Physics of Sensors

5

5.1 Thermocouple

The temperature sensing in embedded systems is achieved by a device called thermocouple. The basic thermocouple structure consists of a junction of two metals with different work functions, Ψ_1 and Ψ_2, as shown in Fig. 5.1. Work function is an energy level between the conduction band of the metal and the vacuum level and changes with temperature. When two metals are welded together, electrons from the metal with lower work function transfer to the metal with the higher work function due to the difference in the conduction band energy levels as shown in Fig. 5.2. When the equilibrium is reached, temperature variations will change the amplitude of the work function difference, $(\Psi_1 - \Psi_2)$, and cause galvanometric voltage drop between the two metals as shown in Fig. 5.3.

The work function difference is recorded as a function of temperature for the two metals used in the thermocouple. Therefore, when a certain voltage is read between the two thermocouple terminals, the corresponding reading identifies the ambient temperature.
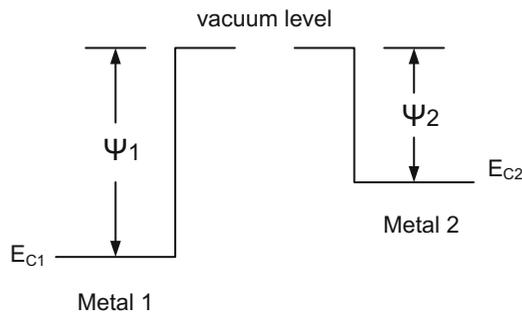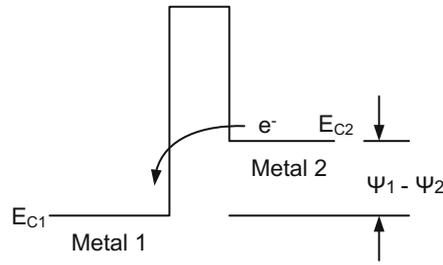

Fig. 5.1 Metal work functions to create a thermocouple

Fig. 5.2 Transfer of electrons due to the conduction energy difference between metals
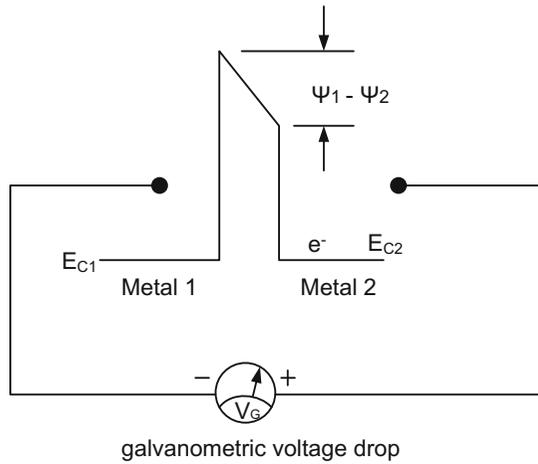

galvanometric voltage drop

Fig. 5.3 Galvanometric voltage drop after equilibrium is reached

The equivalent circuit of the thermocouple is indicated in Fig. 5.4 where the equivalent resistance is in milliohms. $V_G(T)$ corresponds to the difference in work functions as a function of temperature and it is usually in millivolts range.
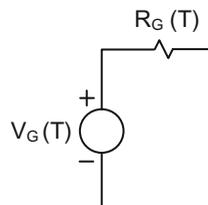

Fig. 5.4 Equivalent circuit of the thermocouple

5.2 Photodiode

Photodiode is a two-terminal semiconductor device composed of N and P-type semiconductors much like a rectifying diode as shown in Fig. 5.5. Once a junction is formed, electrons flow from the N-type to the P-type semiconductor until the Fermi levels (E_F) of both sides become equal. This makes the valance (E_V) and conduction bands (E_C) bend across the junction to form a basic diode as shown in Fig. 5.6.
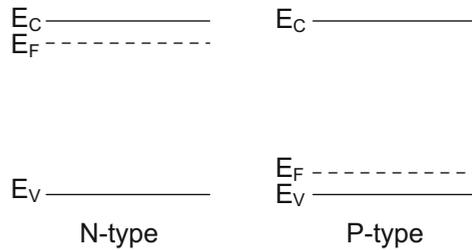
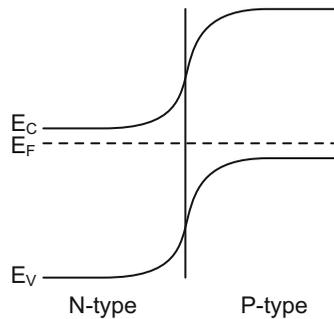**Fig. 5.5** N and P-type semiconductors

Fig. 5.6 N and P-type semiconductors after forming the PN junction

This device is designed to operate with a reverse bias voltage applied across its terminals as shown in Fig. 5.7, and it produces a short circuit current, I_{SC}, composed of dark current, I_{DARK}, and photon-generated current, I_{PH}. The basic biasing and operation of the device are shown in Fig. 5.8. When the junction is reverse-biased with a voltage equal to V, the Fermi level on the P-side of the junction raises by an amount qV. This causes thermally generated minority carriers (holes in N-type semiconductor and electrons in P-type semiconductor) to be pushed towards the junction and combine there. The overall process forms a reverse saturation current across the junction. With the increase in temperature more electron-hole pairs are created, increasing the reverse saturation current. The same effect can occur by illuminating the junction with a light source. When light energy is exposed to the PN junction, more electrons in the valance band make the transition to the conduction band in

proportion to the light intensity, increasing the level of reverse saturation current as shown in Fig. 5.9. The dark current is essentially the reverse saturation current when no light is present, and equivalent to the minority carrier conduction when only thermal effects are present.
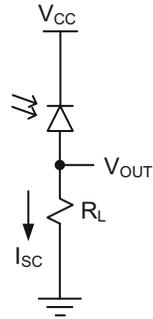

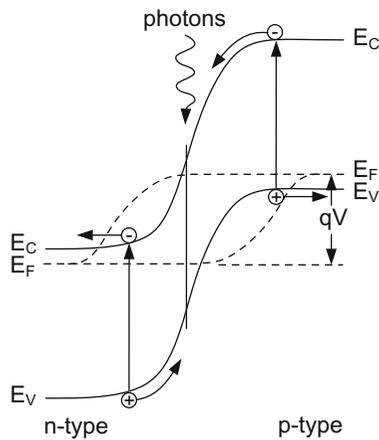**Fig. 5.7** Photodiode biasing circuit

Fig. 5.8 N and P-type semiconductors after reverse bias is applied to the PN junction
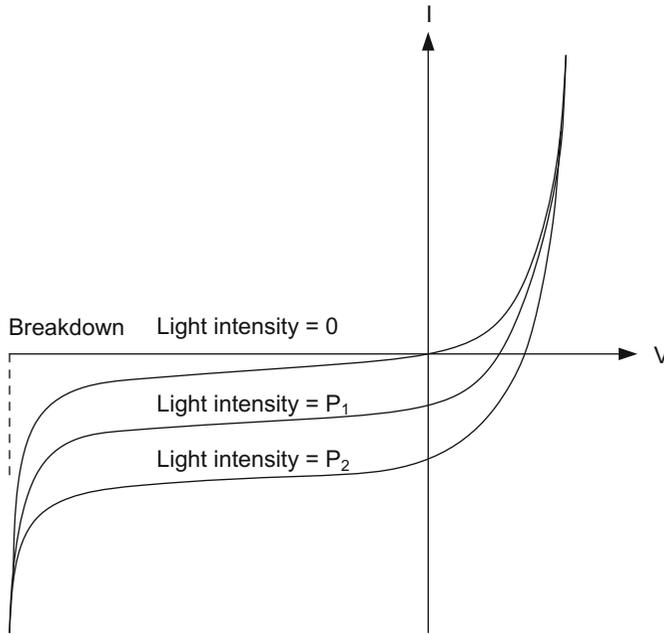
Fig. 5.9 Photodiode I-V characteristics as a function of light intensity

5.3 Solar Cell

Solar cell is not considered a sensor but it is another optical device that may be useful in an embedded system. The device requires no external voltage source and essentially a PN junction diode as shown in Fig. 5.6.

When the PN junction is illuminated with a light beam, electrons in the valance band transition to the conduction band and leave holes behind as shown in Fig. 5.10. The majority carriers (electrons in the N-type semiconductor and the holes in P-type semiconductor) have a very brief lifetime and recombine. The minority carriers, however, have a lot longer lifetime which enables them to move towards the junction because of the energy band bending in the band structure. When they arrive at the junction, they recombine. This process gives rise to a light-generated current and production of photovoltaic voltage as shown in Fig. 5.11.
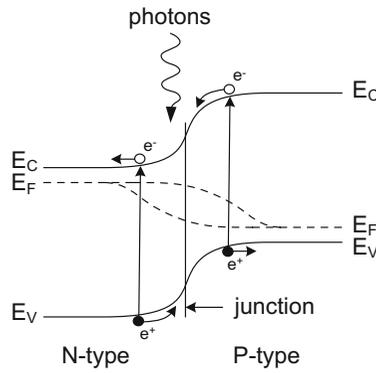
Fig. 5.10 Light illumination at the PN junction and the resulting electron-hole pairs
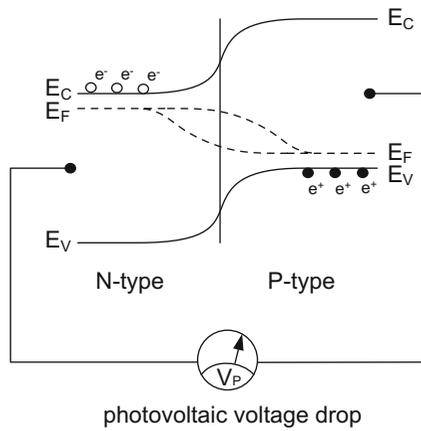

Fig. 5.11 Photovoltaic voltage drop between P and N regions as a result of light illumination

The resulting equivalent circuit of a photodiode exhibits constant current source characteristics, I_P, in proportion to the light intensity, and a large parallel resistance, R_P, as shown in Fig. 5.12.
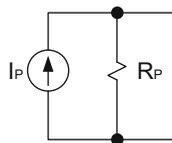

Fig. 5.12 Equivalent circuit of solar cell

5.4 Photo-resistor

Detection of light can also be achieved using a photo-resistor as shown in Fig. 5.13. In normal conditions where light is not present, the photo-resistor slab shows low conductivity due to the lack of surface electrons.
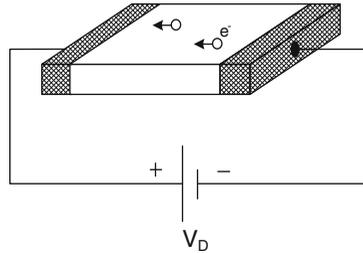

Fig. 5.13 Photo-detector made out of a photo-resistor

When a beam of light is exposed on a photo-resistive material shown in Fig. 5.14, photons are absorbed by the material, and electron-hole pairs are generated. Surface electrons (minority carriers) increase the conductivity of the material between the two terminals of the device, giving rise to a photonic drift current.
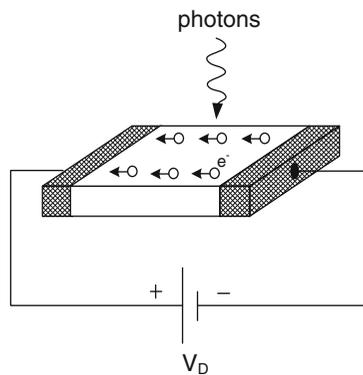

Fig. 5.14 Photo-resistor under light produces more surface electrons

5.5 Piezoelectric Materials and Accelerometers

Accelerometers measure mass movement in specific directions. Figure 5.15 describes the use of piezoelectric resistor to measure the mass movement. If one end of the piezoelectric material is kept fixed while the other end is attached to a moving mass which moves freely, the tensile stress will bend the material and induce a change in conductivity. When the difference in conductivity is measured, the applied stress and the amount of mass movement can be correlated and quantified.
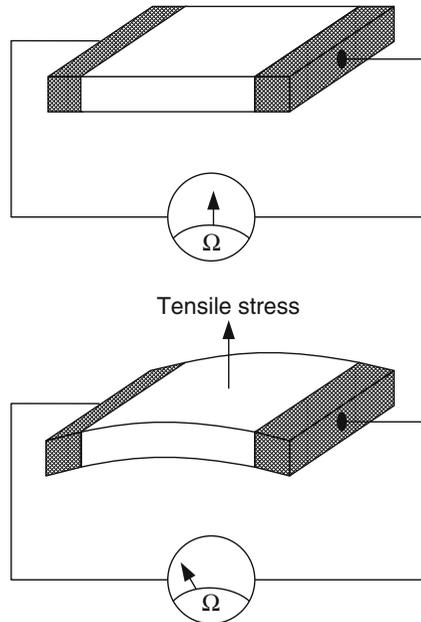
Fig. 5.15 Piezoelectric-resistor under no tensile stress (*top*) and under stress (*bottom*)

Figure 5.16 shows the true structure of the piezoelectric resistor where the piezoelectric bridges in serpentine form are laid on a fixed and floating semiconductor slabs. As the sensitive axis moves because of the movement in semiconductor slab, the change in the piezoelectric bridge conductivity is recorded as shown in the figure. Since this measurement is directly proportional to the motion of the slab, it produces how much and how fast the slab moves along the sensitive axis.

The same structure in Fig. 5.16 can be laid out to measure the movement in three different axes and provide valuable information for systems detecting the stability of a structure.
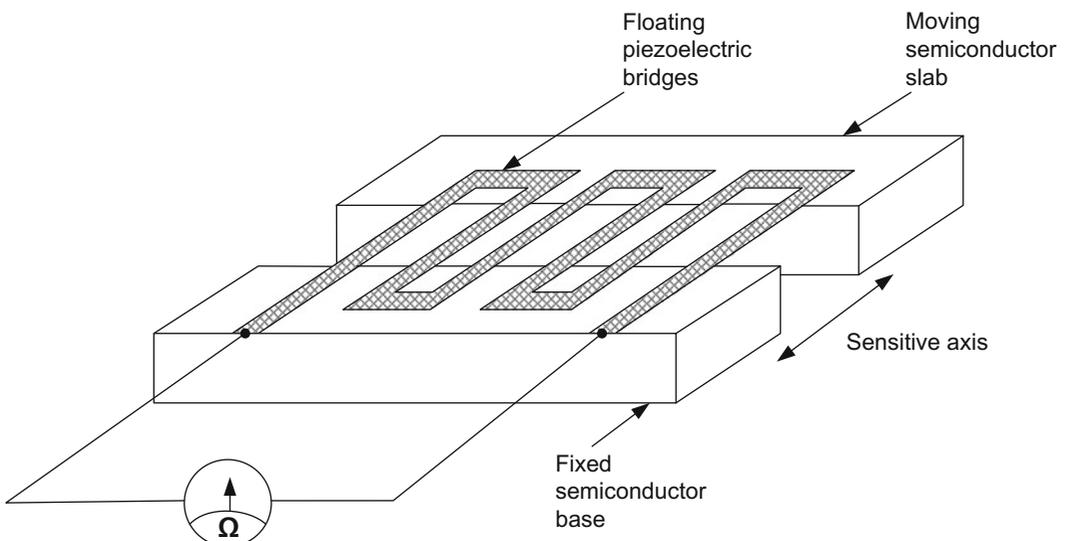

Fig. 5.16 Piezoelectric-resistor on moving semiconductor slab under stress

Accelerometers can also be based on differential capacitance measurements. Such an accelerometer is shown by the top figure in Fig. 5.17. This time the moving mass floats between two fixed plates as shown in the figure, and allowed to move in one direction. As the slab movement takes place, the gap between the first pair of plates decreases in relation to the other. Since capacitance is inversely proportional to the distance between the plates, the change in capacitance produces how much and how fast the floating mass moves. Here, d_1 and d_2 correspond to the distance between the first and second parallel plates. A is the area of each plate, and ε is the dielectric constant.

To increase the accuracy of the slab's movement further, the capacitance values, C_1 and C_2, are measured and amplified simultaneously by a differential amplifier as shown by the bottom figure in Fig. 5.17.
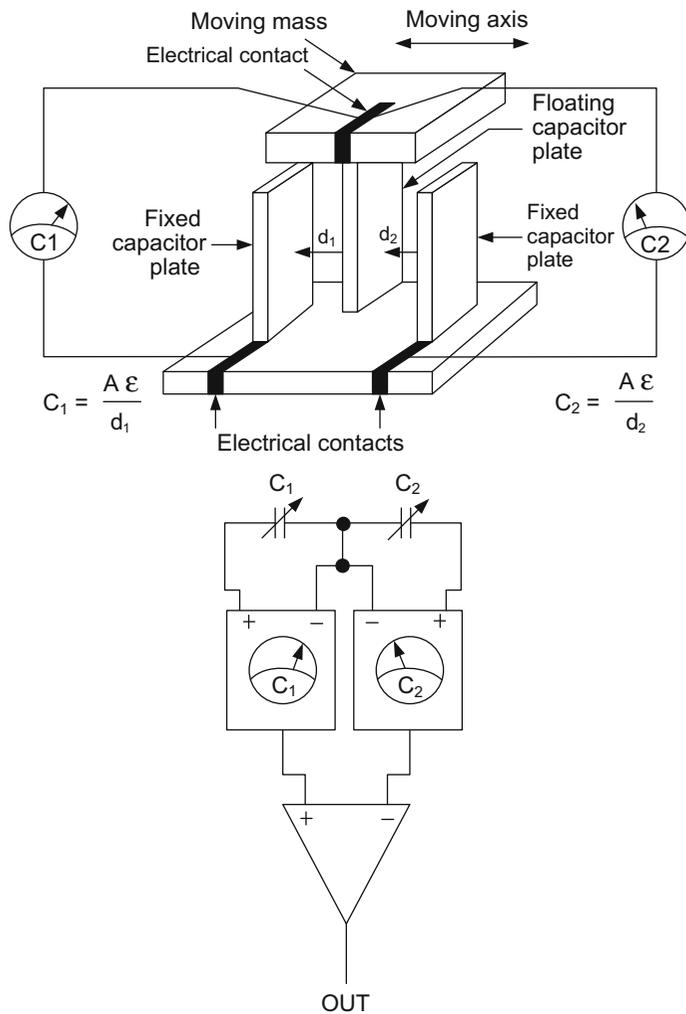

Fig. 5.17 Movement detection by differential capacitance measurement method

5.6 Hall-Effect Devices

Hall-Effect devices operate with the presence of a magnetic field and form a very useful device for embedded systems. The basic idea behind the Hall-effect device is the formation of Hall-voltage when the device is exposed to a magnetic field. When there is no magnetic field, electrons drift according to the direction of the electric field produced by V_D as shown in Fig. 5.18. The lateral voltage, V_H, measured between the two ends of the semiconductor will be 0 V.
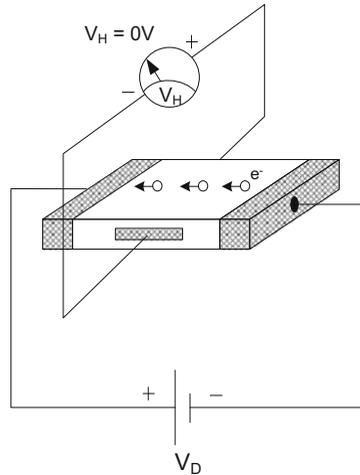

Fig. 5.18 Hall-effect device with no magnetic field ($V_H = 0$ V)

However, when a magnetic field, B, is applied perpendicular to the semiconductor surface as shown in Fig. 5.19, the conducting electrons are diverted from their original path by a lateral force field and accumulate on one side of the semiconductor slab according to the equation below.

$$F = -q(\overrightarrow{v} \times \overrightarrow{B})$$

Here, F is the magnetic force exerted on the electron, q is the electronic charge and v is the velocity of the electron. As a result of this accumulation, V_H forms between the two ends of the slab perpendicular to the electric field. This voltage is called Hall voltage and increases with the applied magnetic field.
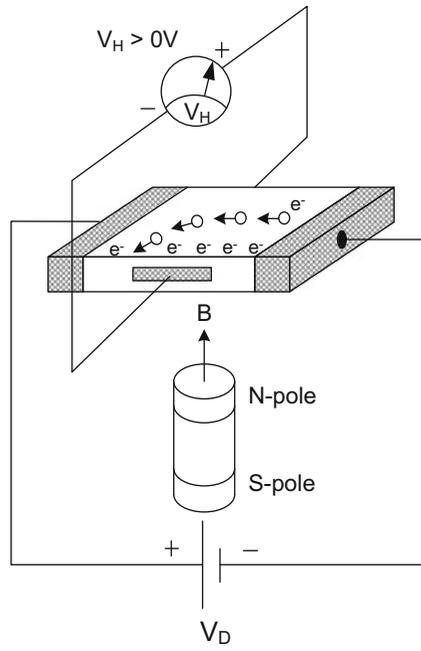
Fig. 5.19 Hall-effect device with magnetic field ($V_H > 0$ V)