MEASURING THE THERMAL DIFFUSIVITY OF SEMICONDUCTORS BY THE LIGHT-PULSE METHOD

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It is shown that the light-pulse method can be used for measuring the thermal diffusivity of semiconductors, if the photothermal effect is eliminated. The apparatus is described and the results of some measurements on various semiconductor materials are also shown.

One of the modern methods of integrated studies concerning the thermal properties of solid-state materials is the method of pulse heating proposed by W. J. Parker [1]. Here the front surface of a thermally insulated specimen of any shape and thickness absorbs instantaneously and uniformly some quantity of luminous energy coming from a flash lamp or from a laser. The subsequent change in the temperature at the back surface, as a function of time, is tracked with a thermal probe which sends a signal through an amplifier to a recording oscillograph. This heating by light almost completely eliminates the problem of thermal contact between specimen and heat source, while the short time interval of measurements and the small thickness of specimens both contribute to a significant reduction of heat losses even at high temperatures. The method yields correct measurements of the thermal diffusivity on specimens of size and mass over a wide temperature range, up to 3500°K.

The thermal diffusivity α is calculated by the formula in [1], where the time $t_{1/2}$ is determined from oscillograms of the temperature rise at the back surface:

$$\alpha = A\frac{d^2}{t_{1/2}}. \tag{1}$$

The numerical coefficient A = 1.37 when the duration of the light pulse τ is much shorter than the characteristic rise time of the back temperature $t_c = d^2/\pi^2\alpha$ and when no heat is lost in the specimen.

It has been shown in [2-4] that the numerical value of A increases with increasing pulse width and decreases with increasing heat losses.

Both these effects can be practically eliminated by an optimum design of the specimen thickness for a given material with a given thermal diffusivity, and A = 1.37 may be assumed correct. Indeed, the width of a light pulse from a given flash lamp is constant and can always be measured, so that the condition $\tau \ll t_c$ can be satisfied by the proper design of specimen thickness at a given thermal diffusivity. With a pulse width $\tau = 10^{-3}$ sec, the optimum thickness of metallic and dielectric specimens is 0.2 and 0.01 cm respectively. It has been shown in [2] that with these thicknesses the heat loss becomes insignificant even at high temperatures. With narrower heating pulses, measurements can be made on even thinner specimens. In this case the results may be largely affected by the thermal inertia of the measuring instruments, which adds another error to the measurement of $t_{1/2}$. This inertia can be accounted for by introducing into formula (1) a correction factor m, according to [5], defined as $m = 1 + \delta/t_c$.

In view of the fact that the pulse method has been used primarily for measuring the thermal diffusivity of metals and dielectrics [1, 3, 5, 6], it would be of interest to study the feasibility of using it also for semiconductors. It is necessary here also to eliminate the photothermal effect, namely the change in the thermal diffusivity of semiconductors as a result of illumination [7].

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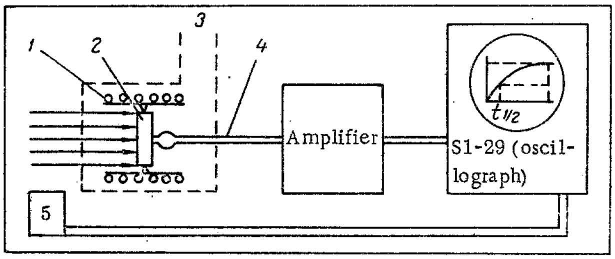

Fig. 1. Schematic block diagram of the test apparatus: 1) furnace; 2) specimen; 3) to vacuum; 4) thermocouple; 5) photodiode.

The apparatus for measuring the thermal properties of semiconductors by the pulse heating method is shown schematically in Fig. 1. A light pulse from a model IFK-120 lamp emitting 120 J of energy at a pulse width $\tau = 2 \cdot 10^{-3}$ sec impinges on the front surface of the specimen. In order to prevent the formation of electron-hole pairs on the semiconductor surface, which causes the photothermal effect, and in order to achieve a uniform absorption of energy, the front surface of the specimen is covered with a thin layer of soot. Rectangular specimens $0.5 \times 0.5 \times 0.2$ cm^3 in size were mounted inside the brass retainer with three screws of stainless steel, the tips of these screws ground to sharp points for reducing the heat leakage and then electrically insulated. In order to prevent light from falling on the back surface and the lateral surfaces of a specimen, a diaphragm of stainless steel and with a hole was fastened to the retainer. Specimens were replaced by screwing the brass retainer into a cylindrical copper block around which a bifilar heater coil of Nichrome wire had been wound. This block was fastened to cupronickel tube and placed inside a quartz chamber with a translucent window and evacuated down to a 0.1 N/m^2 pressure level.

The test temperature was measured with a Chromel–Alumel thermocouple made up of 0.12 mm (diameter) wires.

As has been mentioned earlier, a substantial error in the thermal diffusivity measurement in the case of good heat conductors is due to the thermal inertia of the instruments, the latter being determined essentially by the inertia of the thermal probe at the back surface of the specimen. It is well known that the inertia of a thermocouple is seated in the junction. In order to properly record the temperature changes at the back surface, the authors used, therefore, a Chromel–Alumel contact thermocouple without a junction. This reduced the system inertia.

The "junction" of such a thermocouple is the given specimen surface, which in the case of dielectrics and semiconductors must be silver coated.

Our contact thermocouple was made as follows: its wires, 0.2 mm in diameter and embedded in ceramic sleeving, were pulled through tube of stainless steel. The sharply pointed ends, for reducing the heat leakage along their surface, were fastened to the back surface of the specimen approximately 1 mm apart. The other junction was in thermal contact with the specimen retainer and not exposed to light. Consequently, this thermocouple was recording the temperature changes at the back surface of the specimen due to illumination of the front surface. These tests have shown that such a contact thermocouple is almost without inertia, while using a conventional thermocouple with specimens of good heat conductors will yield erroneous and unrepeatable data.

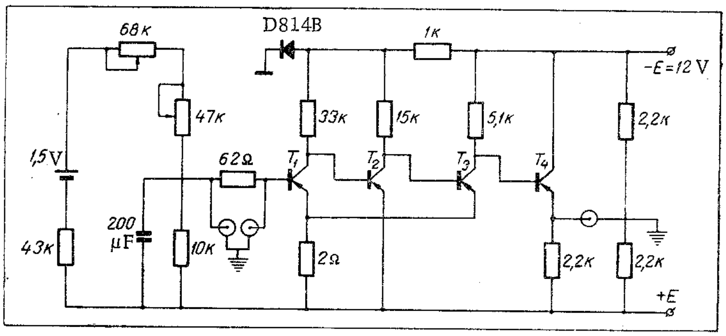

Fig. 2. Schematic circuit diagram of the transistor amplifier.

TABLE 1. Results of Thermal Diffusivity Measurements, α, at 300°K, and Comparison with Published Values

Material	Carrier concentration (m^{-3})	Specimen thickness $d \cdot 10^3$ (m)	$\alpha_{meas} \cdot 10^5$ (m^2/sec)	$\alpha_{publ} \cdot 10^5$ (m^2/sec)
Ge	$n=4 \cdot 10^{21}$	2,1	4,1	4,2 [7]
Si	$n=2 \cdot 10^{22}$	2,6	9,8	10 [9]
GaSb	$p=1,2 \cdot 10^{23}$	2,2	2,5	—
GaAs	$n=3 \cdot 10^{22}$	2,4	4,4	4,3 [10]
InSb	$n=1,4 \cdot 10^{23}$	2,1	1,5	—
HgTe	$n=5 \cdot 10^{23}$	1,7	0,15	0,18 [11]

Since the maximum temperature rise at the back surface due to a light pulse does not exceed 3-4°C, corresponding to a thermocouple emf of approximately 140 μV, it becomes necessary to amplify the signal before recording it on the oscillograph. The amplifier is an important component of the test apparatus and, in order to transmit a signal without distortion, it must have a fast response and a wide band. The direct-coupled amplifier circuit on four MP42-B transistors, as described in [8] but modified and adapted for measuring the thermal emf of a contact thermocouple, was used by the authors as the preamplifier. The modification was effected by breaking the circuit of the contact thermocouple, disconnecting the base of the input-stage transistor and taking it out of operation. The operating point of the first-stage amplifying transistor is established by means of a separate source of emf. Moreover, provisions are made for regulating it by means of two variable resistors. In order to eliminate self-excitation and to reduce the ripple in the rectified voltage, the first two stages are supplied through a parametric stabilizer built on a D814G silicon stabilitron. The thus modified amplifier has a high sensitivity and a high gain (approximately 1000) at a low noise level. Its schematic diagram is shown in Fig. 2.

The amplified signal is transmitted to a model S1-29 memory oscillograph whose sweep is triggered by an FD-3 photodiode in synchronism with the light flash. The thermal diffusivity α of a specimen was calculated by formula (1) with the average time $t_{1/2}$ based on ten measurements.

An analysis of possible errors in the thermal diffusivity measurement has shown that, owing to the short duration of a measurement and to the excellent thermal insulation of the specimen, errors caused by heat leakage along sheaths and leads of a contact thermocouple are negligible. The excellent thermal insulation of the specimen is indicated by the trend of the temperature rise at the back surface of the specimen, with no appreciable drop after the maximum temperature has been reached.

A careful observance of the procedural rules under which formula (1) is valid makes it possible to estimate the accuracy of thermal diffusivity measurements. According to calculations, the maximum possible error in the value of α, essentially due to the error in measuring the time $t_{1/2}$, is ±6%.

The results of thermal diffusivity measurements made on several semiconductors at room temperature have been compiled in Table 1 together with published values.

NOTATION

α is the thermal diffusivity of the material;
d is the thickness of the specimen;
$t_{1/2}$ is the time of reaching half the maximum temperature rise at the back surface;
A is the dimensionless parameter, equal to 1.37 when the heat loss is negligible and t_c is much longer than the pulse duration;
t_c is the characteristic time of temperature rise at the back surface;
τ is the duration (width) of light pulse;
m is the correction factor accounting for the thermal inertia of the instruments;
δ is the response time of the instruments.

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