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Analysis of the process of aluminium destruction on the surface of silicon during the electrical explosion of the conductor

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The work considers the processes of formation of aluminium melt drops, dispersion of aluminium melts and dynamics along the surface of the semiconductor during the electrical explosion of the metal film. It has been shown that in conditions of flow of rectangular high-density current pulses (amplitude $j_{\max} = 2 \cdot 10^{11}$ A/m^2 and duration up to 2.0 ms), an electrical explosion of a conductor occurs through a test structure based on aluminium film (thickness $5\,\mu$m). Dispersion of up to 30% of the mass of the aluminium film is observed. It has been established that the main parameter characterizing the dispersion during the destruction of an aluminium film is the energy of an electrical pulse. The distribution of rounded aluminium particles by size (diameter) has been determined experimentally. It has been found that the largest number of particles in the conditions considered are $1-3\,\mu$m in size.

Keywords: non-stationary states, heat shock, formation of drops on the surface, non-stationary surface mass transfer.

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The phenomenon of electrical explosion of conductors is well known [1,2] and is of great interest for research in condensed matter physics, thermal physics, high-voltage electrical engineering, and related fields of science [3]. The physics of this phenomenon is still under detailed investigation, which allows controlling the process, including technology to suppress high current density conductor explosion by adding micron-scale surface defects [4]. In addition, development of electroexplosive technology allows solving a number of technological problems associated with obtaining local sources of pulse pressure, application of thin films, obtaining nanopowders of metals and alloys of different phase and chemical composition [3,4].

Processes of electrical explosion of conductive films deposited on the surface of semiconductors and dielectrics have their own specifics associated with the modes of heat dissipation in a film system. Electrical explosion of conductors in such systems makes it possible to solve the problems of controlling the processes of liquid phases spreading on the surface of solids in various external fields [5,6], to model thermal overloading of structures in printed [7] and power [8] electronics.

As for „power“ electronic devices and structures, it is known from literature that electrical explosion of typical conductors (Al, Cu, Ag, Au) initiated by passing a high-density current pulse ($j \geqslant 10^6$ A/cm^2), causes melting of the metal, disturbance of electrical conductivity and formation of molten zones, their migration across the surface, as well as generation of shock waves and electromagnetic radiation [2–5]. It is obvious that this exposes the conductor to extreme non-equilibrium conditions, analysis of which is very important in predicting the area of safe operation of metal systems and the issues of non-stationary mass transfer of melt over the surface [5,6].

Therefore, the present paper considers the issues of non-stationary mass transfer (destruction and dispersion) of aluminum metal film on silicon under electric explosion conditions.

Experimental studies were carried out according to the method [9,10] on a setup comprising a pulse generator based on high-capacity capacitors $C = 4000\,\mu$F (maximum amplitude of the square current pulse and pulse duration did not exceed $I_{\max} = 150$ A and $\tau_{\max} = 2$ ms respectively with the sample resistance not more than $R_{\max} = 1\,\Omega$, the steepness of the leading and trailing edges was 7 and $10\,\mu$s respectively), a digital storage oscillograph and optical microscope to record the „thermal“ fracture processes of metallization systems [11].

The experimental structures were an aluminum film sprayed on silicon wafers. The aluminum film (with max thickness of $5\,\mu$m) served as the main conductive layer. Phosphorus-doped silicon wafers with a thickness of $400\,\mu$m, oriented in the direction of (111), with resistivity of $25\,\Omega \cdot$ cm were used as substrates. The technique for preparing the structures is described in detail in [9,10].

Temperature changes in the thin-film structure were recorded according to the technique [9,10]. Square current pulses were passed through a metallization track with oscillographic recording of voltage drop $U(t)$ from the test structure section. Signal shape $U(t)$ was used to determine dynamics of system heating in process of current pulse passage.

According to classification [2], if pulse current densities exceed 10^{10} A/m^2, the discrete wire is damaged. And

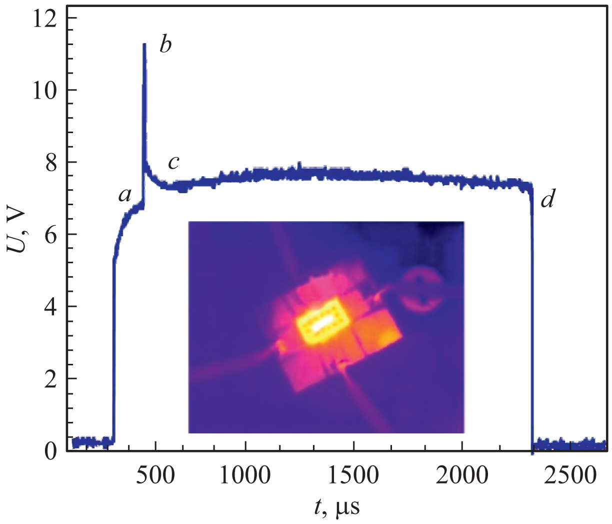

Figure 1. Connection oscillogram $U(t)$ under single current pulse of square shape with amplitude $j = 8\cdot10^{10}\,\mathrm{A/m^2}$ and duration $\tau = 2\,\mathrm{ms}$. The inset — is a photograph of a semiconductor structure obtained with a thermal imager.

most metal is sprayed in the form of drops. Our experimental research conducted in wire conductors with diameter $150\,\mu$m, confirm it: thus, passage of single current pulse $j = 5.5\cdot10^{11}\,\mathrm{A/m^2}$ and duration $400\,\mu$s resulted in thermal damage of the discrete wire. In case of film model structures of „aluminum on silicon“ type, we recorded experimentally that degradation processes in the considered systems start at amplitude of square current pulses $j\sim4\cdot10^{10}\,\mathrm{A/m^2}$ and duration τ of at least $200\,\mu$s. Under such electrothermal loads the conductor heating and directional melting of the metal film were observed, and with increasing pulse duration — processes of contact melting in the metal film–semiconductor substrate system. Besides, the conductor was heated to a temperature close to the aluminum melting point ($T_L = 934\,\mathrm{K}$). Aluminum melting under such conditions was accomplished by moving the solid-liquid interface along the metallization track.

It was previously shown [10] that directional melting occurs due to unbalanced heat release in a finite thickness l_x layer at the interface of solid (s) and liquid (l) Al. Length of the melted layer and the rate of interface displacement can be calculated based on thermal balance considerations. Let us consider that when a current pulse passes through in time $d\tau$, the power released W_{sl} (at aluminum melting temperature) is spent to melt some volume of metal Sdx

$$W_{sl}d\tau = HSdx. \qquad (1)$$

Here $H = 10.2\cdot10^8\,\mathrm{J/m^3}$ — specific heat of aluminum melting, dx — length of the melted portion of the metallization track. Writing down the left-hand part of equation (1), we will get

$$\left[I(\tau)^2(\rho_{0l}-\rho_{0s})\frac{l_x}{S}\right]d\tau = HSdx, \qquad (2)$$

where $I(\tau)$ — amplitude of square pulse, $\rho_{0l} = 2.4\cdot10^{-7}\,\Omega\cdot\mathrm{m}$, $\rho_{0s} = 0.98\cdot10^{-7}\,\Omega\cdot\mathrm{m}$ — resistivity of liquid and solid aluminum respectively, $S = bh$ — conductor cross section area, $b = 75\,\mu$m, $h = 5\,\mu$m — width and thickness of the track respectively. If l_x is treated as comparable to thickness of the layer, where temperature gradient $l_x = 2\sqrt{a_1\tau_x} = (1-4)\cdot10^{-4}\,\mathrm{m}$ is established, you may get the following from (2)

$$dx = \frac{I^2(\rho_{0l}-\rho_{0s})2\sqrt{a_1\tau}}{S^2H}\,dt, \qquad (3)$$

were a_1 — thermal diffusivity of aluminum. Integration of equation (3) allows us to obtain the dependence of the melting depth of the metallization track x_l as a function of the melting time τ_x

$$x_l(\tau_x) = \frac{4}{3}\,\frac{I^2(\rho_{0l}-\rho_{0s})\sqrt{a_1}}{S^2H}\,\tau_x^{3/2}. \qquad (4)$$

The results of the study on the studied structures (inset in Fig. 1) also demonstrated satisfactory coincidence of the length of the melted zones depending on the power of a single square current pulse. Maximum propagation velocities of the zones in our experiments reached $35\,\mathrm{m/s}$. Thus, under the conditions considered, the process of thermal degradation of the track was associated with the directional movement of the interphase (melt–metal) boundary and had the signs of electrical explosion of the conductor [12].

As current pulse amplitude increased to $j = 8\cdot10^{10}\,\mathrm{A/m^2}$ and above, we observed an electrical explosion of a film conductor accompanied by damage of the structure and thermal migration of metal drops on the silicon surface.

As a result of research of specific damage times, it was found that under current density $j = 8\cdot10^{10}\,\mathrm{A/m^2}$ the processes of noninvertible degradation]o are accompanied by quick ($\tau_{0a}\sim75\,\mu$s) heating of metal film (section $0a$ in fig. 1), melting of current-conducting layer ($\tau_{ab}\sim15\,\mu$s), characterized by potential burst $U(t)$ (section ab in fig. 1). Besides, metal spraying was observed on the semiconductor surface (fig. 2). The mass transfer of melt droplets under consideration leads to the formation of conductive metallic „islands“ and doped surface channels, which provides a stable current flow despite the fragmentary rupture of the metallic track. Therefore, there is „reset“ of potential on the curve $U(t)$ (section bc in Fig. 1) and subsequent quasistable value of $U(t)$ until the pulse is turned off (section cd in Fig. 1). Possible disturbances of $U(t)$, which we sometimes observed, may be associated with local surface oxidation of silicon and contact melting processes in the aluminum–silicon substrate system.

Obviously, in process of electric explosion of the film conductor, some pulse energy passes into the kinetic energy of the dispersion products projection [13]. In addition, strong thermal gradients generated near the thermal shock source [14] influence the migration dynamics of the molten zones. The results of the microscopic analysis (inset) and

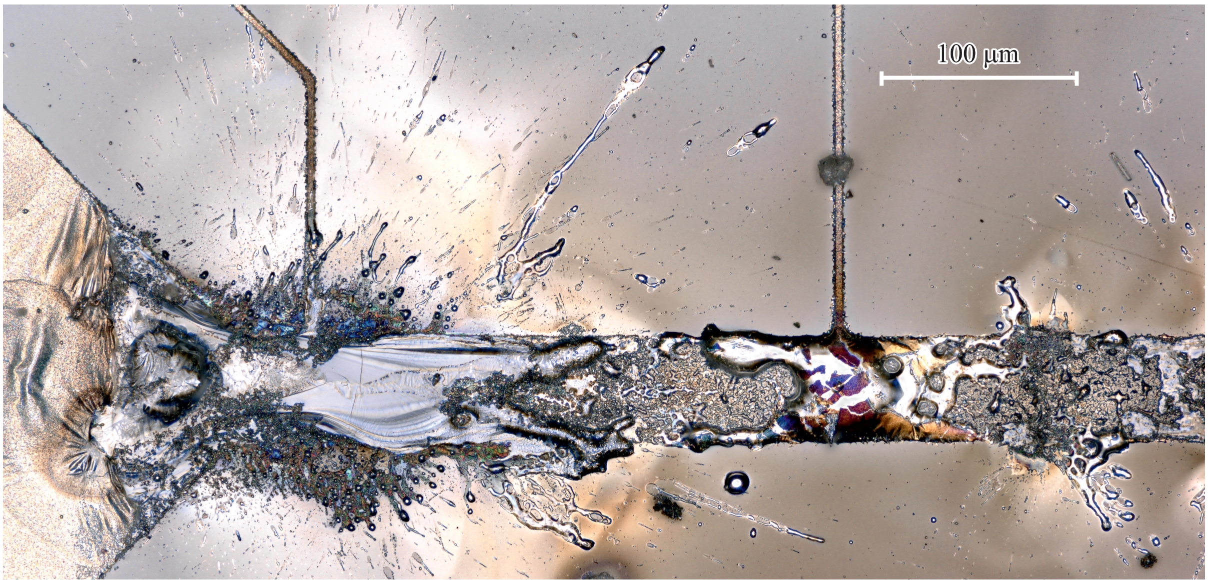

Figure 2. Microphotograph of test structure section after passage of single square current pulse with amplitude $j = 9 \cdot 10^{10}$ A/m^2 and duration $\tau = 500\,\mu$s.

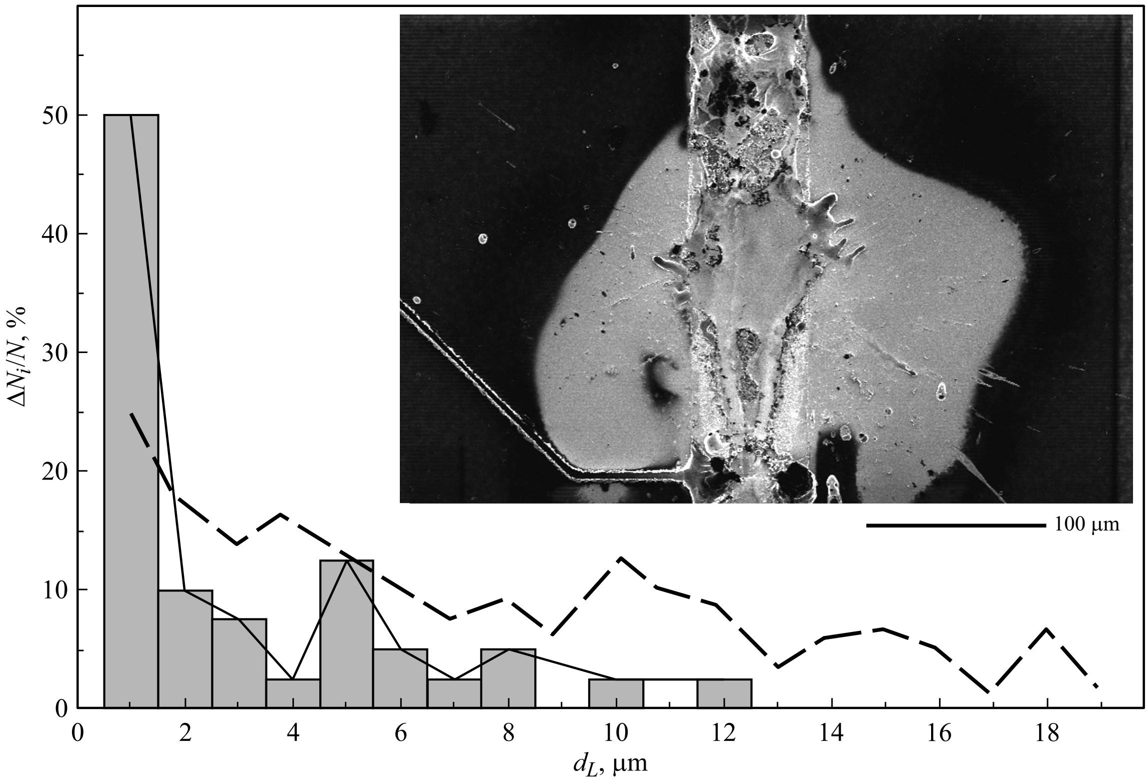

Figure 3. Distributions by aluminum particle size after current pulse passage. Solid line — $j = 9 \cdot 10^{10}$ A/m^2 and $\tau = 500\,\mu$s, dotted line — $j = 6 \cdot 10^{10}$ A/m^2 and $\tau = 500\,\mu$s. On the inset — a photograph produced by method of raster electronic microscopy of a section of aluminum metallization caused by passage of a single square current pulse with amplitude $6 \cdot 10^{10}$ A/m^2 and duration $\tau = 500\,\mu$s.

the size distribution of the formed melt zones d_L are shown in Fig. 3. The research results demonstrated that as current pulse amplitude is growing, the sizes of generated drops move towards submicron area, and nanoparticles may be observed in the dispersion products [15].

Therefore, the paper analyzed electric thermal damage of the aluminum-silicon metallization system up to electrical explosion. The impact of electric power of a current pulse passing through a test structure on the nature of its damage was found experimentally: starting from the processes of directional melting up to spraying of metal drops on the surface (electrical explosion mode). Parameters of current pulses for various mechanisms of metal film electric thermal damage were identified. The distribution of crystallized aluminum particles by size (diameter) was recorded experimentally. When distributions were compared for various pulse capacities, it was found that growth of current pulse amplitude (with fixed duration) moved the sizes of generated drops to submicron area.

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Conflict of interest

The authors declare that they have no conflict of interest.

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