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FORMATION OF THERMAL PHENOMENA IN METAL–COMPOSITE CONTACTS AND THEIR MANIFESTATION LAWS

[1]Mamirov Abduvoxid Muxammadamin o'g'li, [2]Olimov Lutfiddin Omanovich
[1]Andijan State Technical Institute. PhD student. abduvoxidmamirov5775@gmail.com
[2]"University of Economics and Pedagogy" non-state educational institution, Professor, Doctor of Physical and Mathematical Sciences. oJimovl266@gmail.com

Abstract

This article provides a comprehensive analysis of thermal phenomena occurring in metal–composite contacts, their formation mechanisms, and the laws governing their manifestation. In modern electronic and electrical engineering devices, metal–semiconductor composite contacts play a crucial role, particularly silicon-based contact systems, which exhibit high efficiency. Therefore, a detailed study of thermal processes in such systems is of significant scientific importance.

Within the scope of this study, composite contacts based on silicon (Si) and various metal elements—iron (Fe), copper (Cu), nickel (Ni), and tin (Sn)—were investigated. The selection of these materials was based on significant differences in their physical, electrical, and thermal properties. Heat generation in metal–composite contacts is primarily explained by the Joule–Lenz effect induced by electric current flow. In this case, the amount of generated heat increases proportionally to the square of the current, contact resistance, and time.

Furthermore, the study examines the influence of microstructural changes, diffusion processes, and phase transformations occurring at the contact interface on thermal behavior. In particular, at elevated temperatures, diffusion of metal atoms into silicon modifies the structure of the contact region, thereby affecting both thermal conductivity and electrical resistance.

The results show that Si–Cu composite contacts possess high thermal conductivity, enabling efficient heat dissipation and reduced local heating. In contrast, Si–Sn composite contacts exhibit greater heat accumulation due to low melting temperature and poor thermal conductivity, which reduces their stability. In Si–Ni and Si–Fe systems, oxidation and diffusion processes are more pronounced.

Keywords

Metal–composite contacts, silicon, thermal phenomena, contact resistance, Joule–Lenz law, diffusion, thermal conductivity, semiconductors, microstructure.

Introduction

In modern electrical engineering and electronics, the development of materials and contact systems with high efficiency is of great scientific and practical importance. In particular, metal–semiconductor composite contacts are widely used in devices such as diodes, transistors, and integrated circuits. The performance efficiency of these composite contacts is directly determined by their electrical and thermal properties.

Silicon-based semiconductors are characterized by high stability and wide applicability. When silicon forms contacts with various metals, complex physicochemical processes occur [1]. Among these processes, thermal phenomena occupy a central role. In metal–composite contacts, heat generation is primarily associated with electric current flow. In any system with contact resistance, heat is generated due to current passage. The magnitude and distribution of this heat depend on the properties of the contact material, surface condition, and external operating conditions [2].

In addition, at elevated temperatures, diffusion, oxidation, and phase transformation processes occur in the contact region. These processes modify both the electrical and thermal properties of the contact. Therefore, studying thermal phenomena in metal–composite contacts is essential for improving their reliability.

This study investigates thermal phenomena in silicon-based contact systems formed with Fe, Cu, Ni, and Sn metals, and analyzes their fundamental governing laws [3].

Materials and Methods

In this study, metal–semiconductor composite systems based on silicon (Si) combined with iron (Fe), copper (Cu), nickel (Ni), and tin (Sn) were selected to investigate their thermal and electrophysical properties. Experiments were conducted using high-purity monocrystalline silicon wafers. Metal layers were deposited using vacuum deposition and mechanical bonding techniques.

The formation of metal–composite contacts was based on two main technological approaches: resistance heating bonding and localized (dispersed) heating methods [4–6].

In the resistance heating bonding process, electric current is passed through the contact region, and the generated Joule heat causes material bonding Fig 1. This process is based on the Joule–Lenz law:

$$Q = I^2Rt \qquad (1)$$

Here, Q is the generated heat, I is the electric current, R is the contact resistance, and t is time. Due to the presence of resistance in the contact region, the maximum heat is generated precisely in this area, which activates plastic deformation of the materials and interatomic diffusion processes.

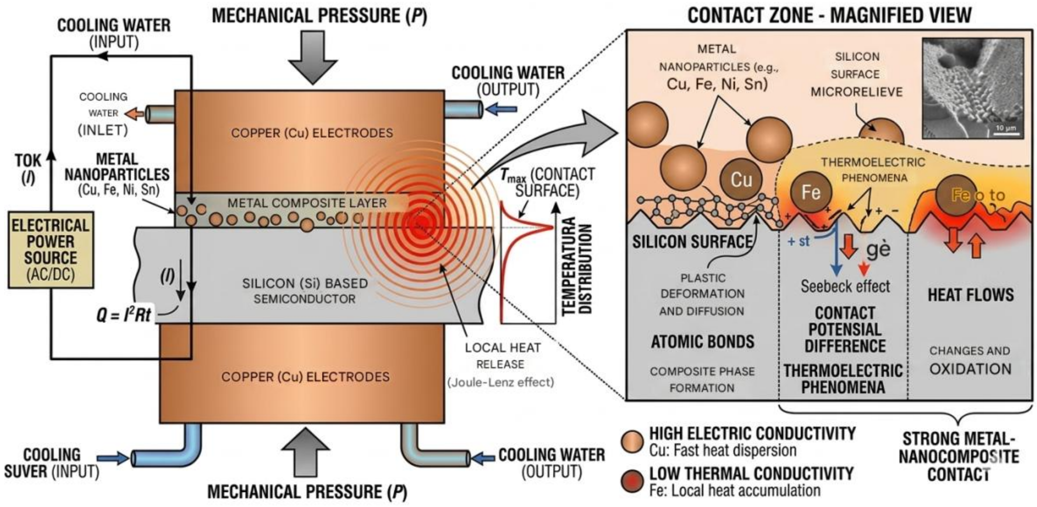

Figure 1. Schematic representation of the resistance heating bonding process

In the dispersed (localized) heating method, heat is concentrated in a specific region. In this case, the heat flux and temperature gradient are high, and the process is described by the following heat conduction equation:

$$q = -\lambda \nabla T \qquad (2)$$

Here, λ is the thermal conductivity coefficient, and ∇T is the temperature gradient. Under these conditions, phase transformations and the formation of intermetallic compounds are observed in the contact region. During the experiment, the electrical properties of the composite contacts were determined using the four-probe measurement method [7,9]. The current and voltage values were measured, and the contact resistance was calculated using the following formula:

$$R_{(c)} = U / I \qquad (3)$$

Infrared thermography was used to analyze thermal processes [8]. This method enabled real-time observation of the temperature distribution on the contact surface. The time-dependent variation of temperature was evaluated using the following heat balance equation:

$$\rho c\, \partial T/\partial t = \lambda \nabla^2 T + Q \qquad (4)$$

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Here, ρ is the density, c is the specific heat capacity, and Q is the internal heat source. The formation of metal–composite contacts was studied in close relation to their thermoelectric and electrophysical properties [10]. In particular, when a temperature gradient exists in the contact region, the Seebeck effect occurs

$$E = S\Delta T \qquad (5)$$

Here, S is the Seebeck coefficient and ΔT is the temperature difference. This phenomenon generates an additional electric field in the contact region and influences the motion of charge carriers. Furthermore, the relationship between current density and electrical conductivity is expressed as follows:

$$J = \sigma E \qquad (6)$$

Here, J is the current density, σ is the electrical conductivity, and E is the electric field strength. An increase in current density intensifies heat generation in the contact region. Diffusion processes at the metal–silicon interface are also of significant importance and are described by Fick's law:

$$J_{(d)} = -D\, dC/dx \qquad (7)$$

Here, D is the diffusion coefficient and C is the concentration. As temperature increases, the diffusion rate also increases, which leads to the formation of new phases in the contact region Fig 2.

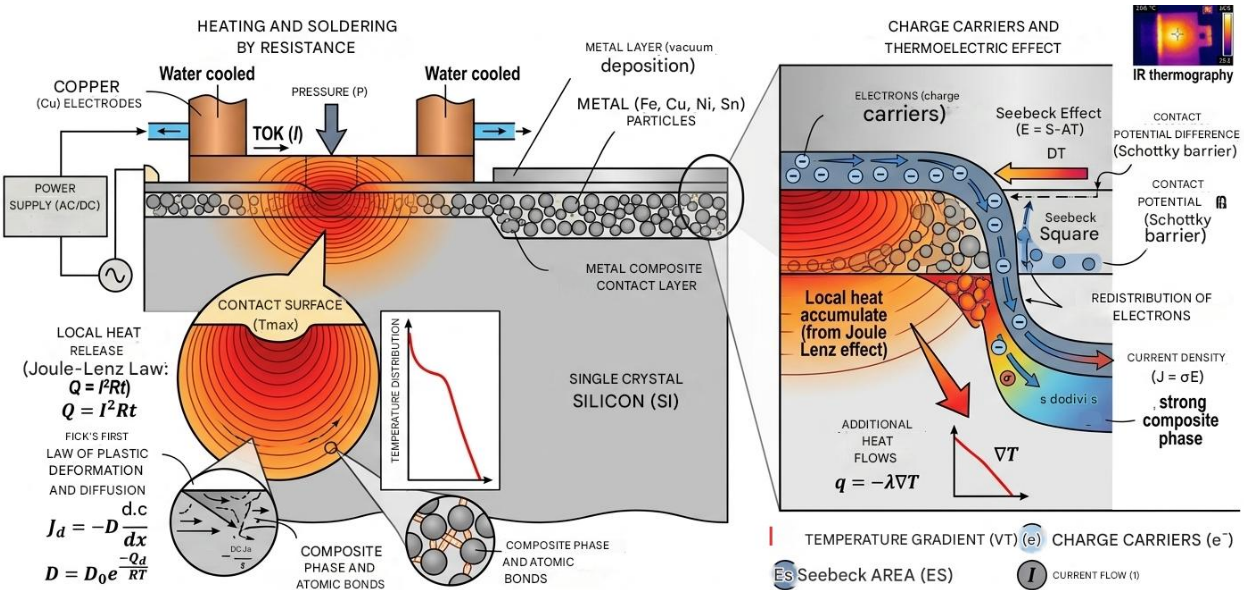

Figure 2. Distribution of heat and charge carriers in the metal–semiconductor contact region

All obtained experimental results were processed using mathematical and statistical methods, enabling the determination of thermal and electrophysical differences between various metal–composite contacts.

Results and Discussion

The experimental results demonstrated that significant differences exist in the thermal and electrophysical properties of metal–composite contacts based on silicon (Si) combined with Fe, Cu, Ni, and Sn metals. During measurements, a strong correlation was observed between contact resistance, temperature distribution, and heat dissipation rate [11].

According to the obtained results, Si–Cu composite contacts exhibited the lowest contact resistance and efficient heat dissipation. This behavior is attributed to the high thermal and electrical conductivity of copper. As a result, the level of local heating was minimal, ensuring high contact stability.

In contrast, Si–Sn composite contacts showed the highest heat accumulation. The low melting point and relatively poor thermal conductivity of tin led to rapid heating and structural instability in the contact region. This behavior may accelerate contact degradation during long-term operation [12–14].

Si–Fe and Si–Ni composite contacts demonstrated intermediate characteristics. In these systems, diffusion processes were more pronounced, and the formation of intermetallic layers at elevated temperatures was observed. These layers increased contact resistance over time and altered heat distribution. The analysis showed that an increase in contact resistance leads to an increase in heat generation power. This confirms that at high current densities, rapid heating processes are intensified in Si–Sn and Si–Fe composite contacts Fig 3.

In addition, thermoelectric effects significantly influenced the overall thermal balance of the composite contacts. Relatively high Seebeck voltage values were observed in Si–Ni and Si–Fe systems, leading to the formation of an additional electric field in the contact region. As a result, an inhomogeneous distribution of charge carriers was observed.

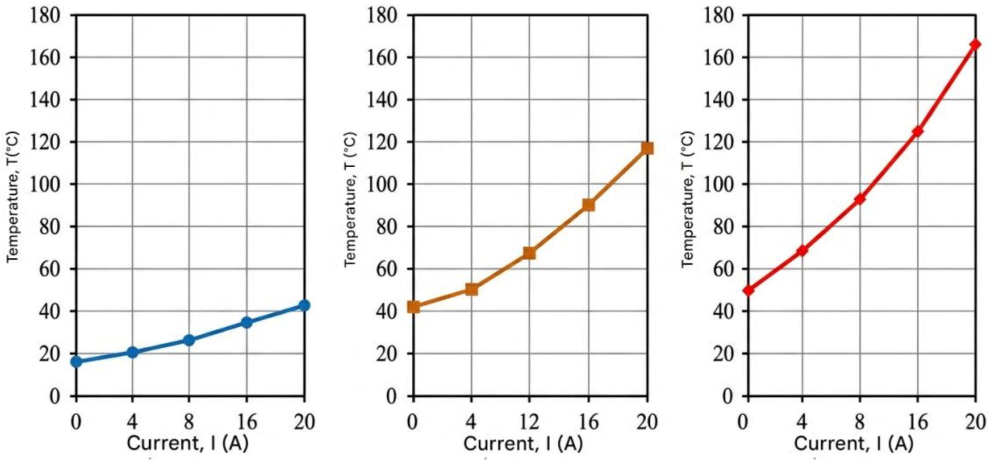

Figure 2. Graph of the dependence of temperature on current in various metal–composite contacts (Si–Cu, Si–Fe, Si–Ni, Si–Sn)

The graphical analysis shows that in all metal–composite contacts, the temperature increases with increasing current; however, the rate of increase depends on the material type. The steepest temperature rise was observed in Si–Sn composite contacts, indicating their low thermal stability. In contrast, Si–Cu composite contacts exhibited the slowest temperature increase, confirming their superior heat dissipation capability.

In general, the obtained results demonstrate that the choice of metal plays a decisive role in controlling the thermal regime and electrophysical properties of composite contacts. Cu-based composite contacts exhibit high thermal stability, whereas Sn-based composite contacts are characterized by rapid heating and low stability. Fe and Ni, on the other hand, demonstrate intermediate but diffusion-active behavior.

Conclusion

In this study, a comprehensive analysis of the thermal and electrophysical properties of metal–composite contacts based on silicon (Si) combined with Fe, Cu, Ni, and Sn metals was carried out. Theoretical and experimental investigations confirmed that the choice of metal has a direct influence on the thermal regime of the contact system, contact resistance, and charge carrier dynamics.

The obtained results showed that Cu-based composite contacts possess the highest thermal stability, and due to their high thermal conductivity and low contact resistance, local heating effects are minimal. This makes Cu composite contacts one of the most suitable options for devices operating under high current density and requiring stable performance.

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In contrast, Sn-based composite contacts are characterized by low melting temperature and insufficient thermal conductivity, resulting in rapid heating and structural instability. This reduces their thermal reliability and accelerates degradation processes during long-term operation. Fe and Ni-based composite contacts exhibit intermediate properties and are characterized by active diffusion processes. In these metals, interaction with silicon leads to the formation of intermetallic layers, which cause time-dependent changes in contact resistance. Nevertheless, under certain conditions, these systems may still maintain stable operation.
The research results demonstrate a strong interdependence between thermal phenomena and electrophysical processes in metal–composite contacts. Current density, thermal conductivity, diffusion, and thermoelectric effects are identified as key factors governing the overall performance of the contact system. The obtained results provide a theoretical basis for selecting efficient contact materials in the design of microelectronic and semiconductor devices.

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