International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2024 | Issue 61 | Volume 16 | Number 4 | Pages 244-252

FRENKEL EFFECT IN THIN FILM SEMICONDUCTOR-POLYMER BASED COMPOSITES

S.M. Ahadzade [1] A.M. Hashimov [1] T.K. Nurubeyli [2,3] G.N. Mammadova [4]
K.A. Asgarov [5]

1. Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan
ahadzade79@mail.ru, a.hashimov@physics.science.az
2. Azerbaijan State Oil and Industry University, Baku, Azerbaijan, t.nurubeyli@physics.science.az
3. Khazar University, Baku, Azerbaijan
4. Nakhichevan State University, Nakhichevan, Azerbaijan, gulsenmemmedova@ndu.edu.az
5. Karabuk University, Karabuk, Turkey, hangardasaskerov@karabuk.edu.tr

Abstract- In the article, the influence of the Frenkel effect, in other words, the electrical conductivity of nonlinear resistances, on the shape of the potential barrier formed between two semiconductor crystallites in semiconductor-polymer composite varistors was studied. Also, the value of the Frenkel coefficient and the shape of the potential barrier were determined. In Si-polymer-based composites, the value of electrical conductivity was calculated, and graphs of the dependence of the electrical conductivity on the intensity of the electric field were constructed. It is known from the parameters established in the Poole-Frenkel coordinate that the dependence corresponds to the Poole-Frenkel theory of thermofield ionization. Also, using this dependence, the value of the Frenkel coefficient was found. Conductivity mechanisms in Si-polymer based composites have been studied. Based on the results obtained, the features of heat transport in the studied samples are explained within the framework of the following models: Schottky emission in the high temperature region, tunnel field emission in large gaps and the mechanism of heat transfer from traps at low temperatures. In this case, different mechanisms of heat transfer change in different temperature ranges and at different values of electrical work. Knowing the shape of the potential barrier in composites, it is possible to determine the spatial distribution of charges near dopant centers or traps. Taking this into account, the forms of potential fences, which allow us to evaluate the parameters of the catchment centers (traps) of cargo carriers, have been determined. It is known that the increase in the percentage of the dispersant leads to a decrease in the height of the potential barrier.

Keywords: Frenkel Effect, Semiconductor, SiC, Varistors, Thermoionization, Potential Barriers, Nonlinearities, Electrical Conductivity, Electric Field, Polymer Composites.

1. INTRODUCTION

New insights into the interaction between semiconductors and polymers: One of the main innovations of this study is the analysis of the interaction between semiconductor materials (ZnO and SiC) and polymer matrices (such as PVDF) in composites, which represents an important advancement in the development of new types of varistors. The author highlights the physical differences between grain boundaries in polycrystalline materials and interfaces between the polymer phase and semiconductor particles in composites. This study demonstrates how the properties of the polymer matrix, such as molecular structure and polarity, influence electrical characteristics, including charge distribution and the shape of potential barriers, making the work distinct from previous studies in polycrystalline varistors.

The article emphasizes the importance of using polymer materials as matrices for semiconductor particles, opening up new opportunities for the creation of varistors with improved electrical properties. In particular, the study links the effect of the volume of dispersing phases (e.g., Si) in polymer composites to their conductivity and the geometry of potential barriers, which could lead to the development of new types of varistors with customizable electrical characteristics. This is especially relevant for the development of materials that can be used in devices with specific requirements for resistance and non-linearity characteristics under high-voltage conditions.

Previous studies [1, 2] focused on single-phase semiconductor materials like ZnO, exploring their grain boundaries and doping effects on varistor performance. However, these studies did not address the interaction between semiconductors and polymer matrices. This work introduces semiconductor-polymer composites (e.g., PVDF matrix with ZnO or SiC), highlighting the role of the polymer phase in influencing electrical properties, an area not covered in earlier research. This study expands the understanding of potential barriers at semiconductor-polymer interfaces and their impact on charge transport, an area previously overlooked in semiconductor research.

Registered: 240601 | Article Info: 1920 | Accepted: 241119
Reserved: 240916 | | Available: 241231

The research demonstrates how varying the dispersant volume (e.g., Si) in polymer composites can tailor electrical conductivity and barrier strength, providing new opportunities for designing customized varistors.

The work applies the Pool-Frenkel ionization theory to polymer-based composites, broadening its application beyond traditional semiconductor systems and offering new insights into charge carrier dynamics.

• Inclusion of Recent Research Developments:

Recent studies, such as Yuksel, et al. [3], explore polymer-semiconductor composites for varistors, highlighting the role of surface-modified ZnO in enhancing electrical properties. This aligns with the current study's focus on semiconductor-particle/polymer interfaces to improve varistor performance.

New research by Cao, et al. [4] has shown that grain boundary engineering in semiconductors can optimize varistor performance. The current work complements this by examining potential barriers at the semiconductor-polymer interface, offering deeper insights into their impact on electrical behavior. Recent breakthroughs in high-performance varistors [5] focus on doped varistors and engineered microstructures for better stability and response times. The present study builds on this by incorporating polymers to improve mechanical flexibility and stability in varistor applications.

• Engineering Applications of Semiconductor-Polymer Composites:

- Surge Protection Devices:

Used in high-voltage surge protectors for power grids, telecom lines, and electronics. The polymer matrix enhances flexibility, making them suitable for compact, flexible surge protectors.

- Flexible Electronics and Wearables:

Ideal for wearable devices and smart textiles, offering flexibility and customizable non-linear behavior for power management in flexible electronics.

- Power Electronics and Voltage Regulation:

Used in voltage regulation for AC/DC converters, inverters, and electric vehicle chargers, providing high surge current handling and stable operation.

- Energy Storage Systems:

Enhances supercapacitors and batteries by controlling voltage spikes and current fluctuations, improving thermal stability and safety.

- Smart Grid Protection:

Applied in voltage clamping for smart grids, protecting distributed energy systems (e.g., solar, wind) from high-voltage transients.

The article investigates the electrical properties of semiconductor-polymer composites used in varistors, focusing on the impact of the interaction between semiconductor particles (e.g., ZnO) and the polymer phase (e.g., PVDF) on their nonlinear behavior. It also explores analysis methods and applications of such composites in surge protection and flexible electronics.

2. EXPERIMENTAL PART

The block diagram can show the key components of the setup, their interactions, and the main experimental process. For example, for the study of semiconductor-polymer composites, Figure 1 can be provided to highlight the main stages of the experiment [6].

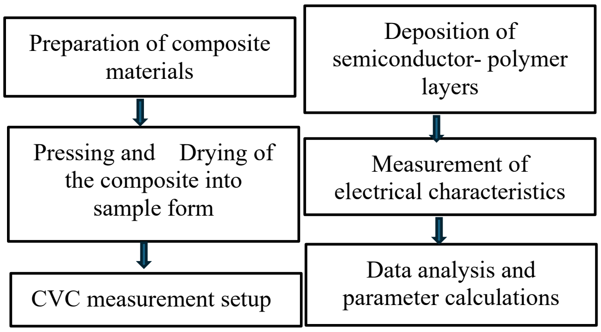


Figure 1. Experimental setup block diagram [6]

• Explanation of the block diagram in Figure 1:

1. Preparation of composite materials: Mixing semiconductor particles (e.g., ZnO) with a polymer (e.g., PVDF).
2. Deposition of layers: Formation of the composite layer on a substrate.
3. Pressing and drying: Preparing the sample using pressing and drying techniques to improve the material structure.
4. Measurement of electrical characteristics (CVC): Measuring the current-voltage characteristics (CVC) to determine the material's behavior.
5. Data analysis: Processing the data to calculate key parameters such as activation energy, Frenkel coefficient, and other characteristics.

• Analysis Process Diagram:

The diagram can illustrate the sequence of steps in analyzing the electrical characteristics and calculations.

The example of the analysis process diagram is shown in Figure 2.

• Explanation of the diagram in Figure 2:

1. CVC measurement: Conducting measurements of the current-voltage characteristics of the material.
2. Calculation of activation energy: Determining the activation energy to describe the dependence of conductivity on temperature and electric field intensity.
3. Calculation of donor and trap concentrations: Estimating the concentration of defects and local levels through the analysis of experimental data.
4. Construction of the relationship: Building a relationship between conductivity and the electric field, as well as analyzing the material's nonlinear properties.

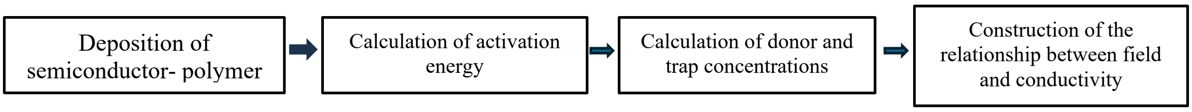


Figure 2. Experimental setup block diagram [7]

2.1. Comparative Tables Summarizing Results for Different Dispersion Ratios

To clearly illustrate the key differences and optimal conditions for improving the performance of semiconductor-polymer composites, we can create a comparative table that shows how varying the dispersion ratio of the semiconductor particles (e.g., Si or ZnO) in the polymer matrix (e.g., PVDF) affects key properties such as conductivity, activation energy, and nonlinear behavior [8].

Table 1. Comparison of electrical properties for different dispersion ratios of semiconductor particles in polymer matrix [8]

Dispersion Ratio	Conductivity (S/m)	Activation Energy (eV)	Nonlinearity Factor	Optimal Ratio for Performance	Remarks
10% Semiconductor	Low	High (0.3-0.4)	Low	Not optimal	Too few particles for effective conduction
30% Semiconductor	Moderate	Moderate (0.2-0.3)	Moderate	Optimal for moderate applications	Good balance of conductivity and stability
50% Semiconductor	High	Low (0.1-0.2)	High	Best for high voltage applications	Provides high conductivity but reduced activation energy
70% Semiconductor	Very High	Very Low (0.05-0.1)	Very High	Best for high surge protection	High conductivity, ideal for surge protection but prone to higher leakage currents
90% Semiconductor	Extremely High	Very Low (0.05-0.08)	Extremely High	May result in high leakage current	Not ideal due to instability at high dispersion

2.2. Key Observations from Table 1

- As the percentage of semiconductor particles increases, the conductivity of the composite improves, but at the cost of activation energy, which decreases, potentially leading to higher leakage currents.
- The optimal dispersion ratio for most applications appears to be around 50%, where a good balance of conductivity and activation energy is achieved, making it suitable for high voltage and surge protection applications.
- Ratios higher than 70% may improve nonlinearity for surge protection but may introduce undesirable leakage currents due to lower activation energy.

Table 2. Comparative effect of dispersion ratios on the nonlinear behavior of the CVC (current-voltage characteristics) [9]

Dispersion Ratio	CVC Nonlinearity	Voltage Clamping Ability	Breakdown Voltage (V)	Overall Performance
10% Semiconductor	Low	Poor	Low (100-200 V)	Poor
30% Semiconductor	Moderate	Moderate	Moderate (200-400 V)	Moderate
50% Semiconductor	High	Good	High (400-800 V)	Excellent
70% Semiconductor	Very High	Very Good	Very High (>800 V)	Excellent
90% Semiconductor	Extremely High	Excellent	Very High (>1000 V)	Risk of instability

2.3. Key Observations from Table 2

- At 50% dispersion, the composite achieves optimal nonlinear behavior with good voltage clamping and a high breakdown voltage, ideal for surge protection and high-voltage varistors.
- Ratios of 70% and higher provide excellent voltage clamping and the highest breakdown voltage, but at the cost of instability and potential leakage current due to excessive semiconductor concentration.
- Lower ratios (10%-30%) show poor performance in terms of voltage clamping and nonlinearity, making them unsuitable for high-voltage or surge protection applications.

3. THEORETICAL PART

It is known that the physics of polycrystals is mainly based on the physics of the boundary between crystallites. Therefore, the core element of the polycrystalline varistor is the potential barrier between the tunnel-transparent crystallites and the potential barrier between the crystallites [10, 11]. According to the results obtained by the Auger-spectroscopy method, the width of the irregular region (amorphous phase) that separates the crystallites from each other is approximately 2×10^{-7} cm [12]. This region is separated from the crystallites by the surface potential barrier. The width of the surface region of the positive space charges i [13].

$$r = (2\ \varepsilon_0 \varepsilon\ \varphi_0 / e^2 N_d)^{1/2} \le 2.5\times10^{-6} \quad (1)$$

where, the level of crystallites is $N_d = 10^{18}$ cm^{-3}. In works [10], it was noted that the width (r) of the surface region of positive space heats in this way leads to improved results. It is estimated that the concentration of donors on the surface of crystallites is higher than the concentration of their donors below. In the work [13], it was shown that Bi^{+3}, which is a donor, is mainly located in the surface layer of ZnO and its depth is ~2×10^{-7} cm. Therefore, the ZnO crystallites are in the woven state and [13].

$$eN_S << eN_d d / 2 \quad (2)$$

The conductivity of the crystallites increases with the size of the tunnel part of the CVC, and since the conductivity is high, the linearity of the CVC is formed at higher values of the current density. In the electrical scheme, the losses flowing along the inter-crystallite boundary are characterized by a resistance of R_S. This resistance is created during the transfer of electric currents with a sliding mechanism. After the opening voltage of the varistor, it is possible to impregnate ZnO with trivalent elements (acceptor) to reduce the R_V resistance, which limits the amplitude of the current. The obtained results show that the activation energy of the local levels created by the additives in the quasi-donor zone of ZnO is ≈ 0.05 eV, i.e. shallow donor levels. Since this effect is of particular importance in the formation of the non-linearity of varistors, let us give a broader analysis of ZnO precipitation with ions of different ionic radii, and its impact on the R_V parameter.

It should be noted that the resistance of crystallites of the semiconductor phase (ZnO, SiC) is of great importance in determining the formation mechanism of the varistor effect of the ZnO-polymer composite based on it. Studies show that Al_2O_3 is the most effective donor for ZnO varistor material. The main reason for this is that Al_2O_3 has a small ionic radius (0.57 Å) and a large diffusion coefficient, and zinc ions are dissolved in the complex system. The non-linearity of the volt-ampere characteristic of the ZnO varistor with the main peak Co is small because Co^{+3} creates deep compensation centers.

Note that the Co ion radius is larger than the corresponding parameters of Al_2O_3. Varistors are multi-transition semiconductors with a density of d^{-1} (the average size of crystallites) in the form of a macroscopic symmetric cross-sectional structure. When the size of the crystallites is 10 mm, their density is equal to $10^{-3}\,\text{cm}^{-1}$. The density of the crystallites is a factor that can affect the properties of the varistor (opening resistance U_{op}, the number and parameters of the potential barrier between the crystallites). Association density can be determined approximately as [13].

$$N_b / L \approx U_a / U_t \ , \ L = E_a / U_t \tag{3}$$

where, N_b is the thickness of the barrier between the crystallites, U_{op} is the opening voltage of the varistor, and L is the width of the varistor. The joint density depends on the uniform distribution of varistor-forming particles at the inter-crystallite boundary.

The junction density of micro varistors can be determined by means of the Volt-Farad characteristic (*C-U*). It is known that the dependence of the special system for the potential multiplier is calculated by [13].

$$\frac{1}{C} = \left(\frac{2}{e^2 \varepsilon_0 \varepsilon_r N_d}\right)^{\frac{1}{2}} \left[(\varphi_0 - eU'_F)^{\frac{1}{2}} + (\varphi_0 + eU'_R)^{\frac{1}{2}} \right] \tag{4}$$

where, U'_F is φ_k deviations of the potential connected in the right direction, and U'_R is φ_R deviations of the connected potential in the opposite direction. If we take the general system of the micro varistor $C' = C_R$ then the $C-U$ characteristic can be expressed as [3].

$$\left(\frac{1}{C'} - \frac{1}{2C'_0}\right)^2 = \frac{2}{e^2 \varepsilon_0 \varepsilon_r N_d} (\varphi_0 + eU'_R) \tag{5}$$

where, $C'_0 = e^2 \varepsilon_0 \varepsilon_r N_d / 8\varphi_0^{\frac{1}{2}}$ is the value of the micro varistor at zero current. If we apply the properties of the micro varistor to the polycrystal, then it becomes [13].

$$C = C' / N_\sigma \ , \ U_R^* = N_\sigma / U'_R = \frac{U}{2}\sqrt{\frac{\varphi_R}{\varphi_0}} \tag{6}$$

And the normalized C-U characteristic is obtained:

$$\left(\frac{C_0}{C} - \frac{1}{2}\right)^2 = \frac{1}{4N_\sigma \varphi_0} (N_\sigma \varphi_0 + eU_R) \tag{7}$$

where, in the U_R^* as varistor, all the negative potentials are closed-loop external currents. For polycrystals [13]:

$$C_0 = e^2 \varepsilon_0 \varepsilon_r N_d / 8N_\sigma \varphi_0^{\frac{1}{2}} \tag{8}$$

$$U_0 = N_\sigma \varphi_0 / e \tag{9}$$

$$\left(\frac{C_0}{C} - \frac{1}{2}\right)^2 = f\ (U_R) \tag{10}$$

If you find U_0 in the dependence, then count N_σ. For example, for standard varistors with a width of 1.5 mm, the density of crystallites in varistors is $N_\sigma = 50$ and $N_\sigma / L = 330\,\text{cm}^{-1}$. To find the concentration of donors [13]:

$$N_d = 1.6 \times 10^{17}\,\text{cm}^{-1} \tag{11}$$

And the concentration of levels on the surface of crystallites from the value of C_0 [3]:

$$N_S = (2N_d \varepsilon_0 \varepsilon_r \varphi_0 / e^2)^{\frac{1}{2}} \approx 1.1 \times 10^{12}\,\text{cm}^{-2} \tag{12}$$

If we want to apply the well-known models, we have analyzed polycrystalline and the *C-U* characteristics to composites, then first, the physical structure of the composite and the structures of polycrystals should be compared, corresponding and different factors should be determined. In the first approach, the role of crystallites in the polycrystal is played by the varistor ceramic particles in the composite, and the polymer phase plays the role of the boundary between the crystals.

However, it should be noted that semiconductor ceramic varistors (ZnO, Si) and semiconductor-polymer varistors are very different in terms of chemical and physical structures of their intercrystallite faces. In addition, if in a semi-conductor, crystallites and the phase separating them differ little in terms of their surface structure and electrophysical properties, on the contrary, in a semiconductor-polymer composite, the structure and electrophysical parameters of the polymer phase separating the particles of the semiconductor are completely different from the corresponding parameters of the semiconductor [11-14].

As we mentioned, in the composite, instead of crystallites, filler phase-semiconductor particles are present, and polymer phase is located at the boundary between crystallites. If the main properties of the inter-crystallite boundary in polycrystals depend on the electron levels and their energy distribution, the concentration of impurities on the inter-crystallite boundary and the atomic structure of the boundary, the properties of the polymer phase between semiconductor particles in composites depend on its molecular structure, polarity, the concentration of local levels of the quasi-galactic zone and the energy distribution. Polycrystals and composites have similar and different parameters of the interphase boundary.

Therefore, if we apply the tested models of polycrystals, which have been widely studied in comparison to composites, it is necessary to consider their specific features such as the special shear densities of the boundaries between inorganic and organic crystallites, the width of the quasi-adjacent zones, and the distribution of local levels in them [14, 15].

4. RESULTS AND DISCUSSION

In solid state physics, the study of the structure of electrons and holes, atoms or other capture centers is of great importance. These structures can be very complex when finished, as the grip centers stimulate the crystal lattice around the face. In addition, the properties of the capture centers depend on their interaction with the free electrons (holes) present in the crystal. Thus, the impact of the Coulomb potential of high centers can be partially or completely shielded by free electrons. By knowing the form of the potential energy distribution $\varphi(r)$ of the interaction of the capture centers with the electron (hole), it is possible to obtain valuable information about their structure [5-11]. For example,

$$\rho = \frac{1}{4\pi}\nabla^2\varphi \tag{13}$$

Using Poisson's equation, they can find the spatial distribution of $\rho(\nu)$ heats near the energy centers. As we mentioned, determining the shape of the potential barrier in materials, including composites, is one of the most important issues. So, knowing it, it is possible to determine the spatial distribution of charges near additional centers or traps. This relationship according to the work of [12] considering the Poisson equation:

$$\varphi(x) = -kT\beta/2e\sqrt{E} = -eEx \tag{14}$$

$$x = \frac{kT\beta}{2e\sqrt{E}} \tag{15}$$

where, x is expressed in terms of the formula. Using experimental results, the forms of the potential fences were determined, which allow us to estimate the parameters of the centers (traps) of the cargo carriers through Equations (14) and (15). It is known that this also increases the probability of thermal escape of electrons from the wires due to the decrease in the potential barrier in the electrical field (Figure 3) [15].

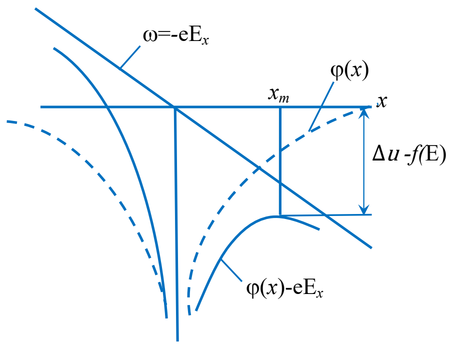


Figure 3. Reduction of the height of the potential barrier under the influence of the electric field [15]

Considering the above, the work is devoted to the study of the influence of the volume percentage of the dispersant on the electrical conductivity and the shape of the potential barrier of polar polyvinylidene fluoride (PVDF) polymer and monocrystalline Si-based composite nonlinear resistors (varistors). Also, the value of the concentration of ionization centers, the length of the free path of charge carriers, the value of the Frenkel coefficient and the shape of the potential barrier were determined [15-20].

The values of electrical conductivity were calculated in the applied samples. Using the results of the calculations, Figure 2 shows the graph of dependence of electrical conductivity on the intensity of the electric field for polar and non-polar polymer matrix composites. $\ln\sigma = f(U/d)$ dependence corresponds to the Pool-Frenkel thermofield ionization theory [15] (Figure 2).

$$\sigma = \sigma_0 \exp(\beta\sqrt{U/d}) \tag{16}$$

where, β is the Frenkel coefficient, σ_0 is the value of electrical conductivity in weak fields, and d is the thickness of the sample [5].

$$\beta = \frac{\sqrt{e^3}}{kT\sqrt{\pi\varepsilon\varepsilon_0}} \tag{17}$$

where, e is electron density, ε is dielectric permittivity of composite, ε_0 is electric constant, k is Boltzmann constant, T is absolute temperature. Using dependence $\ln\sigma = f(U/d)$, the value of the Frenkel coefficient was found to be $\beta = 2.2\times10^{-2}(\text{cm/V})^{1/2}$ .The electrical conductivity values of the applied samples were calculated using the $I = f(U)$ sequence. Using the results of the calculations, a graph of the dependence of electrical conductivity on the intensity of the electric field for composites with polar PVDF polymer matrix is shown in Figure 4.

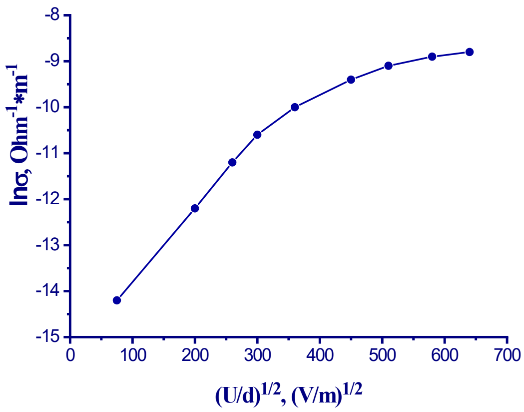


Figure 4. Dependence of electrical conductivity on intensity of electric field for PVDF matrix composites (T=300 K) 40% Si + 60% PVDF [18]

It can be seen from Figure 4 that the value of electrical conductivity increases depending on the intensity of the electric field. It was determined that the $\ln\sigma = f(U/d)$ dependence corresponds to the theory of Pool-Frenkel thermofield ionization [18, 20, 22]. The minimum value of the electric field, which corresponds to the nonlinear dependence of the electric conductivity, allows us to obtain information about the conductivity and the concentration of defects that cause thermofield ionization in the composites. According to research [8, 23, 24]:

$$N_t = \left(2e/kT\beta\sqrt{E_{kr}}\right)^3 \tag{18}$$

where, k is the Bolsmann constant, T is the absolute temperature, E is the intensity of the electric field, e is the charge of the electron, and β is the Frenkel coefficient.

As we mentioned, determining the shape of the potential barrier in materials, including composites, is one of the most important issues. So, knowing it, it is possible to determine the spatial distribution of charges near additional centers or traps. This relationship by considering Poisson's equation [25, 23]:

$$\varphi(x) = -kT\beta/2e\sqrt{E} = -eEx \quad (19)$$

$$x = \frac{kT\beta}{2e\sqrt{E}} \quad (20)$$

It is expressed with the help of the formula. Using the experimental results, the forms of the potential fences were determined, which allow us to estimate the parameters of the centers (traps) of the cargo carriers through the Equations (19) and (20). The results of calculations are given in Figures 5 and 6. The Figures 5 and 6 show that:
1) the dimension of the potential barrier decreases with the increase of the volume percentage of the dispersant and the electric field in the studied composites.
2) in polar matrix composites, the geometry of the potential barrier reaches the maximum value in the percentage of the small volume of the dispersant compared to the non-polar matrix composite [23-26].

The shape of the potential barrier for composites was determined and it was shown that an increase in the volume percentage of the dispersant leads to a decrease in the strength of the potential barrier [20-24].

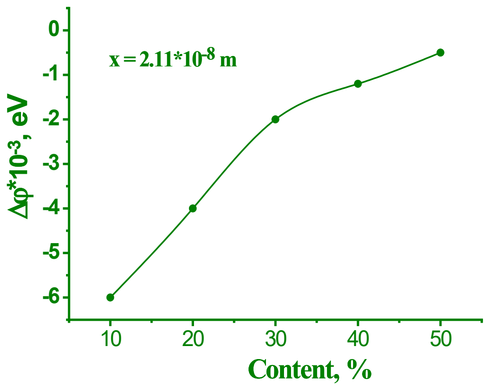


Figure 5. Dependence of potential barrier geometry in polar (PVDF) polymer matrix composites on dispersant (Si) volume percentage [23, 24]

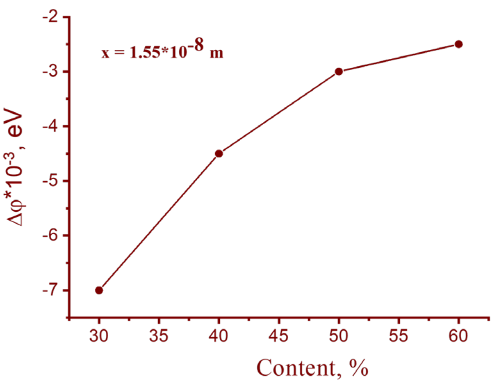


Figure 6. Dependence of potential barrier geometry in non-polar (Pe) polymer matrix composites on dispersant (Si) volume percentage [23, 24]

4.1. Practical Applications of the Results

Power Electronics: The study can be applied in surge protection systems and overcurrent protection in power converters, inverters, and transformers, improving the reliability and safety of power electronic circuits.
- High-Voltage Varistors: The findings can enhance high-voltage varistors used in electrical grids to protect equipment from voltage surges, improving their performance and energy absorption capabilities.
- Flexible Electronics: The research supports the development of flexible surge protection devices and wearable electronics, offering lightweight, durable protection against voltage spikes in compact devices.
- Energy Storage Systems: The results are useful in energy storage protection circuits, safeguarding batteries and capacitors from overvoltage conditions, crucial for electric vehicles and renewable energy grids.
- High-Performance Electronics: The composite materials can be applied in protection circuits for semiconductor devices, ensuring reliable voltage clamping in microprocessors and power transistors.

While the current study provides valuable insights into semiconductor-polymer composites for varistors, updating with recent datasets is crucial for enhancing engineering relevance. New data from nanocomposites (e.g., graphene, CNTs), wide-bandgap semiconductors (e.g., SiC, GaN) for high-voltage applications, and 3D printed composites for tailored properties would improve performance in advanced electronics and power systems. Additionally, data on smart materials with IoT integration and environmental stability under extreme conditions would support applications in flexible electronics, smart grids, and automotive systems.

Potential Issues and Solutions for Semiconductor-Polymer Composites
1. Durability and Longevity
- Problem: Degradation from moisture, UV exposure, and high electric fields.
- Solution: Use UV-resistant, thermally stable polymers (e.g., PVDF) and apply protective coatings to enhance material stability.
2. Economic Efficiency
- Problem: High costs of semiconductor materials and complex manufacturing processes.
- Solution: Use cost-effective materials like Si or Al_2O_3, and adopt scalable production techniques (e.g., roll-to-roll, 3D printing).
3. Electrical Performance
- Problem: Breakdown at high voltage and non-linearity saturation.
- Solution: Optimize particle size, use hybrid composites with ceramic layers, and incorporate heat dissipation structures to manage voltage and thermal stress.
4. Manufacturing Consistency
- Problem: Variability in material properties due to inconsistent dispersion of particles.
- Solution: Employ advanced mixing techniques (e.g., ultrasonic dispersion) and real-time quality control for consistent electrical characteristics.

These strategies can help improve the practicality and scalability of semiconductor-polymer composites in various electronic and energy applications.

4.2. Future Research Areas

- Optimization of Varistor Performance: Investigate doping effects, interface engineering, and thermal stability to enhance varistor efficiency, reliability, and longevity in high-voltage applications.
- New Composite Materials: Explore nanomaterials, alternative polymer matrices, and smart materials (e.g., self-healing composites) for improved conductivity, durability, and environmental resistance.
- Advanced Characterization: Use in-situ monitoring and computational models to better understand the microstructure and performance of composites under real-world conditions.
- Sustainability: Develop eco-friendly materials and recycling methods to reduce environmental impact and improve the lifecycle of semiconductor-polymer composites in electronics.

5. CONCLUSIONS

Let's say that the determination of the influence of the concentration (width and density of the bands) of the levels created by the impurities in the Si and ZnO barrier zone on the parameters of the potential barrier formed at the interface between the Si-polymer and polymer composite phases in general is an important issue for the solution of the above problem. The equalization of Fermi levels at the contact boundary (ZnO-polymer, Si-polymer) and the influence of extreme levels on this will lead to the determination of the mechanism of the varistor effect in composites and the development of technologies capable of improving the parameters of composite varistors. It should be noted that to develop more effective composite varistors in the future, reducing the resistance of the polymer phase between the semiconductor particles to several Ohms is one of the important issues.

Regarding the development of composite varistors, it is very important to choose which type of semiconductor (p or n-type) and to study the impact of the bandgap zone width of the semiconductor phase on the characteristics of the varistor. The electrical properties of many polycrystalline semiconductors and semiconductor ceramics are determined by the potential difference created at the crystallite boundary. Since the electrical properties are determined by the Schottky-type double potential coefficient between the crystallites, the microscopic study of the processes taking place at the intercrystallite boundary under the influence of an electric field is of particular importance for discovering the nature of the processes occurring in the interfacial layer of semiconductor-polymer composites. An example of this is the determination of the mechanism of formation of a high conductivity layer in semiconductor-polymer varistors. Here, according to the results of the calculations, it was determined that:

1) the dimension of the potential barrier decreases with the increase of the volume percentage of the dispersant and the electric field in the studied composites.

2) in polar matrix composites, the geometry of the potential barrier reaches the maximum value in the percentage of the small volume of the dispersant compared to the non-polar matrix composite.

Considering the results of the calculations, we can say that the main reason for the observed change in the potential diameter in polar and non-polar composites is the high value of dielectric constant due to the presence of initial dipole moments in polar polymers.

REFERENCES

[1] F. Greuter, "ZnO, Varistors: From Grain Boundaries to Power Applications", In: Oxide Electronics (ed., Asim Ray), pp. 157-226, Published 2021 John Wiley and Sons Ltd 2021.

[2] J. Wang, Z. Liu, X. Wang, S. Li, "Improved Electrical Properties of TiO2-Doped LiNbO3 Crystals by High-Temperature Annealing", Journal of the American Ceramic Society, Vol. 103, Issue 12, pp. 4875-4881, 2020.

[3] P. Yuksel, G. Hardal, B. Kinac, "Influence of V2O5 and B2O3 Addition on the Sintering Behavior and Physical Properties of ZnO Ceramics", Process. Appl. Ceram., Vol. 16, pp. 48-54, 2022.

[4] W. Cao, Y. Guo, J. Su, J. Liu, "Effect of Sintering Temperature on the Microstructural Evolution of ZnO Varistors", J. Electron, Mater, Vol. 52, pp. 1266-1273, 2023.

[5] M.C. Kelleher, "ZnO Varistors-the Ideal Microstructure and Characteristics, and Methods Investigated and Developed to Achieve These", In Haseeb A.S.M.A., Editor. Encyclopedia of Materials: Electronics, Vol. 3, pp. 392-418, Amsterdam, The Netherlands, 2023.

[6] S.M. Ahadzade, "Research of the Electrical Properties of the Intercrystallite Boundary and Mechanisms of Conductivity in a ZnO Varistor with Impurities", Global Journal of Engineering and Technology (GJET), Issue 2, Vol. 1, pp. 58-62, May 2022.

[7] C. Zhao, Y. Wang, W. Feng, T. Lin, X. Wu, M. Gao, C. Lin, "High Energy Harvesting Performance in Piezoelectric Composite Films Employing Large Piezoelectric Fillers and Interface Engineering", ACS Applied Polymer Materials, Vol. 6, No. 1, pp. 56-62, 2024.

[8] G.B. Ibragimov, R.Z. Ibayeva, B.G. Ibragimov, A.S. Alekberov, "Light Absorption by Free Charge Carriers in the Presence of Phonons in an Anisotropic Quantum Wire", Advanced Physical Research, Vol. 6, No. 1, pp. 56-62, 2024.

[9] A.M. Hashimov, S.M. Hasanli, R.N. Mehtizadeh, S.M. Azizova, K.B. Bayramov, "The Nonlinear Resistor on the Basis of a Composition Polymer - Ceramics", JTF, Vol. 77, No. 8, pp. 127-130, 2007.

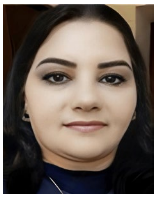
[10] S.M. Ahadzade, A.M. Hashimov, "Variation of the Main Parameters Composite Varistors Based on ZnO", The 16th International Conference on Technical and Physical Problems of Engineering (ICTPE), Rumeli University, pp. 99-101, Istanbul, Turkey, 12-13 October 2020.

[11] S.M. Ahadzade, "Study of Kinetic Parameters in ZnO-Polyethylene Based Composite Varistors", Fizika, No. 1, pp. 18-21, 2014.

[12] S.M. Ahadzadeh, A.M. Hashimov, S.G. Khalilova, "Research of the Electrical Properties of Composite

Varistors Based on ZnO-Polymer", The 17th International Conference on Technical and Physical Problems of Engineering (ICTPE), Rumeli University, pp. 86-89, Istanbul, Turkey, 18-19 October 2021.
[13] S.M. Ahadzadeh, A.M. Hashimov, "Possibility Varistor Effect of Different Properties in Polymers", The 12th International Conference on Technical and Physical Problems of Power Engineering (ICTPE), University of the Basque, pp. 181-183, Bilbao, Spain, 7-9 September 2016.
[14] A. Kherodia, A.K. Panchal, "Poole-Frenkel Emission and Defect Density in a-Si:H/nc-Si:H Multilayer Films for All Silicon, Third Generation Photovoltaics", Journal Thin Solid Films, Vol. 654, pp. 16-22, 2018.
[15] S.M. Ahadzade, T.K. Nurubeyli, I.A. Vakulenko, K.A. Asgarov, "Study of the Main Electrophysical Parameters of Semiconductor - Polymer Based Composite Varistors", Journal Manufacturing Technologies and Applications (MATECA), Issue 1, Vol. 5, pp. 34-45, April 2024.
[16] G.B. Ibragimov, R.Z. Ibayeva, "Light Absorption by Free Charge Carriers with Scattering Mechanisms in a Semiconductor Superlattice", Journal of Surface Investigation: X-Ray, Synchrotron and Neutron Techniques, Vol. 18, No. 1, pp. 116-120, 2024.
[17] S.M. Gasanly, A.Y. Imanova, U.F. Samedova, "Thin-Film Composite Resistors Based on Polypropylene and Silicon", Electronic Processing of Materials, No. 2, pp. 88-91, 2010.
[18] S.M. Hasanli, A.Y. Imanova, U.F. Samedova, "Electrophysical Characteristics of Composite Non-Linear Resistors Based on Polymer and Silicon", Journal of Technical Physics, No. 8, pp. 150-152, 2011.
[19] T.K. Nurubeyli, "Coefficient of Relative Sensitivity in Mass Spectrometers with Inductively Coupled Plasma", Inorganic Materials: Applied Research, Vol. 11, pp. 552-557, 2020.
[20] F. Kharirchi, S.M. Hasanli, S.M. Azizova, J.J. Khalilov, "Spectroscopy of Dielectric Parameters of ZnO-Based Varistors", Electronic Processing of Materials, Vol. 48, No. 1, pp. 58-62, 2012.
[21] M.A. Kurbanov, S.M. Ahadzadeh, I.S. Ramazanova, Z.A. Dadashov, I.A. Farajzade, "Varistor Effect in Highly Heterogeneous Polymer-ZnO Systems", FTP, Vol. 51, Issue 7, pp. 992-997, 2017.
[22] Sh.M. Ahadzadeh, A.M. Hashimov, Sh.G. Khalilova, "Research of the Electrical Properties of Composite Varistors Based on ZnO-Polymer", International Journal on Technical and Physical Problem of Engineering (IJTPE), Issue 50, Vol. 14, No. 1, pp. 166-171, March 2022.
[23] S.M. Ahadzadeh, T.K. Nurubeyli, E.Z. Quliyev, A.N. Sultanli, "Technological and Electrophysical Parameters of ZnO Varistor with Impurities", International Journal on Technical and Physical Problem of Engineering (IJTPE), Issue 55, Vol. 15, No. 2, pp. 307-311, June 2023.
[24] S.M. Ahadzade, I.A. Vakulenko, K.A. Asgarov, "Influence Factors on Electrophysical Parameters of Composite Varistors", Transport Science and Progress, No. 1, Vol. 101, pp. 29-36, 2023.
[25] S.M. Ahadzade, A.Y. Imanova, "Varistor Characteristics of Composites Made Based on ZnO and Si Semiconductor Materials", 5th International Scientific and Practical Conference Science and Innovation of Modern World, Cognum Publishing House, No. 1, pp. 85-95, London, United Kingdom, 25-27 January 2023.
[26] S.M. Ahadzadeh, T.K. Nurubeyli, K.A. Asgarov, "Analysis of the Main Parameters of ZnO-Polymer Composites with Different Thicknesses", International Journal on Technical and Physical Problem of Engineering (IJTPE), Issue 58, Vol. 16, No. 1, pp. 138-143, March 2024.

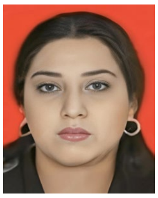
BIOGRAPHIES



Name: **Shafaq**
Middle Name: **Mirbaba**
Surname: **Ahadzade**
Birthday: 16.02.1979
Birthplace: Shirvan, Azerbaijan
Bachelor: Department of Electrotechnics, Electromechanics and Electrotechnology, Faculty of Electrical Engineering, Azerbaijan Technical University, Baku, Azerbaijan, 2000
Master: Engineering and Physics of Cables and Conductors, Department of Electrotechnics, Electromechanics and Electrotechnology, Electrical Engineering Faculty, Azerbaijan Technical University, Baku, Azerbaijan, 2002
Ph.D.: Energy, Physics and Technique of High Voltages, Physical Electronics, Institute of Physics Ministry of Science and Education, Baku, Azerbaijan, 2010
The Last Scientific Position: Assoc. Prof., Since 2016, Leading Research of Laboratory of High Voltage Engineering, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, Since 2015
Research Interests: Non-Linear Varistors Based on Zinc Oxide Doped with Various Metal Oxides by Ceramic Method, High Voltage Limiters Based on Them, Non-Linear Resistors Based on ZnO and Si Semiconductor Materials, Nonlinear Resistor Based on Polymer and Solid Solutions, Electrophysical and Optical Properties of the Composites Materials
Scientific Publications: 50 Papers, 2 Patents, 4 Projects, 17 Theses

Name: **Arif**
Middle Name: **Mamed**
Surname: **Hashimov**
Birthday: 28.09.1949
Birthplace: Shahbuz, Nakhichevan, Azerbaijan
Master: Power Engineering Department, Faculty of Energy, Azerbaijan Institute of Oil and Chemistry, Baku, Azerbaijan, Baku, Azerbaijan, 1971
Ph.D.: Power Engineering, Institute of Electrodynamics, Ukrainian Academy of Sciences, Kiev, Ukraine, 1980
Doctorate: Prof., Doctor of Technical Science, Power Engineering, Institute of Electrodynamics, Ukrainian Academy of Sciences, Kiev, Ukraine, 1993

The Last Scientific Position: Academician (2007), the First Vice-President, Azerbaijan National Academy of Sciences, Baku, Azerbaijan, 2007-2013 and Since 2023 - Director of Institute of Physics of Azerbaijan National Academy of Sciences, Baku, Azerbaijan, 2002-2009 and Since 2021 - Laureate of Azerbaijan State Prize, 1978 - Honored Scientist of Azerbaijan, 2005
Research Interests: Theory of Non-linear Electrical Networks, Renewable Energy, High Voltage Physics and Techniques
Scientific Publications: 350 Papers, 21 Patents, 5 Monographs
Scientific Memberships: Member of the Editorial Board of the Journal Electronic Processing Materials, Published at Institute of Applied Physics of the MEA of Moldova - Member of the Editorial Board of the "International Journal for Knowledge Science and Technology", Published at University of the Bosque Country, Bilbao, Spain, Deputy Editor of Power Engineering Problems, Journal Published at Institute of Physics of ANAS, Baku, Azerbaijan - Member of the Editorial Board of the News, Journal of the National Aerospace Agency of the Ministry of Defense Industry, Baku, Azerbaijan - Cochairman of International Conferences on "Technical and Physical Problems of Power Engineering" (ICTPE) - Editor in Chief and Member of Editorial Board of International Journal on "Technical and Physical Problems of Engineering" (IJTPE)



Name: **Tarana**
Middle Name: **Kamil**
Surname: **Nurubeyli**
Birthday: 17.02.1978
Birthplace: Baku, Azerbaijan
Bachelor: Physical Electronics Department, Faculty of Physics, Baku State University, Baku, Azerbaijan, 1999
Master: Plasma Physics, Physical Electronics Department, Faculty of Physics, Baku State University, Baku, Azerbaijan, 2001
Ph.D.: Electronics, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, 2010
Doctorate: Energy, Physics and Technique of High Voltages, Physical Electronics, Institute of Physics Ministry of Science and Education, Baku, Azerbaijan, 2021
The Last Scientific Position: Prof., Head of Laboratory of High Voltage Engineering, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, Since 2021
Research Interests: Investigation of the Contribution of Non-Spectral Matrix Effects in Inductively Coupled Plasma Mass Spectrometry (ICP-MS); Methods Possible to Increase the Reliability of Forecasting When Searching for Oil and Gas Fields; Study of the Composition of Transformer and Lubricating Oils for Early Diagnosis of Transformer Operation
Scientific Publications: 60 Papers, 1 Book, 4 Patents, 4 Projects, 2 Theses
Scientific Memberships: The Russian Mass Spectrometry Society, Member of Editorial Board and Reviewer of Journal of Materials Science: Materials Review, Journal of Chemistry and Physics with Certificates of SCIREA - Science Research Association, American Journal of Physics and Applications, Journal of Energy Problems

Name: **Gulshan**
Middle Name: **Nuraddin**
Surname: **Mammadova**
Birthday: 07.09.1980
Birthplace: Baku, Azerbaijan
Bachelor: Electronic Equipment, Electronic Devices Department, Faculty of Automation and Computing Techniques, Azerbaijan Technical University, Baku, Azerbaijan, 2002
Master: Electronic Equipment, Electronic Devices Department, Faculty of Automation and Computing Techniques, Azerbaijan Technical University, Baku, Azerbaijan, 2004
Ph.D.: Semiconductor Physics, Nakhichevan State University, Nakhichevan, Azerbaijan, 2018
The Last Scientific Position: Senior Lecturer, Electrical Power Engineering Department, Faculty of Architecture and Engineering, Nakhichevan State University, Nakhichevan, Azerbaijan, Since 2018
Research Interests: Lubricating Oils for Early Diagnosis of Transformer, Operational Electronic and Optical Properties of Semiconductors
Scientific Publications: 12 Papers, 1 Book, 5 Theses

Name: **Khangardash**
Middle Name: **Adigozel**
Surname: **Asgarov**
Birthday: 08.06.1956
Birthplace: Shirvan, Azerbaijan
Bachelor: Metallurgy Department, Faculty of Materials Science in Mechanical Engineering, Dnepropetrovsk State University, Dnipro, Ukraine, 1983
Postgraduate Studies: Metallurgy Department, Metal Physicist Faculty, Dnepropetrovsk State University, Dnipro, Ukraine, 1985
Doctorate: Metallurgy, Metal Physicist, Solid State Physics, Dnepropetrovsk State University, Dnipro, Ukraine, 1992
The Last Scientific Position: Prof., Department of Mechanical Engineering, Metallurgy Faculty, Karrabuk University, Karrabuk, Turkey, Since 2016
Research Interests: Mechanical Properties and of Carbon Steel, Characteristic Properties of Railway Wheel and Rail Steel, Composite Varistors, Plastic Deformation Methods on Steel, Effects of Heat Treatment on Steels
Scientific Publications: 90 Papers, 2 Patents, 3 Projects, 43 Theses