# Flow of Electric Currents in Ohmic Contacts of Friction Couples of Braking Devices

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**Abstract**

The paper exams the energy levels of contacts in the frictional interaction of metal-polymer and semiconductor materials; ohmic contact in the system: "metal-polymer" and "metal-semiconductor"; the analysis of results. In this case, the height of the potential barrier between their materials in the near-contact zone and in the "metal-semiconductor" interface with "n" and "p" types of conductivity was taken into account. The different degree of regulation of their surfaces that contribute to the concentration of charge carriers and dislocations of imperfections in the crystal lattice of materials. In this case, thermionic, field and thermal field emissions were formed, accompanied by emerging metal shunts. As for the Fermi energy level, it affects the surfaces in the middle and in the depth of the band gap, near the edge of the valence band, as well as the resulting shift at the edge of the conduction band. All of these factors were under the influence of impulse specific loads and energy load, which contributed to the generation of electric currents of various magnitudes and directions along with alternating thermal currents.

**Keywords:** friction pair, contact microprotrusions, electric and thermal currents, energy levels, polymeric and semiconductor materials.

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# Əyləc qurğularının sürtünmə cütündəki omik kontaktlarda elektrik cərəyan axını

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**Xülasə**

Məqalədə metalpolimer və yarımkeçirici materialların friksion qarşılıqlı təsiri zamanı kontaktlarının enerji səviyyələri; sistemdə omik əlaqə: "metal-polimer" və "metal-yarımkeçirici" kimi məsələlər nəzərdən keçirilib. Bu zaman kontakt zonasında və "metal-yarımkeçirici" ilə "n" və "p" keçiricilik növlərinin keçid sərhəddində onların materialları arasındakı potensial maneənin hündürlüyü nəzərə alınıb. Onların səthlərinin tənzimlənməsinin müxtəlif dərəcəli olması yük daşıyıcılarının konsentrasiyasına və materialların kristal qəfəsindəki qüsurların dislokasiyasına kömək edir. Bu zaman yaranan metal şuntları ilə müşayiət olunan termelektron, sahə və termo-sahə emissiyaları meydana gəlir. Fermi enerji səviyyəsinə gəldikdə, o, qadağan olunmuş zonanın səthinin ortasına və dərinliyinə, valentlik zonasının kənarına yaxın səthlərə, həmçinin keçiricilik zonasının yerdəyişməsinə təsir edib. Bütün sadalanan amillər xüsusi impuls yüklərinin və enerji yüklənməsinin təsiri altında idi ki, bu da dəyişən istilik cərəyanının və müxtəlif kəmiyyət və istiqamətlərdə elektrik cərəyanının yaradılmasına kömək edir.

**Açar sözlər:** sürtünmə cütü, kontaktların mikro-çıxıntıları, elektrik və istilik cərəyanları.

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# Протекание электрических токов в омических контактах пар трения тормозных устройств

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**Аннотация**

Рассматриваются энергетические уровни контактов при фрикционном взаимодействии металлополимерных и полупроводниковых материалов; омический контакт в системе «металл-полимер» и «металл-полупроводник». При расчете учитывалась высота потенциального барьера между их материалами в приконтактной зоне и в переходной границе «металл-полупроводник» с «n» и «p» типами проводимости. Разная степень регулирования их поверхностей способствует концентрации носителей заряда и дислокациям несовершенств кристаллической решетки материалов. При этом образовывалась термоэлектронная, полевая и термополевая эмиссии, сопровождающиеся возникающими металлическими шунтами. Энергетический уровень Ферми воздействовал на поверхности посередине и в глубине запрещенной зоны, вблизи края валентной зоны, а также на сдвиге зоны проводимости. Все факторы находились под воздействием импульсных удельных нагрузок и энергонагруженности, что способствовало генерированию переменных тепловых токов и электрических токов различной величины и направлений.

**Ключевые слова**: пара трения, микровыступы контактов, электрические и тепловые токи, энергетические уровни, полимерные и полупроводниковые материалы.

## Introduction

*Kragelsky I.V.* formulated and introduced into consideration tribotechnology with sequential and interrelated friction processes, namely: frictional interaction of surface microprotrusions, changes in surface and near-surface layers as a result of interaction and destruction of surfaces due to the two previous stages [1]. All three stages friction occurs in the following fields: mechanical, electrical, thermal, chemical and electromagnetic. The driving force in the specified fields is local potential with its gradients, evaluated in a particular process, phenomenon and effect in the longitudinal and transverse directions in a metal friction element. As for the currents of the washing medium, they take into account the transverse temperature gradient (determined by the ratio $C_p/C_\upsilon$, i.e., the ratio of the heat capacity at constant pressure to the heat capacity at constant volume). In all processes, phenomena and effects, the main role is played by ohmic contact.

## Analysis of literary sources and the state of the problem

The paper [2] provides a review of literature data on the properties of ohmic metal-semiconductor contacts and the mechanism of current flow in them (thermionic emission, field emission, thermal field emission, as well as current flow through metal shunts). The theoretical dependences of the resistance of an ohmic contact on temperature and the concentration of charge carriers in a semiconductor were compared with experimental data for ohmic contacts to semiconductors of the $A^{II}B^{VI}$ (ZnSe, ZnO), $A^{III}B^{V}$ (GaN, AlN, InN, GaAs, GaP, InP), $A^{IV}$ (SiC, diamond) and a solid solution of these semiconductors. In ohmic contacts based on lightly doped semiconductors, the main current flow mechanism is thermionic emission, and the height of the «metal-semiconductor» potential barrier is most often 0,1–0,2 eV. In ohmic contacts based on lightly doped semiconductors, the current flows due to field emission, and the height of the «metal-semiconductor» potential barrier is approximately 0,3-0,5 eV. In alloyed In contacts to GaP and GaN, a current flow mechanism is manifested, which is not typical for Schottky diodes - current flow through metal shunts formed due to the deposition of metal atoms on dislocations or other imperfections in the semiconductor.

It is known that the resistance of ohmic contacts was determined from the dependence of the potential difference between several contacts on the distance between them [2]; from the dependence of the resistance of the “metal-semiconductor-metal” structure with two ohmic contacts on the thickness of the structure [3]; from the analysis of the characteristics of contacts of different diameters [4], as well as by the heat transfer line method [5].

Currently, research is being carried out on the dependence of the resistance of ohmic contacts on temperature, charge carrier concentration, band gap of a semiconductor, and so on, in order to establish the mechanism of current flow through an ohmic contact. Theoretically, both current flow mechanisms traditional for Schottky barriers (thermionic emission, thermal field emission, field emission) and other mechanisms (recombination, metal shunts) were considered. The current flow mechanism was determined from a comparison of experimental results with these theories. These studies were carried out both for semiconductors $A^{II}B^{VI}$, $A^{III}B^{V}$, $A^{IV}B^{IV}$, and for solid solutions based on them.

The resulting structures with zero ohmic resistance for direct and sinusoidal electric current [6].

As in the case of superconductivity, this fact is due to the exchange-correlation interaction of electrons, but its cause is different and consists in the polarization of the structure by the electric field, and not in the polarization of the lattice by Cooper pairs.

In [7], the electrophysical processes of real “metal-semiconductor” contacts are considered, in the near-contact semiconductor region in which an additional electric field of the contact potential difference (spot field) arises both between microsections with different heights of potential barriers on the contact surface, and between contact surface and adjacent to it, and free surfaces of the metal and semiconductor. Energy models of real metal-semiconductor contacts and current flow mechanisms based on the theory of thermionic emission have been developed.

The features of determining the electrophysical parameters of the peripheral region of the contact surface and measuring the existing electrophysical parameters of real "metal-semiconductor" contacts are presented.

In [8], the phenomenon of electronic switching of polymer film currents as a result of changing the boundary conditions at the metal-polymer interface was studied. It is shown that the transition of the polymer to a highly conductive state can be realized by spatial separation of the metal, in which the position of the electrochemical potential changes, from the region of the polymer film, in which the electrical switching occurs.

An explanation of the effect is proposed on the basis of an injection model for the appearance of conductivity in a metal-polymer-metal structure.

In the materials of the article, the types of contacts of microprotrusions of metal-polymer and semiconductor materials are given [9]. The latter are modified in the form of tablets into the working surface of polymer linings.

The energy levels of microcontacts of friction pairs are illustrated.

A critical review of the literature indicated what needs to be done:

- to evaluate the energy load of metal-polymer and metal-semiconductor contact spots of microprotrusions of friction pairs of brakes;

- generalize the dependence for calculating the main operational parameters of metal-semiconductor contacts;

- to show the role of metal shunts in the contact frictional interaction on the distribution of pulsed electric currents between the spots of microprotrusions of friction pairs.

## Formulation of the problem

The main questions of the article: energy levels of contacts in the frictional interaction of metal-polymer and semiconductor materials; ohmic contact in the system: "metal-polymer" and "metal-semiconductor"; the discussion of the results.

**The purpose of the work** is to establish the patterns of change in pulsed electric currents in ohmic contacts "metal - semiconductor" during their contact-pulse frictional interaction in friction pairs of brake devices.

**Energy levels of contacts in the frictional interaction of metal-polymer and semiconductor materials**

In polymer overlays, composed of heterogeneous materials, there are amorphous and crystalline phases, a capture of a different kind occurs - at interphase boundaries. The accumulation of charges at the boundaries is due to the difference in the conductivities of the considered phases (the Maxwell-Wagner effect) [9, 10].

When such a material is electrified, the carriers will collect near a given interface or, vice versa, leave it, depending on which of the two conduction currents is greater: flowing to the charge boundary or leaving it. Differences in local conduction currents also lead to charge dissipation during the subsequent thermally stimulated discharge, since in this case the currents already flow in the opposite direction. For charge neutralization processes, the properties of the working surface of the metal friction element also play an important role. The relationship between the energy levels is determined by the frictional contact interaction of microprotrusions of friction pairs [4].

In table 1, in fig. 1 *a*, *b*, *c* conditionally shows the difference between ***neutral, ohmic*** and ***blocking contacts.***

Let us consider the cases of the appearance of neutral contacts on microprotrusions of metal-polymer friction pairs according to fig. 1 *a* and table 1.

The first case refers to the surface temperatures of the polymer lining, which are below the allowable values for its materials. According to the table 1 and fig. 1 and the work function of electrons and ions from the metallic and non-metallic friction elements is equal to each other.

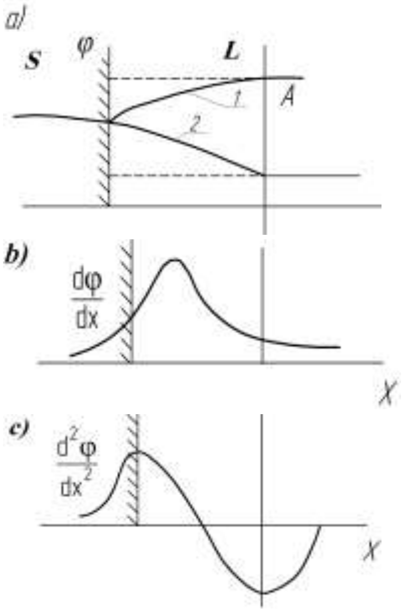



**Fig. 1 a, b, c. –** Dependence of the electrokinetic potential φ (a), field strength E = dφ/dx (b) and charge density $\rho = d^2\varphi/dx^2$ (c) on the X coordinate: A – boundary of the fixed part of the electrical double layer; L - liquid; S is a solid body; curves 2 and 1 - respectively, up to the permissible temperature of the materials of the surface layer of the lining and above

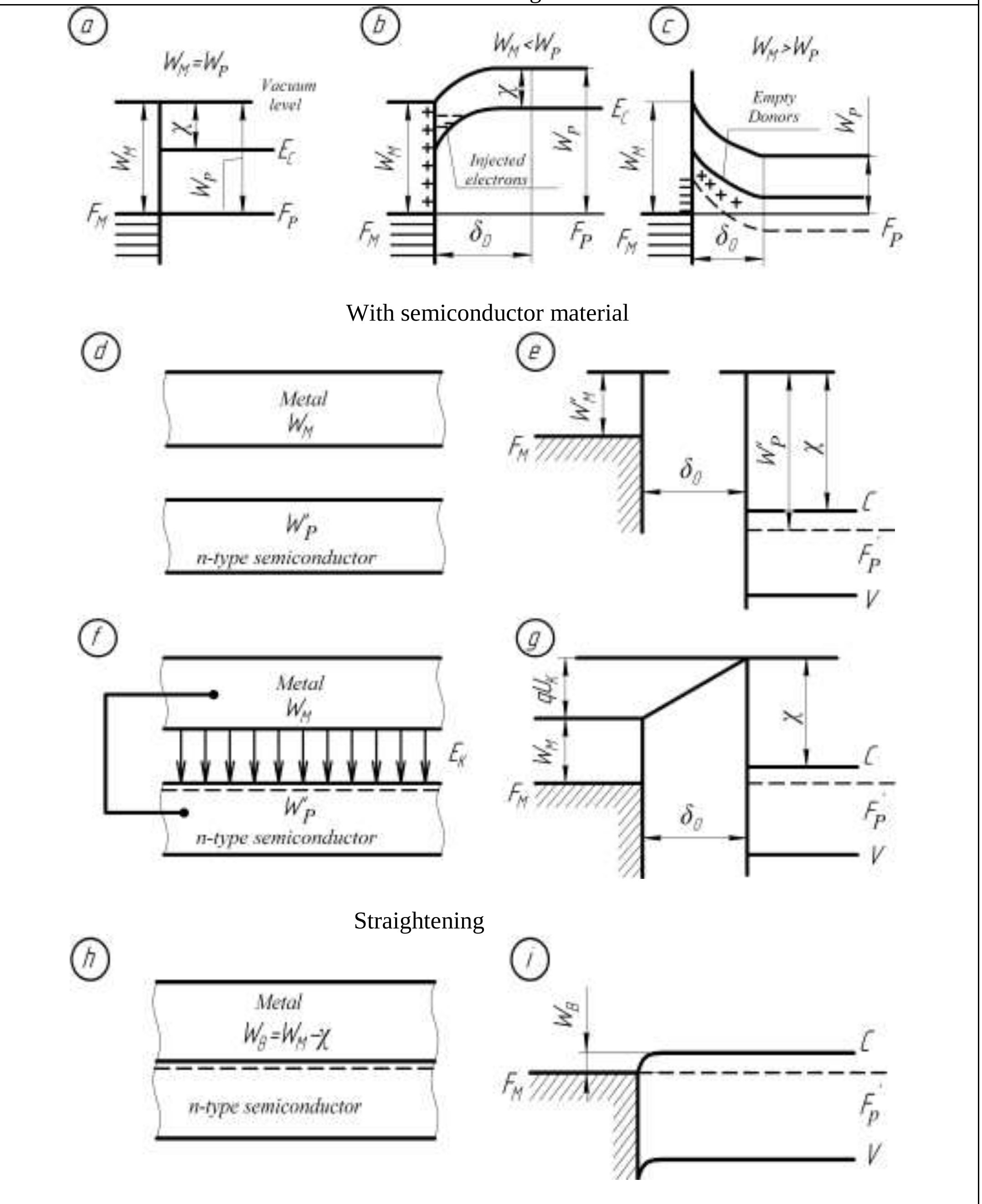
**Neutral contact**

A large increase in the work function of ions from the surface layer of the overlay is given by electron affinity. The latter is the ability of some atoms and molecules to attach an additional electron and turn into positive ions. The measure of electron affinity is the energy released in this case. Purposeful reorientation of electrons into ions makes it possible, due to this effect, to achieve equality of the work functions of particles.

<u>Second case</u>

When the working surface of the polymer lining reaches a temperature above the allowable for its materials, burnout occurs from the surface and near-surface layers of the binder components, which leads to the formation of liquid islands on the surface of the lining.

**Table 1 –** Energy diagrams during frictional interaction of microprotrusions of friction pairs "metal-polymer" (a, b, c) and "metal-semiconductor" (i) with n-type conductivity

| Name contacts | | Traditional<br>Neutral Blocking Ohmic |
|---|---|---|
| Contacts of microprotrusions of friction pairs "metal-semiconductor" are disconnected (*d*) connected to an electric circuit (*f*) frictionally interact (*h*) | Work function of electrons and ions (*a, b, c, d, g, i*) |  |



**Legend:** χ – electron affinity; $F_m$, $F_p$, $F'_p$ – Fermi levels: metal, polymer, semiconductor; $E_c$ is the energy of the formed capacitance of the capacitor (*C*); $\delta_0$ is the distance between microprotrusions; $U_k$ is the contact potential difference; *q* is the electron charge; $W_f$ is the work function of electrons and ions from the rectifying contact; *V* is the field voltage

When the working surface of a metal friction element comes into contact with a liquid, the transition of ions from the metal to the liquid is observed (Fig. 1a, curve 1).

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In addition to the chemical mechanism of electrical phenomena in the contact of metal and liquid, another mechanism is also possible - electrification of the surfaces of metal and liquid during the movement of the latter, because the liquid layer, moving, carries away with itself an ionic charge. Calculations show that a significant accumulation of charges during the movement of a liquid occurs when its specific resistance is above 109 Ohm•cm. It is believed that in this case a double electric layer is formed on the surface of the metal in contact with the liquid.

The surface of the metal, as a result of the loss or capture of ions, acquires a certain chemical potential, and a certain charge is distributed over it. The opposite charge is in the liquid. The distribution of charges in a liquid can be characterized by a potential φ that varies with distance from the surface in accordance with the electrostatic forces and the Boltzmann distribution (Fig. 1*a*).

An analytical expression for calculating the value of the potential φ is obtained by solving the Poisson equation under the assumption of the existence of a screening double electric layer.

The metal enters the solution in the form of either positive ions or complex negative ions if it interacts with a liquid solution. In this case, the surface of the metal acquires a certain specific potential, which establishes a balance between the process of isolation and deposition of ions. This potential depends both on the nature of the metal and on the concentration of ions in the liquid. At a certain value of acidity (pH), the metal does not send ions into the solution, but, on the contrary, takes them from the solution, acquiring a charge before the onset of electrical equilibrium.

Metals are arranged in an electrochemical series with respect to the positive hydrogen ion $H^+$. When two different metals are immersed in a liquid, each of them has a certain potential with respect to the liquid.

When metals come into contact, an electric current arises until all metal ions or all ions of the solution are exhausted in the solution. Electric currents can also flow between different points of the same metal surface if it is charged and inhomogeneous.

**Blocking contact**

The behavior of the microprotrusions of the polymer lining is highly dependent on the material of the microprotrusions of the metallic friction element. Usually, the contact spots of microprotrusions covered with films are blocking contacts at low and intermediate field strengths (table 1, *c*).

Such a contact prevents the transfer of charge carriers from the electrode into the surface and near-surface layers of the polymer lining, while at the same time, it itself can receive carriers from these layers.

In a dielectric with blocking contacts, containing no charge carriers at all, the flow of a stationary current is obviously impossible. If in the dielectric there are carriers of both signs, and with very different values of their mobility, then near the contact spots of microprotrusions of a metal friction element, the sign of which coincides with the sign of more mobile carriers, a Schottky barrier is formed. The polarization of the contact patches of the microprotrusions of the lining arising under these conditions is due precisely to the presence of electrons. This situation is quite easily explained in the limiting case when there is no mobility of carriers of one polarity (for example, electrons) and no further generation of free carriers occurs. The applied field in this case removes positive carriers from the contact spots of the microprotrusions of the lining (anodes), (located, say, at $x = 0$).

Since this electrode is not able to transfer positive charges to materials, a cloud of negative space charge with a density ρ is formed near it in a layer of thickness ss between the planes $x = 0$ and $x = s_S$. After the space charge layer has been fully formed, the voltage V, which initially fell across the entire thickness of the metal microprotrusion, will now become applied to layers of thickness $s_S$.

As a result, the current will go to zero. The length of the layer is determined by the formula $s_s = \sqrt{2\varepsilon V / \rho}$ and does not depend on the applied electric field.

For example, at a density of immobile (captured) carriers $\rho = 1 \cdot 10^{-4}$ *C/cm*, $\varepsilon = 2 \cdot 10^{-13}$ *F/cm* и $V = 1{,}0$ толщина слоя $s_S$ составляет $1{,}25 \cdot 10^{-3}$ cm. So, the use of blocking contacts prevents the complete removal of mobile carriers from the dielectric, and regardless of

The presence of a non-conductive interlayer of finite thickness between the dielectric and the electrode can cause the formation of barrier polarization.

True, the molecular dimensions of the resulting double layer of positive and negative carriers do not allow it to be detected in ordinary external measurements, for example, compensation charges on the electrode. In addition, the formation of a double electric layer does not give a blocking effect.

Thus, if the contacts are blocked, neutralization must take place inside the metallic friction element, regardless of the type of contact (whether it is injecting electrons or blocking). It depends only on which of the work functions of electrons or ions is greater: a metal or polymer friction element. If the work function of the first element is greater than that of the second element, a blocking barrier is formed. The presence of the latter makes it possible to study the method of thermally stimulated discharge of semi-insulators and semiconductors, which are characterized by large conduction currents. Blocking contacts act in the opposite way: they prevent both injection and neutralization of charges.

## Ohmic contact in the system "Metal - polymer"

Most often, in metal-polymer friction pairs in relation to two-layer ("metal-polymer") structures of braking devices, an ohmic (injecting) contact is encountered (Table 1, *c*).

On fig. 2 shows the band diagram of the contact “metal - electrically conductive polymer”. A feature of this diagram is the presence of a narrow electrically conductive zone in the middle of the polymer gap. According to one of the hypotheses, just such a narrow band can be responsible for the transport properties of thin dielectric films.

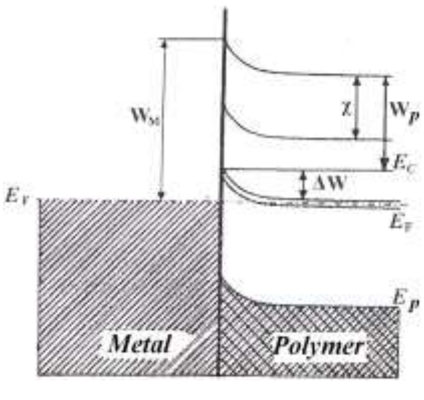


**Figure 2 –** Energy diagram of the friction pair "metal - polymer": $E_F$, $F_V$ - energy levels: metal (Fermi); polymer; $W_M$; $W_P$ - work function: electrons of their metal; ions and electrons from polymer; χ - electron affinity

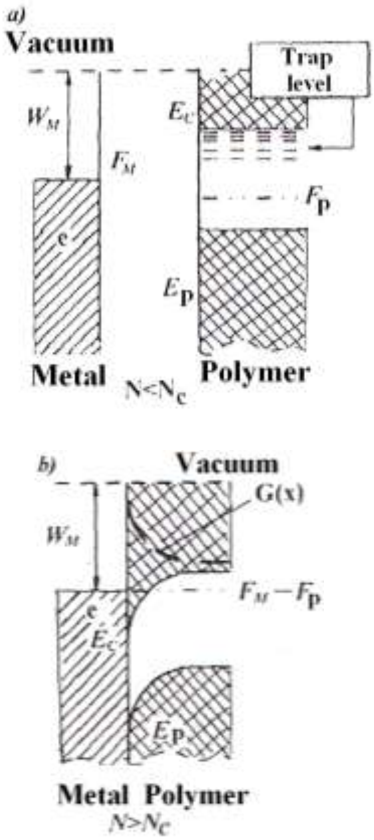


**Figure 3 a, b** – Qualitative picture of the energy bands in the "metal-polymer" system with pulsed normal forces acting on the polymer film: a – N < NC; b – N > NC; EC, EV are the energies of the zones: the conduction bottom and the valence top of the polymer; FM and FP are the Fermi and polymer levels; WM is the work function of an electron from a metal; dashed curve G(x) is the distribution of injected electrons in the polymer film

The change in the position of the Fermi level of a metal in the region of its phase transition relative to a narrow band in the polymer dictates the conditions for the injection of electrons and ions from the metal into the polymer and thus characterizes the change in the conductivity of the system as a whole.

On fig. 3 *a*, *b* shows the model of energy bands in the “metal-polymer” system stimulated by pulsed normal forces injection of current carriers from the metal into the conduction band of the polymer. According to this model, the compression of a polymer causes the decay of surface states that play the role of electron acceptors. It is also possible that, due to the increase in polarizability, the bottom of the conduction band of the polymer simultaneously decreases.

As a result, at a certain value of N=NC, the structure of the energy bands near the metal-polymer interface is favorable for carrier injection, although at N<NC this process either does not occur at all or has an extremely low efficiency.

With a decrease in the thickness of the polymer film, a situation may arise when the charges concentrated near the opposite boundaries of the considered contact begin to interact with each other, leading to a distortion of the shape of the potential barrier. The maximum film thickness at which the interaction of boundary charges begins can be considered to be twice the value of such a contact parameter as the penetration depth of the surface charge. The interaction of surface charges can lead to the formation of a local minimum in the middle of the barrier, which, in principle, can lead to the intersection of the curve describing the envelope of the potential barrier with the Fermi level (Table 2).

With such a hypothetical variant, new electronic states can arise in the middle of the barrier at the Fermi level, which increase its permeability for electrons. If we learn to control such states, then in fact it will mean the creation of a fundamentally new electronic hybrid nanostructured metal-polymer material.

If the contacts are blocked, neutralization must take place inside the metallic friction element, regardless of the type of contact (whether it is electron-injecting or blocking). It depends only on which of the work functions of electrons or ions is greater:

a metal or polymer friction element. If the work function of the first element is greater than that of the second, a blocking barrier is formed. The presence of the latter makes it possible to study the method of thermally stimulated discharge of semiconductors, which are characterized by large conduction currents.

Blocking contacts act in the opposite way: they prevent both injection and neutralization of charges.

In the case when the work function of the electrons and ions of the semiconductor $W_P$ is greater than the work function of the metal $W_M$ (Table 1, d, e), then when the metal and the n-type semiconductor are connected by a wire, the electrons pass from the metal to the semiconductor (Table 1, f). As a result, after the establishment of thermodynamic equilibrium, an electrostatic field $E_K$ is formed between them directed to the surface of the semiconductor, and a contact potential difference $U_K$ appears as shown in the energy diagram (Table 1, g).

The electric field between the metal and the semiconductor is created by the missing electrons on the surface of the metal and the excess electrons on the surface of the semiconductor. With a decrease in the thickness δ of the charge layer, naturally, the surface density of excess charges on the surfaces increases, as well as the electric field strength in the gap.

When the gap thickness decreases to the order of interatomic distances, i.e. in direct contact between a metal and a semiconductor, the surface atomic layer of the metal and the semiconductor forms a single quantum mechanical system (Table 1, h) and there is practically no potential barrier at the interface for free electrons (Table 1, i).

Thus, the contact of a metal with an n-type semiconductor has a potential barrier, i.e. has rectifying properties if $W_M > W'_S$ and - ohmic if $W_M \leq W'_s$ (Fig.4).

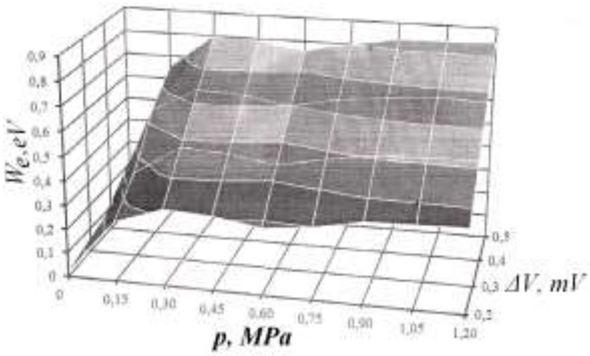


**Figure 4 –** Patterns of the work function of electrons from the working surfaces of friction pairs of the brake ($W_e$) on specific loads (p) at various values of the contact potential difference (ΔV) during frictional interaction

In the case when the metal is in contact with *p*-type zinc, the "metal-semiconductor" contact has rectifying properties if $W_M < W'_s$, and ohmic if $W_M \geq W'_s$ (Fig. 1 a, b, c). It should be noted that if the contact of a metal with an *n*-type and *p*-type semiconductor has the corresponding barrier heights $F_{Vp}$ and $F_{Vr}$, then their sum becomes equal to the band gap of this semiconductor $F_D$.

The initial data for calculating the mechanical and electrical parameters of the contact spot of microprotrusions for determining the current are the characteristics of the surface microgeometry - the maximum height of the protrusions above the middle line of the profile Rp and the maximum radius of the protrusions rmax; physical and mechanical characteristics of the material - the modulus of elasticity (Young's modulus) E, Poisson's ratio μ, electrical resistivity of the material r; operational characteristics, impulsive normal force compressing the contact.

**Table 2 –** Dependence of the potential difference in the contact on the difference between the Fermi levels of friction pair materials

| $F_1$-$F_2$, eV | 0,15 | 0,20 | 0,25 | 0,30 | 0,35 | 0,40 | 0,45 | 0,50 | 0,55 | 0,60 | 0,65 | 0,70 | 0,75 | 0,80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ΔV, мV | 0,09 | 0,13 | 0,16 | 0,19 | 0,22 | 0,25 | 0,28 | 0,31 | 0,34 | 0,38 | 0,41 | 0,44 | 0,47 | 0,50 |

**Table 3 –** Mechanical and electrical characteristics of the contact patch of two spherical microprotrusions of metal-polymer friction pairs

| Parameter name | | Estimated dependency | |
|---|---|---|---|
| Radius of a single contact patch | | $a=(0{,}75Nr/E)^{2/3};$ | (1) |
| Deformation of contacting micro-protrusions | | $\delta=\dfrac{a^2}{r}=\left[\left(0{,}56N^2/\left(rE^2\right)\right)\right]^{0,25};$ | (2) |
| Specific load on the contact patch of microprotrusions | maximum | $P_1=\left(\dfrac{6NE^2}{\pi^2a^2}\right)=1{,}5N/\left(\pi a^2\right);$ | (3) |
| | average | $P_2=0{,}66P_1=N/\left(\pi a^2\right);$ | (4) |
| Reduced Young's modulus | | $1/E=\left(1-\mu_1^2\right)/E_1+\left(1-\mu_2^2\right)/E_2.$ | (5) |
| Current strength | | $I=\sqrt{\dfrac{t_{\max}\cdot\alpha_T\cdot l_k}{R_k\cdot\rho}}.$ | (6) |

In table 3 shows the main dependences for calculating the characteristics of a single contact of two spherical microprotrusions of the contact patch. In table 3, depending on 6, the following conventions are used: $t_{max}$ – maximum temperature at the contact patch of microprotrusions, ˚C; αT – external heat transfer coefficient, W/(m2 •˚C); Rk – contact thermal resistance, ˚C/W; ρ – electrical resistivity, (Ohm•mm2)/m; lk – contact length, mm.

The computer model is practically implemented as a Windows application, written in C++ using the Borland class library. Programmatically, the model is included in the main calculation module, which includes an assessment of the external and internal parameters of metal-polymer friction pairs at the macro-, micro- and nanolevels. In addition to the main one, there is an additional module responsible for the convenience of data presentation and user interface.

For greater clarity, on the basis of the proposed formulas, it is possible to build graphs of the dependences of the contact characteristics on external factors, which are the currents of the washing air and mixture components. Within the framework of the computer model, the contact characteristics are calculated as follows. A pair of random numbers is generated, distributed according to a given law, corresponding to the height and radius of the protrusion of a rough surface. The logic of the program is illustrated by a block diagram of the main calculation module for the parameters of mechanical, electrical and thermal fields (Fig. 5).

The program is connected to the MS Access database, which consists of two tables, each of which includes 33 fields. The first table contains the values of the initial and intermediate data, and the second table contains the values of the results. Tables are used to build graphs.

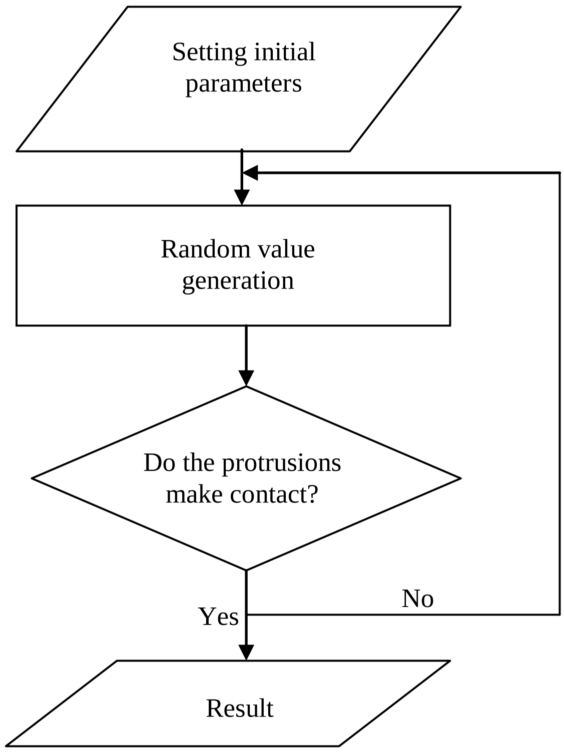


**Figure 5 –** Block diagram of the main calculation module

In this case, the first field of each table is reserved for the verified initial combination of initial parameters and is used only at the beginning of work and only for reading. First of all, the program reads the initial combination of initial parameters from the database and supplements the initial data fields with these values.

The user then edits them, executes calculation, after which the table of values is filled in and a graph is built on it. The adequacy of the model was checked by comparing the simulation results with the data of other authors, obtained on the basis of analytical models for some special cases [11, 12].

**"Metal is a semiconductor"**

The "metal-semiconductor" contact, which has both ohmic and rectifying properties, is the main multifunctional physical element of the contact patches of microprotrusions of friction pairs of brake devices.

In metallic and non-metallic friction elements of brake devices, semiconductor components are contained in the material structures. On fig. 6 shows the components of the resistance of the ohmic contact "metal - semiconductor".

The resistance of the near-contact region is the resistance of the heavily doped region and the resistance of the $n - n^+$ and $p - p^+$ transitions. The resistance of a heavily doped near-contact region is usually low in semiconductors with high carrier mobility. For example, the resistance of the near-contact layer $n^+$ - GaAs with a thickness of~1 μm at an electron density of $n^+ \approx 10^{19}$ cm$^{-3}$ and a mobility of ~ $10^3$ cm$^2$/(V·s) is about $6 \cdot 10^{-8}$ Ohm·cm$^2$. At the same time, in semiconductors such as SiC and $A^{II}B^{VI}$, it is often impossible to achieve a strong doping of the near-contact region, and, moreover, the charge carrier mobility is low 10 – 100 cm$^2$/(V·s)). In this case, the resistance of the near-contact region can reach ~ $10^{-4}$ - $10^{-5}$ Ohm·cm$^2$. Consider the resistance of transitions n - n+, p - p + using the example of n+ - n -transition. It is inversely proportional to the electron concentration [13, 14].

Calculated dependence of the resistance of an ohmic contact on the concentration of charge carriers and the height of the metal-semiconductor potential barrier when field emission is the main mechanism of current flow. To reduce the resistance of the ohmic contact in such contacts, the height of the metal-semiconductor potential barrier is reduced due to changes in the chemical composition of the semiconductor in its near-surface region.

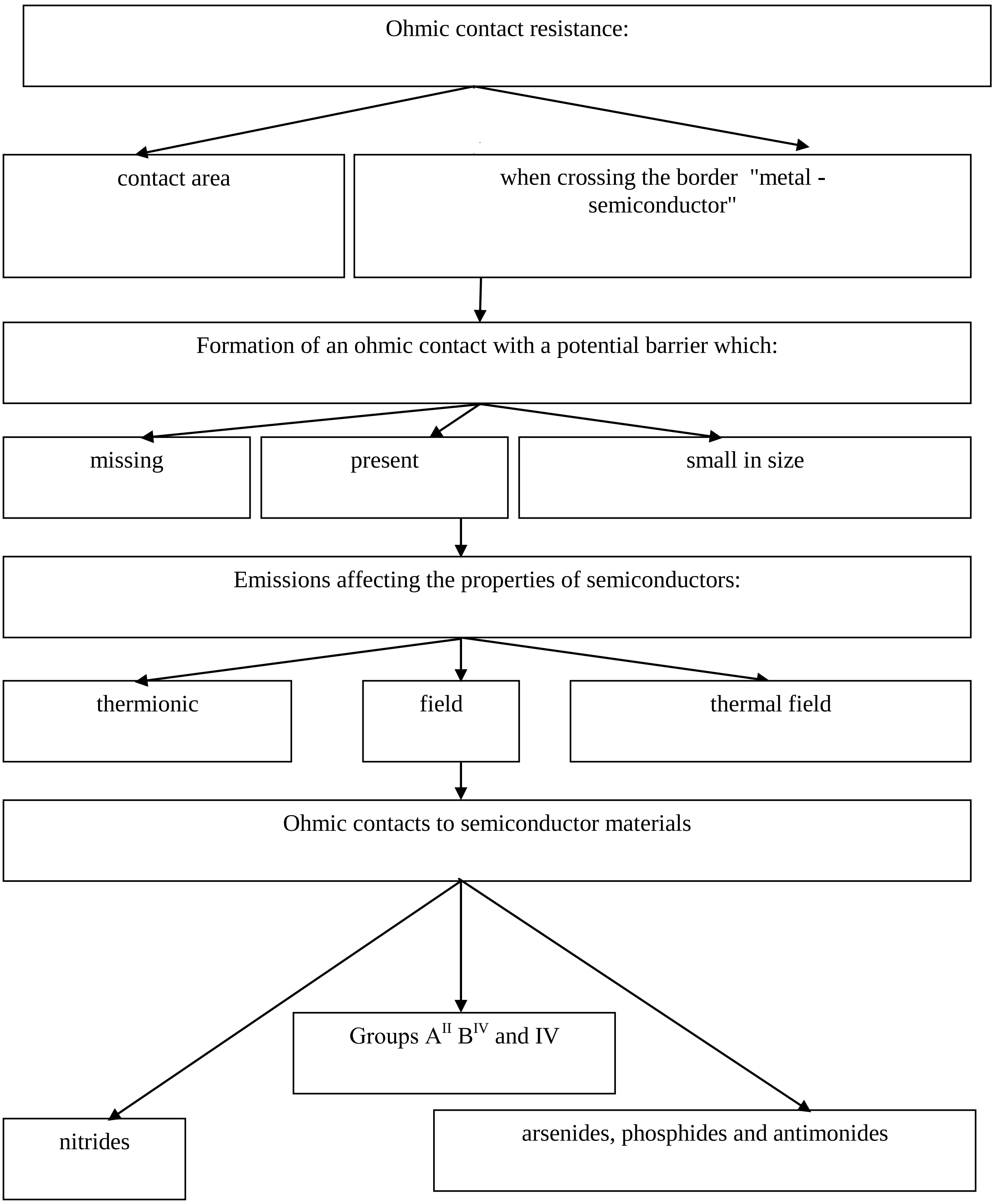


**Figure 6 –** Methods of current flow in ohmic contacts in the "metal-semiconductor" system

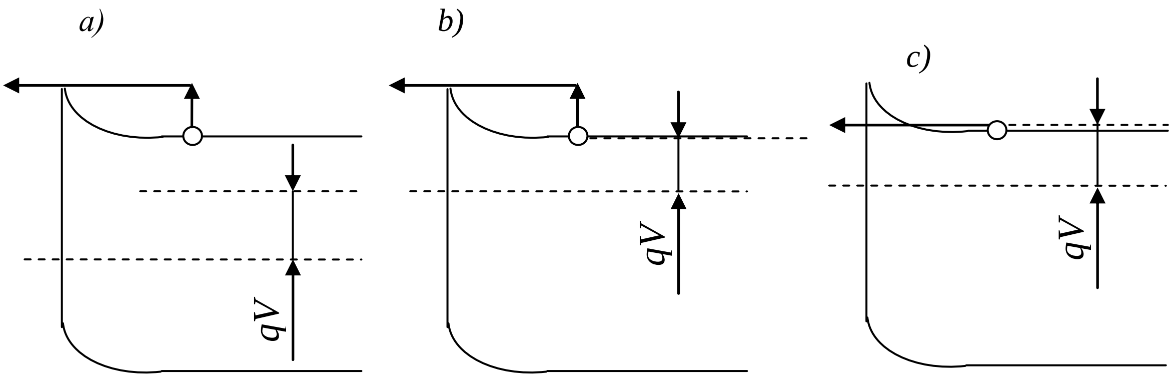


**Figure 7** – Methods of current flow in an ohmic metal-semiconductor contact: a – thermionic emission of electrons over the barrier; b – thermal field emission of electrons through the top of the barrier; c - tunneling (field emission) of electrons through the barrier

For the case of a p-type semiconductor, Nd is replaced by Na, the concentration of ionized acceptors in the semiconductor; Is – saturation current, n – coefficient of ideality of current-voltage characteristic, φb – potential barrier height, Δφb – reduction of potential barrier height by mirror image forces and other reasons; S is the contact area; T(E) is the probability of passing a carrier having energy E through a barrier less than qφb by ΔE; E00 is the Padovani-Stratton parameter [15], Vd is the diffusion (contact) potential difference. The transition of the metal-semiconductor interface by electrons can occur:

- above the barrier (thermionic emission, Fig. 7 a);
- through the top of the barrier (thermal field emission, Fig. 7b);
- through the barrier at the Fermi energy level (tunneling, field emission, Fig. 7c).

To determine the conditions under which one or another mechanism of current flow manifests itself.

*Padovani* and *Straton* [15] introduced the parameter E00, which depends on the nature of the semiconductor and the degree of its doping.

For clarity, we systematize the calculated dependences (7)-(17) borrowed from [1], where $L_D$ is the Debye length in the *n*-region, $N_c$ is the density of state in the semiconductor conduction band, μn is the electron mobility in the *n*-region, $N$ and $N^+$ - electron concentration in *n* and $n^+$ - regions, *K* - coefficient showing how many times the concentration of electrons at the Fermi level in $n^+$ - region exceeds *N*, *q* - electron charge.

For an ohmic contact to GaAs, it makes the main contribution to the contact resistance at $N < 5 \cdot 10^{17}$ cm$^{-3}$; $\chi$ is the Fermi level energy, $A^* = 4\pi q m^* k^2 h^{-3} = 120m$, A/(cm$^2$K$^2$) is the effective Richardson constant, $m_r = m^*/m_0$, $m_0$ is the free electron mass, *k* is the Boltzmann constant, $\varepsilon_s$ is the permittivity of the semiconductor; $\varepsilon_0$ is the vacuum permittivity; $N_d$ is the concentration of ionized donors in the semiconductor. For the case of a *p*-type semiconductor, $N_d$ is replaced by $N_a$, the concentration of ionized acceptors in the semiconductor; $I_s$ – saturation current, *n* – coefficient of ideality of current-voltage characteristic, $\varphi_b$ – potential barrier height, $\Delta\varphi_b$ – reduction of potential barrier height by mirror image forces and other reasons; *S* is the contact area; T(E) is the probability of passing a carrier having energy *E* through a barrier less than $q\varphi_b$ by $\Delta E$; $E_{00}$ is the Padovani-

Stratton parameter [15], $V_d$ is the diffusion (contact) potential difference.

Let's analyze dependences according to tabl. 4 concerning different types of emissions. If the current flow through an ohmic contact is determined by thermionic emission, then:

- the contact resistance increases exponentially with the height of the potential barrier $\varphi_b$;
- the contact resistance decreases with increasing temperature, and the dependence $R_cT = f(1/T)$ on a semi-logarithmic scale should be linear, and its slope is proportional to the barrier height $\varphi_b$, and the cutoff at $1/T \to 0$ is proportional to A*;
- contact resistance depends on the type of semiconductor and decreases slightly with increasing doping level $(\Delta\varphi \propto N_d^{1/4})$. If the current flow through an ohmic contact is determined by field emission, then: the contact resistance will increase exponentially with the height of the potential barrier; contact resistance is practically independent of temperature.

**Table 4 –** Calculation dependences for determining the operational parameters of ohmic contacts "metal - semiconductor"

| | | | | | |
|---|---|---|---|---|---|
| Ohmic contact resistance | Contact area | | | $R_{n-n^+} \approx \dfrac{L_D N_c}{q\mu_n KNN^+}$ | (7) |
| | | | | $R_{n-n^+} = \left(\dfrac{k}{qA^*T}\right)\dfrac{1}{\ln[1+\exp(\chi/kT)]}$ | (8) |
| | | | | $R_{n-n^+} = \left(\dfrac{kN_c}{qA^*TN}\right)$ | (9) |
| | Associated with the transition of the border "metal - semi-conductor" | | | $E_{00} = \dfrac{h}{2}\sqrt{\dfrac{N_d}{\varepsilon_s\varepsilon_0 m^*}},$ | (10) |
| I s s u e s | Thermionic | Parameters: | $J$ | $J = J_s \exp\left(\dfrac{qV}{nkT}-1\right),$ | (11) |
| | | | $R_c$ | $R_c = \left(\dfrac{k}{qA\cdot T}\right)\exp\left[\dfrac{-q(\varphi_b-\Delta\varphi_b)}{kT}\right]$ | (12) |
| | Field | | T | $T(E) \propto \exp\left[\dfrac{-2(\Delta E)^{3/2}}{3E_{00}V_d^{1/2}}\right]$ | (13) |
| | | | $R_c$ | $\dfrac{1}{R_c} = \dfrac{m\cdot q^2}{2\pi h^3}\int_0^\infty \dfrac{T(E)}{\exp[(E-\chi)/kT]-1}dE,$ | (14) |
| | Thermofield | | $J_s$ | $J_s = \dfrac{AT\sqrt{\pi E_{00}(q\varphi_b - qV + \chi)}}{kcth(E_{00}/kT)}\exp\left(\dfrac{\chi}{kT} - \dfrac{\varphi_b+\chi}{T_0}\right)$ | (15) |
| | | | $R_c$ | $R_c \propto \exp\left(\dfrac{\varphi_b}{E_{00}cth(E_{00}/kT)}\right)$ | (16) |
| | | | $T$ | $T(E_1) = \exp\left[-\dfrac{q\varphi_b - qV - (E_1-\chi)}{E_{00}}\right]$ | (17) |

For thermal field emission it is established that: - the dependence of direct current on voltage is exponential;

- at each temperature value, the slope of this dependence on a semi-logarithmic scale is equal to 1/E0, and this value at a given temperature depends on the intrinsic parameters of the semiconductor, and not on the properties of the barrier;

- cutoff along the y-axis of the dependence of current on voltage on a semi-log scale gives the value of the saturation current, and the dependence

$\frac{J_s cth(E_{00} / kT)}{T}$ from $\frac{1}{E_0}$

linear on a semi-logarithmic scale, its slope corresponds to the height of the metal-semiconductor potential barrier.

Thus, if the current flow through an ohmic contact is determined by thermal field emission, then: the contact resistance increases exponentially with the height of the potential barrier $\varphi_b$; contact resistance decreases with increasing temperature, but much weaker than in the case of thermionic emission.

Processes, phenomena, and effects in friction units take place differently under pulsed and long-term loading of contact spots of microprotrusions, since here it is necessary to take into account the current residual surface-volume temperatures. The latter grow all the time, reaching the steady and thermal stabilization state of metal friction elements.

A significant part of the equivalent stresses arising in the process of braking is concentrated in the surface and near-surface layers of metal friction elements. These voltages become proportional to pulsed electric currents and flash temperatures on the contact spots of microprotrusions of friction pairs "metal-semiconductor". Here, another way of current flow is manifested - through metal shunts.

What is a shunt - a branch, an electrical conductor connected in parallel to a section of an electrical circuit to divert part of the electric current around this section. Shunts are metal atoms deposited along the lines of imperfections, such as dislocations, and short-circuit the space charge layer. At the same time, an electric field is concentrated at the edges of such "needles" and the current flow is carried out due to field emission.

Thus, metal shunts act as distributors of electrical currents in an extensive network. They unload some contact spots, others overload the contact spots of microprotrusions. The effect of "needles" causes strong local heating in thin layers of the friction surface, leading to the formation of burns of thermal spots and satellite foci of microcracks.

During cooling after braking of the metal friction element, a changeable surface and deep temperature gradient is formed, causing large thermal stresses.

**Conclusion**

The results of the study of the energy levels of contacts in the frictional interaction of metal-polymer and semiconductor materials in friction pairs of brake devices made it possible to formulate the following discovery.

Previously unknown patterns of changes in pulsed electric currents in ohmic contacts "metal-semiconductor" during their contact-pulse frictional interaction are established, which consist in the fact that under the action of pulsed specific loads and energy load due to the height of the potential barrier between their materials in the contact zone and in the transition zone "metal-semiconductor" boundary with "*n*" and "*p*" types of conductivity at different degrees of their regulated surfaces, which contribute to the concentration of charge carriers and dislocations of imperfections of the crystal lattice, and at the same time, thermionic, field and thermal field emissions are formed, accompanied by emerging metal shunts, and the energy surface Fermi level changes the effect on the surface, in the middle and in the depth of the band gap, near the edge of the valence band, as well as the resulting shift at the edge of the conduction band, which contributes to the generation of electric currents along with alternating thermal currents of various sizes and directions.

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