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Chalcogenide thin films with specific properties

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References

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Abstract

This work deals with the preparation of thin films of chalcogenide glasses from solution using the spin-coating method. The focus of this work was the preparation of chalcogenide glass thin films with specific properties. The properties of the thin film were controlled by adjusting the composition of the source chalcogenide glass solution. Two methods of adjusting the solution composition were studied. The first approach was mixing solutions of chalcogenide glasses of different compositions. The second option was to adjust the solution composition by dissolving elemental chalcogen in an already prepared glass solution.

Thin films with high optical quality were prepared by both methods. Their properties were studied using EDS spectroscopy (elemental composition, organic residue content), UV-VIS-NIR spectroscopy (thickness, refractive index and optical band gap), Raman spectroscopy (chemical structure), SEM and AFM microscopy (surface topography and surface roughness) and by measuring the etching kinetics in a basic aprotic bath (chemical resistance).

This work proved that both methods for altering the source solution composition are applicable. Both methods produce films with high optical quality and allow for a gradual change in the composition of the source solution and thus the composition and properties of deposited thin films.

Keywords

Chalcogenide glass, thin films, solution processing, spin-coating, composition tailoring

Abstrakt

Tato práce se zabývá přípravou tenkých vrstev chalkogenidových skel z roztoku pomocí metody spin-coating. Hlavním cílem této práce byla příprava tenkých vrstev chalkogenidových skel se specifickými vlastnostmi. Vlastnosti tenkých vrstev byly řízeny úpravou složení výchozího roztoku chalkogenidového skla. Byly studovány dvě metody úpravy složení roztoku. První metodou bylo míchání roztoků chalkogenidových skel různých složení. Druhou možností byla úprava složení roztoku rozpuštěním elementárního chalkogenu v již připraveném roztoku skla.

Pomocí obou metod byly připraveny vrstvy v optické kvalitě. Jejich vlastnosti byly dále studovány pomocí EDS spektroskopie (prvkové složení, obsah organických residuí) UV-VIS-NIR spektroskopie (tloušťka, index lomu a optická šířka zakázaného pásu), Ramanovy spektroskopie (chemická struktura), SEM a AFM mikroskopie (topografie povrchu a povrchová hrubost) a pomocí měření kinetiky leptání v bazické aprotické lázni (chemická odolnost).

Tato práce prokázala použitelnost obou metod změny složení výchozího roztoku. Obě metody produkují opticky kvalitní vrstvy a umožňují postupnou změnu složení výchozího roztoku a tím i složení a vlastností tenkých vrstev.

Klíčová slova

Chalkogenidová skla, tenké vrstvy, příprava z roztoku, spin-coating, úprava složení

Table of content

Introduction

Chalcogenide glasses are non-oxide glasses containing S, Se, Te, or their combination as the main component. The first discovered chalcogenide glass was amorphous As_2S_3, whose discovery is attributed to Rudolf Frerichs in 1953 [1]. In the following years, research gradually expanded, and new binary and ternary systems of chalcogenide glasses were investigated. The research of Ovshinsky in 1968 [2] proved to be particularly groundbreaking when he discovered the possibility of controlling the changes between the amorphous and crystalline phase in chalcogenides using an electric field. Subsequent research also discovered differences in the optical properties of the crystalline and amorphous phases. This research significantly increased interest in chalcogenide glasses and led to the first practical applications of chalcogenide glasses, such as xerography, X-ray detectors, phase-change memory, and optical recording media (CDs, DVDs) [3].

One of the main advantages of chalcogenide glasses is the wide range of possible compositions, each with specific properties. Chalcogenide glasses can be used in the form of bulk glasses (windows, lenses), in the form of optical fibers, or as thin films on a suitable substrate.

The focus of this work is to prepare thin films of chalcogenide glass with specific properties from solution using the spin-coating method. The properties of the deposited thin films were controlled by altering the composition of the source solution via two methods. The first method involves mixing solutions of two binary glass compositions to prepare thin films of the ternary glass system from the newly formed solution. The second method modified the solution by dissolving elemental chalcogen in an already prepared source bulk glass solution.

Experimental part

Glass synthesis

The bulk glasses were prepared by direct synthesis from elements that were stored under a nitrogen atmosphere before weighing. The pure elements in semiconductor purity (5N) were weighed into precleaned quartz glass ampoules and sealed under high vacuum (10^{-3} Pa). The evacuated ampoule was placed in a rocking tube furnace and gradually heated to 850 °C. The synthesis was performed over the course of 32 h. After completion of the synthesis, the ampoule was quenched in cold water.

Preparation of solutions

Preparation of bulk glass solutions

To prepare the solution, the bulk glass was crushed in an agate bowl and subsequently weighed into a glass vial. The vial was then placed under a nitrogen atmosphere, and the exact amount of solvent was added using a pipette. Organic amines – n-butylamine (BA) or ethylenediamine (EDA) were used as solvents. The solution was stirred either using a vortex (Vortex Classic, Velp) - in the case of EDA solutions or using a glass stirrer on a magnetic stirrer (Multistirrer 6, Velp) - in the case of BA solutions. The prepared solution was either directly used for the deposition of thin films, mixed with other solution in a defined ratio, or modified by the addition of elemental chalcogen.

Preparation of thin films by spin-coating

The entire preparation of thin films by dynamic spin-coating was performed in a glove box under a nitrogen atmosphere. The precleaned substrate was placed on the vacuum holder of a spin coater, spun at a selected speed, and the solution was then pipetted onto the rotating substrate. The rotation continued for 60 seconds to evaporate the majority of the solvent. The film was then heated to 60 °C (or 100 °C) on an annealing table for 20 minutes to stabilize the thin film (as-prepared thin films). The prepared thin films were subsequently annealed under an inert atmosphere to higher temperatures (annealed thin films) in the range selected based on previous experiments.

Composition analysis of thin films and SEM microscopy

For EDS analysis and SEM microscopy, thin films were deposited on the conductive substrates (soda-lime glass with sputtered gold film). A LYRA 3 scanning electron microscope (Tescan) equipped with an Aztec X-Max 20 energy dispersive analyzer (Oxford Instrument) was used for elemental analysis. The elemental composition of the thin films was determined by measuring five 400x400 μm areas at an accelerating voltage of 5 kV (interaction volume of approximately 200 nm). The presented data are the average of these measurements. SEM scans were taken at an accelerating voltage of 10 kV.

Study of the structure of the glasses using Raman spectroscopy

The structure of bulk glasses, thin films, and source solutions was studied using Raman spectroscopy (MultiRAM, Bruker). For comparison, Raman spectra of the pure solvents used were also measured. All samples were measured using a Nd:YAG laser with a wavelength of 1064 nm. The resulting spectra are the averages of 64 measurements with a resolution of 2 cm^{-1} in the case of bulk samples and thin films. For solutions, due to the weaker signal, an average of 200 measurements with a resolution of 2 cm^{-1} was used. The spectra of bulk samples and thin films were normalized to the intensity of the most intense band, and the spectra of solutions to the most intense band of the solvent used in the region of 200-500 cm^{-1}.

Determination of thin film optical properties

UV-VIS-NIR spectroscopy was used to study the optical properties of thin films. Transmission spectra were measured in the range of 190 – 2000 nm using a spectrometer (UV-3600, Shimadzu). A model based on the equations presented by R. Swanepoel [4], where the dispersion of refractive index was parametrized using the Wemple-DiDomenico approximation [5], was used to evaluate the thickness and refractive index.

The optical band gap was determined using the Tauc method [6].

Study of surface roughness using AFM microscopy

The surface roughness was studied using atomic force microscopy in semi-contact mode using an NTEGRA atomic force microscope (NT-MDT) equipped with HA_HR tips (Scansense). Three areas of 5 x 5 μm were measured, and the surface roughness values were determined following the ISO 4287/1 norm.

Study of the chemical resistance of thin films

The chemical resistance of thin films was studied using etching in a bath of n-butylamine (BA) or ethylenediamine (EDA) in dimethyl sulfoxide (DMSO). The etching kinetics were measured in situ using a fiber UV-VIS-NIR spectrometer (EPP 2000 UV-VIS, StellarNet). The thickness loss (Δd) can be described by the equation:

$$\Delta d = (\Delta k \cdot \lambda)/2n$$

, where Δk is the order change of the interference maximum, λ is the wavelength of the radiation and n is the refractive index for a given wavelength λ. The method is further described in [7].

Results and discussion

The presented work was divided into three parts. The first part deals with the preparation of thin films of the ternary As-S-Se system by mixing solutions of binary glasses of $As_{33}S_{67}$ and $As_{33}Se_{67}$. The second part deals with the modification of $As_{40}S_{60}$ glass solutions via the addition of Se, and the third with the modification of $As_{50}Se_{50}$ glass solutions via the addition of S or Se.

1. Mixing the solutions of As-S and As-Se binary glass systems.

The first part of this work dealt with the preparation of chalcogenide glass thin films with specific properties by mixing binary glass solutions. Solutions of five compositions ($As_{33}S_{67}$, $As_{33}S_{50}Se_{17}$, $As_{33}S_{33}Se_{33}$, $As_{33}S_{17}Se_{50}$, and $As_{33}Se_{67}$) were prepared from ternary bulk glasses, and solutions of three compositions ($As_{33}S_{50}Se_{17}$, $As_{33}S_{33}Se_{33}$, and $As_{33}S_{17}Se_{50}$) were also prepared by mixing solutions of binary $As_{33}S_{67}$ and $As_{33}Se_{67}$ glasses to directly compare both methods. Ethylenediamine was chosen as a suitable solvent for all glass systems. The mixed solutions were prepared by pipetting calculated volumes of binary glasses $As_{33}S_{67}$ and $As_{33}Se_{67}$ into a glass vial and mixing the resulting solution for 30 minutes using a vortex mixer. Solution gradually changed color from yellow $As_{33}S_{67}$ to red $As_{33}Se_{67}$ (Figure 1).

Figure 1 – Chalcogenide glass solutions of $As_{33}S_{67-x}Se_x$ glass system prepared by mixing binary solutions of $As_{33}S_{67}$ and $As_{33}Se_{67}$ chalcogenide glass.

The thin films were deposited from the solutions by spin-coating onto pre-cleaned soda-lime glass substrates. After deposition, the thin films were stabilized by 20-minute annealing at 100 °C (as-prepared thin films) and subsequently annealed at temperatures of 120, 140, 160, and 180 °C (annealed thin films) to remove residual solvent and decompose organic-inorganic salts formed during the dissolution of bulk chalcogenide glass. The preparation of solutions and thin films, as well as annealing, took place under an inert atmosphere inside a glove box.

The composition of the thin films was verified by EDS analysis and corresponded to the targeted values within the measurement accuracy. Only

samples containing a large amount of S show a decrease of S content (around 2 at. %) when annealed to higher temperatures.

The chemical structure of the solutions and subsequently prepared thin films was studied using Raman spectroscopy. No measurable difference was observed between the solutions prepared by mixing binary glass solutions and those prepared from ternary bulk glasses. Therefore, all chemical changes occurred in the solution phase and did not affect the properties of the thin films. The chemical structure of as-prepared thin films differs from the structure of bulk glass. Due to the fragmentation of the structure during dissolution, As_4S_4 clusters and chalcogens in the form of chains and rings are present in the structure of as-prepared thin films. Upon annealing, the clusters react with chalcogens and form a polymerized structure of $AsX_{3/2}$ pyramids (where X is a chalcogen). Additionally, the residual solvent evaporates, organic-inorganic salts decompose, and the glass matrix polymerizes during the annealing. The structure of annealed thin films is similar regardless of the preparation method (Figure 2).

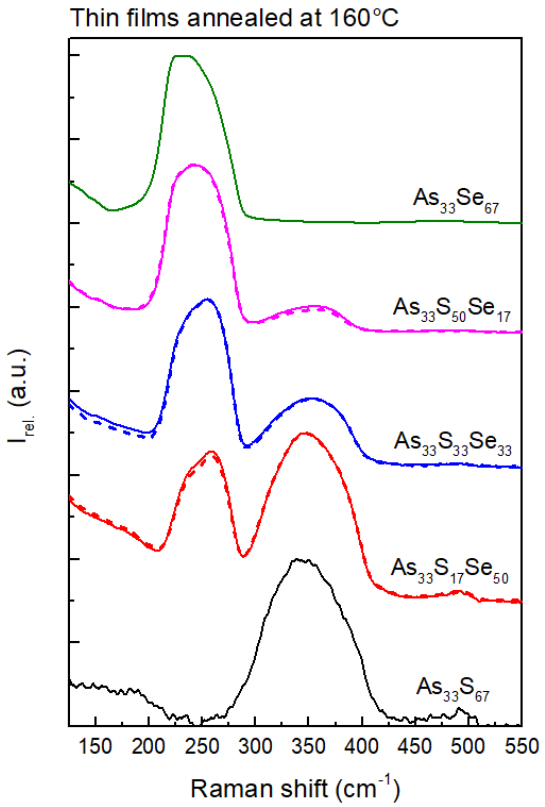

Figure 2 - *Raman spectra of annealed thin films (160 °C) from $As_{33}S_{67-x}Se_x$ system prepared by dissolution of the ternary bulk glass and by mixing solutions of $As_{33}S_{67}$ and $As_{33}Se_{67}$ binary bulk glass.*

All prepared thin films possessed high optical quality without visible defects, as demonstrated by SEM microscopy and surface roughness measurements (AFM microscopy in semi-contact mode). The refractive index

and optical band gap of the prepared thin films were evaluated from the UV-VIS-NIR transmission spectra. With increasing Se content, the refractive index increased linearly (Figure 3), and the optical band gap decreased. The chemical resistance of the thin films, studied by measuring the etching kinetics in a basic aprotic bath, also increased with increasing Se content.

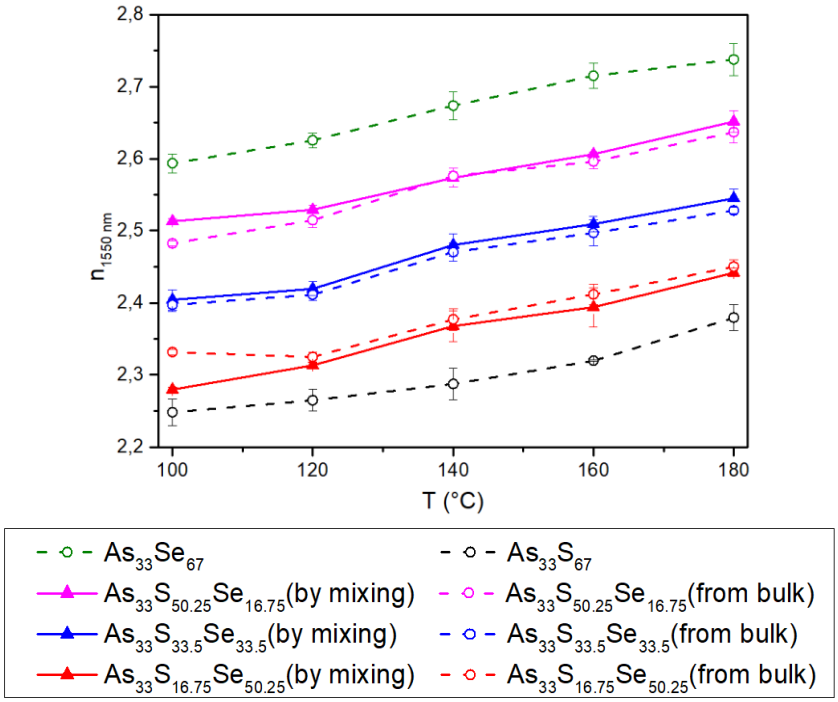

Figure 3 – Refractive index dependence on annealing temperature of thin films from the $As_{33}S_{67-x}Se_x$ glass system prepared by dissolution of the ternary bulk glass and by mixing solutions of $As_{33}S_{67}$ and $As_{33}Se_{67}$ binary bulk glass.

No difference in properties between the films prepared from ternary bulk glasses and films prepared by mixing binary glass solutions was observed. This proves the applicability of this preparation method for a wide range of $As_{33}S_{67-x}Se_x$ glass compositions and the possibility of specifically controlling the composition and thus the optical and chemical properties of the thin films prepared in this manner. This method offers a technologically simpler alternative for the preparation of thin films. Instead of synthesizing a series of bulk glasses, which is relatively time-consuming, it is sufficient to prepare two bulk glasses and by mixing their solutions, it is possible to prepare any composition and thus control the properties of the films. This significantly simplifies the preparation of thin films from solutions and provides an alternative to vacuum techniques such as evaporation, sputtering, where similar mixing is difficult.

2. Modification of As-S glass solutions via the addition of Se

The second part of this work investigated the modification of the $As_{40}S_{60}$ glass solutions by adding amorphous Se. Although Se is insoluble in most organic solvents, it is soluble in solutions of chalcogenide glasses, due to the presence of reactive As_4S_4 clusters in the solution. Four compositions of solutions from n-butylamine (BA) and ethylenediamine (EDA) were prepared - the original composition $As_{40}S_{60}$ and the modified compositions $As_{36}S_{54}Se_{10}$, $As_{32}S_{48}Se_{20}$, and $As_{28}S_{42}Se_{30}$. To prepare the modified solutions, a varying amount of crushed amorphous Se was added to a previously prepared $As_{40}S_{60}$ solution. The dissolution of Se was carried out while mixing the solution using a vortex. During this time, all Se dissolved without any signs of solution degradation (precipitate formation, phase separation). The color of the solution gradually changed from yellow ($As_{40}S_{60}$) to red ($As_{28}S_{42}Se_{30}$ in BA) or black ($As_{28}S_{42}Se_{30}$ in EDA) – see Figure 4.

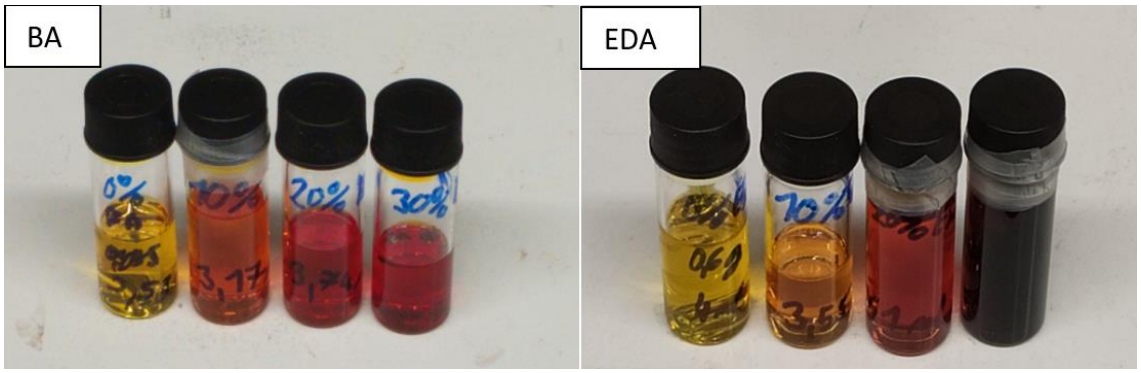

Figure 4 – Solutions of chalcogenide glasses in BA and in EDA. Compositions (left to right: $As_{40}S_{60}$, $As_{36}S_{54}Se_{10}$, $As_{32}S_{48}Se_{20}$, $As_{28}S_{42}Se_{30}$).

The solutions prepared by this method were subsequently used for the deposition of thin films by the spin-coating method. The prepared thin films were stabilized by annealing at 60 °C for 20 minutes (as-prepared thin films) to evaporate the majority of the solvent. The temperature was chosen below the boiling point of n-butylamine (78 °C), but it was also used for ethylenediamine films for direct comparison of the results. Subsequently, the thin films were annealed to higher temperatures (90, 120, 150, and 180 °C), which were chosen based on preliminary experiments.

The composition of the prepared thin films was verified using the EDS method and corresponded to the target values.

The chemical structure of the solutions and subsequently prepared thin films was very similar for samples from n-butylamine and ethylenediamine. Raman spectroscopy has shown that during the dissolution of glass, fragmentation of the glass structure occurs, and the prepared solution contains a

higher amount of As_4S_4 clusters than the source glass. After the addition of Se, bands corresponding to Se_8 rings (267 cm^{-1}) [8,9] and Se_n chains (244 cm^{-1}) [8,9] appear and subsequently grow in the spectra of the solutions, while the intensity of the As_4S_4 cluster (328, 376 cm^{-1}) [10] bands gradually decreases, suggesting that the presence of As_4S_4 clusters enables the dissolution of Se (Figure 5). Due to the fragmentation of the structure during dissolution, As_4S_4 clusters are also present in the structure of the as-prepared glass thin films. During annealing, decomposition of organic-inorganic salts and reaction of As_4S_4 clusters with the present S and Se occurs, forming $AsS_{3/2}$ pyramids and mixed pyramids ($AsS_{1/2}Se$ and $AsSeS_{1/2}$), thus polymerizing the glass matrix.

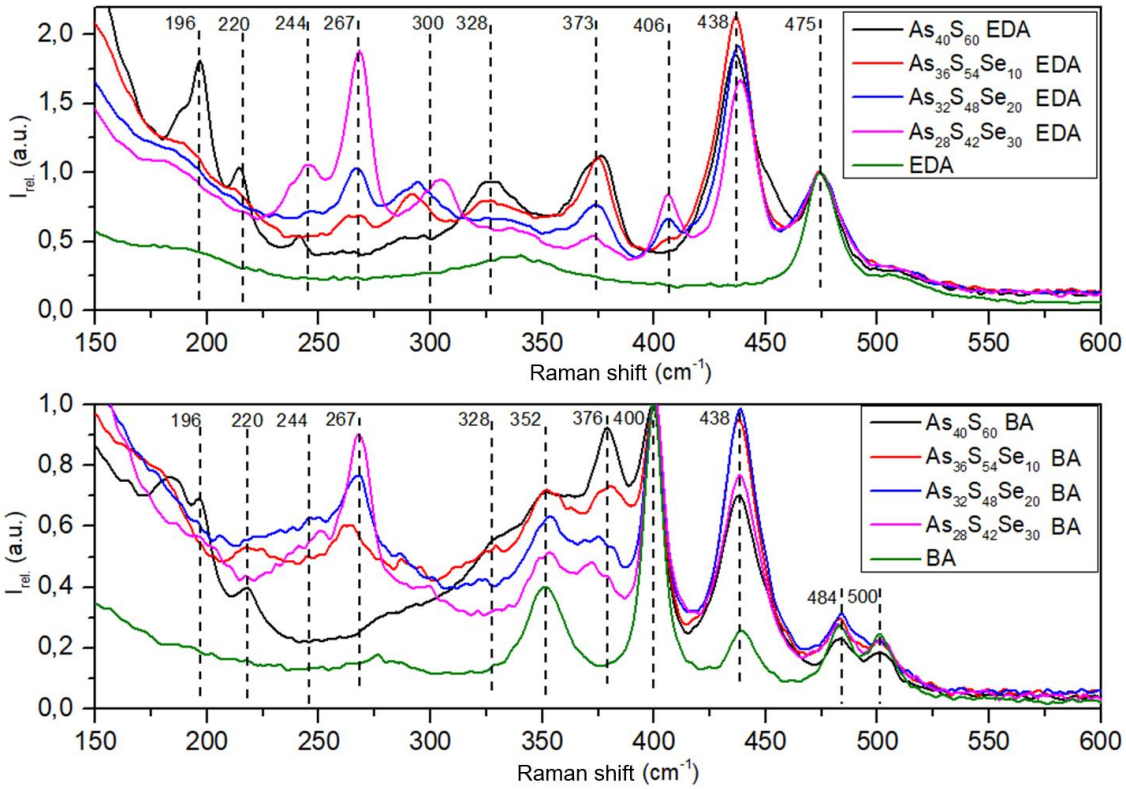

Figure 5 – Raman spectra of $As_{40}S_{60}$, $As_{36}S_{54}Se_{10}$, $As_{32}S_{48}Se_{20}$, $As_{28}S_{42}Se_{30}$ chalcogenide glass solutions in BA and in EDA.

SEM and AFM microscopy showed that the thin films prepared from solutions in ethylenediamine possessed high optical quality in the whole range of annealing temperatures, while the thin films from solutions in n-butylamine annealed to lower temperatures (90 and 120 °C) showed high porosity and low optical quality. For thin films prepared from n-butylamine solutions, evaluation of optical parameters was not possible due to the low optical quality of the films. For thin films prepared from ethylenediamine solutions, the refractive index and optical band gap were subsequently determined from UV-VIS-NIR transmission spectra. With the increasing addition of Se to the films, the refractive index of the prepared thin films gradually increased (Figure 6), and the optical band gap

gradually decreased. The chemical resistance of thin films, studied by measuring etching kinetics in a basic aprotic bath, decreases with increasing Se content because of an increase in overstoichiometry with the addition of Se, thereby reducing chemical resistance.

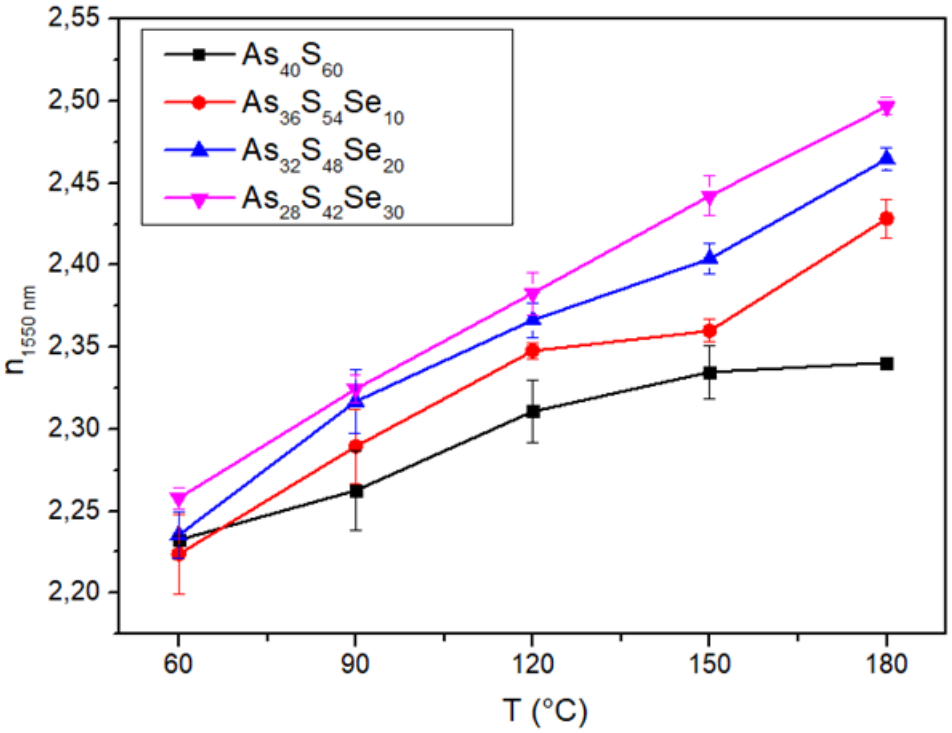

Figure 6 - Refractive index dependence on annealing temperature of $As_{40}S_{60}$ thin films and thin films of the As-S-Se chalcogenide glass system prepared from $As_{40}S_{60}$ solution and Se in EDA.

It was demonstrated that the described method can be used to prepare a wide range of thin film compositions within the As-S-Se system, enabling a precise control of the thin film's optical properties. Although the films prepared from n-butylamine solutions possessed poor optical quality, the films from ethylenediamine achieved high optical quality in the entire range of annealing temperatures for all investigated compositions. Furthermore, the source bulk glass $As_{40}S_{60}$ and elemental Se are commercially available, which allows the preparation of these thin films even in laboratories without equipment for glass synthesis.

3. Modification of As-Se glass solutions via the addition of S, Se

The third part of this work explored the modification of $As_{50}Se_{50}$ bulk glass solution within the As-Se system (by adding amorphous Se) and within the As-S-Se system (by adding S). The $As_{50}Se_{50}$ glass was chosen due to its large overstoichiometry of As and the high content of reactive clusters As_4Se_4 and

As_4Se_3. This composition has already been investigated in the past at our laboratory in the form of vacuum evaporated films and is known for its photoinduced phenomena [11]. Ethylenediamine was chosen as the solvent, which has already proven itself as a suitable solvent for the As-Se system in the past.

In total, solutions of nine compositions were prepared – the original $As_{50}Se_{50}$ solution, four solutions of the As-Se system by adding Se to the source solution ($As_{45}Se_{55}$, $As_{40}Se_{60}$, $As_{35}Se_{65}$ and $As_{30}Se_{70}$) and four solutions of the As-S-Se system by adding S to the source solution ($As_{45}S_{10}Se_{45}$, $As_{40}S_{20}Se_{40}$, $As_{35}S_{30}Se_{35}$ and $As_{30}S_{40}Se_{30}$). Dissolution was carried out while stirring the solution for 30 minutes using a vortex. During this time, all chalcogen was dissolved without any signs of solution degradation (precipitate formation, phase separation). The gradual color changes are presented in Figure 7.

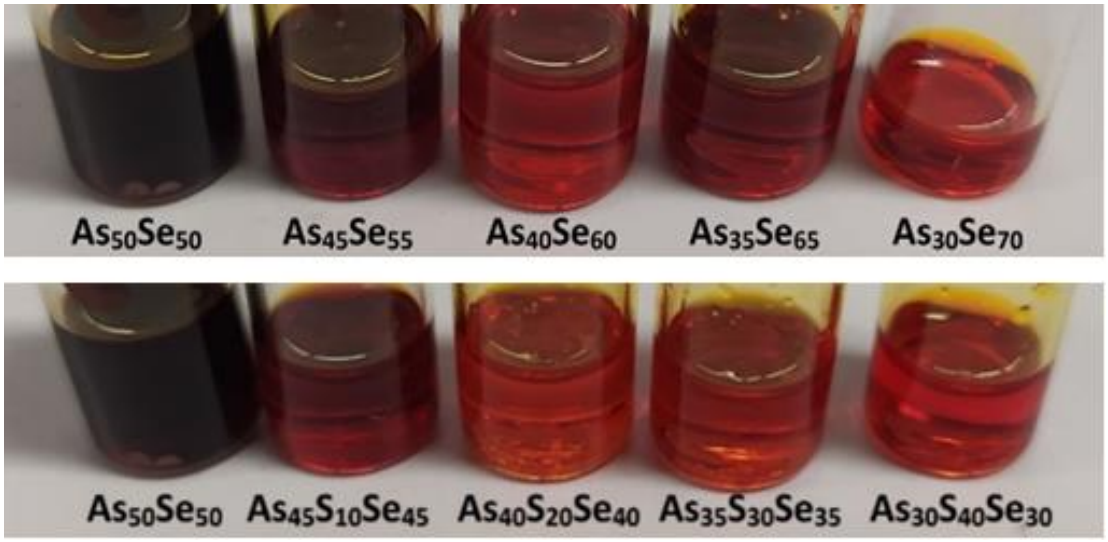

Figure 7 – Solution of $As_{50}Se_{50}$ chalcogenide glass and solutions prepared from $As_{50}Se_{50}$ chalcogenide glass and amorphous Se or S.

The prepared solutions were subsequently used for the preparation of thin films by the spin-coating method. The prepared thin films were stabilized by annealing at 60 °C for 20 minutes (as-prepared thin films) to evaporate the majority of the solvent. The temperature was chosen for a direct comparison of the results with the previous experiment. Subsequently, the thin films were annealed at higher temperatures - 90, 120, 150, and 180 °C (annealed thin films).

The composition of the thin films was verified by EDS spectroscopy and corresponded to the target values. The chemical structure of the solutions and thin films was studied using Raman spectroscopy. During dissolution, the structure is fragmented, and the solution of the source $As_{50}Se_{50}$ glass is composed of reactive clusters As_4Se_4 (204, 244 cm^{-1}) [12, 13] and As_4Se_3 (204, 237, 255 cm^{-1}) [12, 13], accompanied by pyramids $AsSe_{3/2}$ (224 cm^{-1}) [12, 13]. No bands

of Se_n chains (232 cm^{-1}) [14] or Se_8 rings (255 cm^{-1}) [13] were observed. With the addition of Se, the bands of clusters gradually disappear and the content of $AsSe_{3/2}$ polymeric structure increases, followed by the emergence of Se_n chains and Se_8 rings bands (Figure 8). With the addition of S, the formation of the $AsSe_{3/2}$ polymeric structure also occurs, as well as the formation of Se_n chains and Se_8 rings. At the same time, the formation of As_4S_4 (371 cm^{-1}) [13,15] clusters was observed by the substitution of Se by S from the As_4Se_4 clusters. With a higher excess of S formation of S_n chains (490 cm^{-1}) [9] was also observed (Figure 9). The analogous structural changes were observed in as-prepared thin films. After annealing, the content of pyramidal units increases in all compositions due to polymerization of the glass matrix.

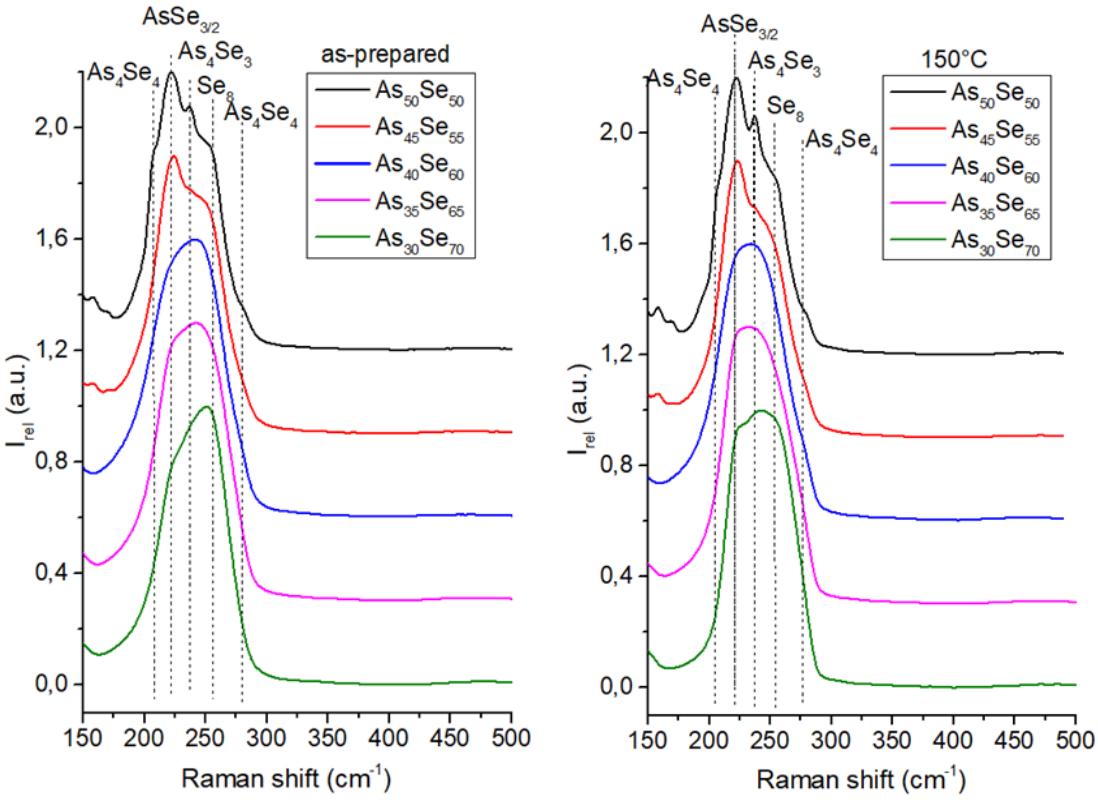

Figure 8 – Raman spectra of as-prepared and annealed (150 °C) thin films of $As_{50}Se_{50}$ chalcogenide glass and thin films of the As-Se chalcogenide glass system prepared from $As_{50}Se_{50}$ glass solution and amorphous Se.

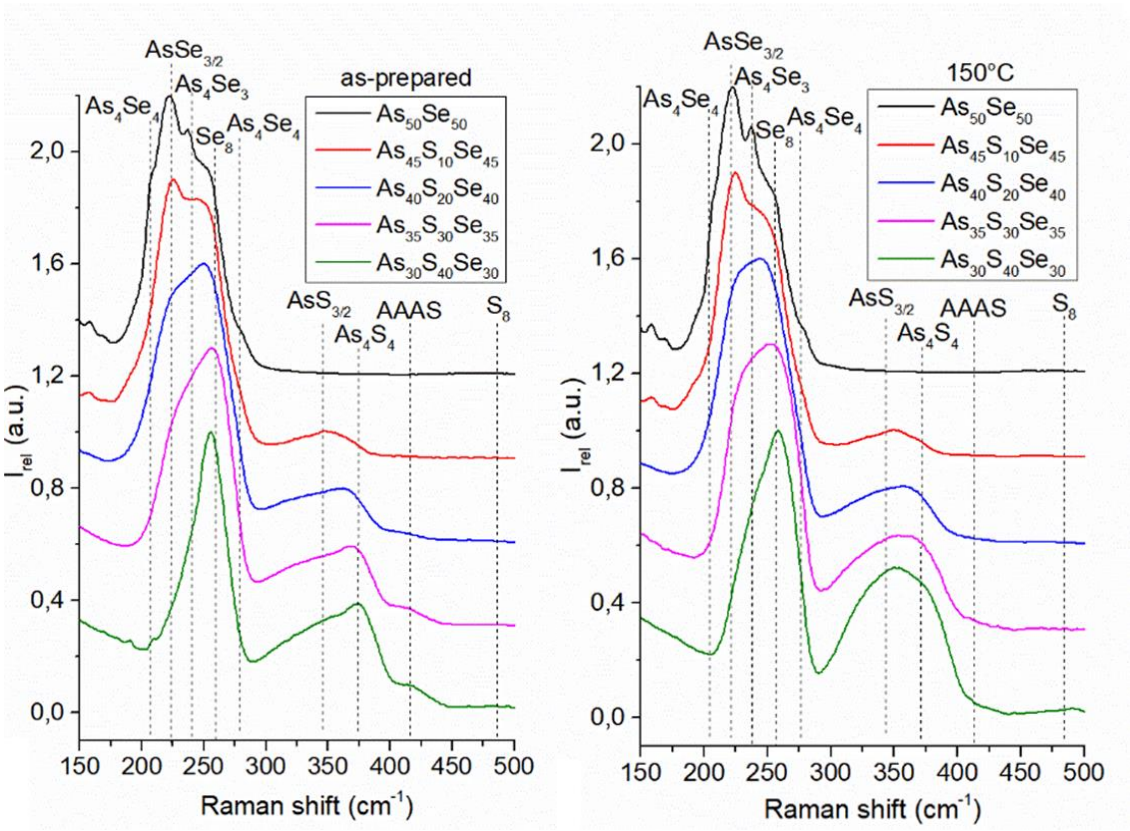

Figure 9 - Raman spectra of as-prepared and annealed (150 °C) thin films of $As_{50}Se_{50}$ chalcogenide glass and thin films of the As-S-Se chalcogenide glass system prepared from $As_{50}Se_{50}$ glass solution and S.

The optical quality of thin films was proven by SEM and AFM microscopy in the entire range of annealing temperatures (except for the compositions $As_{50}Se_{50}$, $As_{30}Se_{70}$, and $As_{30}S_{40}Se_{30}$ annealed to a temperature of 180 °C – higher than T_g). With the addition of Se, a slight increase in the refractive index was observed, while the optical band gap did not change significantly. With the addition of S, a gradual decrease of the refractive index (Figure 10) and an increase of the optical band gap were observed. The chemical resistance of prepared thin films was also studied by measuring the etching kinetics in a basic aprotic bath.

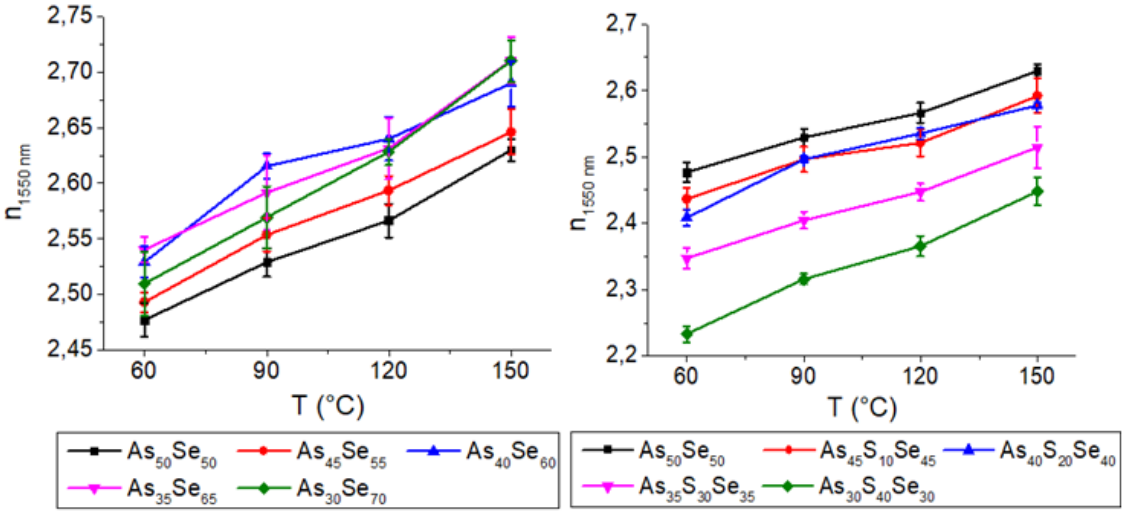

Figure 10 - Refractive index dependence on annealing temperature of $As_{50}Se_{50}$ thin films and thin films of As-Se and As-S-Se chalcogenide glass system prepared from $As_{50}Se_{50}$ solution and amorphous Se or S in EDA.

By combining both described methods (mixing and modification), a wide range of solutions and thin film compositions of As-S, As-Se, and As-S-Se system glasses can be prepared (Figure 11). This allows precise control of the optical and chemical properties of thin films and easy preparation of thin films with specific properties.

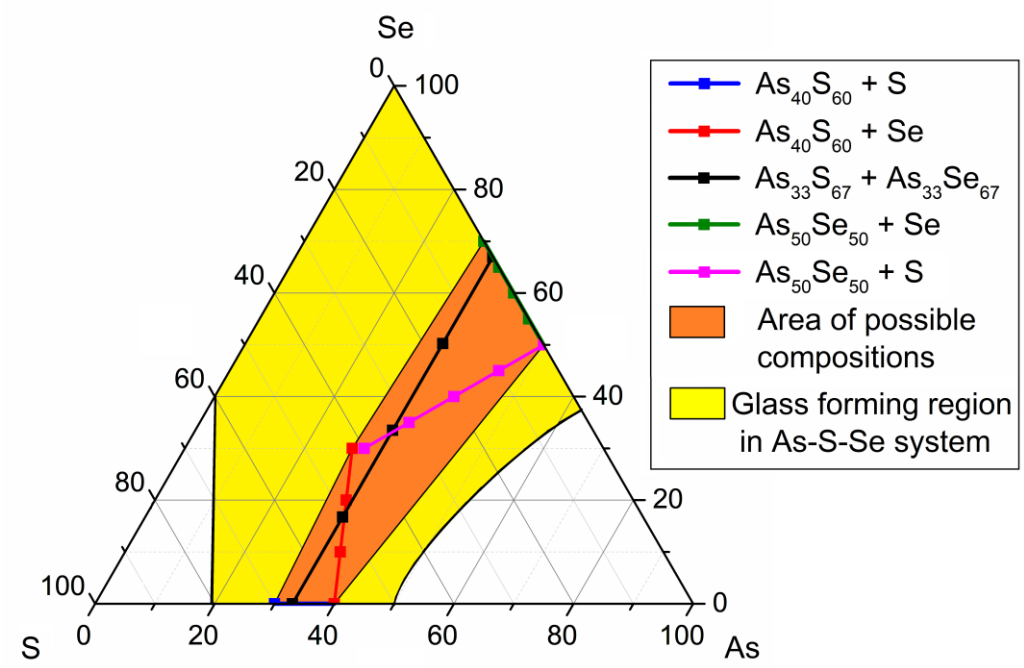

Figure 11 – The glass forming region of the As-S-Se chalcogenide glass system and area of compositions that can be prepared from $As_{40}S_{60}$ bulk glass, $As_{50}Se_{50}$ bulk glass, and elemental chalcogens using both mixing and modification.

Starting from the $As_{40}S_{60}$ and $As_{50}Se_{50}$ bulk glasses and elemental chalcogens, thin films with a specific value of refractive index (from 2.33 to 2.74) and a specific value of optical band gap (from 1.59 to 2.25) can be prepared. Optionally, commercially available chemicals (As-S, As-Se system glasses and elemental chalcogens) can be used for this method. This makes the presented methods of thin film preparation available even to laboratories without equipment for glass synthesis. At the same time, these methods can significantly simplify and reduce the cost of preparing optical components, when precise control of optical properties is often required. Thin films prepared in this way can also be structured either using lithography (VIS, UV, or electron) or hot embossing, which will be the subject of further research.

Conclusion

The focus of the submitted work was the controlled preparation of chalcogenide glass thin films with specific properties from their solutions in aliphatic amines using the spin-coating method. The properties of the deposited thin films were controlled by altering the composition of the source solution. The submitted work is divided into three parts. The first part deals with the preparation of thin films of the ternary As-S-Se system with defined composition by mixing solutions of binary $As_{33}S_{67}$ and $As_{33}Se_{67}$ glass systems. The second part deals with the controlled modification of the $As_{40}S_{60}$ bulk glass solution by adding Se, and the third part deals with the modification of the $As_{50}Se_{50}$ bulk glass solution by adding S or Se, in order to prepare chalcogenide glass thin films with high optical quality and specific properties.

It was discovered that modification of the source solution by S or Se is a viable method of thin film preparation for As-S, As-Se, and As-S-Se chalcogenide glass systems. Using the combination of both modification of source solution composition and glass solution mixing allows for an even broader range of chalcogenide solutions and thin film compositions. This enables precise control over the optical and chemical properties of the resulting films. An additional advantage of these methods is the possibility of using commercially available materials. The glasses of As-S and As-Se glass systems, as well as elemental chalcogens, are commercially available in high purity, making this method accessible even to laboratories without any equipment for bulk glass synthesis. Moreover, this approach can significantly simplify and reduce the cost of producing optical components, where precise control of optical properties is often required.

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