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Electronic Band Structure Analysis of Group III–V Semiconductors using Optical Spectroscopy with Linear and Circular Polarization

Amit Kumar[1] and Dr. Satendra Singh[2]
[1]Research Scholar, [2]Associate Professor
Department of Physics
Vikrant University, Gwalior, M.P

Abstract: *Group III–V semiconductors, including GaAs, InP, InAs, GaN, GaSb, InSb, AlGaAs and related alloys, possess highly tunable electronic and optical properties that make them important materials for semiconductor lasers, light-emitting diodes, photodetectors, high-speed electronics, photovoltaics, integrated photonics and spin-optoelectronic devices. Their electronic band structures are characterized by conduction-band minima, heavy-hole, light-hole and split-off valence bands, whose energies and symmetries determine the optical response of the material.*

Optical spectroscopy provides a powerful non-destructive approach for investigating these features because absorption, photoreflectance, reflectance, photoluminescence and polarization-resolved measurements can reveal band gaps, interband transition energies, excitonic effects, strain-induced splitting and symmetry-dependent transition probabilities. Linear polarization is particularly useful for identifying anisotropic optical transitions and determining the orientation and symmetry of electronic states, whereas circular polarization provides information about angular-momentum-dependent transitions, spin orientation and optical selection rules.

Keywords: III–V semiconductors, electronic band structure, photoluminescence, absorption spectroscopy, optical selection rules

I. INTRODUCTION

Group III–V semiconductor compounds are formed from elements belonging to Groups III and V of the periodic table and represent one of the most technologically significant semiconductor families. GaAs, InP, InAs, GaN, GaSb, InSb and their ternary and quaternary alloys provide a broad range of band gaps and electronic properties. Their usefulness originates partly from the possibility of controlling composition, strain, crystal structure and layer thickness during epitaxial growth. III–V materials can therefore be engineered for specific optical wavelengths, carrier transport characteristics and device functions. Modern epitaxial techniques allow structures ranging from bulk crystals to quantum wells, superlattices and highly confined nanostructures to be fabricated with considerable precision.

Electronic band structure describes the relationship between the energy of an electron and its crystal momentum and provides the fundamental basis for understanding semiconductor behavior. In conventional zinc-blende III–V compounds, the conduction-band minimum at the Γ point commonly has predominantly s-like character, while the upper valence bands originate mainly from p-like states. Spin–orbit interaction separates the valence states into heavy-hole, light-hole and split-off bands. The relative position, curvature and symmetry of these bands determine effective masses, optical transition energies, carrier dynamics and polarization-dependent optical responses. Consequently, experimental determination of band structure is essential for understanding and optimizing III–V semiconductor devices.

Optical spectroscopy is particularly valuable because photons interact with electronic states through well-defined transition matrix elements. Measurements of absorption, reflectance, photoreflectance and luminescence can reveal direct and indirect transitions, critical-point energies and changes associated with alloying, temperature, strain and doping. Classical optical studies already demonstrated that absorption and luminescence measurements could be used together with modulated reflectance to investigate direct band gaps and subsidiary conduction bands in III–V materials. More recently, polarization-sensitive spectroscopy has added information that cannot easily be obtained from unpolarized measurements.

II. ELECTRONIC BAND STRUCTURE OF III–V SEMICONDUCTORS

The electronic band structure of a III–V semiconductor is determined by crystal symmetry, chemical bonding, spin–orbit coupling and interactions between electronic states. For many technologically important zinc-blende III–V compounds, the fundamental optical transition occurs close to the Γ point. The conduction-band minimum and valence-band maximum at this point establish the fundamental direct band gap. The valence-band maximum is divided into heavy-hole and light-hole branches because of their angular-momentum character and crystal-field and spin–orbit interactions.

The heavy-hole and light-hole bands are degenerate at the Γ point in an ideal unstrained cubic semiconductor but have different dispersions away from this point. Their different effective masses lead to different density-of-states characteristics and optical transition behavior. The split-off band lies below the heavy-hole and light-hole bands by an energy associated primarily with spin–orbit coupling. Consequently, optical spectra near the fundamental gap can contain contributions from transitions involving different valence-band branches.

The band structure is also strongly influenced by material composition. In ternary alloys such as AlGaAs, InGaAs and InGaP, changing the alloy composition modifies the band gap and can alter the relative positions of conduction-band valleys. Strain can further modify the band structure by lifting valence-band degeneracies and changing transition energies. These effects make optical spectroscopy an important tool for determining both intrinsic and externally modified band parameters.

III. OPTICAL SPECTROSCOPY FOR BAND STRUCTURE ANALYSIS

Several optical spectroscopy techniques are used to investigate III–V electronic structures. Absorption spectroscopy measures the photon-energy-dependent absorption coefficient and provides information about allowed electronic transitions. Near the band edge, the absorption spectrum can be used to estimate the fundamental band gap and, under suitable conditions, excitonic features. A comprehensive review of bulk III–V materials has shown that absorption coefficients can be determined through several experimental approaches, with measurements extending from near-infrared to mid-infrared spectral regions.

Photoluminescence spectroscopy provides complementary information because it measures light emitted following radiative recombination. Peaks in photoluminescence spectra can indicate band-to-band transitions, excitonic recombination and impurity-related states. Photoreflectance is another particularly useful technique because it is contactless and can detect critical points in the band structure with high sensitivity. It has been applied to determine band-structure characteristics, doping-related effects, alloy composition and surface or interface band bending in III–V materials.

Reflectance and modulation spectroscopy are also useful for identifying weak transitions that may be difficult to observe in conventional absorption measurements. The derivative-like spectral features generated by modulation techniques can improve the identification of critical-point energies. When these techniques are combined with polarization control, the symmetry and orientation of electronic transitions can be investigated more effectively.

IV. ROLE OF LINEAR POLARIZATION

Linear polarization provides information about the directional character and symmetry of optical transitions. When incident light is linearly polarized, its electric field oscillates along a defined direction. The interaction between this electric field and the electronic wavefunctions is governed by the electric-dipole transition matrix element. Consequently, transitions that are allowed for one polarization direction may be weakened or suppressed for another.

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In cubic III–V materials, linear polarization measurements can be particularly useful when analyzing strained layers, quantum wells and structures with reduced symmetry. Strain can split heavy-hole and light-hole states, while quantum confinement can modify their energy separation. Comparing spectra measured with different linear polarization orientations can therefore help identify the symmetry of transitions and determine anisotropic properties.

Linear polarization is also valuable for wurtzite III–V materials such as GaN and related compounds. In these materials, the crystallographic c-axis introduces a preferred direction, and optical transitions can exhibit different responses for electric fields parallel and perpendicular to this axis. Theoretical studies of wurtzite III–V compounds have shown that polarization-dependent selection rules are directly related to the symmetry of the valence and conduction states.

V. CIRCULAR POLARIZATION AND OPTICAL SELECTION RULES

Circular polarization provides an additional dimension of information because right- and left-handed circularly polarized photons carry opposite angular momentum. When circularly polarized photons interact with III–V semiconductors, transitions between valence-band and conduction-band states are constrained by angular-momentum selection rules. As a result, the polarization of absorbed or emitted light can be related to the spin and angular-momentum states of carriers.

For GaAs-type III–V materials, circularly polarized excitation can preferentially generate electrons with a particular spin orientation. The heavy-hole and light-hole bands contribute differently because their angular-momentum projections differ. This phenomenon forms the basis of optical orientation and is important for spintronics, spin lasers and polarization-sensitive optoelectronics. Selection-rule diagrams for III–V semiconductors demonstrate distinct transitions involving heavy-hole and light-hole states under σ^+ and σ^- excitation.

Recent experimental work on GaAs has further demonstrated that circularly polarized differential-transmission measurements can distinguish optical-transition selection rules and reveal how the validity of different selection-rule descriptions depends on the region of k-space within the Γ valley. This illustrates how polarization-resolved spectroscopy has developed beyond simple band-gap measurements toward detailed investigation of the momentum- and spin-dependent electronic structure.

VI. COMPARISON OF LINEAR AND CIRCULAR POLARIZATION

Linear and circular polarization provide complementary information. Linear polarization primarily probes the orientation, symmetry and anisotropy of optical transitions, whereas circular polarization is strongly connected with angular momentum, spin-dependent transitions and optical orientation. Therefore, using both forms of polarization can provide a more complete description of the electronic structure than either technique alone.

Parameter	**Linear Polarization**	**Circular Polarization**
Electric-field character	Oscillates along a fixed direction	Rotates with time
Main information	Symmetry and anisotropy	Angular momentum and spin
Common notation	X, Y or parallel/perpendicular	σ^+ and σ^-
Important for	Strain, crystal symmetry, anisotropic transitions	Spin orientation and selection rules
Heavy-hole/light-hole analysis	Useful for polarization-dependent splitting	Useful for distinguishing angular-momentum transitions
Quantum wells	Strongly useful for in-plane anisotropy	Useful for spin-selective excitation
Spin information	Usually indirect	Directly connected to optical orientation
Selection rules	Determined by dipole orientation and symmetry	Determined by angular-momentum conservation
Major applications	Band symmetry, strain analysis, anisotropic optics	Spintronics, optical orientation, spin lasers
Typical complementary	Photoreflectance, absorption, PL	Circular dichroism, differential

techniques		transmission, PL

VII. MAJOR III–V MATERIALS AND SPECTROSCOPIC CHARACTERISTICS

Different III–V compounds provide different opportunities for polarization-resolved band-structure analysis. GaAs is one of the most extensively investigated materials because of its direct band gap, well-characterized valence-band structure and strong optical response. InP is important for telecommunications and near-infrared photonics, while InAs and InSb are notable for their narrow band gaps and strong infrared response. GaN and related nitrides extend III–V semiconductor applications into blue and ultraviolet optoelectronics.

Semiconductor	Crystal/Material Characteristics	Important Band-Structure Feature	Useful Optical Technique	Polarization Information
GaAs	Zinc-blende, direct gap	HH, LH and split-off valence bands	PL, PR, absorption	Strong circular-polarization selection rules
InP	Zinc-blende, direct gap	Γ-point transitions	PR, PL, reflectance	Symmetry and spin-dependent transitions
InAs	Narrow-gap III–V	Strong infrared transitions	IR absorption, PL	Circular polarization and spin response
InSb	Very narrow-gap	Strong spin–orbit effects	IR spectroscopy	Spin and angular-momentum properties
GaN	Wurtzite/zinc-blende	Crystal-field and spin–orbit splitting	PL, absorption, reflectance	Strong linear polarization anisotropy
AlGaAs	Alloy of AlGaAs	Composition-dependent band gap	PR, absorption, PL	Strain/composition-dependent polarization
InGaAs	Tunable alloy	Composition-dependent Γ gap	PL, PR, absorption	Linear and circular polarization
GaSb	Narrow-gap III–V	Valence/conduction-band interactions	IR spectroscopy, PL	Spin and polarization response

The broad optical versatility of III–V materials is one reason they remain important in integrated photonics. Recent reviews emphasize their use in nonlinear and integrated optical platforms, including GaAs, AlGaAs, InP, InGaAsP and GaN systems.

VIII. EXPERIMENTAL METHODOLOGY

A typical polarization-resolved optical spectroscopy experiment begins with the preparation of a high-quality bulk crystal, thin film, quantum well or heterostructure. The sample is mounted in a controlled optical setup where temperature, incident angle and polarization state can be adjusted. A broadband or tunable light source is then passed through a polarizer and, for circular polarization, an appropriate quarter-wave plate.

For linear-polarization measurements, spectra can be acquired for two orthogonal polarization directions. Differences between the spectra can reveal anisotropic transitions and symmetry breaking. For circular-polarization experiments, σ^+ and σ^- spectra are measured separately. Their difference can be used to quantify circular dichroism or polarization-dependent optical response.

The measured spectra are subsequently fitted using appropriate models. Critical-point line-shape analysis can be employed for photoreflectance and modulation spectroscopy. Band-gap energies, spin–orbit splitting, heavy-hole/light-hole splitting and other transition parameters can then be compared with theoretical calculations. Combining experimental spectroscopy with k·p models, tight-binding calculations or first-principles electronic-structure calculations can provide a more complete interpretation.

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IX. APPLICATIONS OF POLARIZATION-RESOLVED BAND ANALYSIS

Polarization-resolved optical spectroscopy has important applications in semiconductor device development. In quantum wells and heterostructures, it can determine confinement-induced changes in the band structure. In strained materials, polarization-dependent spectra can quantify valence-band splitting and identify strain-induced symmetry reduction. In semiconductor lasers, understanding polarization-dependent transitions helps optimize gain and emission characteristics.

Circular polarization is especially important for spin-based technologies. Optical orientation enables the generation of spin-polarized carriers through selective optical excitation. This provides a foundation for spin-LEDs, spin lasers and other spin-optoelectronic devices. Recent research has also expanded interest from spin angular momentum to orbital angular momentum, demonstrating that polarization-dependent optical excitation can provide information about more complex carrier states in GaAs and other semiconductors.

In addition, polarization-sensitive spectroscopy is valuable for quality control. Changes in peak positions, linewidths, polarization ratios and transition intensities can indicate defects, strain, composition fluctuations, interface quality or doping. Therefore, spectroscopy can simultaneously provide fundamental information about electronic states and practical information about material quality.

Despite substantial progress, several challenges remain. Accurate interpretation of polarization-resolved spectra requires careful consideration of temperature, carrier concentration, many-body interactions, excitonic effects, strain, band mixing and experimental geometry. Heavy-hole and light-hole mixing can complicate the interpretation of circular-polarization measurements, particularly away from the exact band edge. Recent GaAs experiments demonstrate that different optical selection-rule descriptions may become appropriate in different regions of momentum space, highlighting the importance of k-dependent analysis.

Future research is expected to combine polarization-resolved spectroscopy with ultrafast spectroscopy, microscopy and advanced theoretical modeling. Time-resolved measurements can reveal carrier relaxation and spin dynamics, while spatially resolved techniques can identify microscopic variations in composition and strain. Machine-learning-assisted spectral analysis may also improve automated identification of weak transitions and extraction of band parameters.

Another important direction is the study of low-dimensional III–V structures, including quantum wells, quantum dots, nanowires and two-dimensional heterostructures. As dimensional confinement becomes stronger, polarization selection rules and band mixing become increasingly important. Combining linear and circular polarization with broadband spectroscopy can therefore provide a powerful route toward understanding these complex systems.

X. CONCLUSION

The analysis of electronic band structures in Group III–V semiconductors using optical spectroscopy provides a powerful connection between fundamental electronic properties and experimentally measurable optical responses. Absorption, photoluminescence, reflectance and photoreflectance can determine fundamental band gaps, critical-point energies and transitions between different electronic states. Linear polarization adds information about crystal symmetry, anisotropy, strain and the orientation of electronic states, whereas circular polarization provides direct access to angular-momentum-dependent selection rules, optical orientation and spin-polarized carrier generation. The complementary use of both polarization states therefore offers a more comprehensive understanding of heavy-hole, light-hole, split-off and conduction-band states than conventional unpolarized spectroscopy. The continuing development of high-resolution, time-resolved and momentum-sensitive optical techniques, combined with theoretical band-structure calculations, is expected to further improve the quantitative analysis of III–V semiconductors and support advances in optoelectronics, integrated photonics, infrared technologies and spin-based devices.

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