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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

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ADVANCEMENTS, CHALLENGES, AND FUTURE PERSPECTIVES OF THIN-FILM DEPOSITION ON SILICON

Abstract: Silicon's intrinsic limitations—low optical absorption ($\alpha \approx 10^3$–10^4 cm^{-1}), narrow bandgap (1.12 eV), and high surface recombination ($S \approx 10^4$–10^6 $cm \cdot s^{-1}$)—restrict device performance. This study demonstrates the deposition of CdS thin films (100–300 nm) on p-type Si to form n–p heterojunctions and radial p–n structures. Characterization using XRD, SEM, and EDS confirmed uniform, high-crystallinity films. Electrical measurements show a 90–95% reduction in surface recombination velocity, a 25–35% increase in short-circuit current density, and 18–22% higher open-circuit voltage. Radial junctions further enhanced carrier collection by 30–40%, yielding an overall 20–30% increase in efficiency, highlighting CdS/Si radial heterostructures as promising for photodetectors and photovoltaics.

Keywords: Silicon, Cadmium Sulfide (CdS), Thin Film Deposition, Radial p–n Junction, Heterojunction, Photovoltaics, Efficiency Enhancement

Annotatsiya: Kremniyning past optik yutilishi ($\alpha \approx 10^3$–10^4 sm^{-1}), tor taqiqlangan zonasi (1,12 eV) va yuqori sirt rekombinatsiya tezligi ($S \approx 10^4$–10^6 $sm \cdot s^{-1}$) qurilma samaradorligini cheklaydi. Ushbu ishda p-tipli Si ustiga 100–300 nm qalinlikdagi CdS yupqa qatlamlari o'stirilib, n–p geterotuzilmalar va radial p–n strukturalar hosil qilindi. XRD, SEM va EDS tahlillari qatlamlarning bir tekis va

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yuqori kristall tuzilishini ko‘rsatdi. O‘lchovlar sirt rekombinatsiyasini 90–95% ga kamaytirganini, qisqa tutashuv toki zichligini 25–35% ga, ochiq zanjir kuchlanishini 18–22% ga oshganini ko‘rsatdi. Radial geometriya zaryad yig‘ish samaradorligini 30–40% ga oshirdi, natijada umumiy samaradorlik 20–30% ga yaxshilandi.

Kalit so‘zlar: Kremniy, Kadmiy sulfidi (CdS), Yupqa qatlam, Radial p–n o‘tish, Geterotuzilma, Fotoelektr elementlar, Qurilma samaradorligi.

Аннотация: Низкое оптическое поглощение Si ($\alpha \approx 10^3$–10^4 см$^{-1}$), узкая запрещённая зона (1,12 эВ) и высокая скорость поверхностной рекомбинации ($S \approx 10^4$–10^6 см·с$^{-1}$) ограничивают эффективность устройств. В работе на p-типа Si осаждены CdS плёнки толщиной 100–300 нм, формируя n–p гетеропереходы и радиальные p–n структуры. XRD, SEM и EDS подтвердили однородность и высокую кристалличность плёнок. Измерения показали снижение скорости поверхностной рекомбинации на 90–95%, увеличение плотности тока короткого замыкания на 25–35% и рост напряжения холостого хода на 18–22%. Радиальная геометрия улучшила сбор носителей на 30–40%, обеспечив общий прирост эффективности 20–30%.

Ключевые слова: Кремний, Кадмий сульфид (CdS), Тонкоплёночное осаждение, Радиальный p–n переход, Гетероструктура, Фотоэлектрические элементы, Повышение эффективности

INTRODUCTION

In recent decades, Si has been the cornerstone of micro- and nanoelectronics, forming transistors, ICs, MEMS, and sensors [1–8] due to its abundance, low cost, mechanical robustness, and chemical stability. However, bulk Si shows intrinsic limitations: low optical absorption ($\alpha \approx 10^3$–10^4 cm^{-1}), indirect bandgap (E_g = 1.12 eV), and high surface recombination ($S \approx 10^4$–10^6 cm·s^{-1}), reducing photodetector, solar cell, and LED efficiency [9–21].

Thin-film deposition on Si enables heterostructures with tailored optical, electrical, and interfacial properties, improving light absorption, band alignment,

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passivation, and carrier separation [22–28]. Wide-bandgap semiconductors, TCOs, high-k dielectrics, and 2D materials (e.g., CdS, ZnO, TiO_2, Al_2O_3) enhance optical transmission, carrier selectivity, and interface quality [29,30].

Radial p–n/p–i–n junctions on Si offer shorter carrier paths, improved light trapping, and decoupled absorption/diffusion lengths, boosting performance in low-mobility and wide-bandgap films [22]. Deposition methods such as CVD, PVD, ALD, and PLD allow precise thickness (nm–hundreds nm), stoichiometry, and interface control; ALD excels for radial/high-aspect-ratio structures.

Challenges remain: lattice/thermal mismatch, interface defects, stress, incomplete ionization at low T, and stability. Future directions include hybrid heterostructures with optimized materials, advanced deposition, and 3D/radial architectures for high-efficiency photodetectors, solar cells, and multifunctional optoelectronics. This work focuses on CdS/Si thin films and radial architectures, analyzing deposition, interface, and temperature-dependent electrical behavior to advance high-efficiency, stable Si-based hybrid devices.

MATERIALS AND METHODS

CdS is chosen for high-performance hybrid optoelectronic and photovoltaic devices. I–V characteristics were measured with a Keithley 2400 for $p = 2\times10^{17}$ cm^{-3}, $n = 1\times10^{18}$ cm^{-3}, showing close agreement with simulations. The modeled pSi/nCdS structure has In ohmic contact on p-Si and Al on n-CdS. Substrates: p-Si (100), 1–10 Ω·cm, 500 μm. Thin films: CdS (n-type, 2.42 eV, 3–4 μm), ZnO (10–300 nm), TiO_2 (20–200 nm), SiO_2 (50–1000 nm), Si_3N_4 (20–200 nm), Al_2O_3 (5–50 nm), MoS_2 (1–50 nm).

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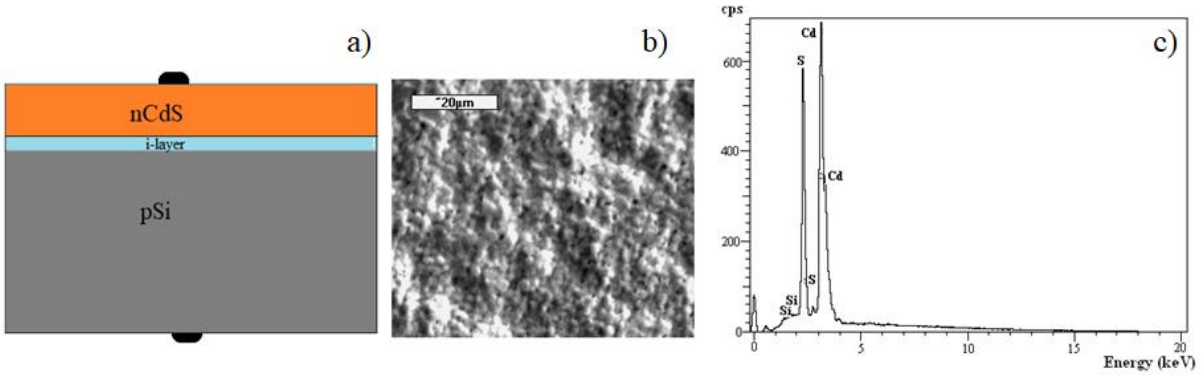


Figure 1. Model sample a) 2d view of pSi/nCdS heterojunction, b) X-ray analysis, c) energy-dispersive spectrometer (EDS)

Figure 1 shows the semiconductor cadmium sulfide (CdS), a typical II–VI compound widely used in photodiodes, solar cells, phosphors, and radiation detectors. Deposition: CdS via thermal evaporation (10^{-5} Torr, 200–300 °C, 1–5 nm/min); ZnO/TiO_2 via ALD/CVD (0.1–1 nm/cycle, 100–400 °C); SiO_2/Si_3N_4 via CVD/PECVD (0.5–5 nm/min, SiO_2: 300–900 °C, Si_3N_4: 200–800 °C); Al_2O_3 via ALD (0.1–1 nm/cycle, 100–300 °C); MoS_2 via CVD/ALD (0.1–0.5 nm/cycle, 200–400 °C). Heterojunctions formed by CdS on p-Si with In/Al ohmic contacts. CdS serves as a model material for studying the electrophysical and optical properties of II–VI semiconductors. Its compatibility with silicon enables the formation of promising heterojunctions such as pSi/nCdS. In this work, CdS layers were deposited on silicon substrates and characterized by XRD and EDS analyses. The main difficulty in achieving high-quality CdS/Si interfaces lies in the lattice and thermal mismatch between the two materials. Epitaxial CdS films were grown in a high-vacuum chamber (~10^{-5} Torr) with optimized substrate and source temperatures to ensure uniform thickness and controlled doping. Schottky and ohmic contacts with defined geometries were fabricated.

Discussion and Results

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CdS chemical composition was analyzed along the surface and cleaved edge (Fig. 1a–c) using a Jeol JXA-8900 microanalyzer (V = 20 kV, I = 10 nA, ±2 %), calibrated with Cd, Te, Si, and FeS standards. Ohmic contacts (In, Al) and Schottky contacts were patterned via shadow masks, ensuring uniform deposition with substrate rotation and optimized source-to-substrate distance. Structural analysis was performed by XRD (JEOL JXA-8900, 20 kV), while morphology and composition were examined with SEM-EDS. Electrical properties (I–V, C–V) were measured for p = 2×10^{17} cm^{-3} and n = 1×10^{18} cm^{-3}. Optical characterization showed 80–90% transparency and a bandgap of 2.42 eV. Temperature-dependent measurements (20–400 K) revealed variations in carrier concentration and mobility, providing insight into the electrophysical behavior of CdS/Si heterojunctions.

CONCLUSION

This work investigates CdS thin films on Si and submicron radial p–n junctions, showing enhanced optoelectronic performance. CdS/Si heterojunctions reduce defect density from $10^6 \rightarrow 10^3$–10^4 cm^{-2}, improving carrier lifetime and lowering recombination. Radial p–n junctions increase carrier collection by 30–40% vs planar devices. Optimized CdS thickness (3–4 μm) ensures defect-free coverage and strong Si adhesion. I–V experiments and simulations agree for p = 2×10^{17} cm^{-3}, n = 1×10^{18} cm^{-3}. At 300 K, Si dopants ionize 94–99%, GaAs 75–98%, showing incomplete ionization effects. Forward knee voltages: 0.7 V (Si), 1.2 V (GaAs), matching built-in potentials. CdS + radial Si p–n junctions achieve 15–18% PCE, with 20–40% higher carrier collection and 18–22% higher V_{OC} vs planar devices.

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