

SEMICONDUCTOR FUSES WITH ALUMINIUM CURRENT-CARRYING PARTS: PROBLEMS AND PROSPECTS

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Importance of the problem. At present, fuse elements of quick-breaking protection fuses are made of silver (Ag), which material is characterized by a variety of valuable properties. The world production of silver (without USSR) in 1983 approached 9869 metric tons, with a 5000 ton deficit¹. Yearly irreparable losses of Ag exceed 4000 tons, with electrical industries responsible for the major part of this figure². This is the situation where instability of market prices, with a tendency towards a considerable growth, is only too natural. Thus, the price of silver doubled five times over the period of 1983-1985, occasionally falling down³. While in 1960 the price of 1 gram of Ag was 2.8 cents, it rose to 26-36 cents in 1980's, even reaching 1.5 \$¹. By the year 2000, the production of silver in developed countries is expected to reach 6000 tons, with the demand three times as high. Hence, a radical solution to the problem would be replacement of silver by another material.

Requirements to high-speed fuses. The technically severe operation conditions of semiconductor devices with high-speed fuses and the emergencies that may arise give rise to contradictory requirements that the fuses should meet. On the one hand, the fuses must provide long-term reliability under the repeated action of arbitrarily varying loads and/or overloads, without demanding reductions in the rated current values through the circuit. On the other hand, if a fault condition develops, the fuse must disconnect the faulty subcircuit, while retaining its own mechanical integrity and preventing inadmissible consequences for the major system. This is achieved through extinguishing the arc at the lowest possible level of its energy and optimizing the values of the Joule integral for the fuses, semiconductor devices and other protection equipment. E.g., in the case of internal short circuiting the condition must

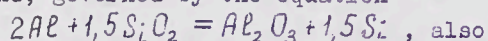
be met

$$W_1 \leq [n(1-K) + K]^2 W_2,$$

where W_1 is the let-through $\int i^2 dt$ integral of the fuse, W_2 the prearcing integral, n the number of parallel circuit branches, and K the nonuniformity coefficient of current sharing. This condition is particularly hard to satisfy for the values often encountered in practice, i.e. $n = 2$, $K = 0.3$ and $U_{arc} \leq U_{main}$. In the case of adiabatic heating, i.e. with high values of the short-circuit current (about $(250 \text{ to } 400) \times I_{rated}$), the integrals assume values between 1.31 and 4.36, which may fail to satisfy the above condition at the level of 2.89. Difficulties can also arise in matching the parameters of automatic circuit breakers or semiconductor devices with performance characteristics of the fuse (such as the peak current, arc energy, $\int i^2 dt$ integrals, etc.). Characteristics of aluminium. Compared with silver, aluminium is characterized by lower (nearly by a factor of two) values of the thermal and electric conductivity, much lower Meyer constant ($37 \text{ A}^2 \text{ sec/mm}^4$ against $72 \times 10^3 \text{ A}^2 \text{ sec/mm}^4$), lower mechanical strength (8 kgf/mm^2 compared with 15 kgf/mm^2), and lower melting point. At low temperatures, the mechanical strength of both Ag and Al increases (almost by a factor of two at $-200 \text{ }^\circ\text{C}$), while at higher temperatures it decreases monotonously to become 1 kgf/mm^2 (at $900 \text{ }^\circ\text{C}$ for Ag and $600 \text{ }^\circ\text{C}$ for Al). The oxide film present on Al has a noticeable strengthening effect at high temperatures. E.g., specimens of aluminium foil (thickness of 0.1 mm , 99.997% pure) annealed at $600 \text{ }^\circ\text{C}$ showed a strength of $2.45 \times 10^6 \text{ Pa}$ and a 12% plasticity. With the oxide film removed through chemical solution the same foil showed a $1.35 \times 10^6 \text{ Pa}$ strength and a 39% plasticity. If the oxide film is removed mechanically, aluminium interacts

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vigorously with water and aqueous solutions of acids or alkalis. The properties of aluminium specimens are markedly influenced by their chemical purity. E.g., the tests performed at 350 °C for two kinds of 99.99 % pure aluminium specimens have revealed ageing and failure effects after 308 and 376 hours, while for specimens of lower purity (99.95 %) after 121 and 206 hours¹. Silver specimens subjected to mechanical straining at high temperatures also showed a noticeable ageing effect. E.g., after 3 hours at 250 °C the mechanical strength was 7.85 kgf/mm² with a relative elongation of 70 %, which values reduced to 6.45 kgf/mm² with a 50 % elongation after 58 hours. At 400 °C, the 3.95 kgf/mm² strength shown after 6 hours dropped down to 2.35 kgf/mm² after 178 hrs. The transition to a melted condition is accompanied by a nearly three-fold increase in the electric resistivity of both Al and Ag (from 8.65x10⁻⁶ to 25.1x10⁻⁶ Ohm·cm in the case of Ag). Aluminium is characterized by an extremely high energy of compound formation with oxygen, sulphur and carbon (specifically, 1672 kJ/mol, whereas the figures for silver and copper are 30.5 kJ/mol and 167 kJ/mol, respectively). The aluminium-oxygen interaction results in the Al₂O₃ oxide, or alumina which is a stable chemical compound. The corresponding exothermal reaction may occur in accordance with the two equations given below⁴. As follows from the calculation, the oxidation reaction, $2Al + 1,5O_2 = Al_2O_3$, should liberate 33.4 kJ of thermal energy resulting from a complete combustion of 1 g Ag. However, this reaction requires 0.672 litre of oxygen per 1 g, while the closed cartridge of a semiconductor fuse, e.g. ПП-60, contains about 0.005 l of oxygen, or 0.7 % of the necessary amount. This quantity is definitely insufficient for supporting the reaction and liberating the heat. In open air, there is enough oxygen to maintain the oxidation reaction but analysis of the literature data on electrically exploded aluminium wires shows no effects of the exothermal reaction. The alloying reaction of aluminium with quartz sand, governed by the equation



should be associated, in accordance with the Hess rule, with the release of 33.4 kJ per 1 g of reacting Al independently of intermediate stages. However, the exothermal oxidation reaction is accompanied by an endothermal reaction, namely reduction of silicon from silica, SiO₂. It consumes 27.6 kJ of thermal energy per 1 g of the reacting aluminium. Hence, 1 g of completely burned aluminium theoretically is able to release 5.8 kJ of extra thermal energy, which is about 25 % of the arc energy. This extra energy has not been revealed in our special experiments which will be described in more detail below. According to paper⁵, the interaction of an aluminium element with a chemically active medium containing hydrogen peroxide in a relatively high concentration had but a "modest" effect on the fuse performance. Nor have we found in our investigations a noticeable chemical impact of the colloidal silica suspension, N₂O · n · SiO₂ · H₂O (plus heating), on the performance of aluminium elements. Thus, despite the high reactivity of Al it is stable against many chemical reagents, owing to the oxide film on its surface. Therefore, the rate of corrosion of aluminium decreases with time in a majority of media. On a freshly worked surface the oxide film becomes 10⁻⁹ m thick after about 10⁻⁵ sec. As a result of 20 years of corrosion tests in air, it has been found that the major part of corrosive destruction of Al, with a 40 % loss of strength, occurs over the first year⁶. Voytovich and Golovko⁷ investigated high temperature oxidation of aluminium in air under isothermal conditions, using thermometry and mass measurements, with continuous 8-hour monitoring of the specimen mass. At temperatures close to the melting point the increase in the oxide mass per unit area of the material surface was very low, specifically (0.1 to 0.3) mg/cm², which is evidence for its high resistance to corrosion. Whereas the loss in the mass of silver specimens resulting from corrosion in air is (0.01-0.3) mg/cm²hr, depending on the resistance group of Ag¹.

Experimental results. Long-term thermal performance. Laboratory experiments and

trial operation have shown that aluminium fuse elements of geometry identical with silver elements and thickness greater by a factor of 1.8 or 1.9 allow producing a quick-breaking fuse with practically the same thermal parameters as those of the prototype with silver elements, provided the aluminium terminals are 2.0 to 2.5 times thicker than copper terminals, in order to compensate for the lower electric conductivity of Al . E.g., the fuses for $U_{rate} = 660$ V and $I_{rate} = 400$ A with silver elements $\Delta = 0.1$ mm and aluminium elements $\Delta = 0.18$ mm, and terminals of either copper ($\Delta = 4$ mm) or Al ($\Delta = 10$ mm) have shown practically the same values of $R = (210 - 215) \times 10^{-6} \Omega m$, temperature rise of the terminals (82 to 87 °C) and power loss (52 to 57 W). Disc-shaped fuses with two-side water cooling (water consumption 3.5 to 4.5 litre/min at $T = 30$ °C), aluminium elements $\Delta = 0.3$ mm, 10 mm thick aluminium terminals and aluminium current-carrying parts ($U_{rate} = 380$ V and $I_{rate} = 1600$ A) have shown the same values of basic parameters as fuses with Ag elements, i.e. $R = (45-55) \times 10^{-6} \Omega m$, power loss (160-170) W and temperature rise below 85 °C under natural cooling. The pressure force against the converter wires was 60 kN. Thus, in the nominal operation duty the temperature of constricted parts does not exceed 300 °C and the oxide film grows by a few angströms which leads to a (0.1-0.2) % increase in the resistance. This results in a high stability of losses both in the elements and terminals and integrity of the contact. Using a hard filler improved the thermal characteristics in both cases by nearly 10 %. With the use of water cooling, the thermal parameter of temperature rise at the terminals becomes meaningless. The parameter of principal importance remains the voltage drop. In a reasonably designed fuse, this latter should be 1.4 to 1.5 times as great as the initial value, i.e. the product of the fuse resistance by the current.

Calculations of the current density and temperature fields in Al and Ag elements show practically coincident patterns for the above listed thicknesses of aluminium parts.

Duties with cyclic and arbitrarily repeated loads and overloads. The tests were performed for various duties with repeated loads described in more detail in paper¹¹. Fuses with planar elements made of aluminium (rated current 400 A at 660 V) loaded by the nominal current with 18 min on and off periods failed after 89 to 127 cycles. Fuses with planar elements made of silver withstood over 200 loading cycles. To attain a similar withstandability with Al fuses, the rated current had to be reduced by 12 to 15 %. In the case of ageing by a rated current (8 hours under a sinusoidal current and a 16 hour pause) fuses with elements failed after 31 or 33 cycles. With other patterns of current loading the level of withstandability shown by fuses with planar Ag elements again could be attained by Al fuses if the rated current were reduced by 12 to 18 %. Comparative tests of fuses with bended Al and Ag elements have shown that equal levels of cycling withstandability can be attained by fuses with aluminium elements if their rated currents are reduced by 10 %, or even 5 % if a hard filler is employed. Similar regularities have been established for transient overload duties, like for instance interruption by a circuit breaker of an emergency regime in a converter. The total number of such uncontrolled overloads (up to $(6-10) I_{rate}$) lasting for ≤ 0.2 sec can reach $20-25$ over the fuse lifetime. In our experiments that involved interruption of a d.c. circuit with a superquick circuit breaker the current through fuses reached the level of $10 I_{rate}$ in 3 msec and then dropped down to zero in another 3 msec. The fuse withstood 15 such pulses (one in every 10 or 20 minutes) without changing its resistance.

As is known⁸, the fracture mechanics has not yet developed, because of the complexity of the physics involved, an adequate theory of metal fatigue that could predict specimen durability, i.e. the dynamics of crack growth as a function of the number of load cycles. The development of a theory of fatigue failure in constricted portions of fuses subjected to cyclic loads is even more complex as the phenomenon involves a

variety of interdependent electrical, thermal and mechanical effects. The formulation and analysis of nonlinear coupled field-theoretic problems that could lead to a living theory, face conceptual difficulties. A theory like that should provide a qualitative and quantitative description of both stages of fatigue failure in constrictions, i.e. i) changes in the metal structure leading to crack formation, and ii) growth of the crack, ending in a fracture of the constricted part. It should be noted that development of a theory relating the fuse longevity to its design parameters, number of loading cycles and load characteristics (such as intensity and waveform of the current, duration of the on-current and currentless periods, etc.) is complicated by the pronounced effect of manufacture technology, sequence of various stages, etc. that are virtually unaccountable for. On the other hand, the present amount of practical expertise is sufficient for designing durable quick-breaking fuses, including those with aluminium current-carrying parts, that combine optimized geometries of the bended fuse element, employment of a hard filler and a reasonable choice of the rated current density through constricted portions. In our experiments, laboratory prototypes with Al elements withstood 100000 loading cycles (each cycle consisted of 15 sec of a $2 I_{rate}$ current flow and a 45 sec currentless pause) applied for 8 to 9 hours daily during one year. At the end of these tests, the fuse resistance remained practically unchanged.

Fault current interruption. The higher cathode voltage drop, characteristic of arcing between aluminium electrodes (16.2 to 18.6 V) as compared with silver electrodes (12.1 to 13.6 V), facilitates arc extinguishing in protection fuses with aluminium elements. Moreover, the oxide film favours inertial storage and further explosive dissipation of energy, thus ensuring excellent switching capabilities of Al elements. The rate of voltage growth during fusion of the constricted portions can be as high as 10^6 V/sec. Special features revealed in the experiments are as follows.

A.c. interruption. Fuses with Al elements

have demonstrated the capability to reliably interrupt currents ranging from $3 I_{rate}$ to $(300+400) I_{rate}$. No effect of the exothermal reaction that could be expected from theoretical considerations has been revealed either in oscillograms or in the condition of sand fulgurites. Moreover, the highest values of let-through currents and Joule integrals were practically the same for Al -based fuses and their Ag prototypes. This conclusion is in agreement with the results of Japanese writers (Ueda et al.) who have found that in a fuse with Ag elements arcing occurs in the atmosphere of an evaporated filler. The claimed independence of arcing of the element Ag material thus is true for Al too.

The arc energy shows no pronounced maximum as a function of the circuit current. In a wide range of available currents ($(10-100) I_{rate}$) the arc energy for $\Psi = 0^\circ$ did not deviate from its maximum value by more than 10 %. Of great importance is the knowledge of conditions when the let-through current is maximal. The maximum current is observed under interruption conditions with $\Psi = 53-57^\circ$, which is also close to the arc energy maximum.

An objective characteristic of the fuse performance at the arc extinguishing stage is provided by the ratio of the total $\int i^2 dt$ integral to its prearcing value. This ratio can be used to obtain fairly accurate quality estimates of different fuses, including those for different current and voltage ratings. By connecting two or more fuses in parallel their reliability can be greatly increased, and all protective qualities generally improved, especially at high current values. During transient prearcing operation, Al -based fuses show special points and zones of performance characteristics similar to those described in paper⁹ for Ag .

Silver and aluminium actually show close values of another theoretically important parameter, namely the adiabatic pressure produced during adiabatic heating and melting of constrictions under the condition that the volume of the gaseous phase should be the same as of the constriction material (the values are 160×10^8 and

155×10^8 Pa for Ag and Al, respectively). This pressure is calculated from the familiar Mendeleev-Klapeyron equation. In fact, a pressure as high as this, conditioned by the fact that the gas volume under normal conditions would be tens of thousands times greater than that of the melted metal, never exists in protection fuses. Indeed, the filler sand is a non-Newtonian liquid, hence the pressure wave arriving at the cartridge walls is weakened and never exceeds 10^6 Pa, irrespective of the fuse element material. Meanwhile, electrical explosion of an Al wire in water which is a classic Newtonian liquid is accompanied by a pressure pulse up to 10^9 Pa with a temperature about 4×10^4 K⁵. The corresponding electric field strength reaches 15 kV/cm, which value is one order of magnitude higher than in the case of sand.

D.c. interruption. Tests have shown that fuses with Al elements can interrupt quite easily currents as high as $(200 \sim 400) I_{rate}$, even with rather great values of τ like $\tau = 35$ msec. Similar as in the a.c. case, effects of an exothermal reaction are not detected. Moreover, the peak voltage can be increased by another 8 or 12 %. The problems that exist relate to the interruption of low currents $(6 \sim 10) I_{rate}$ with $\tau = 35$ msec or more. The difficulties are characteristic of all quick-breaking fuses, independently of the fuse element material. They are associated with the reactive energy stored in the circuit inductance, which component may reach 75 % of the total arc energy¹⁰. The physics of interrupting low currents has been investigated for fuse elements of various lengths, with the highest admissible voltage at which the circuit can be reliably interrupted fixed for each length. Besides, the authors have discovered a special feature in the process of interrupting low currents with great τ by Al-based protection fuses. It consists of the restriking effect, when the current through the fuse starts to increase some 40 or 100 msec after it has dropped down to zero. The energy dissipated in the fuse before occurrence of the effect happens to

be 20 to 40 % lower than in the a.c. case, which manifested itself through a shorter length of the sand fulgurite. Reliable interruption could be achieved by reducing the length of Al fuse elements by 12 to 20 % or reducing the circuit voltage (or time constant) by the same fraction. The interruption of low and medium currents in circuits with high time constants, $\tau = 35$ to 70 msec, was accompanied by nonuniform burn-out of the fuse elements. While some of the elements were burnt nearly completely, others retained about one half of their metal and still others were damaged near constricted portions only. On some occasions, just a single element burnt completely brought about piercing of the end cap independently of the element material.

REFERENCES

- [1] V.V. Malyshev and D.V. Rumyantsev. Silver, 1987, "Metallurgiya" Publ. Co., Moscow (in Russian).
- [2] G. Tornbitz. Optimierung des Edelmetall. Einsatzes bei Schaltern und Schaltgeräten, 1981, Electr. Anz., vol. 34, No. 14, 25-29.
- [3] J.G. Leach. New application flexibility for medium voltage current-limiting fuses, 1985, IEEE Transactions on Industr. Applications, vol. , No 4, 1075-1080.
- [4] T. Lipski. Bezpieczniki nizkonapie- rowe, 1969, Warszawa, 299 p.
- [5] R.E. Runovsky. Fuse opening switches for pulse power applications: Open switches, 1987, 209-232.
- [6] Corrosion (A Reference Book). Russian Translation of the English Edition, 1981, "Metallurgiya" Publ. Co., Moscow.
- [7] R.F. Voytovich and E.I. Golovko. High temperature oxidation of metals and alloys, 1980, "Naukova Dumka" Publ. Co., Kiev, (in Russian).
- [8] David Broek. Elementary Engineering: Fracture Mechanics, 1980, Noordhoff Int'l Publishing Co., Leyden (Russian Translation: "Vysshaya Shkola", Moscow, 368 p.).

- [9] K.K. Namitokov, N.A. Ilyina, and I.G. Shklovsky. A finite element analysis of the thermal behaviour of notched fuse elements in semiconductor fuses, 1989, Sixth Int'l Conference on Switching Arc Phenomena, 12-15 September, Lodz, Poland, 212-217.
- [10] K.K. Namitokov, N.A. Ilyina, and I.G. Shklovsky. Protection of semiconductor devices. 1988, Energoatomizdat, Moscow.
- [11] K.K. Namitokov, N.A. Ilyina, and I.G. Shklovsky. Pulse withstandability of semiconductor protection fuses, 1989, Six Int'l Conference on Switching Arc Phenomenon, 12-15 September, Conference Materials, 205-211, Lodz, Poland.