Preface

In recent years, with the advent of fine line lithographical methods, molecular beam epitaxy, organometallic vapour phase epitaxy and other experimental techniques, low dimensional structures having quantum confinement in one, two and three dimensions (such as inversion layers, ultrathin films, nipi's, quantum well superlattices, quantum wires, quantum wire superlattices, and quantum dots together with quantum confined structures aided by various other fields) have attracted much attention, not only for their potential in uncovering new phenomena in nanoscience, but also for their interesting applications in the realm of quantum effect devices. In ultrathin films, due to the reduction of symmetry in the wave–vector space, the motion of the carriers in the direction normal to the film becomes quantized leading to the quantum size effect. Such systems find extensive applications in quantum well lasers, field effect transistors, high speed digital networks and also in other low dimensional systems. In quantum wires, the carriers are quantized in two transverse directions and only one-dimensional motion of the carriers is allowed. The transport properties of charge carriers in quantum wires, which may be studied by utilizing the similarities with optical and microwave waveguides, are currently being investigated. Knowledge regarding these quantized structures may be gained from original research contributions in scientific journals, proceedings of international conferences and various review articles. It may be noted that the available books on semiconductor science and technology cannot cover even an entire chapter, excluding a few pages on the Einstein relation for the diffusivity to mobility ratio of the carriers in semiconductors (DMR). The DMR is more accurate than any one of the individual relations for the diffusivity (D) or the mobility (μ) of the charge carriers, which are two widely used quantities of carrier transport in semiconductors and their nanostructures.

It is worth remarking that the performance of the electron devices at the device terminals and the speed of operation of modern switching transistors are significantly influenced by the degree of carrier degeneracy present in these devices. The simplest way of analyzing such devices, taking into account the degeneracy of the bands, is to use the appropriate Einstein relation to express the performances at the device terminals and the switching speed in terms of carrier concentration (S.N. Mohammad, *J. Phys.* ***C***, **13**, 2685 (1980)). It is well known from the fundamental works of Landsberg (P.T. Landsberg, *Proc. R. Soc.* ***A***, **213**, 226, (1952); *Eur. J. Phys*, **2**, 213, (1981)) that the Einstein relation for degenerate materials is essentially determined by their energy band structures. It has, therefore, different values in different materials having various band structures and varies with electron concentration, the magnitude of the reciprocal quantizing magnetic field, the quantizing electric field as in inversion layers, ultrathin films, quantum wires and with the superlattice period as in quantum confined semiconductor superlattices having various carrier energy spectra.

This book is partially based on our on-going researches on the Einstein relation from 1980 and an attempt has been made to present a cross section of the Einstein relation for a wide range of materials with varying carrier energy spectra, under various physical conditions.

In Chap. 1, after a brief introduction, the basic formulation of the Einstein relation for multiband semiconductors and suggestion of an experimental method for determining the Einstein relation in degenerate materials having arbitrary dispersion laws are presented. From this suggestion, one can also experimentally determine another two seemingly different but important quantities of quantum effect devices namely, the Debye screening length and the carrier contribution to the elastic constants. In Chap. 2, the Einstein relation in bulk specimens of tetragonal materials (taking n-Cd_3As_2 and n-$CdGeAs_2$ as examples) is formulated on the basis of a generalized electron dispersion law introducing the anisotropies of the effective electron masses and the spin orbit splitting constants respectively together with the inclusion of the crystal field splitting within the framework of the $\boldsymbol{k.p}$ formalism. The theoretical formulation is in good agreement with the suggested experimental method of determining the Einstein relation in degenerate materials having arbitrary dispersion laws. The results of III–V (e.g. InAs, InSb, GaAs, etc.), ternary (e.g. $Hg_{1-x}Cd_xTe$), quaternary (e.g. $In_{1-x}Ga_xAs_{1-y}P_y$ lattice matched to InP) compounds form a special case of our generalized analysis under certain limiting conditions. The Einstein relation in II–VI, IV–VI, stressed Kane type semiconductors together with bismuth are also investigated by using the appropriate energy band structures for these materials. The importance of these materials in the emergent fields of opto- and nanoelectronics is also described in Chap. 2.

The effects of quantizing magnetic fields on the band structures of compound semiconductors are more striking than those 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. 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. Besides, the influence of cross-field configuration is of fundamental importance to an understanding of the various physical properties of various materials having different carrier dispersion relations. In Chap. 3, we study the Einstein relation in compound semiconductors under magnetic quantization. Chapter 4 covers the influence of crossed electric and quantizing magnetic fields on the Einstein relation in compound semiconductors. Chapter 5 covers the study of the Einstein relation in ultrathin films of the materials mentioned.

Since Iijima's discovery (S. Iijima, *Nature* **354**, 56 (1991)), carbon nanotubes (CNTs) have been recognized as fascinating materials with nanometer dimensions, uncovering new phenomena in different areas of nanoscience and technology. The remarkable physical properties of these quantum materials make them ideal candidates to reveal new phenomena in nanoelectronics. Chapter 6 contains the study of the Einstein relation in quantum wires of compound semiconductors, together with carbon nanotubes.

In recent years, there has been considerable interest in the study of the inversion layers which are formed at the surfaces of semiconductors in metal–oxide–semiconductor field-effect transistors (MOSFET) under the influence of a sufficiently strong electric field applied perpendicular to the surface by means of a large gate bias. In such layers, the carriers form a two dimensional gas and are free to move parallel to the surface while their motion is quantized in the perpendicular to it leading to the formation of electric subbands. In Chap. 7, the Einstein relation in inversion layers on compound semiconductors has been investigated.

The semiconductor superlattices find wide applications in many important device structures such as avalanche photodiode, photodetectors, electro-optic modulators, etc. Chapter 8 covers the study of the Einstein relation in nipi structures. In Chap. 9, the Einstein relation has been investigated under magnetic quantization in III-V, II-VI, IV-VI, HgTe/CdTe superlattices with graded interfaces. In the same chapter, the Einstein relation under magnetic quantization for effective mass superlattices has also been investigated. It also covers the study of quantum wire superlattices of the materials mentioned. Chapter 10 presents an initiation regarding the influence of light on the Einstein relation in optoelectronic materials and their quantized structures which is itself in the stage of infancy.

In the whole field of semiconductor science and technology, the heavily doped materials occupy a singular position. Very little is known regarding the dispersion relations of the carriers of heavily doped compound semiconductors and their nanostructures. Chapter 11 attempts to touch this enormous field of active research with respect to Einstein relation for heavily doped materials in a nutshell, which is itself a sea. The book ends with Chap. 12, which contains the conclusion and the scope for future research.

As there is no existing book devoted totally to the Einstein relation for compound semiconductors and their nanostructures to the best of our knowledge, we hope that the present book will be a useful reference source for the present and the next generation of readers and researchers of solid state electronics in general. In spite of our joint efforts, the production of error free first edition of any book from every point of view enjoys the domain of impossibility theorem. Various expressions and a few chapters of this book have been appearing for the first time in printed form. The positive suggestions of the readers for the development of the book will be highly appreciated.

In this book, from Chap. 2 to the end, we have presented 116 open and 60 allied research problems in this beautiful topic, as we believe that a proper identification of an open research problem is one of the biggest problems in research. The problems presented here are an integral part of this book and will be useful for readers to initiate their own contributions to the Einstein relation. This aspect is also important for PhD aspirants and researchers. We strongly contemplate that the readers with a mathematical bent of mind would invariably yearn for investigating all the systems from Chapters 2 to 12 and the related research problems by removing all the mathematical approximations and establishing the appropriate respective uniqueness conditions. Each chapter except the last one ends with a table containing the main results.

It is well known that the studies in carrier transport of modern semiconductor devices are based on the Boltzmann transport equation which can, in turn, be solved if and only if the dispersion relations of the carriers of the different materials are known. In this book, we have investigated various dispersion relations of different quantized structures and the corresponding electron statistics to study the Einstein relation. Thus, in this book, the alert readers will find information regarding quantum-confined low-dimensional materials having different band structures. Although the name of the book is extremely specific, from the content one can infer that it will be useful in graduate courses on semiconductor physics and devices in many Universities. Besides, as a collateral study, we have presented the detailed analysis of the effective electron mass for the said systems, the importance of which is already well known, since the inception of semiconductor science. Last but not the least, we do hope that our humble effort will kindle the desire of anyone engaged in materials research and device development, either in academics or in industries, to delve deeper into this fascinating topic.

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K.P. GHATAK
S. BHATTACHARYA
D. DE

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