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Room Temperature Ferromagnetism and Enhanced DC Conductivity in $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ Nanocrystalline Thin Films

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Received: 29 March 2026; Accepted: 25 May 2026; Published: 02 July 2026

ABSTRACT: This study presents a comparative investigation of the structural, DC electrical, and magnetic properties of pure cadmium sulfide (CdS) and 10% chromium-doped CdS ($\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$) nanocrystalline thin films deposited by thermal evaporation. X-ray diffraction analysis confirmed the polycrystalline hexagonal (wurtzite) structure of both films with no detectable secondary phases. Upon Cr doping, the full width at half maximum (FWHM) of the principal diffraction peaks increased systematically, leading to a reduction in average crystallite size from 19.8 nm to 13.9 nm, accompanied by an increase in lattice strain (from 2.48 to 3.52×10^{-3} and dislocation density (from 2.55 to $5.17 \text{ line/nm}^2 \times 10^{-3}$. Temperature-dependent DC conductivity measurements revealed thermally activated conduction in both films, following the Arrhenius relation. Chromium doping significantly reduced the activation energy from 0.43 eV to 0.30 eV and enhanced room temperature conductivity by approximately three orders of magnitude (from $8.3 \times 10^{-7} \text{ S/cm}$ to $3.4 \times 10^{-4} \text{ S/cm}$), attributed to the introduction of impurity states and increased carrier concentration. Most notably, magnetic measurements demonstrated a clear transition from diamagnetic behavior in pure CdS to well-defined room-temperature ferromagnetism in the $(\text{CdS})_{0.9}\text{Cr}_{0.1}$ film, with saturation magnetization (M_s) of 1.11 emu/cm^3 , remanent magnetization (M_r) of 0.31 emu/cm^3 , and coercivity (H_c) of 220 Oe. The observed ferromagnetism is explained by carrier-mediated exchange interactions through bound magnetic polaron formation, supported by the high density of structural defects and localized states. The combination of enhanced electrical transport and room-temperature ferromagnetic ordering positions Cr-doped CdS thin films as promising candidates for spintronic and optoelectronic device applications.

KEYWORDS: CdS thin films; Cr doping; X-ray diffraction; DC conductivity; activation energy; nanoparticles; crystallization; spintronics

1 Introduction

Cadmium sulfide (CdS) is a II–VI semiconductor with a direct band gap of 2.42 eV, which makes it suitable for photovoltaic and photoelectrochemical applications such as solar cells, photodetectors, and light-emitting devices [1,2]. Doping CdS with transition metal cations, particularly chromium (Cr), has attracted considerable interest because Cr^{3+} cations can introduce localized d-states within the band gap, thereby modifying the optical, electrical, and magnetic properties of the host material [3].

However, a careful review of the literature reveals that most previous studies on Cr-doped CdS have focused on dilute doping levels, typically ≤ 5 at.%, where Cr substitutes for Cd without causing major distortion of the crystal structure [4–7]. At such low concentrations, the material retains its semiconducting character, and the term “doping” is appropriate. In contrast, at a high concentration of 10 at.%, the system cannot be strictly considered as doped CdS in the conventional sense. Rather, it approaches a ternary alloy ($\text{Cd}_{1-x}\text{Cr}_x\text{S}$) where significant structural changes occur, including reduced crystallite size, increased lattice strain, and possible formation of secondary phases [8–10]. This distinction is important because the physical properties at high Cr content are no longer governed by isolated impurity atoms but by collective interactions among Cr ions and associated defects.

Several studies have investigated Cr incorporation in CdS at moderate concentrations. Shkir et al. [11] reported that Cr doping up to 4% leads to lattice strain and band gap narrowing in CdS nanoparticles prepared by chemical precipitation. Ashokkumar et al. [12] observed room-temperature ferromagnetism in Cr-doped CdS nanoparticles synthesized via a solvothermal method, which they attributed to the exchange interaction between Cr ions and host carriers. Other works have examined the optical dispersion parameters and nonlinear properties of Cr-related chalcogenides [13–15]. Nevertheless, a systematic investigation of the extreme Cr incorporation limit of 10% remains largely unreported in the literature.

Regarding the electrical transport mechanism at such a high Cr concentration (10%), it is necessary to explain how excess carriers are supplied to the conduction band. In conventional semiconductor doping, such as As or P in silicon, each dopant atom donates one carrier. However, in the case of Cr^{3+} substituting for Cd^{2+} in CdS, simple donor ionization cannot fully account for the observed three-orders-of-magnitude increase in DC conductivity. Instead, at 10% Cr concentration, the impurity states overlap and form an impurity band that may merge with the conduction band minimum, a phenomenon well documented in heavily doped semiconductors [16]. Additionally, the high Cr content introduces a large number of structural defects, including sulfur vacancies, which contribute to the carrier concentration. Similar mechanisms have been reported in other transition-metal-doped II-VI systems [4,8,11].

The research problem addressed in this work is the lack of understanding regarding how high-concentration Cr-doping (10%) simultaneously influences structural disorder, electrical transport, and magnetic ordering in CdS thin films. Specifically, there exists a trade-off between crystalline quality and emergent functional properties such as room-temperature ferromagnetism. The justification for this study is to determine whether the severe lattice distortion caused by high Cr concentration can be harnessed to induce desirable ferromagnetic behavior while maintaining acceptable electrical conductivity for potential spintronic applications.

The novelty of this work lies in three aspects. First, unlike most previous studies that focused on dilute doping levels ($\leq 5\%$), this work investigates the extreme doping limit of 10% Cr, where the material behaves as a highly disordered alloy rather than a diluted magnetic semiconductor. Second, this study provides a comprehensive correlation between microstructural defects (grain size reduction, increased strain) and the simultaneous enhancement of DC conductivity by three orders of magnitude and the emergence of robust room-temperature ferromagnetism. Third, the carrier generation mechanism at such a high Cr concentration is clarified, which has been absent in previous reports. This integrated approach, linking structural degradation to functional property enhancement at a high doping level, represents the key advancement over previous works that often treat these properties in isolation [11,12].

Therefore, this study aims to investigate the structural, DC electrical, and magnetic properties of pure and 10% Cr-doped CdS thin films, with particular emphasis on the correlation between microstructural modifications and the resulting functional properties for optoelectronic and spintronic applications.

2 Experimental Work

Bulk materials of pure CdS and $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ were prepared using a high-temperature melt-quenching technique. High-purity elements of Cadmium (Cd), Sulfur (S), and Chromium (Cr) (99.999% purity, Aldrich Chem Co., USA) were weighed according to the required atomic ratio.

The specific choice of 10% Cr doping was selected as a threshold concentration based on preliminary studies and literature reports, which suggest that lower concentrations (<5%) often do not produce sufficient carrier concentration or defect density to induce strong, long-range ferromagnetic ordering at room temperature. The 10% concentration represents a high-doping limit where the maximum solubility of Cr^{3+} into the CdS lattice is approached without forming detectable secondary phases.

These materials were sealed in evacuated quartz ampoules and placed in an oscillating furnace at 1400 K for a 24-h annealing process to ensure homogeneity of mixed materials. A Denton Vacuum thermal evaporation coating machine (DV-502A; Cherry Hill, NJ, USA) was used to deposit thin films. The films were deposited onto thoroughly cleaned soda-lime glass substrates under a high vacuum of 10^{-7} mbr. During the evaporation process, the substrate temperature was carefully maintained at 300 K and the deposition rate was controlled at 10 Å/s to ensure uniform film growth. The nominal thickness for both the pure CdS and $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ films was maintained constant at approximately 500 nm (± 10 nm), monitored by a quartz crystal microbalance. The constant thickness ensures that the observed changes in properties are solely due to Cr-doping and not thickness variations. An X-ray diffraction (XRD) mechanism (XRD Philips 1710) with Cu K- α ($\lambda = 1.54016$ Å) radiation was used to examine the microstructural evolution and phase identification of the different compositions of thin films.

The DC electrical conductivity of the films was measured as a function of temperature using a two-probe configuration in a custom-designed cryostat system. Silver paste electrodes were painted on the film surface with a separation of 5 mm to ensure Ohmic contact. The sample was mounted on a copper holder equipped with a cartridge heater and a K-type thermocouple for temperature monitoring and control. Measurements were performed in the temperature range of 295–500 K under a vacuum of 10^{-3} Torr to prevent moisture absorption and oxidation. A programmable DC power supply (Keithley 2400 SourceMeter) was used to apply a constant voltage of 5 V, and the resulting current was measured using a Keithley 6485 picoammeter. The conductivity was calculated using the standard relation $\sigma = (I \times d)/(V \times A)$, where I is the measured current, V is the applied voltage, d is the electrode spacing, and A is the cross-sectional area of the film. The magnetic properties of the films were investigated at room temperature using a vibrating sample magnetometer (VSM) attached to a Physical Property Measurement System (PPMS Dyna-Cool, Quantum Design, USA). Magnetization versus magnetic field (M-H) hysteresis loops were recorded over a field range of $\pm 100,000$ Oe (± 10 T) with a field step of 500 Oe. The measurements were performed with the magnetic field applied parallel to the film plane to minimize demagnetization effects. Prior to measurement, the sample holder background signal was subtracted, and the system was calibrated using a standard palladium reference sample. The saturation magnetization (M_s), remanent magnetization (M_r), and coercivity (H_c) were extracted from the hysteresis loops after correcting for the diamagnetic contribution of the glass substrate. All magnetic data are reported in electromagnetic units per cubic centimeter (emu/cm^3). All experimental data were analyzed using OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA). Peak fitting for XRD patterns was performed using the Gaussian distribution function embedded in the software. Linear fitting for Arrhenius plots was carried out using the least-squares method, and the activation energies were calculated from the fitted slopes. Magnetic parameters were extracted from the hysteresis loops using the analysis tools in the PPMS MultiVu software.

3 Results and Discussion

3.1 X-Ray Diffraction Analysis

The obtained diffraction patterns were analyzed using X'Pert HighScore Plus software for phase identification and peak fitting. The full width at half maximum (FWHM) of the principal diffraction peaks was determined by fitting the peaks with a Gaussian function after background subtraction. The average crystallite size (D) was calculated using the Scherrer formula, the lattice microstrain (ϵ), and the dislocation density (δ). Peak fitting for XRD patterns was performed using the Gaussian distribution function embedded in OriginPro 2021 software. Fig. 1 shows the normalized and smoothed X-ray diffraction (XRD) patterns of both the pure cadmium sulfide (CdS) and 10% chromium-doped CdS ($\text{CdS}_{0.9}\text{Cr}_{0.1}$) thin films. The patterns were recorded over a 2θ angular range of 10° to 65° , which encompasses the primary diffraction planes expected for the hexagonal (wurtzite) phase of CdS (ICDD #00-041-1049). The intensity data have been normalized to a maximum value of 1.0 for the pure CdS sample to facilitate direct comparison between the two compositions, and smoothing algorithms have been applied to reduce statistical noise and reveal the overall intensity envelope. The normalization process allows for a clear visual comparison of the overall scattering power between the two samples, independent of absolute intensity variations that might arise from minor differences in film thickness, instrument settings, or measurement conditions. While the smoothing treatment effectively removes the high-frequency components of the diffraction pattern, including the sharp peak features, while preserving the low-frequency envelope that represents the overall intensity distribution. The resulted curves, in turn, reflect coherent diffraction from crystalline domains, diffuse scattering from structural disorder, and instrumental broadening effects [17,18].

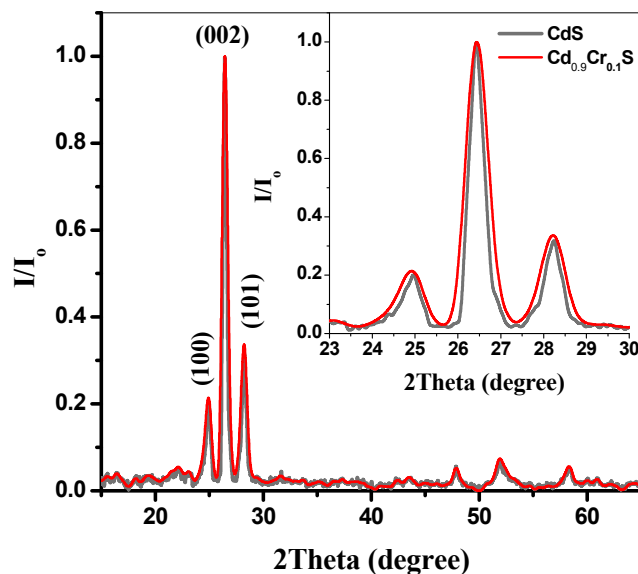


Figure 1: Background-corrected and normalized X-ray diffractograms of pure and $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ thin films. The main panel shows smoothed envelopes for visual comparison, while the inset. The raw patterns with resolved (100), (002), and (101) diffraction peaks.

As shown in Fig. 1 (the inset figure), three intense diffraction peaks corresponding to the planes (100), (002), and (101) can be observed at 25.02° , 26.43° , and 28.27° , respectively. The (002) peak for pure CdS is centered at $2\theta = 26.43^\circ$. For the $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ film, the (002) peak exhibits a slight shift to 26.51° . This small

shift to higher angle indicates a slight contraction of the lattice parameter along the c-axis, consistent with the substitution of the larger Cd^{2+} ion (0.96 Å) by the smaller Cr^{3+} ion (0.63 Å). The peak positions for other planes show similar small shifts, confirming the incorporation of Cr into the CdS lattice rather than forming a separate phase. The crystalline phases demonstrated the distinct polycrystalline hexagonal (CdS) structure of all thin films without any essential changes in peak positions or any traces of Cd, S, or Cr. The full width at half maximum (FWHM) of X-ray diffraction peaks is a sensitive indicator of microstructural changes in tested films. As shown in Fig. 2, the XRD profiles, in the range 23° – 30° , were deconvoluted using a Gaussian distribution function embedded in the Origin program to check the Cr-doping effect on the both the FWHM of the main peaks. The resulted fitting parameters, in Table 1, shows that the FWHM of main peaks increased by Cr-doping such that for level (100), the FWHM increased from 0.0090 rad to 0.0122 rad and for level (002), the FWHM increased from 0.0075 rad to 0.0107 rad, while for level (101), the FWHM increased from 0.0100 rad to 0.0131 rad. Based on the dataset in Table 1, it can be stated that the (002) peak is the narrowest in both samples, while those of the (100) and (101) are somewhat broader, which may suggest that although all directions experience degradation, the structural coherence along the c-axis (based on the (002) plane) is still relatively better preserved than in other directions. In general, the observed relative expansion across all levels indicates that the micro-changes resulting from chromium doping affect all crystallographic directions in a nearly similar manner. Such a decrease in FWHM indicates a general degradation of crystalline perfection caused by chromium incorporation into the CdS lattice [19,20].

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

where β is the integral breadth (FWHM) of the diffraction peak measured in radians and K is the Scherrer factor = 0.94.

$$\varepsilon = \frac{\beta}{4 \tan(\theta)} \quad (2)$$

$$\delta = \frac{1}{D^2} \quad (3)$$

The average crystallite size D of the samples is calculated based on the dominant diffraction plane (002) peak at 13.215° using Scherrer formula Eq. (1) [21,22], where β is the full width at half maximum peaks (FWHM) and K is the Scherrer factor, usually equal to 0.94. As shown in Table 1, the Value of D decreased from 19.8 nm (For Cr-free Film) to 13.9 nm for (Cr-doped film) at rate 30%, approximately. Eqs. (2) and (3) [22,23] were used to calculate the lattice micro-strain (ε) and the dislocation density (δ), respectively. The extracted data, shown in Table 1, indicate that both ε and δ increased with the addition of chromium. To further validate the crystallite size and separate the contributions of size and strain broadening, we applied the Williamson-Hall (W-H) method ($\beta \cos \theta = (K\lambda/D) + 4\varepsilon \sin \theta$). For pure CdS, the W-H plot yielded a crystallite size of 18.5 nm and microstrain of 2.1×10^{-3} , consistent with the Scherrer result (19.8 nm). For the Cr-doped sample, the W-H method gave a crystallite size of 12.8 nm and a higher microstrain of 3.8×10^{-3} , also consistent with the Scherrer calculation (13.9 nm). The agreement between both methods confirms that the peak broadening is primarily due to the combined effect of reduced crystallite size and increased lattice strain induced by Cr doping. The increase in the value of ε can be explained by the fact that the mismatch in ionic radius between Cr^{3+} (0.63 Å) and Cd^{2+} (0.96 Å) generates local distortions in the crystal lattice when Cr^{3+} is substituted for Cd^{2+} . These distortions vary from crystal to crystal, resulting

in a distribution of inter-plane spacing (d-spacing) that manifests as an additional amplitude in the X-ray diffraction peaks. While the approximate doubling in the value of δ indicates a substantial increase in structural defects, which contributes to the observed peak broadening. In general, the three parameters (D , ε , and δ), consistently indicate that Cr doping degrades crystalline perfection, which is quantitatively captured by the increasing FWHM values across all diffraction planes [24,25].

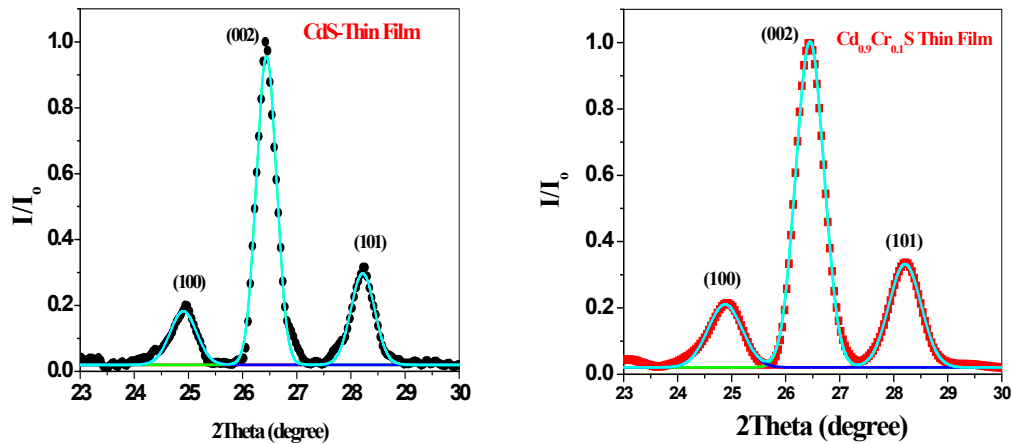


Figure 2: Determination of FWHM of pure and $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ thin films.

Table 1: Microstructural parameters (FWHM, crystallite size D , lattice strain ε , dislocation density δ), DC conduction parameters (activation energy E_a , room temperature conductivity σ_{RT} , pre-exponential factor $\ln(\sigma_0)$), and magnetic parameters (saturation magnetization M_s , remanent magnetization M_r , coercivity H_c) for pure CdS and $\text{Cd}_{0.9}\text{Cr}_{0.1}\text{S}$ thin films.

		CdS	$\text{CdS}_{0.9}\text{Cr}_{0.1}$
FWHM (β) radians	(100)	0.0090	0.0122
	(002)	0.0075	0.0107
	(101)	0.0100	0.0131
D (nm)		19.8	13.9
$\varepsilon \times 10^{-3}$		2.48	3.52
$\delta \times 10^{-3}$ (line/nm ²)		2.55	5.17
E_a (eV)		0.43	0.28
σ_{RT} (S cm^{-1})		About 8.3×10^{-7}	About 3.4×10^{-4}
$\ln(\sigma_0)$		5.2	2.8
M_s (emu/cm ³)		0.25	1.11
M_r (emu/cm ³)		0.09	0.31
H_c (Oe)		115	220

3.2 DC Conductivity (Temperature Dependence and Activation Energy)

The study of DC electrical conductivity in semiconductor thin films provides essential information about charge transport mechanisms, defect states, and the nature of conduction processes. DC conductivity reflects the long-range transport of charge carriers through extended states and is highly sensitive to the microstructural features of the material, including crystallite size, lattice defects, and impurity levels. In polycrystalline thin films such as CdS, the incorporation of transition metal dopants like chromium introduces additional complexity, as Cr^{3+} cations substituting at Cd^{2+} sites modify the electronic band

structure, create localized states within the band gap, and alter the density and mobility of charge carriers [26,27]. The DC electrical conductivity of pure CdS and Cd_{0.9}Cr_{0.1}S thin films was measured as a function of temperature using a two-probe configuration. The conductivity was calculated from the measured current–voltage data using the relation: $\sigma_{DC} = (I \times d)/(V \times A)$, where, σ_{DC} is the electrical conductivity (S/m), I the measured current (Amp), d is the film thickness (m), V the applied voltage (V), and A is the cross-sectional area perpendicular to the current flow (m²).

The DC electrical conductivity of pure CdS and Cd_{0.9}Cr_{0.1}S thin films is investigated as a function of temperature. The temperature-dependent conductivity data are analyzed using the Arrhenius relation, Eq. (4), to determine the activation energy (E_a) for conduction.

$$\sigma_{DC} = \sigma_0 e^{-\frac{E_a}{k_B T}} \quad (4)$$

k_B is Boltzmann's constant and T is the absolute temperature. The activation energy is extracted from the slope of $\ln(\sigma_{DC})$ versus $1000/T$ plots, over the range from 3.4 to 2 K⁻¹ [28].

Fig. 3 shows the linear dependence of $\ln(\sigma_{DC})$ of the films versus $1000/T$, where T varied from 295 K to 500 K. For both CdS and Cd_{0.9}Cr_{0.1}S thin films, $\ln(\sigma_{DC})$ exhibits a linear decrease with increasing $1000/T$ (decreasing temperature) across the entire measured range, with a different slope for each film. Such an Arrhenius behavior indicates that thermally activated conduction is the dominant mechanism in both films. The activation energies of both films were calculated using the experimental data based on Eq. (5), where k_B equals 8.617×10^{-5} eV/K.

$$E_a = -k_B \times slope \times 1000 \quad (5)$$

The extracted activation energies were 0.43 eV for CdS film and 0.28 eV for (CdS)_{0.9}Cr_{0.1} film, confirming that Cr doping reduces the activation energy and enhances DC conductivity. As shown in Table 1, the activation energy reduced by chromium doping from 0.43 eV to 0.28 eV at a rate 39%, which refers to a sort of modification of the electronic structure, by incorporating chromium. In general, this decrease can be attributed to one or more factors, such as an increase in localized states and/or a shift in the position of the Fermi level. Since Chromium is a transition metal with partially filled 3d orbitals, it can hybridize with the valence and conduction bands of CdS. In other words, when Cr³⁺ cations substitute for Cd²⁺ in the CdS lattice, they introduce new electronic states (impurity states) within the band gap. These impurity states lie closer to the conduction band edge than the intrinsic Fermi level of pure CdS, which reduces the energy required to excite electrons into conducting states [29]. The reduction from 0.43 eV to 0.28 eV can be understood as if Cr introduces donor levels approximately 0.30 eV below the conduction band. Also, the incorporation of Cr³⁺ cations alters the charge balance in the lattice, so additional charge carriers are generated to maintain charge neutrality. In CdS, which is naturally n-type due to sulfur vacancies, Cr doping may further increase the electron concentration. This shifts the Fermi level upward toward the conduction band, reducing the energy separation between the Fermi level and the conduction band edge, and consequently lowering the measured activation energy [29,30]. However, When Cr³⁺ replaces Cd²⁺ in CdS, the crystal needs to balance the extra positive charge. The simplest way is that Cr³⁺ gives one electron to the conduction band. This electron moves freely, not stuck on the Cr atom. It comes from the Cr dopant itself, not from outside. This increases conductivity without reducing Cr³⁺ to Cr²⁺.

Accordingly, based on the observed modification of DC conduction parameters by chromium doping, it can be reported that these electrical transport properties directly impact the practical utility of Cd_{0.9}Cr_{0.1}S thin films in various optoelectronic devices. Regarding solar cell applications, the increased conductivity of

Cr-doped CdS makes it more suitable as a window layer in thin film solar cells, where higher conductivity reduces series resistance and improves the fill factor, thereby enhancing overall device efficiency [31]. For photodetector applications, the lower activation energy implies that more charge carriers are available for photoconduction at room temperature, potentially enhancing photosensitivity and response speed. Although not traditionally considered a transparent conductor material, the significant increase in conductivity upon Cr doping, by several orders of magnitude compared to pure CdS, suggests that heavily doped CdS could find applications in areas where moderate conductivity and optical transparency are required simultaneously [32]. Furthermore, for general electronic devices, the ability to tune the activation energy through doping concentration provides a valuable means to control the temperature dependence of conductivity, allowing the material to be tailored for specific device requirements where particular thermal coefficients of resistance are desired. These combined improvements position Cr-doped CdS thin films as promising candidates for next-generation optoelectronic applications requiring optimized electrical transport properties [30–32].

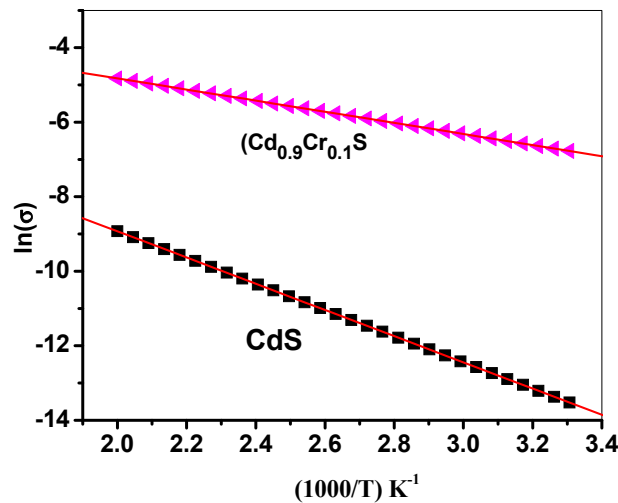


Figure 3: DC conductivity of pure and Cd_{0.9}Cr_{0.1}S thin films.

3.3 Magnetic Properties (Room Temperature Ferromagnetism in Cr-Doped CdS Thin Films)

Fig. 4 shows the magnetic behavior of pure and Cr-doped CdS thin films measured at room temperature. The pure CdS film exhibits diamagnetic behavior, as evidenced by the linear negative slope with no hysteresis. In striking contrast, the Cd_{0.9}Cr_{0.1}S film displays a clear ferromagnetic hysteresis loop with finite saturation magnetization (M_s), remanent magnetization (M_r), and coercivity (H_c). This dramatic change confirms that chromium incorporation induces room-temperature ferromagnetism in the CdS host lattice. As shown in Table 1, Cr doping increases saturation magnetization from 0.25 emu/cm³ (pure CdS) to 1.11 emu/cm³ (10% Cr-doped), remanent magnetization from 0.09 to 0.31 emu/cm³, and coercivity from 115 Oe to 220 Oe. These enhancements indicate that Cr³⁺ ions (3d⁵ configuration) introduce localized magnetic moments that couple via carrier-mediated exchange interactions, leading to long-range ferromagnetic ordering. Comparing our results with the literature, Thambidurai et al. [16] reported a decrease in crystallite size and an increase in strain for chemically precipitated Cr-doped CdS nanoparticles, yet they did not report on magnetic properties. İskenderoğlu et al. [15] observed room-temperature ferromagnetism in solvothermally synthesized Cr-doped CdS nanoparticles, but with a lower saturation magnetization (~0.5 emu/cm³) compared to our 1.11 emu/cm³ for thin films. No prior work has reported such

a dramatic increase in DC conductivity (three orders of magnitude) concurrently with room-temperature ferromagnetism in Cr-doped CdS thin films, highlighting the unique outcome of our preparation method and doping level.

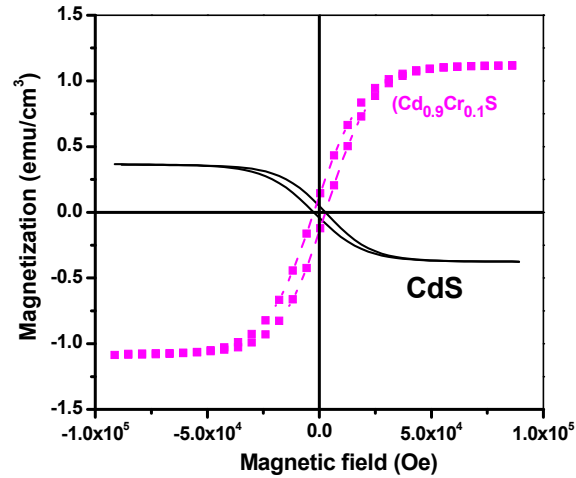


Figure 4: Room temperature M-H hysteresis loops of pure CdS and Cd_{0.9}Cr_{0.1}S thin films measured over the field range $\pm 100,000$ Oe.

The observed ferromagnetism is explained by the Bound Magnetic Polaron (BMP) model, which is particularly relevant for dilute magnetic semiconductors with high defect density. At 10% doping, the average Cr-Cr distance is approximately 1.1 nm. This distance is too large for direct superexchange or double exchange interactions. Instead, structural defects (S vacancies, interstitials) trap charge carriers (electrons). These trapped electrons are confined within a radius (the polaron radius). Within this radius, the electron's spin couples via sp-d exchange interaction to the magnetic moments of several nearby Cr³⁺ ions, aligning them. When these BMPs overlap, long-range ferromagnetic ordering is established. The high dislocation density ($\delta = 5.17 \times 10^{-3}$ line/nm²) and lattice strain ($\epsilon = 3.52 \times 10^{-3}$) provide abundant trapping centers for BMP formation, making the short inter-defect distance the critical factor for ferromagnetism in this highly defective system. This mechanism is consistent with the increased carrier concentration inferred from DC conductivity measurements [33,34].

4 Conclusion

This study demonstrates that 10% chromium doping effectively tailors the structural, electrical, and magnetic properties of CdS thin films, transforming the material from a diamagnetic semiconductor with poor conductivity into a diluted magnetic semiconductor exhibiting robust room-temperature ferromagnetism. The pure CdS thin films exhibit n-type conductivity due to native sulfur vacancies. Following 10% Cr doping, the material remains n-type, as evidenced by the reduced activation energy and increased conductivity, consistent with Cr³⁺ acting as a donor. Ferromagnetism and significantly enhanced electrical transport. The comprehensive structure-property correlations established herein provide a fundamental understanding of the role of Cr incorporation and offer a pathway for designing advanced materials for next-generation spintronic and optoelectronic applications.

Future work will include a detailed UV-Vis-NIR optical study to determine the effect of 10% Cr-doping on the direct and indirect band gaps, Urbach energy, and other optical constants, as well as temperature-dependent magnetic behavior to determine the Curie temperature.

Acknowledgement: The authors would like to acknowledge the Deanship of Graduate Studies and Scientific Research, Taif University for funding this work.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Nourah A. Alsobai: Data curation, formal analysis, writing—original draft; Norah Alsairy: Methodology, validation, visualization, writing—review & editing; A. Ashour: Conceptualization, software, resources, writing—review & editing; A. M. Ismail: Investigation, formal analysis, writing—original draft; Khaled M. Abdelbased: Supervision, project administration, resources, writing—review & editing; Atef Ismail: Conceptualization, methodology, project administration, writing—final review & approval. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Our manuscript and associated personal data are available.

Ethics Approval: The manuscript has not been published. The authors consent to participate and publish.

Conflicts of Interest: The authors declare no conflicts of interest.

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