PRINCIPAL MANUFACTURE TECHNOLOGIES FOR SEMICONDUCTOR FUSES

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Problem formulation. The basic technical and cost parameters of semiconductor fuses are largely determined by the technology employed to produce the hard filler. The traditional methods[1], in particular those involving thermal hardening of a binder-impregnated filler present certain difficulties as they require complex equipment and happen to be power consuming (over 10 kW.hr per unit). Besides, the technological procedures last for a long time (10 to 15 hr) and often result in fracturing of the fuse terminal coating in the furnace. The present writers have suggested a new technology[2] in which the filler is baked through heating of the current-carrying fuse pieces with electric current. In this approach, many of the technical problems are removed. Currently the method is subjected to practical tests and theoretic analysis in view of the its potential advantages.

Experimental set-up. The set-up involves an insulated base capable of accomodating as many as 10 ПП 60М fuses (rated current and voltage values are 630 A and 660 V); buses of variable length and cross-section area (40 to 300 mm and 30 to 400 mm^2, respectively) used to seriesly connect the fuses, and an adjustable power supply to produce currents up to 30 kA at 4 V. The ПП 60М fuse is shown in Fig. 1. It consists of an ultraporcelain cartridge 1 containing bended fuse elements 2 made of copper that are welded to copper terminals 3. Cover caps 4 are at the top and bottom; the filler is charged through the opening 5 in the top end cap 4, which is shut by the lid 6. The drain opening in the bottom end cap 4 is screened with the gauze 7 adjacent to which is the outlet tube 8 to release products of the baking process. The fuse is fixed to the buses with terminals 3. It is filled with quartz sand and impregnated with a 30 % colloidal silica suspension in water.

Phenomenology of the hardening process; experimental results for standard parameters. For practical purposes, of interest would be analysis of the processes in an installation with standard parameters typical of industrial applications, e.g. rated current density through the fuse about 550 A/mm^2 in constricted parts, and conducting buses of length 175 mm and cross-section area 180 mm^2. The Joule heat released in fuse elements and terminals supports a variety of complex thermodynamical processes in the dense sand/binder mixture. Following Barrow and Howe[3], we assume chemical reactions to be absent or, at least, to have no important effect on the process, provided they are characterized neither by heat release or absorption, nor influence on the mass transfer in the liquid or vapour-gas phase. The preheating stage represents an increase to the boiling point in the temperature of the liquid component directly adjacent to the current-carrying parts. At this stage, no products are released through the drain opening, gauze screen or the outlet pipe. Objective external manifestations of this stage are a noticeably greater voltage drop across the fuse and a weakly increased temperature of the cartridge and terminals. The end to this stage is marked by the first liquid drop released from the drain opening. This occurs some 5 or 11 minutes after the onset of the process. The temperature of the first drop is close to the ambient temperature (i.e. 30 to 40 °C). At the following stage the liquid component is partially evaporized and the vapour expands to force part of the liquid through the pipe. During this stage which last for 13 to 19 minutes, the products are released mainly in the liquid phase, with the temperature and flow rate progressively increasing (Fig. 2). The hot liquid forced out by the vapour carries away various contaminants, thus performing "steam cleaning" of the filler. As a result, the fuse insulation resistance increases (to tens megohms after the breakdown current has been switched off). Of the 52 to 61 grams of

colloidal silica suspension introduced into the sand, it is hardly 15 grams that are released out of the fuse as a liquid. A stage close to the final is that of nucleate boiling. Under the action of overheated vapour (about 200 °C), individual bubbles appear first, at the end of the pipe, and later become a continuous flow of white steam of characteristic odour and growing temperature. Most of the product (up to 30 grams in mass) are released from the fuse during the stage, in the form of the gas-vapour mixture described. The stage does not last for more than 15 minutes. By the end of the stage, the outflow of the white steam becomes less intense and the vapour turns colourless. The stage of invisible vapour release is the longest among all (lasting for 40 to 50 min) and can be detected, e.g. with a sweating mirror. It is characterized by a rather quick increase in the temperature of all parts of the fuse and an increased voltage drop. An important practical criterion for the completion of the hardening process is cessation of the colourless vapour flow from the structure. The absolute criterion is provided by evaluation of the fuse mass. If the mass at the end of the hardening process is 0 to 2 g greater than before introduction of the colloidal silica, then the result may be considered excellent. With a 2 to 5 g mass increase the result is good, while with 5 to 11 g it is merely satisfactory. The complete cessation of the steam outflow and the nearly zero value of the mass increase speak in favour of the hypothesis suggesting a predominant role of heat and mass transfer effects without noticeable chemical transformations. With regard to performance characteristics, the quality of baking is estimated from the magnitudes of the Joule integral and the arc energy. The technology described does not have a destructive effect on the temperature sensitive parts of the fuse like constrictions or welding points, nor does it affect the fuse resistance. If the 10 fuses placeable on the base are baked simultaneously, then process stages in each piece are shifted in time with respect to other specimens (within a few minutes), so that they should not interface.

Effects of different factors. The character of the hardening process is largely determined by two basic parameters which are the current density in the fuse elements and the bus geometry (i.e. cross-section area and length). With a proper allowance for the electric conductivity magnitude, the kind of the material the current carrying parts are made of is of no importance. By increasing the current density by 4 to 11 % against the rated value, the baking process can be greatly intensified (the total duration reduces by nearly 20 %), while all the stages mentioned remain. Further increase in the density of current through the fuse elements is not advisable for reliability reasons, while lower densities are impractical. The cross-section area and length of the conducting buses fully determine the course of the hardening process near the cartridge ends and have an important effect on the areas adjacent to the fuse elements. The effect of variations in the bus length within 40 to 300 mm is equivalent to changes of the cross-section area. For the sake of designer's convenience, we have selected buses of 170 mm in length for the experiments described, while the cross-section area could be varied from 30 to 400 mm^2. With 30 mm^2, the process of filler hardening was characterized by extreme intensity. The outgoing products appeared in the gas-vapour phase alone, although the outflow started with a noticeable delay (about 2 min). Note that the process developed within 30 minutes, which was 2 or 3 times quicker than for rated parameter values, and with excellent quality at that. (The excess mass was practically zero.) However, the copper buses showed heavy blackening and proved unfit for further use, while the fuse element constrictions and welding points remained in a good condition. In the case of the largest cross-section area, 400 mm^2, the general pattern, as described for the rated parameter values, remained but the process lasted as long as 5 hours. The quantitative characteristics were sizably lower and the filler in the cartridge end portions did not solidify at all. Thus, buses of small cross-section area in fact play the part of a

heater, whereas larger buses act as a radiator.

Prior heating of the buses, e.g. owing to the preceding technological process, is of no special importance because of the quick cooling of the set-up (e.g., the temperature of buses drops from 110 to 35 °C over 4 minutes). Yet in some cases, the time necessary for the liquid component to appear in the outlet pipe reduced by 2 or 3 minutes. It seems noteworthy that the time interval between introduction of a binder in the filler and the beginning of the hot hardening process virtually has no effect either on the process or the condition of the (copper) fuse element, at least for times within 100 hours. On the other hand, decreasing the current value in the course of the process, even for a relatively short time, has a negative effect on the quality of baking. This is even more true for a fully halted baking process with a completely cooled set-up. The quality can be restored only by repeating the baking procedure all over again, even many months after the initial process. As a special aspect of investigations, the quartz sand-colloidal silica mixture in the cartridge in some experiments was blown through with air, prior to the baking procedure, the air being compressed to $(0.35 \div 0.45) \times 10^5$ Pa. Of the 52 to 61 g of the silica suspension introduced, about 22 to 31 g leave the cartridge through the drain opening during the initial 1 or 2 minutes of the blow-through. Further blowing, even during lengthy periods of time (10 to 18 minutes), of an air either at ambient temperature or at 120 to 150 °C, does not remove more of the suspension from the fuse cartridge. At other stages of the filler hardening process, the products are released practically in the gas-vapour phase alone, i.e. air blowing has suppressed the stage of liquid product release, thus reducing duration of the process by 30 or 40 %, with the high quality of the hard filler retained. By prolonging the procedure, a zero mass increment is guaranteed, however characteristics of the filler are not changed.

Temperature field measurements in the filler and the fuse element performed in the course of the process have allowed determining the effective thermal conductivity λ_e [4]. If combined with the solution of the direct heat conduction problem, e.g. by the iterative technique [6], this knowledge enables evaluating the effective heat capacity c_e of the filler. To that end, the calculated temperature field T_{calc} resulting from successive refinements of the input data was compared with the measured values T_{meas}. The value of c_e was chosen from the condition

$$|T_{calc}(x,y,z,t) - T_{meas}(x,y,z,t)| \leq \delta_0$$

where δ_0 is the limiting value of the mismatch which determines the solution accuracy. In the course of filler hardening, λ_e and c_e changed with time between 1.3 and 3.2 W/m deg, and 1.5 and 4.2 J/g deg, respectively, following rather complex laws. The values of λ_e and c_e obtained were employed to improve the mathematical model described below.

An attempt of theoretical description.

Problem formulation and basic equations.

We will analyze the physical processes in a fuse volume representing a cylindrical sector filled with a sand-liquid mixture. All the boundary surfaces, except the drain opening aperture, are assumed to be impenetrable, according to the symmetry conditions. The filler is heated by the fuse element whose thermal condition in the current carrying state is described by

$$\frac{\partial^2 T}{\partial R^2} + \frac{1}{R}\frac{\partial T_1}{\partial R} + \frac{1}{R}\frac{\partial^2 T}{\partial Z^2} + \omega(R,\theta,z) = \frac{c_1 \gamma_1}{\lambda_1}\frac{\partial T_1}{\partial z} \quad (1)$$

where T_1, c_1, γ_1 and λ_1 are the temperature, heat capacity, mass density and thermal conductivity of the fuse material, respectively. This equation is valid only for the fuse element of thickness δ in the domain specified by the equations $R_1 + \delta > R > R_1$; $\theta_0 > \theta > 0$ and $H > z > 0$, where R_1 is the radial location of the elements; θ is the angle at the vertex of the sector considered, and H the sector height. The equation for the filler adjacent to the fuse elements from its both sides is

$$\frac{\partial^2 T_2}{\partial R^2}+\frac{1}{R}\frac{\partial T_2}{\partial R}+\frac{1}{R^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T_2}{\partial z^2}=\frac{C_2\gamma_2}{\lambda_2}\frac{\partial^2 T}{\partial \tau}\quad (2)$$

$R_1>R>0;\ \theta_0>\theta>0$ and $H>z>0$

where T_2, C_2, γ_2 and λ_2 are, respectively, the temperature, heat capacity, mass density and thermal conductivity of the filler. The boundary conditions are

$$\left.\frac{\partial T_i}{\partial z}\right|_{\substack{z=0\\ z=H}}=K_i(T_i-T_{amb});\quad \lambda_1\frac{\partial T_1}{\partial R}=\lambda_2\frac{\partial T_2}{\partial R}\Bigg|_{\substack{R=R_1\\ \theta_0>\theta>0\\ H>z>0}}\quad (3)$$

$$\left.\frac{\partial T_j}{\partial R}\right|_{\substack{R=R_3\\ \theta_0>\theta>0\\ H>z>0}}=K_j\left(T_j-T_{amb}\right);$$

$$\left.\frac{\partial T_i}{\partial \theta}\right|_{\substack{R_1>R>0\\ H>z>0\\ \theta=\theta^0}}=0;\qquad \lambda_1\frac{\partial T_1}{\partial R}=\lambda_2\frac{\partial T_3}{\partial R}\Bigg|_{\substack{R=R_1+\delta''\\ \theta_0>\theta>0\\ H>z>0}}$$

As a result of heating, the temperature of some filler areas can reach the boiling point for the liquid component, hence the heating is accompanied by phase transitions. In such areas, the temperature field is described by the differential equation

$$\frac{\partial^2 T_i}{\partial R_2}+\frac{1}{R}\frac{\partial T_i}{\partial R}+\frac{1}{R^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T_i}{\partial z^2}-\frac{2\gamma'}{\lambda_2\delta\tau}=\frac{C_2\gamma_2}{\lambda_2}\frac{\partial T_i}{\partial \tau}\quad (4)$$

where γ is the specific heat of vaporization and γ' the mass density of the liquid component. Boiling of the liquid is accompanied by an increase in pressure, hence the liquid is forced through the drain opening. The law followed by the varying pressure can be found from the material balance and energy balance equations and the equation of state. The material balance equation takes the form

$$M'-M''=\frac{\partial}{\partial \tau}\left(v'\gamma'+v''\gamma''\right),\quad (5)$$

where M' is the liquid mass arriving to an elemental volume, M'' the mass of the vapour released, v' and v'' are the liquid volume and that of the vapour, respectively, and γ' and γ'' the liquid and vapour mass densities. The energy balance equation is

$$M'i'-M''i''+Q=\frac{d}{d\tau}\left(v'\gamma'i'+v''\gamma''i''+Gc_sT_s\right)\quad (6)$$

where i' is the liquid enthalpy, i'' that of the vapour; $M'i'$ is the amount of heat arriving to the elemental volume with the liquid and $M''i''$ the amount of heat leaving the volume with the vapour; Q is the amount of heat transferred to the elemental volume either from neighbouring elemental volumes of the medium or from the fuse element; G the sand mass in the elemental volume; c_s the specific heat capacity of the sand and T_s the sand temperature. The saturated vapour density and that of the boiling liquid both vary with pressure, therefore the equation of state is broken up in a series of equations like

$$\gamma'=\gamma'(P);\ \gamma''=\gamma''(P);\ i'=i(P')\quad \text{, etc.}\quad (7)$$

As follows from geometrical considerations, the total volume of the vapour and the liquid component should be equal to v both under static and dynamic conditions; i.e. $v=v'+v''$, where v is the constant value of the elemental volume. This implies that time derivatives of v' and v'' should be equal (apart from the sign). At this stage we can linearize the equation set (4-6), assuming for simplicity's sake that $M'=M''=0$. The latter condition implies that no liquid arrives to a boiling elemental volume from adjacent volumes, nor does it release vapour outwards. With allowance for the above mentioned equality of the time derivatives, we have

$$\left(v_0'\frac{d\gamma'}{dP}+v_0''\frac{d\gamma'}{dP}\right)\frac{d\Delta P}{d\tau}+(\gamma'-\gamma'')\frac{d\Delta v'}{d\tau}=0\quad (8)$$

In fact, this is an incremental form of equation (5), with v_0' and v_0'' denoting initial volumes. The energy balance equation becomes

$$dQ=\left(v_0'\frac{d\gamma'}{dP}i'+v_0''\frac{d\gamma''}{dP}i\right)\frac{d\Delta P}{d\tau}+\left(\gamma'i'-\gamma''i''\right)\frac{d\Delta v'}{d\tau}+Gc_s\frac{d\Delta T_s}{d\tau}\quad (9)$$

which form takes into account that $M'=M''=0$. Equation (9) implies that the heat arriving to the volume is spent to change the heat content of the sand, water and water vapour. To analyze equations (8) and (9), we substitute t' instead of T_s. These are equal values as the temperature of sand follows that of the liquid, and $dT_s/d\tau=d\Delta t'/d\tau$. Combining equation (7) with the solution of (8) and (9), we arrive at

$$\frac{d\Delta P}{d\tau}=\frac{\Delta Q}{\Phi}\rightarrow d\Delta P=\frac{\Delta Q}{\Phi}d\tau;\ \Phi=\Phi_1+\Phi_2+\Phi_3 \qquad (10)$$

with $$\Phi_1=v_0\left(\frac{\gamma''_2}{\gamma'-\gamma''}\frac{d\gamma'}{dP}+\gamma'\frac{di'}{dP}\right)$$

$$\Phi_2=v''_0\left(\frac{\gamma'_2}{\gamma'-\gamma''}\frac{d\gamma''}{dP}+\gamma''\frac{di''}{dP}\right)$$

and $$\Phi_3=Gc_s\frac{dt}{dP}$$

The relations derived permit determining the pressure whose increase shifts the boiling front, as well as the rate of liquid and vapour flow through the drain opening.

The temperature field and volume variations of the filler where liquid filtering occurs under the action of high-pressure vapour can be analysed with several simplifying assumptions. First, we shall assume that the porous medium obeys Darcy's law. Second, the viscous and the inertial term in the equation of motion will be neglected in view of the low values of Darcy's and Reynolds numbers. With these assumptions, the equation of mass, momentum and energy conservation in a non-stationary three-dimensional flow through an isotropic porous medium takes the form

$$\frac{\partial P}{\partial\tau}+\frac{\partial(RW_R)}{\partial R}+\frac{1}{R}\frac{\partial W_\theta}{\partial\theta}+\frac{\partial W_z}{\partial z}=0. \qquad (11)$$

Actual boundary conditions are

$$\frac{1}{R}\frac{\partial(RP)}{\partial R}+\frac{\mu}{K}W_R=0;\quad \frac{1}{R}\frac{\partial P}{\partial\theta}+\frac{\mu}{K}W_\theta=0 \qquad (12)$$

and $$\frac{\partial P}{\partial z}+P_g+\frac{\mu}{K}W_z=0.$$

These equations govern liquid flow through the porous medium, representing in fact the equation of filtration, with W_i denoting the velocity of motion in the i-th direction; μ the liquid viscosity; K — the penetrability of the porous medium, and g the gravity forces acceleration. The thermal flux diffusion equation is

$$W_R\frac{1}{R}\frac{\partial R(RT_i)}{\partial R}+W_\theta\frac{1}{R}\frac{\partial T_i}{\partial\theta}+W_z\frac{\partial T_i}{\partial z}=$$

$$=\frac{\partial^2T_i}{\partial R^2}+\frac{1}{R}\frac{\partial T_i}{\partial R}+\frac{1}{R^2}\frac{\partial^2T_i}{\partial\theta^2}+\frac{\partial^2T_i}{\partial z^2}-\frac{c_2\gamma_2}{\lambda}\frac{\partial T_i}{\partial\tau}=0 \qquad (13)$$

with the boundary conditions of equation (3). Equation (13) describes the thermal state of such elemental volumes that have not yet reached the boiling point, however accepts the liquid carrying heat away and forced through the volume. The three terms in the left-hand side describe the heat carried out by water along the directions R, θ and z, respectively. Equations (2), (4), (12) and (13) with the boundary conditions (3) and (12) were solved in the mathematical simulation technique with the aid of an R-network processor. The calculation error was within 7 to 13 %.

Test results for the fuses manufactured in the technology described. The fuses ПП 60М were developed for diode converters of electric railway locomotives. Therefore, the conditions of primary importance that dictated the choice of a hard filler were prevention of filler leakage during operation and strict maintenance of a fixed packing density through the fuse lifetime. Besides, the method has proven to be highly efficient for cyclic loading duties (the 60М fuses have withstood 200 thousand current pulses in 2 years). Technical details are described in[5]. Here we will rather dwell on the effect of technological parameters on the performance in the fault current interruption regime. The fuses were subjected to tests of two kinds. Specimens with a normal degree of filler compaction (5 types) were tested for easy circuit breaking conditions, i.e. a voltage of 730 V and effective current of 11 kA. The filler types were:

a) standard granular filler without a binding agent; b) granular filler with 52 g of a binder introduced during 1 min under a pressure of 0.35 atm; c) binder-impregnated filler blown through during 1 min at 0.35 atm. After the blown-down the specimens contained 25 g of the binder; d) binder-impregnated filler subjected to a 1 min blow-down at 0.35 m and drying. The specimens contained 3.8 or 10 g of the binder; e) binder-impregnated filler that was not blown-through but subjected to drying. The specimens contained 3.8 or 10 g of the binder.

All of these fuses have shown practically identical performance characteristics, specifically I_o =14÷15 kA, t_o=9÷10 ms and W_{break}=(600 to 700)x10^3 A^2 sec. Type b) specimens released 25 g of the binder suspension, forced through the gauze under the arc

pressure at the switch-off.
Heavy duty tests (730 V, 150 kA effective, cos φ =0.1 and $\Psi_{sw\ on}$=52 to 62°) were performed for specimens of two groups. The first group (normal degree of filler compaction) comprised fuses of three types, namely a) with a standard granular filler; b) with a binder-impregnated filler subjected to drying. The residual binder content is up to 5 g; and c) with a binder-impregnated and dried filler of a 15 to 19 g residual binder content. The peak current magnitudes fed through this group of fuses and total Joule integrals were 32 to 35; 27 to 28 and 38 to 41 kA, and 1.5×10^6; 0.85×10^6 and 2.9×10^6 A^2.sec for the three types, respectively. The second group (loosely packed filler) involved fuses of two types, namely a) with a standard granular filler and b) with a binder-impregnated and dried filler of residual binder content below 3 g. The peak currents and let-through Joule integrals were, respectively, 42.2 and 28.5 kA, and (2.4 to 3.2)$\times 10^6$ and (1.6 to 1.7)$\times 10^6$ A^2.sec. Type a) specimens showed end cap spiking and arc bursts.
Conclusions. The undoubtful advantages resulting from the new technology are
i) the high mechanical strength of the filler, plus longevity and structural and dielectric uniformity owing to "internal" heating and "steam cleaning";
ii) improved protection characteristics of the fuse (i.e. peak currents, arc energy and let-through $\int i^2 dt$ integral reduced by a factor of 1.5 or 2) with retained integrity of the terminal coating and good appearance;
iii) the high productivity and low costs of the technological process. A single manufacturing set-up for 10 fuses can provide up to 40 thousand fuses per year if operated in two shifts. The power consumed to bake 10 fuses is below 4 or 6 kW/hr. The laboratory breadboard installation (operated by a team including the present writers) has yielded over 3 thousand fuses.

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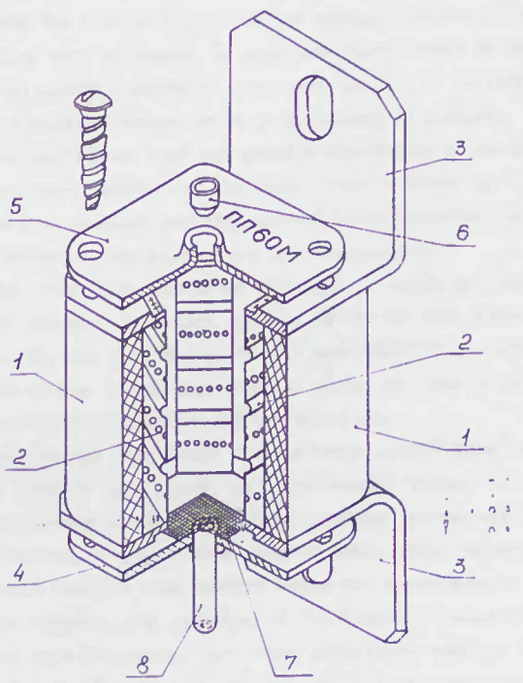

Fig. 1.

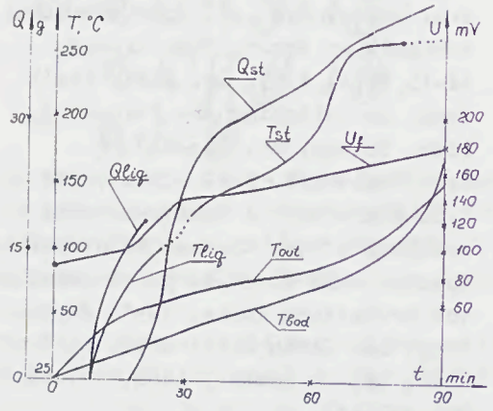
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Fig. 2