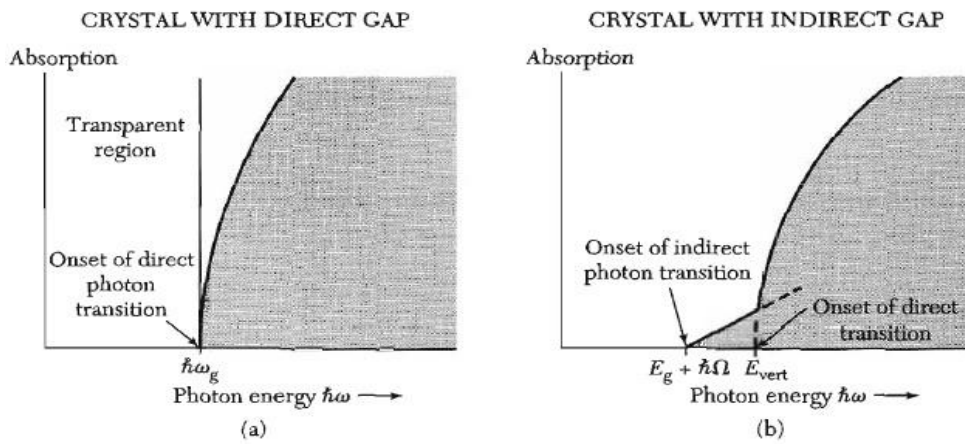


Figure 1

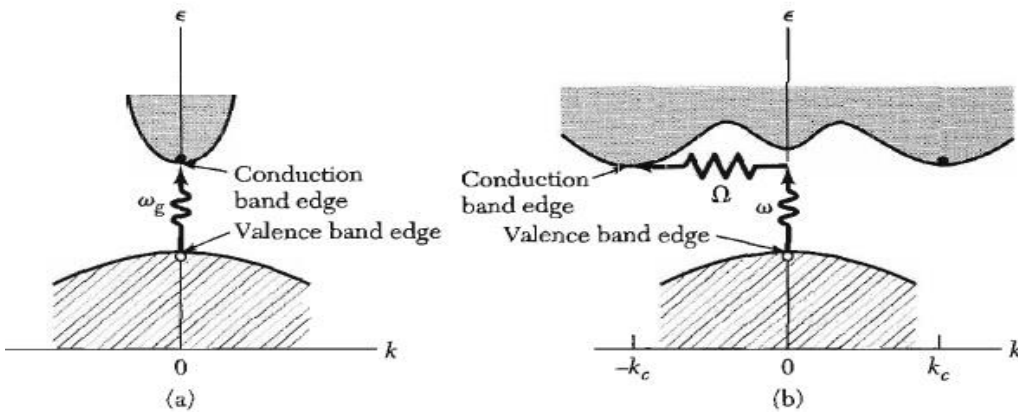


Figure 2

## ➤ Intrinsic Semiconductors

A highly purified semiconductor exhibits intrinsic conductivity, as distinguished from the impurity conductivity of less pure specimens.

Intrinsic semiconducting behaviour occurs in an insulating solid when  $k_0T$  is large enough to permit some thermal excitation of electrons from the upper part of an otherwise filled band to the lower portion of the next higher (normally empty) band.

The number of conduction band electrons and valence band holes as follows:

$n_0$  = density of conduction band electrons for a situation of thermodynamic equilibrium.

$n$  = total density of conduction band electrons (not necessarily at equilibrium).

$n_e = (n - n_0)$  = excess electron density in the conduction band caused by a departure from equilibrium.

$p_0$  = density of valence band holes in thermodynamic equilibrium,

$p$  = total density of valence band holes.

$p_e = (p - p_0)$  = excess free hole density caused by a departure from equilibrium

If a semiconductor is completely pure and crystallographically perfect, the densities  $n_0$  and  $p_0$  must be equal, for conduction band electrons can then be derived only by excitation of valence band states.

$n_i$  is the intrinsic electron-hole density. A single Fermi level characterizes the energy distribution of both the free holes and the free electrons, and this intrinsic Fermi level is close to the center of the intrinsic gap,

we must review the relationship between electron density and Fermi energy for a single band.

The semiconductors are defined as insulators with small forbidden gaps. At finite temperature some electrons are excited from the lower valence band to the upper, conduction one. So there are holes in the valence band and the electrons in the conduction one. Such semiconductor is called intrinsic.

For electron

Number of electrons  $n = \int_{E_c}^{\infty} f(E) \cdot g(E) dE$

$$n = \int_{E_c}^{\infty} \frac{1}{2\pi^2} \left( \frac{2m_e^*}{\hbar^2} \right)^{3/2} (E - E_g)^{1/2} \cdot \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \cdot dE$$

$$n = 2 \left\{ \frac{2\pi m_e^* kT}{\hbar^2} \right\}^{3/2} e^{\frac{E_F - E_c}{kT}}$$

$$N_c = 2 \left\{ \frac{2\pi m_e^* kT}{\hbar^2} \right\}^{3/2}$$

Effective density of conduction band states

$$n = N_c e^{\frac{E_F - E_c}{kT}}$$

For hole

$$N_v = 2 \left\{ \frac{2\pi m_h^* kT}{\hbar^2} \right\}^{3/2}$$

Effective density of valence band states

$$P = N_v e^{\frac{E_v - E_F}{kT}}$$

Normally electron excited from valence band leave hole.

In equilibrium  $n = P$  i.e. number of holes = number of electrons.

$$n_i = \sqrt{np} \quad \text{effective mass law}$$

$$n_i = (N_c N_v)^{1/2} e^{\frac{E_v - E_c}{2kT}} = (N_c N_v)^{1/2} e^{-\frac{E_g}{2kT}}$$

$$n_i = 2 \left( \frac{kT 2\pi}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-\frac{E_g}{2kT}}$$

➤ **Variation of energy gap with temperature**

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

➤ **Conductivity**

$$\sigma = n_i e \mu = n_i e (\mu_h + \mu_e)$$

Intrinsic material has limited application carefully chosen impurity alter electrical properties since conductivity in intrinsic

$$\sigma = n_i e \mu$$

➤ **The Holes:**

The properties of vacant orbitals in an otherwise filled band are important in semiconductor physics and in solid state electronics. Vacant orbitals in a band are commonly called holes, and without holes there would be no transistors.

A hole acts in applied electric and magnetic fields as if it has a positive charge +e. The reason is given in five steps that follow.

$$1. \quad k_h = -k_e$$

The total wavevector of the electrons in a filled band is zero:  $\sum k = 0$ , where the sum is over all states in a Brillouin zone. This result follows from the geometrical symmetry of the Brillouin zone: every fundamental lattice type has symmetry under the inversion operation  $r \rightarrow -r$  about any lattice point; it follows that the Brillouin zone of the lattice also has inversion symmetry. If the band is filled all pairs of orbitals  $k$  and  $-k$  are filled, and the total wavevector is zero.

If an electron is missing from an orbital of wavevector  $k_e$ , the total wavevector of the system is  $-k_e$  and is attributed to the hole. This result is surprising: the electron is missing from  $k_e$ , and the position of the hole is usually indicated graphically as situated at  $k_e$ , as in Fig. 3. But the true wavevector  $k_h$  of the hole is  $-k_e$ , which is the wavevector of the point G if the hole is at E. The wavevector  $-k_e$  enters selection rules for photon absorption.

The hole is an alternate description of a band with one missing electron, and we either say that the hole has wavevector  $k_e$  or that the band with one missing electron has total wavevector  $-k_e$ .

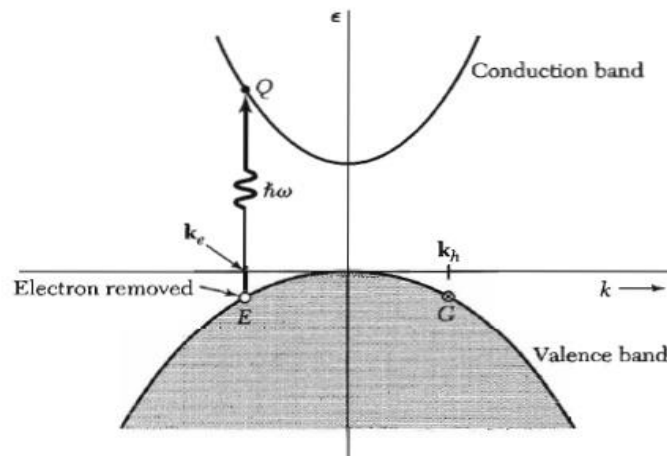


Figure 3

$$2- \quad \epsilon_h(k_h) = -\epsilon_e(k_e)$$

Here the zero of energy of the valence band is at the top of the band. The lower in the band the missing electron lies, the higher the energy of the system.

The energy of the hole is opposite in sign to the energy of the missing electron, because it takes more work to remove an electron from a low orbital than from a high orbital. Thus if the band is symmetric,

$$\epsilon_e(k_e) = \epsilon_e(-k_e) = -\epsilon_h(k_e) = -\epsilon_h(k_h).$$

We construct a band scheme to represent the properties of a hole. This hole band is a helpful representation because it appears right side up.



3-  $v_h = v_e$

The velocity of the hole is equal to the velocity of the missing electron. From Fig. 4 we see that  $\nabla \epsilon_h(k_h) = \nabla \epsilon_e(k_e)$ , so that  $v_h(k_h) = v_e(k_e)$

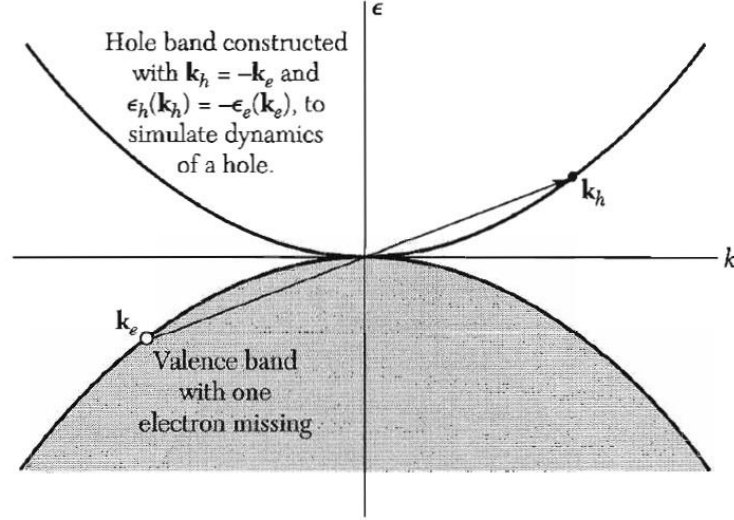


Figure 4

4-  $m_h = -m_e$

We show below that the effective mass is inversely proportional to the curvature  $d^2 \epsilon / dk^2$  and , for the hole band this has the opposite sign to that for an electron in the valence band. Near the top of the valence band  $m_e$  is negative, so that  $m_h$  is positive.

5-  $\hbar \frac{dk_h}{dt} = e(E + \frac{1}{c} v_h \times B)$

This comes from the equation of motion

$$\hbar \frac{dk_e}{dt} = e(E + \frac{1}{c} v_e \times B)$$

that applies to the missing electron when we substitute  $-k_h$  for  $k_e$  and  $v_h$  for  $v_e$ . The equation of motion for a hole is that of a particle of positive charge  $e$ . The positive charge is consistent with the electric current carried by the valence band, the current is carried by the unpaired electron in the orbital G:

$$j = (-e)v(G) = (-e)[-v(E)] = ev(E)$$

which is just the current of a positive charge moving with the velocity ascribed to the missing electron at E. The current is shown in Fig. 5

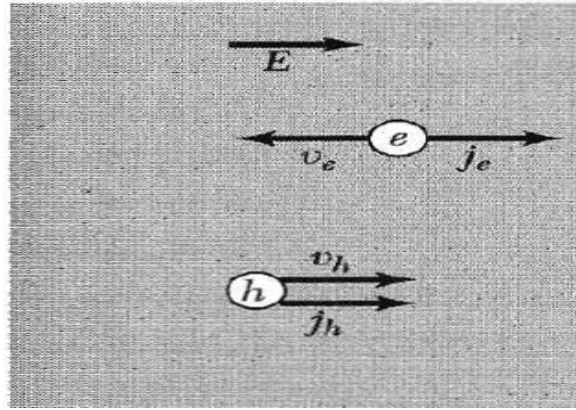


Figure 5

### ➤ Extrinsic Semiconductors

An addition of impurities to a semiconductor is called doping. Certain type of impurities and imperfection affect the electric properties of a semiconductor. Addition of 1B atom to  $10^5$  Si atoms increases the conductivity of pure Si by a factor of  $10^3$  at room temperature.

### ➤ Doped semiconductor

The semiconductors are defined as insulators with small forbidden gaps. At finite temperature some electrons are excited from the lower valence band to the upper, conduction one. So there are holes in the valence band and the electrons in the conduction one. Such semiconductor is called intrinsic. The modern way to produce materials for electronics is to “dope” semiconductor material with impurity atoms which introduce carriers in a controllable way.

The impurity level is usually situated in the forbidden gap. If the impurity level is situated near the bottom of conduction band the atom are ionized at low enough temperatures and provide extra electrons to

the band (such impurities are called donors). Contrary, if the levels are near the top of the valence band, they take electrons from the band producing holes (they are called acceptors). We will come back to this classification later to describe special features of different materials.

Adding small percentage of atom of other materials group, we can control electrical properties.

- impurity atom should fit in crystal without crystal distortion.
- Doped atom produces electronic state  $E_D$  or  $E_A$ .

### ➤ Impurity n- type (donor atoms)

Donor atom has one electron extra.

$$n_n = \frac{1}{\sqrt{2}} \{N_D N_C\}^{1/2} e^{-\frac{E_d}{2kT}} \quad \text{if} \quad N_D \gg \frac{1}{2} N_C e^{-\frac{E_d}{kT}}$$

$$\text{Or } n_n = N_D \quad \text{if} \quad N_D \ll \frac{1}{2} N_C e^{-\frac{E_d}{kT}}$$

- impurity states spreading band width increase as impurity density increase i.e. gap between  $E_d$ ,  $E_C$  decrease as impurity increase.
- Electron density = donor atom density. These electrons appear in conduction band and no corresponding hole in valence band.

### ➤ Impurity p- type (acceptor atoms)

Acceptor atom needs one electron

$$P_P = \frac{1}{\sqrt{2}} \{N_V N_A\}^{1/2} e^{-\frac{E_A}{2kT}} \quad \text{if} \quad N_A \gg \frac{1}{2} N_V e^{-\frac{E_A}{kT}}$$

$$\text{Or } P_P = N_A \quad \text{if} \quad N_A \ll \frac{1}{2} N_V e^{-\frac{E_A}{kT}}$$

- Energy transfer small from valence band, i.e. hole generated in valence band.

- Hole density = acceptor atom density.
- Hole appears in valence band and no corresponding electron in conduction band.

### ➤ **Optical properties for semiconductor**

1) Fundamental absorption process.

2) Absorption by impurities

#### **1) Fundamental absorption process**

Transition of electron from valence band to conduction band, have two conditions i) energy conserve. ii) Momentum conserves.

Dependent on momentum conserve divided fundamental absorption process into a) direct fundamental absorption process and b) indirect fundamental absorption process.

##### **(a) Direct fundamental absorption process**

Divided direct fundamental absorption process into allow direct fundamental absorption process and forbidden direct fundamental absorption process. The difference between them the wave function for electron in conduction band the same as in the valence band for allow direct fundamental absorption process, but the wave function for electron in conduction band different from the wave function in the valence band for forbidden direct fundamental absorption process. Give the absorption coefficient by the relation:

$$\alpha_d = A(h\nu - E_g)^{1/2} \quad \text{Allow direct fundamental absorption process}$$

When  $h\nu \succ E_g$

$$\alpha_d = 0 \quad \text{if} \quad h\nu \prec E_g$$

$$\alpha_d = B(h\nu - E_g)^{3/2} \quad \text{Forbidden direct fundamental absorption}$$

process In this process generation electron – hole couple lead to change the conductivity.

**(b) Indirect fundamental absorption process.**

In this transition the momentum is none conserved so that addition phonon.

$$\alpha_i = \alpha_e + \alpha_a$$

$$\alpha_i = \alpha_e \quad \text{Emission phonon}$$

$$\alpha_i = \alpha_a \quad \text{Absorption phonon}$$

**2) Absorption by impurities**

This process take place when the incident wavelength has energy less than energy gap for semiconductor, with condition as below

$$\text{i) } h\nu \succ E_d \quad \text{or} \quad E_A$$

ii) deionization of impurities

$$\alpha_{imp} = N_t \delta$$

➤ **Photoconductivity**

The phenomenon of photoconductivity occurs when an incident light beam impinges upon a semiconductor and causes an increase in its electrical conductivity. This is due to the excitation of electrons across the energy gap, which leads in turn to an increase in the number of free carriers-both electrons and holes-and hence to an increase in conductivity. Excitation can occur only  $\hbar\omega > E_g$ .

photoconductivity is very important, as it is this mechanism which underlies infrared solid-state detectors.

Before the light beam is tuned on, the conductivity is given by

$$\sigma_o = e(n_o\mu_e + p_o\mu_h)$$

Where  $n_o$  and  $p_o$  are the concentrations at equilibrium, and  $\sigma_o$  is the conductivity in the dark.

When the light is incident, as shown in figure 6, the concentrations of the free carriers increase by the amounts  $\Delta n$  and  $\Delta p$ , and the current

increases suddenly. Since electrons and holes are always created in pairs, therefore,  $\Delta n = \Delta p$ . the conductivity is now

$$\sigma = \sigma_o + e\Delta n(\mu_o + \mu_h)$$

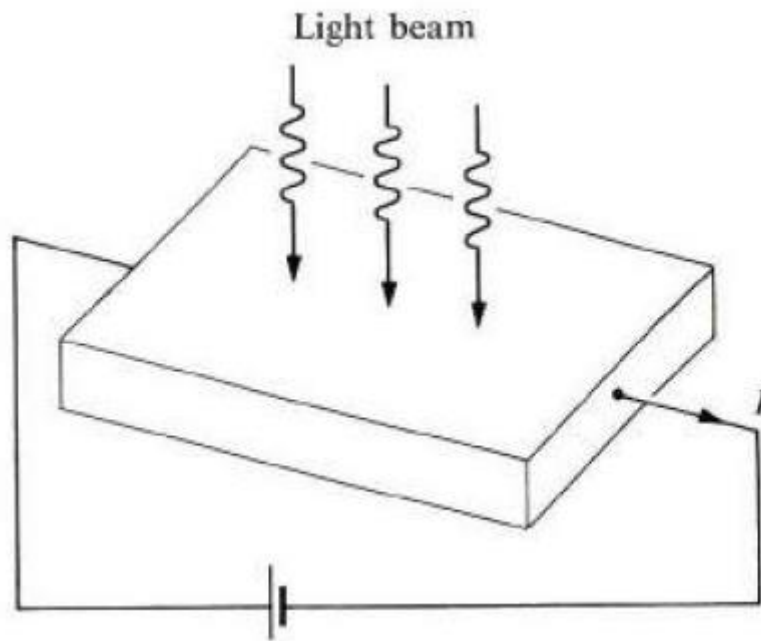


Figure 6 the basic experimental setup for photoconductivity.