AD2

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Contents

ABSTRACT

1 Introduction

Cadmium sulfide (CdS) is in the class II-VI semiconductor.

In 2.1 The free Electron Model we will use the free elecon model to obtain some results for a given metal and discribe some of the basic concepts. In the model it is assumed that the metal contains a large concentration of essentialy free electrons. These assumption leads to an satisfying description of many effects in metal, are of great importance in our daily live.

In 2.2 Chap 2 *Elementary Solid State Physics* [1] delivered insights in these concepts to get

In 2.3 Semiconductors

Semiconductor devices can display a range of useful properties, such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat. Because the electrical properties of a semiconductor material can be modified by doping, or by the application of electrical fields or light, devices made from semiconductors can be used for amplification, switching, and energy conversion.

2 Results

2.1 The free Electron Model

By using the free electron model, some of the parameter of a given metal can be calculated. The given metal crystllizes in the fcc structue with a lattice parameter for the convential unit cell of $0.409nm$. And a given resistivity for room temperature.

(Source [1, Elementary Solid State Physics Chapter 4])

Collision Time

For calculating the collision time the following relation is used.

$$\sigma = \frac{Ne^2\tau}{m^*} \tag{1}$$

At it is a monovalent metal and the FCC-Unit cell contains 4 atoms the concentration of the conduction electrons N can be calculated as ($a = 4.09\mathring{A}$):

$$N = \frac{4}{a^3}$$

So for the collision time τ follows: With ($m^* = m_0$) the free electron mass.

The electrical resitivity is given as: $\rho = 2.13\mu\Omega cm$

which leads to a conducitivity of $\sigma = \frac{1}{\rho} = 4.695 \cdot 10^7 \frac{1}{\Omega m}$

$$\tau = \frac{\sigma \cdot m^* \cdot a^3}{4e^2} = 28.5 \cdot 10^{-14} s$$

Question 2

For a thin metal wire with a length of $10\,cm$, a square cross section with a side of $0.1\,mm$ and a potential difference along the wire of $0.2\,V$

The electric field E in the wire can be calculated as:

$$E = \frac{U}{L} = 2\frac{V}{m}$$

As for the current density the following relations are known.

$$J = \sigma E \qquad J = Nev_D$$

So for the drift velocitiy follows:

$$v_D = \frac{\sigma E}{Ne} = 1.003 \frac{m}{s}$$

Question 3

The resitivity of a metal as a function can be best described;

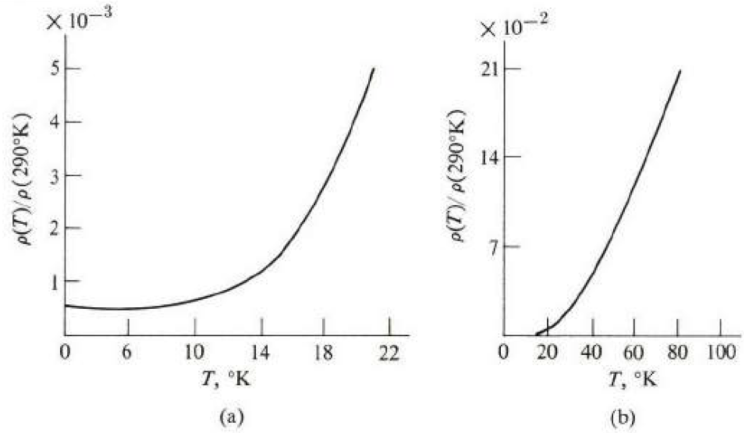

Figure 1: The normailized resitivity $\rho(T)/\rho(290°K)$ versus T for Na in the low-temperature region (a), and at higher temperatures (b) [1, Elementary Solid State Physics p. 148]

At temperatures near $0°K$ the resitivity has a small constant valuu. The resitivity increases with T Figure 1 a.

Fermi

The energy of the electron in a metal is quantized according to quantum mechanics. As so they follow the *Pauli exclusiion principle*, which means only two electrons with diffenrent spin can occupy one energy level. The highest occupied energy level is then called the Fermi energy or the fermy level.

The situation described obtains in metals as $T = 0°K$. The probability that an level below the fermi energy is occupied is 1 and above equals 0.

If the system is heated, the electrons near the fermi level get excited as the electrons below the fermi level can not absorb energy due to the exclusiion principle.

Which leads to the *Fermi-Dirac distribution*, which gives the probability that the level E is occupied by an electron

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \tag{2}$$

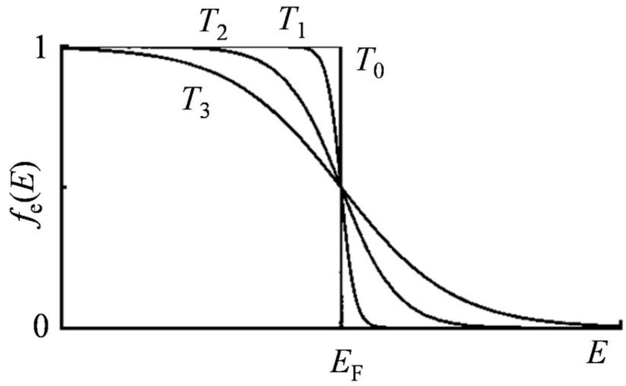

Figure 2: Fermi-Dirac distribution function at different temperatures: T3> T2>T1 (and T0 = 0 K). At the absolute zero temperature (T0), the probability of an electron to have an energy below the Fermi energy EF is equal to 1, while the probability to have higher energy is zero.

As the energy of an electron is entirely kinetic, it is possible to write the energy as:

$$E = \frac{1}{2} m^* v^2$$

As for the $T = 0°$ the fermi energy is the highest possible value a maximum velocitiy v_F of the particles can be found.

$$E_F = m^* v_F^2$$

This leads to a shere in the three dimesional velocitiy space (v_x, v_y, v_z) the sphere has an radius of v_F

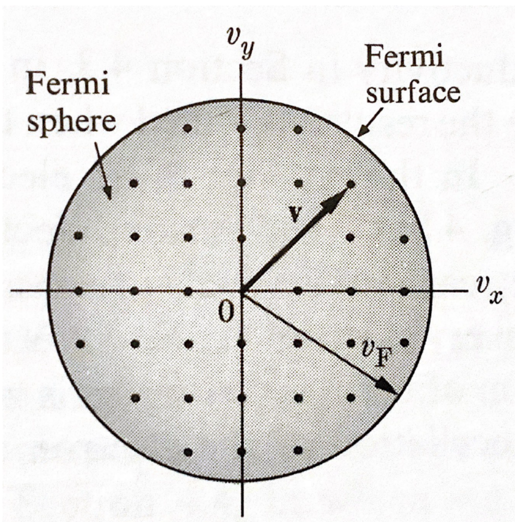

Figure 3: The Fermi surface and the Fermi sphere [1, Elementary Solid State Physics p. 268]

Cyclotron

$$-e(\vec{v} \times \vec{B}) = m\frac{d\vec{v}}{dt} \tag{3}$$

With the given information that $\vec{B} = B\vec{z}$ The equation above lead to the following:

$-ev_y B = m\frac{d}{dt}v_x$
$ev_x B = m\frac{d}{dt}v_y$

Which can be solved with the additional information

$$x = k_{0x}$$

$$\omega = \frac{eB}{m^*}$$

Plasma Frequency

$$w_P = \frac{Ne^2}{\epsilon_L m^*} \tag{4}$$

With the parameter given

$m^* = m_0$

$\epsilon_L = \epsilon_0$

Tha plasma frequency can be calculated as:

$$w_P = 1.861 \cdot 10^{11}\frac{1}{s}$$

2.2 Chap 2

2.3 Semiconductors

(Source [1, Elementary Solid State Physics Chapter 6])

Question 1

The carrier distribution function in CB für an intrinsic semiconductor is given as the product:

$$g_e(E)f(E)$$

with

$$g_e(E) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar}\right)^{\frac{3}{2}}(E-E_C)^{\frac{1}{2}}$$

$$f(E) = \frac{1}{e^{(E-E_F)/k_BT}+1} \approx e^{-\frac{E-E_F}{k_BT}}$$

So for the maximum

$$\frac{d}{dE}\left(\frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar}\right)^{\frac{3}{2}}(E-E_C)^{\frac{1}{2}}e^{-\frac{E-E_F}{k_BT}}\right) = 0$$

By dividing through the constant factors:

$$\frac{d}{dE}\left((E-E_C)^{\frac{1}{2}}e^{-\frac{E}{k_BT}}\right) = 0$$

$$\frac{1}{2}(E-E_C)^{-\frac{1}{2}}e^{-\frac{E}{k_BT}} + \frac{-1}{k_BT}(E-E_C)^{\frac{1}{2}}e^{-\frac{E}{k_BT}} = 0$$

And finaly

$$E = E_C + \frac{k_BT}{2}$$

Question 2

For the effective density of states in theh conducition beand the following relation is known:

$$N_c = 2\left(\frac{m_e^*k_BT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$$

Which lead to the following result

$$N_c = 2.415 \cdot 10^{24} \frac{1}{m^3}$$

In the same manner also the density of states in the valence band can be calculatetd.

$$N_v = 2 \left(\frac{m_h^* k_B T}{2\pi\hbar^2} \right)^{\frac{3}{2}}$$

$$N_v = 1.796 \cdot 10^{25} \frac{1}{m^3}$$

In an intrinsic semiconductor the concentration of the holes and the electron are equal and this concentration is named as intrinsic carrier's concentration.

Which is knwon to be:

$$n_i = p_i = 2 \left(\frac{k_B T}{2\pi\hbar^2} \right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} e^{-\frac{E_g}{2k_B T}}$$

$$n_i = p_i = 0.959 \cdot 10^3 \frac{1}{m^3}$$

For the intrinsic Fermi can be calculatetd as

$$E_{Fi} = \frac{E_g}{2} + \frac{3}{4} k_B T \ln \left(\frac{m_h^*}{m_e^*} \right)$$

$$E_{Fi} = 1.326eV$$

Question 3

If the given semiconductor CdS was doped p-type with a concentration of 10^{15} acceptor impurities the following about the concentration and holes at $T = 0°K$ can be said.

At this point the thermal energy becomes too small to cause electron exication, which means that all electrons fall from the conducition Band into the donor level. Also the conductivity goes to zero. This process is called freeze out. So for the concentration of electron and holes at $T = 0°K$

The concentration of the elctrons:

$n(T = 0°K) = 0$

As the semiconductor is doped with holes the concentration of the holes is the same as it was initaly.

$p(T = 0°K) = 10^{15} cm^{-3}$

Question 4

As the concentration of acceptor impurities is much higher then the holes concentration of the intrinsic semiconductor ($10^{15}\frac{1}{cm^3} \gg p_i$)

The concentration of the holes in the semiconductor is equal to concentration of the impurities.

$$p = 10^{15}\frac{1}{cm^3} = 10^{18}\frac{1}{m^3}$$

As the square of the intrinsic concentrationnn_i is equal to the product of the sum of the concentration of the holes and the concentration of the electrons.

$$np = n_i^2$$

$$n = \frac{n_i^2}{p} = \frac{(0.959 \cdot 10^3 \frac{1}{m^3})^2}{10^{18}\frac{1}{m^3}} = 9.197 \cdot 10^{-13}\frac{1}{m^3}$$

As for calculating $(E_F - E_{Fi})$ the temperature dependence of the concentration on electrons and holes can be used:

$$n = n_i e^{\frac{E_F - E_{Fi}}{k_B T}} \qquad p = n_i e^{-\frac{E_F - E_{Fi}}{k_B T}}$$

Which leads to:

$$(E_F - E_{Fi}) = \ln\left(\frac{n}{n_i}\right) \cdot k_B T$$

$$(E_F - E_{Fi}) = -0.896eV$$

Question 5

As the potential for Hole is given as:

$$V(r) = -\frac{e^2}{4\pi\epsilon_r\epsilon_0 r} \tag{5}$$

By using the Bohr model, the beinding energy can be found, which corresponds to the ground state of the acceptor and calculatetd. With using $\epsilon_r = 8.9$ and $m_h = 0.80\,m_0$

$$E_a = \frac{1}{\epsilon_r^2}\left(\frac{m_h}{m_0}\right)\underbrace{\left[\frac{e^4 m_0}{2(4\pi\epsilon_h\hbar)^2}\right]}_{13.6eV}$$

$$E_a = 0.14eV$$

Figure 4 shows the acceptor level inside the energy gap.

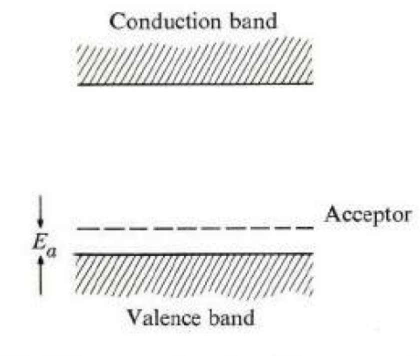

Figure 4: The acceptor level in a semiconductor [1, Elementary Solid State Physics p. 268]

Question 6

Question 7

3 Conclusion

This report

For a given monovalent metal which crystals in the FFC structure with a unit cell size of $a = 4.09\AA$ the the collistion time could be calculated as:

$$\tau = 28.5 \cdot 10^{-14} s$$

Also an expression for the cycloton frequency could be obtained

$$\omega = \frac{eB}{m^*}$$

The value of the intrinsic fermi level for CdS was found to be

$$E_{Fi} = 1.326 eV$$

as well as the intrinsic carrier concentration is

$$n_i = 0.959 \cdot 10^3 \frac{1}{m^3}$$

References

[1] M.A. Omar, *Elementary Solid State Physics: Principles and Applications*, Addison-Wesley, London, 1993.

[2] Charles Kittel, *Introduction to Solid State Physics*, 7th ed., Wiley, 1996

[3] METAL OXIDE PHOTOCATALYTIC NANOSTRUCTURES FABRICATED BY DYNAMIC SHADOWING GROWTH - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Fermi-Dirac-distribution-function-at-different-temperatures-T3-T2T1-and-T0-0-K-At_fig2_280311898 [accessed 16 Jun, 2020]

List of Tables

List of Figures