acta phys. slov. 34 (1984), No. 4

EFFECT OF MAGNETIC QUANTIZATION ON THE PLASMA FREQUENCY IN DEGENERATE KANE-TYPE SEMICONDUCTORS

ВЛИЯНИЕ МАГНИТНОГО КВАНТОВАНИЯ НА ЛЕНГМЮРОВСКУЮ ЧАСТОТУ В ВЫРОЖДЕННЫХ ПОЛУПРОВОДНИКАХ КЕЙНА

S. S. DE[1]), Calcutta

It has widely been demonstrated that the non-parabolicity of the energy bands significantly affects the basic parameters of the semiconductors and influences the performances of the semiconductor devices having Kane-type energy bands, particularly under the condition of carrier degeneracy [1, 2]. In recent years, it has been shown [3, 4] that the speed of operation of modern switching semiconductor devices and their performances at the device terminals are mainly governed by the degree of carrier degeneracy present in these devices. It appears then that these features would be affected significantly by the effects of band non-parabolicity. Nevertheless, the interest for further investigations of the different physical aspects of non-parabolic semiconductors is becoming increasingly important. One such parameter is the plasma frequency in semiconductors which has been studied in literature under different physical conditions [5, 6]. It may be mentioned that the numerical calculations presented there are not generalized ones and based upon different approximations. In the present communication a generalized expression of the plasma frequency in degenerate Kane-type semiconductors in the presence of a quantizing magnetic field has been derived.

The plasma frequency of the electrons in semiconductors can in general be expressed [6] in the presence of magnetic quantization as

$$\omega_{pB}^2 = c_0 \sum_{n=0}^{n_{max}} \int k_z \frac{\partial E}{\partial k_z} \frac{\partial f(E)}{\partial E} \, dE \tag{1}$$

where $c_0 = -2e^3B/\hbar^2\varepsilon_0\varepsilon_s\pi^2$, e is the electronic charge, B is the quantizing magnetic field applied in the k_z direction, $\hbar = h/2\pi$, h is the Planck constant, ε_0 is the permittivity of the free space, ε_s is the dielectric constant of the semiconductor, E is the energy of the electron as measured from the edge of the conduction band in the absence of the magnetic field and $f(E)$ is the Fermi–Dirac factor. Incidentally, the $E-k$ relation of the electrons in the Kane-type semiconductors can be expressed [7] under magnetic quantization as

$$E(1+\alpha E) = \left(n+\frac{1}{2}\right)\hbar\omega_0 \pm \frac{1}{2} g\mu B + \frac{\hbar^2 k_z^2}{2m^*} \tag{2}$$

---

[1]) Centre of Advanced Study in Radiophysics and Electronics, University of Calcutta, 1, Girish Vidyaratna Lane, CALCUTTA-700 009, India.

where the different symbols are defined in the reference [7]. Thus, using (1) and (2) we get

$$\omega_{pB}^2 = c_0 \sum_{n=0}^{n_{max}} \int_{E'_\pm}^{\infty} l_0 \left[\left\{+E(1+\alpha E) - \left(n+\frac{1}{2}\right)\hbar\omega_0 + \frac{1}{2} g\mu B\right\} + \left\{+E(1+\alpha E) - \left(n+\frac{1}{2}\right)\hbar\omega_0 - \frac{1}{2} g\mu B\right\}\right] \frac{\partial f(E)}{\partial E}\, dE \quad (3)$$

where $E'_\pm$ can be determined from the equation

$$E'_\pm(1+\alpha E'_\pm) = \left(n+\frac{1}{2}\right)\hbar\omega_0 \pm \frac{1}{2} g\mu B \quad \text{and} \quad l_0 = [1+2\alpha E]^{-1}.$$

It may be stated that under the condition of extreme degeneracy $\partial F(E)/\partial E = -\delta(E-E_F)$, where δ is the Dirac delta function and E_F is the Fermi energy in the presence of magnetic quantization as measured from the edge of the conduction band when $B=0$. Thus (3) can be simplified as

$$\omega_{pB}^2 = c_0 \sum_{n=0}^{n_{max}} [D_+(E_F) + D_-(E_F)]\,[1+2\alpha E_F] \quad (4)$$

where

$$D_\pm(E_F) = +E_F(1+\alpha E_F) - \left(n+\frac{1}{2}\right)\hbar\omega_0 \pm \frac{1}{2} g\mu B.$$

Equation (4) is the generalized expression of plasma frequency under magnetic quantization in degenerate Kane-type semiconductors. Thus for the computation of the above equation (4), a relation between the electron concentration and the Fermi energy in the presence of magnetic quantization is required. This in turn needs the corresponding expression for the density-of-states function. Using (2) the density-of-states function can be expressed as

$$N(E) = \pi\hbar\omega_0 \left(\frac{2m^*}{h^2}\right)^{3/2} \sum_{n=0}^{n_{max}} l_0^{-1} \left[\frac{1}{\sqrt{E(1+\alpha E) - \left(n+\frac{1}{2}\right)\hbar\omega_0 - \frac{1}{2} g\mu B}} + \frac{1}{\sqrt{E(1+\alpha E) - \left(n+\frac{1}{2}\right)\hbar\omega_0 + \frac{1}{2} g\mu B}}\right]. \quad (5)$$

Equation (5) leads to the expression of electron concentration, under the condition of extreme degeneracy, as

$$n_0 = 2\pi\hbar\omega_0 \left(\frac{2m^*}{h^2}\right)^{3/2} \sum_{n=0}^{n_{max}} \left[E_F(1+\alpha E_F) - \left(n+\frac{1}{2}\right)\hbar\omega_0 - \frac{1}{2} g\mu B\right]^{1/2} + \left[E_F(1+\alpha E_F) - \left(n+\frac{1}{2}\right)\hbar\omega_0 + \frac{1}{2} g\mu B\right]^{1/2}. \quad (6)$$

Using the appropriate equations we can determine the dependence of the plasma frequency on a quantizing magnetic field in degenerate Kane-type semiconductors having the electron concentration given, provided the band gap and the effective mass at the band edge are known. Taking $n-Hg_{1-x}Cd_xT_e$, as an example, E_g and m^* can be expressed [8—9] in terms of the alloy composition x as follows:

$$E_g(x) = [-.303 + 1.73x + 5.6\times10^{-4}(1-2x)\,T + .25x^4]\ \text{eV} \quad (7)$$

$$m^*(x) = \frac{3\hbar^2}{4P^2} E_g(x) \quad (8)$$

P being the interband momentum-matrix element, which is a very slowly varying function of x [8]. With

the help of the above expressions, the normalized plasma frequency $(\omega_{pB}/\omega_{p0})$, $\omega_{p0} = n_0 e^2/\varepsilon_0\varepsilon_s m_0$ as a function of the inverse magnetic field has been computed in $n-Hg_{1-x}Cd_xT_e$ from two different alloy compositions taking $P = 1\times10^{-7}$ eV cm [8], $T = 4.2$ K and $n_0 = 3\times10^{16}$ cm^{-3}, as shown in the Fig. 1. It can be observed from the Fig. 1 that the plasma frequency is an oscillatory function of the quantizing magnetic field. This is expected due to the dependence of the same on the Fermi energy, which oscillates with the changing magnetic field. Moreover, this behaviour is expected only at relatively low temperatures, since the magnetic quantum effects are prominent at such temperatures. The periods of

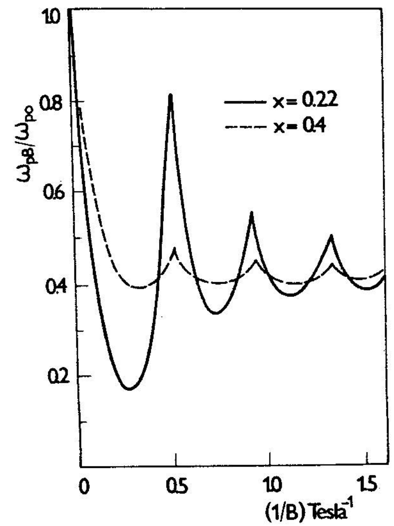

Fig. 1. Plot of the dependence of the normalized plasma frequency as a function of quantizing magnetic field in $n-Hg_{1-x}Cd_xT_e$ at very low temperatures for two different alloy compositions ($n_0 = 3\times10^{16}$ cm^{-3}).

oscillations being given by $\Delta(1/B) = (e/h)$, $(8/3n_0\sqrt{\pi})^{2/3}$ is only dependent on the carrier concentration and is independent of other parameters of the semiconductor. Incidentally, the effects of electron spin and collision-broadening have not been considered in obtaining the oscillatory plot. Moreover, the effect of electron-electron interaction is also neglected in this analysis. Nevertheless, the basic qualitative features of this analysis will not be altered even if the above improvements are taken into account.

REFERENCES

[1] Kane, E. O.: J. Phys. Chem. Solids *1* (1957), 24.
[2] Rautuszkiewicz, J., Gorska, M., Kaczmarek, E.: *Physics of Narrow Gap Semiconductors*. Polish Sci. Publishers. Warsaw 1978.
[3] Hachtel, G. D., Ruchli, A. E.: IEEE Trans. on Electron Devices, ED — *15* (1968), 437.
[4] Kamins, T. I., Muller, R. S.: Solid State Electronics *10* (1967), 423.
[5] Sarkar, C. K., Chattopadhyay, D.: J. Phys. Chem. Solids *40* (1979), 565.
[6] Sarkar, C. K., Chattopadhyay, D.: Phys. Stat. Sol. (b) *102* (1980), K 51 and the references cited therein.

[7] Chakrabarti, A. N., Chowdhury, A. K., Ghosh, S., Ghatak, K. P., Dhar, A.: Czech. J. Phys. B *31* (1981), 1037.
[8] Dornhaus, R., Nimtz, S.: In *Springer Tracts in Modern Physics 78*. Springer. Berlin, Heidelberg, New York 1976.
[9] Scott, M. W.: J. Appl. Phys. *40* (1969), 4577.

Received April 13th, 1983