Effect of thermal annealing on the optical stability of amorphous Ge–Se–Te films

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Abstract
Ge–Se–Te chalcogenide films with Ge content from 10% to 27% were prepared using thermal evaporation. The films were annealed with different times, and the changes of the linear refractive index and optical band gap of the films with different chemical compositions were investigated. It was found that, after 30 h of annealing, the Ge20Se8.5Te71.5 film exhibits the smallest change ratio in terms of linear refractive index (<0.5%), optical band gap (<1.5%), and thickness (<2.5%). Therefore, this component has the best optical stability in the Ge–Se–Te system studied in this paper. The optical band gap of Ge20Se8.5Te71.5 is about 0.8 eV, and the refractive index exceeds 3.4, which is beneficial to the applications in Te-based optical waveguide devices.

1. Introduction

Chalcogenide glass is an amorphous compound consisting of one or more chalcogen elements (S, Se, Te) that are covalently bonded with other elements like Ge, As, Sb. The chalcogenide glasses are widely used in optical and information storage devices because of their excellent optical properties, like broad infrared transmission range, high linear and nonlinear refractive index, and low phonon energy [1–4]. High nonlinear refractive index can make them play an important role in applications such as supercontinuum, all-optical switching, and wavelength conversion [5–8]. In the fabrication process of many optical devices based on planar waveguide, a very important step is to prepare high quality optical films with stable physical properties. However, the internal defects of the films and their amorphous nature lead to that the structural relaxation usually occurs under external energy input (such as light illumination, ion-irradiation, thermal annealing, etc). This in turn would cause the change of the optical parameters, like the transmission, refractive index, optical band gap, etc, leading to the deterioration of the performance in chalcogenide-based optical devices. Many studies have concentrated on the effect of external energy input on the properties of the films, for example, photo-bleaching and photo-darkening effects in the films [9–13], thermal stability was also investigated in As–S, Ge–As–Se, Ge–Sb–Se, Ge–Ga–S thin films [14–17]. However, these compounds containing toxic arsenic may volatilize during deposition or annealing, which are environmentally unfriendly.

In contrast, Te-based chalcogenide glasses are becoming attractive due to the emerging applications of the materials in a waveguide range beyond 10 μm. Te element has a larger relative atomic mass and lower phonon energy than the S and Se elements, resulting in a higher nonlinear coefficient and a far infrared cutoff wavelength [18, 19]. At the same time, the material does not contain arsenic, which seems to be more environmentally compatible. However, the development of tellurium-based materials is limited by poor stability, and they tend to crystallize, resulting in a small glass-forming area of the material [20]. In order to screen the best film for the applications in Te-based planar waveguide devices, it is very important to find the relatively stable composition...
in the formation of the films [21]. This paper mainly studies the effect of annealing on the optical stability of amorphous Ge–Se–Te films. We deposited a series of the films with different compositions and annealed them with different times, and investigated the changes of the optical parameters such as refractive index, optical band gap, and transmittance of the films with an aim to find out the film with stable optical performance.

### 2. Experimental

**Ge$_x$Se$_{10-x}$Te$_{90-x}$** glasses with different compositions ($x = 15, 17.5, 20, 22.5, 25, and 30$ at.%) were prepared by a melt–quenching technique. Appropriate amount of high purity Ge, Se and Te elements were weighted and placed into a quartz tube and then evacuated to $10^{-7}$ Torr before being sealed using hydrogen torch. The tube then was placed into a rocking furnace with a maximum temperature of 950°C. After 24 h homogeneous rocking of the mixture, the tube was rapidly cooled in an ice-water mixture, and then annealed at a temperature of 20 ~ 30°C below its $T_g$ for 2 h. The as-prepared glasses were then used as starting materials for thermal evaporation.

The films were deposited on both silicon and quartz substrates using thermal evaporation. Before deposition, noteworthy, the substrates of silicon were stripped with a solution of 20% HF in order to eliminate native oxide layer. All the substrates were ultrasonically cleaned using acetone, alcohol, and pure water, step by step. After that, the substrates were placed onto the rotatable substrate holder. The distance from the evaporation boat to the substrate is 300 mm. In each run of the experiment, the chamber was evacuated to $10^{-7}$ Torr, and then Ar gas was introduced. Before deposition, Ar$^+$ was used to clean the substrate for 10 min and this procedure has been demonstrated to be able to improve the adhesion between the film and substrate. The beam current was 25 mA. The deposition rate can be changed by tuning the value of the current applied onto the evaporation source. The thickness of the thin films can be in situ read via a quartz thickness monitor placed near the substrates, and ex situ measured using a DEKTAK 3 Veeco mechanical profiler. The compositions of the as-deposited films were examined by using an Energy Dispersive x-ray Spectrometer (EDS) installed in a Tescan VEGA3 SB–Easyprobe Scanning Electron Microscope. X-ray diffractometer (Bruker D2) was employed to examine possible crystallization of the film, and check the amorphous or crystalline nature of the films. The transmission spectra of the films were measured in a range from 500 to 2500 nm using an ultraviolet visible near infrared spectrophotometer (PerkinElmer Lambda 950), and the energy band gap spectrum was estimated from the Tauc plot of the absorption edge. The refractive index of the films was measured using an infrared ellipsometer (J. A. Woollam IR-Vase II). Differential scanning calorimetry (DSC) was used to determine the glass transition temperature ($T_g$) of the Ge–Se–Te glasses. Noteworthy, in the previous literature [9], the researcher measured $T_g$ both of the bulk glasses and the films by using a flash DSC which only tens of nanograms of materials are needed, and found the difference of $T_g$ between the bulk and film is less than 5°C. It indicates that, there is only negligible change of $T_g$ between the film and bulk with the same composition. Thus, we here obtained the $T_g$ of Ge–Se–Te film by measured $T_g$ values of the bulk glasses with the same compositions of the films using the conventional DSC. The $T_g$ values are shown in table 1. Thermal annealing of the films was performed in a vacuum annealing furnace, and the annealing temperature was around 20°C below $T_g$ with different duration time of 5, 10, 15, 20, 25, and 30 h.

### 3. Results and discussion

The compositions of the films were shown in table 1. It is well known that thermal evaporation generally leads to the deviation of the composition from the starting materials. In this case, we tuned the compositions via different evaporation rates, and found that, Ge content in the film generally is lower than that in the corresponding starting material. Nevertheless, we chose a group of the films with similar Se content around 10

| Sample name | Bulk composition | Film composition | Deposition rate(A s$^{-1}$) | $T_g$ (°C) | $T_a$ (°C) | Thickness (nm) |
|-------------|------------------|------------------|----------------------------|------------|------------|---------------|
| Ge10        | 15/10/75         | 10/10.5/79.5     | 5                         | 105        | 85         | 330           |
| Ge12        | 17.5/10/72.5     | 12/10/78         | 5                         | 118        | 95         | 324           |
| Ge17        | 20/10/70         | 17/10/73         | 7                         | 142        | 120        | 305           |
| Ge20        | 22.5/10/67.5     | 20/8.7/71.5      | 10                        | 164        | 145        | 285           |
| Ge23        | 25/10/65         | 23/12/65         | 10                        | 180        | 160        | 262           |
| Ge27        | 30/10/60         | 27/13/60         | 10                        | 206        | 185        | 255           |

Table 1. The thermal evaporation coating rate, film composition, transition temperature of the film, annealing temperature and film thickness are shown.
at.%. The annealing temperature ($T_a$) is about 20 °C lower than $T_g$, which is obtained from the bulk glasses that has the similar composition as the films. See the details in table 1.

XRD pattern of the as-deposited and 30 h-annealed films were shown in figures 1(a) and (b), respectively. No sharp diffraction peaks can be found, and the broad XRD features indicate that thermal annealing below $T_g$ for 30 h cannot induce any crystallization in the films. Therefore, any changes of the optical parameters in the rest part of the paper is not due to the phase change behavior that has been frequently reported in Te-based films since the annealing temperature is too low to induce phase change.

The transmission spectra of the as-deposited thin films were shown in figure 2(a). We are particularly interested in the transmission edges that move towards the short wavelength with the decrease of Te content. In order to obtain the exactly value for the short wavelength cutoff, an enlarge transmittance spectra in visible-near infrared is provided in figure 2(b). The value of short wavelength cutoff is $\sim 1040$, $\sim 980$, $\sim 960$, $\sim 900$, $\sim 850$, and $\sim 780$ nm (the corresponding transmittance is $\sim 5\%$), for Ge10, Ge12, Ge17, Ge20, Ge23, and Ge27, respectively.

Figure 1. XRD patterns of (a) the as-deposited, and (b) annealed films for 30 h.

Figure 2. (a) Transmittance spectra of the as-deposited Ge–Se–Te thin films; (b) The enlarge transmittance spectra in visible-near infrared.

Figure 3. (a) Optical band gap of the as-deposited films; (b) Refractive index of the as-deposited films (1.55–5 μm).
This is in good agreement with that Te element has greater atomic mass and polarizability, leading to smaller optical bandgap with increasing Te content in the films.

The absorption coefficient ($\alpha$) of the films can be calculated from the relationship

$$\alpha = \frac{1}{d} \ln \left( \frac{1}{T} \right)$$

where $d$ is the thickness of films and $T$ is the transmittance. The optical band gap $E_{opt}^g$ can be calculated according to the Tauc formula [23],

$$\alpha h\nu = B(h\nu - E_{opt}^g)^n$$

where $B$ is the tail parameter, and the value of $n$ is selected as 2 for indirect transition amorphous materials like the Ge–Se–Te films [24]. The main panel of figure 3(a) shows the relationship between $(\alpha h\nu)^{1/2}$ and $h\nu$ of the as-deposited films. The value of $E_{opt}^g$ was estimated by extending the linear region to the intersection of the abscissa. The optical band gap of the as-deposited film was further shown in the inset of figure 3(a). It is evident that, as the Te content increases, the optical band gap decreases gradually. As we know that, the size of the atom can play a very important role in changing the energy band-gap of materials [25]. In the amorphous films, the insufficient number of atoms will produce some unsaturated bonds and saturated bonds, and the unsaturated bonds will form some defects in the amorphous structure. Te element has a larger atomic radius, which will increase the number of unsaturated bonds and the local density of states, and ultimately reduce the optical band gap of the amorphous film [26]. Figure 3(b) is the refractive index of the films measured by the infrared ellipsometer, where the Cauchy model was used to fit the optical parameters of the films with a mean square error (MSE) less than 2.5. With the increase of Te content, the refractive index of the films is gradually increased. The refractive index of the sample is generally related to the polarizability of the constituent elements. The Te element has a greater relative atomic mass and ion polarizability, which leads to an increase in the refractive index in the Te-rich films.

To study the refractive index dispersion below the energy band gap for the as-deposited Ge–Se–Te thin films, we here performed the Wemple–DiDomenico Single oscillator model [27]. Such model consists of inter band transition of electron as a single oscillator. The dependance of refractive index on photon energy below inter-band absorption edge ($h\nu < E_{opt}^g$) is given as [28],

$$n^2(\lambda) = 1 + \frac{E_0 E_d}{(E_0^2 - E^2)}$$

where $E_0$ is the single oscillator energy, $E_d$ is the dispersion energy, $E = h\nu = \text{photon energy}$. Figure 4 shows plots of $(n^2 - 1)^{-1}$ versus $(h\nu)^2$ of the as-deposited Ge–Se–Te thin films. By linearly fitting the above curve, the single oscillator energy ($E_0$) and dispersion energy ($E_d$) can be derived. The parameter $E_0$ corresponds to the

Table 2. Dispersive parameters of the as-deposited Ge–Se–Te thin films.

| Sample name | Ge10 | Ge12 | Ge17 | Ge20 | Ge23 | Ge27 |
|-------------|------|------|------|------|------|------|
| $E_d$(eV)   | 24.25| 24.22| 23.36| 23.08| 21.99| 19.95|
| $E_0$(eV)   | 2.08 | 2.14 | 2.15 | 2.19 | 2.20 | 2.22 |

![Figure 4. Plots of $(n^2 - 1)^{-1}$ versus $(h\nu)^2$ of the as-deposited Ge–Se–Te thin films.](image-url)
Figure 5. Annealing time dependence of thickness change ratio ($\Delta d/d$) for Ge–Se–Te films. The black solid line indicates no change ratio of the thickness. The dashed lines are guides to the eyes.

Figure 6. The dispersion of (a) Ge10; (b) Ge20; and (c) Ge27 film. (d) The change of the refractive index at 3 $\mu$m for the films with different annealing times. The dashed lines are guides to the eyes.

Figure 7. The effect of annealing on the transmission spectrum of the material, (a) Ge10; (b) Ge20; (c) Ge27.
distance between centers of gravity of the valance and conduction band, while the other parameter $E_d$ corresponds to the average strength of the inter-band optical transitions [29]. We list the specific values of $E_0$ and $E_d$ of these films in table 2. The introduction of Te element can improve the nonlinear parameters of the material. Similarly, the smaller single oscillator energy ($E_0$) indicates that the material has superior nonlinear optical quality.

We investigated the effect of annealing on the films with different durations below $T_g$. Figure 5 shows the variation of the thickness change ratio of Ge–Se–Te thin films with different annealing time, where $d$ is the thickness of the as-deposited films and $\Delta d$ is the thickness difference between the as-deposited and annealed film. We found that, with increasing annealing time, the thickness of Ge10, Ge12, and Ge17 gradually decreases; while that of Ge20, Ge23 and Ge27 increases.

Figures 6(a)–(c) show the dispersion of the refractive indexes of Ge10, Ge20 and Ge27 films with different annealing time, respectively. It can be seen that, the refractive index at a certain wavelength in figure 6(a) increases with the increase of the annealing time, but that in figures 6(b) and (c) decreases with the increase of annealing time. However, the variation range in Ge20 is smaller compared with other two films. In order to

Table 3. The specific values of the refractive index ($n$) and optical band gap ($E_{opt}$) of the film under different annealing conditions are shown.

| Optical parameters | Annealing time(h) | Ge10 | Ge12 | Ge17 | Ge20 | Ge23 | Ge27 |
|--------------------|-------------------|------|------|------|------|------|------|
| $n$ at 3μm         | 0                 | 3.620| 3.559| 3.502| 3.445| 3.373| 3.215|
|                    | 5                 | 3.660| 3.609| 3.515| 3.436| 3.318| 3.193|
|                    | 10                | 3.672| 3.613| 3.518| 3.432| 3.302| 3.185|
|                    | 15                | 3.678| 3.616| 3.520| 3.432| 3.298| 3.181|
|                    | 20                | 3.680| 3.618| 3.521| 3.432| 3.296| 3.180|
|                    | 25                | 3.684| 3.620| 3.522| 3.430| 3.294| 3.179|
|                    | 30                | 3.688| 3.622| 3.523| 3.430| 3.295| 3.178|
| $E_{opt}$ (eV)     | 0                 | 0.6797| 0.7137| 0.7447| 0.7919| 0.7993| 0.8352|
|                    | 5                 | 0.6717| 0.7072| 0.7405| 0.7962| 0.8098| 0.8505|
|                    | 10                | 0.6669| 0.7038| 0.7365| 0.7988| 0.8215| 0.8542|
|                    | 15                | 0.6639| 0.7014| 0.7348| 0.7989| 0.8244| 0.8575|
|                    | 20                | 0.6607| 0.6992| 0.7331| 0.7995| 0.8275| 0.8598|
|                    | 25                | 0.6586| 0.6978| 0.7332| 0.7996| 0.8297| 0.8611|
|                    | 30                | 0.6579| 0.6951| 0.7298| 0.8005| 0.8328| 0.8628|

Figure 8. The optical band gap obtained by extrapolating the curve of $\alpha(h\nu)^{1/2}$ versus $h\nu$ for before and after heat annealing of (a) Ge10; (b) Ge20; (c) Ge27 films. (d) Annealing time dependent optical band gap of Ge–Se–Te films. The dashed lines are the guides to eyes.
clearly elucidate, figure 6(d) shows the annealing time dependent refractive index at a wavelength of 3 μm for all the Ge–Se–Te films. With the increase of annealing time, the refractive index of Ge10, Ge12, and Ge17 films gradually increases, while the refractive index of Ge20, Ge23, and Ge27 films decreases. Previous studies have confirmed that the refractive index is closely related to the density of the material [30, 31]. Because thermal annealing induces the change of the thickness in the films as shown in figure 5, the decrease of the film thickness would increase the density, leading to the increase of the refractive index. Otherwise, the decrease of the thickness would induce the decrease of the refractive index.

We have annealed each group of films for different times, and tested the transmission spectra of the films after each annealing. The transmission spectra of the three typical groups of films are shown in figure 7. We can see that, after the Ge10 film is annealed for different times, the cutoff edge of the transmission spectrum has a red shift. However, Ge20 and Ge27 show the opposite trend to Ge10. The transmission spectra of Ge12 and Ge17 also have a red shift, while the transmission spectra of Ge23 have a blue shift after annealing (details are not shown in here). The change rule of the transmission spectrum corresponds to the refractive index. All films conform to this pattern, and the red shift of the cut-off edge corresponds to a larger refractive index.

Figures 8(a)–(c) shows the typical changes of the optical band gap of Ge10, Ge20, Ge27 films with the annealing time, respectively. Apparently, as the annealing time increases, the optical band gap of Ge10 tends to decrease, but the optical band gap of Ge27 tends to increase. Interestingly, the optical band gap of Ge20 changes insignificantly with the annealing time. Figure 8(d) shows the change of the optical bandgap for all the films. We found that, the optical band gaps of Ge10, Ge12, and Ge17 films gradually decrease with the increase of annealing time, while the tendency of the changes in Ge20, Ge23, and Ge27 films is opposite to those films with lower Ge contents. The change of the optical band gap is usually correlated with the atomic polarizability [32].

Previously investigations on chalcogenide materials indicated that a material with smaller $E_{opt}^{pp}$ was more likely to show a higher refractive index n, especially n increased with decreasing $E_{opt}^{pp}$ when a chalcogenide glass was subjected to photodarkening [33]. This phenomenon can also be explained by the model proposed by Mott and Davies [34], suggesting that thermal annealing should improve network topology and reduce the number of the
defects. Since the films are created under non-equilibrium conditions, they contained a large amount of the disorders, which occupied the band tails or at positions within the bandgap. The change of the numbers of the disorders leads to the change of the bandgaps upon thermal annealing.

In order to show the changes of optical parameters with annealing time more intuitively, we list all the film parameters in table 3. The fitting error of refractive index (n) and optical band gap ($E_{opt}$) is less than 0.3% and 0.5%, respectively.

Figure 9 shows the absolute changes of thickness (\(\frac{\Delta d}{d}\)), optical band gap (\(\frac{\Delta E_{opt}}{E_{opt}}\)), and refractive index (\(\frac{\Delta n}{n}\)) with the film composition. It is obvious that, the change of three parameters exhibit a minimum in the film with Ge content of 20% (mean coordination number, MCN = 2.4), indicating that the optical parameters around Ge20 composition would not change significantly with the increase of the annealing time. Such excellent thermal stability in Ge20 film is beneficial to the applications in chalcogenide-based planar waveguide devices.

4. Conclusion

In this paper, Ge–Se–Te chalcogenide thin films were prepared by thermal evaporation method. We found that, the actual compositions of the films are closer to the bulk glass when the deposition rate is 5–10 Å s\(^{-1}\). The optical properties of the deposited films were characterized, and then the effects of different annealing times on the optical properties of the films were investigated. The results show that the optical band gap of the films increases with the increase of annealing time, and the change rate of the band gap is the lowest when the content of Ge is 20%. Simultaneously, as the annealing time increases, we found that the refractive index of films with a Ge content of less than 20% gradually increases, while the refractive index of films with a Ge content of more than 20% gradually decreases. The change in refractive index shows the opposite trend to the change in the thickness of the films. Comprehensive experimental results show that, the refractive index, optical band gap, and thickness change index of the film with 20% Ge content are the lowest in the whole annealing process. Among the thin film components studied here, Ge\(_{20}\)Se\(_{85.5}\)Te\(_{14.5}\) showed the best thermal stability, and this component may be a potential material for photonic device applications.

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References

[1] Tanaka K and Shimakawa K 2011 Amorphous Chalcogenide Semiconductors and Related Materials (New York: Springer) (https://doi.org/10.1007/978-1-4419-9510-0)
[2] Wang R 2014 Amorphous Chalcogenides: Advances and Applications (Singapore: Pan Stanford Publishing) (https://doi.org/10.1201/b15599-5)
[3] Khan S A, Al-Agel F A and Al-Ghamdi A A 2010 Optical characterization of nanocrystalline Se85Te10Pb5 and Se80Te10Pb10 chalcogenides Superlattices Microstruct. 47 695–704
[4] Fernandes B J, Naresh N, Kamesh K, Sridharan K and Udayashankar N K 2017 Crystallization kinetics of Sn doped Ge20Te80–xSnx (0 ≤ x ≤ 4) chalcogenide glassy alloys J. Alloy. Compd. 721 674–82
[5] Aly K A 2009 Optical properties of Ge–Se–Te wedge-shaped films by using only transmission spectra J. Non-Cryst. Solids. 355 1489–95
[6] Sharma P and Katyal S C 2007 Optical study of Ge10Se90–xTe glassy semiconductors Thin Solid Films. 515 7966–70
[7] Svboda R, Krbal M and Mälek J 2011 Crystallization kinetics in Se–Te glassy system J. Non-Cryst. Solids. 357 3123–9
[8] Wang H, Wang G, Chen Y, Shen X, Lv Y and Nie Q 2015 Advantages of Mo4.9(Sb2Te)95.1 film with improved crystallization properties for phase change memory Mater. Lett. 161 240–3
[9] Wang R, Zhang Z, Chen Y, Xu S and Shen X 2020 Photo-induced effects in Ge–As–Se films in various states Opt. Mater. Express. 10 540–8
[10] Wang R P, Rode A V, Madden S J, Zha C J, Jarvis R A and Luther-Davies B 2007 Structural relaxation and optical properties in amorphous Ge33As12Se55 films J. Non-Cryst. Solids. 353 950–8
[11] Zhang S, Chen Y, Wang R, Shen X and Dai S 2017 Observation of photobleaching in Ge-deficient Ge16.8Se83.2 chalcogenide thin film with prolonged irradiation Sci Rep. 7 14585
[12] Su X, Wang R, Luther-Davies B and Wang L 2013 The dependence of photosensitivity on composition for thin films of Ge_{x}As_{y}Se_{1-x-y} chalcogenide glasses Applied Physics A 113 575–81
[13] Stäbl M and Tichy L 2004 Photo-induced changes of the short wavelength absorption edge in some Ge–As–S amorphous thin films Opt. Mater. 27 549–57
[14] Bulla D A P, Wang R P, Prasad A, Rode A V, Madden S J and Luther-Davies B 2009 On the properties and stability of thermally evaporated Ge–As–Se thin films Applied Physics A 96 615–23
[15] Svboda R, Knick M and Mälek J 2015 Thermal characterization of Se–Te thin films J. Alloy. Compd. 644 40–6
[16] Teng N, Qin J, Chen Y, Wang R, Shen X and Xu T 2020 Optical properties and thermal stability of amorphous Ge–Sb–Se films J. Non-Cryst. Solids. 532 119888
[17] Niu L, Chen Y, Shen X and Xu T 2020 Thermal stability of magnetron sputtering Ge–Ga–S films Chin. Phys. B 29 087803
[18] Sharma P and Katyal S C 2008 Far-infrared transmission and bonding arrangement in Ge10Se90–xTex semiconducting glassy alloys J. Non-Cryst. Solids. 354 3836–9
[19] Zavadil J, Kostka P, Pedlikova J, Zdansky K, Kubiliu M, Labas V and Kaluzny J 2009 Electro-optical characterization of Ge–Se–Te glasses J. Non-Cryst. Solids. 355 2083–7
[20] Pan H, Yang Z, Chen Y, Wang R and Shen X 2018 X-ray photoelectron spectra of Ge–As–Te glasses AIP Advances. 8 075208
[21] Vigreux C, Thi M V, Maulion G, Kribich R, Barillot M, Kirschner V and Pradel A 2014 Wide-range transmitting chalcogenide films and development of micro-components for infrared integrated optics applications Opt. Mater. Express. 4 1617
[22] Singh P, Kaur R, Sharma P, Sharma V, Mishra M, Gupta G and Thakur A 2017 Optical band gap tuning of Ag doped Ge_{2}Sb_{2}Te_{5} thin films J. Mater. Sci.-Mater. Electron. 28 11300–5
[23] Safarini G, Saiter J M and Schmitt H 2007 The composition dependence of the optical band gap in Ge–Se–In thin films Opt. Mater. 29 1143–7
[24] Fouda S S, Amin G A M and El-Bana M S 2018 Physical and optical characteristics of Ge10Se90–xTex thin films in view of their spectroscopic ellipsometry data J. Non-Cryst. Solids. 481 314–20
[25] Sridharan K, Ollakkan M S, Philip R and Park T J 2013 Non-hydrothermal synthesis and optical limiting properties of one-dimensional Se/C, Te/C and Se–Te/C core–shell nanostructures Carbon 63 263–73
[26] Sharma P and Katyal S C 2007 Thickness dependence of optical parameters for Ge–Se–Te thin films Mater. Lett. 61 4516–8
[27] Joshi J H, Kalainathan S, Kanchan D K, Joshi M J and Parikh K D 2020 Effect of l-threonine on growth and properties of ammonium dihydrogen phosphate crystal Arabian Journal of Chemistry. 13 1532–50
[28] Joshi J H, Dixit K P, Parikh K D, Jethva H O, Kanchan D K, Kalainathan S and Joshi M J 2018 Effect of Sr2+ on growth and properties of ammonium dihydrogen phosphate single crystal J. Mater. Sci.-Mater. Electron. 29 5837–52
[29] Joshi J H, Kalainathan S, Kanchan D K, Joshi M J and Parikh K D 2019 Crystal growth, A.C. electrical and nonlinear optical studies of pure and dl-methionine doped ammonium dihydrogen phosphate single crystals J. Mater. Sci.-Mater. Electron. 30 2985–93
[30] Wang T, Gai X, Wei W, Wang R, Yang Z, Shen X, Madden S and Luther-Davies B 2014 Systematic z-scan measurements of the third order nonlinearity of chalcogenide glasses Opt. Mater. Express. 4 1011
[31] Iglesias-Otero M A, Troncoso J, Carballo E and Romani L 2008 Density and refractive index in mixtures of ionic liquids and organic solvents: correlations and predictions The Journal of Chemical Thermodynamics. 40 949–56
[32] Yang Z, Luo L and Chen W 2010 Red Color Ge_{2}Sb_{2}Se_{5}-based chalcogelide glasses for infrared optics J. Am. Ceram. Soc. 89 2327–9
[33] Tanaka K 2014 Photo-induced phenomena in chalcogenide glasses Chalcogenide Glasses. 5061 139–68
[34] Mott N F, Davis E A and Weiser K 1972 Electronic processes in Non-Crystalline materials Phys. Today. 25 55–55