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Kamakhya Prasad Ghatak
Department of Electronics
and Communication Engineering, Institute
of Engineering and Management
University of Engineering and Management
Kolkata, West Bengal, India

Arindam Biswas
Department of Computer Science, School
of Mines and Metallurgy
Kazi Nazrul University
Berhampore, West Bengal, India

Madhuchhanda Mitra
Department of Applied Physics
University of Calcutta
Kolkata, West Bengal, India

ISBN 978-981-16-9843-9 ISBN 978-981-16-9844-6 (eBook)
https://doi.org/10.1007/978-981-16-9844-6



This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

*The authors are grateful in the real sense of the term to Prof. Biswadip Basu Mallik, the HOD of Mathematics unit of Basic Science and Humanities Department of the Institute of Engineering and Management, Kolkata, for his constant inspiration and through checking of the manuscript from every point of view.*

# Preface

In this book, an attempt is made to investigate the **ELECTRON STATISTICS (ES)** whose importance is well known since the inception of semiconductor science [1–36]. The ES is connected **to many important transport topics of quantum effect devices, namely** *thermoelectric power, Debye screening length, diffusivity-mobility ratio, diffusion coefficient of the minority carriers, the elastic constants, generalized Raman gain, reflection coefficient, hydrostatic piezoresistance coefficient and the gate capacitance, respectively* [37–61]. **It is worth remarking that in this book we shall suggest the methods of experimental determination of the three important transport quantities, namely the Debye screening length, the carrier contribution to the Elastic Constants and the Einstein relation, respectively. The wide applications of Heisenberg's Uncertainty Principle (HUP) in different areas of quantum science are already well established since its inception [62]. In this first of its kind book, we shall use the HUP for finding out the ES for different technologically important quantum materials under different physical conditions in the presence of heavy doping without using the as usual density of states (DOS) function approach in the context for formulating the ES**.

**The present monograph explores the ES** in heavily doped (HD) nanostructures of nonlinear 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 quantum confined HD superlattices with graded interfaces, quantum confined HD doping superlattices, quantum confined effective mass superlattices, in the presence of intense light and electric fields and superlattices of HD optoelectronic materials with graded interfaces in addition to other quantized systems. Incidentally, even after forty years of continuous effort, we see that the complete investigation of the ES comprising of the whole set of the HD materials and their quantized counter parts is really a sea and permanently enjoys the domain of impossibility theorems. The ES has different forms for different materials and changes under one-, two- and three-dimensional quantum confinement of the charge carriers. In this context, it may be written that excluding the classic book *Semiconductor Statistics* by J. S. Blakemore (originally published in 1962 by Pergamon press and later on appeared in Dover publication in 1987 with less than 10%

change) which deals only with the ES in bulk and under magnetic quantization in semiconductors having **parabolic energy bands by using the usual DOS function approach and without using the HUP** (in pages 79–116), the available reports on the said areas are not containing the detailed investigations regarding **the ES in the present context by using the HUP**.

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 [63–64]. It is an amazing fact that although the HDS have been investigated in the literature, the study of the ES by formulating the corresponding dispersion relations (DRs) of HDS **is still one of the open research problems**. Our method is not at all related to the DOS technique as used in the literature. From the DR, one can obtain the DOS but the DOS technique, as used in the literature cannot generate the dispersion laws. **Therefore, our study is more fundamental than those in the existing literature, because the ES which controls the charge carrier properties of the semiconductor devices is being derived in this monograph in various cases without using the difficult DOS function technique but by directly applying the well-known HUP. This book, containing thirteen chapters, is partially based ongoing research of the different physical properties of the quantized structures from 1980 and we try to present a cross-section preview of the ES for a wide range of HD quantum materials with various DRs under different physical conditions.**

With the advent of radiation science and technology, the study of the optical properties of quantized structures is gaining importance with the assumption that the carrier energy spectra will be unaltered under strong radiation, which is not basically right. The physical properties of semiconductors in the presence of strong light waves which alter the basic dispersion relations have relatively been much less investigated in [63–64] as compared with the cases of other external fields and in opto-electronics the influence of strong light waves is needed for the characterization of the low-dimensional opto-electronic devices. The solo Chap. 1 investigates the ES in bulk specimens of HD Kane type III-V, ternary and quaternary semiconductors under intense radiation by applying the HUP. The same chapter explores the ES in the presence of magnetic quantization, cross-field configuration, quantum wells (QWs), nano-wires (NWs), quantum dots (QDs), magneto size quantization, doping superlattices, magneto doping superlattices, QWHD, NWHD and QDHD effective mass superlattices, magneto QWHD effective mass superlattices, magneto HD effective mass superlattices, QWHD, NWHD and QDHD superlattices with graded interfaces, magneto QWHD superlattices with graded interfaces and magneto HD superlattices with graded interfaces, respectively. **In Chap. 1, we suggest the methods of experimental determinations of the second- and third-order carrier contribution to the elastic constants, the Debye screening length and the Einstein relation, respectively. Additionally, for the purpose of investigating at least one ES-dependent electronic property in this case, we have also investigated the effective electron mass (EEM) which is a very important transport quantity [65–74]**.

***The physical properties of ultra-short modern electronic devices have been investigated by using the assumption of invariant carrier dispersion relations under intense electric field, which is not basically right.*** Chapter 2 of this book investigates the ES by applying the HUP under intense electric field, chronologically for all the specific cases as given in the content of Chap. 2 [75–90]. **It is interesting to note that the EEM depends on the strong electric field** (which is not observed elsewhere) together with the fact that the EEM in the said systems depends on the respective quantum numbers in addition to the Fermi energy the scattering potential and others system constants which are the characteristics features of such hetero-structures.

Chapter 3 deals with the influence of quantum confinement on the ES by applying the HUP in non-parabolic HDS and we study the ES in HDQWs of all the materials as given chronologically in the content of Chap. 3. 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. One important consequence of the HDS forming band tails is that the EEM 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. In Chap. 4, the ES for HDNWs of all the materials as stated in the content has respectively been investigated. As a collateral study, we shall observe that the EEM in such NWs becomes a function of size quantum number, the Fermi energy, the scattering potential and other constants of the system which is the intrinsic property of such 1D systems in general. In Chap. 5, the ES for QDs has been studied chronologically for all the materials as stated in the content of Chap. 5.

The various types of semiconductor superlattices (SLs) find extensive device-oriented applications [91–108]. In Chap. 6, we study the ES in doping superlattices (DSL) for all the cases as written in the content of the said chapter. With the advent of MOSFETs, there has been considerable interest in studying the 2D electron transport in such systems [109–128], and in Chap. 7, we study the ES by using HUP in accumulation layers for all the cases as given in the content of Chap. 7. Besides, we have numerically investigated the diffusivity to mobility ratio (DMR) in this context.

The effects of quantizing magnetic field (B) on the band structures of compound semiconductors are profound [129–143], and in Chap. 8, we shall study the ES by applying HUP under magnetic quantization for all the HD materials chronologically as given in the content of the said chapter, and additionally, we investigate at least one ES-dependent property, namely the DMR in this case. It is worth remarking that the effects of crossed electric and quantizing magnetic fields on the transport properties of semiconductors having various band structures have relatively been less investigated as compared with the corresponding magnetic quantization, although the study of the cross-fields is of fundamental importance with respect to the addition of new physics and the related experimental findings in modern quantum effect devices. **Chapter 9 investigates the ES by applying the HUP under cross-field configuration for all the cases as written in the content. This chapter also tells us that the EEM in all the cases is a function of the finite scattering potential,**

**the magnetic quantum number, the electric field, the quantizing magnetic field and the Fermi energy even for HD semiconductors whose bulk electrons in the absence of band tails are defined by the parabolic energy bands. As a co-lateral study, we investigate the DMR in this context.** Chapter 10 explores the ES in QWs of HD semiconductors under magnetic quantization for all the cases as stated in the content. In Chap. 11, we shall study the ES under cross-field configuration in QWs of HD nonlinear optical, III-V, II-VI, IV-VI and stressed Kane type semiconductors. The cross-fields introduce energy and quantum number-dependent mass anisotropy. Chapter 12 explores the ES in the doping super-lattices chronologically for all the materials as stated in the preface of Chap. 12. The last chapter explores the magneto ES in accumulation layers of different materials.

This book is based on the **'iceberg principle'** [144] 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 ES by applying the HUP for HD quantized structures to the best of our knowledge, we earnestly hope that the present book will be a useful reference source for the present and the next generation of the readers and the researchers of materials and allied sciences in general. We have discussed enough regarding the ES in different quantized HD materials although lots of new computer-oriented numerical analysis are being left for the purpose of being computed by the readers, to generate the new graphs and the inferences from them which all together is a sea in itself. Since the production of error free first edition of any book from every point of view is a permanent member of impossibility theorems, therefore in spite of our joint concentrated efforts for couple of years together with the seasoned team of Springer-Verlag, the same stands very true for this monograph also. **Various expressions and few chapters of this book have been appearing for the first time in printed form**. At last, we infer that this book 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.

Kolkata, India — Kamakhya Prasad Ghatak
Kolkata, India — Madhuchhanda Mitra
Berhampore, India — Arindam Biswas

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# Acknowledgments


## Acknowledgment by Kamakhya Prasad Ghatak

I am extremely grateful to all the teachers and specifically the students for the last fifty years for teaching me the various aspects of mathematical methods, quantum mechanics and statistical mechanics together with the device aspects from vacuum tubes up to nano-technology at present. I offer special thanks to the present members of my research team for placing their combined effort toward the development of this book in the DO-LOOP of a computer and critically reading the manuscript in its last phase.

*As always, I am with the members of my research team grateful to Dr. Loyola D'Silva, publishing Editor Physics, Springer, Singapore, in the real sense of the term for his inspiration and priceless technical assistance from the very start of our this first monograph from Springer, Singapore.* Naturally, the authors are responsible for non-imaginative shortcomings. We firmly believe that our Mother Nature has propelled this project in her own unseen way in spite of several insurmountable obstacles.

## Acknowledgment by Madhuchhanda Mitra

It is a great pleasure to express my gratitude to Prof. Kamakhya Prasad Ghatak for instigating me to carry out extensive research in the field of nano science and nano technology. I am thankful to the faculty members and staffs of Department of Applied Physics, University of Calcutta, for support and cooperation. My family members especially my husband and son deserve a very special mention for forming the backbone of my long research carrier. Lastly, I wish to offer special thanks and respect to Mr. B. Nag in the Department of Applied Physics for his constant support, motivation and guidance.

## Acknowledgment by Arindam Biswas

I am extremely grateful to my parents without whose active cooperation my carrier would be a mere dream. With deep pleasure, I offer my speechless gratitude to Prof. Dr. S. Chakraborti, the Hon'ble Vice-Chancellor of Kazi Nazrul University for constant inspiration and guidance in this context.

West Bengal, India
December 2021

Kamakhya Prasad Ghatak
Madhuchhanda Mitra
Arindam Biswas

# Contents

# About the Authors

**Prof. Dr. Engg. Kamakhya Prasad Ghatak** of IEM, Kolkata obtained his Ph.D. Degree from the Institute of Radio Physics and Electronics of the Calcutta University in 1988 on the basis of 27 research papers in reputed SCI Journals which is still a record of the said Institute. He is the first Doctor of Engineering Degree awardee of Jadavpur University in 1991(h-index-35, i-10 index- 181 and T.C.-5740, the author of 370 SCOPUS publications, 17 books on Nano Technology) and as per World Ranking of top 2% Scientists as prepared by Stanford University, USA, in 2020 (shorturl.at/qHIJ4), he stays within top 1% in the field of Applied Physics. From the position of Assistant Professor in Calcutta University in 1983 up to Senior Professor in the Institute of Engineering and Management, Kolkata in 2015 he was at the top of the merit lists in all the cases. His score in Vidwan portal unit of Government of India is 8.7 out of 10, the highest score among the private Engineering Universities and Institutions of West Bengal. He has produced more than 50 Ph.D. students and the list includes Director, Vice Chancellor, Professors and CEO's of different organizations. For more please go through the link https://www.amazon.com/Kamakhya-Prasad-Ghatak/e/B003B09OEY%3Fref=dbs_a_mng_rwt_scns_share and he can be goggled in this regard.

**Prof. Dr. Madhuchhanda Mitra** (h-index-25, i-10 index- 69 and T.C.-3555), received her Ph.D. (Tech) degrees in 1998 respectively, from the Calcutta University and she is a recipient of "Griffith Memorial Award" of the said University. She is the principal co-author of 150 scientific research papers in International peer reviewed journals and is the supervisor of sixteen Ph.D. candidates.

For more please log in to https://scholar.google.co.in/citations?user=LVoCtQgAAAAJ&hl=en.

**Dr. Arindam Biswas** (h-index-15, i-10 index- 30 and T.C.-970), is the Associate Professor of Kazi Nazrul University, West Bengal, India and has received the research grant from different national and international funding agencies like SERB, DST-ASEAN, DST-JSPS, UGC, Centre of Biomedical Engineering, Tokoyo Medical and Dental University in association with RIE, Shizouka University, Japan respectively. He is a famous teacher of the University and also connected with various administrative responsibilities.

For more please go through the link https://scholar.google.co.in/citations?user=ht4qPJsAAAAJ&hl=en.

# Chapter 1
# The Heisenberg's Uncertainty Principle (HUP) and the Electron Statistics (ES) in Heavily Doped (HD) Kane-type III-V and Opto-Electronic Materials in the Presence of Intense Radiation

## 1.1 Introduction

Under intense radiation, the different physical properties of quantized nanostructures have been studied [1], using the idea that the $E - k$ relations are not altered under radiation fields which is fundamentally questionable. The electronic properties of electronic materials under strong radiation which changes their dispersion relations have mainly been investigated by Ghatak et al. [2, 3]. The first chapter investigates the ES in HD III-V quantized structures under strong radiation by applying the HUP directly without using the usual density-of-states (DOS) function approach.

We investigate chronologically the ES in accordance with the content of this chapter taking various III-V, ternary, quaternary systems and their low dimensional counterparts which find extensive uses in various device applications [4]. Section 1.4 contains the result and discussions.

## 1.2 Mathematical Basis

### *1.2.1 The Bulk Compounds*

The carrier dispersion relations (DRs) for III-V and opto-electronic compounds become [5–28]

$$\overline{G}_4 k^2 = I_{11}(E) \tag{1.1a}$$

$$\overline{G}_4 k^2 = E(1 + \alpha E) \tag{1.1b}$$

 
K. P. Ghatak et al., *Heisenberg's Uncertainty Principle and the Electron Statistics in Quantized Structures*, https://doi.org/10.1007/978-981-16-9844-6_1

and

$$\overline{G}_4 k^2 = E \tag{1.1c}$$

where, $\overline{G}_4 = \frac{\hbar^2}{2m_c}$, $I_{11}(E) = \frac{E(E+E_g)(E+E_g+\Delta)(E_g+\frac{2}{3}\Delta)}{E_g(E_g+\Delta)(E+E_g+\frac{2}{3}\Delta)}$, $\alpha = \frac{1}{E_g}$

and the other notations mean as usual.

In the presence of radiation, Eqs. (1.1a), (1.1b) and (1.1c) assume the forms [29]

$$\overline{G}_4 k^2 = \beta_0(E, \lambda) \tag{1.1d}$$

$$\overline{G}_4 k^2 = \tau_0(E, \lambda) \tag{1.2}$$

and

$$\overline{G}_4 k^2 = \rho_0(E, \lambda) \tag{1.3}$$

where the other notations are written in [29].

Under certain constraints, Eqs. (1.1d), (1.2) and (1.3) become [29]

$$\overline{G}_4 k^2 = U_\lambda I_{11}(E) - P_\lambda \tag{1.4}$$

$$\overline{G}_4 k^2 = t_{1\lambda} E + t_{2\lambda} E^2 - \delta_\lambda \tag{1.5}$$

and

$$\overline{G}_4 k^2 = t_{1\lambda} E - \delta_\lambda \tag{1.6}$$

where the other notations are defined in [29].

The distribution function $F(V)$ here can be written as [6, 7]

$$F(V) = (\pi \eta_g^2)^{-1/2} \exp(-V^2/\eta_g^2) \tag{1.7}$$

Using Eqs. (1.4), (1.5), (1.6) and (1.7) get transformed as [29]

$$\overline{G}_4 k^2 = T_{11}(E, \eta_g, \lambda) \tag{1.8}$$

$$\overline{G}_4 k^2 = T_{21}(E, \eta_g, \lambda) \tag{1.9}$$

and