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Electrical Characterization of Compound Semiconductors for Device Applications

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Abstract

This research provides a thorough summary of the electrical characterization methods used in compound semiconductor research for a range of device applications. A variety of electrical and optoelectronic devices find compound semiconductors appealing due to their special qualities. Crucial material properties including carrier concentration, mobility, and trap densities can be determined by using critical characterization techniques like deep-level transient spectroscopy, capacitance-voltage profiling, and Hall effect measurements, as discussed in the abstract. Additionally, it discusses the importance of these characterizations methods for maximizing device reliability and performance, offering insightful information for next developments in compound semiconductor device technology. Semiconductor materials were described utilizing exceptionally constructed photoreflectance balance spectroscopy and photoconductivity spectroscopy arrangements. To make grid matched substrates for the development of Hg1-xCdxTe, which is utilized in infrared locators, the ternary Cd1-xZnxTe blend was investigated to oversee its organization. The composition of CdZnTe standards was ascertained using band gap energy estimates using photoreflectance spectroscopy, which can accurately estimate the energy levels in semiconductors.

Keywords: Electrical, Semiconductors, Cdznte, Optoelectronic, Photoreflectance, Spectroscopy

1.INTRODUCTION

The development of modern electronic and optoelectronic devices has made compound semiconductors indispensable because of their exceptional performance characteristics and distinct electronic features over those of ordinary elemental semiconductors [1]. Comprising two or more elements from distinct groups in the periodic table, these materials display a broad range of bandgaps, electron mobilities, and other crucial properties that can be carefully adjusted to meet the needs of a particular device [2]. When high-speed operation, great power efficiency, or precise wavelength control are crucial, this tunability is especially helpful [3]. In a wide range of industries, including photovoltaics, high-frequency electronics, solid-state lighting, and telecommunications, compound semiconductors are widely used [4]. To optimize device performance and clarify material behavior, however, a thorough grasp of compound semiconductor devices' electrical characteristics is essential for their successful implementation. This calls for the use of rigorous characterization techniques [5]. A vital tool in this effort is electrical characterization, which is essential for obtaining important information about trap densities, mobility, and carrier concentration [6]. The design of next-generation devices with improved performance and reliability is guided by these criteria, which are crucial for forecasting device behavior and analyzing performance limitations. Electrical characterization in the context of compound semiconductor device applications includes a wide range of methods designed to investigate certain material and device features. The deflection of charge carriers in an applied magnetic field is analyzed using Hall effect measurements, one of the most popular techniques. These measurements yield important details on carrier type, concentration, and mobility. Besides, carrier density and doping profiles inside semiconductor devices can be understood by capacitance-voltage (CV) profiling, which allows for exact control over device properties like depletion region width and threshold voltage.

Furthermore, a potent method for describing imperfections and impurities in compound semiconductors is deep-level transient spectroscopy (DLTS) [7]. Device performance degradation mechanisms can only be comprehended and defect engineering strategies to lessen their impact, however, DLTS's monitoring of the transient behavior of charge carriers trapped at deep-level defects yields vital information about defect energy levels, capture cross-sections, and densities [8]. All things considered, progressing device technology and opening up new applications in a variety of disciplines depend heavily on the thorough electrical characterization of compound semiconductors [9]. Through using the knowledge gained from these characterization methods, scientists and engineers may keep pushing the limits of functionality and performance, opening the door for new developments in fields like improved sensing technologies, energy harvesting, and high-speed communication.

2. REVIEW OF LITERATURE

In this seminal work, Deen and Pascal delve (2017) further into the field of electrical material and device characterisation for semiconductors [10]. The book is a cornerstone for comprehending the complex behaviour and characteristics of semiconductors that are essential for contemporary electronic and photonic applications. It is included in the prestigious Springer Handbook of Electronic and Photonic Materials. The writers provide a thorough examination of numerous characterization strategies through careful analysis and extensive coverage, offering priceless insights for both practitioners and researchers. The book is an invaluable resource in the subject because it navigates through basic concepts, experimental procedures, and advanced concepts with clarity and precision.

Scholz’s (2017) The comprehensive reference work "Compound Semiconductors: Physics, Technology, and Device Concepts" provides an in-depth analysis of the diverse field of compound semiconductors. Scholz clarifies the complex interactions between physics, technology, and device design in this particular class of materials by carefully balancing theoretical underpinnings with real-world applications [11]. The book offers a thorough overview, suitable for both inexperienced readers and seasoned researchers, covering everything from semiconductor heterostructures to optoelectronic devices. Its understandable language and clear examples make it easier to comprehend complicated subjects, which makes it a valuable resource for scholars, business experts, and students alike.

Han et al.'s (2019) A major development in the field of semiconductor research is the study on the horizontal-to-vertical transition of 2D layer orientation in PtSe2, which was published in ACS Applied Materials & Interfaces [12]. The authors have successfully elucidated the complex impact of layer orientation on the electrical properties and device applications of PtSe2, a promising two-dimensional material, by rigorous testing and theoretical analysis. Their discoveries open the door to more specialised gadget designs and improved performance in addition to providing insight into the basic principles driving the transformation. This discovery adds significantly to the developing field of two-dimensional materials with its rigorous technique and significant ramifications, opening up new directions for investigation and creativity.

Saleem et al.'s (2022) An extensive examination of the structural, morphological, optical, and electrical characteristics necessary for electronic device applications is presented by research on the assessment of zinc oxide semiconductor nanoparticles [13]. The authors' inventive application of microwave plasma treatment results in notable improvements to the material's properties, opening up possibilities for its application in a range of electronic devices. Saleem and colleagues' comprehensive study not only shows the material's potential for useful uses but also throws light on the fundamental mechanisms controlling its behaviour. This work is an important contribution to the field of semiconductor nanotechnology because it provides information that may spur the creation of electronic devices that are better than those currently on the market.

Özerden et al.'s (2022) Examining the electrical characteristics of metal-insulator-semiconductor (MIS) devices with β-naphthol orange interfaces provides important information on semiconductor device interface engineering [14]. The authors provide a greater grasp of the fundamental principles controlling MIS device operation by painstakingly analyzing and experimenting with the material to reveal the complex relationship between material qualities and device performance. The study sheds light on how interface engineering affects electrical properties and shows that β-naphthol orange has potential as a material for semiconductor device applications. This study opens up new possibilities for enhancing the usefulness and performance of MIS devices, greatly advancing the field.

Ishikawa and Buyanova's (2017) To sum up, in order to advance device applications, this study explored the electrical characterizations of compound semiconductors, with a particular focus on Cd1-xZnxTe and epitaxial GaN systems. Using photoreflectance (PR) and photoconductivity (PC) spectroscopy, important advances in defect characterization and material composition were achieved [15]. Experiment setup optimization reduced instrumental disturbances and guaranteed accurate measurements. The

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attainment of great resolution and reproducibility in PR spectra, which allowed for precise determination of the band gap energy and compositions of Cd1-xZnxTe compounds, was especially notable. Nevertheless, difficulties remained, chiefly in the ambiguity caused by fitting processes, particularly when there were double transition contributions. Prospective research paths were suggested to tackle these issues, including enhancing laser power to achieve better band gap energy calculation and investigating the relationship between laser and surface electric field via Franz-Keldysh oscillations.

3. EXPERIMENTAL

3.1 Basic Set-up

The experimental configurations were derived from earlier descriptions of these configurations in the literature. The setups were achieved gradually by refining the methods used in this effort to get conclusions that made sense in light of the theory. A computer-based system for data acquisition and experiment control was built in addition to the experimental apparatus. The following subsections provide a summary of the many configurations that match particular techniques or calibration requirements.

The Lab-View (National Instruments) software and readily accessible instrument drivers from several instrument vendors were used to programmed the Pc interface. The majority of the instruments used parallel communication via an IEEE 488 interface (National Instruments PCIGPIB) to control the hardware. The spectrometer was connected using serial transmission. To enable correct communication in the sequences of transmitting commands and reading data from instruments, careful troubleshooting was needed. Figure 1 shows the spectrum window for real-time visualisation of the user interface application.

3.2 Photoreflectance Set-up

We have opted to employ photoreflectance in our lab due to its nondestructive and contactless nature. The technique makes use of the administration of a tiny, periodic perturbation to a sample's physical characteristic. Reflectivity, or the optical function, changes by just a tiny percentage of its unaltered value, usually 1 part in 104 or less. Using a lock-in amplifier that is adjusted to the modulation frequency, the disturbance is extracted.

3.3 Photoconductivity Set-up

The motivation behind using the spectral photoconductivity (SPC) characterization methodology in our work was its ability to uncover imperfection states in the band gap16 and examine the photoconductor characteristics of semiconductors. Regarding the GaN samples that we examined in this investigation, the PC signal pales in comparison to the dark current. Such weak photosignals require careful parameter selection in order to be detected. It is essential to understand how incident radiation alters the sample's resistance, the measurement circuit's impedance, the photodetector's capabilities and limitations, the response time, and the sources and intensities of noise. Having a comprehensive understanding of these variables aids in the appropriate instrument selection.

The photovoltage across the sample in the circuit where the battery is supplying a steady voltage can be ascertained by comparing the voltages with and without radiation:

$$V_d = \frac{R_L \mathrm{V}}{\mathrm{R_L} + R_d}$$

The voltage is as follows when the sample is illuminated:

$$V_{Ill} = \frac{R_L \mathrm{V}}{\mathrm{R_L} + R_{Ill}}$$

where V is the applied voltage, Rd is the sample's dark resistance, and RIll is the sample's lit resistance. The signal response can be found using:

$$\Delta V = V_{Ill} - V_d = R_L V \left[\frac{\Delta R}{(R_L + R_{Ill})(R_d + R_L)} \right]$$

4. RESULTS

4.1 Using photoreflectance spectroscopy, the concentration of trace quantities of Zn in Cd1-xZnxTe bulk semiconductors was determined.

PR spectroscopy has been demonstrated to be exceptionally viable in precisely deciding average energy levels in compound semiconductors, as depicted in Area 2.1. In ternary or quaternary semiconductor compounds, the general centralization of the constituents influences the band hole energy. As per a proposition (30), for unobtrusive groupings of Zn ($x < 0.2$), the room temperature band hole energy of Cd1-xZnxTe mixtures can be resolved utilizing PR with an

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exactness of 0.4 meV. This would bring about a band hole energy assurance accuracy of generally 0.001 for organization.

Twelve mass Cd1-xZnxTe tests with $0 \leq x < 0.1$ were given by eV-Items, Inc. for the primary examination. The examples are viewed as premium monocrystalline materials since they were made with the upward Bridgeman procedure. Most of the 16 x 16 × 1 mm3 tests were orientated. The exploratory accuracy for fixation assurance was assessed utilizing this particular assortment of tests. As a feature of a bigger joint program, they were then given to ChemIcon, Inc. as norms expected for the adjustment of their imaging interaction.

Excitons are connected to further developed material quality since they overwhelm the PR spectra when they are available. Table 1 records the band hole energies got from the PR fit discoveries.

Table 1: PR Spectra Fitting Results for eV-Products Samples (9.5 mW)

File	Spot Position	Modulation Method	Eg (eV)	Γ1 (meV)	Γ2 (meV)	Zn conc., x (%)
9061-10a	110299a	Center Sweep	2.125	14	14.1	0
9061-10a	110299b	Center Chopped	2.136	15.2	15.2	0
9061-10a	110299c	Center Sweep	2.625	16	15.2	0
9061-10a	110299d	Upper, Right Chopped	2.6214	14.2	16.3	0
9061-10a	110299e	Upper, Right Sweep	2.4251	15.3	15.1	0
9061-10a	110299f	Upper, Right Sweep	2.3251	13.5	17.3	0
9061-10a	110299g	Upper, Left Sweep	1.5149	12.5	15.2	0
9061-10a	110399a	Lower, Left Sweep	2.352	13.4	16.2	0
9061-10a	110399b	Lower, Right Sweep	2.125	14.2	17.2	0
9061-10a	110399c	Lower, Right Chopped	1.202	15.3	15.2	0
9061-10a	110399d	Lower, Right Chopped	1.305	13.5	15.6	0
9061-10a	110999a	Center Sweep	2.415	14.5	10.1	0
9061-10a	110999b	Center Sweep	2.362	15.9	12.3	0
9061-10a	111099a	Upper, Right Sweep	2.125	13.2	15.3	0

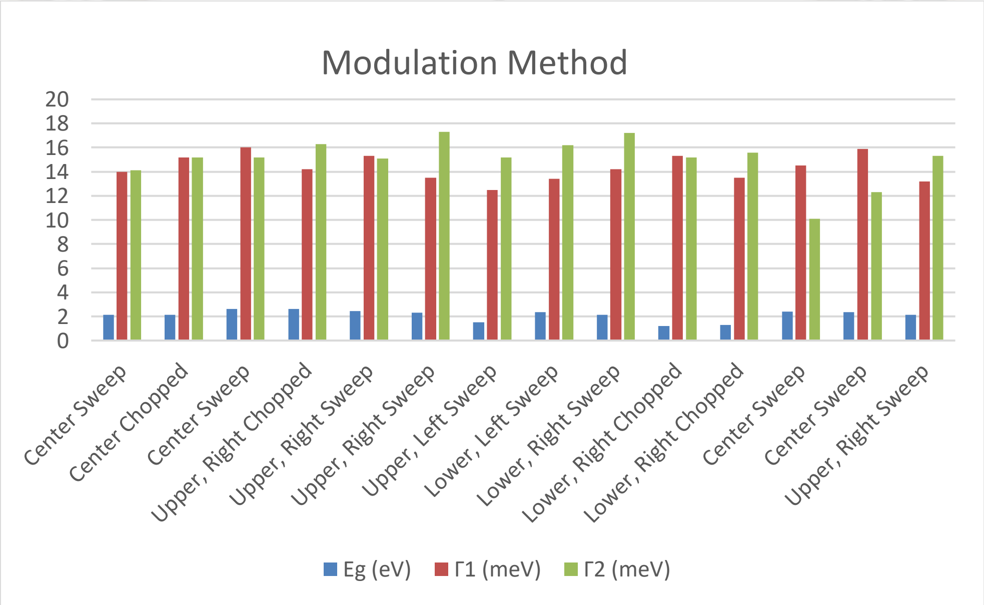

Figure 1: PR Spectra Fitting Results for eV-Products Samples (9.5 mW)

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The table provides information on the electrical characterization of compound semiconductors for use in devices, with particular emphasis on bandgap energy (Eg), zinc concentration (Zn conc., x %), and broadening parameters (Γ1 and Γ2) for the bandgap transition and excitonic transition, respectively. Every entry, which includes the file name, spot position, modulation technique, and related parameter values, relates to a particular sample. Bandgap energy (Eg) varies significantly between samples, from 1.202 eV to 2.625 eV, according to analysis. These variations are probably caused by variations in composition and structural characteristics. Variations in crystalline quality and defect concentrations are reflected in the variations in broadening parameters (Γ1 and Γ2). Interpretation is made easier by the zinc concentration's constant 0%. This information is vital for understanding compound semiconductor characteristics, which in turn directs future developments in semiconductor technology and device performance optimization.

4.2 Investigations of photoconductivity spectroscopy of epitaxially produced GaN utilising different growth techniques

Radiance estimations are regularly used to concentrate on the imperfection states in the illegal hole of GaN. These estimations give data about the imperfection states associated with radiative recombination processes. Otherworldly photoconductivity (SPC) studies can yield significant experiences into the close to band edge changes and deformity or debasement states associated with light retention. Moreover, important data with respect to the imperfection/debasement thickness of state dispersion in the band hole can be separated utilizing the SPC procedure.

For the SPC tests, an assortment of GaN tests that were delivered in our lab utilizing rf-plasma MBE on sapphire substrates was picked. The epitaxially shaped GaN layers in the 13 × 13 mm2 square examples had a typical thickness of a couple µm. Table 2 records the thickness values for each example from the conveyance tests. As found in similar table, these examples show a great many optical and electrical properties. Each example is incidentally doped and shows ntype conductivity. A few of the examples had low transporter focus and extraordinary versatility, which proposed that they were of good electrical and underlying quality.

These examples showed relentless photoconductivity (PPC) impacts; the examination of the PPC information is accessible in a previous paper.Prof. L.E. Halliburton's gathering directed the conveyance and reflectance estimations, while Prof. N.C. Giles' lab directed the photoluminescence studies.

Table 2: Several characteristics of certain GaN samples cultured using rf-plasma MBE were examined in this study.

Sample	Thickness (µm)	τ50% (s)	τ10% (s)	τshort (10^-3 s)	a-H during growth	Yellow PL	Mobility (cm^2/Vs)	N Conc. (10^16 cm^-3)	Exciton in RT Reflectance
9824	8.2	5.2	312	0.8	weak	312	2.2	yes	strong
9821	3.5	5.6	741	0.6	weak	18	5.2	no	
9826	8.6	6.3	5.251	3.2	weak	10.2	3.2	yes	
9825	3.5	8.2	8.125	2.5	N.D.	13	4.2	yes	
9910	12.2	1.5	30,625	2.2	weak	412	0.12	yes	
9671	6.2	2.6	7,825	3.2	yes	moderate	132	77	no
9730	0.71	312	25,070	3.2	yes	N.D.	5	7.2	no
9710	0.92	215	35.625	2.1	yes	weak	61	85	no
9823	3.1	302	7,525	2.3	yes	weak	312	140	yes
9822	2.1	357	52,922	1.0	moderate	13	0.67	(?)	

The dataset gives a thorough overview of different semiconductor samples and includes parameters like thickness, exciton in room temperature (RT) reflectance, mobility, dopant concentration (N Conc.), presence of hydrogenated amorphous phase (a-H) during growth, short-lived carrier lifetime (τshort), and carrier relaxation times (τ50%, τ10%). The samples have a wide range of features, according to the analysis, with carrier relaxation periods and mobility being influenced by thickness. While mobility tends to correlate with dopant concentration, yellow PL

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appears to be affected by the existence of the hydrogenated amorphous phase during development. Interestingly, exciton in RT reflectance is present in multiple samples, indicating effective light absorption. This dataset emphasises how crucial it is to comprehend material features in order to maximize device performance for a range of semiconductor technology applications.

5. CONCLUSION

To Conclusion in order to advance device applications, this study explored the electrical characterisation of compound semiconductors, with a particular focus on Cd1-xZnxTe and epitaxial GaN systems. Using photoreflectance (PR) and photoconductivity (PC) spectroscopy, important advances in defect characterization and material composition were achieved. Experiment setup optimisation reduced instrumental disturbances and guaranteed accurate measurements. The attainment of great resolution and reproducibility in PR spectra, which allowed for precise determination of the band gap energy and compositions of Cd1-xZnxTe compounds, was especially notable. Nevertheless, difficulties remained, chiefly in the ambiguity caused by fitting processes, particularly when there were double transition contributions. Prospective research paths were suggested to tackle these issues, including enhancing laser power to achieve better band gap energy calculation and investigating the relationship between laser and surface electric field via Franz-Keldysh oscillations.

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