Preface

This three-volume handbook represents the only comprehensive treatise on semiconductor and device fundamentals and technology under the overall umbrella of wide bandgap nitride semiconductors with comparison to GaAs when applicable. As it stands, the book is a reference book, a handbook, and a graduate text book all in one and would be beneficial to second-year graduate students majoring in semiconductor materials and devices, graduate research assistants conducting research in wide bandgap semiconductors, researchers and technologists, faculty members, program monitors, and managers. The philosophy of this endeavor is to present the material as much clearly and comprehensively as possible, so that there is very little need to refer to other sources to get a grasp of the subjects covered. Extreme effort has been expended to ensure that concepts and problems are treated starting with their fundamental basis so that the reader is not left hanging in thin air. Even though the treatise deals with GaN and related materials, the concepts and methods discussed are applicable to any semiconductor.

The philosophy behind *Nitride Semiconductors and Devices* was to provide an adequate treatment of nitride semiconductors and devices as of 1997 to be quickly followed by a more complete treatment. As such, *Nitride Semiconductors and Devices* did not provide much of the background material for the reader and left many issues unanswered in part because they were not yet clear to the research community at that time. Since then, tremendous progress both in the science and engineering of nitrides and devices based on them has been made. While LEDs and lasers were progressing well even during the period when *Nitride Semiconductors and Devices* was written, tremendous progress has been made in FETs and detectors in addition to LEDs and lasers since then. LEDs went from display devices to illuminants for lighting of all kinds. Lasers are being implemented in the third generation of DVDs. The power amplifiers are producing several hundred watts of RF power per chip and the detectors and detector arrays operative in the solar-blind region of the spectrum have shown detectivities rivaling photomultiplier tubes. The bandgap of InN has been clarified which now stands near 0.7 eV. Nanostructures, which did not exist

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during the period covered by *Nitride Semiconductors and Devices*, have since become available. The technological breakthroughs such as epitaxial lateral overgrowth, laser liftoff, and freestanding GaN were either not fully developed or did not exist, neither did the highly improved quantum structures and devices based on them. In the interim period since then, the surfaces of nitrides and substrate materials, point defects and doping, magnetic ion doping, processing, current conduction mechanisms, and optical processes in bulk and quantum structures have been more clearly understood and many misconceptions (particularly, those dealing with polarization) identified, removed and/or elucidated. The handbook takes advantage of the fundamental and technological developments for a thorough treatment of all aspects of nitride semiconductors. In addition, the fundamentals of materials physics and device physics that are provided are applicable to other semiconductors, particularly, wurtzitic direct bandgap semiconductors.

The handbook presents a thorough treatment of the science, fundamentals, and technology of nitride semiconductors and devices in such a width and depth that the reader would seldom need to engage in time-consuming exploration of the literature to fill in gaps. Last but not the least, the handbook contains seamless treatments of fundamentals needed or relied on throughout the entire book. The following is a succinct odyssey through the content of the three-volume handbook.

Volume 1, Chapter 1 discusses the properties of nitride-based semiconductors with plenty of tables for reference. Volume 1, Chapter 2 treats the band structure of III–V nitrides, theories applied to determining the band structure, features of each theory with a succinct discussion of each, band structure of dilute III–V semiconductors doped with N, strain and stress, deformation potentials, and in-depth discussion of piezo and spontaneous polarization with illustrative and instructive artwork. Volume 1, Chapter 3 encompasses substrates that have been and are used for growth of nitride semiconductors, mainly, structural and mechanical (thermal) properties of those substrates, surface structure of planes used for growth, and substrate preparation for growth. Orientation and properties of GaN grown on those substrates are discussed along with commonly used surface orientations of GaN. The discussion is laced with highly illustrative and illuminating images showing orientations of GaN resulting through growth on *c*-plane, *a*-plane, *m*-plane, and *r*-plane substrates whichever applicable and the properties of resulting layers provided. The treatment segues into the discussion of various growth methods used for nitrides taking into account the fundamentals of growth including the applicable surface-oriented processes, kinetics, and so on, involved. A good deal of growth details for both OMVPE and MBE, particularly, the latter including the fundamentals of *in situ* process monitoring instrumentation such as RHEED, and dynamics of growth processes occurring at the surface of the growing layer are given. Of paramount interest is the epitaxial lateral overgrowth (ELO) for defect reduction. In addition to standard single multistep ELO, highly attractive nanonetwork meshes used for ELO are also discussed. Specifics in terms of growth of binary, ternary, and quaternaries of nitride semiconductors are discussed. Finally, the methods used to grow nanoscale structures are treated in sufficient detail.

Volume 1, Chapter 4 focuses on defects, both extended and point, doping for conductivity modulation and also for rendering the semiconductor potentially ferromagnetic segueing into electrical, optical, and magnetic properties resulting in films, with sufficient background physics provided to grasp the material. A clear discussion of extended defects, including line defects, are discussed with a plethora of illustrative schematics and TEM images for an easy comprehension by anyone with solid-state physics background. An in-depth and comprehensive treatment of the electrical nature of extended defects is provided for a full understanding of the scope and effect of extended defects in nitride semiconductors, the basics of which can be applicable to other hexagonal materials. The point defects such as vacancies, antisites, and complexes are then discussed along with a discussion of the effect of H. This gives way to the methods used to analyze point defects such as deep level transient spectroscopy, carrier lifetime as pertained to defects, positron annihilation, Fourier transform IR, electron paramagnetic resonance, and optical detection of magnetic resonance and their application to nitride semiconductors. This is followed by an extensive discussion of n-type and p-type doping in GaN and related materials and developments chronicled when applicable. An in-depth treatment of triumphs and challenges along with codoping and other methods employed for achieving enhanced doping and the applicable theory has been provided. In addition, localization effects caused by heavy p-type doping are discussed. This gives way to doping of, mainly, GaN with transition elements with a good deal of optical properties encompassing internal transition energies related to ion and perturbations caused by crystal field in wurtzitic symmetry. To get the reader conditioned for ferromagnetism, a sufficient discussion of magnetism, ferromagnetism, and measurement techniques (magnetic, magneto transport, magneto optics with underlying theory) applied to discern such properties are given. This is followed by an in-depth and often critical discussion of magnetic ion and rare earth-doped GaN, as well as of spintronics, often accompanied by examples for materials properties and devices from well-established ferromagnetic semiconductors such as Mn-doped GaN and Cr-doped ZnTe.

Volume 2, Chapter 1 treats metal semiconductor structures and fabrication methods used for nitride-based devices. Following a comprehensive discussion of current conduction mechanisms in metal semiconductor contacts, which are applicable to any metal semiconductor system, specific applications to metal-GaN contacts are treated along with the theoretical analysis. This gives way to a discussion of ohmic contacts, their technology, and their characterization. In particular, an ample discussion of the determination of ohmic contact resistivity is provided. Then etching methods, both dry (plasma) and wet, photochemical, process damage, and implant isolation are discussed. Volume 2, Chapter 2 deals with determination of impurity and carrier concentrations and mobility mainly by temperature-dependent electrical measurements, such as Hall measurements. Charge balance equations, capacitance voltage measurements, and their intricacies are treated and used for nitride semiconductors, as well as a good deal of discussion of often brushed off degeneracy factors.

Volume 2, Chapter 3 is perhaps one of the most comprehensive discussions of carrier transport in semiconductors with applications to GaN. After a discussion of scattering processes in physical and associated mathematical terms, the methods discussed are applied to GaN and other related binaries and ternaries with useful ranges of doping levels, compositions, and lattice temperatures. Comparisons with other semiconductors are also provided when applicable. This discussion segues into the discussion of carrier transport at high electric fields applicable to field-effect transistors, avalanche and pin (biased) photodiodes. This is followed by the measurement of mobility and associated details, which are often neglected in text and reference books. The discussion then flows into magnetotransport beyond that present in Hall measurements. Low, medium, and high magnetic field cases, albeit only normal to the surface of the epitaxial layers, determination of which is affected by the value of the mobility and various cases are treated. The treatise also includes cases where the relaxation time, if applicable, is energy-dependent and somewhat energy-independent. The discussion of the magnetotransport paves the way for a fundamental and reasonably extensive discussion of the Hall factor for each of the scattering mechanisms that often are not treated properly or are treated only in a cursory manner in many texts leading to confusion. After providing the necessary fundamental knowledge, the transport properties of GaN are discussed. This gives way to the discussion of various scattering mechanisms in two-dimensional systems that are relied on in high-performance FETs. For determining the mobility of each layer (in the case of multiple layer conduction), quantitative mobility spectrum analysis including both fundamentals and experimental data obtained in nitride semiconductors is discussed. The quantum Hall effect and fractional quantum Hall effect in general and as germane to GaN are discussed along with parameters such as the effective mass determined from such measurements.

Volume 2, Chapter 4 is devoted to p–n junctions, beginning with the discussion of band lineups, particularly, in the binary pairs from the point of view of theoretically and experimentally measured values. Current conduction mechanisms, such as diffusion, generation-recombination, surface recombination, Poole–Frenkel, and hopping conductivity are discussed with sufficient detail. Avalanche multiplication, pertinent to the high-field region of FETs, and avalanche photodiodes, are discussed-followed by discussions of the various homojunction and heterojunction diodes based on nitrides.

Volume 2, Chapter 5 is perhaps the most comprehensive discussion of optical processes that can occur in a direct bandgap semiconductor and, in particular, in nitride-based semiconductors and heterostructures inclusive of 3, 2-, and 0-dimensional structures as well as optical nonlinearities. Following a treatment of photoluminescence basics, the discussion is opened up to the treatment of excitons, exciton polaritons, selection rules, and magneto-optical measurements followed by extrinsic transitions because of dopants/impurities and/or defects with energies ranging from the yellow and to the blue wavelength of the visible spectrum. Optical transitions in rare earth-doped GaN, optical properties of alloys, and quantum wells are then discussed with a good deal of depth, including localization effects and their possible sources particularly media containing InN. The discussion then leads to the treatment of optical properties of quantum dots, intersubband transitions in GaN-based heterostructures, and, finally, the nonlinear optical properties in terms of second and third harmonic generation with illuminating graphics.

Volume 3, Chapter 1 is devoted, in part, to the fundamentals of light emitting diodes, the perception of vision and color by human eye, methodologies used in conjunction with the chromaticity diagram and associated international standards in terms of color temperatures and color rendering index. Specific performances of various types of LEDs including UV varieties, current spreading or the lack of related specifics, analysis of the origin of transitions, and any effect of localization are discussed. A good deal of white light and lighting-related standards along with approaches employed by LED manufacturers to achieve white light for lighting applications is provided. The pertinent photon conversion schemes with sufficient specificity are also provided. Finally, the organic LEDs, as potential competitors for some applications of GaN-based LEDs are discussed in terms of fundamental processes that are in play and various approaches that are being explored for increased efficiency and operational lifetime.

Volume 3, Chapter 2 focuses on lasers along with sufficient theory behind laser operation given. Following the primer to lasers along with an ample treatment based on Einstein's A and B coefficients and lasing condition, an analytical treatment of waveguiding followed by specifics for the GaN system and numerical simulations for determining the field distribution, loss, and gain cavity modes pertaining to semiconductor lasers are given. An ample fundamental treatment of spontaneous emission, stimulated emission, and absorptions and their interrelations in terms of Einstein's coefficients and occupation probabilities are given. This treatment segues into the extension of the gain discussion to a more realistic semiconductor with a complex valence band such as that of GaN. The results from numerical simulations of gain in GaN quantum wells are discussed, as well as various pathways for lasing such as electron-hole plasma and exciton-based pathways. Localization, which is very pervasive in semiconductors that are yet to be fully perfected, is discussed in the light of laser operation. Turning to experimental measurements, the method for gain measurement, use of various laser properties such as the delay on the onset of lasing with respect to the electrical pulse, dependence of laser threshold on cavity length to extract important parameters such as efficiency are discussed. The aforementioned discussions culminate in the treatment of performance of GaN-based lasers in the violet down to the UV region of the optical spectrum and applications of GaN-based lasers to DVDs along with a discussion of pertinent issues related to the density of storage.

Volume 3, Chapter 3 treats field effect transistor fundamentals that are applicable to any semiconductor materials with points specific to GaN. The discussion primarily focuses on 2DEG channels formed at heterointerfaces and their use for FETs, including polarization effects. A succinct analytical model is provided for calculating the carrier densities at the interfaces for various scenarios and current voltage characteristics of FETs with several examples. Experimental performance of GaN-based FETs and amplifiers is then discussed followed by an in-depth analysis of anomalies in the current voltage characteristics owing to bulk and barrier states, including experimental methods and probes used for cataloging these anomalies. This is followed by the employment of field spreading gate plates and associated performance improvements. This segues into the discussion of noise both at the low-frequency end and high-frequency end with sufficient physics and practical approaches employed. The combined treatment of various low-frequency noise contributions as well as those at high frequencies along with their physical origin makes this treatment unique and provides an opportunity for those who are not specialists in noise to actually grasp the fundamentals and implications of low- and high-frequency noise. Discussion of high-power FETs would not be complete without a good discussion of heat dissipation and its physical pathways, which is made available. Unique to GaN is the awareness of the shortfall in the measured electron velocity as compared to the Monte Carlo simulation. Hot phonon effects responsible for this shortfall are uniquely discussed with sufficient theory and experimental data. A section devoted to reliability with specifics to GaN based high power HFETs is also provided. Finally, although GaN-based bipolar transistors are not all that attractive at this time, for completeness and the benefit of graduate students and others who are interested in such devices, the theory, mainly analytical, of the operation of heterojunction bipolar transistors is discussed along with available GaN based HBT data.

Volume 3, Chapter 4 discusses optical detectors with special orientation toward UV and solar-blind detectors. Following a discussion of the fundamentals of photoconductive and photovoltaic detectors in terms of their photo response properties, a detailed discussion of the current voltage characteristic of the same, including all the possible current conduction mechanisms, is provided. Because noise and detectors are synonymous with each other, sources of the noise are discussed, followed by a discussion of quantum efficiency in photoconductors and p–n junction detectors. This is then followed by the discussion of vital characteristics such as responsivity and detectivity with an all too important treatment of the cases where the detectivity is limited by thermal noise, shot current noise, generation-recombination current noise, and background radiation limited noise (this is practically nonexistent in the solar-blind region except the man-made noise sources). A unique treatment of particulars associated with the detection in the UV and solar-blind region and requirements that must be satisfied by UV and solar-blind detectors, particularly, for the latter, is then provided. This leads the discussion to various UV detectors based on the GaN system, including the Si- and SiC-based ones for comparison. Among the nitride-based photodetectors, photoconductive variety as well as the metal-semiconductor, Schottky barrier, and homo- and heterojunction photodetectors are discussed along with their noise performance. Nearly solar-blind and truly solar-blind detectors including their design and performance are then discussed, which paves the way for the discussion of avalanche photodiodes based on GaN. Finally, the UV imagers using photodetectors arrays are treated.

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