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Diagnostics of Heat Removal from Semiconductor Solar Cells by Laser Thermowave Methods

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Abstract—Methods of laser thermowave diagnostics have been used to study the process of heat transfer between a semiconductor solar cell and heat-removal ceramics. A theoretical model is proposed that describes the propagation of thermal waves in these systems with allowance for a layer of solder present between the semiconductor and ceramics. It is shown that, using laser thermowave methods, it is possible to evaluate the thermal properties of solder joint layers and the character of their degradation under the action of working temperature variations.

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One of the most important directions in modern power engineering is the development of effective solar cells based on nanostructured semiconductor multi-junction photovoltaic elements (MPEs) and solar radiation concentrators [1]. The efficiency of solar energy conversion into electricity by these MPEs at a degree of radiation concentration of up to 10 suns presently reaches a level of about 30% [2], while about 70% of solar energy is spent only to heat the MPE. For this reason, thermal processes play an extremely important role in the operation of solar cells. Allowance for these effects is especially important during the development of high-efficiency devices mounted on board space vehicles with solar radiation concentrators, which operate under conditions of sharp temperature variations (from –170 to +150°C) in the absence of convection. In this case, an important condition for the reliable operation of solar cells is to ensure the effective heat removal from MPEs and dissipation of this heat in space.

The optimization of heat-exchange processes in space solar cells is achieved by solving two tasks. The first is to arrange the MPE on a substrate that possesses high thermal conductivity and a thermal expansion coefficient close to that of the solar cell material. The second task is to provide effective contact between MPEs and ceramics so as ensure reliable heat removal from these elements. The efficiency of heat removal is determined by the quality of the connecting layer (solder joint) between the MPE and heat-removing ceramics.

The present study was aimed at evaluating the quality and heat-exchange properties of solder joints between MPEs based on InGaP/GaAs/Ge heterostructures and AlN ceramics. The joints were formed using a commercial Kester Easy Profile 256 solder paste. The brazing was effected in accordance with a temperature profile recommended by the manufacturer.

The solder paste contains a surfactant flux, which is intended to produce wetting of the jointed surfaces by the soldering metal and ensure reliable joint in cases when the site of soldering is exposed to atmosphere and the boiling flux can be completely evaporated. In the case under consideration, the solder joint was formed between planar elements and, hence, uniform escape of the evaporated flux from the entire soldered surface was hindered. Gases retained at the soldering site form cavities in the solder layer, which can violate hermeticity of the joint and hinder reliable heat removal from MPEs. Moreover, the flux that flows away from the soldered joint can deteriorate the quality of assembly and characteristics of MPEs. In order to eliminate these drawbacks, the total amount of the solder paste needed for soldering was divided into two parts. One part was heated in an exhaust hood at a temperature of 120 ± 10°C for several minutes in order to remove a certain fraction of the flux. Then, the two parts were thoroughly mixed and, for the convenience of application onto metallized surface of a ceramic heat-removal base, diluted with a small amount of ethyl alcohol.

The level of heat-exchange properties of the solder joints between MPEs and ceramics was evaluated using the method of laser thermowave photodeflection (PD) method. According to this, thermal wave are locally excited by pumping laser radiation that is strongly absorbed by the probed object material. This radiation is modulated at a preset frequency and focused onto the object surface. The laser-induced thermal waves are detected by monitoring the deviation of a probing laser beam, which is produced by a thermal lens formed in air near the object surface during the excitation of thermal waves. This approach was successfully used to monitor nonstationary thermal processes in semiconductors and ceramics [3, 4].

The thermal properties of soldered MPE–ceramics contacts were studied in a geometry that is presented in Fig. 1. Prior to experiments, the sample surface was polished so as to ensure the optical uniformity of the semiconductor material near the contact. The efficiency of heat transfer by the solder joint layer was evaluated by studying the character of PD response signal variation during the approach of a zone of thermal wave generation from the side of semiconductor to ceramics. The pumping beam was generated by an Ar laser operating at a wavelength of $\lambda = 0.514$ μm. Since this radiation is strongly absorbed by MPE, the thermal wave generation in the probed object has a surface character. The pumping laser radiation was modulated at 1 kHz and focused onto the sample surface in a spot 2 μm in diameter. Deviations in the reflected probing beam generated by an He–Ne laser were monitored using a coordination-sensitive photodetector.

The efficiency of heat removal from MPEs was quantitatively characterized using a specially developed theoretical model that takes into account the presence of a layer of solder between the semiconductor substrate and ceramics. In regions *1* and *3* (Fig. 1), the process of heat transfer was described by the equation of heat exchange between the semiconducting structure and ceramics. The level of thermal conductivity in the solder layer for particular MPEs was evaluated by comparing the measured and calculated PD response characteristics.

It should be noted that the PD measurements only employ the variable temperature component. It has been established that, at frequencies above 10^2 Hz, the Biot number is significantly below unity for most materials [5] and the convective heat removal hardly influences the characteristics of the thermal wave. Accordingly, the generation of thermal waves in the structure under consideration can be considered for the following boundary conditions:

$$\left.\frac{\partial T_1}{\partial z}\right|_{z=0} = \left.\frac{\partial T_2}{\partial z}\right|_{z=0} = \left.\frac{\partial T_3}{\partial z}\right|_{z=0} = 0,$$
$$K_1\left.\frac{\partial T_1}{\partial x}\right|_{x=0} = K_2\left.\frac{\partial T_2}{\partial x}\right|_{x=0}, \qquad (1)$$
$$K_2\left.\frac{\partial T_2}{\partial x}\right|_{x=-l} = K_3\left.\frac{\partial T_3}{\partial x}\right|_{x=-l},$$

where $T_1(x, y, z, t)$, $T_2(x, y, z, t)$, and $T_3(x, y, z, t)$ are nonstationary temperature distributions in the semiconductor, solder, and ceramics, respectively; K_1, K_2, and K_3 are the corresponding thermal conductivities; and l is the thickness of the solder layer.

According to the well-known results [3, 4], the contributions of the thermal lens to the PD response are added in the direction of the propagation of the probing laser beam. In the geometry of Fig. 1, this direction of axis y is normal to the plane of the figure. In this study, the deviation of the probing laser beam by the thermal lens was measured in the direction perpendicular to the sample surface. Therefore, the PD response was proportional to the temperature gradient $\partial\bar{T}_g(x, z, t)/\partial z$ (averaged over y), where

$$\bar{T}_g(x, z, t) = \int_{-\infty}^{\infty} dy\, T_g(x, y, z, t).$$

For the exciting laser radiation modulated according to a harmonic law with circular frequency ω, the temperature can also be expressed as

$$\bar{T}(x, z, t) = \bar{T}(x, z, \omega)e^{i\omega t},$$

where

$$\bar{T}_g(x, z, \omega) = \bar{T}(x, z = 0, \omega)\exp\left(-\sqrt{\frac{i\omega}{\kappa_g}}z\right).$$

is the temperature distribution in the gas near the sample surface and κ_g is the temperature diffusivity of air.

The above considerations concerning the determination of the PD signal allow the problem of determining the harmonic thermal wave to be reduced to a two-dimensional (2D) case. A method of solving these 2D problems for thermal waves transmitted through and reflected from a flat interface between two materials was proposed by Shendeleva [6, 7]; however, that solution did not allow for the presence of an interme-

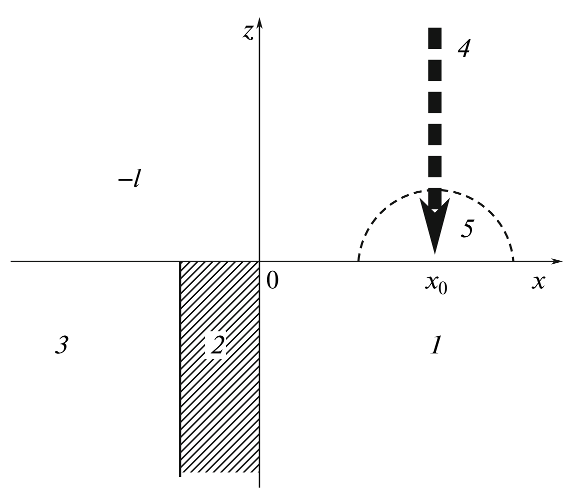

Fig. 1. Geometry of sample excitation by modulated laser radiation: (*1*) semiconductor; (*2*) solder layer; (*3*) ceramics; (*4*) beam of exciting laser radiation; (*5*) thermal lens.

diate layer between the two contacting media. We have generalized the method proposed in [6, 7] in order to determine the temperature distribution in a structure with the solder layer between the semiconductor and ceramics. Here, without dwelling on the details of the calculations, we present only the final result for the $\bar{T}_1(x, z, \omega)$ temperature wave generated by the exciting laser radiation in the vicinity of the semiconducting structure in solder-jointed contact with the ceramics as follows:

$$\bar{T}_1(x, z, \omega) = \frac{W}{4\pi K_1}\int_{-\infty}^{\infty} d\eta e^{-i\eta z}\int_{0}^{\infty} dx'[Q(x')G(x'|x) + R(\eta)Q(x')G(x'|x=0)e^{-q_1 x}], \quad (2)$$

where $Q(x)$ is the power density of the exciting laser radiation; $G(x'|x)$ is the Green's function of the one-dimensional Helmholtz equation with coefficient $-q_1^2$; $q_j^2 = \left(\eta^2 + \frac{i\omega}{\kappa_j}\right)$; κ_1, κ_2, κ_3 are the temperature diffusivities of the semiconductor, solder, and ceramics, respectively;

$$R(\eta) = \frac{(h_1 - h_3)h_2\cosh(q_2 l) - (h_1 h_3 - h_2 h_2)\sinh(q_2 l)}{(h_1 + h_3)h_2\cosh(q_2 l) - (h_1 h_3 + h_2 h_2)\sinh(q_2 l)}$$

is the coefficient of reflection of the thermal wave from the semiconductor–solder boundary; and $h_j = q_j K_j$. It should be noted that expression (2) with $l = 0$ transforms into the corresponding result [6, 7] fort the thermal wave in region *1* (Fig. 1).

Formula (2) was used to calculate the behavior of the PD response signal for the zone of thermal wave generation approaching ceramics from the side of a semiconducting MPE structure. In the solar cells with MPEs based on InGaP/GaAs/Ge heterostructures, the ceramic heat sink was contacting with a rather thick germanium substrate. Therefore, the $\bar{T}_1(x, z, \omega)$ temperature wave was calculated for the thermal parameters of this semiconductor. The thermal wave length in the germanium substrate radiation-heated at a modulation frequency of 1 kHz was about 100 μm.

Figure 2 shows the results of laser thermowave experiments using the proposed method, which are compared to the results of PD signal calculations performed by formula (2). The experimental values of the PD response were averaged over 1-mm-long region along the semiconductor–solder interface. In order to study the process of MPE aging under

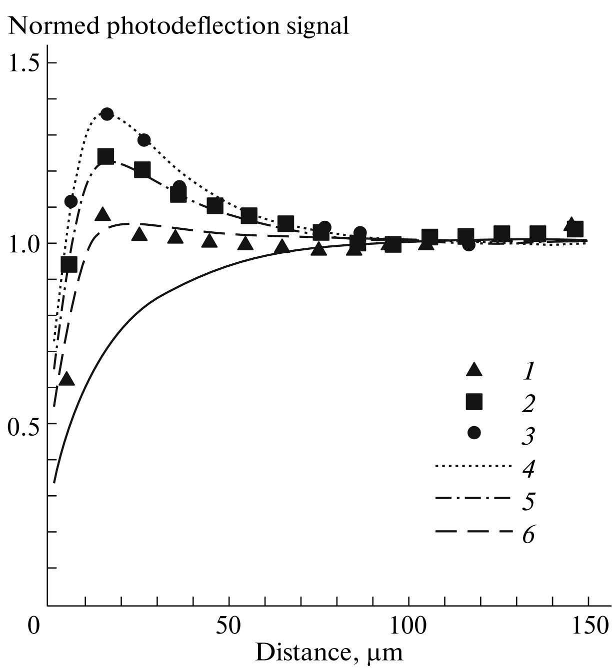

Fig. 2. Normalized PD signal profiles in the semiconductor (Ge) substrate near its solder-jointed boundary with ceramics for a sample (*1*) in the initial state and (*2*, *3*) upon one and ten cycles of cooling in liquid nitrogen, respectively. Theoretical curves were calculated for various values of the thermal conductivity of the solder joint layer: K_2 = 0.13 (*4*), 0.05 (*5*), and 0.02 W/(cm K) (*6*); solid curve corresponds to the ideal thermal contact between the MPE semiconductor substrate and ceramics.

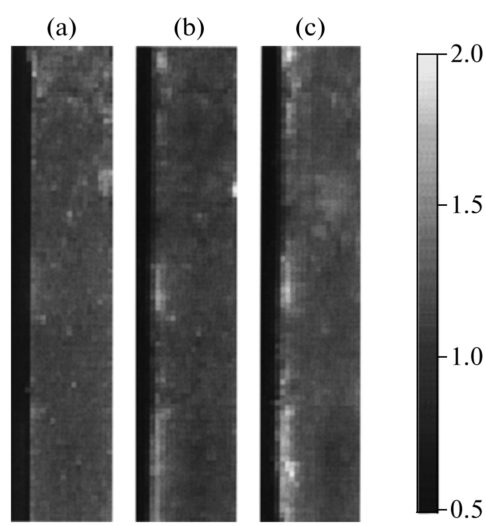

Fig. 3. PD images of 200 × 920 μm^2 region of contact between the MPE semiconductor substrate and AlN ceramics for a sample (a) in the initial state and (b, c) upon one and ten cycles of cooling in liquid nitrogen, respectively.

working conditions, the experiments were performed with samples both in the initial state and upon one or ten cycles of deep cooling by immersion into liquid nitrogen. The period of each immersion was 10 s with an interval of 1 min. As can be seen from Fig. 2, the experimentally observed behavior of the PD signal in the MPE semiconductor substrate is well described by the proposed three-layer model. The thermal conductivity of the solder joint was $K_2 = 0.13$ W/(cm K) in the initial state, decreased to 0.05 W/(cm K) after the first cooling cycle, and amounted to 0.02 W/(cm K) after ten immersions in liquid nitrogen. The well-known relation for the specific thermal resistance of a layer, $r_T = \frac{l}{K}$, shows that this resistance was 7.7×10^{-3} (cm^2 K)/W for the solder layer in the initial state and increased to 2×10^{-2} and 5×10^{-2} (cm^2 K)/W, respectively, after the first and last immersion into liquid nitrogen.

In addition to quantitatively evaluating the heat-removal properties of the MPE soldered contact with ceramics, the PD method can also be used for assessing the degree of heat-sink uniformity along the boundary. Figure 3 shows the PD images of a region of contact between the MPE semiconductor substrate and AlN ceramics, where brighter areas correspond to higher PD response intensities. As can be seen, an increase in the PD signal on the passage from MPE substrate to ceramics is uniform along the entire contact area. The mean statistical scatter of the PD signal amplitude was 12% in the initial state and increased to 17 and 23% after the first and tenth cycle of cooling in liquid nitrogen, respectively.

In conclusion, the results of our investigation show that the laser thermowave methods can be used for diagnostics of the quality of heat transfer in soldered contacts between MPEs and ceramics. These methods can be employed for establishing the optimum conditions of heat exchange in contacts of this type.

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