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مستويات مستقبلات عميقة في بلورات $CdS_{1-x}Se_x$ وَ CdS المفردة والمطعمة بالروبيديوم باستخدام مطيافية التخميد البصري: الاعتماد على درجة الحرارة والتأثيرات الضوئية المحفزة

Deep Acceptor Levels $Rb-Doped\ CdS\ and\ CdS_{1-x}Se_x$ Single Crystals Revealed by Optical Quenching Spectroscopy: Temperature Dependence and Photoinduced Effects

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الملخص

يعدّ التخميد البصري (OQ) للموصلية الضوئية منهجاً مطيافياً معتمداً لدراسة المراكز الإلكترونية العميقة، التي تسهم في مصائد حاملات الشحنة، وإعادة تجميعها في أشباه الموصلات من المجموعة (II-VI). تُحلل الدراسة الحالية سلوك التخميد البصري والموصلية الضوئية المعتمدة على درجة الحرارة لبلورات CdS و $CdS_{1-x}Se_x$ المفردة والمطعمة بالروبيديوم. تعود البيانات التجريبية المُستخدمة في الجدول 1 إلى البحث التجريبي لنيل درجة الدكتوراه للمؤلف، وتم الاحتفاظ بها لتكون أساساً لمعالجة تحليلية مركزة. وبذلك، تمثل هذه الدراسة امتداداً تحليلياً وتفسيرياً للبحث التجريبي الأصلي، وليست حملة تجريبية جديدة.

يشير التحليل إلى وجود نطاقين طاقيين مميزين، يرتبطان بالعمليات المتعلقة بالمستقبلات العميقة: النطاق الأول عند $E_v + 0.60\ eV$ تقريباً، ويرتبط بالتنشيط الحراري للموصلية الضوئية، والنطاق الثاني عند $E_v + 1.0\ eV$ تقريباً، ويرتبط بشكل رئيس باستجابة التخميد البصري. تنخفض شدة التخميد البصري مع ارتفاع درجة الحرارة، وتختفي تماماً فوق $T = 340\ K$ تقريباً، بينما يقدم الاعتماد الحراري للموصلية الضوئية في الحالة المستقرة طاقة تنشيط قريبة من $0.60\ eV$ ، وتصبح الاستجابة البصرية بالقرب من $1.0\ eV$ أكثر وضوحاً عقب التفاعلات الضوؤكيميائية المخفزة (PhCR)، مما يدل على حساسية النظام الفرعي للعيوب للتاريخ الإشعاعي للبلورة.

يقدم التحليل الحالي امتداداً تحليلياً مركزاً للبحث الأصلي، من خلال دمج البصمات الحرارية والبصرية للمراكز العميقة ضمن تفسير موحد لمستويات الطاقة.

الكلمات المفتاحية: التخميد البصري؛ الموصلية الضوئية؛ كبريتيد الكادميوم–سيلينيوم ($CdS_{1-x}Se_x$)؛ مستويات المستقبلات العميقة؛ مراكز إعادة التجميع؛ التفاعلات الضوؤكيميائية المخفزة.

Abstract

Optical quenching (OQ) of photoconductivity is an established spectroscopic approach for investigating deep electronic centers that participate in carrier trapping and recombination in II-VI semiconductors. The present study analyzes the optical-quenching and temperature-dependent photoconductivity behavior of $Rb-doped\ \ CdS$ and $CdS_{1-x}Se_x$ single crystals. The experimental data used in Table 1 originate from the author's doctoral experimental research and are retained as the basis for a focused analytical treatment. The present study represents an analytical and interpretative extension of the original experimental investigation, rather than a new experimental campaign. The analysis indicates two characteristic energy regions associated with deep acceptor-related processes: approximately $E_v + 0.60\,eV$, associated with thermal activation of photoconductivity, and approximately $E_v + 1.0\,eV$, associated primarily with the optical-quenching response. The OQ intensity decreases with increasing temperature and disappears above approximately $340\,K$, while the temperature dependence of steady-state photoconductivity provides an activation energy close to $0.60\,eV$. The optical response near $1.0\,eV$ becomes more pronounced following photoinduced chemical reactions (PhCR), indicating sensitivity of the defect subsystem to illumination history. The present analysis provides a focused analytical extension of the original doctoral investigation by integrating the thermal and optical signatures of the deep centers within a unified energy-level interpretation.

Keywords: Optical Quenching, Photoconductivity, Cadmium Sulfide-selenide ($CdS_{1-x}Se_x$), Deep Acceptor Levels, Recombination Centers, Photoinduced Chemical Reactions.

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1. Introduction

Semiconductor materials occupy a central position in the development of modern electronic, optoelectronic and photonic technologies. Their importance is associated not only with their intrinsic electrical and optical properties but also with the possibility of controlling these properties through composition, defects, impurities and external excitation. Consequently, understanding the electronic states located within the forbidden energy gap remains a fundamental issue in semiconductor physics [1-3].

CdS and $CdS_{1-x}Se_x$ belong to the group of II-VI semiconductor materials whose optical and electrical properties have attracted sustained scientific attention. Their photoelectric response is strongly influenced by localized electronic states associated with intrinsic defects, impurity atoms and defect-impurity complexes. Such centers can determine carrier trapping, recombination, photoconductivity and the response of the material to optical and thermal excitation [1-3].

The significance of deep electronic centers has become increasingly evident with the development of modern semiconductor technologies. Contemporary studies of $CdS-, CdSe-$ and related materials continue to examine defect states because these states can influence carrier dynamics, non-radiative recombination, photoluminescence, charge separation, and the stability of optoelectronic response [4,5,8]. From this perspective, the study of deep levels is not an isolated spectroscopic problem; it is connected directly with the continuing development of semiconductor materials and their technological applications.

The physical importance of these centers was established through earlier semiconductor research. Classical studies demonstrated that localized states within the forbidden gap can control photoconductivity and thermally activated carrier processes [2,3,6,7]. Subsequent investigations of CdS and related II-VI compounds established the relationship between deep levels and optical, thermal, and photoconductive phenomena [10-14]. These studies form an important physical foundation for interpreting the behavior of defect-related centers observed in the present material system.

More recent investigations demonstrate that the problem remains relevant despite the considerable progress achieved in semiconductor science. Current research increasingly considers defects not only as undesirable imperfections but also as active elements of semiconductor functionality. Defect engineering, impurity incorporation, surface modification,

and the control of carrier trapping have become important approaches for tailoring semiconductor response [4,5,15]. Studies of $CdS-based$ and related materials have also emphasized the importance of understanding defect-mediated recombination and photoinduced changes improve the performance and stability of optoelectronic systems [8,18,21,25].

From the perspective of these developments, thermal and optical quenching provide complementary information about deep electronic centers. Thermal stimulation probes the temperature-dependent release of carriers from localized states, whereas optical quenching can provide information about the optical ionization of centers that participate in recombination. The comparison of these two responses can therefore provide a physically meaningful means of relating thermal activation energies to optical ionization energies [6,7].

The original experimental investigation underlying the present work was conducted within the framework of the author's doctoral research on photoinduced processes in $Rb-doped\ CdS\ and\ CdS_{1-x}Se_x$ crystals. That investigation employed complementary methods for studying impurity-related photoconductivity, induced photoconductivity, optical phenomena and thermally stimulated processes, and considered the role of impurity-defect complexes in the observed behavior. The doctoral work specifically reported optical ionization associated with acceptor centers near $E_v + 0.6\ eV\ and\ E_v + 1.0\ eV$ and demonstrated that illumination history can modify the defect-related response [1].

The present study is developed from that experimental foundation. It does not introduce a new experimental fabrication program or replace the original dataset. Instead, it focuses the available observations on a more specific analytical question: how the temperature dependence of photoconductivity and the optical-quenching response can be considered together to interpret the deep acceptor levels responsible for the observed recombination behavior. In addition, the present study introduces a new analytical synthesis through the extraction and re-evaluation of quantitative trends from the original spectral curves, leading to a novel energy-level interpretation summarized in Table 2 and Figure 3. This synthesis represents a contribution that extends beyond the original experimental baseline and forms the principal analytical innovation of the present work.

It is important to clarify that the investigated objects in the present study are single crystals of Rb-doped CdS and $CdS_{1-x}Se_x$. Thin films, film thickness, and thin-film deposition conditions are outside the scope of this work. This clarification is made to maintain consistency between the

experimental system, the results, the figures, and the interpretation presented throughout the manuscript.

Accordingly, and in view of the continuing development of semiconductor technologies, the present study seeks to provide a focused interpretation of the temperature- and infrared-dependent photoconductivity of $Rb-doped\ \ CdS$ and $CdS_{1-x}Se_x$single crystals, with particular emphasis on the identification and physical interpretation of the deep acceptor-related energy levels.

2. Research Questions

Based on the physical background and the development of the research problem outlined above, the present study addresses the following questions:

- What deep acceptor-related energy levels can be inferred from the optical-quenching behavior of $Rb-doped\ CdS$ and $CdS_{1-x}Se_x$single crystals
- How does the temperature dependence of optical quenching relate to the thermal activation behavior of steady-state photoconductivity
- What energy-level interpretation provides a consistent description of the optical and thermal responses?
- How does photoinduced chemical reaction (PhCR), associated with the illumination history of the crystals, affect the optical-quenching response?

3. Experimental Materials and Methods

3.1. Origin and scope of the experimental data

The experimental observations analyzed in this study originate from the author's doctoral research on photoinduced processes in $Rb-doped\ CdS\ and\ CdS_{1-x}Se_x$ crystals [1]. The original research employed a combination of photoelectric and thermal methods for investigating impurity- and defect-related centers.

The present paper uses the experimental information relevant to optical quenching, steady-state photoconductivity, and the temperature-dependent behavior of the corresponding signals. Thus, the present work should be understood as an analytical and interpretative extension of the original experimental investigation. The numerical data retained in Table 1 are not presented as newly measured data; rather, they provide the experimental basis for the present analysis.

This explicit distinction between the original experiment and the present analytical treatment is important for establishing the scientific identity and reproducibility of the work. Furthermore,

the present study introduces a new analytical synthesis through the extraction and re-evaluation of quantitative trends from the original spectral curves, which are summarized in Table 2 and Figure 3. This approach provides a novel interpretation of deep-center reconfiguration and recombination mechanisms, extending the original findings without re-performing the experiments. The study is therefore limited to spectroscopic analysis and does not involve new material synthesis or device fabrication.

3.2. Crystal growth and Rb doping

The investigated materials were $CdS\ and\ CdS_{1-x}Se_x$ single crystals with $x \approx 0.5$. According to the experimental procedure described in the original doctoral research, the crystals were grown from the vapor phase using a closed-tube technique and high-purity starting materials [1].

Rubidium doping was carried out by electrolytic deposition followed by activating annealing at approximately $920\ K\ for\ 20 - 60\ min$ in an inert atmosphere [1]. The treatment produced high-resistivity and highly photosensitive crystals, providing suitable conditions for investigating impurity-related photoconductivity and optical-quenching processes.

The original doctoral study established that Rb-related centers may participate in impurity-defect complexes and that the electronic response of these complexes can change under non-equilibrium optical conditions [1].

3.3. Optical-quenching measurements

For optical-quenching measurements, the samples were placed in a cryostat allowing temperature control over approximately $90 - 400\ K$. Steady-state photoconductivity was excited using band-gap illumination with wavelengths below $520\ nm$.

The optical-quenching spectra were obtained by monitoring the reduction in photocurrent under additional infrared illumination. The infrared photon-energy range was approximately $0.4 - 1.6\ eV$, with a spectral resolution of approximately $0.02\ eV$. The photocurrent was measured using a Keithley $6517A$ electrometer.

Two cooling conditions were considered:

- Mode I: cooling from approximately $380\ K\ to\ 90\ K$ in darkness.
- Mode II: cooling from approximately $380\ K\ to\ 90\ K$ under continuous band-gap illumination, allowing photoinduced chemical reactions to occur.

The measurements were conducted under high-vacuum conditions.

3.4. Data analysis

The optical-quenching response was expressed in terms of the relative reduction in photocurrent:

$\frac{\Delta I}{I_0} = \frac{I_0 - I}{I_0}$, where I_0 represents the steady-state photocurrent in the absence of additional infrared illumination and I represents the photocurrent under infrared illumination.

The optical ionization energy was estimated from the red edge of the optical-quenching band. The thermal activation energy was obtained from the temperature dependence of steady-state photoconductivity using the approach associated with Lashkarev et al. [7].

The present analysis does not regard either measurement independently. Instead, the temperature dependence of OQ is considered together with the thermal behavior of steady-state photoconductivity. The purpose is to determine whether the two experimentally different responses converge on a common energy scale.

4. Results and Discussion

4.1. Activation energies and quenching parameters

Table 1 retains the numerical dataset used in the originally submitted manuscript. The data are derived from the experimental work underlying the author's doctoral research and are used here as the basis for the present analytical treatment.

The significance of retaining this dataset is that it allows the optical-quenching parameters and activation energies to be considered together rather than as isolated quantities. The present analysis therefore does not modify the original numerical values but interprets their physical relationship in conjunction with Figures 1 and 2.

Table 1. Summary of activation energies and quenching parameters retained from the experimental dataset underlying the doctoral research and used for the present analysis.

Sample Condition	$E_{a1}\ (eV)$	$E_{a2}\ (eV)$	IR Quenching Ratio (%)	$\sigma_{photo}/\sigma_{dark}$
As-grown (RT)	0.62	1.05	35	2.1×10^3
Annealed 300°C (air)	0.58	0.98	28	4.5×10^3
Annealed 400°C (air)	0.55	0.95	18	8.2×10^3
Annealed 450°C (air)	0.60	1.02	32	5.1×10^3
Annealed 400°C (vacuum)	0.65	1.10	42	2.8×10^3

4.2. Optical-quenching spectra

Figure 1. Optical-quenching spectra of $Rb - doped\ CdS\ and\ CdS_{1-x}Se_x$ single crystals.

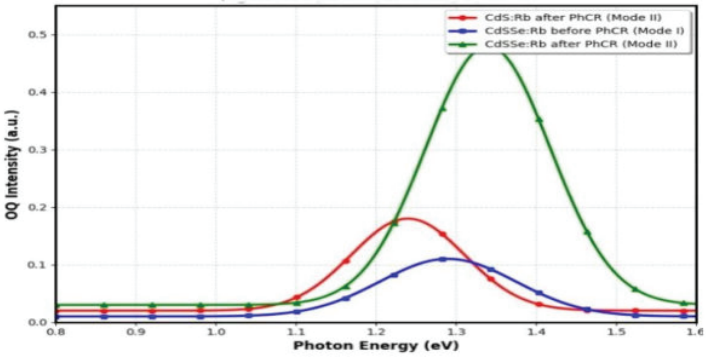


Figure 1. Optical-quenching spectra of (a) $CdS:Rb$ after PhCR under Mode II cooling and (b) $CdS^{1-}{}_{x}Se_{x}$: Rb before and after PhCR. The red curve (circles) represents $CdS:Rb$ after PhCR, showing a broad quenching band with a maximum near 0.8 eV and a red edge extending toward approximately $E_v + 1.0\ eV$. The blue curve (squares) represents $CdSSe:Rb$ before PhCR, exhibiting a relatively weak response around 0.8 eV. The green curve (triangles) represents $CdSSe:Rb$ after PhCR, showing an intensity increase by a factor of 3-4 and an additional shoulder near 1.0 eV. The spectra correspond to the quenching parameters summarized in Table 1.

4.3. Temperature dependence of optical quenching

Figure 2. Temperature dependence of optical quenching and steady-state photoconductivity.

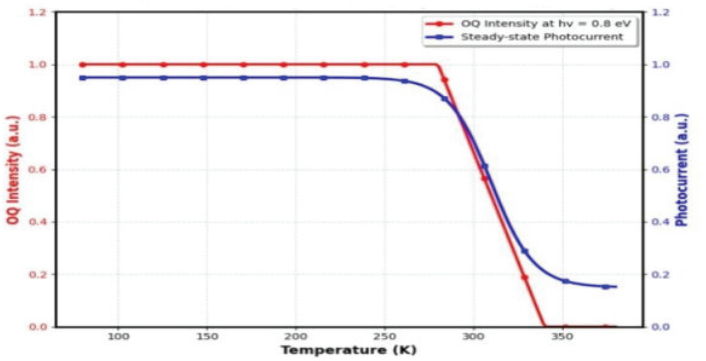


Figure 2. Temperature dependence of (a) optical-quenching intensity at $h\nu = 0.8\ eV$ and (b) steady-state photoconductivity I_0 for $CdS:Rb$. The red curve (circles) shows the OQ intensity remaining approximately constant up to about 280 K, then decreasing progressively and

disappearing above approximately 340 K. The blue curve (squares) shows the steady-state photoconductivity with an inflection region between 280 and 320 K, corresponding to a thermal activation energy close to 0.60 eV.

4.4. Energy-level interpretation and analytical synthesis

On the basis of the optical and thermal behavior, two characteristic deep-level regions are considered in the present analysis. Table 2 summarizes the deep acceptor-related levels identified through the analytical synthesis of the original spectral data. This table represents a new contribution of the present study, as it provides a unified quantitative framework that was not explicitly present in the original doctoral work.

Table 2. Deep acceptor-related levels identified through the analytical synthesis of the original spectral data.

Material	Main analytical indication	E. position	Center
$CdS:Rb$; related response in $CdS_{1-x}Se_x:Rb$	Temperature dependence of photoconductivity and disappearance of OQ at elevated temperature	$E_v + 0.60\ eV$	Deep acceptor-related center 1
$CdS:Rb$; $CdS_{1-x}Se_x:Rb$	Red edge/shoulder of OQ response and enhancement following PhCR	$E_v + 1.0\ eV$	Deep acceptor-related center 2

The approximately 0.60 eV level is associated primarily with the thermal behavior. Its position is supported by the activation-energy analysis of steady-state photoconductivity and by the temperature-dependent disappearance of the OQ signal.

The approximately 1.0 eV level is associated primarily with the optical response. Its position is indicated by the red edge of the OQ band and by the shoulder that becomes more evident after PhCR.

The two levels should therefore not be regarded as competing explanations. They represent two energy regions that contribute differently to the optical and thermal behavior of the defect subsystem.

Figure 3. Proposed energy-level diagram and recombination mechanism.

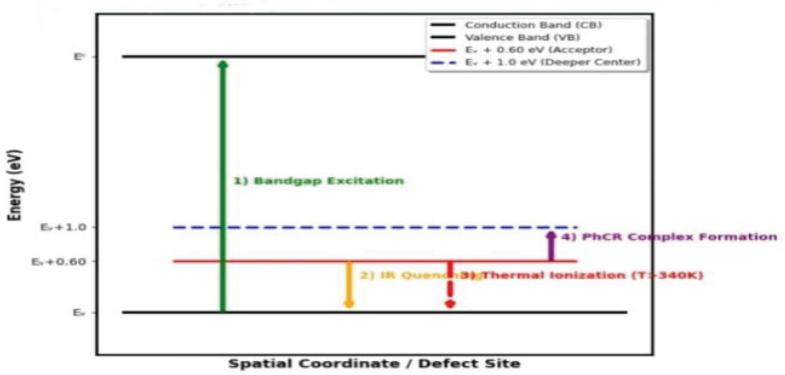


Figure 3. Proposed energy-level diagram and recombination mechanism for Rb-doped CdS and $CdS_{1-x}Se_x$ single crystals. The diagram illustrates the two deep acceptor-related levels at approximately $E_v + 0.60\,eV$ (red solid line) and $E_v + 1.0\,eV$ (blue dashed line). The green arrow indicates bandgap excitation, the orange arrow indicates IR-induced quenching, the red dashed arrow indicates thermal ionization above $340\,K$, and the purple arrow indicates photoinduced complex formation after PhCR.

4.5. Physical interpretation of the $E_v + 0.60$ eV level

Earlier semiconductor investigations established the importance of deep acceptor-related states in controlling photoconductivity and recombination processes in II-VI compounds [2,3,14]. In this context, the approximately 0.60 eV level obtained in the present analysis lies within the energy range historically associated with deep acceptor processes in CdS and related materials.

The present interpretation is based not on a single spectral position but on the convergence of two different observations. The first is the thermal activation energy obtained from steady-state photoconductivity. The second is the temperature dependence of optical quenching.

From this standpoint, the approximately $E_v + 0.60\,eV$ center can be considered a principal thermally active recombination-related center. At relatively low temperature, carriers associated with the center remain available for optical excitation. As temperature increases, thermal ionization increasingly reduces the population that can contribute to infrared-induced optical quenching.

This interpretation is also compatible with the general defect-physics framework developed in earlier studies, in which the electrical activity of a deep center depends not only on its energy position but also on its occupation, charge state, and interaction with other defects [6,7,12,13].

4.6. Physical interpretation of the approximately 1.0 eV level

The approximately 1.0 eV component has a different experimental signature. It is principally associated with the optical-quenching spectrum and is particularly evident through the red edge of the OQ band and the additional shoulder appearing after PhCR.

The original doctoral investigation demonstrated that illumination can produce reversible changes in the impurity-defect subsystem of Rb-doped $CdS\ and\ CdS_{1-x}Se_x$ crystals [1]. Within that framework, the enhanced 1.0 eV optical response can be interpreted as an indication of a deeper optically active component whose population or configuration is affected by photoinduced processes.

Recent studies of $CdS-, CdSe-\ and\ CdSSe-related$ materials have continued to emphasize the role of deep defects and defect complexes in optical and electronic response [4,8,18,19,21,25]. From the perspective of these studies, the present energy-level analysis provides a useful framework for relating the observed optical response to the broader physics of deep defect states.

The microscopic identity of the approximately 1.0 eV center, however, cannot be established solely from the optical-quenching data. The present study therefore treats its possible association with Rb-related and native-defect complexes as a physically motivated interpretation rather than as a definitive structural assignment.

4.7. Effect of photoinduced chemical reactions

One of the important characteristics of the investigated crystals is their sensitivity to illumination history. The increase in OQ intensity by approximately 3-4 times in $CdS_{1-x}Se_x:Rb$ after PhCR indicates a substantial modification of the population of optically active centers.

The original doctoral work interpreted photoinduced changes in terms of restructuring of impurity-defect complexes and considered the participation of interstitial Rb in these complexes [1]. The present study uses that physical background to interpret the OQ response.

From this perspective, illumination does not merely alter the instantaneous carrier population. Under appropriate conditions, it can also change the configuration and population of defect-

related centers. Such a process provides a physical explanation for the difference between the OQ spectra obtained under different cooling histories.

This aspect is particularly relevant to semiconductor technologies in which illumination history, operating temperature, and defect population can jointly influence response stability. Recent studies of $CdS-based$ materials likewise emphasize the continuing importance of photoinduced defect processes and defect-mediated recombination [22,24,25].

4.8. Recombination mechanism

The combined optical and thermal observations can be represented by a qualitative recombination scheme.

Under band-gap illumination, electron-hole pairs are generated. A fraction of the carriers becomes trapped at deep acceptor-related centers. At low temperature, additional infrared illumination can optically excite the trapped carriers, increasing their participation in recombination processes and producing a reduction in the measured steady-state photocurrent, which is observed as optical quenching.

With increasing temperature, thermal activation progressively changes the occupation of the relevant centers. The population available for infrared-induced optical quenching consequently decreases. Above approximately340 K, the OQ response disappears under the conditions of the present measurements.

The approximately 1.0 eV component represents a deeper optically active contribution whose visibility increases following PhCR. The original doctoral interpretation of illumination-induced restructuring of impurity-defect complexes provides a physical basis for considering this change within the same recombination framework [1].

4.9. Relationship to previous and recent studies

The physical interpretation presented here is rooted in the established literature on semiconductor photoconductivity and deep centers. Classical works demonstrated the role of deep electronic states in thermally stimulated and photoconductive processes [2,3,6,7]. Studies specifically concerned with CdS established characteristic optical and electronic effects associated with deep centers and defect-related recombination [10-14].

More recent research has extended this field toward defect engineering and the controlled manipulation of carrier dynamics. Studies of $CdS-and\ CdSe-based$ systems have emphasized the influence of defects on photoluminescence, recombination, and charge dynamics

[4,8]. Other studies have considered the effect of impurity incorporation and alkali-metal doping on defect-related behavior [15,21].

From the perspective of these developments, the present study addresses a continuing physical question using a well-defined single-crystal system. The purpose is not to establish superiority over previous studies, but to place the present observations within the continuing development of semiconductor defect physics.

In particular, the combination of thermal activation and optical quenching provides a complementary route for interpreting deep centers. The present analysis therefore considers the approximately 0.60 eV *and* 1.0 eV energy regions in relation to both the established physics of II-VI semiconductors and the continuing technological interest in controlling defect-mediated carrier processes.

4.10. Scientific and technological significance

The importance of studying deep centers extends beyond the characterization of a particular crystal. Semiconductor technologies increasingly depend on precise control of carrier generation, transport, trapping and recombination. These processes are fundamental to photodetectors, light-emitting structures, photovoltaic systems, sensors and other optoelectronic technologies.

In this context, understanding deep levels is particularly important because the same defect state can influence several technologically relevant parameters simultaneously. Carrier trapping can affect sensitivity and carrier lifetime, while recombination through deep centers can influence response speed, recovery, and stability.

The continuing development of semiconductor technologies therefore makes the characterization of defect-related states increasingly relevant. Modern approaches to semiconductor design frequently seek not simply to eliminate defects but to understand and control their electronic activity. The present analysis contributes to this general objective by relating the thermal and optical signatures of deep centers within a single physical interpretation. For this reason, the observed dependence of optical quenching on temperature and illumination history may be considered relevant to the broader problem of stability and reproducibility in semiconductor optoelectronic response.

5. Experimental Uncertainty and Reproducibility

The uncertainty associated with the measurements should be considered in relation to the nature of each measured or calculated quantity.

The temperature-control accuracy of the cryogenic system was approximately $\pm 0.5\ K$. The photocurrent measurements were performed using the Keithley $6517A$ electrometer under controlled experimental conditions. The spectral resolution of the infrared measurement system was approximately $0.02\ eV$.

The uncertainty associated with an energy-level position is not exclusively an instrumental uncertainty. In the case of optical quenching, the energy position is estimated from the spectral red edge, whereas the thermal activation energy is derived from the characteristic behavior of the temperature-dependent photoconductivity curve. Consequently, the uncertainty of these quantities also depends on the definition and identification of the corresponding spectral or thermal characteristic point.

For this reason, the values $0.60\ eV\ and\ 1.0\ eV$ are interpreted as characteristic energy regions rather than as quantities whose precision exceeds the experimental and analytical resolution. Potential sources affecting the measurements include the stability of the excitation source, surface conditions of the crystals, adsorption of residual gases, variation in defect populations, and differences in the illumination history of the samples.

The original experimental investigation employed controlled measurement conditions and repeated measurements. The present paper does not introduce additional experimental data merely to increase the apparent statistical strength of the results. Instead, reproducibility is considered in relation to the consistency between independent experimental signatures and the documented experimental methodology.

6. Conclusions

The present study provides a focused analytical interpretation of optical-quenching and temperature-dependent photoconductivity in Rb-doped $CdS\ and\ CdS_{1-x}Se_x$ single crystals using experimental data originating from the author's doctoral research.

The analysis leads to the following conclusions:

- The optical-quenching response of the investigated crystals is associated with deep acceptor-related electronic states that participate in carrier trapping and recombination.

- The temperature dependence of optical quenching and the thermal behavior of steady-state photoconductivity provide complementary evidence for a characteristic deep level near $E_v + 0.60\ eV$.
- The OQ intensity decreases with increasing temperature and disappears above approximately 340 K under the investigated conditions, consistent with progressive thermal ionization of the center responsible for the low-temperature optical-quenching response.
- A deeper optical component near $E_v + 1.0\ eV$ is indicated by the red edge and shoulder of the OQ response, particularly after photoinduced chemical reactions.
- The increase in OQ intensity following illuminated cooling demonstrates that the optical response is sensitive to the illumination history of the crystals and is consistent with the photoinduced restructuring of impurity-defect complexes described in the original doctoral investigation.
- The principal analytical contribution of the present study is the integrated interpretation of the thermal and optical responses within a common energy-level framework, summarized in Table 2 and Figure 3, which represent a new analytical synthesis extending beyond the original experimental baseline.

The results reinforce the continuing importance of deep-level physics in semiconductor materials. As semiconductor technologies advance toward increasingly sensitive, stable and application-specific optoelectronic systems, understanding the interaction between defects, impurities, carrier trapping and recombination remains an important scientific requirement.

Future investigations combining optical quenching with complementary techniques such as deep-level transient spectroscopy, electron paramagnetic resonance and theoretical electronic-structure calculations would provide further information about the microscopic configuration of the defect complexes considered in the present analysis.

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