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Polymeric Materials Modified by Semiconductor Substances in Friction Units of Braking Devices

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The materials of the article disclose contact-impulse frictional interaction of microasperities of friction pairs of band-shoe brake, based on the principles of the gradient theory of electric and thermal fields. It is proved that the electric field acts across, and the thermal field – longitudinally with frictional interaction of microasperities of friction pairs. At one of the main semiconductor substances Si (silicon), the characteristics and parameters of the metal – polymer – semiconductor structure in instantaneous electric fields observed at the initial moment of the frictional interaction are illustrated. Semiconductor elements are mounted on the side of the working surface of the friction linings and, when braking, interact with the chemical elements of the brake pulley rim, which contributes to the emergence of complex combinations of electrical conductivity junctions. They are capable of operating in the modes of microthermogenerators and microthermal coolers, diodes and transistors with their instantaneous switching. This leads to the emergence of direct and reverse electrical currents, loading and unloading the pulley rim. The effect of "transistor" is applied by selecting friction pairs of the brake to reduce their energy load, and as a result, increase wear resistance. Experimental studies of the improved friction pairs of the band-shoe brake show stabilization of the friction force and dynamic coefficient of friction, reduction of the surface and volume temperature gradients of the pulley rim and reduction of the braking moment to 3.0 %. This allows preventing overheating of the surface layers of the polymer linings and significantly increasing the effectiveness of the brake friction pairs. Due to the effect of the transistor, a reduction in the energy load of the friction pairs of the brake to 15.0 % and the wear of the working surfaces of the linings to 11.5 % have been achieved.

Keywords: Polymers, Semiconductor materials, Energy levels, Microasperities of friction pairs, Transistor effect.

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1. INTRODUCTION

An important problem in modified friction materials of various types of brake devices is the intense heating of the friction lining body due to heat transfer from the working surface of the metal friction element [1]. This problem can be solved in two ways. The first way is the insertion of intrinsic and extrinsic semiconductors into one of the friction elements. When interacting with the structural components of the friction element material, they form additional friction pairs of the following types: "polymer-intrinsic semiconductor", "metal-intrinsic semiconductor", "polymer-extrinsic semiconductor", "metal-extrinsic semiconductor", etc. Such an approach allows creating "*pp*", "*nn*", "*npn*", "*pnp*", and "*pnn*" junctions artificially, which can work in the modes of microthermobatteries (generators and refrigerators), diodes and transistors. That is, conditions are created for the purposeful control of the energy load of friction pairs. This allows preventing overheating of the surface layers of the polymer linings and significantly increasing the effectiveness of the friction pairs of braking devices.

2. STATE OF THE PROBLEM

Modern brake materials are multicomponent systems having polymer matrix. It represents a single polymer or a mixture of several polymers. This depends on operating conditions, design requirements and other factors.

The electrodynamics of contact-thermal friction interaction in metal-polymer friction pairs of braking devices and its influence on the energy levels of their surface and near-surface layers were considered in [2]. Here, attention is also paid to hydrogen wear as one of the processes affecting the intensity of destruction of metal friction elements. It is due to the decomposition of hydrocarbon bonds with the release of hydrogen, which diffuses into the surface layer of steel, causing its embrittlement [3].

Currently, work is underway to create various composite materials as a polymer matrix with various kinds of inclusions, for example, carbon [4] and metal particles [5, 6]. The principle of creating such composites is based on using the effect of percolation (flow) of current through conductive particles distributed in a polymer matrix. The theory of the conductivity of such a composite is based on the formation of an infinite cluster of conducting particles [7], which enhances the effect of reducing the brake energy load. Promising is the use of nanomaterials [8].

Nevertheless, the problem of reducing the energy load of friction pairs of braking devices is very urgent.

In this work, it is proposed to use a semiconductor frame with *n*-conductivity and p-conductivity to inter-

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act with chemical particles of semiconductors located on the working surface of a metal friction element.

3. CHARACTERISTICS AND PARAMETERS OF THE METAL-POLYMER-SEMICONDUCTOR (MPS) STRUCTURES IN INSTANT ELECTRIC FIELDS

As a semiconductor material under study, consider silicon (Si). It is a typical semiconductor element with a valence band filled in the unexcited state. In silicon, all p-orbitals are occupied, and electrically active vacancies are acceptors. Silicon of hole conductivity doped with boron and silicon of electronic conductivity doped with antimony, as well as unalloyed silicon of various electrical resistance, were used as silicon particles.

In pulsed electric MPS structures, depending on the polarity, a triangular potential barrier is formed at the Si – SiO_2 (silicon – silicon dioxide) or metal – SiO_2 interface, and quantum mechanical transmission of electrons through the Fowler-Nordheim barrier occurs. At small thicknesses of the oxide, direct tunneling is performed through the dielectric layer. The boundary between direct tunneling and Fowler-Nordheim tunneling lies in the range of 3.5-4 nm.

The dependence of the density of the tunneling current of a strong field injection on the electric field intensity during tunneling according to Fowler-Nordheim is described by the following expression:

$$J_d = \frac{q^3 m_0}{16\pi^2 h m^* \phi_{в}} E^2 \boldsymbol{exp}\left(-\frac{4\left(2m^*\right)^{1/2} \phi_h^{3/2}}{3qhE} \right), \qquad (1)$$

where J_d is the current density of the tunnel injection; q is the electron charge; m_0 is the electron rest mass; m* is the effective electron mass; h is Planck's constant divided by 2π; ϕ_h is the potential barrier height for electrons at the injecting interface; E is the intensity of the cathode electric field.

This expression was obtained under the assumption of the parabolic dependence of the electron energy on the wave vector. It does not take into account: the dependence of the effective electron mass on the energy under the potential barrier in the silicon dioxide band gap; thermal blurring of the electron energy distribution in the metal or semiconductor electrodes due to the fact that the electric field is directed across, and thermal along the surface of the friction interaction; reducing the height of the potential barrier due to the influence of the forces of the mirror image. Accounting for these factors greatly complicates the analytical description of the dependence of the density of the tunnel current on the electric field strength at the injection interface. From equation (1), we can determine the effective electron mass and the height of the potential barrier at the injecting interface. For the Si–SiO_2 interface, the values of the effective mass and the height of the potential barrier obtained by various authors vary within the limits $m^* = 0,32m_0 ... 1,03m_0$; $\phi_h = 2,8...3,19$ eV. The observed variation in the parameters is associated with different experimental conditions, accumulation intensity and charge concentration in the dielectric, the effect of defects at the semiconductor-metal interface, as well as the use of various models of the tunnel process in mathematical processing of the results, which take into account the deviations of the dispersion dependence on the parabolic one. Z. Weinberg using the models of the tunnel process obtained experimental dependences of the tunnel current on the electric field. The values of the effective electron mass and the height of the potential barrier are determined from them. Analysis of the results shows that the experimental data are well approximated by a theoretical curve obtained under the assumption of a parabolic dependence of the electron energy on the wave vector at $m^* = 0,5m_0$.

The current-voltage characteristics of MPS-structures with thermal silicon dioxide as a semiconductor are well straightened in the Fowler-Nordheim coordinates $\boldsymbol{ln}\left(\frac{J_d}{E^2}\right) = f\left(\frac{1}{E}\right)$ in the range of 6-10 MV/cm. In fields larger than 10 MV/cm, which corresponds to the initial moment of the frictional interaction of microasperities of friction surfaces, the current increased more strongly than follows from dependence (1). In the field region of < 6 MV/cm, the current flowing through the MPS structures also exceeds the values obtained from dependence (1), which is explained by the effect of defects in the silicon dioxide film.

It has been established that for thin silica films with a thickness of 4-7 nm, when considering the process of injection of electrons, it is also necessary to take into account the interference of electrons related to their wave nature. This phenomenon is observed during the superposition of waves and consists in the amplification or weakening of the amplitude of the resulting wave due to the different height of the microasperities of the friction surface of the metal element. At the same time, the phase difference of the emerging waves is not constant, that is, the waves correspond to incoherence. In this case, the density of the tunneling current is defined as the product of J_d (see formula (1)) and the coefficient B, which takes into account the effect of the interference of electrons and is a function of the Airy function (Ai) and its derivative:

$$J = BJ_d, \quad B = \left[Ai^2\left(-aL_{cb}\right) + \left(a/k\right)^2 \left(Ai'\right)^2 \left(-aL_{cb}\right) \right]^{-1},$$

where k is the wave result vector; L_{cb} is the distance of movement of electrons in the conduction band of silicon dioxide. In this case, the normalization coefficient for the Airy function is

$$a = \left(\frac{2m^* qE}{h^2} \right)^{1/3}.$$

When reducing the thickness of the semiconductor, it is necessary to take into account the interference phenomena and the change in the height of the potential barrier depending on the thickness of the oxide film. For semiconductor layers of silicon dioxide with a thickness of more than 10 nm, the height of the potential barrier can be considered constant. For electrons, it is equal to 3.2 eV, for holes – 3.8 eV [9]. With a decrease in the thickness of the silicon dioxide layer to several nanometers, the height of the effective potential barrier decreases and becomes equal for electrons to 2 eV at a dielectric thickness of 2 nm. Reducing the thickness of the layer affects the value of its effective mass.

For example, a silicon semiconductor in a polymer will ensure the interaction of dangling chemical bonds on the surface of a silicon particle with chemical bonds of silicon atoms or oxygen groups of polymer molecules.

According to the results of calculations of the potential barrier height at the silicon – silicon dioxide interface, the following was established. Three areas can be distinguished in the change of the potential barrier: a non-stoichiometric SiO_x oxide layer of 1 nm thick; four-membered rings of SiO_4 tetrahedral dominate at a distance from the interface of 1-3 nm; six-membered rings are located at a distance of 3 to 6 nm (the properties of the third layer differ little from the properties of the oxide volume).

The components compositions of the materials of the pulley rim and the friction lining of the drawworks band-brake are given in Table 1 and Table 2, respectively.

Table 1 – Chemical composition of steel 35KhNL

Chemical element	Percentage, %
Iron (Fe)	97.8-96.6
Silicon (Si)	0.20-0.42
Copper (Cu), not more than	0.30
Manganese (Mn)	0.40-0.90
Nickel (Ni)	0.70-0.90
Phosphorus (P), not more than	0.047
Chrome (Cr)	0.50-0.80
Sulfur (S), not more than	0.04

Table 2 – The chemical composition of the friction material retinax FC-24A

Polymeric material		Retinax FC-24A
Elements and their content, %	phenolic-formaldehyde resin	15
	asbestos	40
	sulfate-barium	35
	brass	6
	plasticizers/modifiers	2/2

4. CONSTRUCTION AND OPERATION OF FRICTIONAL UNITS OF BAND-SHOE BRAKE IN TRANSISTOR MODE

Semiconductor elements operating in the "transistor" mode are installed into the polymer linings of the friction brake units from their working surfaces.

According to the kinematic schemes of the drawworks (Fig. 1a) and the band-shoe brake (Fig. 1b), the improved linings 3 are mounted on the brake bands 2. The tapes are attached at one end (from the direction of the falling branch II) to the balancer 11, and the other (with side of the oncoming branch I) – to crankpins 6 and 9 of the crankshaft 10.

In Fig. 1b, the following conventions are used: S_s, S_i are the tension of the slack and incoming branches of the band; F_w is the worker's effort; R_p, r are the radii of the working surface of the pulley rim and crank of the crankshaft; ω is the angular velocity of the brake pulley.

Serial band-shoe brakes of drawworks (Fig. 1) operate as follows. By moving the crank 1, the crankshaft 10 is rotated, as a result of the driller tightens the brake band 2 with improved friction linings 3, and they tack to the brake pulleys 4. The braking process of the band-shoe brake is characterized by the following stages: initial (first), intermediate (second) and final (third).

Consider the design of modified friction lining 3 (see Fig. 1b) and the features of the operation of its cooling units (Fig. 1c-h).

In Fig. 1f, g, the following conventions are used: E_C; E_A and E_D; E_V is the energy: contact electric field; donor levels of p- and n-types of conduction; space charge (eV); E_{Fn}, E_{Fp} are Fermi energy levels; $e\varphi = E_{Fp} - E_{Fn}$ is the height of the potential barrier; e is the electron charge; φ is the contact potential difference; U is the external field voltage; G is the Gibbs energy; R is the contact electrical resistance; electric currents: $I = I_n + I_p$ – diffusion; $I_s = I_{ns} + I_{ps}$ – drift; I_n, I_p – diffusion current: electrons; ions; I_{ns}, I_{ps} are drift currents: electron carriers, minor for the p-region, that are returned to the n-region by the contact electric field; minor carriers for the n-region – holes returned to the p-region; $d\gamma$, dp, dn are areas of coating: common, p- and n-types of conductivity; L_1, L_2 are the lengths of the regions of p- and n-types of conductivity.

The friction lining 3 has a bar 12 with fastening tendrils 13 on its working surface. The metal bar 12 is fixed to the frame 15 of the lining 3 with wire 14. Tendrils 13 of the lining 3 are attached to the brake band 2 (Fig. 1c).

In a cross-section of the lining body 15, vertical cylindrical sockets 16 of the same diameter are made to the level of allowable wear of the lining 3. On the non-working surface 17 of the lining 3 to the level of its allowable wear, the transverse grooves 18 of the square section are made. NPN and PNP transistors of П- and T-shaped cross-sections with alternated substances 19, 20, 21 and 22, 23, 24 are installed (see Fig. 1h) in the formed hollows of the lining 3 on its incoming III and running down IV parts of surface. П- and T-shaped multi-row transistors by external surfaces of the shelves 25 are interconnected with a strip 26 that is below the level of the non-working surface 17 of the lining 3. The end surfaces of n-type and p-type semiconductors are friction surfaces 27. As the working surfaces of the lining 3 and the pulley rim 4 are the surfaces 28 and 29.

When choosing intrinsic semiconductor substances that provide n-p-n (19, 20, 21) and p-n-p (22, 23, 24) junctions, it is necessary to observe the inequality [10]:

$$E_{12} > E_{23},$$

where E_{12} is the interaction energy of the micro-irregularities contact spots of the friction surfaces of the polymer-metal pair; E_{23} is the interaction energy of the microirregularities contact spots of friction surfaces of the metal-intrinsic semiconductors pair.

The electro-mechanical frictional interaction of the chemical components of material of the pulley rim with the elements of semiconductor substances is shown in Table 3.

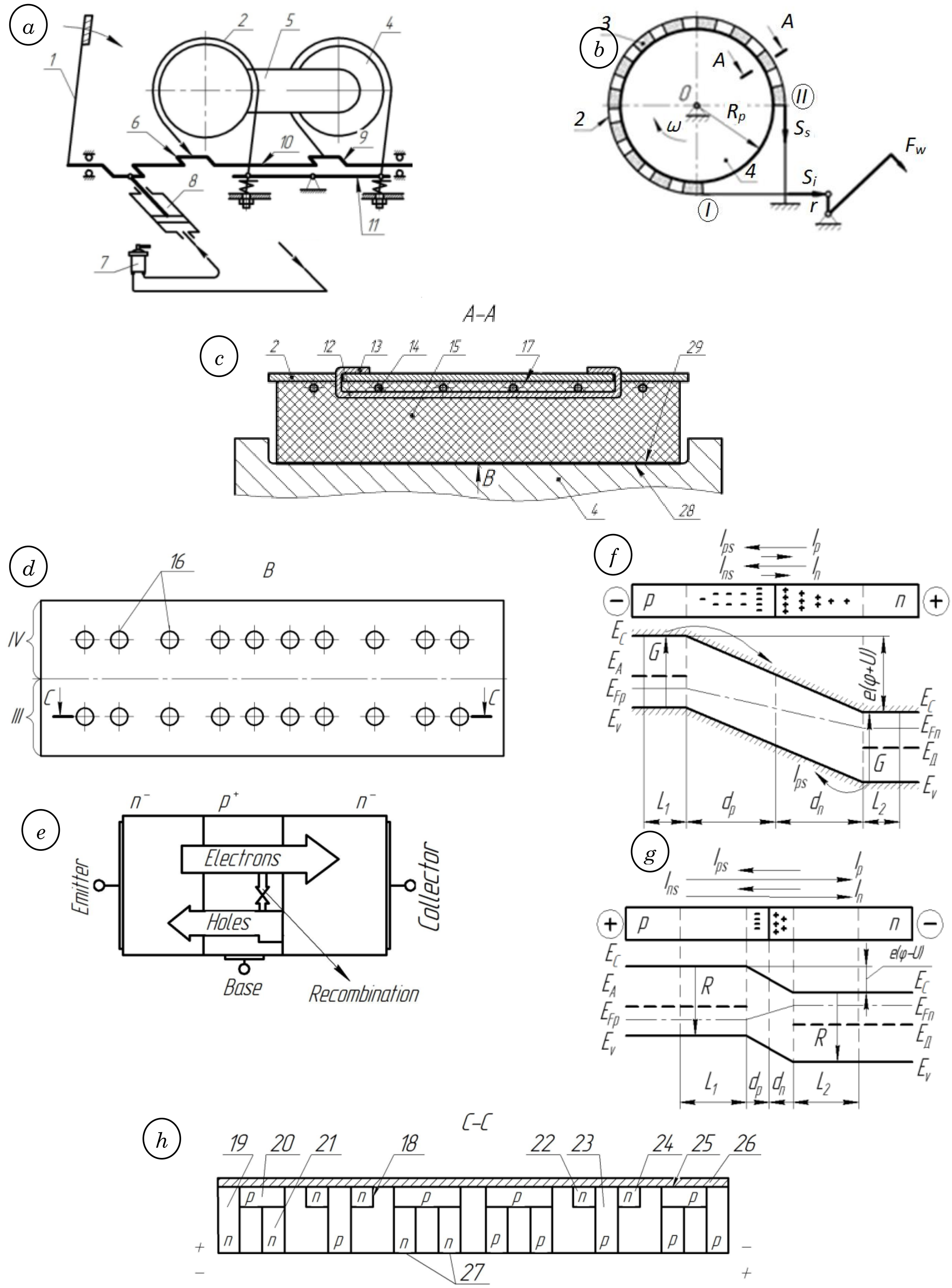

Fig. 1 – Kinematic schemes of the band-shoe brake of the drawworks (a, b); longitudinal section of a modified friction assembly (c); view B on the working surface of the lining (d); serial transistor (e) circuit; multi-row connection scheme of NPN and PNP transistors (f); energy areas in violation of the external electric field in *p-n* junction in intrinsic semiconductors in the event of the reverse (g) and direct (h) direction of currents: 1 – brake control lever; 2, 3, 15, 17, 18 and 29 – brake bands with linings, their body, and longitudinal grooves made on non-working and working surfaces of linings; 4, 28 – brake pulley with a working surface; 5 – winch drum; 6, 9 – crankpins of crankshaft; 10 – crankshaft; 7, 8 – valve of a pneumatic cylinder; 11 – balancer; 12, 13 – bar with mounting whiskers; 14 – reinforcing wire; 16 – vertical holes; 19, 20, 21 and 22, 23, 24 – semiconductors forming NPN and PNP transistors of Π-shaped and T-shaped cross-sections; 25 – outer surfaces of the transistor shelves; 26 – strip; 27 – friction surfaces of semiconductors

Table 3 – The electro-mechanical frictional interaction of the chemical components of material of pulley rim with the elements of semiconductor substances

Semiconductors and conductivity types	Chemical elements of the pulley and conductivity type				
	Si	Cu	Mn	Ni	Cr
B - (*p-n*)	*p-n-p*	*p-n-n*	*p-n-n*	*p-n-n*	*p-n-p*
C - (*n*)	*n-p*	*n-n*	*n-n*	*n-n*	*n-p*
Si - (*n*)	*n-n*	*n-n*	*n-n*	*n-n*	*n-p*
β - SiC - (*p-n*)	*p-n-p*	*p-n-n*	*p-n-n*	*p-n-n*	*p-n-p*
Cu_2O - (*n-p*)	*n-p-p*	*n-p-n*	*n-p-n*	*n-p-n*	*n-p-p*
Al_2O_3 - (*n-p*)	*n-p-p*	*n-p-n*	*n-p-n*	*n-p-n*	*n-p-p*

Table 4 shows the properties of intrinsic and extrinsic semiconductor substances.

Table 4 – Properties of intrinsic/extrinsic semiconductors

Properties		Chemical elements		
		B/β - SiC	C/Cu_2O	Si/Al_2O_3
Density, $\times 10^3$, kg/m^3		2.35/3.21	2.245/6.05	2.3/4.15
Melting point, $\times 10^3$, °C		2.35/2.83	4.5/1.5	1.4/1.07
Specific resistance, Ohm·mm		$4 \cdot 10^3/10^{11}$	$10^6/3 \cdot 10^6$	$21 \cdot 10^3/$ $1.05 \cdot 10^4$
Type	conductivity	*p-n*/*p-n*	*n*/*n*	*n*/*n-n*
	chemical bond	– / ion covalent	–/covalent	– / ion covalent
Band gap, eV		1.1/3.5	5.5/ (2.2-3.9)· ·10^{-1}	1.1/1.6
mobility, cm^2/(V·sec)	electron	0.4-1.0/ $1.5 \cdot 10^3$	$1.6 \cdot 10^3/$ $7.8 \cdot 10^2$	$1.5 \cdot 10^3/$ $2.0 \cdot 10^2$
	hole	0.2-50.0/ $1.1 \cdot 10^3$	$1.5 \cdot 10^3/$ 7.1	$4.8 \cdot 10^2/$ $5.5 \cdot 10^2$

The choice of intrinsic semiconductor substances for strip linings should be made taking into account:

– structural components of the metal friction element;

– in mixed rows of Π- and T-shaped structures with *n*- and *p*-types of electrical conductivity, they work constantly in friction pairs under electrothermal-mechanical friction interaction, acquiring the properties of extrinsic semiconductor substances.

In mixed rows of Π- and T-shaped structures of intrinsic semiconductor substances, the hole (*p*) – electronic (*n*) junction dominates. It is formed due to the contact of two intrinsic semiconductors with different types of conductivity (*n*-type and *p*-type). To obtain contact with permanent well-controlled properties, it is necessary to create it in the form of an internal boundary of the section, on which a semiconductor of one type continuously transforms into a semiconductor of another type. This is achieved by doping with impurities in the appropriate places when growing a crystal, or by diffusion or implantation of an impurity into a ready-made crystal.

Requirements for intrinsic semiconductor substances acting as energy-absorbing elements in blocks of Π- and T-shaped structures of transistors are formed taking into account the conditions of regulation and control of the internal electric field excited by impulse specific loads and flash points on the contact spots of microasperities friction pairs during electrothermal-mechanical friction interaction. In this case, an external electric field is generated, which effectively interacts with the internal electric field.

Let us consider the kinetics of *p-n* junctions in proper semiconductor materials in the event of an equilibrium disturbance with an external electric field caused by frictional interaction of the friction surface microlevels of the brake (Fig. 1g, h).

At the beginning of electrothermal friction, the contact layer formed at the ends of intrinsic semiconductor substances with *n*-conductivity and *p*-conductivity is a barrier layer. The resistance of the barrier layer can be changed using an external electric field. Semiconductors with *p-n* junctions, which are components of multiple transistors, are connected to the current source so that the positive source pole is connected to the *n*-region, and the negative one is connected to the *p*-region. The field arising in this case in semiconductors coincides in direction with the contact electric field (Fig. 1f). Since the junction zone has a large electrical resistance compared with the rest of the multi-row transistors, the applied external potential difference almost completely falls on the barrier layer. The voltage drop on other sections of semiconductor substances indicates that the energy loading of the microasperities of the brake friction surfaces is reduced.

The external voltage U shifts the energy levels in the contacting zones by the value of eU. Fermi levels are also shifted, which is caused by an imbalance in the equilibrium state. The height of the potential barrier increases and becomes equal to e ($\varphi + U$). The applied voltage prevents diffusion movement of the main carriers, which move away from the pn junctions. This leads to an increase in the contact area (*d*) of microasperities and an increase in the electrical resistance of the contact layer. However, an insignificant amount of minority charge carriers from the *n*- and *p*-regions can cross the *pn* junction. A small current arises in the circuit, called reverse current. The voltage across the *pn* junction, in this case, is called reverse, and is considered to be negative.

If the *pn* junctions in multi-row transistors are connected to a current source, so that the positive pole of the source is connected to the *p*-type junction and the negative pole is connected to the *n*-type junction, then the height of the potential barrier will decrease by the value of the applied voltage. It becomes equal to e ($\varphi - U$) (Fig. 1g).

A decrease in the height of the potential barrier leads to an increase in the number of electrons in the *n*-region, which have the energy necessary for its overcoming. This causes a rapid increase in the diffusion current. In addition, in this case, the external and contact electric fields in the junction region have opposite directions. Therefore, the reducible field is weakened, the contact zone (*d*) and the resistance of its layer are reduced, which also contributes to the growth of the diffusion current. With an insignificant drift current, the current flowing through the pn junction is entirely due to the flows of the main charge carriers. The current strength in this case will increase with increasing voltage of the current source. In this case the applied to the pn junctions voltage is direct and is considered positive. Thus, the pn junction has one-sided conductivity.

The alternation of direct and reverse currents circulating in multi-row transistors allows aligning the energy load of the oncoming (III) and escaping (IV) parts of the lining surface 3, as well as along the oncoming (I) and escaping (II) branches of the brake band 2.

Thus, the circulation of direct and reverse currents in metal-polymer and metal-semiconductor friction pairs contributes to the reduction of their energy loading.

5. RESULTS AND DISCUSSION

During frictional interaction of friction surfaces microhairs of a band-shoe brake in the regime of high sliding speeds and specific loads, electrical currents are generated and thermal currents are accumulated. As a result, surface temperatures and their gradients increase. At temperatures above 400 °C, the binding component, phenol-formaldehyde resin, burns out of the surface layers of the friction lining. In this case, a corrosive hydrogen-containing medium is formed, which creates conditions for tribocracking accompanied by the release of free hydrogen. The latter, interacting with chemical elements (silicon, sulfur, white phosphorus, titanium, iron, etc.) of the surface and subsurface layers of friction surfaces, forms non-stable hydrides. Surface layers are polarized by longitudinal heat fluxes, at which a sharp jump in the temperature gradient over the thickness of the surface layer is observed. At the same time, films of primary and secondary metal structures are "glued" with electric current of the same transverse field, significantly accelerating their wear. This contributes to the intensification of hydrogen wear of the friction pairs surface layers of a drawworks band-shoe brake.

Owing to the tribocracking of the polymer lining, active release of hydrogen and its continuous flow into the surface layer of the pulley steel rim are observed. This is accompanied by: adsorption of hydrogen on the surfaces of metal-polymer friction pairs; its diffusion into the deformed surface layer of the pulley rim, the intensity of which depends on the temperature and stress gradients; a special type of surface damage due to the simultaneous development of a large number of microcrack nuclei throughout the contact zone

On the working surface of the polymer lining in the process of polymer radical molecules tribodestruction, centers are formed that can capture charge carriers at the time of tribocontact of the lining with a metal friction element. This occurs at surface temperatures exceeding the allowable for the lining material. The influence of surface temperature, sliding speed, unit loads and contact time of friction surfaces microasperities on the magnitude and sign of triboelectromotance was established. It is noted that the contact potential difference with increasing temperature increases for electropositive polymers, and decreases for electronegative ones. When homogeneous polymeric materials (polycapromide, tetrafluoroethylene, ethylene, fluoropolymer, epoxy resin ED-20) are contacted during electrothermal friction, they are positively charged on the metal. This occurs at temperatures not exceeding the allowable one. An increase in sliding speed at low specific loads on the contact spots of friction surfaces microasperities leads to an increase in triboelectromotance for all polymeric materials due to the intense removal from the surface of the plastic adsorbed from the environment ions of opposite sign.

It was established that the direction and magnitude of the electric current [2] affect the wear rate of metal polymer tribosystems. It depends on the sign of the electric charge supplied to the polymer. When applying the potential difference with the "+" sign to the polymer lining, the wear of the metal friction element is two times higher than when the "–" sign is applied. This is due to the intensification of the process of hydrogenation of the steel working surface of the friction element by an electric field. The supply of positive charge to polymer surfaces of polymer linings leads to destructive processes in lining material and, as a result, to an increase in wear intensity.

It has been established that during friction in each element of a friction pair a double electric layer is formed.

During friction, iron cations are transferred from the steel friction element to the working surface of the polymer lining, and the metal components of the lining material and its wear products to the working surface. Depending on the nature of the functional groups formed, the polymer is the center of capture of electrons or ions from the metal surface, which determines the sign of triboelectromotance.

An analysis of the results on the study of the mechanism of friction element formation on the steel surface of a polymer film of frictional transfer from lining wear products showed the following. The basis of the kinetic condition of the unstable state of formation of a film of frictional transfer is its destruction at different rates over time. Let us single out several stages of the formation of a film of frictional transfer at temperatures below and above the polymeric lining acceptable one for the material.

The study of the mechanism of polymer film formation on a steel surface of the friction element due to friction transfer from wear products of the lining showed that the kinetic condition of an unstable state of the friction transfer film formation is based on its destruction at various time rates. We single out several stages of the frictional transfer film formation at temperatures below and above the allowable value for a polymer lining material.

The first stage refers to the period when the dynamic coefficient of friction decreases. On the surface of the metal friction element, the content of the products of frictional transfer of FC-24A material, which are negatively charged, increases. They are capable of forming a strictly oriented film with a simultaneous decrease in the frictional transfer of the lining material binder component in the range of surface temperatures of 75.0-175.0 °C.

At the second stage, the dynamic coefficient of friction increases due to an increase in the concentration of the binder component in the total mass of wear products, which are positively charged (surface temperature range is 175.0-350.0 °C).

The third stage is characterized by a further increase in the concentration of the binder component during frictional transfer. A trybocracking phenomenon occurs accompanied by a fall of the dynamic coefficient of friction. We found (Table 5) that while retaining a number of the basic technical characteristics of the analogue, the proposed friction pairs reduce the energy intensity of the linings wear by a factor of 1.3 for the given modes of their loading, affecting the potential difference between the microasperities of the friction surfaces (Table 6).

Table 5 – Triboelectric and operational parameters of an improved band-shoe brake of the drawworks U2-5-5

Friction pair	Charge sign		Performance parameters					
	+	–	Friction force $F_f = S_1 - S_2$, kN	Dynamic coefficient of friction, f	Temperature gradients		Braking moment M_f, kNm	Energy wear rate of linings I, mg/J
					Surface t, °C/mm	volumetric t_v, °C/mm		
Two chemically identical elements	Element density							
	high	low						
FC-24A – steel 35KhNL	Polymer	Metal	259.6	0.38	40.0-60.0	6.0-15.0	188.2	2.50
NPN semiconductors – steel 35KhNL	Generated currents	Direct	220.5	0.42	20.0-30.0	10.0-15.0	195.0	2.30
PNP semiconductors – steel 35KhNL		Reverse	240.8	0.45	10.0-20.0	5.0-10.0	200.5	2.45
The results of experimental studies of improved friction pairs			260.0	0.43	10.0-35.0	5.0-13.0	198.0	2.35

Note: the surface area of the tablet inserts with friction elements is (45-75)° of the arc of contact of the band with linings of the pulley rim

The greatest potential difference has the friction pair "NPN semiconductors – steel 35KhNL", since part of the surface of the polymer lining with the transistors of П-shaped and T-shaped cross-sections is 21.5 %. Therefore, their presence practically does not affect the dielectric permeability of the lining material, which contributes to the generation of positive charges in this friction pair and, as a result, the appearance of a positive transverse electric field. This prevents the adsorption of hydrogen ions in the surface layers of friction pairs in their closed and open states, reducing the hydrogen wear of their working surfaces.

Table 6 – The potential difference between the microasperities of the friction surfaces of the band-shoe brake of the drawworks U2-5-5

Friction pairs	FC-24A – steel 35KhNL	Semiconductors	
		NPN – steel 35KhNL	PNP – steel 35KhNL
The potential difference ΔV, mV	0.47	0.64	0.55

The area of transistor inserts embedded in the friction elements of the polymer material FC-24A and located around the perimeter of the pulley rim depends on its diameter and width.

6. CONCLUSIONS

1. Friction material FC-24A of the linings, modified by selected intrinsic (B, C and Si) and extrinsic (β-SiC, Cu_2O and Al_2O_3) semiconductor substances, which interact with chemical elements (Si, Cu, Mn, Ni, Cr) of the working surface of the brake pulley rim, contributes to the formation of combinations of conductivity types (*p-n-p*, *n-p-n*, *p-nn*, *n-p-p*, *n-p*, etc.). They are capable of operating in the modes of microthermogenerators and microthermal coolers, diodes and transistors with their instantaneous switching. This contributes to a significant reduction in the energy load of friction pairs of the brake.

2. In mixed rows of П- and T-shaped structures of intrinsic semiconductor substances of the lining, a pn junction with an internal interface, where a semiconductor of one type continuously transforms into another semiconductor due to their affinity, dominates.

3. Experimental studies of the improved friction pairs of the band-shoe brake showed: stabilization of the friction force and dynamic coefficient of friction, reduction of the surface and volume temperature gradients of the pulley rim and reduction of the braking moment to 3.0 %. Due to the effect of the transistor, a reduction in the energy load of the friction pairs of the brake to 15.0 % and the wear of the working surfaces of the linings to 11.5 % have been achieved.

REFERENCES

1. X. Xiao, Y. Yin, J. Bao, L. Lu, X. Feng, *Adv. Mech. Eng.* **8** No 6, 1 (2016).
2. M.V. Kindrachuk, A.I. Vol'chenko, D.A. Vol'chenko, D.Yu. Zhuravlev, V.M. Chufus, *Mater. Sci.* **54**, 69 (2018).
3. M.V. Kindrachuk, D.A. Vol'chenko, N.A. Vol'chenko, N.M. Stebeletskaya, A.V. Voznyi, *Mater. Sci.* **53**, 282 (2017).
4. O. Sapronov, P. Maruschak, N. Buketova, O. Leschenko, S. Panin, *Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures*, 020194 (Melville: American Institute of Physics Inc: 2016).
5. Z.M. Elimar, F.S. Al-Agrabawi, T. Abu Hazeem, Y. Ramadin, *Int. J. Thermophys.* **34**, 2009 (2013).
6. I.H. Dobrotvor, P.D. Stukhlyak, A.V. Buketov, *Mater. Sci.* **45**, 790 (2009).

7. W.J. Wang, F. Wang, K.K. Gu, H.H. Ding, H.Y. Wang, J. Guo, Q.Y. Liu, M.H. Zhu. *Wear* **330**, 498 (2015).
8. V.Ye. Panarin, M.Ye. Svavil'nyy, A.I. Khominych, M.V. Kindrachuk, A.O. Kornienko, *J. Nano- Electron. Phys.* **9** No 6, 06023 (2017). [In Ukrainian].
9. T. Blythe, D. Bloor, *Electrical properties of polymers* (New York: Cambridge University Press: 2005).
10. I.G. Goryacheva, *Mechanics of friction interaction* (Moscow: Science: 2001). [In Russian].

Полімерні матеріали, модифіковані напівпровідниковими речовинами, у вузлах тертя гальмівних пристроїв

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У статті досліджено контактно-імпульсну фрикційну взаємодію мікровиступів поверхонь тертя стрічково-колодкового гальма, виходячи з принципів градієнтної теорії електричного і теплового полів. Доведено, що при фрикційній взаємодії мікровиступів поверхонь тертя електричне поле діє перпендикулярно напрямку сили тертя, а теплове поле – паралельно. На прикладі однієї з основних напівпровідникових речовин Si (кремній) проілюстровано характеристики і параметри структури "метал – полімер – напівпровідник" у миттєвих електричних полях, які спостерігаються в початковий момент фрикційної взаємодії мікровиступів поверхонь тертя. Напівпровідникові елементи, вмонтовані з боку робочої поверхні фрикційних накладок, при гальмуванні взаємодіють з хімічними елементами матеріалу ободу шківа гальма, що сприяє виникненню складних комбінацій переходів електропровідності. Вони здатні працювати в режимах мікротемогенераторів і мікротемохолодильників, діодів і транзисторів з миттєвим їх перемиканням. При цьому виникають прямі й зворотні електричні струми, які навантажують і розвантажують обід шківа. Для зниження їх енергонавантаженості і підвищення зносостійкості при підборі матеріалів пар тертя гальма досягається ефект "транзистора". Проведено експериментальні дослідження вдосконалених пар тертя стрічково-колодкового гальма, які показали стабілізацію сили тертя і динамічного коефіцієнта тертя, зменшення поверхневих і об'ємних градієнтів температури обода шківа і зниження гальмівного моменту до 3.0 %. Це дозволить запобігти перегріву поверхневих шарів полімерних накладок і суттєво підвищити ефективність дії пар тертя гальмівних пристроїв. За рахунок ефекту транзистора досягнуто зменшення енергонавантаженості пар тертя гальма до 15.0 % і зносу робочих поверхонь накладок до 11.5 %.

Ключові слова: Полімери, Напівпровідникові матеріали, Енергетичні рівні, Мікровиступи поверхонь тертя, Ефект транзистора.