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EFFECT OF MAGNETIC QUANTIZATION ON FIELD EMISSION FROM QUATERNARY ALLOYS

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An attempt is made to study theoretically the influence of magnetic quantization on the field emission from quaternary alloys at low temperatures on the basis of three-band Kane model, taking $In_{1-x}Ga_x As_yP_{1-y}$ lattice matched to InP as an example. It is found that the current density due to field emission increases with increasing carrier degeneracy in an oscillatory manner. Besides, the same current density increases with increasing electric field and decreasing alloy composition, respectively. In addition, the corresponding results of parabolic energy bands are also obtained from the expressions derived.

1. Introduction

In recent years, there has been considerable interest in studying different useful electronic properties of degenerate materials under various physical conditions because of their importance in device technology[1-2]. One such important parameter is the field emitted current density and it is well-known that at field strengths of the order of 10^9 V/m, the potential barrier at the surfaces of metals, alloys and semiconductors usually become very thin and result in field emission of the electrons due to tunnel effect[3-7]. This has been extensively studied under various physical conditions with the availability of a wide range of materials and of facilities for precisely controlling the band gap. Nevertheless, it appears from the literature that the current density due to field emission has yet to be investigated for quaternary alloys having nonparabolic energy bands and obeying Kane's dispersion relation[8] for the more interesting case which occurs from the presence of a quantizing magnetic field. This is very important since such alloys have received considerable attention recently as a possible material for fabrication of heterojunction lasers[9-10], light emitting diodes[11], avalanche photodiodes in the near infrared region of the spectrum[12-13], microwave devices such as field effect transistors[14] and have an additional advantage that the band gap of these materials can be made very narrow by varying the alloy compositon. We shall use the three-band Kane model for the purpose of theoretical formulation. We may note that our analysis is a generalized one, since we can obtain the corresponding results of two-band Kane model and that of parabolic energy bands under certain limiting conditions from our expression. It would, therefore, be of much interest to study the field emitted current density from quaternary alloys under magnetic quantization. This is done, in what follows taking $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP as an example.

2. *Theoretical background*

The net current density due to field emission along the direction of magnetic quantization at zero temperature is given by

$$J = \frac{1}{2} \sum_{n=0}^{n_{max}} ev\, n_{0n}\, T, \tag{1}$$

where the factor $\frac{1}{2}$ is introduced due to the reason that half of the electrons which are enable to contribute the emission will migrate back to the lattice[15], e is the electron charge, v is the velocity of the electrons along z-direction and can be written as $v = \frac{1}{\hbar}\frac{\partial E}{\partial k_z}$ in which $\hbar \equiv h/2\pi$, h is Planck's constant, E is the electron energy in the presence of magnetic quantization as measured from the edge of the conduction band in the absence of any quantization and can be expressed for three-band Kane model[16a] as

$$\gamma(E) = \left(n + \frac{1}{2}\right) \hbar \omega_0 + \frac{\hbar^2 k_z^2}{2m^*} \pm \Phi(E), \tag{2}$$

where the symbol $\gamma(E)$ is defined elsewhere[16b], $\omega_0 = eB/m^*$, e is the electron charge, B is the quantizing magnetic field along z-direction, n is the Landau quantum number and $\Phi(E) = eB\Delta \left[6m^* \left(E + E_g + \frac{2}{3}\Delta\right)\right]^{-1}$, n_{0n} is the electron concentration for the n-th Landau subband and is given by[17]

$$n_{0n} = \frac{eB}{2\pi^2 \hbar} \int_{k_z=0}^{\infty} \left[\frac{\partial k_z}{\partial E}\right] f(E)\, \mathrm{d}E$$

in which $f(E)$ is the Fermi-Dirac occupation probability factor, T is the transmission coefficient and is given by[18)]

$$T = \exp\left[-\frac{2}{\hbar}\int_{z} |p_z|\, dz\right].$$

Thus using all the equations, the net field emitted current density under magnetic quantization for three-band Kane model can be written as

$$T = \frac{e^2 B}{4\pi^2 \hbar^2} \sum_{n=0}^{n_{max}} [E_F - E_n] \exp[-G(n)] \tag{3}$$

where E_F is the Fermi energy in the presence of magnetic quantization as measured from the edge of the conduction band in the absence of any quantization and can be related to the total electron concentration n_0, under the condition of extreme degeneracy, as

$$n_0 = (eB\sqrt{2m^*}/2\pi^2\hbar^2) \sum_{n=0}^{n_{max}} [\gamma(E_F) - \left(n + \frac{1}{2}\right)\hbar\omega_0 \mp \Phi(E_F)]^{1/2} \tag{4}$$

$$G(n) \equiv \frac{4}{3}(\sqrt{2m^*}/\hbar)\,[K_1(n)]^{2/3}\,[e F_s K_2(n)]^{-1},$$

$$K_1(n) \equiv C\,A(n)/L(n),$$

$$C \equiv \left[1 + \frac{2}{3}\alpha\Delta\right][1 + \alpha\Delta]^{-1},$$

$$\alpha \equiv 1/E_g,$$

$$A(n) \equiv \alpha^2 \Phi^3(n) + (2\alpha + \alpha^2\Delta)\Phi^2(n) + \Phi(n),$$

$$\Phi(n) \equiv [\Phi_0 + E_F - F_n],$$

Φ_0 is the work function, E_n can be determined from the equation

$$\gamma(E_n) - \left(n + \frac{1}{2}\right)\hbar\omega_0 \pm \Phi(E_n) = 0 \tag{5}$$

$L(n) \equiv \left[1 + \alpha\Phi(n) + \frac{2}{3}\alpha\Delta\right]$, F_s is the surface electric field along z axis,

$$K_2(n) \equiv [e/L(n)]\,\{g(n) - A(n)\,[E_g L(n)]^{-1}\}$$

and

$$g(n) \equiv [3\alpha^2 \Phi^2 (n) + 2\Phi (n) (\alpha^2 \Delta + 2\alpha) + 1].$$

Under the condition $\Delta \to \infty$ as for two-band Kane model, equation (2) assumes the form[17]

$$E(1 + \alpha E) = \left(n + \frac{1}{2}\right) \hbar \omega_0 + \frac{\hbar^2 k_z^2}{2m^*} \pm C_0, \tag{6}$$

where

$$C_0 \equiv eB/4m^*.$$

Equation (6) is the well-known expression of the dispersion relation of the conduction electrons according to two-band Kane model under magnetic quantization. Thus under the condition $\Delta \to \infty$, the forms of the equations (3) and (4) remain same where $K_1 (n) \equiv \Phi (n) \; [1 + \alpha \Phi (n)]$, $K_2 (n) \equiv [1 + 2\alpha \Phi (n)]$, $\gamma (E_F) \equiv \equiv E_F (1 + \alpha E_F)$, $\Phi (E_F) \equiv C_0$ and E_n is the real of the equation $E_n (1 + \alpha E_n) = = \left(n + \frac{1}{2}\right) \hbar \omega_0 \pm C_0$.

Under the condition $\alpha \to 0$ as for parabolic energy bands, equation (6) assumes the well-known form[17]

$$E = \left(n + \frac{1}{2}\right) \hbar \omega_0 + \frac{\hbar^2 k_z^2}{2m^*} \pm C_0. \tag{7}$$

Thus under the condition $\alpha \to 0$, the expressions of the field emitted current density and electron concentration under magnetic quantization at 0 K can respectively be expressed, for parabolic energy bands, as

$$J = \frac{e^2 B}{4\pi^2 \hbar^2} \sum_{n=0}^{n_{max}} [E_F - E_n] \exp \left[- \frac{4}{3} \left(\frac{2m^*}{\hbar^2}\right)^{1/2} \frac{\Phi^{3/2} (n)}{e F_s} \right] \tag{8}$$

and

$$n_0 = (e B \sqrt{2m^*}/2\pi^2 \hbar^2) \sum_{n=0}^{n_{max}} \sqrt{E_F - E_n}, \tag{9}$$

where

$$E_n = \left(n + \frac{1}{2}\right) \hbar \omega_0 \pm C_0.$$

Finally we may note that, in the absence of magnetic quantization $B \to 0$ equation (8) gets simplified into the form

$$J = \frac{e^3 F_s^2}{8\pi h \Phi_0} \exp \left[- \frac{4}{3} \sqrt{2m^*}/\hbar) (\Phi_0^{3/2}/e F_s) \right]. \tag{10}$$

Equation (10) was derived for the first time by Fowler and Nordheim[19].

3. *Results and discussion*

Using the appropriate equations and taking $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP as an example together with the parameters[20–22)]

$$E_g = [1.35 - 0.738y + 0.138y^2]\,\text{eV},$$

$$\Delta = [3.11 - 0.87y + 0.30y^2 + 0.007y^3]\,\text{eV},$$

$$m^* = [0.080 - 0.039y]\, m_0,$$

we have plotted the field emitted current density as a function of carrier concentration for $y = 0.2$, $\Phi_0 = 3$ eV, $F_s = 10^9$ V/m and $B = 1$ T as shown in plot a of Fig. 1 in which the other plots exhibit the same dependence in accordance

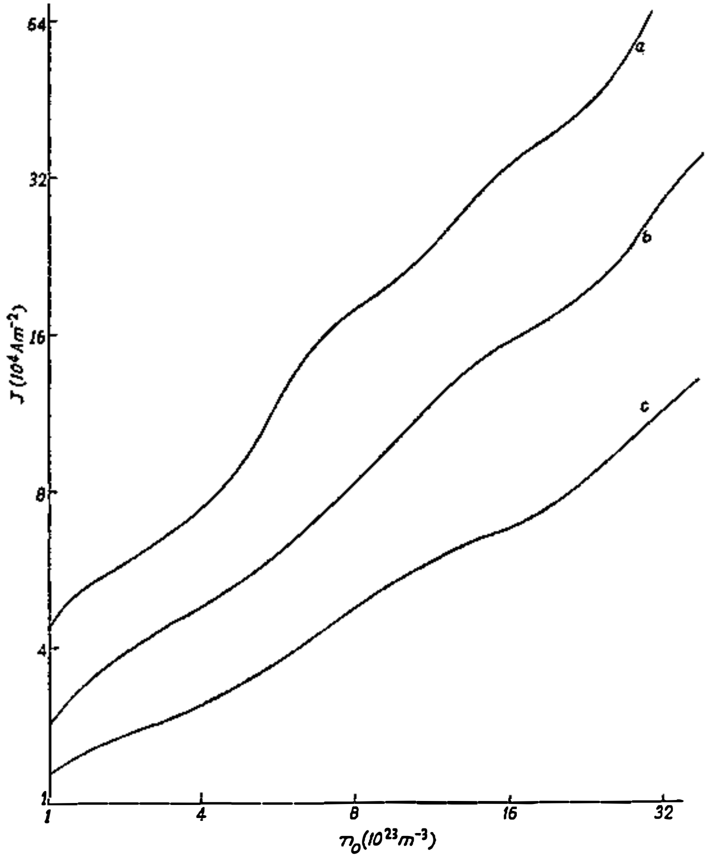

Fig. 1. Plot of the magnetic field emission current density as a function of electron concentration in $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP: Curve a: Three-band Kane model; curve b: Two-band Kane model and curve c: Parabolic energy band.

with isotropic two-band Kane model and also for parabolic energy bands, respectively. Using the same parameters as used in Fig. 1 we have further plotted the field emitted current density as functions of F_s and y as shown in Figs. 2 and 3, respectively, in the magnetic quantum limit in which the other simplified limiting cases have further been demonstrated for the purpose of comparison. It appears from Fig. 1 that the current density increases with increasing electron concentration in an oscillatory manner and the three-band Kane model enhances the current density in quaternary alloys as compared to two-band Kane model at a given value of electron concentration in the whole range of concentrations considered. Though

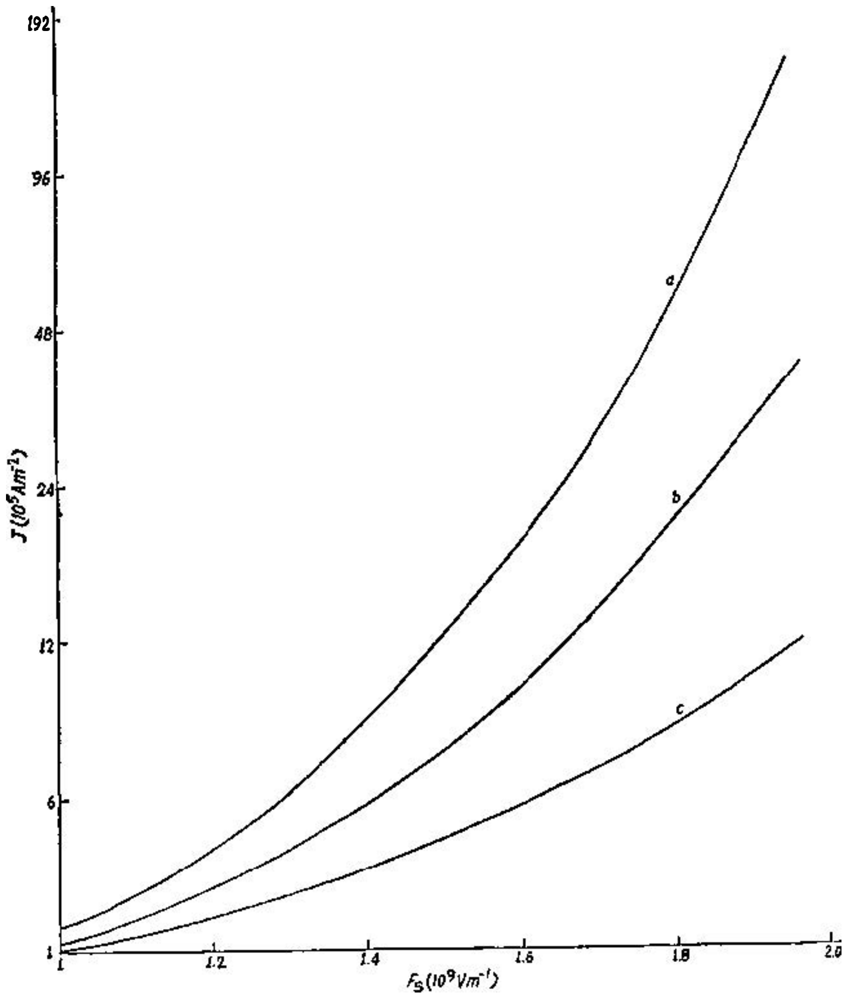

Fig. 2. Plot of the magneto field emission current density as a function of electric field in the magnetic quantum limit in $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP: Curve a: Three-band Kane model; curve b: Two-band Kane model and curve c: Parabolic energy bands. $B = 4$ T and $n_0 = 10^{23}\ m^{-3}$.

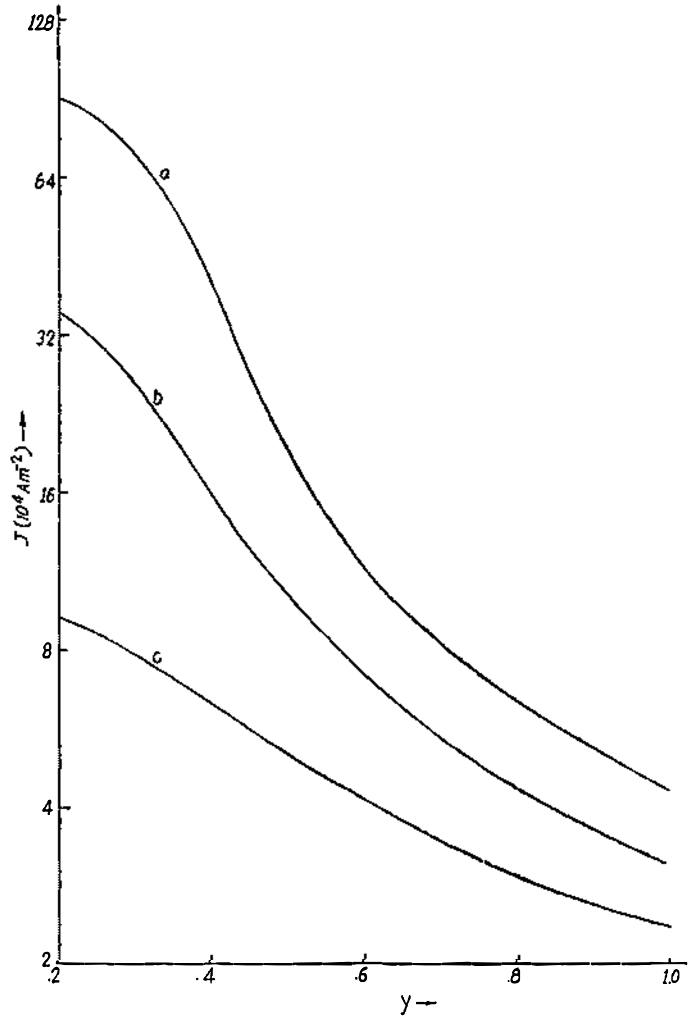

Fig. 3. Plot of the magneto field emission current density as a function of alloy composition in the magnetic quantum limit in $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP: Curve a: Three-band Kane model; curve b: Two-band Kane model and curve c: Parabolic energy bands. $n_0 = 10^{23}\ m^{-3}$ and $F_s = 10^{19}$ V/m.

the current density also increases with electron concentration in the cases of degenerate two-band Kane model and that of a degenerate parabolic band, the rates of increase are different from that in the three-band Kane model. The appearance of the humps in Fig. 1 is due to the redistribution of the electrons among the quantized energy levels when the quantum number corresponding to the highest occupied level changes from one fixed value to the other. It appears from Fig. 2 that the current density increases with increasing electric field in the magnetic quantum limit in a monotonous manner and the numerical value of the current density is larger for three-band Kane model specially for relatively higher values of the electric field. From Fig. 3 it appears that the current density in the magnetic quantum limit decreases with increasing alloy composition.

It may be noted that the influence of broadening, finite temperature, image force and electron-electron interactions have been neglected in this work. It is worth remarking that though the experimental verification of the basic content of our result is not available in the literature to the best of our knowledge, this simplified analysis exhibits basic features of the field emission from quaternary alloys in the presence of magnetic quantization.

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EFEKT MAGNETSKE KVANTIZACIJE NA EMISIJU POLJEM IZ KVATERNARNIH SLITINA

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Teoretski je razmatran utjecaj magnetske kvantizacije na emisiju poljem iz kvaternarnih slitina na niskim temperaturama. Za osnovu je uzet Kaneov model s tri vrpce, a kao primjer $In_{1-x}Ga_x As_yP_{1-y}$ usklađen s rešetkom InP. Nađeno je da intenzitet struje raste s degeneracijom nosilaca na oscilatorni način.