ESTADO DEFLETIDO DO SEMICONDUTOR DA ÁREA DE CONTATO PRÓXIMO NA ELETRODEGRADAÇÃO DA FAIXA DE METALIZAÇÃO NA SUPERFÍCIE

DEFLECTED STATE OF SEMICONDUCTOR NEAR-CONTACT REGION AT ELECTRO-DEGRADATION OF METALLIZATION TRACK ON ITS SURFACE

НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ ПРИКОНТАКТНОЙ ОБЛАСТИ ПОЛУПРОВОДНИКА ПРИ ЭЛЕКТРОДЕГРАДАЦИИ ДОРОЖКИ МЕТАЛЛИЗАЦИИ НА ЕГО ПОВЕРХНОСТИ

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RESUMO

É sabido que um estado não homogêneo de estresse ocorre em compostos de materiais diferentes após aquecimento. Na avaliação da resistência das juntas, é necessário levar em consideração as especificações físicas dos elementos soldados, as dimensões geométricas e as condições de temperatura de sua operação. O objetivo da pesquisa foi realizar a análise do estado de tensão-deformação da zona de contato de um semicondutor mediante eletrodegradação de uma trilha de metalização em sua superfície. Estruturas de metal semicondutor de película fina foram pesquisadas. Como substratos, foram usadas bolachas monocristalinas de silício dopadas com fósforo, orientadas nas direções (111) e (100), com resistividade no intervalo $\rho = 1 \dots 0,01 \Omega \cdot \text{cm}$ e $30 \dots 50 \mu\text{m}$. A camada n-epitaxial foi depositada em uma parte das bolachas. Como um filme metálico condutor, foi utilizado alumínio com espessura de $1 \dots 2 \mu\text{m}$. A estrutura do teste foi formada por fotolitografia óptica. Os oscilogramas da inclusão de U (t) no processo de passagem do pulso de corrente foram obtidos pelas sondas correspondentes de locais potenciais e registrados por um osciloscópio de armazenamento digital. Um procedimento de estimativa para a região sob tensão de semicondutores no aquecimento superficial local de uma área de superfície metalizada com pulso elétrico foi fornecido. O tamanho calculado da região do substrato de silício deformado foi comparado com o experimental sob passagem de pulsos elétricos quadrados. Foi estimada a região desviada, que depende da duração e amplitude do pulso elétrico. Uma não uniformidade considerável da pista de metalização após a passagem do pulso elétrico foi fixada experimentalmente.

Palavras-chave: aquecimento de semicondutores, estado de tensão, fusão por contato, área de tensão-deformação.

ABSTRACT

It is well known that a nonhomogeneous state of stress occurs in compounds of dissimilar materials upon heating. Upon the assessment of the strength of the joints, it is necessary to factor in the physical specifications of the soldered elements, the geometric dimensions and temperature conditions of their operation. The purpose of the research was to perform the stress-strain state analysis of the contact zone of a semiconductor upon electrodegradation of a metallization track on its surface. Thin-film metal-semiconductor structures were researched. As substrates, it was used phosphorus-doped silicon single-crystal wafers oriented in the (111) and (100) directions, with a resistivity in the range $\rho = 1 \dots 0.01 \Omega \cdot \text{cm}$, and a $30 \dots 50 \mu\text{m}$ n-epitaxial layer was deposited on a part of the wafers. As a conductive metal film, aluminum $1 \dots 2 \mu\text{m}$ thick was used. The test structure was formed by optical photolithography. The oscillograms of the U(t) inclusion in the process

of passage of the current pulse were taken by the corresponding probes from potential sites and recorded by a digital storage oscilloscope. An estimation procedure for the semiconductor stressed region at local surface heating of a metallized surface area with electric pulse was given. The calculated size of deformed silicon substrate region was compared with the experimental one under passage of square electric pulses. It was estimated the deflected region that depends on duration and amplitude of electric pulse. A considerable nonuniformity of the metallization track after electric pulse passage was fixed experimentally.

Keywords: *semiconductor heating, stressed state, contact melting, deflected region.*

АННОТАЦИЯ

Хорошо известно, что в соединениях разнородных материалов при нагреве возникает неоднородное напряженное состояние. При оценке прочности соединений необходимо учитывать физические характеристики спаянных элементов, геометрические размеры и температурные режимы их работы. Цель исследования – провести анализ напряженно-деформированного состояния приконтактной области полупроводника при электродеградации дорожки металлизации на его поверхности. В работе исследовались тонкопленочные структуры металл-полупроводник. В качестве подложек использовались легированные фосфором кремниевые монокристаллические пластины, ориентированные в направлении (111) и (100), с удельным сопротивлением в диапазоне $\rho = 1 \dots 0.01 \text{ } \Omega \cdot \text{cm}$, а на части пластин был нанесен 30...50- μm n-эпитаксиальный слой. В качестве проводящей металлической пленки был использован алюминий толщиной 1...2 μm . Формирование тестовой структуры осуществлялось методом оптической фотолитографии. Осциллограммы включения $U(t)$ в процессе прохождения импульса тока снимались соответствующими зондами с потенциальных площадок и фиксировалось цифровым запоминающим осциллографом. Приведена методика оценки области напряженного состояния полупроводника при локальном поверхностном нагреве металлизированного участка поверхности импульсом тока. Проведено сопоставление результатов расчета размера деформированной области кремниевой подложки с экспериментом в условиях прохождения прямоугольных токовых импульсов. Проведена оценка напряженно-деформированной области, которая зависит от длительности и амплитуды электрического импульса. Экспериментально зафиксирована существенная неоднородность дорожки металлизации после прохождения импульса.

Ключевые слова: *нагрев полупроводника, напряженное состояние, контактное плавление, напряженно-деформированная область.*

1. INTRODUCTION

It is well known that heating compounds of dissimilar materials leads to appearance of a non-uniform stressed state (Kapitonov *et al.*, 2017; Kashniyal and Pandey, 2018; Lim and Meguid, 2019; Dong and Wang, 2019). In the course of heating such compound, stresses in the layers of elements increase at the expense of thermal expansion. This may result in the destruction of the layer (Dang *et al.*, 2017; Shejko *et al.*, 2017; Chen *et al.*, 2018; Xu *et al.*, 2018; Ishitani *et al.*, 2018; Bojita *et al.*, 2018). When estimating joint efficiency, one has to take into account the physical characteristics of soldered elements as well as their geometric sizes and temperature modes of their operation (Sirazijeva *et al.*, 2004; Li *et al.*, 2016; Skvortsov *et al.*, 2016; Mailman *et al.*, 2017; Romashevskiy *et al.*, 2018; Voss *et al.*, 2018; Çiçek *et al.*, 2019).

Earlier it has been shown that electric current $I(t)$ flowing along the X-axis leads to appearance of (i) a heat flow with density (Equation 1) (here I , b , and R are respectively

length, width, and resistance of the metallization track) and (ii) a temperature field $T(x,y,z)$ (Equation 2) (Skvortsov *et al.*, 2016).

Here the X, Y and Z coordinate axes are directed along length, width and into a plate, respectively; λ is plate heat conduction; T_0 is temperature of environment; (Equation 3) is silicon thermal diffusivity; (Equation 4) is integral exponent.

Equation 2 describes temperature distribution over the surface of plate with a square heating source. Decreasing a minimum topological size of joint elements leads to the problem of "thermal overloads" in the layers (Hu *et al.*, 2012; Zhao *et al.*, 2018; Joi *et al.*, 2019). This may result in destruction of contacts and near-contact regions (Zheng *et al.*, 2017; Amrastanov *et al.*, 2018; Tsai, 2018; Kreiml *et al.*, 2019). On a number of occasions technologists try to apply the methods of correcting mechanical stresses by additional oxidizing the reverse side of silicon plates (Lee *et al.*, 2017; Nguyen *et al.*, 2018; Yao *et al.*, 2019). Nevertheless, in some cases partial destruction of joint integrity (Makara

et al., 2015; Bondariev *et al.*, 2018) as well as mechanical damage of the sample under investigation (up to crack formation) (Tsay and Wu, 2017; Hu *et al.*, 2018; Brincker *et al.*, 2018; Ishii *et al.*, 2018; Wang *et al.*, 2019; Mikhelashvili *et al.*, 2019) are observed. In this connection the problem of mechanism of the observed phenomena seems to be urgent.

It is known (Skvortsov *et al.*, 2006; Skvortsov *et al.*, 2016; Moser *et al.*, 2019) that passage of an electric pulse through metallization track may result in processes of (i) contact melting (as the eutectic melting temperature T_{eu} achieves 850 K at the Al-Si interface) and (ii) aluminum film melting (as the aluminum melting temperature T_{Al} achieves 934 K). It was established by the authors in their earlier works (Skvortsov *et al.*, 2006; Skvortsov *et al.*, 2016) that development of processes of contact melting and electro-degradation for the Al-Si systems can appear when heating thin-film systems by an electric pulse of energy up to 250 μ J and interval duration of 50...1000 μ s.

The purpose of the research was to perform the stress-strain state analysis of the contact zone of a semiconductor upon electrodegradation of a metallization track on its surface.

2. MATERIALS AND METHODS

Thin-film metal-semiconductor structures were studied in this work. As substrates, we used phosphorus-doped silicon single-crystal wafers oriented in the (111) and (100) directions with a resistivity in the range $\rho = 1...0.01 \Omega \cdot \text{cm}$, and on parts of the plates was applied 30...50- μm n-epitaxial layer. High-resistance layers prevented shunting of metallization systems, facilitating thermal field analysis. As a conductive metal film, aluminum 1 ... 2 μm thick was used. The test structure was formed by optical photolithography and is shown in Figure 1. The developed measuring complex consisted of a master oscillator, a current pulse shaper of various shapes (rectangular, sawtooth, sinusoidal, etc.) and a digital storage oscilloscope. The current pulse shaper of various shapes, which is part of the installation, provided the following parameters: current adjustment range up to 60 A; the duration of the leading and trailing edges from 10 μs , respectively; maximum pulse duration from 1 ms; maximum pulse repetition rate of at least 0.2 Hz. The measuring complex was used to record temperature operating conditions and defect formation in semiconductor structures

under pulsed influences.

The registration of temperature changes in the surface layers of silicon was carried out using the test structure described earlier. Through it pulses of various shapes were passed with the recording of the waveforms $U(t)$. The oscillograms of the inclusion of $U(t)$ during the passage of the current pulse were taken by the corresponding probes from potential sites and recorded by a digital storage oscilloscope.

3. RESULTS AND DISCUSSION:

A typical $U(t)$ dependence when passing square electric pulses of different amplitudes (pulse duration $\tau_i = 500 \mu\text{s}$) is presented in Figure 1. The feature of switching oscillograms and construction of safe area of the metallization system are presented in Figure 2. The points on the oscillograms 1-7 show the moments of oscillogram deviation related to the beginning of contact melting processes at the Al-Si interface and Al film melting. Current pulse power was no more than 170 mJ. It should also be stressed that, at considered parameters of single electric pulses (Kreiml *et al.*, 2019; Li *et al.*, 2016; Kim *et al.*, 2018; Yao *et al.*, 2019; Lu and Yeh, 2019) passing through the metallization-substrate track, the melting-crystallization processes may be wave-like (Figure 3).

3.1. Explosive loading factors in the metallization systems

The main acting factors of explosive-loading in the metallization systems are relaxation of tangential stresses (Msolli *et al.*, 2018; Wang *et al.*, 2019) and concomitant formation of macro-deformations. They lead to formation in the silicon substrate of a deflected wake whose stressed state is close to biaxial or triaxial compression. Detonation in the moment of explosive current pulse passing through metallization is realized in the sliding mode. In this case, 3D configurations of metal flow are realized. A substantially nonhydrostatic stressed state of metal is typical for them. Under these conditions, the role of deviator component of stress tensor increases (Skvortsov *et al.*, 2006). Because of this, relaxation of tangential stresses becomes considerably easier. The final result of this is formation of a deflected wake with $\sigma_x \approx \sigma_y \approx \sigma_z$. Configuration of a wake appearing in the relaxed material at explosive detonation in the moment of current pulse (with critical current density) passing through metallization (width b_0

and thickness δ_0) is sketched in Figure 4.

Cross sizes (v and w) of the region within which relaxation of tangential stresses occurred depend on the thermal shock mode, energy and geometric parameters of Al metallization, physical-mechanical properties of material and substrate geometry, etc. To estimate approximately v and w , let us suppose that (Equation 5) and (Equation 6) (here q_0 is the linear mass of conditional charge) and ascribe the basic part of energy of real wave field to a conditional wave of profile compression. This wave is symmetric about the x -axis; its duration is $\sim \delta_0 D^{-1}$ (Skvortsov *et al.*, 2006). Because of assumption of equality between the kinetic and potential energies in such wave, the total specific energy in it is determined from the following formula (Equation 7). Here σR is stress that is normal to the curvilinear front of a shock wave, cc is propagation velocity of a weak plastic wave, D is propagation velocity of a shock wave, E is Young modulus and R is distance from the x -axis.

Let us liken action of a thin film on semiconductor to successive elastic collisions of mass q_0 elements (zone I₀ Solid, Figure 2) moving along a normal to the Z -axis at speeds proportional to $\sqrt{2Q_0}$. Here Q_0 is specific heat of explosion with very big mass of metal whose density is ρ_1 (i.e., one can write down $\rho_1 \delta_0^2 c_c^2 D^{-2}$). Hence the energy delivered to the substrate in the moment of explosion pulse passing is expressed by (Equation 6). It follows from Equations 7-8 that (Equation 9).

Thus, the sizes of deflected region will be determined by the stress values in a wave sufficient to achieve deflected state in the substrate. Equation 9 allows to apply the theory of explosive loading for analysis of thermoelastic state of the metal-semiconductor systems. Moreover, variation of "explosive pulse" can affect the size of deflected substrate region. This may result later in formation of point and linear defects, appearance of friction near the thermal shock source and even to system damage.

3.2. Consequences of increasing impulsive action power

Increasing of pulse power action (zone II Liquid, Figure 1) leads to degradation processes in the aluminum metallization system, taking into account electric transport and development of the contact melting processes. The state of the Al-Si interface after crystallization is presented in Figure 5. The contact interaction at pulse

advancing to the metal-semiconductor system may be described by the following model. Geometry of the problem is such. There are two solid-state objects: a plate (Si) and a bar (Al). At the instant of an electric pulse (with critical current density) transmission, the aluminum film (Figure 5) is melting and, under action of electric transport (zone II Liquid, Figure 2) and thermal expansion, realizes microscopic travel over the silicon substrate surface. The bar is sliding over the plate with a given speed. In this case, the resulting friction produces heat, thus performing heating both things.

In the general case, the given problem is nonlinear. To simplify calculation, we allow an ideal contact between the contacting surfaces. A natural convective heat exchange with environment is organized on the object surfaces. Calculations were performed using the ANSYS program complex where the mechanical-thermal properties of materials were specified, a finite-element model was developed, boundary conditions and loadings were applied (Figure 6).

At first let a bar is forced down into a plate under the action of surface tension (at the instant of applying a pulse with critical current density) and let this lasts for 0.5 μ s. Then the bar will move along the plate due to electric transport. The absolute thermal contact is applied by default. This means that temperature does not drop as heat is transferred from one surface to another. However, numerous "real" conditions lead to the conclusion that thermal conductivity of a real thermal contact differs from absolute one.

Course of computation was controlled by the use of construction of a force convergence graph. The contact stresses calculated in the course of work in the ANSYS program complex are presented in Figure 7. Their numerical values for the structure studied with given geometric parameters lie in the range from 16 to 18 MPa.

4. CONCLUSIONS:

Thereby an analysis of a deflected state of semiconductor near-contact region at electro-degradation of metallization track on its surface revealed some important aspects related to construction of a chart of regions of safe and critical activity of aluminum-silicon contact. This made it possible to perform rapid analysis of safe operation modes for the structures under investigation. We estimated a deflected region depending on electric pulse duration and amplitude. An analysis performed in the ANSYS system from solution of contact problem for the

aluminum-silicon system showed that considerable stresses appear in the contact region. They may result in formation of defects in the near-contact region as well as have an influence upon geometry and formation of wavy geometry of a crystallized aluminum film after its melting.

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6. REFERENCES:

1. Amrastanov, A.N., Seregina, E.V., Stepovich, M.A., Filippov, M.N. *Journal of Surface Investigation*, **2018**, 12(4), 778-782.
2. Bojita, A., Boianceanu, C., Purcar, M., Florea, C., Simon, D., Plesa, C.-S. *Microelectronics Reliability*, **2018**, 87, 142-150.
3. Bondariev, V., Gorushko, V., Pilipenko, V., Solodukha, V. *High Temperature Material Processes*, **2018**, 22(1), 1-6.
4. Brincker, M., Walter, T., Kristensen, P.K., Popok, V.N. *Journal of Materials Science: Materials in Electronics*, **2018**, 29(5), 3898-3904.
5. Chen, Y.-L., Wu, J., Lee, C.C. *Journal of Materials Science: Materials in Electronics*, **2018**, 29(12), 10037-10043.
6. Çiçek, O., Kurnaz, S., Bekar, A., Öztürk, Ö. *Composites Part B: Engineering*, **2019**, 174, article number 106987.
7. Dang, G.T., Kawaharamura, T., Furuta, M., Allen, M.W. *Applied Physics Letters*, **2017**, 110(7), article number 073502.
8. Dong, A., Wang, H. *Annalen der Physik*, **2019**, 531(7), 1800440.
9. Hu, C.-K., Ohm, J., Gignac, L.M., Breslin, C.M., Mittal, S., Bonilla, G., Edelstein, D., Rosenberg, R., Choi, S., An, J.J., Simon, A.H., Angyal, M.S., Clevenger, L., Maniscalco, J., Nogami, T., Penny, C., Kim, B.Y. *Journal of Applied Physics*, **2012**, 111(9), Article number 093722.
10. Hu, X., Liu, H., Wang, X., Zhang, X., Shan, Z., Zheng, W., Li, H., Wang, X., Zhu, X., Jiang, Y., Zhang, Q., Zhuang, X., Pan, A. *Advanced Optical Materials*, **2018**, 6(12), 1800293.
11. Ishii, T., Yamakawa, H., Kanaki, T., Miyamoto, T., Kida, N., Okamoto, H., Tanaka, M., Ohya, S. *Scientific Reports*, **2018**, 8(1), article number 6901.
12. Ishitani, Y., Aoki, T., Funabashi, H., Morita, K. *Applied Physics Letters*, **2018**, 113(19), article number 192105.
13. Joi, A., Venkatraman, K., Tso, K.-C., Dictus, D., Dordi, Y., Wu, P.-W., Pao, C.-W., Akolkar, R. *ECS Journal of Solid State Science and Technology*, **2019**, 8(9), 516-521.
14. Kapitonov, S.S., Bespalov, N.N., Il'in, M.V., Gulyaev, I.V. *Russian Electrical Engineering*, **2017**, 88(6), 351-354.
15. Kashniyal, U., Pandey, K.P. *Vacuum*, **2018**, 152, 109-113.
16. Kim, W.K., Melnick, C., Shim, J.H., Kaviani, M. *Journal of Nuclear Materials*, **2018**, 511, 148-163.
17. Kreiml, P., Rausch, M., Terziyska, V.L., Winkler, J., Mitterer, Ch., Cordill, M.J. *Scripta Materialia*, **2019**, 162, 367-371.
18. Lee, J.-G., Kim, D.-H., Eom, S.-K., Roh, S.-H., Seo, K.-S., Kim, H.-S., Kim, H., Cha, H.-Y., Byun, Y.-C. *Journal of the Korean Physical Society*, **2018**, 72(1), 166-170.
19. Li, Y., Lee, H.-T., Saka, M. *Microelectronics Reliability*, **2016**, 65, 178-183.
20. Lim, L.Y., Meguid, S.A. *Materials and Design*, **2019**, 164, Article number 107543.
21. Lu, C.-L., Yeh, M.-K. *Microelectronic Engineering*, **2019**, 213, 47-54.
22. Mailman, A., Leitch, A.A., Yong, W., Steven, E., Winter, S.M., Claridge, R.C.M., Assoud, A., Tse, J.S., Desgreniers, S., Secco, R.A., Oakley, R.T. *Journal of the American Chemical Society*, **2017**, 139(6), 2180-2183.
23. Makara, V.A., Steblenko, L.P., Vesna, G.V., Naumenko, S.N., Kurilyuk, A.N. *Physics of the Solid State*, **2015**, 57(2), 349-352.
24. Mikhelashvili, V., Yofis, S., Shacham, A., Khanonkin, I., Eyal, O., Eisenstein, G. *Journal of Applied Physics*, **2019**, 126(5), article number 054501.
25. Moser, S., Zernatto, G., Kleinbichler, M., Nelhiebel, M., Zechner, J., Cordill, M.J., Pippin, R. *JOM*, **2019**, 71(10), 3399-3406.
26. Msolli, S., Alexis, J., Kim, H. *Advanced Engineering Materials*, **2017**, 19(8), article

number 1700109.

27. Nguyen, M.-C., On, N., Ji, H., Nguyen, A.H.-T., Choi, S., Cheon, J., Yu, K.-M., Cho, S.-Y., Kim, J., Kim, S., Jeong, J., Choi, R. *IEEE Transactions on Electron Devices*, **2018**, 65(6), 2492-2497.
28. Romashevskiy, S.A., Tsygankov, P.A., Ashitkov, S.I., Agranat, M.B. *Applied Physics A: Materials Science and Processing*, **2018**, 124(5), article number 376.
29. Shejko, S., Shalomeev, V., Mishchenko, V. *Materials Science and Technology Conference and Exhibition 2017, MS and T 2017*, **2017**, 1, 238-244.
30. Sirazijeva, L.F., Stepin, S.N., Makhotkina, L.Yu. *Lakokrasochnye Materialy i Ikh Primenenie*, **2004**, 10, 25-28.
31. Skvortsov, A.A., Orlov, A.M., Rybin, V.V. *Technical Physics Letters*, **2006**, 32(3), 240-242.
32. Skvortsov, A.A., Zuev, S.M., Koryachko, M.V., Glinskiy, V.V. *Microelectronics International*, **2016**, 33(2), 102-106.
33. Tsai, C.-Y. *Microelectronics Reliability*, **2018**, 91, 335-343.
34. Tsay, C.-Y., Wu, P.-H. *Japanese Journal of Applied Physics*, **2017**, 56(3), article number 03BA02.
35. Voss, L.F., Murphy, J.W., Shao, Q., Henderson, R.A., Frye, C.D., Stoyer, M.A., Nikolic, R.J. *Applied Physics Letters*, **2018**, 113(24), article number 24103.
36. Wang, M., Zhao, L., Fourmeau, M., Nelias, D. *Journal of the Mechanics and Physics of Solids*, **2019**, 122, 472-488.
37. Xu, T., Ji, G.P., Cao, Z.X., Ji, A.L. *Journal of Physics D: Applied Physics*, **2018**, 51(5), article number 055303.
38. Yao, Y., Chalifoux, B.D., Heilmann, R.K., Schattenburg M.L. *Optics Express*, **2019**, 27(2), 1010-1024.
39. Zhao, J., Zhai, J., Lu, Y., Liu, N. *International Journal of Heat and Mass Transfer*, **2018**, 120, 241-249.
40. Zheng, D., Yu, C., Zhang, Q., Wang, H. *Nanotechnology*, **2017**, 28(50), article number 505201.

$$q = I^2 R / lb \quad (\text{Eq. 1})$$

$$T(y, \tau) - T_0 = \frac{I^2 R}{2\pi \lambda l b} \left[\left(\frac{b}{2} - y \right) E_1 \left(\frac{(b/2 - y)^2}{4a\tau} \right) + \left(\frac{b}{2} + y \right) E_1 \left(\frac{(b/2 + y)^2}{4a\tau} \right) \right] + \frac{I^2 R \sqrt{a\tau}}{\sqrt{\pi \lambda l b}} \left[\Phi \left(\frac{b/2 - y}{\sqrt{4a\tau}} \right) + \Phi \left(\frac{b/2 + y}{\sqrt{4a\tau}} \right) \right] \quad (\text{Eq. 2})$$

$$a = \lambda / (cd) \quad (\text{Eq. 3})$$

$$E_1(z) = \int_z^\infty \exp(-\xi) \frac{d\xi}{\xi} \quad (\text{Eq. 4})$$

$$b_0 = \delta_0 \quad (\text{Eq. 5})$$

$$\rho_0 = q_0 \delta_0^{-2} \quad (\text{Eq. 6})$$

$$U = \pi R \delta_0 c \sigma_R^2 (DE)^{-1} \quad (\text{Eq. 7})$$

$$U \approx \frac{q_0^2 Q_0 D^2}{\rho_1 \delta_0 c^2} \quad (\text{Eq. 8})$$

$$\sigma_R(R) \approx \frac{\delta_0 \rho_0^2}{\pi R \rho_1} \left(\frac{D}{c_c}\right)^3 Q_0 E \quad (\text{Eq. 9})$$

Figure 1. a – Appearance of switching oscillograms $U(t)$ at a single current pulse passing through an Al metallization track on Si. Al film thickness of $3\ \mu\text{m}$; length and width of $5\ \text{mm}$ and $50\ \mu\text{m}$, respectively; Si substrate thickness of $1\ \text{mm}$; pulse duration $\tau = 500\ \mu\text{s}$, amplitude $j = 5.8 \cdot 10^{10}\ \text{A/m}^2$. τ zone is contact melting duration; b – Appearance of test structures used when performing experiment

Figure 2. Chart of safe operation region of an Al-Si contact (I. Solid is bounded above by a dash-dotted line) constructed on the basis of switching oscillograms taken at passing through the structure of a single square current pulse with amplitude (in A/m^2): 1 – $j = 8.8 \cdot 10^{10}$; 2 – $8.6 \cdot 10^{10}$; 3 – $8.2 \cdot 10^{10}$; 4 – $6.7 \cdot 10^{10}$; 5 – $6.6 \cdot 10^{10}$; 6 – $6.1 \cdot 10^{10}$; 7 – $5.8 \cdot 10^{10}$

Figure 3. a – wave-like form of Al metallization (1) on Si substrate (2) after a current pulse passing through it (melting); b – ΔT_b temperature profile of metallization track at passing a current pulse with duration $\tau_0 = 1000 \mu s$ and amplitude (in A/m^2): $\alpha - 2.0 \times 10^{10}$; $\beta - 2.8 \times 10^{10}$; $\gamma - 3.5 \times 10^{10}$; c – stress diagram in the metal-substrate system at a moment of current pulse passing

Figure 4. Configuration of "momentary" deflected region produced in the Si substrate by an explosive current pulse passing through Al metallization in the sliding supersonic detonation mode: 1 – Si substrate, 2 – Al metallization, 3 – detonation front, 4 – track contour; the I_0 arrow shows direction of current motion

Figure 5. Scanning electron microscope picture of wave-like parts of the Al-Si metallization system after passing a critic current pulse

Figure 6. 3D model used for calculations, arrow shows direction of electric current flow

Figure 7. Contact stresses at the Al-Si interface