Preface

The combination of the concept of asymmetry of the wave-vector space of charge carriers in semiconductors with modern techniques of fabricating nanostructured materials such as MBE, MOCVD and FLL in one, two and three dimensions (such as quantum wells (QWs), doping superlattices, accumulation and inversion layers, quantum well superlattices, carbon nanotubes, quantum wires, quantum wire superlattices, magnetic quantization, magneto size quantization, quantum dots, magneto accumulation and inversion layers, magneto NIPIs, magneto quantum well superlattices, quantum dot superlattices and other field aided low-dimensional systems) spawns not only useful quantum effect devices but also unearths new concepts in the realm of low-dimensional solid-state science and related disciplines. These semiconductor nanostructures occupy a central position in the entire arena of condensed matter science in general, by their own right and find extensive applications in quantum registers, quantum switches, quantum sensors, quantum logic gates, quantum well and quantum wire transistors, quantum cascade lasers, heterojunction field-effect transistors, high-speed digital networks, high-frequency microwave circuits, high-resolution terahertz spectroscopy, superlattice photo-oscillator, advanced integrated circuits, superlattice photocathodes, resonant tunneling diodes and transistors, thermoelectric devices, superlattice coolers, thin film transistors, intermediate-band solar cells, micro-optical systems, high performance infrared imaging systems, band-pass filters, thermal sensors, optical modulators, optical switching systems, single electron electronics, molecular electronics, nanotube-based diodes and other nanoelectronic devices. Knowledge regarding these quantized structures may be gained from original research contributions in scientific journals, various patents, personal communications, proceedings of the conferences/seminars, review articles and different research monographs [1] respectively. In this context, it may be noted that the available reports on the said areas cannot afford to cover even an entire chapter regarding the Einstein Relation (ER) for the diffusivity-mobility ratio of carriers in heavily doped (HD) two-dimensional (2D) quantized structures and the single first book on ER [2] does not contain even a paragraph regarding this important specialized topic of research and, after 30 years of continuous effort, we see that the complete investigations of the ER comprising the whole set of materials and allied sciences is really a sea and is a permanent member of the domain of impossibility theorems.

It is well known that the ER occupies a central position in the whole field of solid-state device electronics and the related sciences since the diffusion constant (a quantity very useful for device analysis where exact experimental determination is rather difficult) can be obtained from this ratio by knowing the experimental values of the mobility. The classical value of the ER is equal to $(k_B T/|e|)$, (k_B, T and $|e|$ are Boltzmann's constant, temperature and the magnitude of the carrier charge respectively). This relation in this form was first introduced by Einstein to studythe diffusion of gas particles and is known as the Einstein relation [2, 3]. It appears that the ER increases linearly with increasing T and is independent of electron concentration. This relation is applicable for both types of charge carriers only under nondegenerate carrier concentration although its validity has been suggested erroneously for degenerate materials [4]. Landsberg first pointed out that the ER for degenerate semiconductors is essentially determined by their energy band structures [5, 6]. This relation is useful for semiconductor homostructures [7, 8], semiconductor–semiconductor heterostructures [9, 10], metals–semiconductor heterostructures [11–19] and insulator–semiconductor heterostructures [20–23]. The nature of the variations of the ER under different physical conditions has been studied in the literature [1–3, 5, 6, 24–49]. Incidentally, A. N. Chakravarti (a recognized leading expert of ER in general) and his research group are still contributing significantly under his able leadership regarding this pinpointed research topic on ER from 1972 [2, 24, 25–28, 34, 39–49] and some of the significant features, which have emerged from these studies, are:

(a) The ER increases monotonically with increasing carrier concentration in bulk semiconductors and the nature of these variations is significantly influenced by the band structures of different materials.
(b) The ER increases with the increasing quantizing electric field as in inversion layers.
(c) The ER oscillates with the inverse quantizing magnetic field under magnetic quantization due to the Shubnikov-de Haas effect.
(d) The ER shows composite oscillations with the various controlled quantities of semiconductor superlattices.
(e) In ultrathin films, quantum wires and other field assisted low-dimensional systems, the value of the ER changes appreciably with the external variables depending on the nature of quantum confinements of different materials.

The ER 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 carriers of different materials have been proposed [50], which have created interest in studying the ER in HD 2D-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 and Schottky contacts respectively [11–19, 51]. It is an amazing fact that although heavily doped semiconductors (HDS) have been investigated in the literature the study of 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 band tails are being formed in the forbidden zone of the HDS and can be explained by the overlapping of the impurity band with the conduction and valence bands [52]. Kane [53] and Bonch Bruevich [54] have independently derived the theory of band tailing for semiconductors having unperturbed parabolic energy bands. Kane's model [53] was used to explain the experimental results on tunneling [55] and the optical absorption edges [56, 57] in this context. Halperin and Lax [58] 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 [59, 60], it may be noted that this model [53, 61] suffers from serious assumptions in the sense that the local impurity potential is assumed to be small and slowly varying in space coordinates [60]. 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 ER based on the concept of the variation of the kinetic energy [52, 60] 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 ERs. 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 [52]. 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 [62]. In a HDS, each impurity atom is surrounded by electrons, assuming a regular distribution of atoms and it is screened independently [59, 61, 63]. 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 (popularly known as the Debye screening length). The screening length changes with the band structure. Furthermore, these entities are important for HDS in characterizing the semiconductor properties [64, 65] and the modern electronic devices [59, 66]. The works on Fermi energy and the screening length in an n-type GaAs have already been initiated in the literature [67], based on Kane's model. Incidentally, the limitations of Kane's model [53, 60], as mentioned above, are also present in their studies.

At this point, it may be noted that many band tail models are proposed using Gaussian distribution of the impurity potential variation [53, 60]. From the very start, we have used Gaussian band tails to obtain the *exact E-k dispersion relations* for HD nonlinear optical, III–V, II–VI, IV–VI, stressed Kane-type semiconductors, Te, GaP, $PtSb_2$, Bi_2Te_3, Ge and GaSb respectively. Our method is not 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