

On the microstructural origin of reversible photoinduced transformations in amorphous As_2Se_3

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A microstructural mechanism of photoinduced structural transformations in amorphous As_2Se_3 thin films was studied by IR Fourier-transform spectroscopy in the range of 300–100 cm^{-1} . It was shown that the stage of irreversible photostructural changes in the freshly-deposited films was connected with coordination of topological defects formation accompanied by homopolar chemical bonds switchings in heteropolar ones. By contrast, the reversible stage of photoinduced effects were caused by two different types of transformations – heteropolar bonds switching in homopolar ones, as well as heteropolar bridge bonds switching in short layer ones. Both processes were associated with the formation of anomalously coordinated topological defect pairs and atomic displacements at the medium-range ordering level.

Keywords: amorphous semiconductors, photoinduced changes, IR Fourier spectroscopy.

1. Introduction

A wide application of amorphous chalcogenide semiconductors (AChS) in optoelectronics is grounded on their unique ability to change physical-chemical properties at the influence of acting external factors, first of all, absorbed light photoexposure. These, so-called, photoinduced effects reveal themselves clearly through the changes in the AChS' optical properties [1–3]. They are well observed in thin films prepared by vacuum deposition, as well as in bulk and powder AChS but with relatively smaller intensity [4].

It has been established that absorbed light photoexposure leads to a long-wave shift of the optical absorption edge and to an increase of the refractive index with a strong dependence on AChS composition and light treatment conditions (temperature, duration of exposure, photons energy, light intensity, etc.). A subsequent thermal annealing at temperatures near the softening range of the correspondent chalcogenide glass restores the initial optical properties of the AChS film so that the observed changes are reversible in multiple cycles of photoexposure and annealing. The irreversible component of these changes is sufficiently important only in the first photoexposure cycle of the freshly-prepared film, but in the next cycles it is negligible [4,5].

Physical features of the above effects were well studied in 1970–1980 [1–3], but now there are some controversies in our understanding of their microstructural origin. There is, so-called, photostructural model for the reversible

photoinduced optical effects, associated with short- and medium-range ordering changes of the AChS' atomic network [4,5]. However, the detailed topological schemes for these changes have been remaining unclear up to now. Only in the case of amorphous a- As_2S_3 thin films, characterised by sharply defined photoinduced optical changes, the reversible photostructural transformations (PhST) can be simply identified as bond-switching processes using Raman spectroscopy [6]. The main result of this experiment is quantitative estimation of bond concentration reversibly transformed by photoexposure and thermal annealing (6–7%), while initial and finite products of these transformations have not been identified exactly.

Recently, we have established that information on PhST nature in AChS could be obtained with IR Fourier-transform spectroscopy [7]. Only a small part of IR absorption spectrum induced by external influence was analysed by this technique. Multiple accumulation of this useful signal, when the fast Fourier-transform is used, allows us to reach a sensitivity of this technique at a ~1% level from the breaking (switching) bonds concentration. Thus, particularly, it was proved that the reversible PhST in the a- As_2S_3 films were explained by heteropolar As-S chemical bonds switching in homopolar As-As and S-S ones, accompanied by simultaneous formation of specific coordination topological defects – anomalously coordinated (under- and over-coordinated) pairs of atoms with opposite electrical charges [7–10]. These PhSTs are not restricted only by short-range ordering level. They stretch into a medium-range structural level included 3–10 coordination spheres owing to relaxation processes in the vicinity of

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switched chemical bonds as it was shown in some experiments using EXAFS [11,12].

Consequently, we can consider the a- As_2S_3 as the model object from the point of qualitative and quantitative investigations of PhST in AChS. It is explained by a good distinction of different vibrational bands in IR absorption spectrum corresponding to own structural fragments with homo- and heteropolar chemical bonds [13,14], as well as by a structural network model well developed for this specimen previously [3,15].

However, this situation becomes more complicated for a- As_2Se_3 thin film, despite of sharply expressed reversible PhST in it (but with less amplitude of changes) [3,4]. The vibrational spectrum of this AChS specimen is characterised by a large number of IR absorption bands overlapping in the narrow range of 275–100 cm^{-1} [16–19]. As a result, the direct study of PhST in the a- As_2Se_3 films using “integrated” experimental technique such as Raman scattering have not been carried out yet. But the method of IR Fourier-transform spectroscopy, successfully applied for PhST study in the a- As_2S_3 films previously [7], is expected to be quite suitable for the a- As_2Se_3 thin films too.

2. Experimental

As to preparation of the investigated a- As_2Se_3 thin films and other experimental details, it should be noted that a correct PhST study at both irreversible and reversible stages needs a strict fulfilment of the following rules:

- using the especially prepared AChS specimens, determined by technological parameters of deposition, thickness, molecular and atomic chemical composition, etc., which possess the sharp reversible photoinduced optical changes,
- correct formation of the reversible channel of PhST in multiple subsequent cycles of absorbed light photoexposure and annealing at the temperatures of 20–30 K less than glass transition point,
- experimental proving for PhST reversibility, i.e., experimental observation of mutually opposite changes of the controlled parameters with equal intensities in the multiple repeated cycles of photoexposure and thermal annealing.

By following exactly these rules, we chose the next features of experimental procedure. The investigated a- As_2Se_3 thin films of ~ 2 μm thickness were deposited by vacuum evaporation (10–15 nm/s) on substrates, made of especially prepared radiation-modified polyethylene having a softening temperature over 430–440 K and a high optical transparency in 300–100 cm^{-1} spectral region. The powder of bulk a- As_2Se_3 glass obtained by direct synthesis from 99.999% purity constituents was used as raw materials for deposition. The quantitative relationship between chemical compositions of bulk glass, thin film and calculated stoichiometric a- As_2Se_3 compound was confirmed by electron probe microanalysis.

The PhST were caused in the investigated a- As_2Se_3 films by photoexposure of absorbed light beam of He-Ne

laser (633 nm) at power density of 25 mW/cm^2 during 120 min. These conditions ensure a 20–25 nm long-wave shift of optical absorption edge and a full absence of non-linear effects caused by extra-high or low light intensities [20]. The thermal annealing of these films was carried out at $T = 430$ K during 30 min.

The method of IR Fourier-transform spectroscopy (IFS-113V “Bruker” spectrometer) was used for mechanism study of photo- and thermally-induced structural transformations in the a- As_2Se_3 films. The measurements covered the previously intensified absorption spectra of these samples in the range of 300–100 cm^{-1} before and after photoexposure or thermal annealing. The investigated bond-switching processes were determined, using changes in optical density D for the main vibrational bands of the a- As_2Se_3 . The positive values of $\Delta D > 0$ correspond to structural complexes, formed by photoexposure or thermal annealing, and the negative values of $\Delta D < 0$ correspond to ones, destroyed by them.

It is known that the main vibrational bands of the a- As_2Se_3 are grouped in a narrow 275–100 cm^{-1} spectral region [16–19]. Apart from $\nu_3 = 217$ cm^{-1} mode of symmetric valence vibrations of As-Se covalent bonds in pyramidal AsSe_3 units [16,17], the sharply defined vibration bands of short layer As-Se bonds at 243 cm^{-1} [16], as well as intermolecular deformation modes of bridge As-Se-As complexes at 172 and 274–269 cm^{-1} [17] are revealed in IR absorption spectra.

This separation is a direct consequence of partial keeping of the main structural features proper to crystalline c- As_2Se_3 in amorphous state. The differences of vibrational modes intensities for heteropolar chemical bonds in the framework of bridge and short layer pyramidal fragments are more sufficient in a- As_2Se_3 in comparison with a- As_2S_3 . If interatomic As-S distances for all structural units (bridge and short layer ones) slightly change, being in the 0.243–0.229 nm range in c- As_2S_3 , this distance in the spiral chains along C axis is 0.010 nm shorter than that in the bridge As-Se-As complexes (0.277 nm) in c- As_2Se_3 [21].

In order to identify the absorption bands of other structural fragments of the a- As_2Se_3 based on homopolar As-As (230, 140 and 120 cm^{-1}) and Se-Se (270, 260, 250–230, 144–136 cm^{-1}) bonds, the well-known experimental results for a-As and a-Se were used [18,19].

3. Results and discussion

3.1. The stage of irreversible PhST

The structural changes observed at the stage of irreversible PhST due to first-cycle photoexposure of the freshly-obtained a- As_2Se_3 thin films correspond to homopolar As-As and Se-Se chemical bonds switching into heteropolar As-Se ones. This result is obvious (see Fig. 1) from an increase in vibrational bands intensities for As-Se bonds (217, 243, 172, 274–269 cm^{-1}), especially in the region of

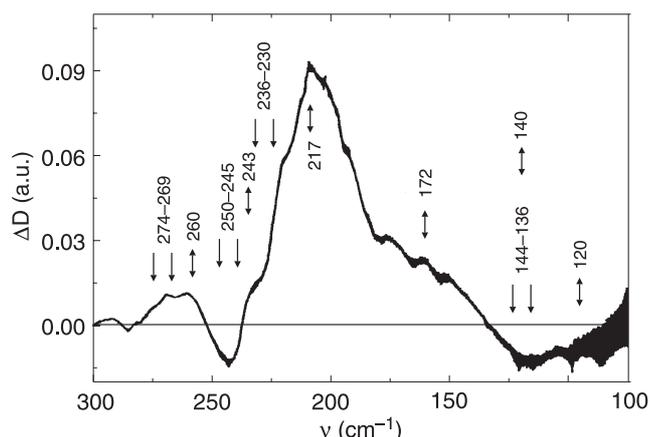
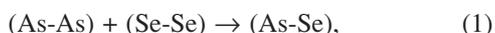


Fig. 1. Additional optical density in the freshly-deposited a-As₂Se₃ thin film induced by first-cycle photoexposure.

217 cm⁻¹ band proper to symmetric valence As-Se vibrations in pyramidal AsSe₃ units [16,17], as well as a decrease of homopolar bonds vibrations at 230, 140, 120 cm⁻¹ (As-As bonds) and 270, 260, 250–230, 144–136 cm⁻¹ (Se-Se bonds) [18,19].

We have observed similar changes previously at first-cycle photoexposure of the freshly-obtained a-As₂S₃ films [7,8]. Using this analogy between a-As₂S₃ and a-As₂Se₃, it is possible to conclude that irreversible PhST are associated with specific structural defects formed owing to the next topological scheme of bonds switching



where expressions in brackets conditionally denote the chemical bonds destroyed (the left part) or formed (the right part) by photoexposure.

These defects can be recognised as the coordination topological ones as they are characterised by uncompensated electrical charge and anomalous atomic coordination. They appear in AChS by pairs (negative and positive, under- and overcoordinated ones), keeping electrical neutrality and average covalent linking of a glassy-like network. Their electrical states and structural configurations were described previously by Mott, Davis, and Street (D-centres) [22], Kastner, Adler and Fritzsche (valence alternation pairs) [23], Kastner (intimate valence alternation pairs) [24], and Street (self-trapping excitons) [25].

Taking into account that the final AChS state with coordination topological defects depends not only on destroyed bond, but also on its nearest neighbourhood or, in other words, that 2 initial bonds take place in one separated process of coordination defects formation, we can introduce 16 topological schemes of the statistically possible PhST for the a-As₂Se₃. They were discussed in details previously for the a-As₂S₃ [8–10].

Only four topological schemes shown in Fig. 2 exactly correspond to the bond-switching reaction (1), the first two schemes being connected with disappearing of As-As bond

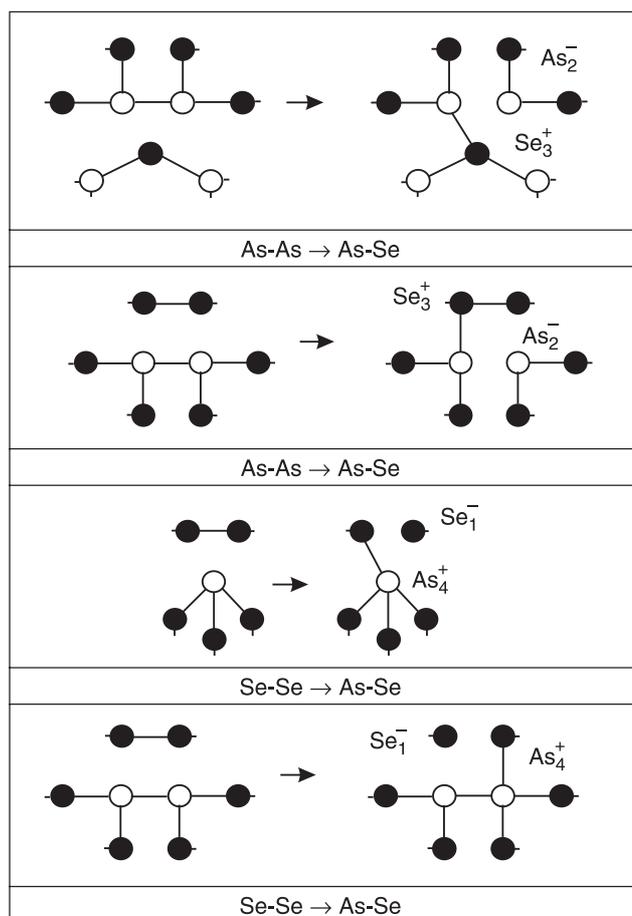


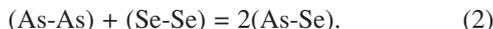
Fig. 2. Topological schemes of coordination topological defects formation associated with irreversible PhST in the freshly-deposited a-As₂Se₃ thin film.

and the second two schemes with S-S bond. The new heteropolar As-S chemical bonds are formed instead of these initial homopolar ones, so that the normal coordination defined by 8-N rule [21] do not satisfy for two atoms after bonds switching. Consequently, the formation of (As₂⁻; Se₃⁺) and (As₄⁺; Se₁⁻) defect pairs is a dominant process for irreversible PhST in the freshly-deposited a-As₂Se₃ thin films (the upper index in a defects signature means the electrical charge and the lower one – the coordination number of atom). The average covalent linking and electrical neutrality of a whole AChS structural network do not change in all these cases.

It must be noted that, owing to the obtained IR Fourier-transform spectrum (see Fig. 1), the heteropolar As-Se chemical bonds, formed at the irreversible PhST stage instead of destructed homopolar As-As and Se-Se ones, appear in the framework of both short layer As-Se and long bridge As-Se-As structural complexes.

The only possible alternative way to explain these experimental results is, so-called, structural polymerisation process, which includes the transformation of As₄Se₄ and Se₂ molecular complexes in homogeneous AsSe_{3/2} network

discussed in Ref. 6. This process is not accompanied by atomic coordination changes and, consequently, coordination defects formation. Two homopolar chemical bonds (As-As and Se-Se) destroy simultaneously and two heteropolar ones (As-Se) appear instead of them in a full correspondence with the next bond-switching reaction



The polymerisation process is possible provided all four atoms, initially formed two homopolar chemical bonds, occupy such sites in a glassy-like network, which allow appearing of two heteropolar chemical bonds without sufficient atomic displacements. If $(As_2^-; Se_3^+)$ and $(As_4^+; Se_1^-)$ defect pairs appear, as it is shown in Fig. 2, this strong requirement must be fulfilled only for two atoms. Hence, the probability of coordination defects formation in the a- As_2Se_3 rises in comparison with non-defect polymerisation process [6]. We suppose that the latter is dominant in the freshly-evaporated AChS films affected to thermal annealing near glass transition temperature, when atomic migrations sufficiently increase [13,14].

3.2. The stage of thermal bleaching of irreversible PhST

The subsequent thermal annealing of the freshly-deposited a- As_2Se_3 thin films, photoexposed previously by absorbed light to saturation of the long-wave shift of fundamental optical absorption edge, causes the same changes in IR spectrum as described by bond-switching reaction (1). However, the intensities of the main vibrational modes associated with structural fragments based on homo- and heteropolar covalent bonds (Fig. 1) are more than twice smaller.

The same feature has been observed in the a- As_2S_3 films previously [8]. So, we can explain this result by thermal annihilation not all, but only a half part of coordination defects created at the previous stage of first-cycle photoexposure. Indeed, as it is stated above, the absorbed light exposure of the freshly-deposited a- As_2Se_3 films lead to homopolar bonds switching in heteropolar ones according to the reaction of Eq. (1). Four coordination defect pairs shown in Fig. 2 appear during these PhST. But in the nearest vicinity of $(As_2^-; Se_3^+)$ and $(As_4^+; Se_1^-)$ coordination defects, formed owing to Eq. (1) and Eq. (3) schemes in Fig. 2, only the high-energetic heteropolar As-Se chemical bonds exist (their dissociation energy is equal to 2.26 eV, while dissociation energies of homopolar As-As and Se-Se chemical bonds are 2.07 and 2.14 eV, respectively [21,26]). These defect pairs are thermally stable at the subsequent thermal treatment, but two other ones with homopolar Se-Se and As-As chemical bonds in the nearest neighbourhood, formed owing to Eq. (2) and Eq. (4) schemes in Fig. 2, annihilate at the thermal annealing (Fig. 3). This process of annihilation is accompanied by subsequent switching of two remaining homopolar As-As and S-S bonds in

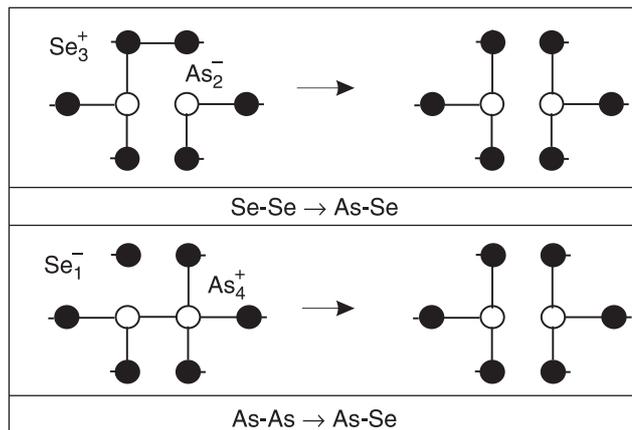


Fig. 3. Topological schemes of coordination topological defects annihilation induced by first-cycle thermal annealing of the previously photoexposed freshly-deposited a- As_2Se_3 thin film.

heteropolar As-Se ones in full agreement with the obtained experimental results.

The freshly-deposited a- As_2Se_3 thin films treated in the first cycle by absorbed light and thermally annealed are fully prepared for the reversible PhST observation.

3.3. The stage of reversible PhST and thermal bleaching

As it follows from Fig. 4(a), the photoexposure of the a- As_2Se_3 film in the third cycle (after two previous cycles of photoexposure and thermal annealing) increases the content of structural complexes based on heteropolar short As-Se (243 cm^{-1}), homopolar Se-Se ($260, 250\text{--}245, 236\text{--}230, 144\text{--}136\text{ cm}^{-1}$) and As-As ($230, 140, 120\text{ cm}^{-1}$) bonds, appeared instead of destructed pyramidal $AsSe_3$ (217 cm^{-1}) and bridge As-Se-As ($274\text{--}269, 172\text{ cm}^{-1}$) units. The subsequent annealing of this film is fully reversible [see Fig. 4(b)]. The observed changes in the optical density D (Fig. 4) can be repeated in multiple photoexposure-annealing cycles without any visible delaying.

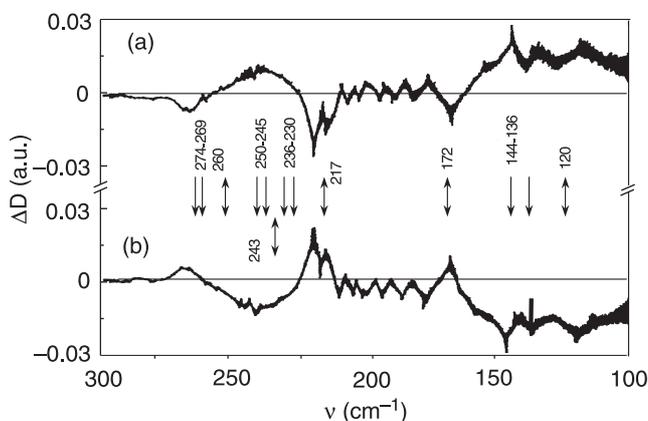


Fig. 4. Additional optical density in the a- As_2Se_3 thin film induced by third-cycle photoexposure (a) and subsequent annealing (b).

Thus, the bonds switching in the a-As₂Se₃ films at the stage of reversible PhST differs from one, observed at the stage of irreversible PhST in accordance to bond-switching reaction of Eq. (1). By comparing the intensities of vibrational band at 217 cm⁻¹ in IR spectrum of the freshly-prepared film with its additional optical density in the spectrum in Fig. 4, it is estimated that no more than 3% of AsSe₃-type atomic oscillators take place at the reversible stage of PhST. However, in contrast to the a-As₂S₃ thin film showing the reversible PhST only due to heteropolar-homopolar bonds switching (the first-type bonds switching – I) defined by Eq. (1), the a-As₂Se₃ film contains an additional channel of the reversible PhST connected with bridge As-Se-As bonds switching in short layer ones of the same type (the second-type bonds switching – II).

The first-type bonds switching I in the a-As₂Se₃ film can be considered likely to the a-As₂S₃ film as (As₂⁻; Se₃⁺) and (As₄⁺; Se₁⁻) coordination topological defects formation induced by photoexposure [7–10]. The full topological scheme for reversible PhST in the a-As₂Se₃ film associated with heteropolar-homopolar bonds switching I is shown in Fig. 5. This scheme contains also the stages of first-cycle photoexposure (transition from initial state 1 to photoinduced state 2 in Fig. 5) and subsequent first-cycle annealing (transition from photoinduced state 2 to thermally in-

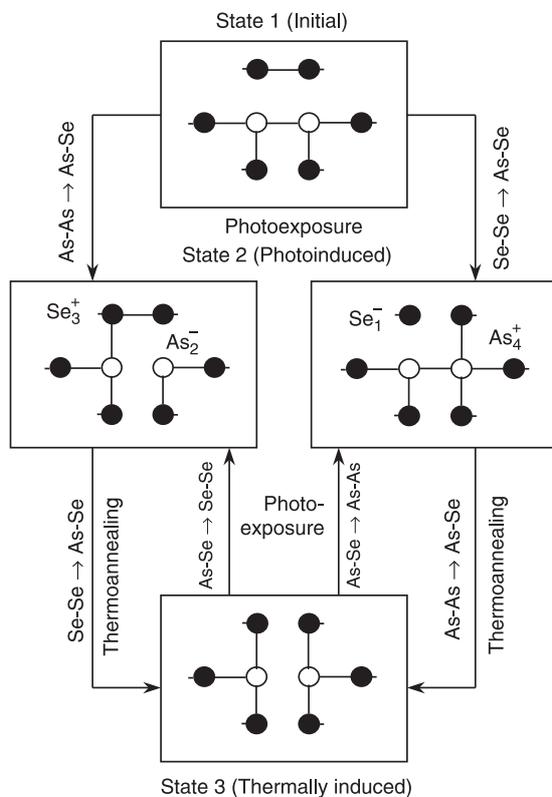


Fig. 5. Topological schemes of the full sequence for reversible PhST formation in the a-As₂Se₃ thin film connected with heteropolar-homopolar bonds switching.

duced state 3 in Fig. 5) of the freshly-deposited a-As₂Se₃ thin film.

Thus, the pyramidal AsSe₃ units, formed in state 3 (Fig. 5) after first-cycle photoexposure and thermal annealing of the freshly-deposited a-As₂Se₃ thin film, are the initial structural fragments for coordination topological defects at the multiple subsequent stages of reversible PhST. Comparing the proposed topological schemes for bonds switching in the a-As₂Se₃ film induced by first-cycle photoexposure (Fig. 2), first-cycle thermal annealing (Fig. 3) and third-cycle photoexposure-annealing (Fig. 4), we conclude that these defect-forming pyramidal AsSe₃ units appear in such nets of a glassy-like network, where originally more extended homopolar covalent bonds existed. It means that an additional intrinsic free volume introduced as a difference in homopolar-heteropolar bond lengths creates the sufficient conditions for reversible PhST in the investigated thin films.

The second-type bonds switching II can be described as destruction of bridge As-Se-As complexes and their subsequent polymerisation with layer-like As-Se bonds formation. One of the possible variants for such PhST is presented in Fig. 6. The homoatomic coordination defects pair (As₂⁻; As₄⁺) is formed in a structural network of the a-As₂Se₃ instead of non-defect pyramidal AsSe₃ and bridge As-Se-As units, the short-layer heteropolar As-Se chemical bond being appeared within As₄⁺-Se₂⁰-As₃⁰ structural chain. The observed small shift in the spectral position for some IR absorption bands (no more than 10 cm⁻¹), in particular the long-wave shift of the bent 172, 274–269 cm⁻¹ modes (see Fig. 3), are produced by strong relaxation processes at

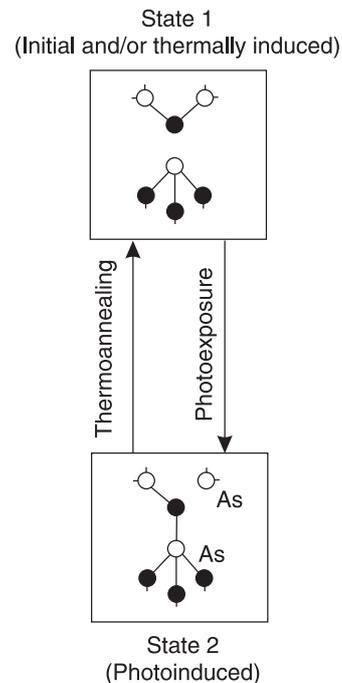


Fig. 6. Topological scheme of the reversible PhST in the a-As₂Se₃ thin film connected with bridge-layer heteropolar bonds switching.

the reversible stage of PhST because of increased intermolecular interactions between defect-containing structural groups [4]. At the stage of irreversible PhST, these features were relatively negligible (Fig. 1).

It should be emphasised that bent vibrational modes ($\nu < 170 \text{ cm}^{-1}$) are dominant in the additional optical density spectrum of the reversibly treated a- As_2Se_3 films (Fig. 4) as they are more sensitive to intermolecular (interlayer) interactions [4]. It testifies that medium-range ordering structural changes (rotations and displacements of atomic blocks) are very important in the observed reversible PhST. Simultaneously, the intensities of stretch vibrational modes in $300\text{--}200 \text{ cm}^{-1}$ spectral region are stronger than ones of bent vibrational modes at the stage of first-cycle photoexposure of the freshly-deposited a- As_2Se_3 films in good accordance to a preference of irreversible short-range ordering structural transformations [4].

The above changes at the level of medium-range ordering must be taken into account to develop the realistic model of reversible PhST in the a- As_2Se_3 film. But they are not illustrated anyway in Fig. 2, 3, 5, and 6. Only schematic topological reactions of bonds switching (e.g., number and type of the nearest neighbours surrounded under- and over-coordinated atomic defects), not the real structural fragments, are shown, in turn, by these figures. In other words, any geometrical parameters (bond lengths or angles) should not be accepted as realistic ones from Figs. 2, 3, 5, and 6.

Apart from, these topological schemes mask the features of intermediate (“light-in”) process between initial and final states, e.g., the origin of initiated processes for bonds switching. We suppose, at the basis of experimental results obtained for a-Se using “in-situ” EXAFS [12] that this stage includes:

- photoexcitation of lp-electrons localised at Se atoms,
- formation of new dynamical covalent bond with these excited lp-electrons,
- relaxation of the created configurational disturbance through destruction of another nearest bond accompanied by correspondent atomic displacements.

Recently, similar experimental [27] and theoretical [28] works have been devoted to study the mechanisms of photoinduced effects in a- As_2Se_3 . In spite of some differences, the both investigations are relevant to chemical bonds switching with an associated coordination defects. However, the real topological schemes for such microstructural transformations have not been identified exactly. Our investigations show the full subsequence of covalent chemical bonds switching in a- As_2Se_3 need for the reversibility of the observed photoinduced effects.

4. Conclusions

The microstructural origin of PhST in the a- As_2Se_3 thin film was studied by IR Fourier-transform spectroscopy in the range of $300\text{--}100 \text{ cm}^{-1}$.

It is shown that irreversible PhST caused by photoexposure of the freshly-deposited a- As_2Se_3 thin film are connected with coordination topological defects formation accompanied by homopolar As-As and Se-Se chemical bonds switching in heteropolar As-Se ones. Such defects can be identified as atomic pairs with uncompensated electrical charge and anomalous coordination. In the case under consideration, $(\text{As}_2^-; \text{Se}_3^+)$ and $(\text{As}_4^+; \text{Se}_1^-)$ defect pairs are formed.

The subsequent thermal annealing of the photoexposed freshly-deposited a- As_2Se_3 thin films causes the same changes in IR absorption spectrum as in the case of their photoexposure, but correspondent intensities of the main vibrational modes are more than twice smaller. This result is explained by thermal annihilation of a half part of coordination topological defects created at the previous stage.

The reversible stage of PhST is caused by two different types of bonds switching – heteropolar bonds switchings in homopolar ones, as well as heteropolar bridge bonds switchings in short layer ones. Both processes are associated with coordination defect pairs and atomic displacements at the medium-range ordering structural level.

References

1. J.P. DeNeufville, S.C. Moss, and S.R. Ovshinsky, “Photostructural transformation in amorphous As_2Se_3 and As_2S_3 films”, *J. Non-Cryst. Solids* **13**, 191–223 (1974).
2. K. Tanaka, “Evidence for reversible photostructural change in local order of amorphous As_2S_3 film”, *Solid State Com.* **15**, 1521–1524 (1974).
3. M.N. Brodsky, *Amorphous Semiconductors*, Mir, Moscow, 1982.
4. S.R. Elliott, “A unified model for reversible photostructural effects in chalcogenide glasses”, *J. Non-Cryst. Solids* **81**, 71–98 (1986).
5. H. Fritzsche, “The origin of reversible and irreversible photostructural changes in chalcogenide glasses”, *Phil. Mag.* **B68**, 561–572 (1993).
6. M. Frumar, A.F. Firth, and A.E. Owen, “A model for photostructural changes in the amorphous As-S system”, *J. Non-Cryst. Solids* **59/60**, 921–924 (1983.)
7. V.N. Kornelyuk, I.V. Savytsky, O.I. Shpotyuk, and I.I. Yaskovets, “The mechanism of reversible photoinduced effects in As_2S_3 thin films”, *Fiz. Tverd. Tela* **31**, 311–313 (1989). (in Russian).
8. O.I. Shpotyuk, “Photostructural transformations in amorphous chalcogenide semiconductors”, *Phys. Stat. Sol.* **B183**, 365–374 (1994).
9. O.I. Shpotyuk, J. Kasperczyk, and I.V. Kityk, “Mechanism of reversible photoinduced optical effects in amorphous As_2S_3 ”, *J. Non-Cryst. Solids* **15**, 218–225 (1997).
10. O.I. Shpotyuk, J. Kasperczyk, S. Szymura, and I. Kityk, “Mechanism of photoinduced optical effects in amorphous As_2S_3 . Part II. Reversible changes of optical properties”, *Opto-Electron. Rev.* **4**, 69–76 (1996).
11. C.Y. Yang, M.A. Paesler, and D.E. Sayers, “Measurement of local structural configuration associated with reversible

- photostructural changes in arsenic trisulphide films”, *Phys. Rev.* **B36**, 9160–9167 (1987).
12. A.V. Kolobov, H. Oyanagi, K. Tanaka, and K. Tanaka, “Photostructural changes in amorphous selenium: an in situ EXAFS study at low temperature”, *J. Non-Cryst. Solids* **198&200**, 709–713 (1996.)
 13. S.A. Solin and G.N. Papatheodorou, “Irreversible thermostructural transformations in amorphous As_2S_3 films: a light scattering study”, *Phys. Rev.* **B15**, 2084–2090 (1977).
 14. U. Strom and T.P. Martin, “Photo-induced changes in the infrared vibration spectrum of evaporated As_2S_3 ”, *Solid State Com.* **29**, 527–530 (1979).
 15. T. Mori, K. Matsuishi, and T. Arai, “Vibrational properties and network topology of amorphous As-S systems”, *J. Non-Cryst. Solids* **65**, 269–283 (1984).
 16. A.M. Shkolnikova, V.S. Gerasimenko, and E.V. Shkolnikov, “Investigation of vibrational spectra of glasses of As_2S_3 -Se system, prepared in different synthesis regimes”, *Fiz. Khim. Stekla* **8**, 497–500 (1982). (in Russian).
 17. E.V. Shkolnikov, V.S. Gerasimenko, and Z.U. Borisova, “Vibrational spectra of glasses and partial volumes of components in Se- As_2Se_3 system”, *Fiz. Khim. Stekla* **3**, 338–342 (1977).
 18. G. Lucovsky and F.L. Galeener. “Infrared studies of amorphous semiconductors”, *Proc. 6th Int. Conf. Structure and Properties of Non-Crystalline Semiconductors*, Nauka, Leningrad, 1976.
 19. J. Zirke and A. Tausend, “Disorder-induced effects on the infrared spectra of amorphous selenium”, *Abst. 6th Int. Conf. Structure and Properties of Non-Crystalline Semiconductors*, Nauka, Leningrad, 1976.
 20. A.L. Kartuzhanskij, *Nonsilver Photographic Processes*, Nauka, Moscow, 1984.
 21. A. Felts, *Amorphous and Vitreous Inorganic Solids*, Mir, Moscow, 1986.
 22. N.F. Mott, E.A. Davis, and R.A. Street, “States in the gap and recombination amorphous semiconductors,” *Phil. Mag.* **32**, 961–996 (1975).
 23. M.A. Kastner, D. Adler, and H. Fritzsche, “Valence-alternation model for localised gap states in lone-pair semiconductors”, *Phys. Rev. Lett.* **37**, 1504–1507 (1976).
 24. M.A. Kastner, “Defect chemistry and states in the gap of lone-pair semiconductors”, *J. Non.-Cryst. Solids* **31**, 223–240 (1978).
 25. R.A. Street, “Recombination in amorphous semiconductors”, *Phys. Rev.* **B17**, 3984–3995 (1978).
 26. K.G. Rao and R. Mohan, “Chemical bond approach to determining conductivity band gaps in amorphous chalcogenides and pteictides”, *Solid State Com.* **39**, 1065–1068 (1981).
 27. G. Chen, H. Jain, S. Khalid, J. Li, D.A. Drabold, and S.R. Elliott, “Study of structural changes in amorphous As_2Se_3 by EXAFS under in situ laser irradiation”, *Solid State Com.* **120**, 149–153 (2001).
 28. J. Li and D.A. Drabold, “Direct calculation of light-induced structural change and diffusive motion in glassy As_2Se_3 ”, *Phys. Rev. Lett.* **85**, 2785–2788 (2000).

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**XVII SCHOOL ON OPTOELECTRONICS
PHOTOVOLTAICS –
SOLAR CELLS and DETECTORS**

Kazimierz Dolny, October 13–16, 2003

Solar Cells:	Detectors:
Photovoltaics in Poland and in the World	Fundamentals of detection (thermal and photon detectors)
Silicon cells (c-Si, a-Si, poli-Si)	Visible and UV detectors
Polycrystalline cells (CuInSe ₂ , CdTe)	Infrared detectors
A ^{III} B ^V cells	Focal plane arrays
Organic cells	Systems of detection
Photovoltaic modules and systems	Applications of detectors
Photovoltaic metrology	

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