

# Chalcogenide Glasses: A Review

**Rishabh Gupta**  
U.G Student

Department of Mechanical Engineering  
JSS Academy of Technical Education Noida, 201301

**Rohit Raj**  
U.G Student

Department of Mechanical Engineering  
JSS Academy of Technical Education Noida, 201301

**Deepak Kumar**  
Assistant Professor  
Department of Physics

JSS Academy of Technical Education Noida, 201301

## Abstract

This review paper describes optical and electrical properties of Chalcogenide glasses. By the virtue of these properties, these glasses have been incorporated in various semi-conducting electronic devices like optical memory, thin-film transistors and the scope of research and development is still extant. The electrical properties discussion includes trends and theories associated with AC/DC conductivities, defect states, dielectric losses and thermally stimulated currents (TSC). In addition, various theories explaining localized states and band gap like Poole Frenkel, Space Charge Limited Current (SCLC), hopping conduction etc. have been introduced. The optical properties summarize methods of measurement of optical band gaps, optical constants and photoconductivity variations in different glasses.

**Keywords: Chalcogenide glasses, optical properties, dielectric losses, conductivity, band gaps**

## I. INTRODUCTION

The exponential growth of semi-conductor based electronic devices has resulted in marked demand of research for new materials which could overcome present limitations like response time, storage capacity, reliability etc. Of the various amorphous semiconducting materials, chalcogenide glasses have held the interest of scientists and engineers for long due to unusual trends in their electric and optical properties. Over the years, various applications have been developed including infrared optical elements [1], optical fibres [2], switching and memory devices [3], fabrication of solar cells [4,5], xerography [6], photolithography[7], phase change memory devices [8]. Ion selective membranes for chemical sensors [9] etc. While the viability of materials in use for solid state technology have been limited by certain properties, but chalcogenide glasses due to their IR properties and photo-induced effects show promising future in the field of optics [10].

Being amorphous in nature, the material lacks long range order. This together with various inherent defects is cited as reasons for the presence of localized states [11]. These characteristics have been interpreted using various models and theories like SCLC (Space Charge limited Current), Poole-Frenkel Effect, Small Polaron Conduction, Hopping Conduction and Tunnelling Conduction [12].

At various instances, several additive elements have also been experimented with binary chalcogenide glasses as they not only influence properties but also increase stability in many cases [13].

## II. ELECTRICAL PROPERTIES

Chalcogenide glasses are amorphous semi-conductors. Consequently relevant information about their structure and in turn, defects can be inferred by several methods, one of which is studying dielectric losses. The dielectric relaxation is a measure of dielectric loss. Unlike other covalent bonded materials, these glasses exhibit dielectric dispersion even at low frequencies.

The glasses have been studied with various additives which are being discussed here. The glassy nature of the material was verified using X-ray Diffraction [14-15]. In all these studies, the glasses prepared after quenching technique are ground and then compressed to form pellets. This was done to avoid gas bubbles inside which could have hampered the dielectric measurements. An appropriate coating was done on the pellets to ensure good electrical contact. A thermocouple was used very close to the pellet to measure temperature [16].

Arora et al. studied the variation of dielectric constant and dielectric loss of  $\text{Se}_{80}\text{Te}_{20}$  and  $\text{Se}_{80}\text{Te}_{10}\text{M}_{10}$  (M= Cd, In, Sb) at several frequencies (0.12-10 kHz) and temperatures below glass transition ( $T_g$ ). At low temperatures (<200K), the dielectric loss and dielectric constant didn't vary significantly with temperature or frequency. While at higher temperatures, a substantial amount of dispersion was monitored which increased with decrease in frequency [17]? Goel et al. [18] did a similar study over  $\text{Se}_{80-x}\text{Te}_{20}\text{Ge}_x$  and found similar trends of variation in the dielectric parameters. However the increase of Ge in this system decreases the dielectric loss. This was attributed to filling up of defect states of the system by Ge[18].

Unlike Se-Te systems,  $\text{Ge}_x\text{Se}_{100-x}$  systems are known to have witnessed absence of dielectric losses within the operating range of temperature and frequency. In the case of additive alloys  $\text{Ge}_{22}\text{Se}_{68}\text{M}_{10}$  ( $\text{M} = \text{Ag, In, Pb}$ ), the DC conduction loss measured was nearly the order of total dielectric loss. On the contrary,  $\text{Ge}_{22}\text{Se}_{68}\text{Cd}_{10}$  exhibited major AC conduction loss as compared to its DC counterpart. This unusual behaviour is accredited to the maximum electronegativity difference between Se and Cd [14]. Unlike similar classes of chalcogenide glasses, Ag doped chalcogenide glasses are known to have ionic conduction. Choudhary et al. [16] experimented by adding Ag to the Se-Te system and concluded that the dielectric loss and dielectric constant, at a certain frequency, is commensurate to the percentage of Ag. However at average coordination number of 2.4 or in other terms a 4% Ag concentration shows a discontinuity in the regular trend. This is accounted using the Phillips and Thorpe model which demonstrates a mechanically stabilised structure at a specific composition [19].

All the above studies were carried out using the hypothesis given by Guintini et al. [20] which stated that each pair of charged defect sites forms a dipole and the charge carriers keep hopping alternatively between defect states. The relaxation time of hoppings are influenced by their activation energies. The theory of the hopping of the carriers over a potential barrier (CBH Model) was originally proposed by Elliott [21] to account for ac conductivity. According to these theories, the dielectric loss ( $\epsilon''$ ) at a particular temperature follows a power law with frequency :

$$\epsilon''(\omega) = (\epsilon_0 - \epsilon_\infty) 2 \pi^2 N (ne^2 / \epsilon_0)^3 * kT \tau_0^m W_M^{-4} \omega^m$$

where  $m = -4kT/W_M$

n is number of electrons that hop

M concentration of localised sites

$\epsilon_0$  and  $\epsilon_\infty$  are static and optical dielectric constants respectively

$W_M$  is the energy required to move electron from one site to infinite

To evaluate the contribution of dc conductivity the following equation was used.

$$\epsilon''_{dc} = \sigma_{dc} / \omega \epsilon_0$$

### A. Conductivity

DC conductivity ( $\sigma$ ) of semiconducting materials usually varies exponentially with temperature indicating its requirement of thermal activation. Mathematically it is expressed by Arrhenius equation

$$\sigma = \sigma_0 \exp(-\Delta E / kT)$$

Where  $\sigma_0$  is pre-exponential factor,  $\Delta E$  is activation energy, k is boltzmann constant and T is temperature.

In most of the semi-conducting materials, pre-exponential factor ( $\sigma_0$ ) is independent of  $\Delta E$  [22]. In contrast, in most of the amorphous materials  $\sigma_0$  increases exponentially with  $\Delta E$ . Meyer-Neldel were the first to formulate an empirical relation

$$\sigma_0 = \sigma_{00} \exp(\Delta E / kT_0)$$

Where  $\sigma_{00}$  and  $kT_0$  are positive constants for a class of similar materials. The parameters affecting activation energy ( $\Delta E$ ) include light soaking, doping, surface absorption and preparation of film under varying conditions. [23-25]

Sharma et al. [26] studied thin films of  $\text{Ge}_{20}\text{Se}_{80-x}\text{Bi}_x$  and bombarded it with Ni ions at room temperature. This leads to the formation of several localized states near fermi level which take part in hopping. Consequently an increase in conductivity of the sample is observed while the  $\Delta E$  decreases [26].

Kushwaha et al. [27] varied activation energy by varying electric field across a sample of  $\text{Se}_{70}\text{Te}_{30-x}\text{Cd}_x$  to observe the influence of temperature on dc conductivity. The measurements were in agreement with Meyer-Neldel rule.

Ge-Se-Ag systems belong to family of superionic conducting glasses where Ag is the mobile cation, Ge is network forming cation and Se is anion. According to measurements done by Mirandou et al. [28] on  $(\text{GeSe}_3)_{100-x}\text{Ag}_x$ , a continuous decrease in conductivity with decrease in Ag concentration was noted. A model named 'Site Memory Effect' accounted for this trend for  $x > 10$ .

Another usual feature of chalcogenide glasses is their thermally stimulated currents (TSC). To study the slightest change in conductivity, these currents are measured at extremely low temperatures. Firstly the temperature of the sample is reduced to the lowest temperature and is then exposed to light briefly. Now when the sample is brought back to normal temperatures, sudden increments in conductivity at several temperatures is observed. This was justified stating the filling up of traps at low temperature on account of illumination and these traps couldn't be crossed without sufficient thermal energy. When the temperature is raised, these electrons are commensurately released resulting in excess current. Agarwal et al. [29] made efforts to measure Thermally Stimulated currents (TSC) in chalcogenide glasses and noted following two unexpected features : (i) heating rate has no influence over TSC (ii) even at high temperatures the decay period of TSC is very large. Attempts were made to justify this using three models namely; a) Rigid Bond Model b) Potential Fluctuations and c) Bond changes produced by light.

Chalcogenide glasses have several defects states which play a pivotal role in deciding their physical properties. These defects either trap the charge carriers or simply eliminate them by recombining them at recombination centres, thereby decreasing the conductivity. Hence the study of phenomena associated with these defects is very important. The I-V characteristics have been explained using many theories [30] like Space Charged Limited current (SCLC), Poole-Frenkel conduction, Tunneling conduction, Hopping conduction etc.

SCLC assumes uniform distribution of localized states near fermi level and is not affected by surface states [31]. Following is the relationship between current (I) at a particular voltage [32]:

$$I = (eA\mu n_0 V/d) \exp(SV)$$

where  $d$  is electrode spacing,  $n_0$  is density of thermally generated charge carriers,  $e$  is electronic charge,  $A$  is area of cross section of thin film,  $\mu$  is mobility,  $S$  is given by-

$$S = 2 \epsilon_r \epsilon_0 / e g_0 k T d^2$$

A-  $\text{Se}_{90}\text{Ge}_{10-x}\text{In}_x$  system was experimented for SCLC by Singh et al. [20] and they concluded that the density of localised states increased on addition of In till 4% approx. Beyond this, Joule heating overshadows the presence of SCLC.[33]

Kushwaha et al. [34] studied about  $\text{Se}_{80-x}\text{Te}_{20}\text{Sb}_x$  and found that at high field ( $\sim 10^4$  V/cm), the sample's  $\ln(I/V)$  vs  $V$  is not a linear plot though it shows superohmic behaviour. This proves the absence of SCLC in the glass.

Kushwaha et al.[31] experimented on  $\text{Se}_{100-x}\text{Sb}_x$  and concluded that on addition of Sb, the density of localised states near Fermi level rises.

Poole-Frenkel and Schottky effect are other theories explaining the observations of high field conduction and state that in the presence of high field, an electron might jump into conduction band without sufficient thermal energy[35]. Although the relation between the conductivity and field for both of them is linear (almost same), the difference lies in the rate of change[36].

$$\ln I = \text{const} + (e \beta V^{0.5} / k T d^{0.5})$$

$\beta$  is given by –

$$\beta = (e / \lambda \pi \epsilon_r \epsilon_0)^{1/2}$$

where  $\lambda = 1$  for Poole Frenkel effect  
and  $\lambda = 4$  for Schottky effect

Dwivedi et al. [37] analysed I-V characteristics of two systems of chalcogenide glasses namely  $\text{Ge}_{22}\text{Se}_{78-x}\text{Bi}_x$  and  $\text{Ge}_x\text{Se}_{80-x}\text{Te}_{20}$ . A linear relation between  $\ln(I/V)$  vs  $V$  was observed in the former sample, leading to inference of presence of SCLC while the latter exhibited a linear relation only in  $\ln(I)$  vs  $V^{1/2}$  suggesting the Poole Frenkel conduction as opposed to SCLC.

Another variation of Poole Frenkel model was given by Jonscher in which he stated that all emissions occurred over a 3-dimensional well. Samanoudy [38] investigated  $\text{Ge}_{25}\text{Bi}_x\text{Sb}_{15-x}\text{S}_{60}$  and concluded that modified Poole Frenkel was operating in high field as data fitted well with Jonscher's model of field independent retrapping.

### III. OPTICAL PROPERTIES

These glasses exhibit amusing optical properties mainly transmittance in IR region, special second/third order optical non-linearity and some light induced effects (like change in volume, elastic and chemical properties)[39-42]. The applications of chalcogenide glasses based on their optical properties include optical imaging, infrared optics, optical data storage and integrated optics.

In general the photo-induced changes can be classified into reversible and irreversible changes. The former class doesn't affect XRD output and the original state can be achieved on annealing. While the latter affects XRD output which can be attributed to photo-structural changes. Shifting of absorption edges to lower energy states has been observed in many binary systems like  $\text{As}_2\text{S}_3$  and  $\text{As}_2\text{Se}_3$  as well as ternary systems like As-S-Ge and As-S-Te systems[43]. The chalcogenide glasses are famous for having optical edges that can not only be reproduced easily but aren't affected by preparation conditions[44]. The absorption edges can be attributed to either of three processes: 1) residual below-gap absorption 2) Urbach tail 3) interband absorption.[45]

The optical constants of interest in amorphous chalcogenide thin films have been refractive index, optical band gap and extinction coefficient. The precise measurements of these parameters help in development of several optical devices like optical modulators and filters.

There are three methods of measuring optical band gaps namely, (a) Swanepoel method, (b) measurement of transmission coefficient only and (c) measurement of transmission and reflection coefficients.

Swanepoel method [46] involves analysis of interference patterns of transmittance spectrum in the region where maxima and minima are obtained. The refractive index  $n$  is given by following relations:

1) For absorption coefficient,  $\alpha=0$

$$n = [N + (N^2 - s^2)^{1/2}]^{1/2}$$

where  $N = 2s/T_m - (s^2 + 1)/2$ ,  $T_m$  is envelope function of transmittance minima and  $s$  is refractive index of substrate.

2) For  $\alpha \neq 0$ ,

$$n = [N + (N^2 - s^2)^{1/2}]^{1/2}$$

where  $N = \{2s(T_M - T_m)/T_M T_m\} + (s^2 + 1)/2$ ,  $T_M$  is envelope function of transmittance maxima.

Calculation of extinction coefficient is done using:

$$k = \alpha \lambda / 4\pi$$

The second method for determining band gap involves measurement of transmission ( $\tau$ ) and reflection ( $\rho$ ) coefficient and the absorption coefficient ( $\alpha$ ) is finally calculated using

$$\alpha = 1 - \rho - \tau$$

The third method is applied when  $\rho$  is negligible and hence involves only the measurement of transmission coefficient. This method is usually not preferred.

Khan et al. [45] investigated  $\text{Se}_{80}\text{Te}_{20-x}\text{Pb}_x$  thin films in wavelength range 500-1000nm and varied the intensity of incident radiation as well as the value of  $x$  in composition. They concluded that  $\alpha$  and  $k$  increases while  $n$  decreases with increase in incident photon energy. Moreover the optical band gap increases and  $n$  and  $k$  decreases with increase in Pb concentration in the

given system. Reduction in the level of disorder is considered to be the explanation of the observed trend. A similar system  $\text{Se}_{85}\text{Te}_{15-x}\text{Pb}_x$  was studied by Pandey et al. [47] in the range 400-2000 nm using Swanepoel method. They observed that optical energy gap reduced with increase in Pb concentration. Also  $n$  increases and  $k$  decreases with increment in wavelength.

El-Den et al. [48] prepared thin films (100-300 nm) of  $\text{AsSe}_{1.5-x}\text{Te}_x$  and illuminated it with light of wavelength 400-2500 nm. However they calculated the values of  $n$  and  $k$  from the experimental values of transmittance and reflectivity using a computer software [49]. Results of the study of El Mously et al. [50] on the bulk form of  $\text{AsSe}_{1.5-x}\text{Te}_x$  also agree with the measurements on thin films. El-Den et al. observed that transmittance increased with wavelength. Also addition of Te content leads to increase in  $n$  and  $k$  and decrease in energy gaps.

Alexander Graham Bell [51] is considered to be the father of photoacoustical techniques which involves generation of sound with the help of light. Pattanaik et al. [52] studied the system of Ge-Se-Te glasses modified by addition of Pb and calculated optical band gap using photo-acoustic technique. They used Xe arc lamp to illuminate the sample in the range of 400-1200 nm. The trends observed on varying composition were accounted using average bond energy.

#### A. Photoconductivity:

Many times the changes in the electrical properties of chalcogenide obtained by varying composition are studied using the measurements of photoconductivity ( $\sigma_{ph}$ ). It becomes necessary to measure dark conductivity ( $\sigma_d$ ) in these experiments to record the exclusive effect of light and its associated parameters. The parameter of our interest is the ratio of  $\sigma_{ph}$  and  $\sigma_d$  which is a measure of photosensitivity.

Various workers have experimented on Se-Te systems and measured transient and steady state photocurrent. It is a very well established fact that photo-crystallization can be achieved by long exposure of light on this system even at normal temperatures. At such temperatures the possibility of thermal crystallization is also very less. Moreover the photoconductivity varies with the extent of crystallization [53]. Dwivedi et al. [54] worked on binary  $\text{Se}_{80}\text{Te}_{20}$  thin films and made measurements of three states a) amorphous b) partially crystalline c) crystalline state. The last two states were achieved by exposing the samples to white light for 8 and 18 hours respectively and their structural nature was verified using XRD. The decay time constant is a function of intensity, temperature and illumination time. Fuhs and Meyer [55] concept can explain the non-exponential decay observed in these glasses.

$$\tau_d = [(1/I_{ph})(dI_{ph}/dt)]$$

Dixit et al. [56] added Sb to the Se-Te system and repeated the experimental procedure of Dwivedi et al. [54] The trends observed by both were similar. While photosensitivity ( $\sigma_{ph}/\sigma_d$ ) reduces with the extent of crystallization, photoconductivity as well as dark conductivity increase. Moreover the decay of photo-current reduces, suggesting the presence of more localised states as compared to its counterpart. During crystallization, not only the carrier mobility increases but the absorption coefficient and the band gap may also change. The unpredictable changes in the latter two results in ambiguity of explanation of the variation in ( $\sigma_{ph}$ ). [56]

Apart from extent of crystallization, the compositional dependence of photoconductivity of this class of systems have also been investigated by several workers. Misra et al. [57] studied  $\text{Se}_{100-x}\text{Te}_x$  and observed that a power law governs the relation between photoconductivity ( $\sigma_{ph}$ ) and intensity.

$$\sigma_{ph} \propto I^\gamma \quad \text{where } \gamma = 0.5 \text{ for } T = 300\text{K}$$

Increase of Te concentration in pure Se increases photoconductivity but this trend is observed only till 15% Te after which it becomes constant. This phenomenon is attributed to some structural changes [58] which also leads to a point of discontinuity in photosensitivity ( $\sigma_{ph}/\sigma_d$ ) and pre-exponential factor ( $\sigma_0$ ). [57]

Hagen and Derks [59] findings support the above observations citing an increment in thermalization distance as a possible cause. Another possible explanation was professed by Abkowitz and Markovics [60], according to which, Te is responsible for increasing deep defect states.

Substantial work has been done on ternary glasses also. Kushwaha et al. [61] investigated amorphous thin films of  $\text{Se}_{85}\text{Te}_{15-x}\text{Pb}_x$  and varied  $x$  and intensity. They observed the trends of steady state photoconductivity. While the undoped sample of Se-Te exhibits a spike in photocurrent plot, the same disappears on addition of Pb. This shows that in intensive bimolecular recombination is taking place in undoped sample but Pb addition generates very deep defect states. The beginning of rise and decay of the photocurrent is affected by the delay in the recombination due to trapping of electrons and holes in deep defect states. Iovu et al. [62] put forward a model which explains photo-kinetics behind this. These observations are in complete agreement with those of Kamboj et al [63] who studied a very similar system namely  $\text{Se}_{80-x}\text{Te}_{20}\text{Pb}_x$ . Same trends were observed including Square root dependence of illumination intensity with photocurrent.

As mentioned previously, Ag addition leads to some unusual characteristics like ionic conduction in chalcogenides. When Sharma et al. [64] doped Se-Te system with Ag, they found that at higher intensities (780-1450 lux) the photocurrent initially increased with time of illumination, reached a maxima and subsequently decreased. Negative values photo-conductivity were also observed at very high temperatures during both stages : rise and decay. This anomalous behaviour was explained by Dember voltage concept [65] which involved diffusion of holes towards back electrode.

On the other hand, when In was added to Se-Te system, an increment in localized states or decrement in mobility gap was observed by Misra et al. [66]. Consequently decay time constant ( $\tau_d$ ) and photoconductivity ( $\sigma_{ph}$ ) increases while photosensitivity ( $\sigma_{ph}/\sigma_d$ ) decreases with increase in concentration of Indium.

Jain et al. [67] studied the dependence of photoconductivity of amorphous  $Se_{25}Ge_{20}Te_{55}$  on temperature. Initially the decay time constant ( $\tau_d$ ) increases with rise in temperature (upto 500 seconds) but later on decreases. This anomalous behaviour was accredited to rise in trap centres generated due to high temperatures. Similar trends were also observed by Moustakas and Weiser [68] in  $As_2Te_3$  and Main and Owen [69] in  $As_2Se_3$ .

Sharma et al. [70] experimented on Ag added Ge-Se glassy system and concluded that increase of Ag concentration increased defect states. This resulted in the increment of dark conductivity ( $\sigma_d$ ) and photoconductivity ( $\sigma_{ph}$ ) and decrement in activation energy ( $\Delta E$ ) and photosensitivity ( $\sigma_{ph}/\sigma_d$ ). A  $Se_{90}Ge_{10-x}In_x$  system was investigated by Singh et al. and a similar progression in activation energy on increasing intensity was observed.

It is noteworthy that all the above samples follow the power law for photocurrent and intensity of illumination. The most common value of  $\gamma$  that has been proposed is 0.5.

#### IV. CONCLUSION

The prospect of development of more applications of chalcogenide glasses is apparent from results of the studies cited above. Recently few methods of ultra-purified synthesis of these glasses were developed overcoming the previous performance limitations. This effort summarizes the base for development of potential application and devices. Further work by varying the stoichiometric combinations and methods of preparation leading to fine tune of properties for specific application would be useful.

#### REFERENCES

- [1] Ilibton AR, Hayes D, Rechten M. J Non-Cryst Solids 1965; 17:319
- [2] Ganon JR. Proc SPIE 1981; 266:62.
- [3] K. Homma, H.K. Henish, S.R. Ovshinsky, J. Non-Cryst. Solids 35/36 (1980) 1105.
- [4] Carlson DE, Wronski CR, Applied Phys Lett 1976;28:671
- [5] N Kushwaha, V S Kushwaha, R K Shukla, A Kumar, J Non-Cryst Sol. 351 (2005) 3414-3420
- [6] Dessaur JH, Clarke HE. Xerography and Related Procedures. Local, London, 1965.
- [7] Ovshinsky R. Phys Rev Lett 1986; 21:1450.
- [8] Fushong J, Okuda M. Jpn Appl Phy 1991;30:97.
- [9] E. Sagbo, D.Houphouet-Boigny, R. Eholic, J.C. Jumas, J. Olivier-Fourcad, M. Maurin, J. Rivet, J. Sol. St. Chem. 113 (1994) 145.
- [10] S.A. Khan, M. Zulfeqar, M. Husain, Curr Appl Phys 2004 ; 1567-1739
- [11] S. Kumar, R. Kumar, A. Kumar, Solid State Communications 1992; 82:9 pg 725-728
- [12] S. Abou El-Hassan, Physica B, 307 (2001) 86-94
- [13] A. Singh, A.K Nagpal, A. Kumar, Eur. Phys. J. AP, 323-328 (1998)
- [14] R. Arora, A. Kumar, Physica B 175 (1991) 381-388
- [15] E. Mariani, V. Tronovcova, D. Lezal, Phys. Stat. Sol. (a) 16 (1973) K51
- [16] A. Kumar, N. Choudhary, IJPAP 44 (2006) pp.62-65
- [17] R. Arora, A. Kumar, Revue Phys. Appl. 25 (1990) 169-176
- [18] D.K. Goel, C.P. Singh, R.K. Shukla, A. Kumar, Journ. Material Sci. 35 (2000) 1017-1021
- [19] J C Phillips, M F Thorpe, Sol Stat Commun, 699 (1985) 53
- [20] J C Guintini, J V Zanchetta, D Jullien, R Enolie, P Houenou, J. Non-Cryst Solids, 45 (1981) 57
- [21] S R Elliott, Phil. Mag. 36 (1977) 1291
- [22] Sangeeta Singh, R K Shukla, A Kumar, J. Non-Cryst Solids, 351 (2005) 1577-1581
- [23] W E Spear, D Allan, P Lecomber, A Gaith, Philos. Mag. B 41 (1980) 419
- [24] R S Crandall, Phys. Rev. B 43 (1991) 4057
- [25] M Tanielian, Philos. Mag. B 45 (1982) 435
- [26] Pratibha Sharma, M Vashistha, I P Jain, Radiation Measurements 36 (2003) 663-666
- [27] V S Kushwaha, N Mehta, N Kushwaha, A Kumar, J. Optoelectro. Adv. Mat. , 7 (2005) 2035-2040
- [28] M Mirandou, M Fontana, B Arcondo, J. Mat. Process. Tech. 143-144 (2003) 420-424
- [29] S C Agarwal, H Fritzsche, Physical Review B 10 (1974) 10
- [30] S. Abou El-Hasan, Physica B 307 (2001) 86-94
- [31] V S Kushwaha, S Kumar, A Kumar, Turk. J. Phys. 29 (2005) 349-354
- [32] M A Lampert, P Mark, Current Injection in solids (Academic Press, New York 1970)
- [33] S. P. Singh, S Kumar, A Kumar, J. Optoelectro. Adv. Mat. 6 (2004) 1153-1157
- [34] V S Kushwaha, A Kumar, J. Optoelectro. Adv. Mat. 6 (2004) 1159-1165
- [35] J. Frenkel, Phys. Rev., 54 (1938) 647-648
- [36] J G Simmons, Phys. Rev., 155 (1967) 3
- [37] S K Dwivedi, A Kumar, S Kumar, Adv. Mat. Opt. electron. 9 (1999) 235-244
- [38] M M El-Samanoudy, App. Sur. Sci., 207 (2003) 219-226
- [39] Q M Liu, X J Zhao, F X Gan, Acta. Phys. Sin. 49 (2000) 1726
- [40] M Asobe, Opt. Fibre Tech. 3 (1997) 142
- [41] A Zakery, S R Elliott, J. No-Cryst. Sol. 330 (2003) 1
- [42] E M Vogel, M J Waber, D M Krol, Phys. Chem. Glasses 32 (1991) 231
- [43] S C Agarwal, H Fritzsche, Phys. Rev. B 10 (1974) 4351-4357
- [44] J Tauc, Amorph. Liq. Semi-con., Plenum Press (1979) 159

- [45] S A Khan, M Zulfequar, M Husain, Curr. App. Phys., (2004)
- [46] R Swanepoel, J. Phys. E. 16 (1983) 1214
- [47] V Pandey, N Mehta, S K Tripathi, A Kumar, J. Opto-electro. Adv. Mat. 7 (2005) 2641-2646
- [48] M B El-Den, M M El-Nahass, Opt. Las. Tech. 35 (2003) 335-340
- [49] H Soliman, N El Kady, O Gamjoum, M M El-Nahaa, H B Darwis Indian j. Optics 17 (1988) 64
- [50] El Mously MK, Kotkata MF, El Den MB., Egypt, J, Solids 1 (1980) 166
- [51] A G Bell, Phil. Mag. 11 (1881) 510
- [52] A K Pattnaik, C Borgohain, R Bhattacharjee, A Srinivasan, Cer. Int. 30 (2004) 1711-1714
- [53] S. K. Srivastav, R Misra, S Goel, A K Agnihotri, A Kumar, J. Mat Sci Let 11 (1992) 1463-1465
- [54] S. K. Dwivedi, M Dixit, A Kumar, Thin Sol. Films 333 (1998) 165-169
- [55] W Fuhs, D Meyer, Phys. Status. Rev. B 15 (1977) 989
- [56] M. Dixit, A Kumar, Physica B 252 (1998) 286-294
- [57] R Misra, S Goel, S K Tripathi, A K Agnihotri, A Kumar, Physica B 167 (1990) 195-199
- [58] T I Ichikawa, J. Phys. Soc. Jpn. 33 (1972) 1729
- [59] S H Hagen, P J A Derks, J. Non-Cryst. Sol. 65 (1984) 241
- [60] M Abkowitz, J M Markovics, Sol. State Comm. 44 (1982) 1431
- [61] N Kushwaha, V S Kushwaha, R K Shukla, A Kumar, J. Non-Cryst. Sol. 351 (2005) 3414-3420
- [62] M S Ivou, S D Shutov, J. Opto electro. Adv. Mat. 2 (2000) 53
- [63] M S Kamboj, G Kaur, R Thangaraj, Thin Sol. Films 420-421 (2002) 350-353
- [64] D Sharma, R. K. Shukla, A Kumar, Thin Film Sol. 357 (1999) 214-217
- [65] K Tanaka, M Itoh, M Yoshida, M. Ohto, Jpn. J. Appl. Phys. 78 (1995) 3895
- [66] R. Misra, S. Goel, A K Agnihotri, A Kumar, J. Mat. Sci. Lett. 11 (1992) 212-215
- [67] S Jain, S Gautam, D. K Shukla, N Goyal App. Sur. Sci. 147 (1999) 19-26
- [68] T D Moustakas, K Weiser, Phys. Rev. 12 (1975) 2448
- [69] C Main, A E Owen, in: Stuke, W. Brenig (Eds.), Amorphous and Liquid semiconductors, Taylor and Francis, London 1974
- [70] R S Sharma, S Singh, D Kumar, A Kumar Physica B 369 (2005) 227-233