

## Chapter 2

# The EP from Nano Wires (NWs) of Heavily Doped (HD) Non-parabolic Semiconductors

### 2.1 Introduction

It is well-known that in nano wires (NWs), the restriction of the motion of the carriers along two directions may be viewed as carrier confinement by two infinitely deep 1D rectangular potential wells, along any two orthogonal directions leading to quantization of the wave vectors along the said directions, allowing 1D carrier transport [1–4]. With the help of modern fabrication techniques, such one dimensional quantized structures have been experimentally realized and enjoy an enormous range of important applications in the realm of nanoscience in the quantum regime. They have generated much interest in the analysis of nanostructured devices for investigating their electronic, optical and allied properties [5–8]. Examples of such new applications are based on the different transport properties of ballistic charge carriers which include quantum resistors [9–14], resonant tunneling diodes and band filters [15, 16], quantum switches [17], quantum sensors [18–20], quantum logic gates [21, 22], quantum transistors and sub tuners [23–25], heterojunction FETs [26, 27], high-speed digital networks [28–31], high-frequency microwave circuits [32], optical modulators [33], optical switching systems [34–36], and other devices.

In this chapter in Sects. 2.2.1, 2.2.2, 2.2.3, 2.2.4, 2.2.5, 2.2.6, 2.2.7, 2.2.8, 2.2.9, 2.2.10 and 2.2.11 we have investigated the EP from NWs of HD non-linear optical, III-V, II-VI, stressed Kane type, Te, GaP, PtSb<sub>2</sub>, Bi<sub>2</sub>Te<sub>3</sub>, Ge and GaAs respectively. The Sect. 2.3 contains the result and discussions pertaining to this chapter. The Sect. 2.4 presents 24 open research problems.

## 2.2 Theoretical Background

### 2.2.1 The EP from Nano Wires of HD Nonlinear Optical Semiconductors

The dispersion relation of the 1D electrons in this case can be written following (1.32) as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_{\parallel}^*T_{21}(E, \eta_g)} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_{\parallel}^*T_{22}(E, \eta_g)} + \frac{\hbar^2k_x^2}{2m_{\parallel}^*T_{21}(E, \eta_g)} = 1 \quad (2.1)$$

where,  $n_z (= 1, 2, 3, \dots)$ ,  $d_z$  are the size quantum number and the nano-thickness along the  $z$ -direction respectively,  $n_y (= 1, 2, 3, \dots)$  and  $d_y$  are the size quantum number and the nano-thickness along the  $y$ -direction respectively.

The 1D DOS function per sub-band is given by

$$N_{1D}(E) = \frac{2g_v}{\pi} \frac{\partial k_x}{\partial E} \quad (2.2)$$

The velocity of the emitted electrons along the  $x$ -direction can be written as

$$v_x(E) = \frac{1}{\hbar} \frac{\partial E}{\partial k_x} \quad (2.3)$$

Therefore the photocurrent is given by

$$I = \frac{\alpha_o e g_v}{2} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} \int_{\Delta_1}^{\infty} \left( \frac{2}{\pi} \frac{\partial k_x}{\partial E} \right) \left( \frac{1}{\hbar} \frac{\partial E}{\partial k_x} \right) f(E) dE \quad (2.4)$$

where,

$$\Delta_1 \equiv E' + W - h\nu. \quad (2.5)$$

Using (2.4), one can write,

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \text{Real part of } \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{61HD}), \quad (2.6)$$

where

$$\eta_{61HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{1HDNW} + W - h\nu)}{k_B T} \right]$$

$E_{F1HDNW}$  in the Fermi energy in this case,  $E'_{1HDNW}$  is the complex sub-band energy which can be expressed in this case as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_{\parallel}^*T_{21}(E'_{1HDNW}, \eta_g)} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_{\parallel}^*T_{22}(E'_{1HDNW}, \eta_g)} = 1 \quad (2.7)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, n_y, n_z, \eta_g) = \frac{\hbar^2}{2} [\text{Real part of } \frac{\partial}{\partial(E_{F1HDNW})} [T_{1HDNW}(E, n_y, n_z, \eta_g)]^2] \quad (2.8)$$

where

$$T_{1HDNW}(E, n_y, n_z, \eta_g) = \left[ \left[ 1 - \frac{\hbar^2(n_z\pi/d_z)^2}{2m_{\parallel}^*T_{21}(E, \eta_g)} - \frac{\hbar^2(n_y\pi/d_y)^2}{2m_{\parallel}^*T_{22}(E, \eta_g)} \right] \frac{2m_{\parallel}^*T_{21}(E, \eta_g)}{\hbar^2} \right]^{1/2} \quad (2.9)$$

Thus, we observe that the EEM is the function of size quantum numbers in both the directions and the Fermi energy due to the combined influence of the crystal field splitting constant and the anisotropic spin-orbit splitting constants respectively. Besides it is a function of  $\eta_g$  due to which the EEM exists in the band gap, which is otherwise impossible.

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \text{Real part of } \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{1HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{2HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.10)$$

where  $T_{2HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [T_{1HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$ ,

In the absence of band-tails, for electron motion along x-direction only, the 1D electron dispersion law in this case can be written following (1.2) as

$$\gamma(E) = f_1(E)k_x^2 + f_1(E)(\pi n_y/d_y)^2 + f_2(E)(\pi n_z/d_z)^2 \quad (2.11)$$

The sub-band energy ( $E'_1$ ) are given by the equation

$$\gamma(E'_1) = f_1(E'_1)(\pi n_y/d_y)^2 + f_2(E'_1)(\pi n_z/d_z)^2 \quad (2.12)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{62})$$

where

$$\eta_{62} \equiv \left[ \frac{E_{F1d} - (E'_1 + W - hv)}{k_B T} \right], \quad (2.13)$$

and  $E_{F1d}$  is the Fermi energy in this case

The electron concentration per unit length can be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [t_1(E_{F1d}, n_y, n_z) + t_2(E_{F1d}, n_y, n_z)] \quad (2.14)$$

where

$$t_1(E_{F1d}, n_y, n_z) \equiv \left[ \gamma(E_{F1d}) - f_1(E_{F1d})(\pi n_y/d_y)^2 - f_2(E_{F1d})(\pi n_z/d_z)^2 \right]^{1/2} [f_1(E_{F1d})]^{-1/2}$$

and

$$t_2(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^s L(r) [t_1(E_{F1d}, n_y, n_z)].$$

### 2.2.2 The EP from Nano Wires of HD III-V Semiconductors

(i) Three band model of Kane

The dispersion relation of the 1D electrons in this case can be written following (1.55) as

$$\frac{\hbar^2 (n_z \pi / d_z)^2}{2m_c} + \frac{\hbar^2 (n_y \pi / d_y)^2}{2m_c} + \frac{\hbar^2 k_x^2}{2m_c} = T_{31}(E, \eta_g) + iT_{31}(E, \eta_g) \quad (2.15)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \text{Real part of } \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{63HD}), \quad (2.16)$$

where

$$\eta_{63HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{2HDNW} + W - hv)}{k_B T} \right],$$

and  $E'_{2HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} = T_{31}(E'_{2HDNW}, \eta_g) + iT_{31}(E'_{2HDNW}, \eta_g) \quad (2.17)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c[T'_{31}(E_{F1HDNW}, \eta_g)] \quad (2.18)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left(\frac{2g_v}{\pi}\right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{3HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{4HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.19)$$

where

$$T_{3HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ [T_{31}(E_{F1HDNW}, \eta_g) + iT_{31}(E_{F1HDNW}, \eta_g) - \frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} - \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c}] \frac{2m_c}{\hbar^2} \right]^{1/2}$$

where  $T_{4HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r)[T_{3HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$

The one dimensional electron dispersion law is given by

$$\frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) = I_{11}(E) \quad (2.20)$$

where,

$$G_2(n_y, n_z) \equiv (\hbar^2\pi^2/2m_c) \left[ (n_y/d_y)^2 + (n_z/d_z)^2 \right]$$

The sub band energy  $E'_2$  can be written as

$$G_2(n_y, n_z) = I_{11}(E'_2) \quad (2.21)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{64}) \quad (2.22)$$

where

$$\eta_{64} \equiv \left[ \frac{E_{F1d} - (E'_2 + W - \hbar\nu)}{k_B T} \right],$$

The electron statistics in this case can be written as

$$n_{1D} = \frac{2g_v\sqrt{2m_c}}{\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [t_3(E_{F1d}, n_y, n_z) + t_4(E_{F1d}, n_y, n_z)] \quad (2.23)$$

where

$$t_3(E_{F1d}, n_y, n_z) \equiv [I_{11}(E_{F1d}) - G_2(n_y, n_z)]^{1/2},$$

$$t_4(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^{S_0} L(r) [t_3(E_{F1d}, n_y, n_z)].$$

(ii) Two band model of Kane

The dispersion relation of the 1D electrons in this case can be written as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} + \frac{\hbar^2k_x^2}{2m_c} = \gamma_2(E, \eta_g) \quad (2.24)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{64HD}), \quad (2.25)$$

where

$$\eta_{64HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{3HDNW} + W - \hbar\nu)}{k_B T} \right]$$

and  $E'_{3HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} = \gamma_2(E'_{3HDNW}, \eta_g) \quad (2.26)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c [\gamma'_2(E_{F1HDNW}, \eta_g)] \quad (2.27a)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{8HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.27b)$$

where

$$T_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ \left[ \gamma_2(E_{F1HDNW}, \eta_g) - \frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} - \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} \right] \frac{2m_c}{\hbar^2} \right]^{1/2}$$

and

$$T_{8HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [T_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)].$$

The expression of 1D dispersion relation, for NWs of III-V materials whose energy band structures are defined by the two-band model of Kane in the absence of band tailing assumes the form

$$E(1 + \alpha E) = \frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) \quad (2.28)$$

In this case, the quantized energy  $E'_3$  is given by

$$E'_3 = (2\alpha)^{-1} \left[ -1 + \sqrt{1 + 4\alpha G_2(n_y, n_z)} \right] \quad (2.29)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{65}), \quad (2.30)$$

where

$$\eta_{65} \equiv \left[ \frac{E_{F1d} - (E'_3 + W - \hbar\nu)}{k_B T} \right],$$

The carrier statistics in the case can be expressed as

$$n_{1D} = \frac{2g_v}{\pi} \frac{\sqrt{2m_c}}{\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [t_5(E_{F1d}, n_y, n_z) + t_6(E_{F1d}, n_y, n_z)] \quad (2.31)$$

where

$$t_5(E_{F1d}, n_y, n_z) \equiv [E_{F1d}(1 + \alpha E_{F1d}) - G_2(n_y, n_z)]^{1/2},$$

$$t_6(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^s L(r) [t_5(E_{F1d}, n_y, n_z)].$$

(iii) Parabolic energy bands

The dispersion relation of the 1D electrons in this case can be written as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} + \frac{\hbar^2k_x^2}{2m_c} = \gamma_3(E, \eta_g) \quad (2.32)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{66HD}), \quad (2.33)$$

where

$$\eta_{66HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{5HDNW} + W - \hbar\nu)}{k_B T} \right]$$

and  $E'_{5HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} = \gamma_3(E'_{5HDNW}, \eta_g) \quad (2.34)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c [\gamma'_3(E_{F1HDNW}, \eta_g)] \quad (2.35a)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{9HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{10HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.35b)$$

where

$$T_{9HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ \gamma_3(E_{F1HDNW}, \eta_g) - \frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} - \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} \right] \frac{2m_c}{\hbar^2}^{1/2}$$

where  $T_{10HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [T_{9HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$ ,

The expression of 1D dispersion relation, for NWs of III-V materials whose energy band structures are defined by the two-band model of Kane in the absence of band tailing assumes the form



$$E = \frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) \quad (2.36)$$

In this case, the quantized energy  $E'_7$  is given by

$$E'_7 = G_2(n_y, n_z) \quad (2.37)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{67}), \quad (2.38)$$

where

$$\eta_{67} \equiv \left[ \frac{E_{F1d} - (E'_7 + W - h\nu)}{k_B T} \right]$$

The carrier statistics in the case can be expressed as

$$n_{1D} = \frac{2g_v \sqrt{2m_c \pi k_B T}}{h} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_{\frac{-1}{2}}(\bar{\eta}_{67}), \quad (2.39)$$

where

$$\bar{\eta}_{67} = [E_{F1d} - E'_7] (k_B T)^{-1}$$

Converting the summation over quantum numbers to the corresponding integrations in (2.38), the photocurrent density from semiconductors having isotropic parabolic energy bands with non-degenerate electron concentration gets transformed into the well known form as given in the preface. Besides, (2.39) is well-known in the literature.

(iv) The Model of Stillman et al.

The dispersion relation of the 1D electrons in this case can be written as

$$\frac{\hbar^2 (n_z \pi / d_z)^2}{2m_c} + \frac{\hbar^2 (n_y \pi / d_y)^2}{2m_c} + \frac{\hbar^2 k_x^2}{2m_c} = \theta_4(E, \eta_g) \quad (2.40)$$

where

$$\theta_4(E, \eta_g) = I_{12}(E, \eta_g)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{69HD}), \quad (2.41)$$

where

$$\eta_{69HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{9HDNW} + W - h\nu)}{k_B T} \right]$$

and  $E'_{9HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2 (n_z \pi / d_z)^2}{2m_c} + \frac{\hbar^2 (n_y \pi / d_y)^2}{2m_c} = \theta_4(E'_{9HDNW}, \eta_g) \quad (2.42)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c [\theta'_4(E_{F1HDNW}, \eta_g)] \quad (2.43a)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{11HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{12HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.43b)$$

where

$$T_{11HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ \left[ \theta_4(E_{F1HDNW}, \eta_g) - \frac{\hbar^2 (n_z \pi / d_z)^2}{2m_c} - \frac{\hbar^2 (n_y \pi / d_y)^2}{2m_c} \right] \frac{2m_c}{\hbar^2} \right]^{1/2}$$

where  $T_{12HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [T_{11HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$ ,

The expression of 1D dispersion relation, for NWs of III-V materials whose energy band structures are defined by the model of Stillman et al. in the absence of band tailing assumes the form

$$I_{12}(E) = \frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) \quad (2.44)$$

In this case, the quantized energy  $E'_9$  is given by

$$I_{12}(E'_9) = G_2(n_y, n_z) \quad (2.45)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{69}),$$

where

$$\eta_{69} \equiv \left[ \frac{E_{F1d} - (E'_9 + W - h\nu)}{k_B T} \right] \quad (2.46)$$

The carrier statistics in the case can be expressed as

$$n_{1D} = \frac{2g_v}{\pi} \frac{\sqrt{2m_c}}{\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [P_9(E_{F1d}, n_y, n_z) + Q_9(E_{F1d}, n_y, n_z)] \quad (2.47)$$

where

$$P_9(E_{F1d}, n_y, n_z) \equiv [I_{12}(E_{F1d}) - G_2(n_y, n_z)]^{1/2}$$

and  $Q_9(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^s L(r) [P_9(E_{F1d}, n_y, n_z)]$ .

(v) The Model of Palik et al.

The dispersion relation of the 1D electrons in this case can be written as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} + \frac{\hbar^2k_x^2}{2m_c} = \theta_5(E, \eta_g) \quad (2.48)$$

where

$$\theta_5(E, \eta_g) = I_{13}(E, \eta_g)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{610HD}), \quad (2.49)$$

where

$$\eta_{610HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{10HDNW} + W - h\nu)}{k_B T} \right],$$

and  $E'_{10HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} = \theta_5(E'_{10HDNW}, \eta_g) \quad (2.50)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c [\theta'_5(E_{F1HDNW}, \eta_g)] \quad (2.51a)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [T_{13HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + T_{14HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.51b)$$

where

$$T_{13HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ \left[ \theta_5(E_{F1HDNW}, \eta_g) - \frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} - \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} \right] \frac{2m_c}{\hbar^2} \right]^{1/2}$$

where  $T_{14HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r)[T_{13HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$ ,

The expression of 1D dispersion relation, for NWs of III-V materials whose energy band structures are defined by the model of Palik et al. in the absence of band tailing assumes the form

$$I_{13}(E) = \frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) \quad (2.52)$$

In this case, the quantized energy  $E'_{10}$  is given by

$$I_{13}(E'_{10}) = G_2(n_y, n_z) \quad (2.53)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{610}), \quad (2.54)$$

where

$$\eta_{610} \equiv \left[ \frac{E_{F1d} - (E'_{10} + W - \hbar v)}{k_B T} \right],$$

The carrier statistics in the case can be expressed as

$$n_{1D} = \frac{2g_v}{\pi} \frac{\sqrt{2m_c}}{\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [P_{11}(E_{F1d}, n_y, n_z) + Q_{12}(E_{F1d}, n_y, n_z)] \quad (2.55)$$

where

$$P_{11}(E_{F1d}, n_y, n_z) \equiv [I_{13}(E_{F1d}) - G_2(n_y, n_z)]^{1/2}$$

and  $Q_{12}(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^s L(r) [P_{11}(E_{F1d}, n_y, n_z)]$ .

### 2.2.3 The EP from Nano Wires of HD II-VI Semiconductors

The 1D electron dispersion law in NW of HD II-VI semiconductors can be written following (1.141) as

$$\gamma_3(E, \eta_g) = a'_0 \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right] \pm \bar{\lambda}_0 \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right]^{1/2} + \frac{\hbar^2 k_z^2}{2m_{\parallel}^*} \quad (2.56)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{613HD}), \quad (2.57)$$

where

$$\eta_{613HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{13HDNW} + W - \hbar\nu)}{k_B T} \right]$$

and  $E'_{13HDNW}$  is the sub-band energy in this case which can be expressed as

$$\gamma_3(E'_{13HDNW}, \eta_g) = a'_0 \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right] \pm \bar{\lambda}_0 \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right]^{1/2} \quad (2.58)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_{\parallel}^* \gamma'_3(E_{F1HDNW}, \eta_g) \quad (2.59)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left(\frac{g_v}{\pi}\right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [T_{17HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) + T_{18HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)] \quad (2.60)$$

where

$$T_{17HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = [[\gamma_3(E_{F1HDNW}, \eta_g) - a'_0[(\frac{n_x\pi}{d_x})^2 + (\frac{n_y\pi}{d_y})^2] \mp \bar{\lambda}_0[(\frac{n_x\pi}{d_x})^2 + (\frac{n_y\pi}{d_y})^2]^{1/2}](\frac{2m_{\parallel}^*}{\hbar^2})]^{1/2}$$

and

$$T_{18HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = \sum_{r=1}^s L(r)[T_{17HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)],$$

The 1D dispersion relation for NWs of II-VI materials in the absence of band-tails can be written as

$$E = b'_0 k_z^2 + G_{3,\pm}(n_x, n_y) \quad (2.61)$$

where

$$G_{3,\pm}(n_x, n_y) \equiv \left[ a'_0 \left\{ \left( \frac{\pi n_x}{d_x} \right)^2 + \left( \frac{\pi n_y}{d_y} \right)^2 \right\} \pm \bar{\lambda}_0 \left\{ \left( \frac{\pi n_x}{d_x} \right)^2 + \left( \frac{\pi n_y}{d_y} \right)^2 \right\}^{1/2} \right]$$

The EP photocurrent from NWs of II-VI materials is given by

$$I = \frac{\alpha_0 e g_v k_B T}{2\pi\hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} \left\{ F_0 \left\{ (k_B T)^{-1} [E_{F1d} - [G_{3,+}(n_x, n_y) + W - \hbar\nu]] \right\} + F_0 \left\{ (k_B T)^{-1} [E_{F1d} - [G_{3,-}(n_x, n_y) + W - \hbar\nu]] \right\} \right\} \quad (2.62)$$

The 1D electron statistics can be written as

$$n_{1D} = \frac{g_v \sqrt{2m_{\parallel}^* \pi k_B T}}{\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_{\frac{1}{2}}(\eta_{68,\pm}, \eta_{68,\pm} = (k_B T)^{-1} [E_{F1d} - [G_{3,\pm}(n_x, n_y)])]. \quad (2.63)$$

### 2.2.4 The EP from Nano Wires of HD IV-VI Semiconductors

#### (i) Dimmock Model

The 1D electron dispersion law in NW of HD IV-VI semiconductors can be expressed following (1.174) as

$$\begin{aligned}
 & \gamma_2(E, \eta_g) + \alpha\gamma_3(E, \eta_g) \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y\pi}{d_y} \right)^2 \right) + \alpha\gamma_3(E, \eta_g) \frac{\hbar^2}{2x_6} k_z^2 \\
 & - (1 + \alpha\gamma_3(E, \eta_g)) \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y\pi}{d_y} \right)^2 \right) \\
 & - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y\pi}{d_y} \right)^2 \right) \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y\pi}{d_y} \right)^2 \right) \\
 & - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y\pi}{d_y} \right)^2 \right) \frac{\hbar^2}{2x_6} k_z^2 \\
 & - (1 + \alpha\gamma_3(E, \eta_g)) \frac{\hbar^2}{2x_3} k_z^2 \\
 & - \alpha \frac{\hbar^2}{2x_3} k_z^2 \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y\pi}{d_y} \right)^2 \right) - \alpha \frac{\hbar^4 k_z^4}{4x_3x_6} \\
 & = \frac{\hbar^2}{2m_1} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2m_2} \left( \frac{n_y\pi}{d_y} \right)^2 + \frac{\hbar^2}{2m_3} k_z^2
 \end{aligned} \tag{2.64}$$

Equation (2.64) can be written as

$$k_z = T_{36}(E, \eta_g, n_x, n_y) \tag{2.65}$$

where

$$\begin{aligned}
 T_{36}(E, \eta_g, n_x, n_y) &= [(2C_{22})^{-1} [-B_{HD}(E, \eta_g, n_x, n_y) \\
 &+ \sqrt{B_{HD}^2(E, \eta_g, n_x, n_y) + 4C_{22}A_{HD}(E, \eta_g, n_x, n_y)}]]^{1/2} \\
 C_{22} &= (\alpha \frac{\hbar^4}{4x_3x_6}), B_{HD}(E, \eta_g, n_x, n_y) \\
 &= [\alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y\pi}{d_y} \right)^2 \right) \frac{\hbar^2}{2x_6} \\
 &+ (1 + \alpha\gamma_3(E, \eta_g)) \frac{\hbar^2}{2x_3} - \alpha\gamma_3(E, \eta_g) \frac{\hbar^2}{2x_6} \\
 &+ \frac{\hbar^2}{2m_3} + \alpha \frac{\hbar^2}{2x_3} \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x\pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y\pi}{d_y} \right)^2 \right)]
 \end{aligned}$$

and

$$\begin{aligned}
 A_{HD}(E, \eta_g, n_x, n_y) = & - \left[ \frac{\hbar^2}{2m_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2m_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right] \gamma_2(E, \eta_g) \\
 & + \alpha \gamma_3(E, \eta_g) \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 & - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 & \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 & - (1 + \alpha \gamma_3(E, \eta_g)) \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right)
 \end{aligned}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} F_0(\eta_{614HD}), \quad (2.66)$$

where

$$\eta_{614HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{14HDNW} + W - \hbar v)}{k_B T} \right], \quad (2.66)$$

and  $E'_{14HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = T_{36}(E'_{14HDNW}, \eta_g, n_x, n_y) \quad (2.67)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [T_{36}^2(E_{F1HDNW}, \eta_g, n_x, n_y)] \quad (2.68)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$\begin{aligned}
 n_{1D} = & \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [T_{36HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) \\
 & + T_{37HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)]
 \end{aligned} \quad (2.69)$$

where

$$T_{36HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = T_{36}(E_{F1HDNW}, n_x, n_y, \eta_g)$$

where  $T_{37HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = \sum_{r=1}^s L(r) [T_{36HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)]$ ,



The 1D electron dispersion law in NW of IV-VI semiconductors in the absence of band tails can be expressed as

$$\begin{aligned}
 E(1 + \alpha E) + \alpha E \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 + \alpha E \frac{\hbar^2}{2x_6} k_z^2 - (1 + \alpha E) \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \frac{\hbar^2}{2x_6} k_z^2 - (1 + \alpha E) \frac{\hbar^2}{2x_3} k_z^2 \\
 - \alpha \frac{\hbar^2}{2x_3} k_z^2 \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) - \alpha \frac{\hbar^4 k_z^4}{4x_3 x_6} \\
 = \frac{\hbar^2}{2m_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2m_2} \left( \frac{n_y \pi}{d_y} \right)^2 + \frac{\hbar^2}{2m_3} k_z^2
 \end{aligned} \tag{2.70}$$

Equation (2.70) can be written as

$$k_z = T_{40}(E, n_x, n_y) \tag{2.71}$$

where

$$\begin{aligned}
 T_{40}(E, n_x, n_y) = \frac{[(2C_{22})^{-1}[-B_0(E, n_x, n_y) \\
 + \sqrt{B_0^2(E, n_x, n_y) + 4C_{22}A_0(E, n_x, n_y)}]]^{1/2}}
 \end{aligned}$$

where

$$\begin{aligned}
 B_0(E, n_x, n_y) = \left[ \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \frac{\hbar^2}{2x_6} + (1 + \alpha E) \frac{\hbar^2}{2x_3} \right. \\
 \left. - \alpha E \frac{\hbar^2}{2x_6} + \frac{\hbar^2}{2m_3} + \alpha \frac{\hbar^2}{2x_3} \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \right]
 \end{aligned}$$

and

$$\begin{aligned}
 A_0(E, n_x, n_y) = \left[ - \left[ \frac{\hbar^2}{2m_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2m_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right] E(1 + \alpha E) \right. \\
 + \alpha E \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \\
 - \alpha \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \left( \frac{\hbar^2}{2x_4} \left( \frac{n_x \pi}{d_x} \right)^2 \right. \\
 \left. + \frac{\hbar^2}{2x_5} \left( \frac{n_y \pi}{d_y} \right)^2 \right) - (1 + \alpha E) \left( \frac{\hbar^2}{2x_1} \left( \frac{n_x \pi}{d_x} \right)^2 + \frac{\hbar^2}{2x_2} \left( \frac{n_y \pi}{d_y} \right)^2 \right) \left. \right]
 \end{aligned}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} F_0(\eta_{615}), \quad (2.72)$$

where

$$\eta_{615} \equiv \left[ \frac{E_{F1d} - (E'_{20} + W - h\nu)}{k_B T} \right],$$

and  $E'_{20}$  is the sub-band energy in this case which can be expressed as

$$0 = T_{40}(E'_{20}, n_x, n_y) \quad (2.73)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [T_{40}^2(E_{F1d}, n_x, n_y)] \quad (2.74)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [T_{40}(E_{F1d}, n_x, n_y) + T_{41}(E_{F1d}, n_x, n_y)] \quad (2.75)$$

where  $T_{41}(E_{F1d}, n_x, n_y) = \sum_{r=1}^s L(r) [T_{40}(E_{F1d}, n_x, n_y)]$ .

(ii) Bangert and Kastner Model

Following (1.194d), the 1D dispersion relation in NW of IV-VI semiconductors in accordance with the present model can be written as

$$F_1(E, \eta_g) \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right] + F_2(E, \eta_g) k_z^2 = 1 \quad (2.76)$$

The (2.76) can be written as

$$k_z = T_{60}(E, \eta_g, n_x, n_y) \quad (2.77)$$

where

$$T_{60}(E, \eta_g, n_x, n_y) = [[1 - F_1(E, \eta_g) \left[ \left( \frac{n_x \pi}{d_x} \right)^2 + \left( \frac{n_y \pi}{d_y} \right)^2 \right]] [F_2(E, \eta_g)]^{-1}]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{\max}} \sum_{n_y=1}^{n_{\max}} F_0(\eta_{615HD}), \quad (2.78)$$

where

$$\eta_{615HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{15HDNW} + W - h\nu)}{k_B T} \right],$$

and  $E'_{15HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = T_{60}(E'_{15HDNW}, \eta_g, n_x, n_y) \quad (2.79)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [T_{40}^2(E_{F1HDNW}, \eta_g, n_x, n_y)] \quad (2.80)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{\max}} \sum_{n_y=1}^{n_{\max}} [T_{50HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) + T_{51HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)] \quad (2.81)$$

where

$$T_{50HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = T_{40}(E_{F1HDNW}, n_x, n_y, \eta_g)$$

$$\text{and } T_{51HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = \sum_{r=1}^s L(r) [T_{50HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)],$$

The 1D dispersion relation in the absence of band tailing can be written in this case following (1.194b) as

$$\omega_1(E) \left[ \left( \frac{\pi n_x}{d_x} \right)^2 + \left( \frac{\pi n_y}{d_y} \right)^2 \right] + \omega_2(E) k_z^2 = 1 \quad (2.82)$$

The (2.82) can be written as

$$k_z = T_{61}(E, n_x, n_y) \quad (2.83)$$

where

$$T_{61}(E, n_x, n_y) = [[1 - \omega_1(E)[(\frac{n_x\pi}{d_x})^2 + (\frac{n_y\pi}{d_y})^2]][\omega_2(E)]^{-1}]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} F_0(\eta_{616}), \quad (2.84)$$

where

$$\eta_{616} \equiv \left[ \frac{E_{F1d} - (E'_{21} + W - h\nu)}{k_B T} \right],$$

and  $E'_{21}$  is the sub-band energy in this case which can be expressed as

$$0 = T_{61}(E'_{21}, n_x, n_y) \quad (2.85)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [T_{61}^2(E_{F1d}, n_x, n_y)] \quad (2.86)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [T_{61}(E_{F1d}, n_x, n_y) + T_{62}(E_{F1d}, n_x, n_y)] \quad (2.87)$$

where  $T_{62}(E_{F1d}, n_x, n_y) = \sum_{r=1}^S L(r)[T_{61}(E_{F1d}, n_x, n_y)]$ .

### 2.2.5 The EP from QWs of HD Stressed Kane Type Semiconductors

The 1D dispersion relation in this case can be written following (1.206) as

$$P_{11}(E, \eta_g) \left( \frac{\pi n_x}{d_x} \right)^2 + Q_{11}(E, \eta_g) \left( \frac{\pi n_y}{d_y} \right)^2 + S_{11}(E, \eta_g) k_z^2 = 1 \quad (2.88)$$

The (2.88) can be written as

$$k_z = T_{70}(E, \eta_g, n_x, n_y) \quad (2.89)$$

where

$$T_{70}(E, \eta_g, n_x, n_y) = [[1 - P_{11}(E, \eta_g) \left(\frac{\pi n_x}{d_x}\right)^2 + Q_{11}(E, \eta_g) \left(\frac{\pi n_y}{d_y}\right)^2] [S_{11}(E, \eta_g)]^{-1}]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} F_0(\eta_{630HD}), \quad (2.90)$$

where

$$\eta_{630HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{30HDNW} + W - \hbar\nu)}{k_B T} \right],$$

and  $E'_{30HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = T_{70}(E'_{30HDNW}, \eta_g, n_x, n_y) \quad (2.91)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [T_{70}^2(E_{F1HDNW}, \eta_g, n_x, n_y)] \quad (2.92)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [T_{70HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) + T_{71HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)] \quad (2.93)$$

where

$$T_{70HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = T_{70}(E_{F1HDNW}, n_x, n_y, \eta_g)$$

and

$$T_{71HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g) = \sum_{r=1}^s L(r) [T_{70HDNW}(E_{F1HDNW}, n_x, n_y, \eta_g)]$$

In the absence of band tailing the 1D dispersion relation in this case assumes the form

$$k_z = t_{70}(E, n_x, n_y) \quad (2.94)$$

where

$$t_{70}(E, n_x, n_y) = [\bar{c}_0(E)[1 - (\frac{\pi n_x}{d_x \bar{a}_0(E)})^2 - (\frac{\pi n_y}{d_y \bar{b}_0(E)})^2]]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} F_0(\eta_{642}), \quad (2.95)$$

where

$$\eta_{642} \equiv \left[ \frac{E_{F1d} - (E'_{42} + W - h\nu)}{k_B T} \right],$$

and  $E'_{42}$  is the sub-band energy in this case which can be expressed as

$$0 = t_{60}(E'_{42}, n_x, n_y) \quad (2.96)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_x, n_y) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [t_{60}^2(E_{F1d}, n_x, n_y)] \quad (2.97)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_x=1}^{n_{x\max}} \sum_{n_y=1}^{n_{y\max}} [t_{60}(E_{F1d}, n_x, n_y) + t_{61}(E_{F1d}, n_x, n_y)] \quad (2.98)$$

where  $t_{61}(E_{F1d}, n_x, n_y) = \sum_{r=1}^s L(r)[t_{60}(E_{F1d}, n_x, n_y)]$ .

### 2.2.6 The EP from Nano Wires of HD Te

The 1D dispersion relation may be written in this case following (1.235) as

$$k_x = t_{72}(E, n_y, n_z, \eta_g) \quad (2.99)$$

where

$$t_{72}(E, n_y, n_z, \eta_g) = \left[ -\left(\frac{n_y \pi}{d_y}\right)^2 + \psi_{5HD}(E, \eta_g) - \psi_6\left(\frac{\pi n_z}{d_z}\right)^2 \right. \\ \left. \pm \psi_7[\psi_{8HD}^2(E, \eta_g) - \left(\frac{\pi n_z}{d_z}\right)^2]^{1/2} \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{631HD}) \quad (2.100)$$

where

$$\eta_{631HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{31HDNW} + W - h\nu)}{k_B T} \right],$$

and  $E'_{31HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = t_{72}(E'_{31HDNW}, \eta_g, n_y, n_z) \quad (2.101)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [t_{72}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.102)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [t_{72HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + t_{73HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.103)$$

where

$$t_{72HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = t_{72}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$t_{73HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [t_{72HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)],$$

In the absence of band tailing the 1D dispersion relation in this case assumes the form

$$k_x = H_{70}(E, n_y, n_z) \quad (2.104)$$

where

$$H_{70}(E, n_y, n_z) = \left[ -\left( \frac{n_y \pi}{d_y} \right)^2 + \psi_5(E) - \psi_6 \left( \frac{\pi n_z}{d_z} \right)^2 \pm \psi_7 [\psi_8^2(E) - \left( \frac{\pi n_z}{d_z} \right)^2]^{1/2} \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{644}) \quad (2.105)$$

where

$$\eta_{644} \equiv \left[ \frac{E_{F1d} - (E'_{44} + W - h\nu)}{k_B T} \right],$$

and  $E'_{44}$  is the sub-band energy in this case which can be expressed as

$$0 = H_{70}(E'_{44}, n_y, n_z) \quad (2.106)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [H_{70}^2(E_{F1d}, n_y, n_z)] \quad (2.107)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [H_{70}(E_{F1d}, n_y, n_z) + H_{71}(E_{F1d}, n_y, n_z)] \quad (2.108)$$

where  $H_{71}(E_{F1d}, n_y, n_z) = \sum_{r=1}^s L(r) [H_{70}(E_{F1d}, n_y, n_z)]$ .

### 2.2.7 The EP from Nano Wires of HD GaP

The 1D dispersion relation may be written in this case following (1.253) as

$$k_x = u_{70}(E, n_y, n_z, \eta_g) \quad (2.109)$$

where

$$u_{70}(E, n_y, n_z, \eta_g) = \left[ -\left(\frac{n_y\pi}{d_y}\right)^2 + t_{11}\gamma_3(E, \eta_g) + t_{21} - t_{31}\left(\frac{n_z\pi}{d_z}\right)^2 - t_{41}\left[\left(\frac{n_z\pi}{d_z}\right)^2 + t_5^2(E, \eta_g)\right]^{1/2} \right]^{1/2}$$



The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{632HD}), \quad (2.110)$$

where

$$\eta_{632HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{32HDNW} + W - h\nu)}{k_B T} \right],$$

and  $E'_{32HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = u_{70}(E'_{32HDNW}, \eta_g, n_y, n_z) \quad (2.111)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [u_{70}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.112)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [u_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + u_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.113)$$

where

$$u_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = u_{70}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$u_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [u_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)],$$

In the absence of band tailing the 1D dispersion relation in this case can be written using (1.260) as

$$k_x = X_{71}(E, n_y, n_z) \quad (2.114)$$

where

$$X_{71}(E, n_y, n_z) = \left[ -\left( \frac{n_y \pi}{d_y} \right)^2 + t_{42}(E, n_z) \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{646}), \quad (2.115)$$

$$\text{where } \eta_{646} \equiv \left[ \frac{E_{F1d} - (E'_{46} + W - \hbar\nu)}{k_B T} \right],$$

and  $E'_{46}$  is the sub-band energy in this case which can be expressed as

$$0 = X_{71}(E'_{46}, n_y, n_z) \quad (2.116)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [X_{71}^2(E_{F1d}, n_y, n_z)] \quad (2.117)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [X_{71}(E_{F1d}, n_y, n_z) + X_{72}(E_{F1d}, n_y, n_z)] \quad (2.118)$$

where  $X_{72}(E_{F1d}, n_y, n_z) = \sum_{r=1}^s L(r) [X_{71}(E_{F1d}, n_y, n_z)]$ .

### 2.2.8 The EP from Nano Wires of HD PtSb<sub>2</sub>

The 1D dispersion relation may be written in this case following (1.275) as

$$k_x = V_{70}(E, n_y, n_z, \eta_g) \quad (2.119)$$

where  $V_{70}(E, n_y, n_z, \eta_g) = [-(\frac{n_y\pi}{d_y})^2 + A_{60}(E, \eta_g, n_y)]^{1/2}$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{634HD}), \quad (2.120)$$

where

$$\eta_{634HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{34HDNW} + W - \hbar\nu)}{k_B T} \right],$$

and  $E'_{34HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = V_{70}(E'_{34HDNW}, \eta_g, n_y, n_z) \quad (2.121)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [V_{70}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.122)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [V_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + V_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.123)$$

where

$$V_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = V_{70}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$V_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [V_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)],$$

In the absence of band tailing the 1D dispersion relation in this case can be written using (1.278) as

$$k_x = D_{71}(E, n_y, n_z) \quad (2.124)$$

where

$$D_{71}(E, n_y, n_z) = \left[ -\left( \frac{n_y \pi}{d_y} \right)^2 + t_{44}(E, n_z) \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{648}), \quad (2.125)$$

where

$$\eta_{648} \equiv \left[ \frac{E_{F1d} - (E'_{48} + W - \hbar \nu)}{k_B T} \right],$$

and  $E'_{48}$  is the sub-band energy in this case which can be expressed as

$$0 = D_{71}(E'_{48}, n_y, n_z) \quad (2.126)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [D_{71}^2(E_{F1d}, n_y, n_z)] \quad (2.127)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [D_{71}(E_{F1d}, n_y, n_z) + D_{72}(E_{F1d}, n_y, n_z)] \quad (2.128a)$$

where  $D_{72}(E_{F1d}, n_y, n_z) = \sum_{r=1}^s L(r) [D_{71}(E_{F1d}, n_y, n_z)]$ .

### 2.2.9 The EP from Nano Wires of HD $Bi_2Te_3$

The dispersion relation in this case can be written following (1.285) as

$$k_x = J_{70}(E, n_y, n_z, \eta_g) \quad (2.128b)$$

where

$$J_{70}(E, n_y, n_z, \eta_g) = \left[ [\gamma_2(E, \eta_g) - \bar{\omega}_2 \left( \frac{n_y \pi}{d_y} \right)^2 - \bar{\omega}_3 \left( \frac{n_z \pi}{d_z} \right)^2 - 2\bar{\omega}_4 \frac{n_y n_z \pi^2}{d_y d_z}] (\bar{\omega}_1)^{-1} \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{650HD}), \quad (2.129)$$

where

$$\eta_{650HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{50HDNW} + W - \hbar v)}{k_B T} \right],$$

and  $E'_{50HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = J_{70}(E'_{50HDNW}, \eta_g, n_y, n_z) \quad (2.130)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [J_{70}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.131)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [J_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + J_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.132)$$

where

$$J_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = J_{70}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$J_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [J_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)],$$

In the absence of band tailing the 1D dispersion relation in this case can be written using (1.278) as

$$k_x = B_{71}(E, n_y, n_z) \quad (2.133)$$

where

$$B_{71}(E, n_y, n_z) = [[E(1 + \alpha E) - \bar{w}_2 \left( \frac{n_y \pi}{d_y} \right)^2 - \bar{w}_3 \left( \frac{n_z \pi}{d_z} \right)^2 - 2\bar{w}_4 \frac{n_y n_z \pi^2}{d_y d_z}] (\bar{w}_1)^{-1}]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{650}), \quad (2.134)$$

where

$$\eta_{650} \equiv \left[ \frac{E_{F1d} - (E'_{50} + W - h\nu)}{k_B T} \right],$$

and  $E'_{50}$  is the sub-band energy in this case which can be expressed as

$$0 = B_{71}(E'_{50}, n_y, n_z) \quad (2.135)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [B_{71}^2(E_{F1d}, n_y, n_z)] \quad (2.136)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [B_{71}(E_{F1d}, n_y, n_z) + B_{72}(E_{F1d}, n_y, n_z)] \quad (2.137)$$

where  $B_{72}(E_{F1d}, n_y, n_z) = \sum_{r=1}^S L(r) [B_{71}(E_{F1d}, n_y, n_z)]$ .

### 2.2.10 The EP from Nano Wires of HD Ge

(a) Model of Cardona et al.

The dispersion relation in accordance with this model in the present case can be written following (1.306b) as

$$k_x = L_{70}(E, n_y, n_z, \eta_g) \quad (2.138)$$

where

$$\begin{aligned} L_{70}(E, n_y, n_z, \eta_g) = & [[\gamma_2(E, \eta_g) + \alpha \left[ \frac{\hbar^2}{2m_{\parallel}^*} \left( \frac{n_z \pi}{d_z} \right)^2 \right]^2 \\ & - (1 + 2\alpha \gamma_3(E, \eta_g)) \frac{\hbar^2}{2m_{\parallel}^*} \left( \frac{n_z \pi}{d_z} \right)^2 \left( \frac{2m_{\parallel}^*}{\hbar^2} \right)]^{1/2} \end{aligned}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{652HD}), \quad (2.139)$$

where

$$\eta_{652HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{52HDNW} + W - \hbar \nu)}{k_B T} \right],$$

and  $E'_{52HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = L_{70}(E'_{52HDNW}, \eta_g, n_y, n_z) \quad (2.140)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [L_{70}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.141)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [L_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + L_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.142)$$

where

$$L_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = L_{70}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$L_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [L_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$$

In the absence of band tailing the 1D dispersion relation in this case can be written using (1.278) as

$$k_x = B_{77}(E, n_y, n_z) \quad (2.143)$$

where

$$B_{77}(E, n_y, n_z) = \left[ [E(1 + \alpha E) + \alpha \left[ \frac{\hbar^2}{2m_{\parallel}^*} \left( \frac{n_z \pi}{d_z} \right)^2 \right]^2 - (1 + 2\alpha E) \frac{\hbar^2}{2m_{\parallel}^*} \left( \frac{n_z \pi}{d_z} \right)^2] \left( \frac{2m_{\parallel}^*}{\hbar^2} \right) \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{660}), \quad (2.144)$$

where

$$\eta_{660} \equiv \left[ \frac{E_{F1d} - (E'_{60} + W - \hbar \nu)}{k_B T} \right],$$

and  $E'_{60}$  is the sub-band energy in this case which can be expressed as

$$0 = B_{77}(E'_{60}, n_y, n_z) \quad (2.145)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [B_{77}^2(E_{F1d}, n_y, n_z)] \quad (2.146)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [B_{77}(E_{F1d}, n_y, n_z) + B_{78}(E_{F1d}, n_y, n_z)] \quad (2.147)$$

where  $B_{78}(E_{F1d}, n_y, n_z) = \sum_{r=1}^s L(r)[B_{77}(E_{F1d}, n_y, n_z)]$ .

(b) Model of Wang et al.

The dispersion relation in accordance with this model in the present case can be written following (1.326) as

$$k_x = \beta_{70}(E, n_y, n_z, \eta_g) \quad (2.148)$$

where

$$\beta_{70}(E, n_y, n_z, \eta_g) = \left[ -\left(\frac{n_y \pi}{d_y}\right)^2 + \frac{2m^*}{\hbar^2} \left[ \bar{\alpha}_8 - \bar{\alpha}_9 \left(\frac{\pi n_z}{d_z}\right)^2 - \bar{\alpha}_{10} \left(\frac{\pi n_z}{d_z}\right)^4 + \bar{\alpha}_{11} \left(\frac{\pi n_z}{d_z}\right)^2 + \bar{\alpha}_{12}(E, \eta_g) \right]^{1/2} \right]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{654HD}) \quad (2.149)$$

where

$$\eta_{654HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{54HDNW} + W - h\nu)}{k_B T} \right],$$

and  $E'_{54HDNW}$  is the sub-band energy in this case which can be expressed as

$$0 = \beta_{70}(E'_{54HDNW}, \eta_g, n_y, n_z) \quad (2.150)$$



The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [\beta_{70}^2(E_{F1HDNW}, \eta_g, n_y, n_z)] \quad (2.151)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [\beta_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + \beta_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.152)$$

where

$$\beta_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \beta_{70}(E_{F1HDNW}, n_y, n_z, \eta_g)$$

and

$$\beta_{71HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [\beta_{70HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$$

In the absence of band tailing the 1D dispersion relation in this case can be written using (1.278) as

$$k_x = P_{77}(E, n_y, n_z) \quad (2.153)$$

where

$$P_{77}(E, n_y, n_z) = [[I_1(E, n_z) - \frac{\hbar^2}{2m_2^*} (\frac{n_y \pi}{d_y})^2] (\frac{2m_1^*}{\hbar^2})]^{1/2}$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{2\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{680}), \quad (2.154)$$

where

$$\eta_{680} \equiv \left[ \frac{E_{F1d} - (E'_{80} + W - h\nu)}{k_B T} \right],$$

and  $E'_{80}$  is the sub-band energy in this case which can be expressed as

$$0 = P_{77}(E'_{80}, n_y, n_z) \quad (2.155)$$

The EEM in this case is given by

$$m^*(E_{F1d}, n_y, n_z) = \frac{\hbar^2}{2} \frac{\partial}{\partial E} [P_{77}^2(E_{F1d}, n_y, n_z)] \quad (2.156)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [P_{77}(E_{F1d}, n_y, n_z) + P_{78}(E_{F1d}, n_y, n_z)] \quad (2.157)$$

where  $P_{78}(E_{F1d}, n_y, n_z) = \sum_{r=1}^s L(r) [P_{77}(E_{F1d}, n_y, n_z)]$ .

### 2.2.11 The EP from Nano Wires of HD GaSb

The dispersion relation of the 1D electrons in this case can be written as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} + \frac{\hbar^2k_x^2}{2m_c} = I_{36}(E, \eta_g) \quad (2.158)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{100HD}), \quad (2.159)$$

where

$$\eta_{100HD} \equiv \left[ \frac{E_{F1HDNW} - (E'_{100HDNW} + W - h\nu)}{k_B T} \right]$$

and  $E'_{100HDNW}$  is the sub-band energy in this case which can be expressed as

$$\frac{\hbar^2(n_z\pi/d_z)^2}{2m_c} + \frac{\hbar^2(n_y\pi/d_y)^2}{2m_c} = I_{36}(E'_{100HDNW}, \eta_g) \quad (2.160)$$

The EEM in this case is given by

$$m^*(E_{F1HDNW}, \eta_g) = m_c [I'_{36}(E_{F1HDNW}, \eta_g)] \quad (2.161)$$

Thus, it appears that the evaluation of  $J_{1D}$  requires an expression of carrier statistics which can, in turn, be written as

$$n_{1D} = \left( \frac{2g_v}{\pi} \right) \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [R_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) + R_{8HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)] \quad (2.162)$$

where

$$R_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \left[ I_{36}(E_{F1HDNW}, \eta_g) - \frac{\hbar^2 (n_z \pi / d_z)^2}{2m_c} - \frac{\hbar^2 (n_y \pi / d_y)^2}{2m_c} \right] \frac{2m_c}{\hbar^2}]^{1/2}$$

where  $R_{8HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g) = \sum_{r=1}^s L(r) [R_{7HDNW}(E_{F1HDNW}, n_y, n_z, \eta_g)]$

The expression of 1D dispersion relation, for NWs of GaSb whose energy band structures in the absence of band tailing assumes the form

$$I_{36}(E) = \frac{\hbar^2 k_x^2}{2m_c} + G_2(n_y, n_z) \quad (2.163)$$

In this case, the quantized energy  $E'_{101}$  is given by

$$I_{36}(E'_{101}) = G_2(n_y, n_z) \quad (2.164)$$

The EP in this case is given by

$$I = \frac{\alpha_o e g_v k_B T}{\pi \hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} F_0(\eta_{101}), \quad (2.165)$$

where

$$\eta_{101} \equiv \left[ \frac{E_{F1d} - (E'_{101} + W - \hbar v)}{k_B T} \right]$$

The carrier statistics in the case can be expressed as

$$n_{1D} = \frac{2g_v}{\pi} \frac{\sqrt{2m_c}}{\hbar} \sum_{n_y=1}^{n_{y\max}} \sum_{n_z=1}^{n_{z\max}} [R_{101}(E_{F1d}, n_y, n_z) + R_{102}(E_{F1d}, n_y, n_z)] \quad (2.166)$$

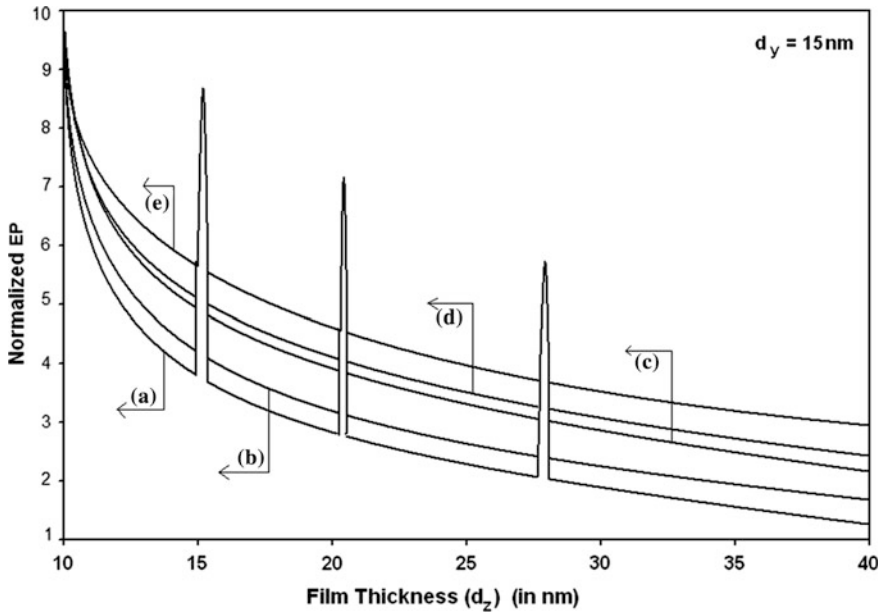
where

$$R_{101}(E_{F1d}, n_y, n_z) \equiv [I_{36}(E_{F1d}) - G_2(n_y, n_z)]^{1/2},$$

$$R_{102}(E_{F1d}, n_y, n_z) \equiv \sum_{r=1}^s L(r) [R_{101}(E_{F1d}, n_y, n_z)].$$

## 2.3 Results and Discussion

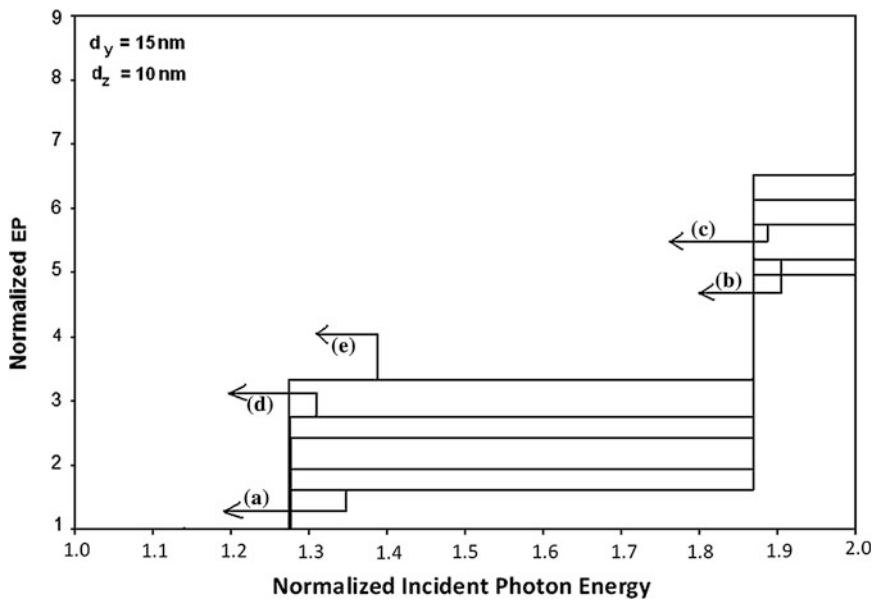
Using the appropriate equations and taking the energy band constants as given in the Table 1.1, we have plotted the normalized EP from NWs of HD CdGeAs<sub>2</sub> (an example of nonlinear optical materials) as a function of  $d_x$  as shown in plot (a) of Fig. 2.1, in which the plot (b) corresponds to  $\delta = 0$ . The plot (c) has been drawn in accordance with the three band model of Kane and the plot (d) refers to the two band model of Kane together with the plot (e) exhibiting the variation in accordance with the parabolic energy bands for the overall assessments of the energy band constants on the EP in this case. The Fig. 2.2 exhibits the plots of the normalized EP from NWs of HD CdGeAs<sub>2</sub> as a function of the normalized incident photon energy



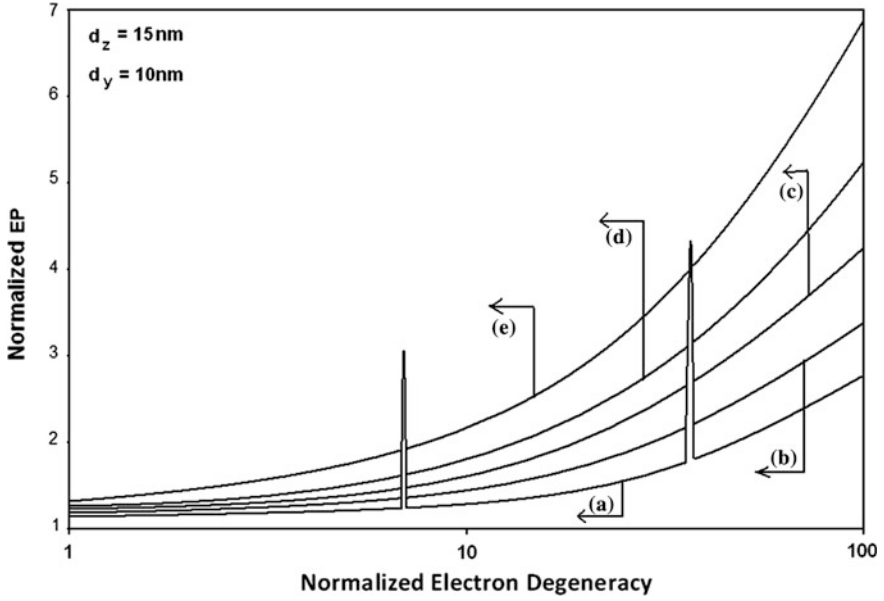
**Fig. 2.1** Plot of the normalized EP from NWs of HD CdGeAs<sub>2</sub> as a function of  $d_x$  in accordance with *a* a generalized band model, *b*  $\delta = 0$ , *c* the three-band model of Kane, *d* the two band model of Kane and *e* the parabolic energy bands

for all cases Figs. 2.1 and 2.3 shows the dependence of the said variable on the normalized electron degeneracy for all cases of Fig. 2.1.

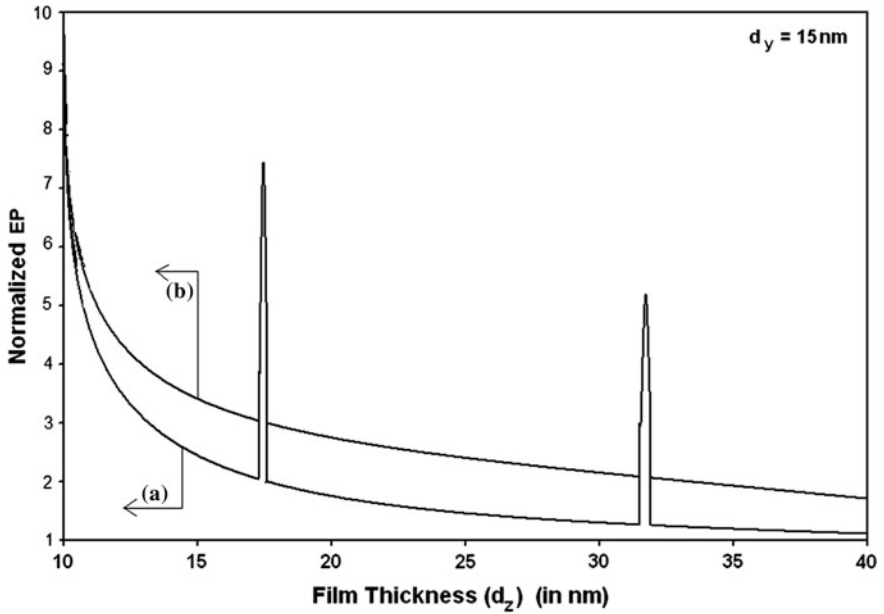
The normalized EP from NWs of HD n-InAs (an example of III-V materials) in accordance with the HD three and two band models of Kane as functions of film thickness, normalized incident photon energy and the normalized electron degeneracy have, respectively, been presented in Figs. 2.4, 2.5 and 2.6. The Figs. 2.7, 2.8 and 2.9 exhibit the variations of normalized EP from NWs of HD n-InSb as functions of film thickness, normalized incident photon energy and the normalized electron degeneracy respectively. The variations of the normalized EP from NWs of HD CdS (an example of II-VI materials) as functions of thickness, normalized incident photon energy and normalized electron degeneracy have respectively been drawn in Figs. 2.10, 2.11 and 2.12, where the plots for  $\bar{\lambda}_0 = 0$  have further been drawn for the purpose of assessing the influence of the splitting of the two-spin states by the spin orbit coupling and the crystalline field. The thickness, normalized photon energy and the normalized electron degeneracy dependences of normalized EP from NWs of HD GaP have been shown in Figs. 2.13, 2.14 and 2.15 respectively. The dependence of normalized EP with reference to the aforementioned variables from NWs of HD n-Ge and PtSb<sub>2</sub>, has been shown in Figs. 2.16, 2.17, 2.18, 2.19, 2.20 and 2.21 in accordance with the HD models of Cardona et al., Wang and Ressler and Emtage respectively. Figures 2.22, 2.23 and 2.24 manifest the variations of the normalized EP from from NWs of HD stressed n-InSb as



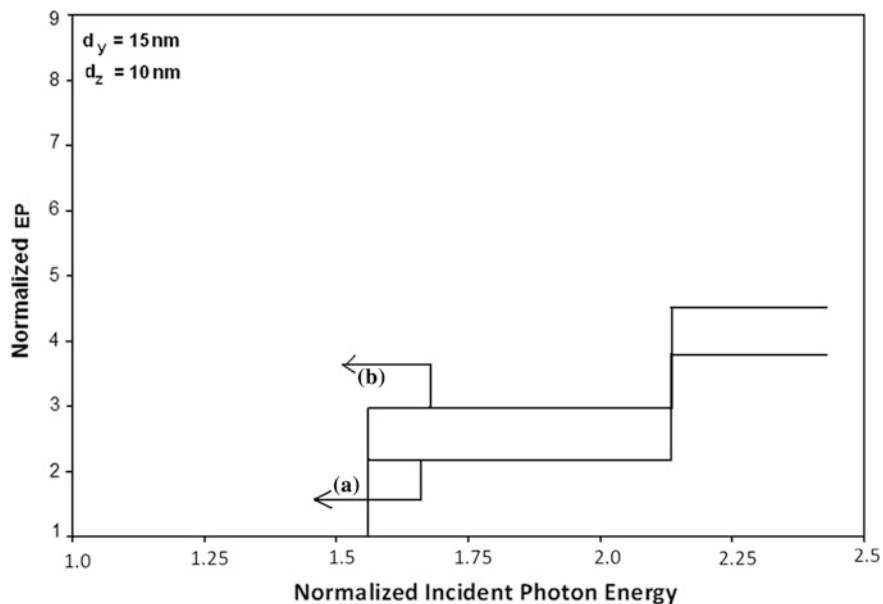
**Fig. 2.2** Plot of the normalized EP from NWs of HD CdGeAs<sub>2</sub> as a function of normalized incident photon energy for all cases of Fig. 2.1



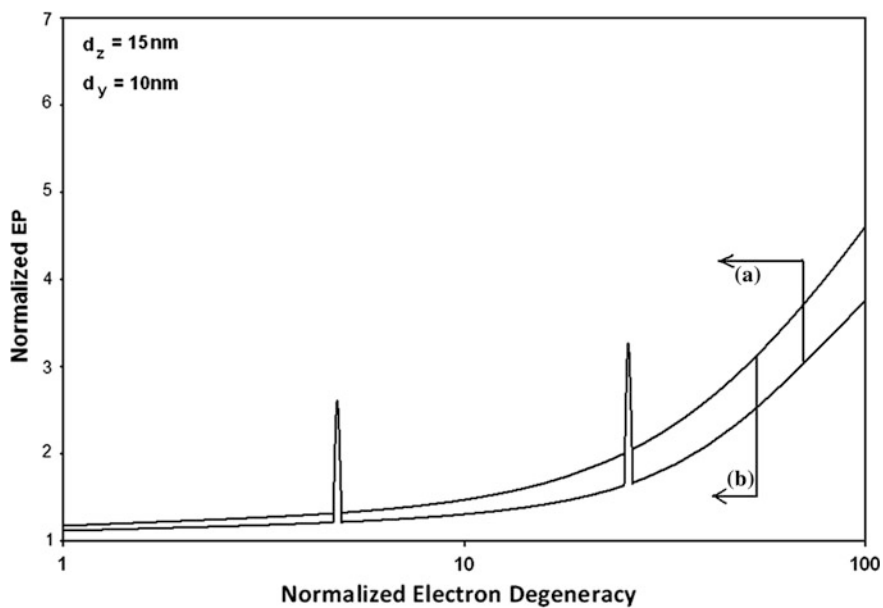
**Fig. 2.3** Plot of the normalized EP from NWs of HD CdGeAs<sub>2</sub> as a function of normalized electron degeneracy for all cases of Fig. 2.1



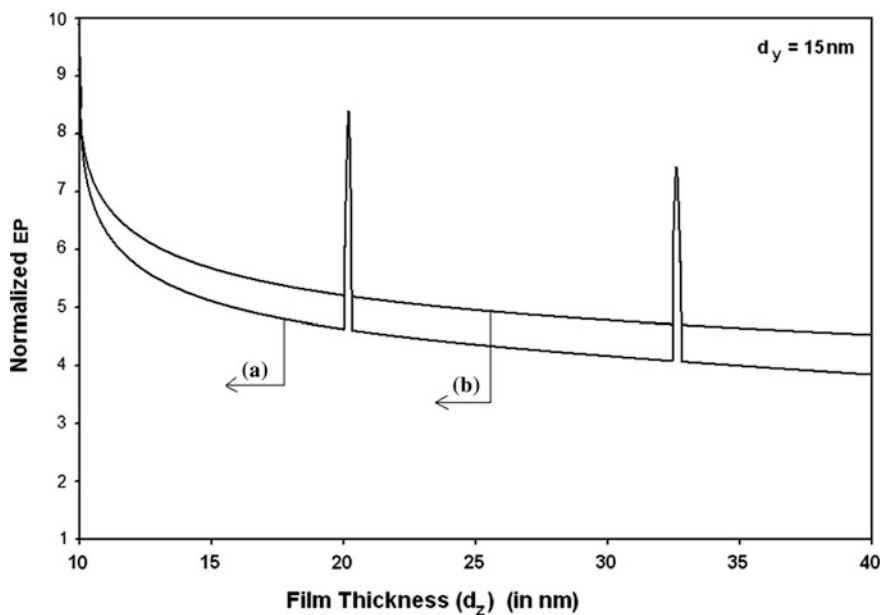
**Fig. 2.4** Plot of the normalized EP from NWs of HD n-InAs as a function of  $d_z$  in accordance with *a* the three band model of Kane and *b* the two band model of Kane



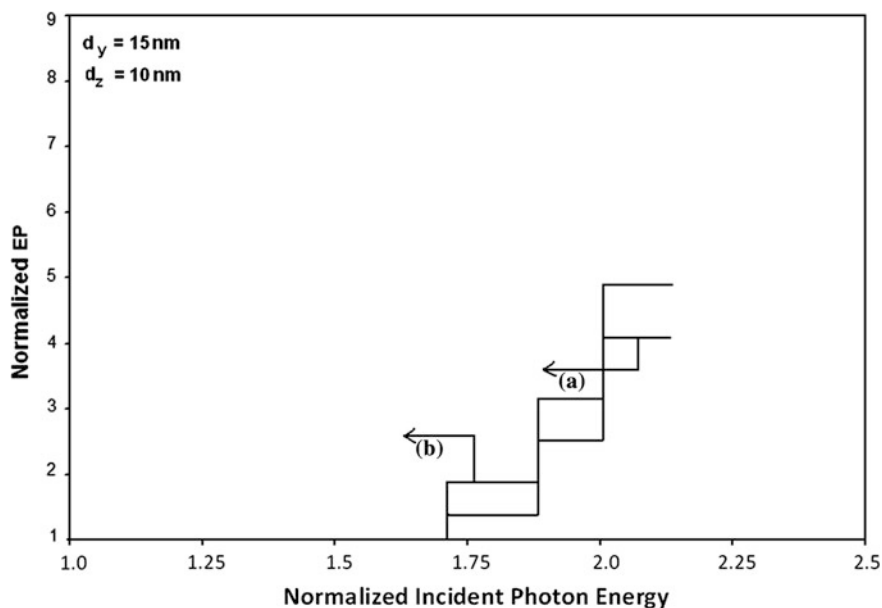
**Fig. 2.5** Plot of the normalized EP from NWs of HD n-InAs as a function of normalized incident photon energy in accordance with *a* the three band model of Kane and *b* the two band model of Kane



**Fig. 2.6** Plot of the normalized EP from NWs of HD n-InAs as a function of normalized electron degeneracy in accordance with *a* the three band model of Kane and *b* the two band model of Kane

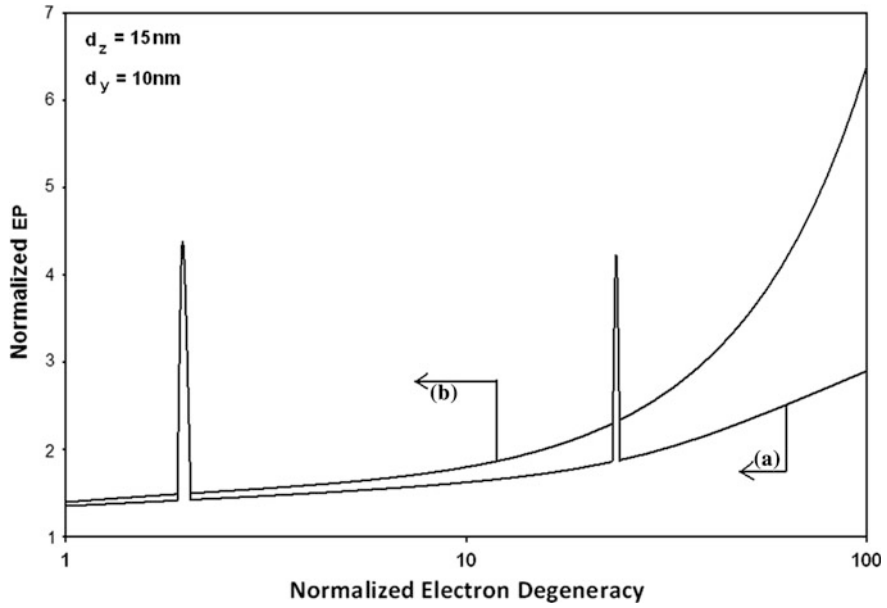


**Fig. 2.7** Plot of the normalized EP from NWs of HD n-InSb as a function of  $d_z$  in accordance with *a* the three band model of Kane and *b* the two band model of Kane

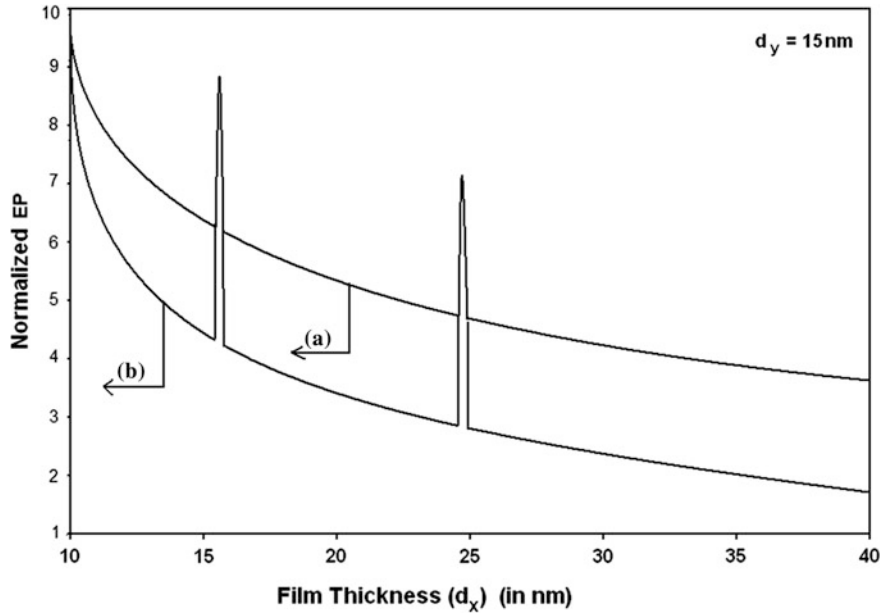


**Fig. 2.8** Plot of the normalized EP from NWs of HD n-InSb as a function of normalized incident photon energy in accordance with *a* the three band model of Kane and *b* the two band model of Kane

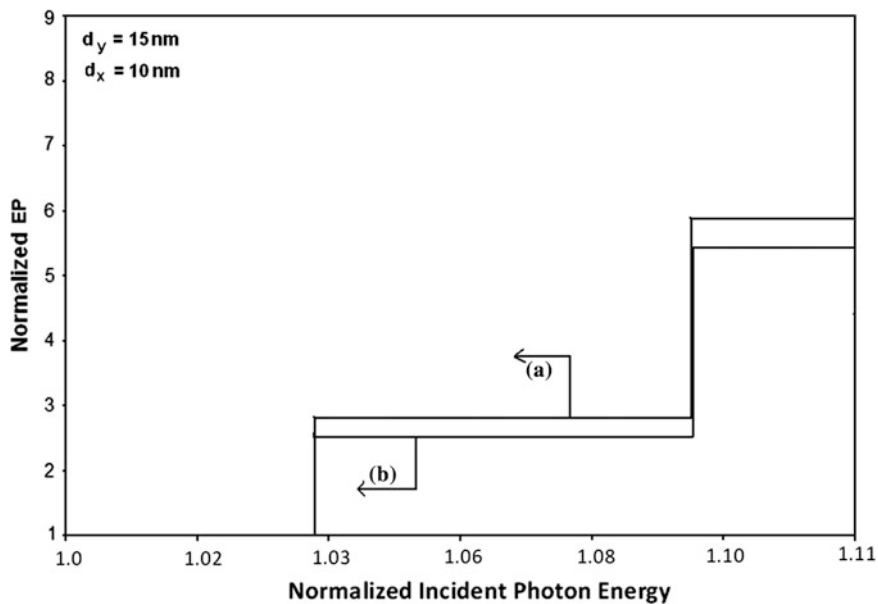




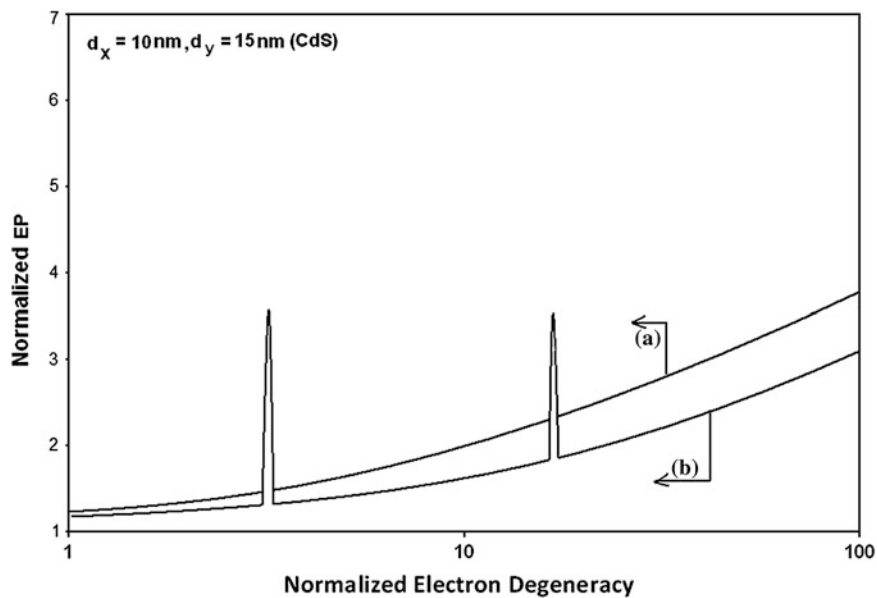
**Fig. 2.9** Plot of the normalized EP from NWs of HD n-InSb as a function of normalized electron degeneracy in accordance with *a* the three band model of Kane and *b* the two band model of Kane



**Fig. 2.10** Plot of the normalized EP from NWs of HD CdS as a function of  $d_z$  with  $a \bar{\lambda}_0 \neq 0$  and  $b \bar{\lambda}_0 = 0$



**Fig. 2.11** Plot of the normalized EP from NWs of HD CdS as a function of normalized incident photon energy with  $a \bar{\lambda}_0 \neq 0$  and  $b \bar{\lambda}_0 = 0$



**Fig. 2.12** Plot of the normalized EP from NWs of HD CdS as a function of normalized electron degeneracy with  $a \bar{\lambda}_0 \neq 0$  and  $b \bar{\lambda}_0 = 0$

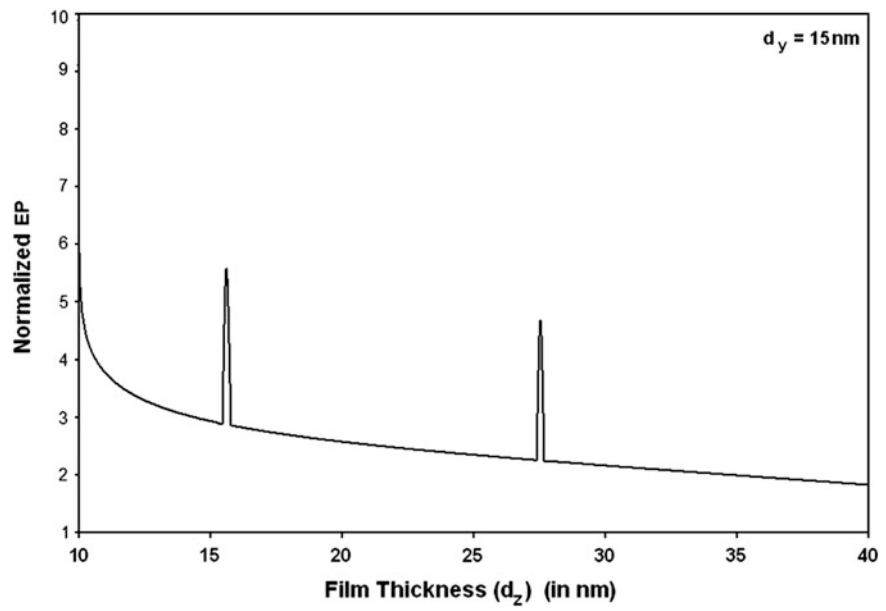


Fig. 2.13 Plot of the normalized EP from NWs of HD n-GaP as a function of  $d_z$

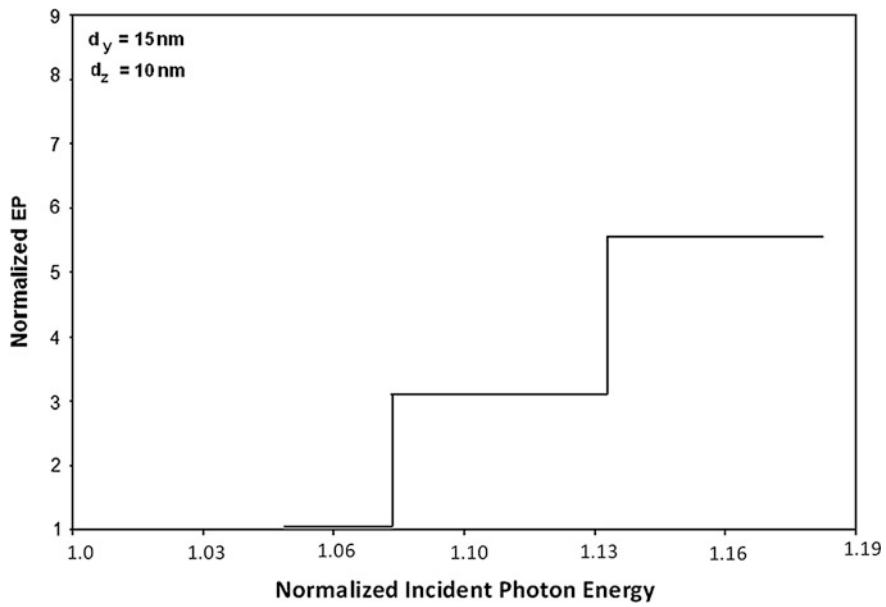
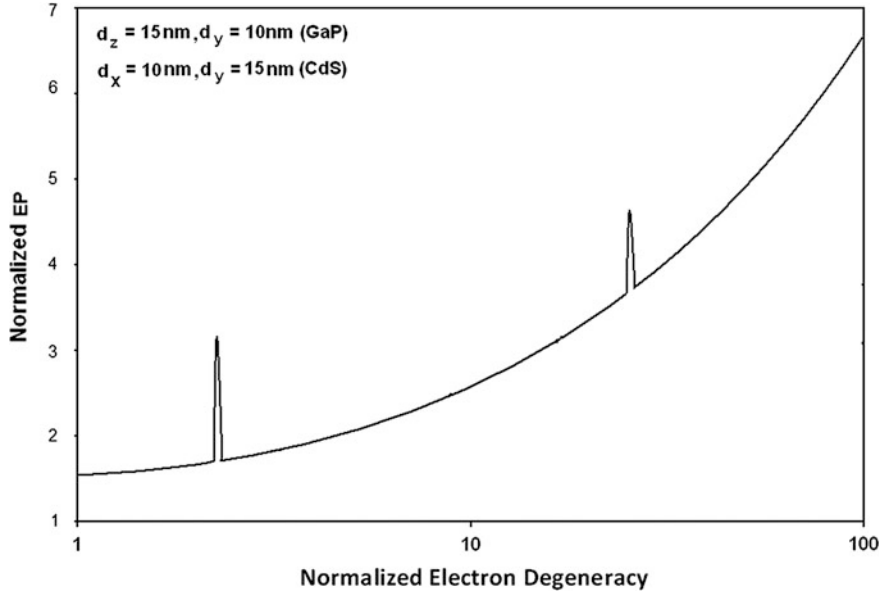
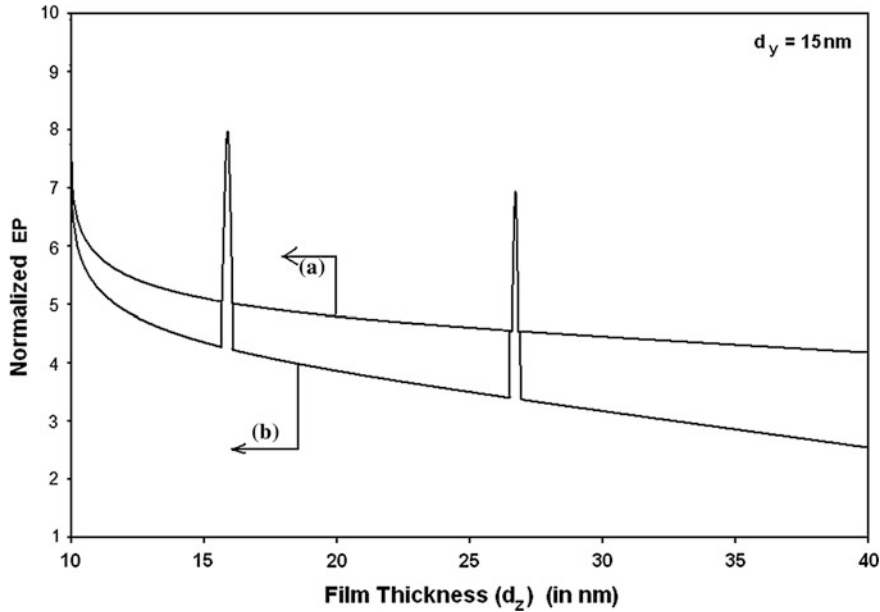


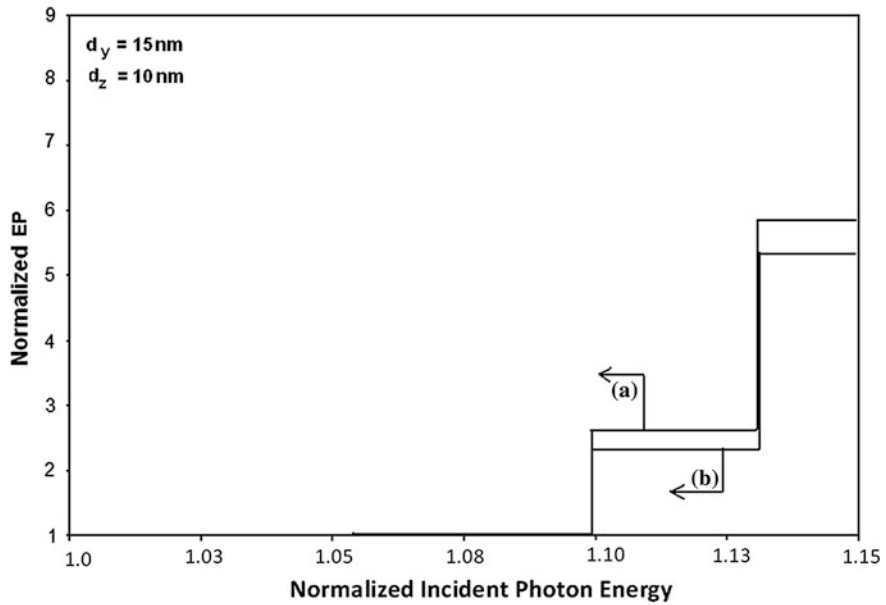
Fig. 2.14 Plot of the normalized EP from NWs of HD n-GaP as a function of normalized incident photon energy



**Fig. 2.15** Plot of the normalized EP from NWs of HD n-GaP as a function of normalized electron degeneracy



**Fig. 2.16** Plot of the normalized EP from NWs of HD n-Ge as a function of thickness in accordance with the models of *a* Cardona et al. and *b* Wang et al.

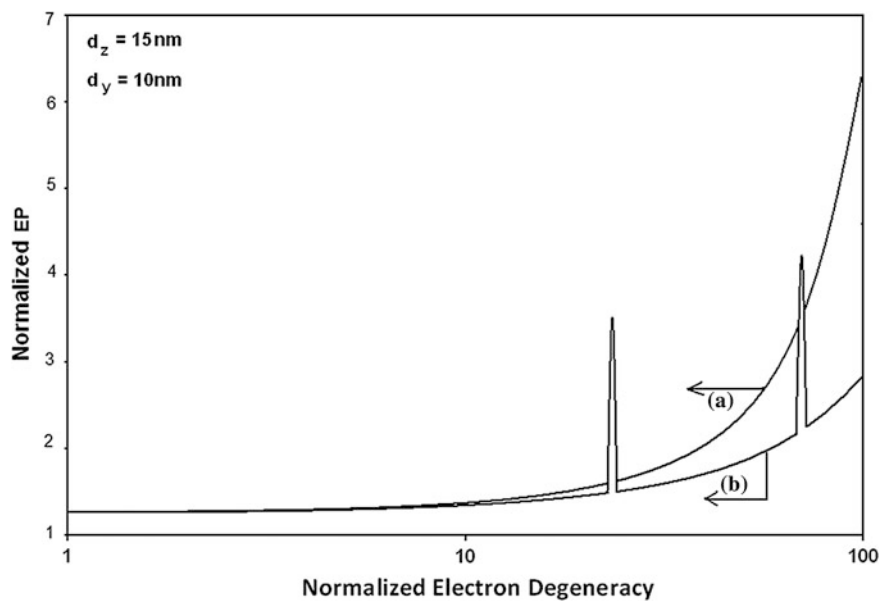


**Fig. 2.17** Plot of the normalized EP from NWs of HD n-Ge as a function of normalized incident photon energy for all the cases of Fig. 2.16

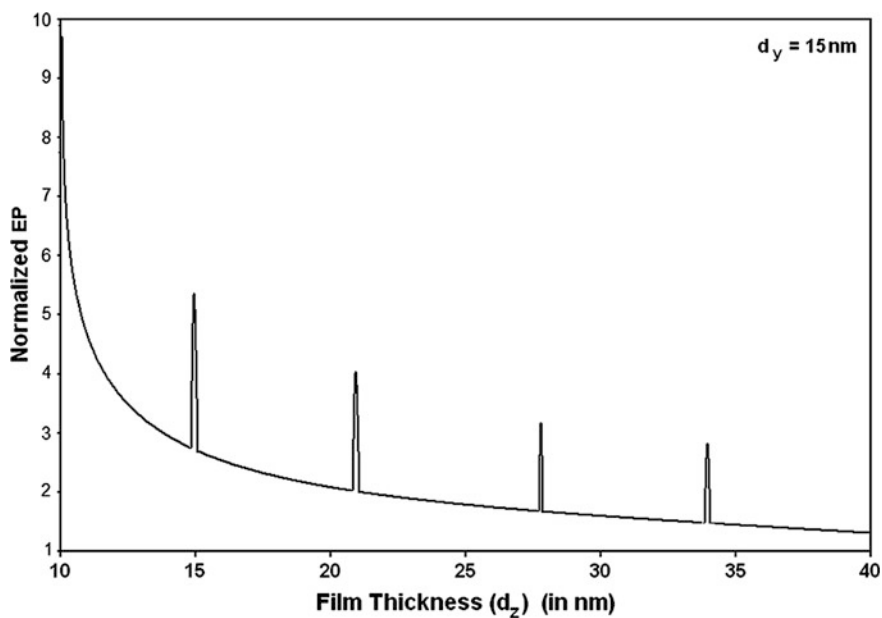
functions of the film thickness, normalized incident photon energy and the normalized electron degeneracy respectively.

The Figs. 2.25, 2.26 and 2.27 exhibit the normalized EP as functions of film thickness, normalized incident photon energy and normalized electron degeneracy from NWs of HD PbTe as a function of film thickness in accordance with the models of (a) the Dimmok and (b) the Bangert and Kastner respectively. The plots (c) and (d) exhibit the same for PbSe.

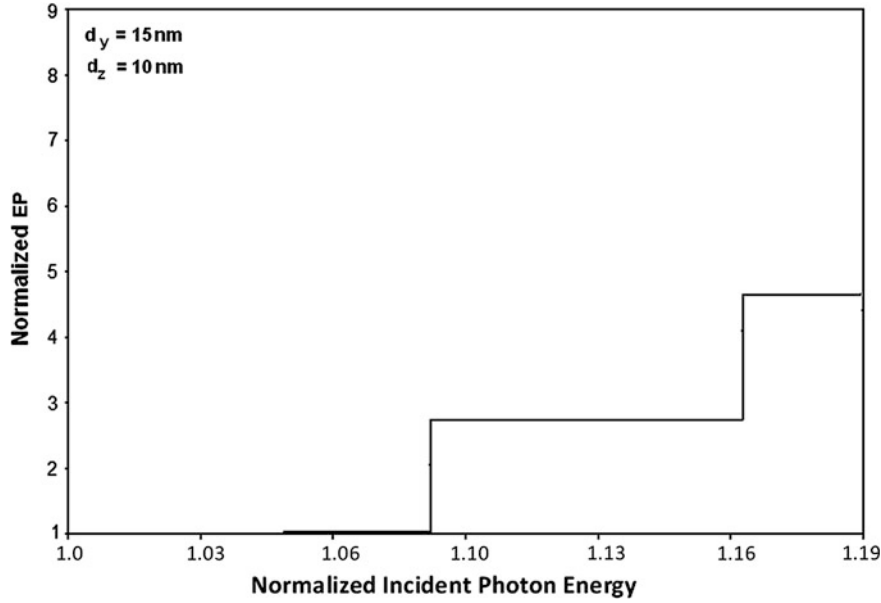
The influence of quantum confinement is immediately apparent from Figs. 2.1, 2.4, 2.7, 2.10, 2.13, 2.16, 2.19, 2.22 and 2.25. Since the EP depends strongly on the thickness of the quantum-confined materials in contrast with the corresponding bulk specimens. The EP decreases with increasing film thickness in an oscillatory way with different numerical magnitudes for HD NWs as compared with HD QWs. It appears from the aforementioned figures that the EP exhibits spikes for particular values of film thickness which, in turn, depends on the particular band structure of the specific material. Moreover, the EP from HD NWs of different compounds can become several orders of magnitude larger than of bulk specimens of the same materials, which is also a direct signature of quantum confinement. This oscillatory dependence will be less and less prominent with increasing film thickness. It appears from Figs. 2.3, 2.6, 2.9, 2.12, 2.15, 2.18, 2.21 and 2.24 that the EP increases with increasing degeneracy and also exhibits spikes for all types of quantum confinement as considered in this chapter. For bulk specimens of the same material, the EP will be found to increase continuously with increasing electron



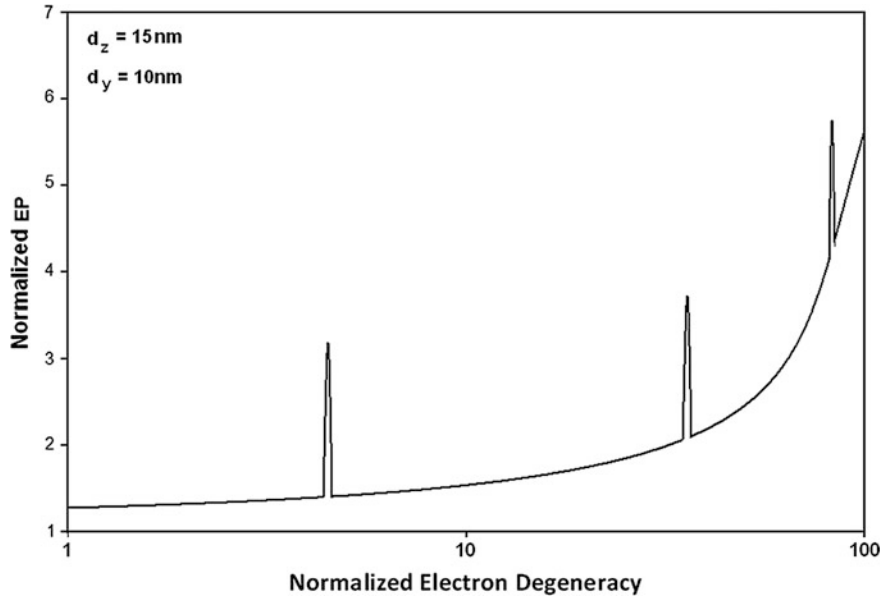
**Fig. 2.18** Plot of the normalized EP from NWs of HD n-Ge as a function of normalized electron degeneracy for all the cases of Fig. 2.16



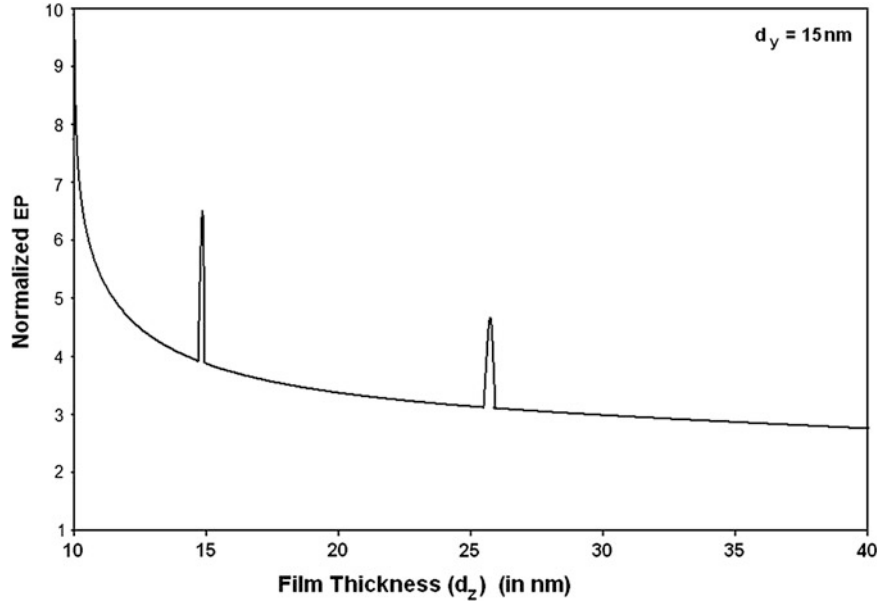
**Fig. 2.19** Plot of the normalized EP from NWs of HD n-PtSb<sub>2</sub> as a function of film thickness



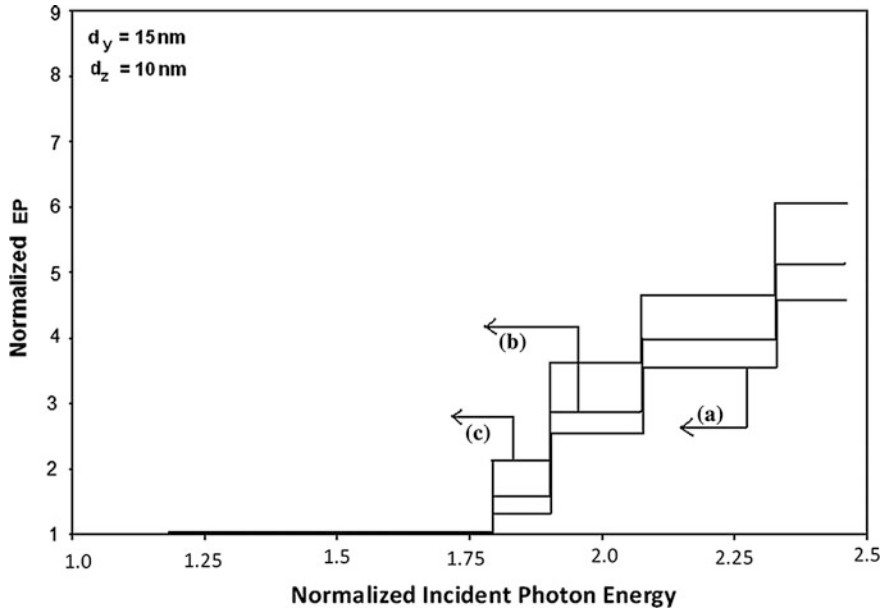
**Fig. 2.20** Plot of the normalized EP from NWs of HD n-PtSb<sub>2</sub> as a function of normalized incident photon energy



**Fig. 2.21** Plot of the normalized EP from NWs of HD n-PtSb<sub>2</sub> as a function of normalized electron degeneracy

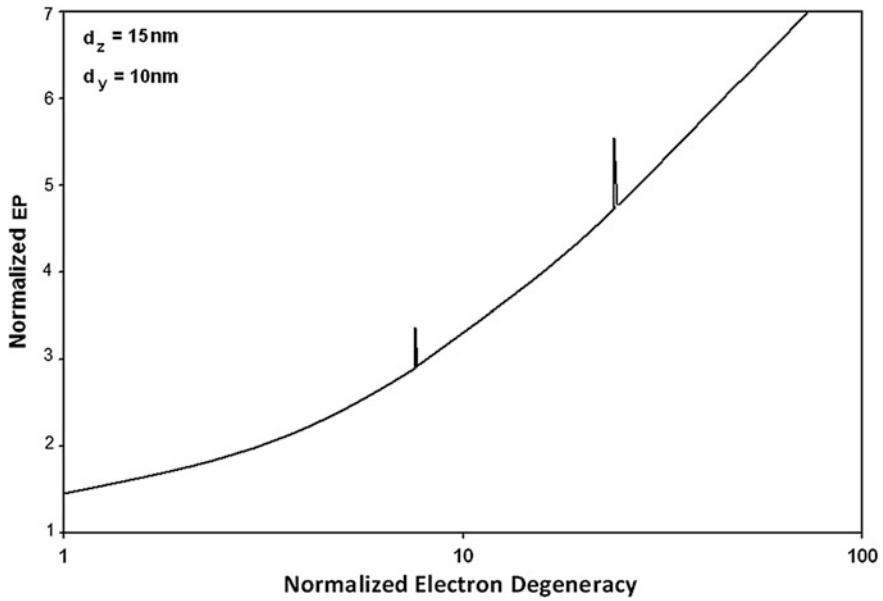


**Fig. 2.22** Plot of the normalized EP from NWs of HD stressed n-InSb as a function of film thickness

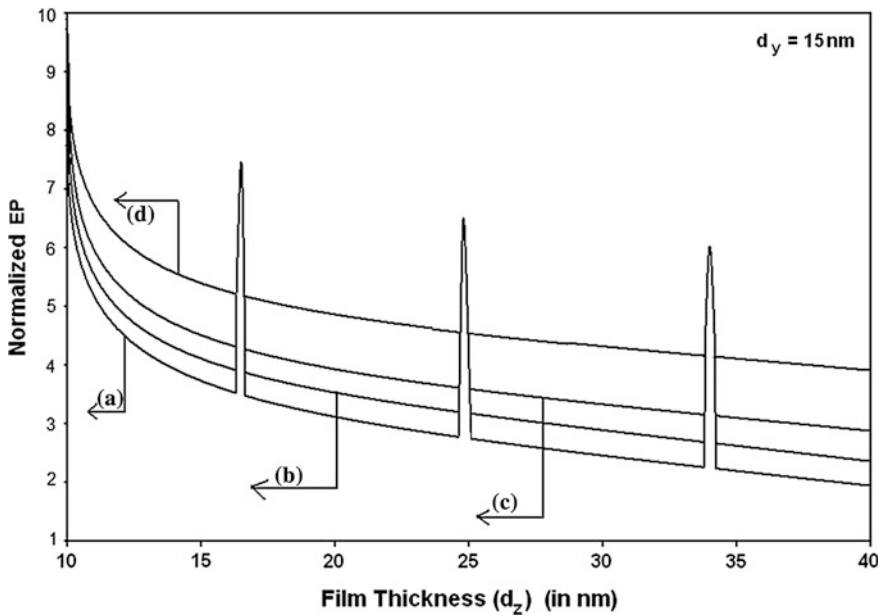


**Fig. 2.23** Plot of the normalized EP from NWs of HD stressed n-InSb as a function of normalized incident photon energy

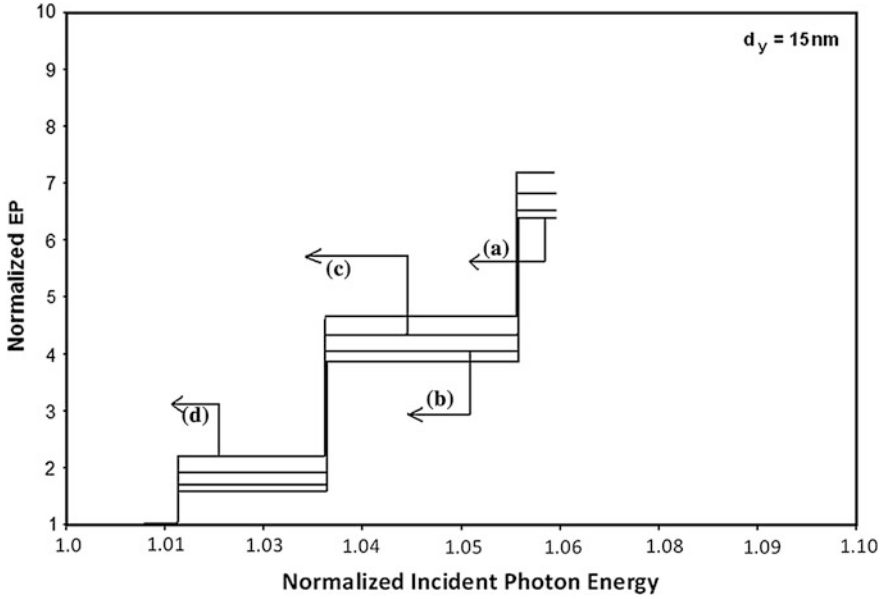




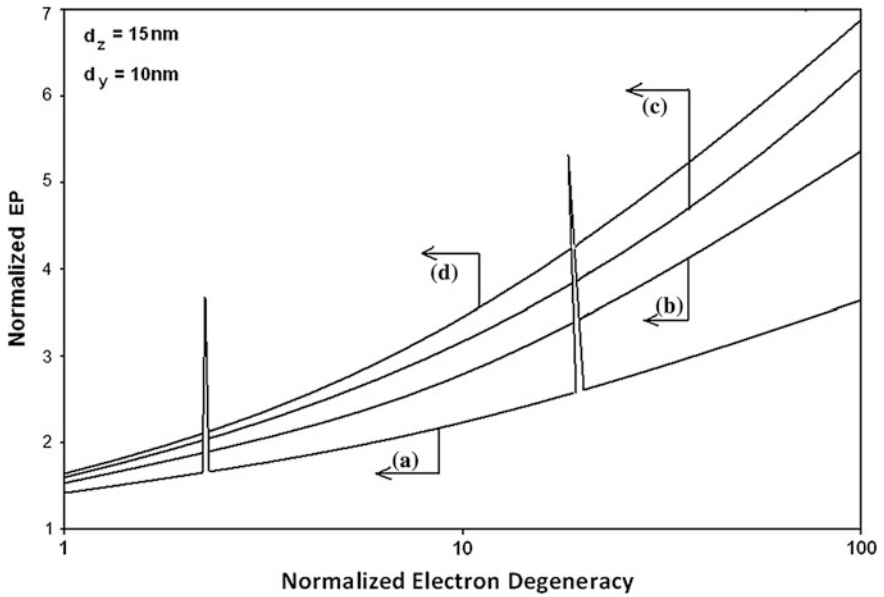
**Fig. 2.24** Plot of the normalized EP from NWs of HD stressed n-InSb as a function of normalized electron degeneracy



**Fig. 2.25** Plot of the normalized EP from NWs of HD PbTe as a function of film thickness in accordance with the models of *a* the Dimmok and *b* the Bangert and Kastner respectively. The plots *c* and *d* exhibit the same for PbSe



**Fig. 2.26** Plot of the normalized EP from QWs of HD PbTe as a function of normalized incident photon energy in accordance with the models of *a* the Dimmok and *b* the Bangert and Kastner respectively. The plots *c* and *d* exhibit the same for PbSe



**Fig. 2.27** Plot of the normalized EP from QWs of HD PbTe as a function of electron degeneracy in accordance with the models of *a* the Dimmok and *b* the Bangert and Kastner respectively. The plots *c* and *d* exhibit the same for PbSe

degeneracy in a non-oscillatory manner. The Figs. 2.2, 2.5, 2.8, 2.11, 2.14, 2.17, 2.20 and 2.23 illustrate the dependence of the EP from quantum-confined materials on the normalized incident photon energy. The EP increases with increasing photon energy in a step like manner for all the figures. The appearance of the discrete jumps in all the figures is due to the redistribution of the electrons among the quantized energy levels when the size quantum number corresponding to the highest occupied level changes from one fixed value to the others. With varying electron degeneracy, a change is reflected in the EP through the redistribution of the electrons among the size-quantized levels. It may be noted that at the transition zone from one sub band to another, the height of the peaks between any two sub-bands decreases with the increasing in the degree of quantum confinement and is clearly shown in all the curves. It should be noted that although, the EP varies in various manners with all the variables as evident from all the figures, the rates of variations are totally band-structure dependent.

Finally, it may be noted that the basic aim of this chapter is not solely to demonstrate the influence of quantum confinement on the EP from NWs of HD non-linear optical, III-V, II-VI, IV-VI, n-GaP, n-Ge, PtSb<sub>2</sub>, and stressed compounds respectively but also to formulate the appropriate electron statistics in the most generalized form, since the transport and other phenomena in quantized structures having different band structures and the derivation of the expressions of many important electronic properties are based on the temperature-dependent electron statistics in such materials.

## 2.4 Open Research Problems

- (R.2.1) Investigate the EP for bulk specimens of the HD semiconductors in the presences of Gaussian, exponential, Kane, Halperian, Lax and Bonch-Burevich types of band tails for all systems whose unperturbed carrier energy spectra are defined in R.1.1 in the presence of strain.
- (R.2.2) Investigate the EP for NWs of all the HD semiconductors as considered in R.1.2.
- (R.2.3) Investigate the EP in the presence of strain for HD bulk specimens of the negative refractive index, organic, magnetic and other advanced optical materials in the presence of an arbitrarily oriented alternating electric field.
- (R.2.4) Investigate the EP for the NWs of HD negative refractive index, organic, magnetic and other advanced optical materials in the presence of an arbitrarily oriented alternating electric field.
- (R.2.5) Investigate the EP for the multiple NWs of HD materials whose unperturbed carrier energy spectra are defined in R.1.1.
- (R.2.6) Investigate the EP for all the appropriate HD low dimensional systems of this chapter in the presence of finite potential wells.

- (R.2.7) Investigate the EP for all the appropriate HD low dimensional systems of this chapter in the presence of parabolic potential wells.
- (R.2.8) Investigate the EP for all the appropriate HD systems of this chapter forming quantum rings.
- (R.2.9) Investigate the EP for all the above appropriate problems in the presence of elliptical Hill and quantum square rings in the presence of strain.
- (R.2.10) Investigate the EP for parabolic cylindrical HD low dimensional systems in the presence of an arbitrarily oriented alternating electric field for all the HD materials whose unperturbed carrier energy spectra are defined in R.1.1 in the presence of strain.
- (R.2.11) Investigate the EP for HD low dimensional systems of the negative refractive index and other advanced optical materials in the presence of an arbitrarily oriented alternating electric field and non-uniform light waves and in the presence of strain.
- (R.2.12) Investigate the EP for triangular HD low dimensional systems of the negative refractive index, organic, magnetic and other advanced optical materials in the presence of an arbitrarily oriented alternating electric field in the presence of strain.
- (R.2.13) Investigate the EP for all the problems of (R.1.12) in the presence of arbitrarily oriented magnetic field.
- (R.2.14) Investigate the EP for all the problems of (R.1.12) in the presence of alternating electric field.
- (R.2.15) Investigate the EP for all the problems of (R.1.12) in the presence of alternating magnetic field.
- (R.2.16) Investigate the EP for all the problems of (R.1.12) in the presence of crossed electric field and quantizing magnetic fields.
- (R.2.17) Investigate the EP for all the problems of (R.1.12) in the presence of crossed alternating electric field and alternating quantizing magnetic fields.
- (R.2.18) Investigate the EP for HD NWs of the negative refractive index, organic and magnetic materials.
- (R.2.19) Investigate the EP for HD NWs of the negative refractive index, organic and magnetic materials in the presence of alternating time dependent magnetic field.
- (R.2.20) Investigate the EP for HD NWs of the negative refractive index, organic and magnetic materials in the presence of in the presence of crossed alternating electric field and alternating quantizing magnetic fields.
- (R.2.21) (a) Investigate the EP for HD NWs of the negative refractive index, organic, magnetic and other advanced optical materials in the presence of an arbitrarily oriented alternating electric field considering many body effects.

- (b) Investigate all the appropriate problems of this chapter for a Dirac electron.
- (R.2.22) Investigate all the appropriate problems of this chapter by including the many body, image force, broadening and hot carrier effects respectively.
- (R.2.23) Investigate all the appropriate problems of this chapter by removing all the mathematical approximations and establishing the respective appropriate uniqueness conditions.

## References

1. P. Harrison, *Quantum Wells Wires and Dots* (Wiley, NY, 2002)
2. B.K. Ridley, *Electrons and Phonons in Semiconductors Multilayers* (Cambridge University Press, Cambridge, 1997)
3. G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Halsted; Les Ulis Les Editions de Physique, New York, 1988)
4. V.V. Martin, A.A. Kochelap, M.A. Strosio, *Quantum Heterostructures* (Cambridge University Press, Cambridge, 1999)
5. C.S. Lent, D.J. Kirkner, J. Appl. Phys. **67**, 6353 (1990)
6. F. Sols, M. Macucci, U. Ravaioli, K. Hess, Appl. Phys. Lett. **54**, 350 (1980)
7. C.S. Kim, A.M. Satanin, Y.S. Joe, R.M. Cosby, Phys. Rev. B **60**, 10962 (1999)
8. S. Midgley, J.B. Wang, Phys. Rev. B **64**, 153304 (2001)
9. T. Sugaya, J.P. Bird, M. Ogura, Y. Sugiyama, D.K. Ferry, K.Y. Jang, Appl. Phys. Lett. **80**, 434 (2002)
10. B. Kane, G. Facer, A. Dzurak, N. Lumpkin, R. Clark, L. PfeiKer, K. West, Appl. Phys. Lett. **72**, 3506 (1998)
11. C. Dekker, Phys. Today **52**, 22 (1999)
12. A. Yacoby, H.L. Stormer, N.S. Wingreen, L.N. Pfeiffer, K.W. Baldwin, K.W. West, Phys. Rev. Lett. **77**, 4612 (1996)
13. Y. Hayamizu, M. Yoshita, S. Watanabe, H.A.L. PfeiKer, K. West, Appl. Phys. Lett. **81**, 4937 (2002)
14. S. Frank, P. Poncharal, Z.L. Wang, W.A. Heer, Science **280**, 1744 (1998)
15. I. Kamiya, I.I. Tanaka, K. Tanaka, F. Yamada, Y. Shinozuka, H. Sakaki, Physica E **13**, 131 (2002)
16. A.K. Geim, P.C. Main, N. LaScala, L. Eaves, T.J. Foster, P.H. Beton, J.W. Sakai, F.W. Sheard, M. Henini, G. Hill et al., Phys. Rev. Lett. **72**, 2061 (1994)
17. A.S. Melinkov, V.M. Vinokur, Nature **415**, 60 (2002)
18. K. Schwab, E.A. Henriksen, J.M. Worlock, M.L. Roukes, Nature **404**, 974 (2000)
19. L. Kouwenhoven, Nature **403**, 374 (2000)
20. S. Komiyama, O. Astafiev, V. Antonov, H. Hirai, Nature **403**, 405 (2000)
21. E. Paspalakis, Z. Kis, E. Voutsinas, A.F. Terziz, Phys. Rev. B **69**, 155316 (2004)
22. J.H. Jefferson, M. Fearn, D.L.J. Tipton, T.P. Spiller, Phys. Rev. A **66**, 042328 (2002)
23. J. Appenzeller, C. Schroer, T. Schapers, A. Hart, A. Froster, B. Lengeler, H. Luth, Phys. Rev. B **53**, 9959 (1996)
24. J. Appenzeller, C. Schroer, J. Appl. Phys. **87**, 31659 (2002)
25. P. Debray, O.E. Raichev, M. Rahman, R. Akis, W.C. Mitchel, Appl. Phys. Lett. **74**, 768 (1999)
26. P.M. Solomon, Proc. IEEE **70**, 489 (1982)
27. T.E. Schlesinger, T. Kuech, Appl. Phys. Lett. **49**, 519 (1986)
28. D. Kasemet, C.S. Hong, N.B. Patel, P.D. Dapkus, Appl. Phys. Letts. **41**, 912 (1982)

- 29. K. Woodbridge, P. Blood, E.D. Pletcher, P.J. Hulyer, Appl. Phys. Lett. **45**, 16 (1984)
- 30. S. Tarucha, H.O. Okamoto, Appl. Phys. Letts. **45**, 16 (1984)
- 31. H. Heiblum, D.C. Thomas, C.M. Knoedler, M.I. Nathan, Appl. Phys. Letts. **47**, 1105 (1985)
- 32. O. Aina, M. Mattingly, F.Y. Juan, P.K. Bhattacharyya, Appl. Phys. Letts. **50**, 43 (1987)
- 33. I. Suemune, L.A. Coldren, IEEE J. Quant. Electronic. **24**, 1178 (1988)
- 34. D.A.B. Miller, D.S. Chemla, T.C. Damen, J.H. Wood, A.C. Burrus, A.C. Gossard, W. Weigmann, IEEE J. Quant. Electron. **21**, 1462 (1985)
- 35. J.S. Blakemore, *Semiconductor Statistics* (Dover, New York, 1987)
- 36. K.P. Ghatak, S. Bhattacharya, S.K. Biswas, A. Dey, A.K. Dasgupta, Phys. Scr. **75**, 820 (2007)

Einstein's Photoemission

Emission from Heavily-Doped Quantized Structures

Ghatak, K.P.

2015, XXXVIII, 495 p. 161 illus., Hardcover

ISBN: 978-3-319-11187-2