PHYSICAL MODEL OF AN INTEGRATING CONVERTER

V. I. Bodnaruk, V. T. Dimitrashchuk,
and M. A. Makedon

UDC 621.360

Results are presented of theoretical investigations of a thermal converter model in a nonstationary operating mode.

The measurement and study of single and rarely duplicated impulses are one of the urgent problems in science and engineering in recent times. Impulsive methods and schemes are utilized extensively in radar, telemetry, measuring and radiometer apparatus, in radio and electrical communications apparatus, in digital computers, automatic control and regulation units. Investigations in the area of semiconductor physics, electromagnetic fields of storms and static discharges, as well as of nuclear, seismic, ballistic, a number of biological, and contact electrical welding processes are quite frequently accompanied by single signals in practice. The extensive domain of utilization of single signals specifies the broad dynamic range of their representative electrical quantities. The voltage range of single pulses encountered in measurement practice is between units of microvolts and hundreds of kilovolts, and the range of durations between fractions of a nanosecond and several seconds [1-2].

Sensors of a thermoelectrical system, thermal converters of contactless vacuum units of the type TVB-1-9 [3], are used to record the integral parameters of single current pulses. However, the low sensitivity, small loverload capacity, high value of threshold sensitivity, large geometric dimensions of the mentioned thermal converters do not permit the solution of a number of important problems on the investigation of pulse processes. Existing integrator structures using metal thermocouples [4] are also barely suitable to measure single current pulses with high accuracy. Consequently, the investigation of the possibilities of producing thermoelectric integrating converters corresponding to modern requirements is urgent.

To clarify the characteristic properties and regularities, interconnection of the fundamental parameters and characteristics with the structure elements, we consider thermal processes proceeding in an integrating semiconductor converter (ISC) whose physical model is displayed in Fig. 1.

The ISC model is a spherical calorimetric body 1 at whose center is a point heater 2. The calorimetric body has contact with a thermal cell 3 whose cold junction is thermostated at the temperature of the environment (the housing 4). In contrast to known thermal converter models [5], the model under consideration contains a characteristic integration element, a calorimetric body. The heat liberated by the heater is absorbed completely by the calorimetric body.

The temperature regime of the calorimetric body is described by the heat conduction equation

$$c_0\rho\frac{\partial T}{\partial t}-\varkappa\frac{\partial^2 T}{\partial r^2}-\frac{2\varkappa}{r}\frac{\partial T}{\partial r}=W_0f(t). \tag{1}$$

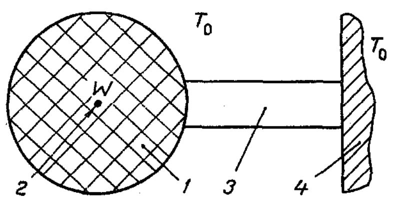

Fig. 1. Physical model of an integrating semiconductor thermal converter.

Chernovits State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 6, pp. 965-970, December, 1988. Original article submitted July 2, 1987.

 0022-0841/88/5506-1396$12.50

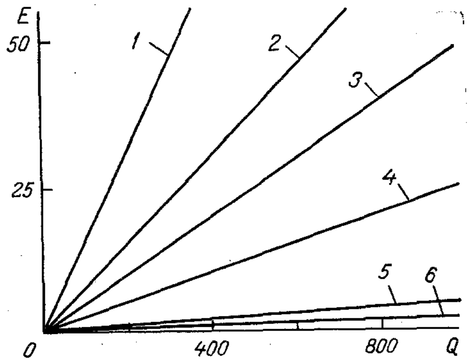

Fig. 2. Volt–joule characteristic with a silver calorimetric body of different dimensions for $\tau_0 = 10^{-7}$ sec: 1) $a = 0.5 \cdot 10^{-4}$ m, 2) $0.62 \cdot 10^{-4}$ m, 3) $0.78 \cdot 10^{-4}$ m, 4) $0.92 \cdot 10^{-4}$ m, 5) $1.3 \cdot 10^{-4}$ m, 6) $1.75 \cdot 10^{-4}$ m. E, mV; Q, μJ.

Under the assumption that the temperature of all points of the surface calorimetric body is identical and that the thermal flux through the thermal element is quasistationary and taking account of convective and radiation losses through the thermal element to the environment and the heat elimination through the thermal element (losses to the environment from the side surface of the thermal element are neglected), the initial and boundary conditions will have the form

$$T(r,\ t)_{t=0} = T_0,\quad T(r,\ t)_{r=0} \neq \infty,$$
$$\left[\varkappa \frac{\partial T}{\partial r} + \gamma (T - T_0) + 4\varepsilon\sigma_0 T^3 (T - T_0) + \frac{S_\text{т}}{4\pi a^2} \frac{\varkappa_\text{т}}{l_\text{т}} (T - T_0)\right]_{r=0} = 0. \tag{2}$$

In general form the solution of the system (1)-(2) is

$$\Theta(r,\ t) = \frac{W_0}{c_0\rho} \sum_{n=1}^{\infty} \frac{A_n a}{\mu_n r} \sin\left(\mu_n \frac{r}{a}\right) \int_0^t f(t) \exp\left[-\frac{\mu_n^2 (t-\tau)}{g_m a^2}\right] dt, \tag{3}$$

where

$$\Theta = T - T_0;\quad A_n = (-1)^{n+1} \frac{2\,\text{Bi}\sqrt{\mu_n^2 + (\text{Bi} - 1)^2}}{\mu_n^2 + \text{Bi}^2 - \text{Bi}};$$

μ_n are roots of the characteristic equation

$$\operatorname{tg} \mu_n = \frac{\mu_n}{1 - \text{Bi}};$$

$1/g_m = \kappa/(c_0\rho)$ is the thermal diffusivity of the calorimetric body material, $\text{Bi} = a\alpha_m$ is the Biot criterion [6],

$$\alpha_m = \frac{1}{\varkappa}\left(\gamma + 4\varepsilon\sigma_0 T_0^3 + \frac{S_\text{т}\varkappa_\text{т}}{4\pi a^2 l_\text{т}}\right).$$

As the heat liberation intensity changes at the heater by the exponential law $W = W_0 e^{-t/\tau_0}$ the solution of the system (1)-(2) for a single pulse is given by the expression

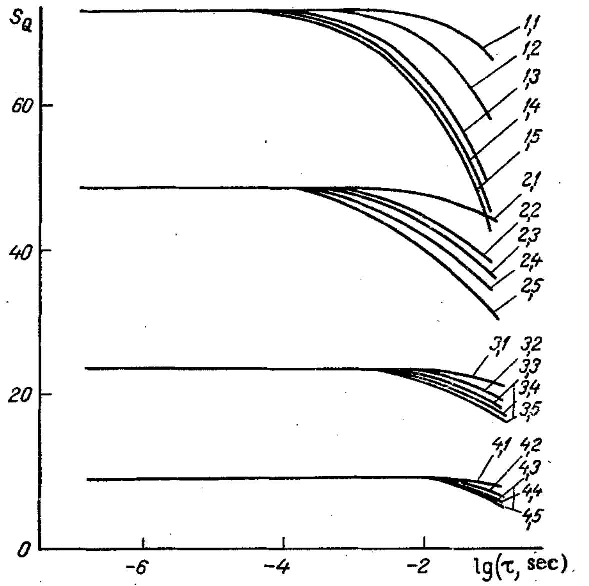

Fig. 3. Dependence of the volt–joule sensitivity of an ISC with a calorimetric body from different materials and sizes for Q = 100 μJ: 1.1) Bi, $a = 0.75 \cdot 10^{-4}$ m; 1.2) Li, $a = 1.5 \cdot 10^{-4}$ m; 1.3) Fe, $a = 0.55 \cdot 10^{-4}$ m; 1.4) Cu, $a = 0.61 \cdot 10^{-4}$ m; 1.5) Ag, $a = 0.62 \cdot 10^{-4}$ m; 2.1) Bi, $a = 0.84 \cdot 10^{-4}$ m; 2.2) Li, $a = 1.75 \cdot 10^{-4}$ m; 2.3) Ag, $a = 0.78 \cdot 10^{-4}$ m; 2.4) Cu, $a = 0.7 \cdot 10^{-4}$ m; 2.5) Fe, $a = 0.68 \cdot 10^{-4}$ m; 3.1) Bi, $a = 1 \cdot 10^{-4}$ m; 3.2) Li, $a = 2.12 \cdot 10^{-4}$ m; 3.3) Fe, $a = 0.73 \cdot 10^{-4}$ m; 3.4) Cu, $a = 0.82 \cdot 10^{-4}$ m; 3.5) Ag, $a = 0.92 \cdot 10^{-4}$ m; 4.1) Bi, $a = 1.56 \cdot 10^{-4}$ m; 4.2) Li, $a = 3 \cdot 10^{-4}$ m; 4.3) Fe, $a = 1 \cdot 10^{-4}$ m; 4.4) Cu, $a = 1.12 \cdot 10^{-4}$ m; 4.5) Ag, $a = 1.30 \cdot 10^{-4}$ m. S_Q, $V \cdot J^{-1}$.

$$\Theta(r, t) = \frac{3W_0\tau_0}{4\pi c_0\rho} \sum_{n=1}^{\infty} \frac{A_n}{r\mu_n} \sin\left(\mu_n \frac{r}{a}\right) \frac{\left[e^{-\frac{t}{\tau_0}} - e^{-\frac{\mu_n^2}{g_m a^2} t}\right]}{\frac{\mu_n \tau_0}{g_m} - a^2}. \tag{4}$$

Upon conservation of the ballistic mode ($\tau_0 \ll \tau_{0.63}$) the magnitude of the heat liberation in the calorimetric body is proportional to the maximal value of the temperature on its surface [7], while the thermal emf is in conformity with the Zeebeck law

$$E_{max} = \alpha Q_{max}. \tag{5}$$

It follows from an analysis of (5) that the properties of the model depend not only on the heat transmission, heat transfer, radiation, geometric size conditions of the thermal element but also on the thermophysical properties of the calorimetric body material; consequently, E_{max} is computed for different materials (aluminum, bismuth, iron, copper, silver) whose radius changes within the limits $(0.5\text{–}10) \cdot 10^{-4}$ m by using an electronic computer. The models were investigated in xenon, air, and a vacuum. A thermoelectric material based on the ternary compounds Bi_2Te_3 that possesses elevated resistance to thermal cycling and has high values of thermoelectric quality was used as thermocouple material. Selection of the materials and sizes of the calorimetric body and the thermal element was realized by starting from considerations of clarifying the characteristic properties of the model and the possibility of performing an experimental verification of them on real models.

Investigations of the model properties showed that the dependence of the thermal element on the energy is linear in a broad energy band for an identical duration of the acting pulse while the slope of the dependence E = f(Q) diminishes as the size of the calorimetric body increases (Fig. 2). The form of the dependence for other materials is analogous.

As is seen from Fig. 3, an increase in the duration τ_0 results in diminution of the volt–joule (henceforth sensitivity) sensitivity $S_Q = E_{max}/Q$. An especially sharp diminution in the sensitivity occurs for $\tau_0 > \tau_{0.63}$. Such a change in S_Q can be explained by the fact that a deviation from the ballistic mode occurs in this duration interval [7].

The range of durations in which the ballistic mode is conserved for identical calorimetric body dimensions can be expanded by logically selecting the material of the calorimetric body.

As follows from Figs. 2 and 3, the sensitivity of semiconductor ISC considerably exceeds the sensitivity of existing integrators (0.3-0.5 V/J) [4]. However, the relative deviation of the sensitivity from the maximum value in the range of durations δ is an important parameter for an unknown duration of the acting pulse. The value of δ diminishes as the size of the calorimetric body increases, but S_Q diminishes here.

For serially manufactured thermal converters of the TVB 1-9 type S_Q = 0.005-6.6 V/J and δ = 10-50% depending on the kind of TVB [3, 8]. For a ISC with a silver calorimetric body of radius $0.92 \cdot 10^{-4}$ m these quantities are 25 V/J and 24%, respectively; the geometric sizes of the ISC are here considerably smaller (not more than 4 × 4 × 4 mm).

The solution of the heat conduction equation for the ISC model permitted investigation of its dynamic properties in a nonstationary operating mode. Optimization of the ISC structure on the basis of the data obtained for the geometric dimensions and materials of the calorimetric body and the thermal element permits creation of a highly sensitive ISC structure, depending on the demands proposed, that would permit measuring the integral parameters in different energy and duration ranges with high accuracy and a low threshold sensitivity. The high ISC sensitivity, its small geometric dimensions, the rectilinearity of the dependence $S = f(\tau_0)$, and the linearity of the volt/joule characteristic indicate the possibility of broad practical application of semiconductor ISC.

Theoretical computations of the ISC model are confirmed satisfactorily by experimental results.

NOTATION

c_0 and ρ, specific heat and density of the calorimetric body material, respectively; T, temperature; t, time; κ and κ_T, specific heat conduction of the calorimetric body and thermal element materials, respectively; r, distance between the center of the calorimetric body and an arbitrary point; W, power; T_0, temperature of the environment; γ, heat-transfer coefficient; ε, coefficient of incompleteness of the radiation; σ_0, Stefan—Boltzmann constant; a, radius of the calorimetric body; S_T, transverse section area of the thermal element; l_T length of the thermal element; Θ, temperature difference; τ_0, duration of an exponential pulse at the 0.37 level of its amplitude value; $\tau_{0.63}$, ISC time constant; E, thermal emf; E_{max}, amplitude value of the thermal emf; α, thermal emf coefficient; Q_{max}, difference between the maximal temperature on the calorimetric body surface and the environment temperature; T_{max}, maximal temperature on the calorimetric body surface; Q, energy; S_Q, volt-joule sensitivity; δ, relative deviation of the sensitivity from the maximal value in the duration range.

LITERATURE CITED

1. Z. V. Magrachev, Analog Measuring Converters of Single Pulses [in Russian], Moscow (1974).
2. E. I. Rekhin and M. E. Glushkovsiii, Measurement of Single Pulses in Modern Nuclear Physics [in Russian], Moscow (1983).
3. V. I. Demichev and A. N. Shcherbina, Izmer. Tekh., No. 12, 63-64 (1982).
4. B. P. Kozyrev and T. Yu. Sheveleva, Metrologiya, No. 8, 43-48 (1974).
5. L. I. Anatychuk, Thermal Elements and Thermoelectrical Apparatus (Handbook) [in Russian], Kiev (1979).
6. A. V. Lykov, Theory of Heat Conduction [in Russian], Moscow (1967).
7. E. Calvet and A. Pratt, Microcalorimetry [Russian translation], Moscow (1966).
8. D. B. Adamov, V. I. Bondaruk, M. A. Makedon, et al., "Exact measurements of alternating-current electrical quantities," Abstracts of Reports [in Russian], Leningrad (1985), pp. 65-66.