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Einstein's Photoemission

Emission from Heavily-Doped Quantized Structures

 Springer

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Professors P.T. Landsberg, P.N. Butcher, K. Seeger and J.S. Blakemore are now living in a wonderful world from where the concept of return visa to this globe called Earth permanently stays in the band gap regime. The long interaction with them for more than three decades through personal contacts and letters has transformed an unsophisticated engineer to the present author. I earnestly believe that they still enjoy the academic output of my research group and I write them mental letters and dedicate this monograph to them but cannot express my gratitude since I do not know the present addresses of the said four first class semiconductors physicists.

Kamakhya Prasad Ghatak

Preface

The unification of the concept of the asymmetry of the wave vector space of the charge carriers in semiconductors with the modern techniques of fabricating nano-structured materials such as molecular beam epitaxy, metal organic chemical vapor deposition, fine line lithography and other modern fabrication techniques in one, two and three dimensions (such as quantum wells (QWs), Doping super-lattices, inversion and accumulation layers, quantum well super-lattices, carbon nano-tubes, quantum wires, quantum wire super-lattices, magnetic quantization, magneto size quantization, quantum dots, magneto inversion and accumulation layers, magneto quantum well super-lattices, magneto NIPs, quantum dot super-lattices and other field aided low dimensional electronic systems) spawns not only useful quantum effect devices but also unearths new concepts in the realm of low dimensional solid state electronics and related disciplines. These semiconductor nanostructures occupy a central position in the entire arena of condensed matter science, materials science, computational and theoretical nano-science and technology, semiconductor optoelectronics, quantized structures and semiconductor physics in general by their own right and find extensive applications in quantum registers, quantum switches, quantum sensors, hetero-junction field-effect, quantum logic gates, quantum well and quantum wire transistors, quantum cascade lasers, high-frequency microwave circuits, high-speed digital networks, high-resolution terahertz spectroscopy, advanced integrated circuits, super-lattice photo-oscillator, super-lattice photo-cathodes, resonant tunneling diodes and transistors, super-lattice coolers, thermoelectric devices, thin film transistors, micro-optical systems, intermediate-band solar cells, high performance infrared imaging systems, band-pass filters, optical modulators, thermal sensors, optical switching systems, single electron/molecule electronics, nano-tube based diodes, and other nano-electronic devices. Knowledge regarding these quantized structures may be gained from original research contributions in scientific journals, various patents, proceedings of the conferences, review articles, and different research monographs [1] respectively. Mathematician Simmons rightfully tells us [2] that the mathematical knowledge is said to be doubling in every 10 years, and in this context, we can also envision extrapolation of the Moore's law by projecting it in the perspective of the advancement of new

research and analyses, in turn, generating novel concepts particularly in the entire arena of materials science in general [3].

Although many new effects in quantized structures have already been reported, the interest for further research of other aspects of such quantum-confined materials is becoming increasingly important. One such significant property is Einstein's Photoemission (EP) which is a physical phenomenon and occupies a singular position in the whole arena of Modern Physics and related disciplines in general and whose importance has already been established since the inception of Einstein's photoelectric effect (for which Einstein won Nobel Prize in 1921), which in recent years finds extensive applications in modern optoelectronics, characterization and investigation of condensed matter systems, photoemission spectroscopy and related aspects in connection with the investigations of the optical properties of nanostructures [4–8]. Interest in low dimensional silicon nanostructures also grew up and gained momentum, after the discovery of room temperature photoluminescence and electroluminescence of silicon nano-wires in porous silicon [4]. Work on ultrathin layers of SiSiO_2 super-lattices resulting into visible light emission at room temperature clearly exhibited low dimensional quantum confinement effect [5] and one of the most popular techniques for analyzing the low dimensional structures is to employ photoemission techniques. Recent observation of room temperature photoluminescence and electro luminescence in porous silicon has stimulated vigorous research activities in silicon nanostructures [6].

In this context, it may be noted that the available reports on the said areas [4–7] cannot afford to cover even an entire chapter regarding the EP from heavily doped (HD) quantized structures and incidentally the second book of the present research group devoted solely to the elementary study of EP [8] from optoelectronic materials and their nanostructures does not even contain a paragraph regarding the EP from HD Quantized Structures. The EP depends on the density-of-states (DOS) function which, in turn, is significantly affected by the different carrier energy spectra of different semiconductors having various band structures. In recent years, various energy wave vector dispersion relations of the carriers of different materials have been proposed [9] which have created the interest in studying the EP from HD materials and their quantized counterparts. The present monograph solely investigates the EP from HD quantized structures of non-linear optical, III-V, II-VI, Gallium Phosphide, Germanium, Platinum Antimonide, stressed, IV-VI, Lead Germanium Telluride, Tellurium, II-V, Zinc and Cadmium diphosphides, Bismuth Telluride, III-V, II-VI, IV-VI and HgTe/CdTe quantum well HD super-lattices with graded interfaces under magnetic quantization, III-V, II-VI, IV-VI and HgTe/CdTe HD effective mass super-lattices under magnetic quantization, quantum confined effective mass super-lattices and super-lattices of HD optoelectronic materials with graded interfaces on the basis of the newly derived appropriate respective HD dispersion relation in each case. Incidentally, even after 20 years of continuous effort, we see that the complete investigation of the EP comprising of the whole set of the HD materials and allied sciences is really a sea and permanently enjoys the domain of impossibility theorems.

It is well-known that the classical equation of the photo-emitted current density is [10] $J = \left[4\pi\alpha_0 e m_c g_v (k_B T)^2 / h^3 \right] \exp[(h\nu - \phi)/(k_B T)]$ (where α_0 , e , m_c , g_v , k_B , T , h , $h\nu$ and ϕ are the probability of photoemission, electron charge, effective electron mass at the edge of the conduction band, valley degeneracy, the Boltzmann constant, temperature, the Planck constant, incident photon energy along z-axis and work function respectively). The afore-mentioned equation is valid for both the charge carriers and in this conventional form it appears that, the photoemission changes with the effective mass, temperature, work function and the incident photon energy respectively. This relation holds only under the condition of carrier non-degeneracy.

The EP has different values for different materials and varies with doping and with external fields which creates quantization of the wave-vector space of the carriers leading to various types of quantized structures. The nature of these variations has been studied in [4–35] and some of the significant features are as follow:

1. The EP from bulk materials increases with the increase in doping.
2. The EP exhibits oscillatory dependence with inverse quantizing magnetic field because of the Shubnikov de Haas (SdH) effect.
3. The EP changes significantly with the magnitude of the externally applied quantizing electric field in electronic materials.
4. The EP from quantum confined Bismuth, nonlinear optical, III-V, II-VI and IV-VI materials oscillate with nano-thickness in various manners which are totally band structure dependent.
5. The nature of variations is significantly influenced by the energy band constants of various materials having different band structures.
6. The EP has significantly different values in quantum confined semiconductor super-lattices and various other quantized structures.

It is well known that heavy doping and carrier degeneracy are the keys to unlock the important properties of semiconductors and they are especially instrumental in dictating the characteristics of Ohmic contacts and Schottky contacts respectively [36]. It is an amazing fact that although the heavily doped semiconductors (HDS) have been investigated in the literature but the study of the carrier transport in such materials through proper formulation of the Boltzmann transport equation which needs in turn, the corresponding HD carrier energy spectra *is still one of the open research problems*.

It is well known that the band tails are being formed in the forbidden zone of HDS and can be explained by the overlapping of the impurity band with the conduction and valence bands [37]. Kane [38] and Bonch Bruevich [39] have independently derived the theory of band tailing for semiconductors having unperturbed parabolic energy bands. Kane's model [38] was used to explain the experimental results on tunneling [40] and the optical absorption edges [41, 42] in this context. Halperin and Lax [43] developed a model for band tailing applicable only to the deep tailing states. Although Kane's concept is often used in the literature for the investigation of band tailing [44, 45], it may be noted that this model

[38, 46] suffers from serious assumptions in the sense that the local impurity potential is assumed to be small and slowly varying in space coordinates [45]. In this respect, the local impurity potential may be assumed to be a constant. In order to avoid these approximations, we have developed in this book, the electron energy spectra for HDS for studying the EP based on the concept of the variation of the kinetic energy [37, 45] of the electron with the local point in space coordinates. This kinetic energy is then averaged over the entire region of variation using a Gaussian type potential energy. On the basis of the $E-k$ dispersion relation, we have obtained the electron statistics for different HDS for the purpose of numerical computation of the respective EPs. It may be noted that, a more general treatment of many-body theory for the DOS of HDS merges with one-electron theory under macroscopic conditions [37]. Also, the experimental results for the Fermi energy and others are the average effect of this macroscopic case. So, the present treatment of the one-electron system is more applicable to the experimental point of view and it is also easy to understand the overall effect in such a case [47]. In a HDS, each impurity atom is surrounded by the electrons, assuming a regular distribution of atoms, and it is screened independently [44, 46, 48]. The interaction energy between electrons and impurities is known as the impurity screening potential. This energy is determined by the inter-impurity distance and the screening radius, which is known as the screening length. The screening radius changes with the electron concentration and the effective mass. Furthermore, these entities are important for HDS in characterizing the semiconductor properties [49, 50] and the modern electronic devices [44, 51]. The works on Fermi energy and the screening length in an n-type GaAs have already been initiated in the literature [52, 53], based on Kane's model. Incidentally, the limitations of Kane's model [38, 45], as mentioned above, are also present in their studies.

At this point, it may be noted that many band tail models are proposed using the Gaussian distribution of the impurity potential variation [38, 45]. From the very start, we have used the Gaussian band tails to obtain the *exact $E-k$ dispersion relations* in HD non-linear optical, III-V, II-VI, Gallium Phosphide, Germanium, Platinum Antimonide, stressed, IV-VI, Lead Germanium Telluride, Tellurium, II-V, Zinc and Cadmium diphosphides, Bismuth Telluride, III-V, II-VI, IV-VI and HgTe/CdTe quantum well HD super-lattices with graded interfaces under magnetic quantization, III-V, II-VI, IV-VI and HgTe/CdTe HD effective mass super-lattices under magnetic quantization, quantum confined effective mass super-lattices and super-lattices of HD optoelectronic materials with graded interfaces respectively. Our method is not at all related with the DOS technique as used in the aforementioned works. From the electron energy spectrum, one can obtain the DOS but the DOS technique, as used in the literature cannot provide the $E-k$ dispersion relation. *Therefore, our study is more fundamental than those in the existing literature, because the Boltzmann transport equation, which controls the study of the charge transport properties of the semiconductor devices, can be solved if and only if the $E-k$ dispersion relation is known.* We wish to note that the Gaussian function for the impurity potential distribution has been used by many authors. It has been

widely used since 1963 when Kane first proposed it and we will also use the Gaussian distribution for the present study.

This book, is divided into two parts (the first and second parts contain four and ten chapters respectively) and four Appendices, is partially based on our on-going researches on the EP from HDS from 1990 and an attempt has been made to present a cross section of the EP from wide range of HDS and their quantized-structures with varying carrier energy spectra under various physical conditions. The first chapter deals with the influence of quantum confinement on the EP from non-parabolic HDS and at first we study the EP from QWs of HD nonlinear optical materials on the basis of a generalized electron dispersion law introducing the anisotropies of the effective masses and the spin orbit splitting constants respectively together with the inclusion of the crystal field splitting within the framework of the $k.p$ formalism. *We will observe that the complex electron dispersion law in HDS instead of real one occurs from the existence of the essential poles in the corresponding electron energy spectrum in the absence of band tails.* It may be noted that the complex band structures have already been studied for bulk semiconductors and super lattices without heavy doping [54] and bears no relationship with the complex electron dispersion law as formulated in this book. The physical picture behind the existence of the complex energy spectrum in heavily doped nonlinear optical semiconductors is the interaction of the impurity atoms in the tails with the splitting constants of the valance bands. The more is the interaction, the more the prominence of the complex part than the other case. In the absence of band tails, there is no interaction of the impurity atoms in the tails with the spin orbit constants and consequently, the complex part vanishes. Besides, the complex spectra are not related to same evanescent modes in the band tails and the conduction bands. One important consequence of the HDS forming band tails is that *the effective mass exists in the forbidden zone, which is impossible without the effect of band tailing. In the absence of band tails, the effective mass in the band gap of semiconductors is infinity. Besides, depending on the type of the unperturbed carrier energy spectrum, the new forbidden zone will appear within the normal energy band gap for HDS.*

The results of HD III-V (e.g. InAs, InSb, GaAs etc.), ternary (e.g. $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$), quaternary (e.g. $\text{In}_{1-x}\text{Ga}_x\text{As}_{1-y}\text{P}_y$ lattice matched to InP) compounds form a special case of our generalized analysis under certain limiting conditions as stated already. The EP from HD QWs of II-VI, IV-VI, stressed Kane type semiconductors, Te, GaP, PtSb_2 , Bi_2Te_3 , Ge, and GaSb has also been investigated by formulating the respective appropriate HD energy band structure. The importance of the aforementioned semiconductors has also been described in the same chapter. In the absence of band tails and under the condition of extreme carrier degeneracy together with certain limiting conditions, all the results for all the EPs from all the HD QWs of Chap. 1 get simplified into the form [10] $J_{2D} = (\alpha_0 e g_v / 2 \hbar d_z^2) \sum_{n_z}^{n_{z\max}} n_z [E_{F2D} - \frac{\hbar^2}{2m_c} (n_z \pi / d_z)^2]$ (where d_z is the film thickness along z direction, n_z is the size quantum number along z direction and E_{F2D} is the Fermi energy in the

presence of size quantization as measured from the edge of the conduction band in the vertically upward direction in the absence of any quantization) exhibiting the necessary mathematical compatibility test. In Chaps. 2 and 3 the EP from nano wires (NWs) and quantum boxes (QBs) of all the materials of Chap. 1 have respectively been investigated.

With the advent of modern experimental techniques of fabricating nano-materials, it is possible to grow semiconductor super-lattices (SLs) composed of alternative layers of two different degenerate layers with controlled thickness [55]. These structures have found wide applications in many new devices such as photodiodes [56], photo-resistors [57], transistors [58], light emitters [59], tunneling devices [60], etc. [61–72]. The investigations of the physical properties of narrow gap SLs have increased extensively, since they are important for optoelectronic devices and also since the quality of hetero-structures involving narrow gap materials has been greatly improved. It is well known that Keldysh [73] first suggested the fundamental concept of a super-lattice (SL), although it was successfully experimental realized by Esaki and Tsu [74]. The importance of SLs in the field of nano-electronics has already been described in [75–77]. The most extensively studied III-V SL is the one consisting of alternate layers of GaAs and $\text{Ga}_{1-x}\text{Al}_x\text{As}$ owing to the relative ease of fabrication. The GaAs layers forms quantum wells and $\text{Ga}_{1-x}\text{Al}_x\text{As}$ form potential barriers. The III-V SL's are attractive for the realization of high speed electronic and optoelectronic devices [78]. In addition to SLs with usual structure, SLs with more complex structures such as II-VI [79], IV-VI [80] and HgTe/CdTe [81] SL's have also been proposed. The IV-VI SLs exhibit quite different properties as compared to the III-V SL due to the peculiar band structure of the constituent materials [82]. The epitaxial growth of II-VI SL is a relatively recent development and the primary motivation for studying the mentioned SLs made of materials with the large band gap is in their potential for optoelectronic operation in the blue [82]. HgTe/CdTe SL's have raised a great deal of attention since 1979, when as a promising new materials for long wavelength infrared detectors and other electro-optical applications [83]. Interest in Hg-based SL's has been further increased as new properties with potential device applications were revealed [84]. These features arise from the unique zero band gap material HgTe [85] and the direct band gap semiconductor CdTe which can be described by the three band mode of Kane [86]. The combination of the aforementioned materials with specified dispersion relation makes HgTe/CdTe SL very attractive, especially because of the possibility to tailor the material properties for various applications by varying the energy band constants of the SLs. In addition to it, for effective mass SLs, the electronic sub-bands appear continually in real space [87].

We note that all the aforementioned SLs have been proposed with the assumption that the interfaces between the layers are sharply defined, of zero thickness, i.e., devoid of any interface effects. The SL potential distribution may be then considered as a one dimensional array of rectangular potential wells. The aforementioned advanced experimental techniques may produce SLs with physical interfaces between the two materials crystallographically abrupt; adjoining their interface will change at least on an atomic scale. As the potential form changes from

a well (barrier) to a barrier (well), an intermediate potential region exists for the electrons. The influence of finite thickness of the interfaces on the electron dispersion law is very important, since the electron energy spectrum governs the electron transport in SLs.

In this context, it may be noted that the effects of quantizing magnetic field (B) on the band structures of compound semiconductors are most striking than that of the parabolic one and are easily observed in experiments. A number of interesting physical features originate from the significant changes in the basic energy wave vector relation of the carriers caused by the magnetic field. The valuable information could also be obtained from experiments under magnetic quantization regarding the important physical properties such as Fermi energy and effective masses of the carriers, which affect almost all the transport properties of the electron devices [88] of various materials having different carrier dispersion relations [89]. In Chap. 4, the magneto EP from III-V, II-VI, IV-VI, HgTe/CdTe and strained layer quantum well heavily doped super-lattices (QWHDSLs) with graded interfaces will be studied. Besides the magneto EP from III-V, II-VI, IV-VI, HgTe/CdTe and strained layer quantum well HD effective mass super-lattices respectively has been explored and the same from the quantum dots of the aforementioned HD SLs has further been investigated in the same chapter.

It is worth remarking that, in the methods as given in the literature, the physics of photoemission has been incorporated in the lower limit of the photoemission integral and assuming that the band structure of the bulk materials becomes an invariant quantity in the presence of photo-excitation necessary for Einstein's photoelectric effect. The basic band structure of semiconductors changes in the presence of intense external light waves in a fundamental way, which has been incorporated mathematically through the expressions of the DOS function on the basis of a newly formulated electron dispersion law and the velocity along the direction of photoemission respectively in addition to the appropriate fixation of the lower limit of the photo-emission integral for the purpose of investigating the EP. The second part of the book investigates the EP from HD III-V semiconductors and their quantized counter parts. In Chap. 5, we study the EP from HD Kane type semiconductors on the basis of the newly formulated electron energy spectrum in the presence of intense light waves. An important concept highly relevant to the measurement of band-gap in HD electronic materials in the presence of external photo-excitation has also been discussed in this perspective. Under the conditions of extreme degeneracy, the invariant band structure concept in the presence of light waves and certain other limiting constraints all the results of this chapter for the EP assumes the well-known form [10] $J = (2\pi\alpha_0 em_c g_v / h)(\nu - \nu_0)^2$, (ν_0 is the threshold frequency) which indicates the fact current density is independent of temperature and when the energy of light quantum is much greater than the work function the material, the condition of extreme degeneracy is reached.

In Chap. 6, the EP has been investigated under magnetic quantization from HD Kane type materials on the basis of the concept as presented in Chap. 5. Chapter 7 covers the study of the EP from QWs, NWs and QBs of HD optoelectronic

materials as an extension of the new dispersion relations of the bulk HD materials as investigated in Chap. 5. In Chap. 8, the magneto EP from HD effective mass super lattices, quantum well, quantum well wire, and quantum dot HD effective mass super-lattices have been investigated by formulating the appropriate electron dispersion laws. The experimental aspects of EP are extremely wide and it is virtually impossible even to highlight the major developments in a chapter. For the purpose of condensed presentation, the experimental aspects of EP from different nano-structured materials have been discussed in Chap. 9 which also contains few important related applications of the content of this book. The Chap. 10 contains the conclusion and the scope for future research.

The Appendix A studies the EP from HD nonlinear optical, III-V, IV-VI, stressed compounds, n-Te, n-GaP, PtSb₂, Bismuth Telluride-Ge, Gallium Antimonide II-V semiconductors and Lead Germanium Telluride under magnetic quantization respectively. In this Appendix we shall observe that the EEM depends on Landau quantum number in addition to Fermi energy and the other system constants due to the specific band structures of the HD material together with the fact EEM exist in the band gap due to the presence of finite scattering potential as noted already. Thus we present a very simplified analysis of the EP from HD non-parabolic semiconductors under magnetic quantization, which is a big topic of research by its own right.

In Appendix B, the magneto EP from HD III-V, II-VI, IV-VI, HgTe/CdTe and strained layer super-lattices with graded interfaces and the HD effective mass super-lattices of the aforementioned materials have been investigated.

It is worth remarking that the influence of crossed electric and quantizing magnetic fields on the transport properties of semiconductors having various band structures are relatively less investigated as compared with the corresponding magnetic quantization, although, the cross-fields are fundamental with respect to the addition of new physics and the related experimental findings. It is well known that in the presence of electric field (E_0) along x-axis and the quantizing magnetic field along z-axis, the dispersion relations of the conduction electrons in semiconductors become modified and for which the electron moves in both the z and y directions. The motion along y-direction is purely due to the presence of E_0 along x-axis and in the absence of electric field, the effective electron mass along y-axis tends to infinity which indicates the fact that the electron motion along y-axis is forbidden. The effective electron mass of the isotropic, bulk semiconductors having parabolic energy bands exhibits mass anisotropy in the presence of cross fields and this anisotropy depends on the electron energy, the magnetic quantum number, the electric and the magnetic fields respectively, although, the effective electron mass along z-axis is a constant quantity. In 1966, Zawadzki and Lax [90] formulated the electron dispersion law for III-V semiconductors in accordance with the two band model of Kane under cross fields configuration which generates the interest to study this particular topic of solid state science in general [91]. *The Appendix C investigates the EP under cross-field configuration from HD nonlinear optical, III-V, II-VI, IV-VI and stressed Kane type semiconductors respectively. This appendix also tells us that the EEM in all the cases is a function of the finite scattering potential,*

the magnetic quantum number and the Fermi energy even for HD semiconductors whose bulk electrons in the absence of band tails are defined by the parabolic energy bands.

With the advent of nano-devices, the build-in electric field becomes so large that the electron energy spectrum changes fundamentally instead of being invariant and the Appendix D investigates the EP under intense electric field from bulk specimens of HD III-V, ternary and quaternary semiconductors. This appendix also explores the influence of electric field on the EP on the basis of HD new dispersion law in for QWs, NWs, QBs, under magnetic quantization, QWs under magnetic quantization and effective mass HD super-lattices under magnetic quantization.

In these four Appendices no graphs together with results and discussions are being presented since we feel that the readers should not lose a chance to enjoy the complex computer algorithm to investigate the EP in the respective case generating new physics and thereby transforming each Appendix into a short monograph by considering various other important materials having different dispersion relations.

It is needless to say that this monograph is based on the 'iceberg principle' [92] and the rest of which will be explored by the researchers of different appropriate fields. Since, there is no existing report devoted solely to the study of EP from HD quantized structures to the best of our knowledge, we hope that the present book will a useful reference source for the present and the next generation of the readers and the researchers of materials and allied sciences in general. Since the production of error free first edition of any book from every point of view is a permanent member in the domain of impossibility theorems, therefore in spite of our joint concentrated efforts for couple of years together with the seasoned team of Springer, the same stands very true for this monograph also. Various expressions and a few chapters of this book have been appearing for the first time in printed form. The suggestions from the readers for the development of the book will be highly appreciated for the purpose of inclusion in the future edition, if any. In this book, from chapter one to till the end, we have presented *300 open research problems* for the graduate students, Ph.D. aspirants, researchers, engineers in this pinpointed research topic. We strongly hope that alert readers of this monograph will not only solve the said problems by removing all the mathematical approximations and establishing the appropriate uniqueness conditions, but also will generate new research problems both theoretical and experimental and, thereby, transforming this monograph into a solid book. Incidentally, our readers after reading this book will easily understand that how little is presented and how much more is yet to be investigated in this exciting topic which is the signature of coexistence of new physics, advanced mathematics combined with the inner fire for performing creative researches in this context from the young scientists since like Kikoin [93] we feel that *A young scientist is no good if his teacher learns nothing from him and gives his teacher nothing to be proud of.* We emphatically write that the problems presented here form the integral part of this book and will be useful for the readers to initiate their own contributions on the EP from HDS and their quantized counter parts since like Sakurai [94] we firmly believe *The reader who has read the book but cannot do the exercise has learned nothing.* It is nice to note

that if we assign the alphabets A to Z, the positive integers from 1 to 26, chronologically, then the word *ATTITUDE* receives the perfect score 100 and is the vital quality needed from the readers since *attitude* is the ladder on which all the other virtues mount.

In this monograph, we have investigated various dispersion relations of different HD quantized structures and the corresponding carrier statistics to study the concentration dependence of the EP from HD quantum confined materials. *Besides, the expressions of effective electron mass and the sub-band energy have been formulated throughout this monograph as a collateral study, for the purpose of in-depth investigations of the said important pinpointed research topics.* Thus, in this book, the readers will get much information regarding the influence of quantization in HD low dimensional materials having different band structures. For the enhancement of the materials aspect, we have considered various materials having the same dispersion relation to study the influence of energy band constants of the different HDS on EP. Although the name of the book is extreme specific, from the content, one can easily infer that it should be useful in graduate courses on materials science, condensed matter physics, solid states electronics, nano-science and technology and solid-state sciences and devices in many Universities and the Institutions in addition to both Ph.D. students and researchers in the aforementioned fields. *Last but not the least, we do hope that our humble effort will kindle the desire to delve deeper into this fascinating and deep topic by any one engaged in materials research and device development either in academics or in industries.*

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volumes Tuttle, two volumes Scott, two volumes Budak, five volumes Chen, five volumes Smirnov.... It is curious to note that they are insisting me in the real sense of the term to verify all the entries of Gradshteyn-Ryzhik and three volumes Bateman manuscript project for the last 40 years. It may be noted that academic output of a nice scholar is the response of a good quality RC coupled amplifier in the mid-band zone whereas the same for a fine research worker is the Dirac's delta function. Incidentally, I can safely say that I belong to neither as a consequence of the academic surroundings which this life presents to me. I express my warm gratitude to H.L. Hartnagel, D. Bimberg, W.L. Freeman and W. Schommers for various academic interactions spanning over the last three decades. I am extremely grateful to Dr. Hari Singh Nalwa, the President and CEO of American Scientific Publishers (www.aspbs.com) an ardent supporter of the work of my research group. I remember the sweet memories of P.N. Robson, I.M. Stephenson, V.S. Letokhov, J. Bodnar and K.F. Brennan with true reverence for inspiring me with the ebullient idea that the publications of the research monographs from internationally reputed Publishers containing innovative concepts is of prime importance to excel in creative research activity.

Late P.T. Landsberg often expressed his desire to write a foreword for this book in 2007 but due to previous other heavy academic and related commitments I was unable to write this present monograph and his wife Mrs. Sophia Landsberg in her letter of desperate sadness dated January 12, 2009 informed me that from 2008 onward due to Alzheimer's disease her husband had to give up scientific works. In 21st December, 1974, A.N. Chakravarti, my mentor in my first interaction with him emphatically energized me that I must master "Semiconductor Statistics" (Pergamon Press, London, 1962) by J.S. Blakemore for my initiation in semiconductor physics. Later on I came in deep touch with K. Seeger, the well-known author of the book "Semiconductor Physics" (Springer Series in Solid State Sciences, vol. 40, Springer-Verlag, Germany, 1982). The solid scientist Late P. N. Butcher has been a steady hidden force since 1983 before his sad demise with respect to our scripting the series in band structure dependent properties of nano-structured materials. He insisted me repeatedly regarding it and to tune with his high rigorous academic standard, myself with my prominent members of my research group wrote [1] as the first one, [2] as the second one, [3] as the third one, [4] as the fourth one, [5] as the fifth one, [6] as the sixth one, [7] as the seventh one and the present monograph as the eighth one. Both P.T. Landsberg and P.N. Butcher visited the Institute of Radio Physics and Electronics and immediately being a young research scholar I formed permanent covalent bonds with them. Consequently at the fag end of my academic life, I dedicate this monograph to the said four Semiconductor Grand Masters as a token of my regards and gratitude to them individually for the long academic interactions lasting for more than three decades.

I offer special thanks to Late N. Guhachoudhury of Jadavpur University for instilling in me the thought that the *academic output = ((desire X determination X dedication) - (false enhanced self ego pretending like a true friend although a real unrecognizable foe))* although a thank you falls in the band gap regime for my beloved better half See who really formed the backbone of my long unperturbed research career, since in accordance with "Sanatan" Hindu Dharma, the fusion of

marriage has transformed us to form a single entity, where the individuality is being lost. I am grateful to all the members of my research group (from 1983 till date) for not only quantum confining me in the infinitely deep quantum wells of *Ramanujan and Rabindranath* but also inspiring me to teach quantum mechanics and related topics from the eight volumes classics of Greiner et al.

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It is curious to note that after serving 18 years as a Professor in the Department of Electronic Science, in 2012 P.K. Bose, the then Director of the National Institute of Technology, Agartala requested me to join as a Professor in the Department of Electronics and Communication Engineering. Being my life-long friend, I accepted his offer and more than ten young scholars around me are again directing my research in the last phase of my life in an altogether new direction. In my 30+ years of teaching life (I have the wide experience of teaching Physics, Mathematics, Applied Mechanics (from engineering statics up to nonlinear mechanics including indeterminate structures) and 70 % of the courses of Electronics and Telecommunication and Electrical Engineering respectively) and 40+ years of research life (mostly in Materials Science, Nano-science and Number Theory), I have finally

realized that the research without teaching is body without blood and teaching without research is body without brain although my all time hero, creatively prolific number theorist Godfrey Harold Hardy in his classic book entitled “A Mathematician’s Apology” (Cambridge University Press, 1990) tells us “I hate teaching”.

I must express my gratitude to S. Debbarma, of Computer Science and Engineering Department of my present working place, one of the strong members of my research group, for offering important suggestions for the condensed presentation of this monograph. I offer special thanks to K. Sarkar, P. Bhardwaj, N. Debbarma, R. Das and other members of my research team for placing their combined effort towards the development of this book in the DO-LOOP of a computer and critically reading the manuscript in its last phase before sending it to C. Ascheron, Executive Editor Physics, Springer-Verlag. Last but not the least; I am grateful for ever to our life long time tested friend S. Sanyal, Principal, Lake School for Girls, Kolkata for not only motivating me at rather turbulent moments of my academic carrier but also instilling in me the concept that *the ratio of total accumulated knowledge in my chosen field of research to my own contribution in my topic of research tends to infinity at any time.*

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About the Author

Professor Kamakhya Prasad Ghatak born in India in 1953, obtained the B.E degree in Electronics and Telecommunication Engineering from the then Bengal Engineering College Shibpur (Presently Indian Institute of Engineering Science and Technology) of the University of Calcutta in 1974, the M.Tech degree from the Institute of Radio Physics and Electronics of the University of Calcutta in 1976. He obtained the Ph.D. (Tech) degree from the University of Calcutta in 1988 on the basis of 27 published research papers in International peer-reviewed S.C.I. Journals which is still a record in the said Institute. He joined as Lecturer in the Institute of Radio Physics and Electronics of the University of Calcutta in 1983, Reader in the Department of Electronics and Telecommunication Engineering of Jadavpur University in 1987 and Professor in the Department of Electronic Science of the University of Calcutta in 1994. After serving 18 years as a Professor in the said Department, from March 2012, he has joined as a Professor in the Department of Electronics and Communication Engineering of National Institute of Technology, Agartala, Tripura and presently acting as Dean (Faculty Welfare) of the said Institute. He was at the top of the merit list in all the cases respectively. Professor K.P. Ghatak is the First Recipient of the Degree of Doctor of Engineering of Jadavpur University in 1991 since the University inception in 1955 and in the same year he received the Indian National Science Academy visiting fellowship to IIT-Kharagpur. He is the principal co-author of more than 200 research papers on Semiconductor Nano-science in eminent S.C.I. Journals and more than 50 research papers in the Proceedings of SPIE and MRS of USA and many of his papers are being cited many times. Professor Ghatak is the invited Speaker of SPIE, MRS, etc., the referee, Editor and Associate Editor of different eminent Journals. He is the supervisor of more than two dozens of Ph.D. candidates in various aspects of materials and nano-sciences and many of them are working as Professor, Associate Professor and Assistant Professor in different Universities and reputed Academic Institutions. He is the principal co-author of the SEVEN research monographs among them three from Springer series in Materials Science (Vols. 116, 137, 167), one form Springer Series in Nanostructure Science and Technology, one form Springer Series in Solid-State Sciences (Vol. 170), and two form Springer Tracts in

Modern Physics (vols. 255, 260). The All Indian Council for Technical Education has selected the first Research and Development project in his life for the best project award in Electronics and second best research project award considering all the branches of Engineering for the year 2006. In 2011, the University Grant Commission recommended a research project to him and placed him at the top in the list of awardees. His present teaching interests are Non-Linear Network Analysis and Synthesis, Non-Linear Devices, Non-Linear Mechanics, Non-Linear Integral and Partial Differential Equations and present research interests are nano science and number theory respectively. His brief CV has been enlisted in many biographical references of USA and UK. Professor Ghatak is the firm believer of the principle of theoretical minimum of Landau and his vision, mission and passion is to stay deeply in solitude. For more information, please log in to <http://www.amazon.com/Kamakhya-Prasad-Ghatak/e/B003B09OEY>.

Symbols

α	Band nonparabolicity parameter
a	The lattice constant
a_0, b_0	The widths of the barrier and the well for super-lattice structures
A_0	The amplitude of the light wave
\vec{A}	The vector potential
$A(E, n_z)$	The area of the constant energy 2D wave vector space for ultrathin films
B	Quantizing magnetic field
B_2	The momentum matrix element
b	Bandwidth
c	Velocity of light
C_1	Conduction band deformation potential
C_2	A constant which describes the strain interaction between the conduction and valance bands
ΔC_{44}	Second order elastic constant
ΔC_{456}	Third order elastic constant
δ	Crystal field splitting constant
Δ_o	Interface width
$\Delta(\frac{1}{B})$	Period of SdH oscillation
d_0	Super-lattice period
$D_0(E)$	Density-of-states (DOS) function
$D_B(E)$	DOS function in magnetic quantization
$D_B(E, \lambda)$	DOS function under the presence of light waves
d_x, d_y, d_z	Nano thickness along the x, y and z-directions
Δ_{\parallel}	Spin-orbit splitting constants parallel
Δ_{\perp}	Spin-orbit splitting constants perpendicular to the C-axis
Δ	Isotropic spin-orbit splitting constant
d^3k	Differential volume of the k space
\in	Energy as measured from the center of the band gap
ε	Trace of the strain tensor

ϵ_0	Permittivity of free space
ϵ_∞	Semiconductor permittivity in the high frequency limit
ϵ_{sc}	Semiconductor permittivity
ΔE_g	Increased band gap
$ e $	Magnitude of electron charge
E	Total energy of the carrier
E_o, ζ_0	Electric field
E_g	Band gap
E_i	Energy of the carrier in the i th band
E_{ki}	Kinetic energy of the carrier in the i th band
E_F	Fermi energy
E_{FB}	Fermi energy in the presence of magnetic quantization
E_n	Landau sub band energy
E_{Fs}	Fermi energy in the presence of size quantization
\bar{E}_{Fn}	Fermi energy for nipsis
E_{FSL}	Fermi energy in super-lattices
\vec{e}_s	Polarization vector
E_{FQWSL}	Fermi energy in quantum wire super-lattices with graded interfaces
E_{FL}	Fermi energy in the presence of light waves
E_{FEL}	Fermi energy under quantizing magnetic field in the presence of light waves
E_{F2DL}	2D Fermi energy in the presence of light waves
E_{F1DL}	1D Fermi energy in the presence of light waves
E_{g0}	Un-perturbed band-gap
$Erfc$	Complementary error function
Erf	Error function
E_{Fh}	Fermi energy of HD materials
\bar{E}_{hd}	Electron energy within the band gap
F_s	Surface electric field
$F(V)$	Gaussian distribution of the impurity potential
$F_j(\eta)$	One parameter Fermi-Dirac integral of order j
f_0	Equilibrium Fermi-Dirac distribution function of the total carriers
f_{0i}	Equilibrium Fermi-Dirac distribution function of the carriers in the i th band
g_v	Valley degeneracy
G	Thermoelectric power under classically large magnetic field
G_0	Deformation potential constant
g^*	Magnitude of the band edge g -factor
h	Planck's constant
\hat{H}	Hamiltonian
\hat{H}'	Perturbed Hamiltonian
$H(E - E_n)$	Heaviside step function

\hat{i}, \hat{j} and \hat{k}	Orthogonal triads
i	Imaginary unit
I	Light intensity
j_{cl}	Conduction current contributed by the carriers of the i th band
k	Magnitude of the wave vector of the carrier
k_B	Boltzmann's constant
λ	Wavelength of the light
$\bar{\lambda}_0$	Splitting of the two spin-states by the spin-orbit coupling and the crystalline field
$\bar{l}, \bar{m}, \bar{n}$	Matrix elements of the strain perturbation operator
L_x, L_z	Sample length along x and z directions
L_0	Super-lattices period length
L_D	Debye screening length
m_1	Effective carrier masses at the band-edge along x direction
m_2	Effective carrier masses at the band-edge along y direction
m_3	The effective carrier masses at the band-edge along z direction
m'_2	Effective- mass tensor component at the top of the valence band (for electrons) or at the bottom of the conduction band (for holes)
m_i^*	Effective mass of the i th charge carrier in the i th band
m_{\parallel}^*	Longitudinal effective electron masses at the edge of the conduction band
m_{\perp}^*	Transverse effective electron masses at the edge of the conduction band
m_c	Isotropic effective electron masses at the edge of the conduction band
$m_{\perp,1}^*, m_{\parallel,1}^*$	Transverse and longitudinal effective electron masses at the edge of the conduction band for the first material in super-lattice
m_r	Reduced mass
m_v	Effective mass of the heavy hole at the top of the valence band in the absence of any field
n	Landau quantum number
n_x, n_y, n_z	Size quantum numbers along the x, y and z -directions
n_{1D}, n_{2D}	1D and 2D carrier concentration
n_{2D_s}, n_{2D_w}	2D surface electron concentration under strong and weak electric field
$\bar{n}_{2D_s}, \bar{n}_{2D_w}$	Surface electron concentration under the strong and weak electric field quantum limit
n_i	Mini-band index for nipi structures
$N_{nipi}(E)$	DOS function for nipi structures
$N_{2DT}(E)$	2D DOS function
$N_{2D}(E, \lambda)$	2D DOS function in the presence of light waves
$N_{1D}(E, \lambda)$	1D DOS function in the presence of light waves

n_0	Total electron concentration
\bar{n}_0	Electron concentration in the electric quantum limit
n_i	Carrier concentration in the i th band
P	Isotropic momentum matrix element
P_n	Available noise power
P_{\parallel}	Momentum matrix elements parallel to the direction of crystal axis
P_{\perp}	Momentum matrix elements perpendicular to the direction of crystal axis
\vec{r}	Position vector
S_i	Zeros of the Airy function
\vec{s}_0	Momentum vector of the incident photon
t	Time scale
t_c	Tight binding parameter
T	Absolute temperature
$\tau_i(E)$	Relaxation time of the carriers in the i th band
$u_1(\vec{k}, \vec{r}), u_2(\vec{k}, \vec{r})$	Doubly degenerate wave functions
$V(E)$	Volume of k space
V_0	Potential barrier encountered by the electron
$V(\vec{r})$	Crystal potential
x, y	Alloy compositions
z_t	Classical turning point
μ_i	Mobility of the carriers in the i th band
μ	Average mobility of the carriers
$\zeta(2r)$	Zeta function of order $2r$
$\Gamma(j+1)$	Complete Gamma function
η	Normalized Fermi energy
η_g	Impurity scattering potential
ω_0	Cyclotron resonance frequency
θ	Angle
μ_0	Bohr magnetron
ω	Angular frequency of light wave
\uparrow', \downarrow'	Spin up and down function