



Effect of Gamma Irradiation on the Optical and Structural properties of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ Chalcogenide Thin Films

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Abstract

In the present study, $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide glass was synthesized using the conventional melt-quenching technique. The thermal behavior of the prepared alloy was investigated through non-isothermal Differential Scanning Calorimetry (DSC) at a constant heating rate of 25 K/min. From the DSC thermogram, the glass transition temperature (T_g), crystallization temperature (T_c), and melting temperature (T_m) were determined to be 349 K, 376 K, and 533 K, respectively. Thin films of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ with a thickness of 400 nm were deposited on glass/Si wafer substrates using the thermal evaporation technique. In order to examine the effect of radiation on phase transformation, the films were subjected to gamma irradiation with doses of 6 kGy and 12 kGy. Optical characterization was carried out for both the as-prepared and irradiated films, and the results indicate that the optical band gap decreases with increasing gamma radiation dose. The structural and phase transformation behavior of the as-grown and irradiated films was further analyzed using High Resolution X-ray Diffraction (HRXRD) and Field Emission Scanning Electron Microscopy (FESEM).

Keywords: Chalcogenide, Thin Films, Optical band gap, XRD, FESEM

Introduction:

Chalcogenide materials possess a viscous and flexible network structure, which makes them highly suitable for the fabrication of technologically important devices across various fields for human welfare [1], [2]. Among amorphous materials, these unique semiconductors have attracted significant attention for the development of advanced optical devices such as optical fibers, photo-induced waveguides, lasers, and optical switches, owing to their extraordinary optical properties [3], [4], [5], [6]. Their strong optical nonlinearity further makes them hopeful candidates for all-optical switching applications [7]. In addition, chalcogenide glasses exhibit high transmittance properties in the mid-infrared region and are photosensitive to visible light, making them appropriate materials for infrared sensor [8].

Phase-change memories based on chalcogenide glasses are considered among the most capable applicants for scaling non-volatile memory technologies beyond conventional flash memory architectures [9]. These materials can be reversibly switched between amorphous and crystalline states, which enable their application in rewritable optical recording media as well as in electrically programmable non-volatile memories [10], [11], [12]. Phase-change optical recording has matured into a well-established technology and is widely utilized in rewritable optical storage systems such as compact discs (CDs) and digital versatile discs (DVDs). In such systems, data recording is based on the formation and erasure of amorphous marks within a crystalline phase-change layer. The amorphous marks are created using a pulsed focused laser beam, which locally raises the temperature of the material above its melting point for a short duration. After

the pulse, the molten region rapidly cools and solidifies into the amorphous phase. Since the optical properties of the amorphous and crystalline phases differ significantly, the stored information can be detected through variations in reflectivity. Detecting phase separation in glasses is often challenging because it may produce only minor changes in the diffraction patterns, while variations in microstructure become evident only when the separating phases differ significantly in electron density. Typically, at normal heating rates, amorphous materials tend to crystallize slightly above the glass transition temperature (T_g). Therefore, the glass transition temperature can be considered a lower limit for the crystallization temperature. Crystallization below T_g occurs extremely slowly due to the high activation energy required for atomic movement. As a result, the glass transition temperature serves as an important parameter for estimating the long-term thermal stability and archival life of phase-change materials.

Phase-change materials represent a rapidly developing class of functional materials with broad technological applications. Their capability to switch between amorphous and crystalline states has led to their widespread usage in optical rewritable data storage media [13], [14]. The transition from amorphous to crystalline phases in glassy systems can be activated by numerous external provocations such as incident light, electric fields, and thermal treatment. These factors can change the structural disorder degree and defect concentration. In recent years, noteworthy research efforts have been directed toward understanding the structural and optical properties of chalcogenide glasses and their dependence on thermal treatment and irradiation [15], [16], [17]. Gamma irradiation can meaningfully influence the optical characteristics of chalcogenide glasses by modifying their structural configuration and defect states. This sensitivity of chalcogenide materials to gamma radiation makes them favorable candidates for a wide range of technological applications. Halyan et al. [18] investigated γ -induced defects and their effects on photoluminescence in the Ag–Ga–Ge–S–Er glassy system. Ahmad et al. [19] studied the impact of gamma-ray irradiation on the optical properties of amorphous Se–Hg thin films. S. A. Gad [20] has been inspected the effect of gamma irradiation on the optical and electrical properties of In–Mn–Se. They have observed that the absorption coefficient decreased with increasing irradiation dose, while the direct optical band gap increased with γ -irradiation. A. M. Abdul-Kader et al. [21] have been studied the effect of γ -irradiation on the optical properties of Ag–Sb–Se thin films in the wavelength range 550–2500 nm.

In the present work, the phase transformation behavior of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin films under gamma irradiation has been investigated. Se–Te alloys exhibit lower aging effects, higher crystallization temperatures, and enhanced photosensitivity compared to pure selenium [22]. Consequently, these alloys have gained increasing attention for applications in laser writing and infrared sensing, although their stability remains a challenge. To improve the thermal and structural characteristics of the alloy, indium (In) has been incorporated into the composition due to its significant role in thermal management and stability enhancement in optoelectronic devices [23].

Experimental Techniques:

Bulk $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ glass was synthesized using the well-established melt-quenching technique. High-purity (5N) constituent elements were weighed according to the required stoichiometric proportions and sealed in a highly evacuated quartz ampoule to prevent oxidation during synthesis. The sealed ampoules were placed in a rocking furnace, where the temperature was gradually increased at a rate of 4 K/min up to 1273 K and maintained at this temperature for 14 hours to ensure complete melting and homogenization of the constituents. During the heating process, the ampoules were continuously rocked by rotating a ceramic rod to which they were attached, allowing thorough mixing and formation of a compositionally homogeneous melt. The molten alloy was subsequently quenched rapidly in ice-cooled water to obtain the amorphous glassy phase. After quenching, the ampoules were carefully broken to retrieve the samples. The Differential Scanning Calorimetry (DSC) analysis of the as-quenched alloy was performed using a DSC Plus instrument (Rheometric Scientific Company, UK) at a heating rate of 25 K/min. Thin films with a thickness of 400 nm were deposited on ultrasonically cleaned silicon wafers and glass substrates using the thermal evaporation

technique under a vacuum of approximately 10^{-5} Torr. The thickness of the deposited films was monitored using a quartz crystal thickness monitor (Edwards Model FTM-7). The prepared thin films were then exposed to gamma radiation doses of 6 and 12 kGy at a dose rate of 2 kGy h^{-1} using a Gamma Chamber (GC-5000) in order to study the phase transformation behavior of the $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide films. The structural characteristics of the as-prepared and irradiated films were investigated using High-Resolution X-Ray Diffraction (HRXRD) with a Rigaku Ultima IV X-ray diffractometer. The surface morphology during phase transformation was examined using a Field Emission Scanning Electron Microscope (FESEM) (QUANTA FEG 450, Amsterdam, Netherlands). Optical absorption measurements were performed using a JASCO UV-Vis spectrophotometer in the wavelength range of 400–1100 nm for both as-prepared and irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ films.

Result and discussion:

The non-isothermal Differential Scanning Calorimetry (DSC) thermogram of the synthesized $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ glass, recorded at a heating rate of 25 K/min , is presented in Fig. 1. The DSC curve exhibits three characteristic thermal events. The first endothermic feature observed at 349 K corresponds to the glass transition temperature (T_g), indicating the onset of softening of the glassy network. This is followed by an exothermic peak at 376 K , which represents the crystallization temperature (T_c), where the material releases energy as atoms rearrange into a more ordered crystalline structure. A further thermal event is observed at 533 K , corresponding to the melting temperature (T_m) of the material. The presence of well-defined endothermic and exothermic peaks in the DSC curve confirms the glassy nature and compositional homogeneity of the synthesized sample.

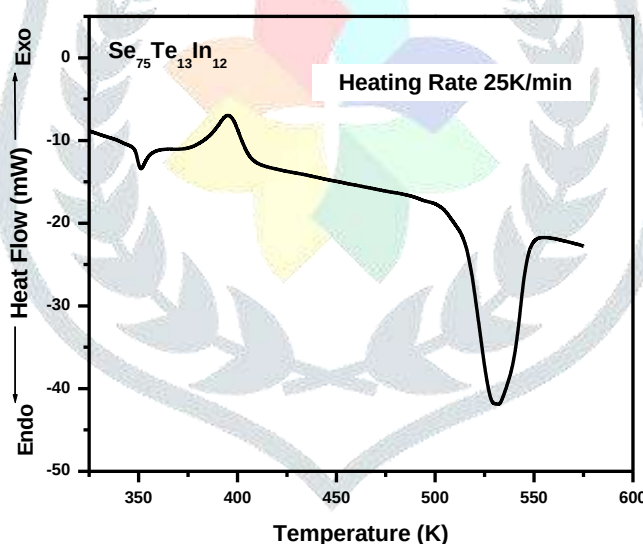


Fig. 1: DSC plot of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ glass at heating rate 25 K/min .

Fig. 2 presents the HRXRD patterns of the as-deposited and gamma-irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ glassy thin films. The diffraction measurements were carried out over a scan range of 20° – 80° using $\text{Cu K}\alpha$ radiation with a wavelength of $1.54178 \text{ \AA}$ as the X-ray source. The absence of sharp diffraction peaks in the pattern of the as-prepared thin film confirms its amorphous nature. In contrast, distinct and intense diffraction peaks appear in the XRD pattern of the film irradiated with a 12 kGy gamma radiation dose, indicating the phase transformation from the amorphous to the crystalline state.

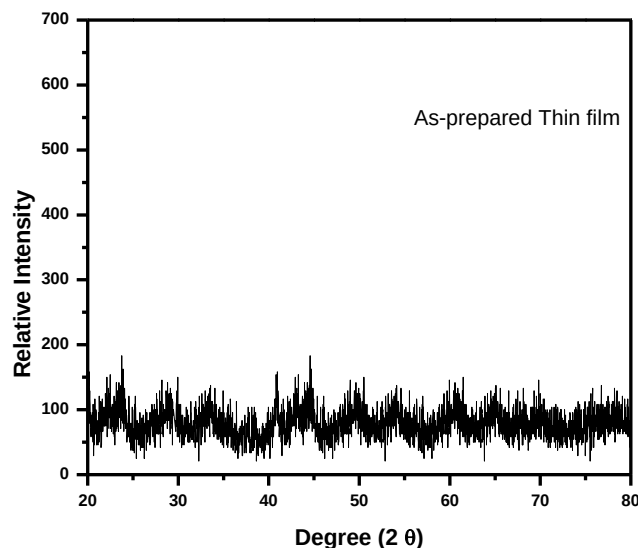


Fig. 2 (a): XRD of as-prepared $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin film.

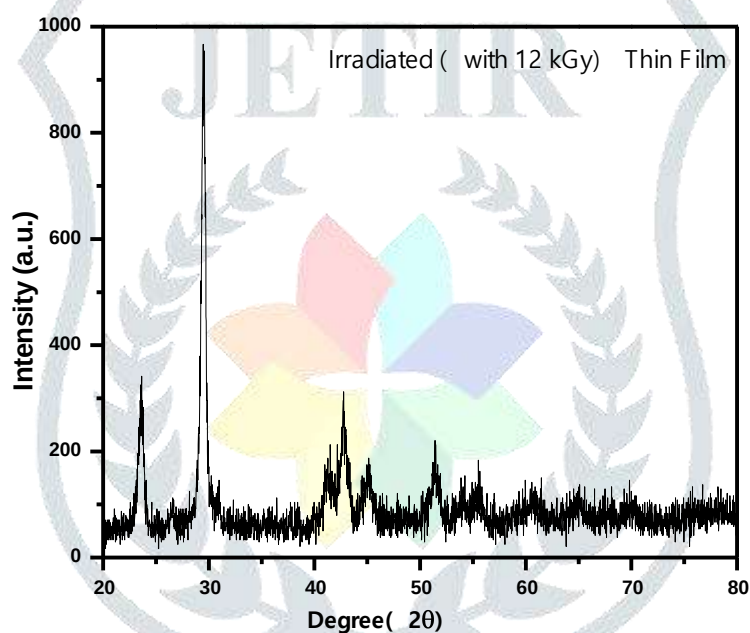


Fig. 2(b): XRD of Gamma Irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin film.

Fig. 3 represents the morphological structure of as-prepared and gamma irradiated thin films deposited on Si wafer substrate. There is a remarkable change in the structure of the film as the films were Gamma irradiated.

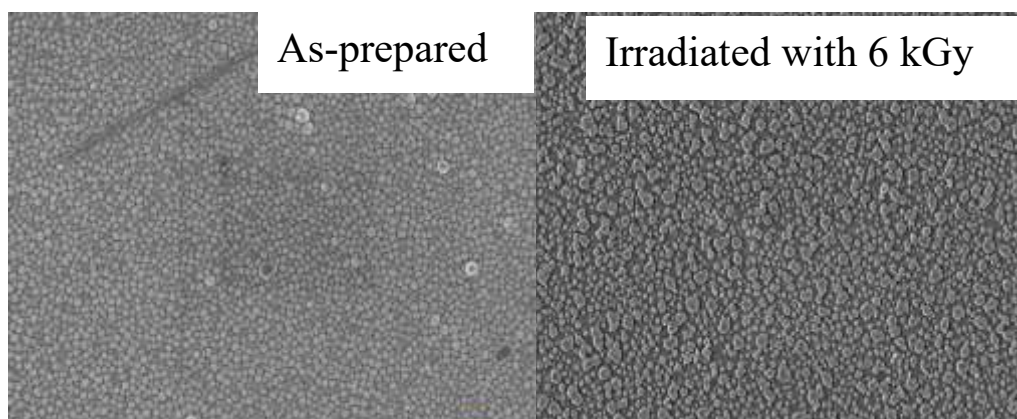


Fig. 3: FESEM images of as-prepared and gamma irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin film

Optical absorption and emission are among the most noteworthy optical phenomenon arising in $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin films. The absorption of light permits the determination of the optical band gap of a semiconductor and also leads to the generation of charge carriers [24]. In amorphous semiconductors, the absorption edge spectrum is generally divided into three distinct regions. The first region is the weak absorption tail, which arises due to the occurrence of defects and impurities in the material. The second region corresponds to the exponential absorption edge, which is strongly associated to the structural disorder inherent in amorphous materials. The third region is the high absorption region, from which the optical band gap energy can be calculated.

In the present study, the optical absorption of as-prepared and gamma-irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ thin films has been recorded as a function of wavelength. The absorption coefficient (α) was calculated by using the following relation [25].

$$\alpha = \text{Absorbance}/\text{thickness of the film} \quad (1)$$

The variation of the absorption coefficient (α) for the as-prepared and irradiated films as a function of incident photon energy is illustrated in Fig. 4.

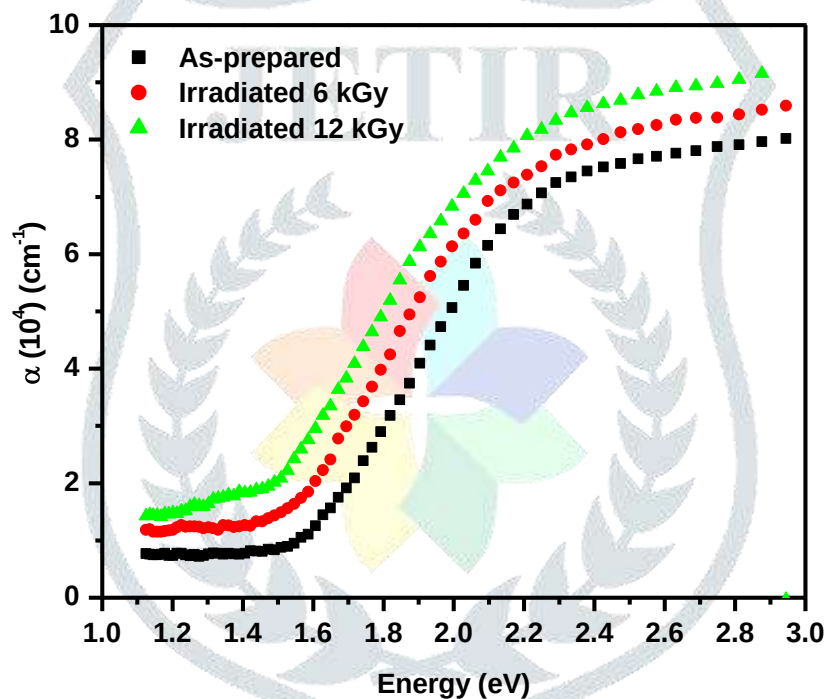


Fig. 4: Plot of absorption coefficient (α) and incident photon energy

It is evident that the absorption coefficient increases with both irradiation dose and photon energy. This behavior suggests that bond rearrangement and bond breaking processes occur within the material, leading to a modification of the absorption edge. The values of the absorption coefficient at 690 nm for the as-prepared and irradiated films are summarized in Table 1.

In amorphous semiconductors, the fundamental absorption edge follows the relation below [26]:

$$(\alpha h\nu)^n = B(h\nu - E_g) \quad (2)$$

Where ν is frequency of incident radiation, h is Planck's constant, B is a constant depending upon the probability of transition, n determines the type of transition, which may be equal to 2, 1/2 or 2/3 for direct, indirect and forbidden transitions respectively and E_g is optical energy band gap [27]. The present $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin film is found to be obeys the rule of indirect transition that means thin film system follows the above rule with $n = 1/2$ [28].

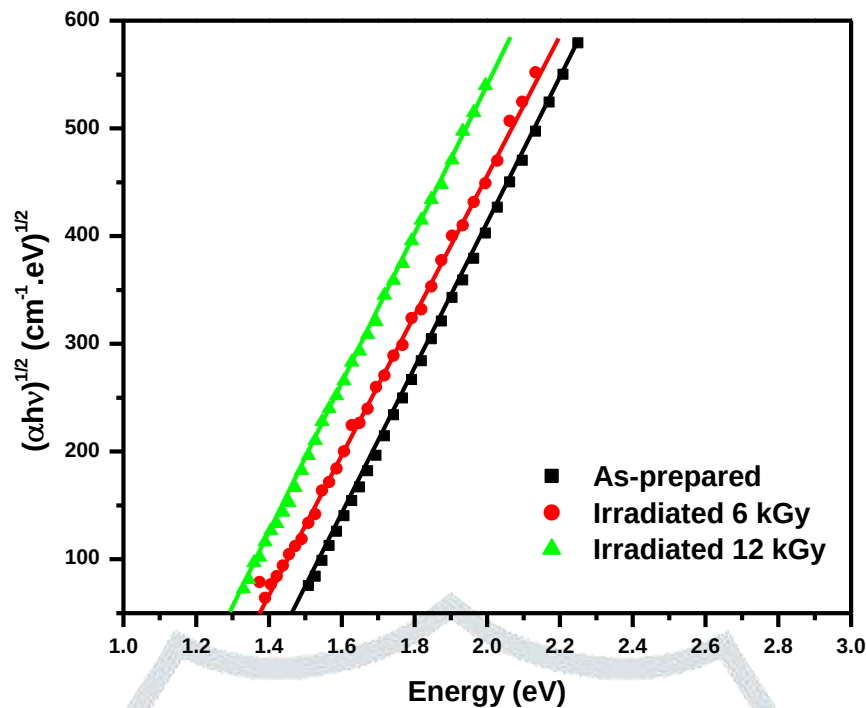


Fig. 5: $(\alpha h\nu)^{1/2}$ versus $h\nu$ for $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ as-prepared and irradiated chalcogenide thin films

Fig. 5 represents the $(\alpha h\nu)^{1/2}$ versus $h\nu$ of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide for as-prepared and irradiated films.

Table-1

Optical parameters of as-prepared and Gamma irradiated $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ chalcogenide thin film

Optical parameters	As-prepared	Irradiated with 6 kGy	Irradiated with 12 kGy
Absorption coefficient(α) (10^4) (cm^{-1}) at 690 nm	2.84	3.99	4.86
Optical band gap (E_g) (eV)	1.45	1.37	1.29

By extrapolating these graphs, we have determined the optical band gap (E_g) for as-grown and annealed films (shown in Table-1). It is clear from the table that the value of optical band gap decreases with increase in radiation doses. The optical properties of amorphous materials strongly depend on the short range ordering in amorphous state and the defect related to them [29]. The localized tail width depends on density of these defects and degree of disorderness also. Unsaturated bonds are also liable for these localized states near the band gap. The decrement in optical band gap with radiation doses may be explained in such a way that crystallization process leads an extreme increase in grain size [30] which is accountable for surface dangling bonds. These bonds are responsible for decrease in optical band gap. Many researchers have found optical band gap decrement with gamma radiation doses in their work [31], [32], [33], [34], [35].

Conclusion:

In this work, we have studied the influence of Gamma irradiation on the optical and structural properties of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ thin films. As-deposited thin films exhibit the amorphous nature whereas the irradiated films are of crystalline in nature. The phase transformation due to irradiation process is conveyed by a change in the optical band gap. It may be attributed to the decrease in defect state density, which results in the decrease of tailing of bands. The absorption coefficient is found to increase by increasing radiation doses which may be due to optical scattering at grain boundaries. These outcomes suggest the applicability of $\text{Se}_{75}\text{Te}_{13}\text{In}_{12}$ glasses in phase change memory and optoelectronics devices.

References

- [1] Z. H. Khan, S. A. Khan, F. A. Agel, N. A. Salah, and M. Husain, "Chalcogenides to Nanochalcogenides; Exploring Possibilities for Future R&D BT - Advances in Nanomaterials," M. Husain and Z. H. Khan, Eds., New Delhi: Springer India, 2016, pp. 135–202. doi: 10.1007/978-81-322-2668-0_4.
- [2] G. K. Ahluwalia, "Fundamentals of Chalcogenides in Crystalline, Amorphous, and Nanocrystalline Forms BT - Applications of Chalcogenides: S, Se, and Te," G. K. Ahluwalia, Ed., Cham: Springer International Publishing, 2017, pp. 3–60. doi: 10.1007/978-3-319-41190-3_1.
- [3] J. Lucas, J. Troles, X. H. Zhang, C. Boussard-Pledel, M. Poulain, and B. Bureau, "Glasses to see beyond visible," *Comptes Rendus Chim.*, vol. 21, no. 10, pp. 916–922, 2018, doi: <https://doi.org/10.1016/j.crci.2018.02.010>.
- [4] A. B. Seddon, "Chalcogenide glasses: a review of their preparation, properties and applications," *J. Non. Cryst. Solids*, vol. 184, pp. 44–50, 1995, doi: [https://doi.org/10.1016/0022-3093\(94\)00686-5](https://doi.org/10.1016/0022-3093(94)00686-5).
- [5] K. Hayashi, D. Kato, and K. Shimakawa, "Photoinduced effects in amorphous chalcogenide films by vacuum ultra-violet light," *J. Non. Cryst. Solids*, vol. 198–200, pp. 696–699, 1996, doi: [https://doi.org/10.1016/0022-3093\(96\)00009-9](https://doi.org/10.1016/0022-3093(96)00009-9).
- [6] O. Stroyuk, A. Raevskaya, and N. Gaponik, "Solar light harvesting with multinary metal chalcogenide nanocrystals," *Chem. Soc. Rev.*, vol. 47, no. 14, pp. 5354–5422, 2018, doi: 10.1039/C8CS00029H.
- [7] S. Asokan and K. P. Lakshmi, "Electrical switching and other properties of chalcogenide glasses," *J. Indian Inst. Sci.*, vol. 91, no. 2, pp. 319–330, 2011.
- [8] V. S. Shiryaev, A. P. Velmuzhov, T. V Kotereva, E. A. Tyurina, M. V Sukhanov, and E. V Karaksina, "Recent Achievements in Development of Chalcogenide Optical Fibers for Mid-IR Sensing," 2023. doi: 10.3390/fib11060054.
- [9] M. Wuttig and N. Yamada, "Phase-change materials for rewriteable data storage," *Nat. Mater.*, vol. 6, no. 11, pp. 824–832, 2007, doi: 10.1038/nmat2009.
- [10] D. Tripathi, H. S. Vyas, S. Kumar, S. S. Panda, and R. Hegde, "Recent developments in Chalcogenide phase change material-based nanophotonics," *Nanotechnology*, vol. 34, no. 50, p. 502001, 2023, doi: 10.1088/1361-6528/acf1a7.
- [11] Y. K. Lee, C. Yoo, W. Kim, J. W. Jeon, and C. S. Hwang, "Atomic layer deposition of chalcogenides for next-generation phase change memory," *J. Mater. Chem. C*, vol. 9, no. 11, pp. 3708–3725, 2021, doi: 10.1039/D1TC00186H.
- [12] J. Teteris and M. Reinfelde, "Application of amorphous chalcogenide semiconductor thin films in optical recording technologies," *J. Optoelectron. Adv. Mater*, vol. 5, no. 5, pp. 1335–1360, 2003.
- [13] E. G. El-Metwally and A. M. Ismail, "Non-isothermal crystallization kinetics and memory switching properties of Tl-Se-Ge-Sb chalcogenide semiconductor alloy for thermally stable phase change memory applications," *Phys. Scr.*, vol. 99, no. 1, p. 15918, 2024, doi: 10.1088/1402-4896/ad1280.
- [14] S. Agarwal, P. Lohia, and D. K. Dwivedi, "Study of optical parameters of Te(1-x) (GeSe_{0.5}) Sc_x (0 ≤ x ≤ 0.15) thin films for optical data storage applications," *J. Non. Cryst. Solids*, vol. 606, p. 122199, 2023, doi: <https://doi.org/10.1016/j.jnoncrysol.2023.122199>.
- [15] S. Ahmad, M. S. Khan, K. Asokan, and M. Zulfequar, "Effect of gamma irradiation on the structural and optical properties of thin films of a-CdSe," *Optik (Stuttg.)*, vol. 126, no. 23, pp. 3501–3505, 2015, doi: <https://doi.org/10.1016/j.ijleo.2015.08.196>.
- [16] A. Ismail, M. Alahmad, H. Kashoua, M. Alsabagh, and B. Abdallah, "Structural and optical effects of low dose rate Co-60 gamma irradiation on PbS thin films," *Microelectron. Reliab.*, vol. 116, p. 114017, 2021, doi: <https://doi.org/10.1016/j.microrel.2020.114017>.
- [17] V. Balitska, R. Golovchak, A. Kovalskiy, E. Skordeva, and O. I. Shpotyuk, "Effect of Co60 γ-irradiation on the optical properties of As–Ge–S glasses," *J. Non. Cryst. Solids*, vol. 326–327, pp. 130–134, 2003, doi: [https://doi.org/10.1016/S0022-3093\(03\)00391-0](https://doi.org/10.1016/S0022-3093(03)00391-0).
- [18] V. V Halyan *et al.*, "EPR of γ-induced defects and their effects on the photoluminescence in the

glasses of the $\text{Ag}_{0.05}\text{Ga}_{0.05}\text{Ge}_{0.95}\text{S}_2\text{--Er}_2\text{S}_3$ system,” *Radiat. Phys. Chem.*, vol. 115, pp. 189–195, 2015, doi: <https://doi.org/10.1016/j.radphyschem.2015.06.019>.

[19] S. Ahmad, S. Islam, M. Nasir, K. Asokan, and M. Zulfequar, “Effects of gamma-ray irradiation on the optical properties of amorphous $\text{Se}_{100-x}\text{Hg}_x$ thin films,” *J. Phys. Chem. Solids*, vol. 117, pp. 122–130, 2018, doi: <https://doi.org/10.1016/j.jpcs.2018.02.014>.

[20] S. A. Gad, “Optical and electrical properties of γ irradiated $\text{In}_{1-x}\text{Mn}_x\text{Se}$,” *J. Radiat. Res. Appl. Sci.*, vol. 8, no. 3, pp. 311–316, 2015, doi: <https://doi.org/10.1016/j.jrras.2015.04.004>.

[21] A. M. Abdul-Kader and Y. A. El-Gendy, “Influence of γ -irradiation on the optical properties of AgSbSe_2 thin films,” *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 305, pp. 22–28, 2013, doi: <https://doi.org/10.1016/j.nimb.2013.04.043>.

[22] A. A. Bahishti, M. A. Majeed Khan, B. S. Patel, F. S. Al-Hazmi, and M. Zulfequar, “Effect of laser irradiation on thermal and optical properties of selenium–tellurium alloy,” *J. Non. Cryst. Solids*, vol. 355, no. 45, pp. 2314–2317, 2009, doi: <https://doi.org/10.1016/j.jnoncrysol.2009.07.005>.

[23] A. Srivastava, S. N. Tiwari, M. A. Alvi, and S. A. Khan, “Studies on $\text{Se}_{75}\text{Te}_{25-x}\text{In}_x$ chalcogenide glasses; a material for phase change memory,” *Mater. Res. Express*, vol. 5, no. 1, p. 15206, 2018, doi: [10.1088/2053-1591/aaa743](https://doi.org/10.1088/2053-1591/aaa743).

[24] R. Woods-Robinson *et al.*, “Wide Band Gap Chalcogenide Semiconductors,” *Chem. Rev.*, vol. 120, no. 9, pp. 4007–4055, May 2020, doi: [10.1021/acs.chemrev.9b00600](https://doi.org/10.1021/acs.chemrev.9b00600).

[25] R. Naik, S. K. Parida, C. Kumar, R. Ganesan, and K. S. Sangunni, “Optical properties change in $\text{Sb}_{40}\text{S}_{40}\text{Se}_{20}$ thin films by light-induced effect,” *J. Alloys Compd.*, vol. 522, pp. 172–177, 2012, doi: <https://doi.org/10.1016/j.jallcom.2012.01.144>.

[26] J. Tauc, “Optical Properties of Amorphous Semiconductors BT - Amorphous and Liquid Semiconductors,” J. Tauc, Ed., Boston, MA: Springer US, 1974, pp. 159–220. doi: [10.1007/978-1-4615-8705-7_4](https://doi.org/10.1007/978-1-4615-8705-7_4).

[27] S. A. Khan, G. Tiwari, R. P. Tripathi, M. A. Alvi, Z. H. Khan, and F. A. Al-Agel, “Structural, Optical and Electrical Characterization of Polycrystalline $\text{Ga}_{15}\text{Te}_{85-x}\text{Zn}_x$ Nano-Structured Thin Films,” *Adv. Sci. Lett.*, vol. 20, no. 7, pp. 1715–1718, Feb. 2014, doi: [10.1166/asl.2014.5578](https://doi.org/10.1166/asl.2014.5578).

[28] S. A. Khan, F. A. Al-Agel, and A. A. Al-Ghamdi, “Optical characterization of nanocrystalline $\text{Se}_{85}\text{Te}_{10}\text{Pb}_5$ and $\text{Se}_{80}\text{Te}_{10}\text{Pb}_{10}$ chalcogenides,” *Superlattices Microstruct.*, vol. 47, no. 6, pp. 695–704, 2010, doi: <https://doi.org/10.1016/j.spmi.2010.03.007>.

[29] Z. H. Stachurski, “On Structure and Properties of Amorphous Materials,” 2011. doi: [10.3390/ma4091564](https://doi.org/10.3390/ma4091564).

[30] A. M. Smith and S. Nie, “Semiconductor Nanocrystals: Structure, Properties, and Band Gap Engineering,” *Acc. Chem. Res.*, vol. 43, no. 2, pp. 190–200, Feb. 2010, doi: [10.1021/ar9001069](https://doi.org/10.1021/ar9001069).

[31] S. A. Khan, R. M. Sahani, R. P. Tripathi, M. S. Akhtar, and A. Srivastava, “Influence of gamma-irradiation on the optical and structural properties of $\text{Se}_{85}\text{Te}_{15-x}\text{Bi}_x$ nano-thin chalcogenide films,” *Radiat. Phys. Chem.*, vol. 188, Nov. 2021, doi: [10.1016/j.radphyschem.2021.109659](https://doi.org/10.1016/j.radphyschem.2021.109659).

[32] M. F. Pervez *et al.*, “Influence of total absorbed dose of gamma radiation on optical bandgap and structural properties of Mg-doped zinc oxide,” *Optik (Stuttg.)*, vol. 162, pp. 140–150, 2018, doi: <https://doi.org/10.1016/j.ijleo.2018.02.063>.

[33] H. El-Zahed, “The effect of γ -doses on the optical band gap of AgInSe_2 films,” *J. Phys. Chem. Solids*, vol. 62, no. 4, pp. 641–646, 2001, doi: [https://doi.org/10.1016/S0022-3697\(00\)00067-6](https://doi.org/10.1016/S0022-3697(00)00067-6).

[34] A. M. Abdul-Kader, “Modification of the optical band gap of polyethylene by irradiation with electrons and gamma rays,” *Philos. Mag. Lett.*, vol. 89, no. 3, pp. 162–169, Mar. 2009, doi: [10.1080/09500830902720891](https://doi.org/10.1080/09500830902720891).

[35] M. Salah, M. Gad, M. Elkattan, and Y. M. Sabry, “Effect of gamma-irradiation and doping on the absorption edge and the optical bandgap of silver-doped PVA films,” *Opt. Commun.*, vol. 473, p. 125933, 2020, doi: <https://doi.org/10.1016/j.optcom.2020.125933>.