Synthesis and Optical, Thermal, Structural Investigation of Zinc-Borate Glasses Containing $\text{V}_2\text{O}_5$

Gökhan KILIÇ$^{1,*}$

$^{1}$Eskisehir Osmangazi University, Faculty of Science and Letters, Department of Physics, TR-26040 Eskisehir, Turkey
gkilic@ogu.edu.tr, ORCID: 0000-0002-6762-6898

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Abstract

Vanadium pentaoxide ($\text{V}_2\text{O}_5$) doped zinc borate (ZnB) oxide glasses that could be used in fiber optic cable cores in optoelectronics, in laser crystals in solar energy systems have been synthesized successfully. Structural characters of synthesized glasses were determined with differential scanning calorimeter (DSC) and Fourier-Transform infrared spectroscopy (FTIR). Glass transition ($T_g$), crystallization ($T_c$) and melting temperatures ($T_m$), and thermal stabilities ($\Delta T$) of the glasses were determined and also their association with the change in $\text{V}_2\text{O}_5$ was explained. Structural units of boron and zinc that form the structure were determined according to FTIR data. As a result, it was determined that boron formed the glass matrix with BO$_3$, BO$_4$ and boroxol ring structural units; on the other hand, zinc contributed to the glass matrix with tetrahedral ZnO$_4$ and octahedral ZnO$_6$ structural units, and vanadium usually had modifier role in the structure with its VO$_4$ and VO$_5$ structural units. $\text{V}_2\text{O}_5$’s presence in the structure with increasing amount changes thermal, structural and physical properties. Among the properties that significantly change, the most important one is optical properties. Indirect optical band gaps, Urbach energies, refractive index values of these synthesized samples were determined, and quite clear shifts towards red region were observed in the transmittance and absorption spectra. Optical band gap decreased to 1.24 eV from 2.55 eV with increasing amount of $\text{V}_2\text{O}_5$; on the other hand,
Urbach energy was determined to increase to 0.630 eV from 0.246 eV. Densities, molar volumes of these synthesized glasses were also examined and commented on.

**Keywords:** ZnO; B$_2$O$_3$; V$_2$O$_5$; Zinc-Borate glass; FTIR.

**V$_2$O$_5$ İçeren Çinko-Borat Camların Sentezi ve Optik, Termal, Yapısal İncelenmeleri**

**Öz**

Optoelektronikte fiber optik kablo korurlarda, laser kristallerinde ve güneş enerji sistemlerinde kullanılabilecek vanadium pentaoksit (V$_2$O$_5$) katkılı çinko borat (ZnB) oksit camlar başarıyla sentezlenmiştir. Sentezlenen camlara ait yapısal karakterler diferansiyel taramalı kalorimetre (DSC) ve Fourier dönüşümülu kızılötesi spektroskopisi (FTIR) ile belirlenmiştir. Camın geçiş ($T_g$), kristallenme ($T_c$), erime sıcaklıkları ($T_m$) ve termal kararlılıklar ($\Delta T$) belirlenerek V$_2$O$_5$ değişimiyle ilgisi açıklanmıştır. FTIR verilerine göre yapıyı oluşturan bor ve çinkonun yapısal birimleri belirlenmiştir. Borun cam matrisini BO$_3$, BO$_4$ ve boroksol halka yapısal birimleriyle oluşturduğu, çinkonun ise cam matrisine tetrahedral ZnO$_4$ ve oktahedral ZnO$_6$ yapısal birimleri ile katkıda bulunduğunu, vanadyumun yapısda çoğunlukla VO$_4$ ve VO$_5$ yapısal birimleriyle yer alarak düzenleyici görev üstlendiği belirlenmiştir. V$_2$O$_5$ katkısının artması yapının termal, yapısal ve fiziksel özelliklerini değiştirmektedir. Belirgin biçimde değiştirdiği özelliklerin başında optik özellikler gelmektedir. Sentezlenen numunelere ait indirekt optik bant aralığı, Urbach enerjisi, kırılma indisi değerleri belirlenmiştir, geçirgenlik ve absorpsiyon spektrumlarında kırmızı dalgaboyuna kaymalar net bir şekilde gözlenmiştir. Optik bant aralığı V$_2$O$_5$ artışıyla 2.55 eV dan 1.24 eV’a azalmış, buna karşılık Urbach enerjisi 0.246 eV’dan 0.630 eV’a arttığı belirlenmiştir. Ayrıca, sentezlenen numunelere ait yoğunluk, molar hacim incelenmiş ve yorumlanmıştır.

**Anahtar Kelimeler:** ZnO; B$_2$O$_3$; V$_2$O$_5$; Çinko-Borat cam; FTIR.

**1. Introduction**

Glass, an amorphous material, has an important place in respect to technology and science. Besides silicon dioxide (SiO$_2$), phosphorus pentoxide (P$_2$O$_5$), boron oxide (B$_2$O$_3$), and vanadium pentoxide (V$_2$O$_5$) are being used in the synthesis of glasses the most. Among these, B$_2$O$_3$ is known to be the best glass former [1, 2]. Borate glasses in which B$_2$O$_3$ establishes the glass network are very important optical materials due to their low melting points, high transmittance properties and high thermal stabilities [3]. They are frequently being used in the making of dielectric materials and used as isolation materials. Though they are being used as dielectric materials, the inclusion
of transition metal ions in the borate glass network leads to the achievement of semiconductor character or these glasses. Transition metals are nowadays being extensively used in glass science due to their presence in two or more valance states that alters the structural and optical characters [4-10].

It is possible to find examination studies performed on binary zinc-borate structures among transition metal doped borate glasses and also ternary structures and structures having more components in the literature [11-22]. Except for glass systems, it is possible to find zinc-borate ceramic structures, as well [23].

Zinc-borate glasses are being used in plasma screens and panels for high quality and performance [24, 25]. Zinc-borate glasses are promising materials for a large field including television panels and computer monitors. They are preferred due to having high voltage resistance in providing rapid surge in dielectric layers and being highly transparent. Since zinc borate glasses that do not contain lead possess all the aforementioned qualities, they are shown to be appropriate materials for applications that are in question [26].

Studies on vanadium due to their interesting optical, electrical and magnetic properties have significantly increased recently. Though studies on transition metal doped glasses can be found in the literature frequently [27-37], there are still components, compositions and properties that have not yet been studied. Glasses containing vanadium, which is a transition metal, show semiconducting properties since they contain V$^{4+}$, V$^{5+}$ valance states [38-45]. Vanadium doped glasses are known to be n-type semiconductors for low V$^{4+}$/V$^{5+}$ ratio [46]. Glasses with vanadium content have a wide range of use from the production of solid-state devices to memory and optical switching, devices like electrical threshold, and in the formation of fiber optics [47, 48]. Therefore, they are materials with potential for most electronic and optoelectronic applications [49]. In the literature, some characteristics of glasses having different compositions as a result of combining zinc-borate glass systems with V$_2$O$_5$ have been elaborated [50, 51].

In this study, ZnO-B$_2$O$_3$-V$_2$O$_5$ glasses doped with V$_2$O$_5$ and containing high ratio of ZnO, so they can find a use in optoelectronics were synthesized successfully. Compared borate glasses that are sensitive to humidity, these synthesized glasses are resistant to air, water; therefore, they are considered to be important since boron is able to find use in respect to technological applications. Structural and thermal properties of these synthesized glasses were examined in a detailed way and discussed. Characterization of this structure considered to become a potential material that could be used in fiber cable cores in optoelectronics, in laser settings and, also in solar energy systems was revealed.
2. Materials and Methods

2.1. Sample preparation

ZnO-B₂O₃ glass samples containing V₂O₅ were synthesized from chemicals having 99.5% purity (Alfa Aesar) according to \((100-x)(0.6\text{ZnO}-0.4\text{B}_2\text{O}_3)\). \((x)\text{V}_2\text{O}_5\) \((x = 1, 2, 3, 4)\) composition. The method that was used in the synthesis of the glasses was melt-quenching method. Chemicals were weighed on an analytical scale having accuracy of 0.00001g, and then weighed chemicals were mechanically mixed for approximately 10 min and made uniform.

Prepared powder mixture was left in a porcelain crucible for 60 minutes in a Nabertherm LHT 02/17 LB brand high temperature furnace that was previously heated to 1100 °C for reaction to take place. At the end of the process, molten glass samples were shaped cylindrically in a steel mold and annealed for 60 minutes at 400 °C.

![Figure 1: Synthesized ZnO-B₂O₃-V₂O₅ glass samples](image)

Glass samples synthesized by this way (Fig. 1) were sliced with a Metkon brand Micracut 152 model cutting device with diamond disc for optical measurements having a diameter of 2.5 cm and a thickness of 2 mm; both surfaces of the cut samples were polished with a Metkon brand Forcipol 102 model polishing device. Some of the samples were grounded with a Retsch RM200 brand grinder to study their thermal and structural properties.

2.2. Characterization

Densities of glasses were determined with the principle of Archimedes. Samples were first weighed in the air with a KERN brand ABT 100-5m model analytical scale having an accuracy of 0.00001g, and then weighed again in immersion fluid. Ultra-pure water was selected as...
immersion fluid. By using the measurements taken in the air and in the immersion fluid, densities of the samples were calculated with the below equation [52]:

\[
D = \frac{W_a}{W_a - W_l} \cdot \rho_o
\]  

(1)

In this equation, \(W_a\) is the weight of the sample in the air, \(W_l\) is the weight of the sample in the fluid and \(\rho_o\) is the density of immersion fluid \((\rho_o = 0.998272 \text{ g.cm}^{-3})\) at 20 °C. Molar volumes \((V_m)\) of glass samples were calculated with the following equation:

\[
V_m = \frac{\sum x_i M_i}{D}
\]  

(2)

Here, \(x_i\) is the mole ratio of the \(i^{th}\) component, \(M_i\) is the molecular weight.

Transmittance and absorption spectra of the glasses were determined with Analytik Jena SPECORD 210 UV-Vis Spectrophotometer with steps of 1 nm. In addition, in order to determine the uniformity of the sample, transmittance spectra were determined with scanning attachment of the device by using 1.5 cm piece of the surface. Absorption spectra were used to calculate optical band gaps and Urbach energies of the synthesized samples.

Refractive index due to optical band gap was calculated with the following empirical relation [53]:

\[
\frac{(n^2 - 1)}{(n^2 + 2)} = 1 - \frac{E_o}{\sqrt{20}}
\]  

(3)

\(n\), is the refractive index of the samples, \(E_o\) is optical band gap.

In order to determine the structural properties, powdered forms of the samples were used and their FTIR spectra were obtained. FTIR analyses were performed at room temperature within the wavenumber range of 400-1400 cm\(^{-1}\) by using diamond ATR with a resolution of 4 cm\(^{-1}\). Origin 2018 program was used to determine hidden bands in the spectrum.

Netzsch STA 449F3 simultaneous thermogravimetric analyze device was used in the determination of thermal properties. DSC measurements were made with approximately 50 mg of powdered sample between the range of room temperature and 1000 °C with increments of 1 °C. Glass transition, crystallization and melting temperatures were calculated from the obtained
graphs with ONSET method (Fig. 3). In addition, thermal stabilities ($\Delta T$) belonging to glasses were calculated with the following equation:

$$\Delta T = T_c - T_g$$  \hspace{1cm} (4)

Here $T_c$ is the first crystallization temperature, $T_g$ is glass transition temperature.

### 3. Results and Discussion

#### 3.1. Density and molar volume

Sample densities and molar volume values calculated with the help of Eqn. (1) are given in Table 1. In addition, sample codes and ratio of components within the glass can also be seen. As you can see in Fig. 2, density values of the samples decreased regularly from 3.392 g.cm$^{-3}$ to 3.329 g.cm$^{-3}$ with increasing amount of V$_2$O$_5$. On the other hand, molar volume values increased from 22.910 cm$^3$.mol$^{-1}$ to 24.289 cm$^3$.mol$^{-1}$ almost linearly. V$_2$O$_5$’s being a more complex molecule led to volume increase, in addition, since masses of shifting vanadium and zinc were close to each other, it resulted in decrease in the molar volume. Similar impact can also be found in the literature [54].

![Figure 2: Change in density and molar volume values according to V$_2$O$_5$ concentration](image-url)
Table 1: Sample codes, % compositions and calculated density and molar volume values of synthesized samples

| Sample Code | ZnO  | B₂O₃ | V₂O₅ | Density (g.cm⁻³ (±0.001)) | Molar volume (cm³.mol⁻¹ (±0.005)) |
|-------------|------|------|------|---------------------------|---------------------------------|
| ZBV1        | 59.40| 39.60| 1.00 | 3.392                     | 22.910                          |
| ZBV2        | 58.80| 39.20| 2.00 | 3.371                     | 23.366                          |
| ZBV3        | 58.20| 38.80| 3.00 | 3.339                     | 23.906                          |
| ZBV4        | 57.60| 38.40| 4.00 | 3.329                     | 24.289                          |

3.2. Thermal properties

DSC thermograms belonging to synthesized ZBV glass samples are given in Fig. 3, and their glass transition temperatures, crystallization and melting temperatures are given in Table 2. As it can be seen in DSC thermograms, curves belonging to 4 samples are almost identical in respect to their shapes. 3 ambiguous exothermic peaks in the shape of shoulders are followed by 1 endothermic peak. Glass transition temperatures can be seen within the range of 530-550 °C and glass transition temperature has decreased with increasing amount of V₂O₅. First crystallization temperature was around 740 °C; the range of 818-833 °C was the region of second crystallization temperature. When we have reviewed the literature, we can see that various crystalline phases are mentioned between glassy transition temperature and melting temperature in similar systems [55]. These are Zn₃B₂O₆ crystalline phase around 680 °C and Zn₃V₂O₈ crystalline phase around 700 °C. In Nb₂O₅ doped zinc-borate glasses, ZnNb₂O₆ crystalline phase containing Nb is found around 740 °C.

Figure 3: DSC thermograms belonging to samples
In the light of all these data, we estimate that the peak that we have observed in the proximity of 740 °C belong to Zn$_3$V$_2$O$_8$ and ZnV$_2$O$_6$ crystalline phases in the glasses that we have synthesized. The second crystallization temperature decreased with increasing amount of V$_2$O$_5$. Melting temperatures belonging to were almost the same and around 935 °C. Decrease in glass transition temperatures and crystallization temperatures remaining almost the same with increasing amount of V$_2$O$_5$ naturally resulted in increase in the thermal stability ($\Delta T$). Glassy transition temperatures are reported to increase in tellurium and silicon-based glasses with the addition of Nb$_2$O$_5$, V$_2$O$_5$ in increasing amounts. Decrease in glass transition temperatures of the samples in this study with increasing concentration of V$_2$O$_5$ can be explained with bond enthalpy. While B-O bond enthalpy was 809 kJmol$^{-1}$, V-O bond enthalpy was lower (637 kJmol$^{-1}$). Substituting O-B-O bonds with weaker O-V-O connections lowers activation energy for structural reorganizations. Accordingly, glass transition temperature decreases with increasing V$_2$O$_5$.

**Table 2:** Glass transition, crystallization, melting temperatures and thermal stabilities of synthesized ZBV glasses

| Sample Code | $T_g$ ($^\circ$C) (±1) | $T_{c1}$ ($^\circ$C) (±1) | $T_{c2}$ ($^\circ$C) (±1) | $T_m$ ($^\circ$C) (±1) | $\Delta T$ ($^\circ$C) (±1.2) |
|------------|-----------------------|------------------------|------------------------|-----------------------|------------------------|
| ZBV1       | 553                   | 743                    | 833                    | 935                   | 190                    |
| ZBV2       | 547                   | 730                    | 831                    | 933                   | 183                    |
| ZBV3       | 541                   | 743                    | 820                    | 935                   | 202                    |
| ZBV4       | 531                   | 743                    | 818                    | 935                   | 212                    |

**3.3. Structural examination**

FTIR spectra are given all together in Fig. 4. In addition, basic structural units of boron and vanadium and their corresponding localizations in our synthesized glasses are also given within this figure. In Fig. 5, deconvolutions of FTIR spectra belonging to samples are given. FTIR spectra were examined in three basic regions.

The first region is the 400-800 cm$^{-1}$ region. In this region, vibrations belonging to various connections can be seen. The second region is between 800-1200 cm$^{-1}$ and mostly vibrations belonging to BO$_4$ structural units of boron are observed in this region. The third region is the region around 1200-1500 cm$^{-1}$ and mostly various vibrations corresponding to BO$_3$ structural unit of boron can be seen in these regions. Except for boron that forms the glass network, vibrations corresponding to various states of zinc and vanadium found in the glass can also be observed within these regions (Table 3).
Figure 4: 400-1600 cm⁻¹ region FTIR spectra and localizations of structural units belonging to ZBV samples

One or more intensive peaks can be seen in all regions. Bands found between 449-464 cm⁻¹ within the first regions are known to belong to the vibrations in the ZnO₄ unit. Apart from this, O-V angular vibration is reported to correspond to 526-534 cm⁻¹, Zn-O stretching vibration correspond to 575-595 cm⁻¹, and B-O-B connection vibration correspond to the bands within 676-730 cm⁻¹. The most intense peak in this region belongs to the band around 680 cm⁻¹ and shows the abundance of B-O-B connections within the structure.

Bands belonging to B-O stretching vibrations belonging to BO₄ unit in the second region are found within the ranges of 873-886 cm⁻¹, 930-939 cm⁻¹, 1042-1055 cm⁻¹. It is also known in V₂O₅ containing structures that the presence of bands belonging to the vibrations of VO₅ and VO₄ structural units are also found within the regions of 873-886 cm⁻¹ and 930-939 cm⁻¹ where B-O stretching vibrations have been encountered. Intensity of bands belonging to B-O vibration is known to decrease with increasing concentration of V₂O₅ in penta- and diborate groups within the range of 1103-1114 cm⁻¹; however, the intensity of the band belonging to B-O vibration in meta- and orthoborate groups increases within the range of 1222-1231 cm⁻¹ found in the third region.
Figure 5: Deconvolution of FTIR spectra belonging to ZBV samples. Straight lines show the FTIR spectra belonging to samples and dashed lines show the Gaussian bands obtained from deconvolution.

Table 3: Bands belonging to ZBV samples and corresponding vibrations

| ZBV1 (cm⁻¹) | ZBV2 (cm⁻¹) | ZBV3 (cm⁻¹) | ZBV4 (cm⁻¹) | Vibrations                                                                 | References |
|-------------|-------------|-------------|-------------|---------------------------------------------------------------------------|------------|
| 449         | 458         | 464         | 464         | Zn-O vibration in ZnO₂ structure                                          | [56]       |
| 527         | -           | 534         | 526         | O-V angular deformation vibration                                          | [57]       |
| 584         | 582         | 595         | 575         | Zn-O stretching vibration                                                 | [58]       |
| 688         | 693         | 686         | 676         | B-O-B connection vibration                                                | [59]       |
| 729         | 730         | 718         | 708         | B-O-B connection vibration                                                | [60]       |
| 882         | 873         | 876         | 880         | ➢ B-O stretching vib. in BO₄ unit                                          | [59]       |
|             |             |             |             | ➢ Stretching vib. of VO₃                                                 |            |
| 939         | 933         | 931         | 930         | ➢ B-O stretching vibration in BO₄ unit                                    | [59]       |
|             |             |             |             | ➢ Stretching vib. of VO₂ in VO₃ unit                                      |            |
| 1042        | 1046        | 1052        | 1055        | Vibration belonging to tetrahedral BO₄ unit                               | [61]       |
| 1110        | 1114        | 1104        | 1103        | B-O vibration in penta- and di- borate groups                              | [59]       |
| 1222        | 1223        | 1231        | 1229        | B-O vibration in meta- and ortho- borate groups                            | [59]       |
| 1313        | 1287        | 1297        | 1296        | B-O vibration in boroxol ring                                             | [58]       |
| 1365        | 1355        | 1356        | 1356        | ➢ B-O-B connection vibration                                              | [10]       |
|             |             |             |             | ➢ Zn-O-B connection vibration                                             | [59]       |
| 1421        | 1433        | 1435        | 1432        | NBO B-O stretching vibration in BO₃ unit                                   | [62]       |

In the third region, it was observed that bands belonging to boroxol ring and BO₃ structure of boron was prominently found; nevertheless, bands belonging to B-O-B and Zn-O-B vibrations...
were also present. Bands within the range of 1287-1365 cm\(^{-1}\) belong to B-O in the boroxol ring, bands in the 1421-1435 cm\(^{-1}\) regions belong to B-O- vibrations found in the BO\(_3\) unit having non-bridging oxygen (NBO). Although the band around 1355 cm\(^{-1}\) is known to belong to B-O-B connection vibration, it was reported in some studies that it corresponded to Zn-B-O connection vibration in similar structures.

3.4. Optical properties

Transmittance spectra obtained with scanning 1.5 cm piece of the surface belonging to the synthesized glassed are given in Fig. 6 and transmittance and absorption spectra obtained from a single point of the samples are given in Fig. 7. Transmittance spectra obtained from surface scanning spectrophotometer were obtained from 16 different regions with intervals of 1 mm each. When compared with the transmittance curves found in these spectra, which were used to determine the uniformity of the samples, transmittance was seen to be similar in spectrum of every sample. This proves that a significant aggregation or bubble was not present and the samples had uniform distribution.

![Figure 6: Transmittance spectra obtained by scanning approximately 1.5 cm regions of the samples](image)

In Fig. 7, in which data obtained from a single point were evaluated collectively, absorption edges of spectra belonging to transmittance and absorption were observed to shift towards red (long wavelength) with increasing concentration of V\(_2\)O\(_5\). Spectra shifted towards long
wavelength for approximately for 25 nm each. Transmittance value decreased significantly. Switching oxygen bond in the glass network and change in the number of non-bridging oxygen (NBO) in the network also changes absorption properties [54]. Shifting of the absorption edge towards long wavelength with increasing amount of \( \text{V}_2\text{O}_5 \) and also decrease in optical band gaps might be explained with this change.

![Absorption-transmittance spectra of ZBV samples against wavelength](image)

**Figure 7:** Absorption-transmittance spectra of ZBV samples against wavelength

Optical band gaps of synthesized glass samples were calculated by using absorption spectrum for indirect transitions. Absorption coefficient is given according to Lambert – Beer – Bouguer Law [63].

\[
\alpha = 0.202 \left( \frac{A}{d} \right) \tag{5}
\]

Here, \( A \) is the absorbance, \( d \) is the thickness of the sample. Photon energies belonging to wavelengths corresponding to linear part of the absorption spectrum were calculated with the help of the following equation [63]:

\[
E = h\nu \tag{6}
\]

Moreover, \((a\nu)_{1/2} \sim h\nu\) graphics were plotted for indirect transitions for each sample. In these equations, \( \alpha \) is the absorption coefficient, \( h \) is the Planck constant, \( \nu \) is photon frequency and in addition, \( h\nu \) is the photon energy.
From the value of this line passing through the linear part of this plotted Tauc curve (Fig. 8) corresponding to \((\alpha h\nu)^{1/2} = 0\) optical band gap belonging to the sample is found. Optical band gaps of \(\text{V}_2\text{O}_5\) doped glasses varied between 2.55 eV and 1.24 eV. Increase in \(\text{V}_2\text{O}_5\) regularly reduced the optical band gap.

![Tauc Plots belonging to ZBV samples](image)

**Figure 8:** Tauc Plots belonging to ZBV samples

With the curve of the absorption edge in the semi-logarithmic plot (Fig. 9),

\[
\Delta E = \frac{d(ln\alpha)}{d(h\nu)}^{-1}
\]

Urbach Energies were calculated [63]. Fitting values of lines plotted from the straight part of the absorption edge were \(R^2 > 0.99\). Here, \(\Delta E\) is named as Urbach energy, \(\alpha\) is absorption coefficient and \(h\nu\) as photon energy.

A stable increase was observed in Urbach energies due to increase in \(\text{V}_2\text{O}_5\) concentration. Urbach energy was calculated between the range of 0.246 eV and 0.630 eV. Urbach energy belonging to non-doped, pure 60% ZnO-40% B\(_2\)O\(_3\) glass was calculated within the range of 0.17 eV [54]. This result is in line with the values that have been obtained in this study. Low Urbach energy value shows us that the structure of the synthesize glass structure is uniform and stable. Increase in \(\text{V}_2\text{O}_5\) concentration in the glass network shows that the structure has become irregular and unstable [64].
Table 4: Optical band gap, Urbach energies and refractive indices of synthesized ZBV glasses

| Sample Code | Optical band gap (eV) | Urbach energies (eV) | Refractive index |
|-------------|-----------------------|----------------------|-----------------|
| ZBV1        | 2.55                  | 0.246                | 2.530           |
| ZBV2        | 2.25                  | 0.346                | 2.635           |
| ZBV3        | 1.63                  | 0.630                | 2.917           |
| ZBV4        | 1.24                  | 0.630                | 3.170           |

Refractive index is an important data for materials that are considered to be used in optoelectronics. Refractive indices were determined with the help of Eqn. (3) using optical band gaps data within the region corresponding to the absorption edge. Refractive indices of the samples were calculated within the range of 2.530-3.170. As it can be seen in Table 4, refractive index increased in direct proportion to increase in $V_2O_5$.

Figure 9: Urbach Energies, slopes, and $R^2$ fitting values of ZBV samples

4. Conclusions

Ternary zinc borate oxide glass samples doped with different ratios of $V_2O_5$ were synthesized successfully. Physical, structural, thermal, and optical characterization of these
synthesized samples were performed. Structural units were determined with FTIR. B$_2$O$_3$ was found to be present in the glass network in the structure of the boroxol ring, planar BO$_3$, tetrahedral BO$_4$. ZnO, acting as the organizer with its low concentration in the structures in which it is found, was determined to be present in the samples of this study in tetrahedral ZnO$_4$ and octahedral ZnO$_6$ structural units; and it was concluded that it might be present in the glass network as a glass former. Vanadium is present in the glass network with VO$_4$ and VO$_5$ structural unit. Increase in VO$_5$ shifted the absorption edge significantly towards the red region and correspondingly decrease optical band gap to 1.24 eV from 2.55 eV and as expected, led to increase in Urbach energy. Increase in Urbach energy proves that V$_2$O$_5$ renders the structure nonuniform and unstable. As a result of thermal characterization, V$_2$O$_5$ increase was found to decrease glass transition temperature to 531 °C from 553 °C. While density decreased with increasing amount of V$_2$O$_5$, molar volume values demonstrated increase, as well. Similar to molar volume, refractive index also increased. High refractive indices increasing to 3.170 from 2.530 showed that synthesized glasses are potential materials that could be used in optical system requiring high refractive index. These glasses, considered to find application in many fields of optoelectronics also have the property of being novel materials for solar energy systems due to their semiconducting properties.

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