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Structural stresses and temperature budget in III-V photoconverters with a thin Ge substrate

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Abstract. In high illumination conditions for photovoltaic converters, it is possible to stabilize the temperature of the photoactive region using a heatsink with high thermal conductivity, and by thinning the substrate that is a holder for semiconductor structure. However, the use of both methods together can lead to significant increase of the possible fragility of the converter. This work is devoted to the searching of balance between brittleness and overheating of GaAs/Ge solar cells installed on a copper heatsink with ceramic intermedia. Such composite heatsink, on the one hand, reduces mechanical stresses in the semiconductor, but, on the other hand, makes better the heat removal mode.

Keywords: photovoltaic cells, temperature overheating, mechanical stress, thinning substrate

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Структурные напряжения и температурный баланс в фотопреобразователях А3В5 с тонкой Ge подложкой

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Аннотация. В условиях высокой освещенности для фотоэлектрических преобразователей стабилизировать температуру фотоактивной области можно с помощью радиатора с высокой теплопроводностью и утончения подложки, являющейся держателем полупроводниковой структуры. Однако совместное использование обоих методов может привести к значительному увеличению хрупкости преобразователя. Настоящая работа посвящена поиску баланса между хрупкостью и перегревом солнечных элементов GaAs/Ge, установленных на медном радиаторе с керамической прокладкой. Такой композитный радиатор, с одной стороны, снижает механические напряжения в полупроводнике, а с другой стороны, улучшает режим отвода тепла.

Ключевые слова: фотоэлектрические преобразователи, температура, перегрев, механические напряжения, утончение подложки

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Introduction

In concentrator photovoltaic modules [1] and transducers of high-power laser radiation [2], the operation of photovoltaic converters (PVC) is associated with significant heating. Therefore, to stabilize the temperature and prevent overheating of the PVC, it is necessary to provide efficient heat removal [3] or a mode of temperature-controlled operation [4]. Thus, the efficiency of solar PVC can exceed 45% under concentrated (400–1000 X) irradiation and at cell temperature of 25 °C [5]. Outdoors, the temperature of the PVCs in concentrator module depends on the type and material of the heatsink and environmental conditions. In practice the most widely used heatsinks are based on materials with high thermal conductivity (copper, ceramics).

Additionally, the operating temperature of the photoactive region (p-n junction) can be further reduced by thinning the PVC's substrate. In this case, if the thermal conductivity of the heatsink is higher than of the semiconductor, the temperature gradient between the active region and the heatsink decreases (the thermal flow takes away from the semiconductor volume). However, together with this, the mechanical strength of the sample also decreases. In the process of high-temperature assembly (soldering), the PVC crystal is mounted on the heatsink. After solidification and cooling up to room temperature, significant mechanical stresses arise in the semiconductor structure. It is caused by the difference in the coefficients of thermal expansion (CTE) of the PVC and the heatsink materials. Thus, at thinning Ge substrate from 200 down to 3 μm the temperature of the GaAs active region can decreases from 41 to 30 °C at 1000X irradiation condition and if copper is used as a heatsink. But if the thickness of the substrate is less than 100 μm, mechanical stress will overcomes the flow stress of Ge if PVC is directly attached on copper holder.

PVC substrate thinning and heatsink selection

This contradiction can be resolved by selecting a heatsink material with a CTE close to the semiconductor. Such materials include aluminum oxide and aluminum nitride ceramics [7]. Since mounting directly on ceramics is difficult, a thin technological copper layer is preliminary deposited on the ceramic base. Thus, in a solar cell soldered on a copper coating of a ceramic heatsink, lower mechanical stresses occur. However, the thermal conductivity of the ceramic material is lower than that of copper. The conditions for heat removal can be improved by using composite systems. In such heatsinks, the main part consists of copper, whereas a thin ceramic with top copper layer is located just below the solar cell. So the ceramic layer compensates the linear expansion of the thin copper layer.

In this work, it was assumed that the semiconductor crystal is rigidly fixed just on the copper layer, in spite of that in practice the mounting of the crystal is carried out using solder. However, the introduction of an additional SnPbAg layer with a thickness of 10 μm does not significantly change the stress distribution inside the semiconductor crystal (the difference in the absolute values of the von Mises stress maximum is less than 2%).

The temperature and mechanical stress in the GaAs layer were studied as a function of the Ge substrate and/or ceramic thicknesses. The simulation of the equilibrium thermal mode and the process of thermal contraction was carried out using COMSOL Multiphysics accounting data given in [8, 9].

Simulation conditions

Figure 1 represents the modeled structure. The dimensions of the semiconductor crystal and heatsink were 3 mm × 3 mm and 10 mm × 10 mm, correspondingly. The thickness of the GaAs photoactive layer was 5 μm, the copper coating was 127 μm, and the copper heatsink was 1 mm. The thicknesses of the Ge substrate and ceramic intermedia were varied.

In the model, temperature and mechanical stresses were calculated separately. In the first part of the calculations, the maximum temperature at the center of the GaAs layer was determined. The irradiance distribution within the PVC designated illumination area (DIA) of a 2.8 mm in diameter was assumed to be Gaussian. The integrated light power was 1.6 W (corresponds to solar irradiance of 1000 W/m^2 concentrated by a Fresnel lens of 40×40 mm^2 optical aperture on the PVC). It was assumed that all light power is absorbed in GaAs layer and converted into heat. The temperature of the rear side of the heatsink was taken equal to the ambient temperature (25 °C).

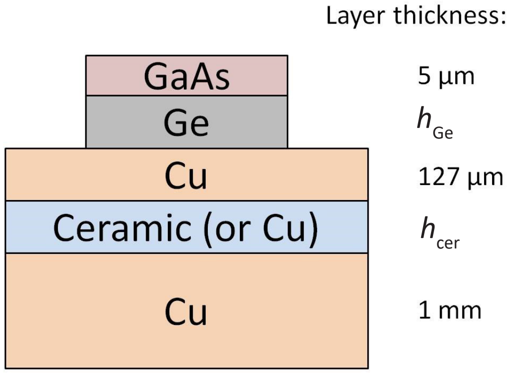

Fig. 1. Model of the structure of a mounted solar cell

In the thermal contraction part, the initial temperature of the PVC crystal and the heatsink was taken equal to 160 °C. At this temperature, their total fixture is ensured. After that, the temperature of the entire system decreased to room temperature (25 °C). Stresses only because of cooling were considered. The effects associated with radiative heating are not considered and will be discussed in the separate paper.

Simulation results

The overheating values of the GaAs layer relative to the environment were calculated. The results on Figure 2 show the maximum overheat values in the center of the structure.

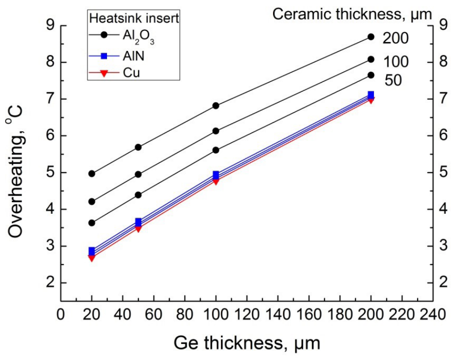

Fig. 2. Overheating relative to the environment in the GaAs layer depending on the thickness of the Ge layer and the thickness of the ceramic insert in the heatsink

Materials with high thermal conductivity significantly reduce overheating of the photoreceiver or solar cell. So a copper thermal dissipation body or a heatsink with an aluminum nitride insert reduce the overheating of the GaAs region from 7 to 2.7 °C if the Ge layer is thinned from 200 to 20 µm. In this case, the variation in the thickness of the AlN intermedia (200, 100, 50 µm) does not significantly affect the overheating value of the GaAs layer. The thermal conductivity of Al_2O_3 is noticeably lower than that of copper or AlN. Therefore, an increase in the thickness of the alumina insert in the heatsink from 50 to 200 µm increases the overheating of GaAs by 1 °C for any thickness of the Ge layer.

In the mechanical stress calculations part, the maximum von Mises values in the GaAs layer are given. This representation allows direct comparison with the flow stress parameter. For example, the flow stress of Ge is ~ 2 GPa [10], while that of GaAs is ~ 10 MPa [11]. In the Ge part, the maximum stress does not exceed 20 MPa. Thus, the GaAs layer should be considered the most fragile part of the structure. In addition, it should also be noted that the localization of the maximum stress in the structure in each simulated case is different: with a decrease in the thickness of the Ge layer, it is located closer to the edge of the crystal.

Figure 3 shows the results of modeling the maximum mechanical stress in the GaAs layer.

A copper heatsink produces significant mechanical stresses in the semiconductor structure.

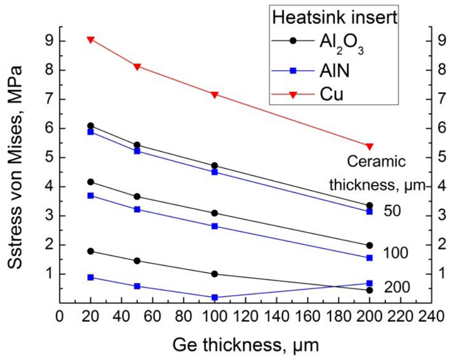

Fig. 3. Von Mises stresses in the GaAs layer depending on the thickness of the Ge layer and the thickness of the ceramic insert in the heatsink

When the Ge layer is thinned, the maximum stress approaches the flow stress. It should be taken into account during operation or in the process of mounting. The solar cell can be additionally stressed from the side of the photoactive region with attached contact grid: for example, when contacting with a measuring probe or during the wiring to the top current-spreading busbar. So it is necessary to provide a factor of safety by optimizing the thickness of the germanium substrate.

The ceramic intemedia in the heatsink significantly reduces mechanical stress directed to the semiconductor crystal. Moreover, an increase in ceramic thickness decreases the effect of a thin copper layer on the PVC and particularly on the GaAs photoactive region. Thus, at a Ge layer thickness of 20 μm, the stress decreases from 9 to 1 MPa if a heatsink with a 200 μm AlN ceramic intermedia is used instead of a full-copper-bodied heatsink.

Conclusion

In this paper, methods for thermal stabilization of a GaAs/Ge PVC for high irradiance conditions were considered. The main approach discussed is to thin the Ge substrate together with the use of a heatsink with high thermal conductivity. The issue of increasing the fragility of a sample is also considered. It appears in process of mounting the cell on a heatsink. The mechanical stress appears because of the difference in the CTE of a metal and a semiconductor. Modifications of the heatsink for increasing the factor of safety of the solar cell are discussed.

The decrease in the thickness of the Ge substrate from 200 to 20 μm reduces the radiative (1.6W) overheating in GaAs from 7 to 2.7 °C relative to the environment. However, in this case, the maximum mechanical stress in GaAs increases from 5 to 9 MPa (in case Cu heatsink), approaching the flow stress (10 MPa) for semiconductor material. The increase in efficiency from the total effect of reducing the operating temperature and reducing the series resistance of the substrate is about 1%.

The implementation of ceramic intermedia into the heatsink directly underneath the PVC crystal significantly reduces mechanical stresses in the GaAs layer. By using aluminium nitride intermedia with 100 μm thickness, mechanical stresses in GaAs are 0.2 MPa that is not critical for effective photoreceiver operation.

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