Electrical properties of amorphous Ge$_{26}$In$_x$Se$_{74-x}$ chalcogenide thin films

W. A. Abd El-Ghany · A. M. Salem · Nahed H. Teleb

Received: 24 February 2022 / Accepted: 13 April 2022 / Published online: 18 May 2022
© The Author(s) 2022

Abstract
Amorphous Ge$_{26}$In$_x$Se$_{74-x}$ (1 ≤ x ≤ 5) chalcogenide thin films have been deposited by thermal evaporation technique. The temperature-dependence of DC conductivity and the temperature and frequency dependence of AC conductivity have been studied in the temperature range 295–523 K and in the frequency range 4–8 MHz. The study of the temperature-dependent of DC conductivity refers to the presence of two distinct conduction mechanisms; the activation energies for each were calculated and it was observed that their values decrease by increasing In content. Besides, in the low-temperature region, the variation of the conductivity against temperature was further analyzed according to the variable-range hopping model based on Mott’s relation, whereby the hopping parameters were evaluated. For all investigated compositions, the variation of the AC conductivity against frequency at the studied temperatures was interpreted according to the correlated barrier hopping (CBH) model which based on Jonscher’s power law, whereby the potential barrier height, $W_M$, and the theoretical optical bandgap, $E_g$, were calculated.

Keywords Ge$_{26}$In$_x$Se$_{74-x}$ thin film · Chalcogenide glasses · DC and AC conductivity · Activation energy · Correlated barrier hopping (CBH) model

1 Introduction
Thin films of chalcogenide glassy materials gained great interest over the past several decades due to their applications in potential in several technological devices. The common feature of this class of glassy materials is the presence of the localized states in the mobility edge as a result of the presence of the short-range order as well as the various inherent defects [1–3]. Previous works have been established that the physical properties of the chalcogenide glassy materials are highly dependent on the atomic ratios of the elements present in the chemical formula [4, 5].

The Ge–In–Se ternary system belongs to the chalcogenide glassy materials. Where it forms glasses through average compositions of a range extending from a coordination number $Z = 2.4$ to $Z = 2.67$ which are considered critical values according to Philips [6]. The system possesses interesting physical properties, such as high infrared transmission spectra, high refractive index, and fast characterization, which make the system attractive for many technological applications, such as IR detector [7], telecommunications [8], acousto-optic devices [9], switching and memory devices [10]. The thermal stability of the thermally evaporated Ge$_{15}$Se$_{85-x}$In$_x$ deposited films increases with increasing the In content [11], while the amorphous to the crystalline state of Se$_{70}$In$_{15}$Ge$_{15}$ has occurred at 413 K [12]. The optical properties of the ternary system Ge$_{30}$Se$_{70-x}$In$_x$ [13], Ge$_x$Se$_{92-x}$In$_8$ [14], Ge$_{20}$Se$_{80-x}$In$_x$ [15], Ge$_{10}$Se$_{90-x}$In$_x$ [16], and Ge$_{26}$In$_x$Se$_{74-x}$ [17] have been reported. In addition, the DC electrical conductivity of Ge$_{20}$In$_x$Se$_{74}$ [18], Ge$_{20}$Se$_{80-x}$In$_x$ [19–21], Ge$_{40}$In$_x$Se$_{60}$ [22], and Se$_{70}$In$_{15}$Ge$_{15}$ [12] has been reported, while there are only two reports concerning the AC conductivity and dielectric properties of the ternary Ge–In–Se system. The first reports the frequency and temperature dependence of the dielectric properties of Se$_{90}$Ge$_{10-x}$In$_x$ thin films at Low Temperature (78–260 K) [23], while the other reports the AC conductivity and dielectric properties of Ge$_{26}$Se$_{75}$In$_5$ films (300–423 K) [24].

In the previous work, the authors have studied the linear and non-linear optical properties of the amorphous...
Ge_{26}In_{x}Se_{74-x} (1 \leq x \leq 5) thin films [17], whereas in the present work they decided to keep the chemical formula of the studied ternary system and study the effect of the In addition on the DC and AC conductivity for the Ge_{26}In_{x}Se_{74-x} system.

2 Experimental method

Bulk ingot materials with a chemical composition Ge_{26}In_{x}Se_{74-x} (x = 1, 2, 3 and 5) have been synthesized from the pure constituent elements (5N, Sigma-Aldrich) in sealed evacuated quartz tubes by the conventional melt quenching technique [17].

Amorphous thin films with exact chemical compositions (a) Ge_{26.4}In_{0.7}Se_{72.7} (b) Ge_{25.4}In_{2.4}Se_{72.2} (c) Ge_{27.4}In_{2.9}Se_{69.3} (d) Ge_{25.8}In_{4.8}Se_{69.4}, respectively, as previously detected from the EDX analysis were deposited at room temperature onto clean glass substrates using a high vacuum coating unit (Type Edwards, E306A) in a vacuum pressure of –2 × 10^{-4} Pa [17]. The amorphous structure of the prepared films is confirmed by X-ray diffractometer (XRD) Type Philips X’Pert as reported in previous work [17].

Silver paste coplanar electrodes of a width of 0.5 cm were thermally evaporated onto terminals of the investigated films to serve Ohmic electrodes for electrical measurements. The DC electrical resistance, R, was measured as a function of temperature, T, in the temperature range 295–523 K by means of a high impedance electrometer (Type Keithley 6517 A). The DC electrical conductivity \( \sigma_{DC} \) was calculated using the relation, \( \sigma_{DC} = d/RA \) (where \( d \) is the sample thickness, \( A \) is the cross-sectional, and \( R \) is the measured sample resistance). Whereas, a programmable RLC bridge (Type Hioki IM 3536) was used to measure the impedance, Z, the resistance, R, and the capacitance, C, in the temperature range 4 Hz–8 MHz and in the temperature range 303–523 K. The dielectric constant, \( \varepsilon_{1} \), has been calculated from the relation \( \varepsilon_{1} = Cd/\varepsilon_{0}A \), where \( \varepsilon_{0} \) is the electrical permittivity of vacuum (\( \varepsilon_{0} = 8.854 \times 10^{-12} \) F.m^{-1}). The dielectric loss \( \varepsilon_{2} \) was calculated from the relation \( \varepsilon_{2} = \varepsilon_{1} \tan \delta \), where \( \delta = 90 - \varphi \), where \( \varphi \) is the phase angle. The AC conductivity \( \sigma_{AC} \) was calculated according to the relation \( \sigma_{AC} = \omega\varepsilon_{0}\varepsilon_{2} \) [24].

3 Results and discussion

3.1 DC conductivity

The temperature-dependence of DC conductivity of the investigated samples with exact chemical compositions (a) Ge_{26.4}In_{0.7}Se_{72.7} (b) Ge_{25.4}In_{2.4}Se_{72.2} (c) Ge_{27.4}In_{2.9}Se_{69.3} (d) Ge_{25.8}In_{4.8}Se_{69.4} films in the temperature range 295–523 K are shown in Fig. 1. The figure depicts that the conductivity increases with increasing temperature through the entire temperature range indicating a semiconductor behavior, with two different conduction mechanisms. The first is in the high-temperature range (\( T > 380 \) K) that can be represented through the thermally activated process across the extended states. While the other is in the low-temperature range (at \( T < 380 \) K) that can be represented through a less thermally activated process and represented by Mott’s formula for the hopping conduction through the localized states. The variation of the conductivity through the extended states follow the Arrhenius relation [20, 25]:

\[
\sigma_{DC} = \sigma_{0} \exp \left( -\Delta E_{DC} / KT \right)
\]

where \( \sigma_{0} \) is the pre-exponential factor, \( \Delta E_{DC} \) is the activation energy and \( K \) is the Boltzmann’s constant. The values of the pre-exponential factor, \( \sigma_{0} \), the activation energy, \( \Delta E_{DC} \), and the room temperature conductivity, \( \sigma_{RT} \), for such regions as a function of In content which is calculated from Fig. 1 are listed in Table 1. It is noticed that, by increasing the In content, the conductivity increases, while the activation energy decreases. This decrease in \( \Delta E_{DC} \) is due to the reduction of average binding energy and formation of defect centers by adding In [19, 26, 27]. On the other hand, the value of \( \Delta E_{DC} \) was found less than the half value of the optical bandgap calculated in our previous work [17] for the samples of the same composition, which indicates the presence of impurities within the gap. Therefore, the value of \( \Delta E_{DC} \) in the present work indicates that the Fermi level is most probably displaced from the center of the gap towards the valence band [12, 16]. The calculated values of \( \Delta E_{DC} \) of investigated films are in agreement with other works, as shown in Table 1.

![Plot of the DC conductivity vs. reciprocal temperature for Ge_{26.4}In_{0.7}Se_{72.7}, Ge_{25.4}In_{2.4}Se_{72.2}, Ge_{27.4}In_{2.9}Se_{69.3}, and Ge_{25.8}In_{4.8}Se_{69.4}](image-url)
The measured conductivity is the sum of two components:

\[ \sigma_{DC} = \sigma_{hop} + \sigma_{ext} \]  

(2)

where \( \sigma_{hop} \) and \( \sigma_{ext} \) are the conduction contribution due to hopping between the nearest localized states and the conduction contribution between the extended states, respectively.

In the high-temperature region, the linearity denoted that \( \sigma_{DC} \) is a thermally activated process [27] according to Eq. 1. As the temperature decreases, the activated Arrhenius behavior is replaced by a power law relationship between the logarithm of conductivity and temperature. The low-temperature variable range hopping conductivity is characterized by Mott's variable-range hopping relation [14, 25, 28]:

\[ \ln (\sigma_{DC} \sqrt{T}) = \frac{-9}{8\pi a N(E_F)K T} \left( \frac{1}{T} \right)^{1/4} \]  

(5)

\[ \sigma_{hop} = \left( \frac{\sigma_{ho}}{\sqrt{T}} \right) \exp \left[ -\left( \frac{T_0}{T} \right)^{1/4} \right] \]  

(3)

where \( T_0 \) is the hopping parameter that is given as

\[ T_0 = \left( \frac{18a^3}{KN(E_F)} \right) \]  

(4)

where \( \sigma_{ho} \) is the pre-exponential factor of the hopping conduction, \( N(E_F) \) is the density of states at the Fermi level, \( \alpha^{-1} \) is the decay length of a localized wave function at the Fermi level which is taken as \( 10^{-9} \) m for electrons and \( K \) is Boltzman's constant.

The linear variation of \( \sigma_{hop} \sqrt{T} \) vs. \( (1/T)^{1/4} \) as shown in Fig. 2 confirms that in this region the transport is due to variable range hopping of charge carriers in the localized states near the Fermi level and is characterized by relation (3). The values of \( T_0, \sigma_{ho} \) as well as the density of states at the Fermi level \( N(E_F) \) determined from Fig. 2 are listed in Table 2.

Two other hopping parameters can be calculated according to Mott [28, 29], which are the hopping distance \( R \) (cm) and the average hopping energy \( W \) (eV), given by

\[ R = \left( \frac{9}{8\pi a N(E_F)K T} \right)^{1/4} \]  

(5)

and

\[ W = \frac{3}{4\pi R^3 N(E_F)} \]  

(6)

The calculated values of \( R \) and \( W \) for the investigated compositions are also listed in Table 2. It is observed that both values of \( R \) and \( W \) decrease by increasing In content. In addition, \( W \cdot KT \) and \( aR \cdot 1 \) indicate that the variation of conductivity at a low temperature of the investigated samples obey the condition of Mott’s model of variable-range hopping (VRH) process [25, 28, 30]. on the other hand, the value of \( N(E_F) \) increases by adding In and this confirms the increase of conductivity due to the increase of localized states in the gap. The determined values of \( R, W \) and \( N(E_F) \) for Ge26In3Se72 are in agreement with those reported for Ge20In8Se72 [14].

### 3.2 AC conductivity

#### a) Frequency dependence of AC conductivity

The measurements of the AC conductivity provide significant information about the conduction mechanism of glassy systems. The real part of AC conductivity is due to trapped...
charges which are active only at higher frequencies and can be calculated from Jonscher’s universal power law [31–33]:

$$\sigma_{AC}(\omega) = \sigma_{DC} + A\omega^S$$  \quad (7)

where \(\sigma_{DC}\) is the DC conductivity, \(A\) is a temperature-dependent constant that determines the strength of the polarizability and \(S\) is the frequency exponent that \(0 < S < 1\).

Figure 3 shows the frequency dependence of AC conductivity for the investigated Ge\(_{26}In\(_x\)Se\(_{74-x}\) films compositions at room temperature. It is observed that for all compositions, there are two distinct regions; the low-frequency region, where the conductivity is frequency independent and attributed to the DC conductivity resulting from the effect of the electrode polarization, followed by the dispersion region at which the conductivity increases rapidly at high frequencies obeys the power-law relation [33, 34]. This increment of the AC conductivity is attributed to the hopping or tunneling of charge carriers as the applied electric field frequency increases [35]. In addition, the AC conductivity increases by increasing In content. This is due to the formation of localized states in the band tail whose density increases by increasing In content and hence increases conductivity [36].

Figure 4 shows the frequency dependence of AC conductivity for Ge\(_{26}In\(_x\)Se\(_{74-x}\) thin films at different temperatures. It is found that the conductivity increases by increasing temperature for all investigated samples due to thermally activated polaron hopping [37]. The values of the frequency exponent \(S\) for different compositions and temperatures are calculated from the slopes of the linear part in Fig. 4.

Figure 5 represents the temperature dependence of the frequency exponent \(S\) for Ge\(_{26}In\(_x\)Se\(_{74-x}\) thin films. It is clear that the value of \(S\) decreases as the temperature increases for all compositions. It is also clear that \(S\) decreases with the increase of the In content in the investigated compositions. This means that the obtained experimental results can be interpreted according to the correlated barrier hopping CBH model [38, 39].

In the CBH model, it is proposed that electrons transfer over a barrier between two defect sites by thermal activation, where each site has a coulombic potential well associated with it. For two adjacent sites separated by distance \(R\), the coulomb wells overlap and hence the effective barrier \(W_M\) will reduce to \(W\) which is given by [38, 39]

$$W = W_M - \frac{ne^2}{\pi\varepsilon'\varepsilon_0 R}$$  \quad (8)

where \(W_M\) is the maximum potential barrier height, \(e\) is the electronic charge, \(\varepsilon'\) is the real part of dielectric constant, \(\varepsilon_0\) is the permittivity of the free space and \(n\) is the number of electrons that hop science \(n = 1\) or 2 for a single polaron and bipolaron processes, respectively. The frequency exponent \(S\) according to this model obeys the relation [36, 40]:

$$S = 1 - \frac{6K_BT}{W_M + K_BT\ln(1/\omega\tau_0)}$$  \quad (9)

where \(K_B\) is the Boltzman constant, \(T\) is the absolute temperature and \(\tau_0\) is the characteristic relaxation time. At lower temperatures, \(W_M >> K_B T\ln(\omega\tau_0)\) hence the value of \(S\) is approximately given by [36]:

$$S = 1 - \frac{6K_BT}{W_M}$$  \quad (10)

For the case of single polaron hopping, the value of \(W_M\) is typically one-quarter of optical bandgap \(E_g\), while \(W_M\) is equal to \(E_g\) for bipolaron hopping [41]. The values of

| Compositions  | \(\sigma_{DC}\) (Scm\(^{-1}\)) | \(T_0\) (K) | \(N\) (E\(_f\)) (cm\(^{-3}\).eV\(^{-1}\)) | \(R\) (cm) at 295 K | \(W\) (eV) at 295 K |
|--------------|----------------|---------|----------------|-----------------|----------------|
| Ge\(_{26.6}In\(_0.7\)Se\(_{72.7}\) | 7.77 \times 10\(^9\) | 5.73 \times 10\(^8\) | 3.64 \times 10\(^{17}\) | 1.40 \times 10\(^{-6}\) | 0.238 |
| Ge\(_{25.4}In\(_2.4\)Se\(_{72.2}\) | 6.34 \times 10\(^9\) | 4.70 \times 10\(^8\) | 4.45 \times 10\(^{17}\) | 1.33 \times 10\(^{-6}\) | 0.226 |
| Ge\(_{27.8}In\(_2.9\)Se\(_{69.3}\) | 1.16 \times 10\(^8\) | 2.45 \times 10\(^8\) | 8.52 \times 10\(^{17}\) | 1.13 \times 10\(^{-6}\) | 0.192 |
| Ge\(_{25.8}In\(_4.8\)Se\(_69.4\) | 3.66 \times 10\(^7\) | 1.18 \times 10\(^8\) | 1.77 \times 10\(^{18}\) | 9.45 \times 10\(^{-7}\) | 0.160 |
Electrical properties of amorphous Ge\textsubscript{26}In\textsubscript{x}Se\textsubscript{74-x} chalcogenide thin films

It is clear that the values of $W_M$ are approximately a quarter of the optical bandgaps of Ge\textsubscript{26}In\textsubscript{x}Se\textsubscript{74-x} thin films, which indicates that the single polaron hopping is the dominating conduction mechanism in such films [41, 42]. In addition, the values of theoretical bandgaps at room temperature for different compositions are tabulated in Table 3.

| Compositions       | $S$   | $W_M$ (eV) | $E_g$ (eV) |
|-------------------|-------|------------|------------|
| Ge\textsubscript{26}In\textsubscript{0.7}Se\textsubscript{72.7} | 0.682 | 0.49       | 1.97       |
| Ge\textsubscript{25.4}In\textsubscript{2.4}Se\textsubscript{72.2} | 0.656 | 0.46       | 1.82       |
| Ge\textsubscript{27.8}In\textsubscript{2.9}Se\textsubscript{69.3} | 0.636 | 0.43       | 1.72       |
| Ge\textsubscript{25.8}In\textsubscript{4.8}Se\textsubscript{69.4} | 0.616 | 0.41       | 1.63       |

Fig. 4 Frequency dependence of AC conductivity for a Ge\textsubscript{26.6}In\textsubscript{0.7}Se\textsubscript{72.7}, b Ge\textsubscript{25.4}In\textsubscript{2.4}Se\textsubscript{72.2}, c Ge\textsubscript{27.8}In\textsubscript{2.9}Se\textsubscript{69.3}, and d Ge\textsubscript{25.8}In\textsubscript{4.8}Se\textsubscript{69.4} thin films at different temperatures.

Fig. 5 Temperature dependence of the frequency exponent $S$ for a Ge\textsubscript{26.6}In\textsubscript{0.7}Se\textsubscript{72.7}, b Ge\textsubscript{25.4}In\textsubscript{2.4}Se\textsubscript{72.2}, c Ge\textsubscript{27.8}In\textsubscript{2.9}Se\textsubscript{69.3}, and d Ge\textsubscript{25.8}In\textsubscript{4.8}Se\textsubscript{69.4}.
compositions are compatible with those determined experimentally in the earlier work [17].

b) Temperature dependence of AC conductivity

The AC conductivity exhibits temperature-dependence and obeys the relation:

\[ \sigma_{AC} = \sigma_0 \exp \left( -\frac{\Delta E_{AC}}{KT} \right) \]  
(11)

where \( \Delta E_{AC} \) is the activation energy for the AC conductivity. Figure 6 shows the plot between \( \ln \sigma_{AC}(\omega) \) and \( 1000/T \) which shows semiconductor behavior as the AC conductivity increases by increasing temperature for all compositions. In addition, the AC conductivity shows the same behavior as the DC conductivity that increases by increasing In content. This is owing to the short-range order of the investigated samples as well as the formation of defects which increases the density of localized states in the band tail [43]. In other words, the formation of the hetero-polar In–Se bond at the expense of the homo-polar Se–Se bond causes the reduction of band energy and consequently, increases the AC conductivity [44, 45]. In addition, there are two slopes for all compositions in the frequency range 10 Hz–10^3 Hz, while there is one slope at higher frequencies. From the slope of the straight line, AC activation energy \( \Delta E_{AC} \) can be calculated.

Table 4 demonstrates the values of \( \Delta E_{AC} \) for Ge_{26.6}In_{0.7}Se_{72.7}, Ge_{25.4}In_{2.4}Se_{72.2}, Ge_{27.8}In_{2.9}Se_{69.3}, \) and Ge_{25.8}In_{4.8}Se_{69.4}.

Fig. 6 Temperature dependence of AC conductivity for a Ge_{26.6}In_{0.7}Se_{72.7}, b Ge_{25.4}In_{2.4}Se_{72.2}, c Ge_{27.8}In_{2.9}Se_{69.3}, and d Ge_{25.8}In_{4.8}Se_{69.4}
that jump large paths at DC conduction but they did not need to do this in presence of the AC conduction [24].

4 Conclusions

The DC and AC conductivity of amorphous chalcogenide thin films of chemical composition Ge26In0.7Se72.7 (a), Ge25.4In2.4Se72.2 (b), Ge27.8In2.9Se69.3 (c) and Ge25.8In4.8Se69.4 (d) were studied at different temperatures and frequencies. The variation of the DC conductivity in the temperature range 295–523 K exhibits a semiconductor behavior in the entire temperature range with two conduction mechanisms. The first was observed in the high-temperature range (T > 380 K), where the conduction is due to the thermally activated process through the extended states with single activation energy. The corresponding electrical parameters (activation energy, ΔE, and pre-exponential factors, σ0) of the Arrhenius relation were calculated for each composition and found that the activation energy decreases from 0.709 to 0.466 eV by increasing In content. While the second is in the low-temperature range (T < 380 K), where the conduction is due to be less thermally activated and can be represented by the hopping conduction through the localized states according to the Mott variable range hopping model. The density of the localized states and the hopping parameter were calculated.

The AC conductivity, measured in the temperature range 295–523 K and over the frequency range 4–8 MHz, reveals that the conductivity in the dispersion region follows the Jonscher’s power-law, σ(ω) ∝ ω^α. In addition, the value of the exponent α decreases with increasing temperature as well as with increasing In content. So, the results were interpreted according to the correlated barrier hopping CBH model. The potential barrier height, WM, and the theoretical optical bandgap, Eg, at room temperature for the investigated compositions were evaluated.

### Table 4 AC activation energies at different frequencies for Ge26InxSe74-x thin films

| Compositions       | Ge26.4In0.7Se72.7 | Ge25.4In2.4Se72.2 | Ge27.8In2.9Se69.3 | Ge25.8In4.8Se69.4 |
|--------------------|------------------|------------------|------------------|------------------|
| AC activation energy | ΔE1 (eV) | ΔE2 (eV) | ΔE1 (eV) | ΔE2 (eV) | ΔE1 (eV) | ΔE2 (eV) | ΔE1 (eV) | ΔE2 (eV) |
| 10 Hz              | 0.387           | 0.132           | 0.336           | 0.123           | 0.274           | 0.119           | 0.189           | 0.113           |
| 10^2 Hz            | 0.322           | 0.131           | 0.294           | 0.120           | 0.247           | 0.113           | 0.183           | 0.110           |
| 10^3 Hz            | 0.227           | 0.121           | 0.220           | 0.108           | 0.186           | 0.098           | 0.161           | 0.097           |
| 10^4 Hz            | 0.135           | –               | 0.132           | –               | 0.098           | –               | 0.097           | –               |
| 10^5 Hz            | 0.099           | –               | 0.091           | –               | 0.089           | –               | 0.055           | –               |
| 10^6 Hz            | 0.067           | –               | 0.052           | –               | 0.038           | –               | 0.033           | –               |

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. E.A. Davis, N.F. Mott, Conduction in non-crystalline systems. V. Conductivity, optical absorption and photoconductivity in amorphous semiconductors. Philosophical Magazine 22:179, 0903–0922 (1970). https://doi.org/10.1080/14786437008221061
2. M. Pollak, On the frequency dependence of conductivity in amorphous solids. Philosophical Magazine 23:183, 519–542 (1971). https://doi.org/10.1080/14786437108216402
3. N.A. Hegab, M.A. Afifi, H.E. Atyia, A.S. Farid, AC conductiv -ity and dielectric properties of amorphous Se95Te20–xGex chalcogenide glass film compositions. J. Alloy. Compd. 477, 925–930 (2009). https://doi.org/10.1016/j.jallcom.2008.11.129
4. A.A. Othman, K.A. Aly, A.M. Abouehly, Effect of Te additions on the optical properties of (As–Sb–Se) thin films. Thin. Solid. Films. 515, 3507–3512 (2007). https://doi.org/10.1016/j.tsf.2006.10.118
5. Ishu Sharma, S.K. Tripathi, P.B. Barman, Compositional depen -dence of the physical properties in a-Ge–Se–In glassy semiconduc -tor. Physica B: Condens. Matter 403, 624–630 (2008). https://doi. org/10.1016/j.physb.2007.09.065
6. J.C. Phillips, Topology Of covalent non-crystalline solids I: Short-range order in chalcogenide alloys. J. Non-Cryst. Solids 34, 153–181 (1979). https://doi.org/10.1016/0022-3093(79)90033-4
7. A. Herzog, B. Hadad, V. Lyubin, M. Klebanov, A. Reiner, A. Shamir, A.A. Ishaaya, Chalcogenide waveguides on a sapphire-substrate for mid-IR applications. Opt. Lett. 39(8), 2522–2525 (2014). https://doi.org/10.1364/OL.39.002522
10. E.G. El-Metwally, E.M. Assim, S.S. Fouad, Optical characteristics and dispersion parameters of thermally evaporated Ge_{26}In_{x}Se_{74-x} thin film. Opt. Laser Technol. 131, 106462 (2020). https://doi.org/10.1016/j.optlastec.2020.106462

11. Y.A. El-Gendy, M. Hammam, A.M. Salem, M.M. Abd El-Aal, Thermal and Optical properties of amorphous chalcogenide Ge_{25}Se_{65}In_{x} thin films. J. Appl. Phys. Res. 7(5), 690–697 (2011)

12. El-Sayed M. Farag. Effect of annealing on the structure and D.C. conductivity of a-Ge_{20}In_{5}Te_{45} thin films. Mater. Lett. 15(1), 19–23 (2004). https://doi.org/10.1023/A:1026286019816

13. R. Todorov, E. Černůšková, P. Knotek, Z. Černošek, M. Vlasov. Temperature dependence of the optical properties of thin Ge-Se-In film. J. Non-Cryst. Solids 498, 415–421 (2018). https://doi.org/10.1016/j.jnoncrysol.2018.02.038

14. M.A. Abdel-Rahim, M.M. Hafiz, M.M. El-Nahass, A.M. El-Sayed, Thermal and Electrical properties of Ge_{20}Se_{50}In_{40} thin film. Vacuum 83(2), 391–396 (2009). https://doi.org/10.1016/j.vacuum.2008.05.023

15. M.K. Rabinal, K.S. Sangunni, E.S.R. Gopal, Chemical ordering in Ge_{50}In_{40}Se_{10} thin films. J. Non-Cryst. Solids 188, 98–106 (1995). https://doi.org/10.1016/0022-3093(94)00699-7

16. N.H. Moussa, Optical and electrical properties of the Ge_{26}In_{x}Se_{74-x} amorphous thin film. Egypt. J. Phys. 45, 39–47 (2017). https://doi.org/10.1155/2016/4257156

17. Nahed H. Teleb, W.A. Abd El-Ghany, A.M. Salem, Synthesis, structure and optical properties of Ge_{20}In_{5}Se_{45} thin films for photonic applications. J. Non-Cryst. Solids. 572, 121103 (2021). https://doi.org/10.1016/j.jnoncrysol.2021.121103

18. H.E. Atiya, Electrical and optical properties of thermally evaporated Ge_{20}In_{5}Se_{45} film. Physica B: Condens. Matter 403, 16–24 (2008). https://doi.org/10.1016/j.physb.2007.08.001

19. I. Sharma, S.K. Tripathi, A. Monga, P.B. Parmar, Electrical properties of a-Ge-Se-In thin film. J. Non-Cryst. Solids 354(27), 3215–3219 (2008). https://doi.org/10.1016/j.jnoncrysol.2008.01.006

20. K.A. Aly, A. Dahshan, Gb Abbady, Y. Saddeek, Electrical and thermo-electric properties of differentcompositions of Ge-Se-In thin films. Physica B: Condens. Matter 497, 1–5 (2016). https://doi.org/10.1016/j.physb.2016.06.001

21. Zishan H. Khan, M. Zulfiquar, Arvind Kumar, M. Husain, Electrical conductivity and thermo-electric power of a-Se_{90}Ge_{10} and Se_{90}Ge_{25}In_{5} thin film. Can. J. Phys. 80(1), 19–27 (2002). https://doi.org/10.1139/p01-078

22. El-Sayed M. Farag, M.M. Sallam, Composition dependence of the grain size, activation energy and coordination number in Ge_{40}In_{5}Se_{50} (10 ≤ x ≤ 40 at.%) thin films. Egypt. J. Solids 30(1), 1–11 (2007). https://doi.org/10.21608/ejs.2007.149052

23. S. Abo El-Hassan, M. Hammam, Frequency and temperature dependence of the dielectric properties of Se_{80}Ge_{20}Te_{8}In_{x} thin films at low temperature. Phys. Stat. Sol. A. 185(2), 413–421 (2001). https://doi.org/10.1002/1521-396X(200106)185:23<413::AID-PSSA213>3.0.CO;2-0

24. A.E. Bekheet, N.A. Hegab, AC conductivity and dielectric properties of Ge_{26}In_{x}Se_{74-x} film. Vacuum 83(2), 391–396 (2009). https://doi.org/10.1016/j.vacuum.2008.05.023

25. N.F. Mott, E.A. Davis, Electronic processes in non-crystalline materials, 2nd edn. (Oxford University Press, Oxford, 1979)
42. G.A. Khan, C.A. Hogarth, The behaviour of SiOx/SnO thin dielectric films in an alternating electric field. J. Mater. Sci. 26, 17–22 (1991). https://doi.org/10.1007/bf00576026

43. H.E. Atyia, A.M. Farid, N.A. Hegab, AC conductivity and dielectric properties of amorphous Ge0.5Sb0.5Se60 thin film. Physica B: Condens. Matter 403(21-22), 3980–3984 (2008). https://doi.org/10.1016/j.physb.2008.07.048

44. A. Abdel Aal, Dielectric relaxation in CdxInSe9-xChalcogenide thin films. Egypt. J. Solids. 29(2), 303–316 (2006). https://doi.org/10.21608/ejs.2006.149278

45. A. Dahshan, P. Sharma, K.A. Aly, Semiconducting quaternary chalcogenide glasses as new potential thermoelectric materials: an As-Ge-Se-Sb case. Dalton. Trans. 44, 14799–14804 (2015). https://doi.org/10.1039/C5DT02047F

46. Aly M. Badr, Haroun A. Elshaikh, Ibrahim M. Ashraf, Impacts of temperature and frequency on the dielectric properties for insight into the nature of the charge transports in the Tl2S layered single crystals. J. Mod. Phys. 2, 12–25 (2011). https://doi.org/10.4236/jmp.2011.21004

47. H.E. Atyia, Deposition temperature effect on the electric and dielectric properties of InSbSe3 thin film. Vacuum 81, 590–598 (2007). https://doi.org/10.1016/j.vacuum.2006.07.011

48. M.M. El-Nahass, H.M. Zeyada, M.M. El-Samanoudy, E.M. El-Menawy, Electrical conduction mechanisms and dielectric properties of thermally evaporatedN-(p-dimethylaminobenzylidene)-p-nitroaniline thin film. J. Phys: Condens. Matter 18, 5163–5173 (2006). https://doi.org/10.1088/0953-8984/18/22/016

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.