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Shingled photovoltaic converters based on GaSb

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The concept of shingled photovoltaic modules based on GaSb has been tested. Various manufacturing and installation regimes for 4×4 mm converters are worked out, and a testing module with a series-parallel (2×2) sample connection scheme is assembled. The influence of the material and thickness of ceramics on the overheating of the module converters is evaluated.

Keywords: photovoltaic converter, photovoltaic module, GaSb.

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Certain applications require combining photovoltaic converters (PVCs) into a module. The concept of shingled modules [1,2] has been proposed and developed for Si-based PVCs. In this case, chips are mounted with an overlap (Fig. 1) in a shingling arrangement. Owing to the mutual overlap of PVCs and the lack of wide bus bars on the receiving surface, the photoactive area of a module increases, it becomes more compact, and shading losses (only strip contacts contribute to them) are reduced [3]. The present study is focused on the design and study of shingled converters based on GaSb. This arrangement will help increase the packing density of PVCs in thermophotovoltaic generators [4–8] and laser radiation converters operating at $\lambda \sim 1550$ nm [9,10], and the output voltage will also increase (which is very important for narrow-gap semiconductors) when several chips are combined into a module.

Since the PVCs were meant to be used for refining the general concepts of shingled assembly, they were fabricated in a simplified technological cycle: single-stage diffusion of zinc into an *n*-type GaSb substrate [11] to a depth of $\sim 0.9\,\mu$m. Tellurium-doped substrates with $n \sim 3 \cdot 10^{17}\,\mathrm{cm}^{-3}$ and the (100) orientation provided by OOO „Girmet“ (Moscow) were used. An anti-reflective coating based on $ZnS + MgF_2$ was applied to the front surface of PVCs by thermal evaporation in vacuum performed using a VUP-4 setup. The designed set of photomasks was used to fabricate converters with a total size of 4×4 mm, a wide one-sided current collector, and an equidistant contact grid (with a pitch of $332\,\mu$m). The left panel of Fig. 1 presents the overall view of the illuminated converter surface. The width of the peripheral bus, which ensures the overlap of PVCs in a shingling arrangement, was 1 mm, and its area was equal to a third of the photosensitive sample surface. The photovoltaic converter was made relatively small in order to save materials in the course of research into finding the optimum topology of the contact grid and geometry of the samples and optimizing the regimes of combining converters into a module.

The current–voltage curve (IV) of the fabricated shingled converter was measured under pulsed illumination with a xenon flash lamp. The samples demonstrated a short-circuit current of 0.26 A and open-circuit voltage $V_{oc} = 0.47$ V.

The soldering regimes for both individual shingled PVCs and modules based on them were optimized. Solder paste NC257-2 based on the Sn42Bi58 alloy with a melting point of 138 °C was used. The key requirements imposed on the solder paste are as follows: a low temperature of solder joint formation, a short reflow time, and a viscosity sufficient to prevent flowing on the side surface of converters. If these requirements are not satisfied, leakage currents increase to the point of short-circuiting the PVC. To prevent the inflow of solder paste, one may apply a special polymer paint coating or other protective coating to the end of the lower converter (Fig. 1). All samples were assembled in a module in a single stage (without reheating) to obviate the need for solder pastes with different melting points and reduce the risk of PVC degradation.

Series connection was established by mutual overlap of the rear contact of the upper PVC with the front bus of the lower sample (Fig. 2, *a*), while parallel connection of cells was established by placing the converters in adjacent rows (Fig. 2, *b*). To ensure equality of generated photocurrents (with series connection) and voltages (with parallel connection), PVCs with the minimum mismatch of photovoltaic parameters were selected. The converters were mounted onto a stepped heat-dissipating base made of copper (Fig. 2, *a*). Al_2O_3 or BeO ceramics were used to provide electrical insulation. Al_2O_3 was chosen for its wide availability, simplicity of its production process, low cost, and the fact that it is matched in the temperature coefficient of linear expansion with GaSb $(6.1 \cdot 10^{-6}\,\mathrm{K}^{-1})$. BeO was used due to the fact that it has a significant (for ceramic materials) thermal conductivity. An alternative assembly option involves the use of a two-level glass-ceramic MACOR substrate (Fig. 2, *b*). This non-porous material based on fluorophlogopite mica and borosilicate glass is highly workable, may be easily processed into

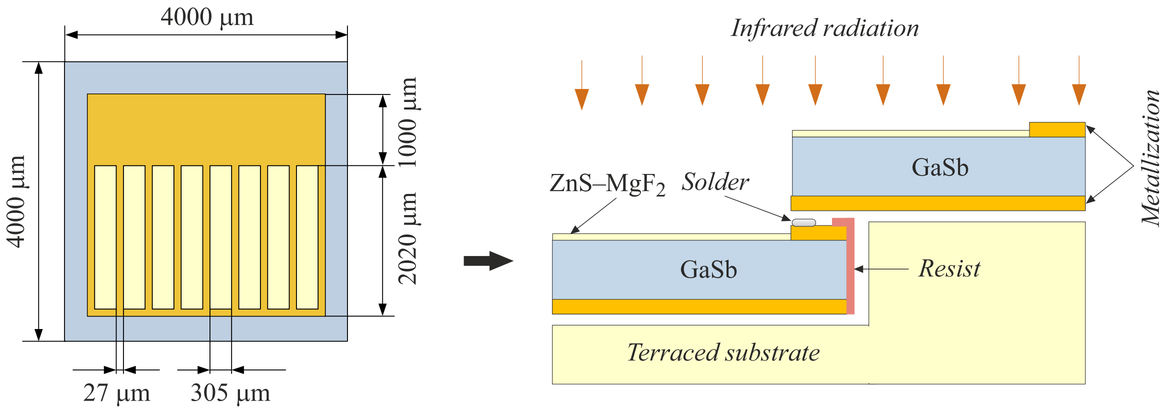

Figure 1. Assembly of two overlapping photovoltaic converters. The illuminated PVC surface is shown on the left.

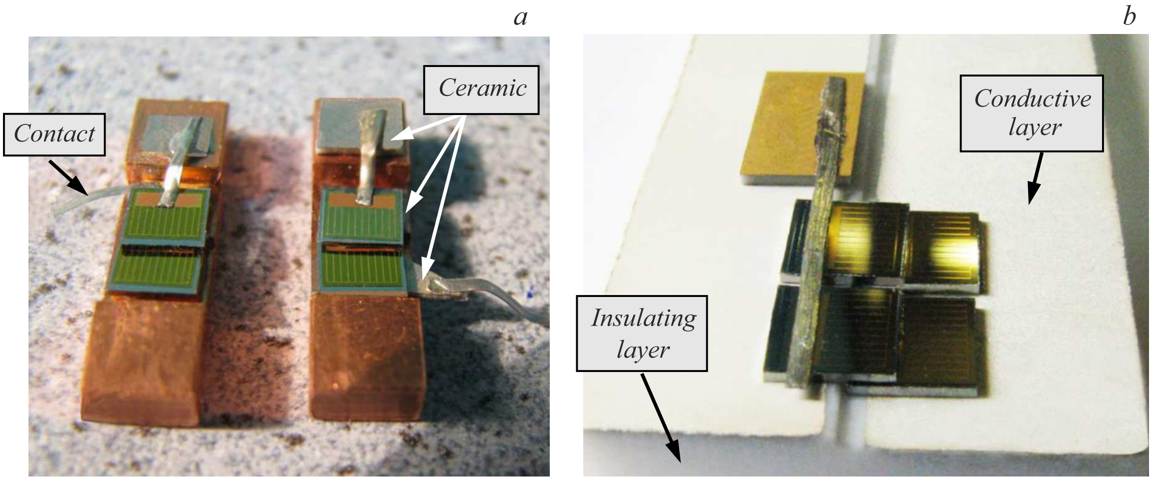

Figure 2. Assembly of converters with a one-sided current collector into a photovoltaic module with the use of a copper stepped base (*a*) and a two-level ceramic heat-dissipating substrate (*b*).

any shape, and does not deform under heating [12]; therefore, it is convenient for forming a terraced profile. One disadvantage of MACOR ceramics is low thermal conductivity. The physical characteristics of the materials used are summarized in Table 1.

The small size of the designed PVCs made it possible to minimize mechanical stresses during heating and cooling, which arise due to differences in the temperature coefficients of linear expansion of MACOR and GaSb. The lack of mechanical stresses in samples of shingled GaSb converters soldered onto AlN ceramics with a thermal expansion coefficient of $(3.6-4.7) \cdot 10^{-6}\,°C^{-1}$ within the range of 25−70 °C (operating temperatures of photovoltaic cells in a thermophotovoltaic system) has already been reported in [13]. Even if ceramic substrates compatible in terms of the temperature coefficient of linear expansion are used, the concept of shingled PVCs carries increased risks for silicon solar cells, which traditionally have significantly larger dimensions.

Exposure to high-power laser radiation or operation in thermophotovoltaic generators with an emitter heated to high temperatures may cause heating (in certain cases, significant heating) of PVCs. The selection of proper insulating, support, and heat-dissipating materials helps prevent unnecessary losses and avoid unfavorable combinations of module components. The influence of ceramic dielectrics and their thickness on converter overheating ΔT was determined by analyzing the change in the current–voltage curve relative to a similar dependence corresponding to pulsed illumination with a xenon lamp (in the latter case, the temperature at the sample is $T \sim 25\,°C$). The results were obtained under the assumption of a linear V_{oc} reduction with increasing temperature at a rate of $\Delta V_{oc}/\Delta T = 1.5\,\mathrm{mV/°C}$ [14]. The sample soldered onto a copper base was mounted on a ceramic substrate and then onto a heat sink with flow-through water cooling. Thermal paste was applied in order to enhance heat transfer between the contacting surfaces (copper base/ceramics and ceramics/heat sink). The use of a copper substrate and thermal paste instead of solder allowed us to study the same photovoltaic converter with a set of different ceramic substrates. In addition to providing an opportunity to switch ceramic materials, copper ensure rapid and uniform heat distribution. The radiation source was a flat infrared emitter

Table 1. Characteristics of the base material and the ceramic substrate

Parameter	Cu	Al_2O_3	BeO	MACOR
Density, g/cm^3	8.89	3.89	2.85	2.52
Bending strength, MPa	400*	310–450	170–190	≥ 94
Temperature coefficient of linear expansion, $10^{-6}\,°C^{-1}$ ($\Delta T = 20-400\,°C$)	16.9–18.1	6.7–7.3	7.2–8.0	9
Thermal conductivity, W/m·K	385	14–29	240–260	1.46
Bulk resistivity, $\Omega \cdot$ cm (25 °C)	$1.7 \cdot 10^{-6}$	10^{14}	10^{14}	10^{17}
Bulk resistivity, $\Omega \cdot$ cm (300 °C)		$> 10^{12}$	$> 10^{11}$	10^9

* Tensile strength.

Table 2. Overheating of PVCs with different bases

Base material	$J_{sc} = 1$ A/cm^2		$J_{sc} = 5$ A/cm^2		$J_{sc} = 6$ A/cm^2	
	ΔV_{oc}, mV	ΔT, °C	ΔV_{oc}, mV	ΔT, °C	ΔV_{oc}, mV	ΔT, °C
Copper	10.5	7.0	24.1	16.1	27.0	18
Copper + BeO (0.5 mm)	12.8	8.5	29.5	19.7	32.4	21.3
Copper + Al_2O_3 (0.5 mm)	13.0	8.7	29.8	19.9	34.1	22.7
Copper + Al_2O_3 (1.0 mm)	15.6	10.4	33.2	22.1	36.9	24.6
MACOR (0.5 mm)						35*
MACOR (1.0 mm)						45*
MACOR (1.5 mm)						67*

* Estimate with extrapolation of experimental data.

made of silicon carbide heated to $T \sim 1000-1600\,°C$ that was located at a distance of 4–5 mm from the PVC. The experimental values of ΔT in Table 2 correspond to short-circuit photocurrent density J_{sc} varying from 1 to 6 A/cm^2. In high-current operation of the converter, overheating does not exceed $\sim 25\,°C$ and is virtually independent of the material of the ceramic substrate used. At low currents (1 A/cm^2), the spread of ΔT between Al_2O_3 and BeO is as small as several tenths of a degree. In view of this, the use of beryllium oxide becomes impractical and should be limited due to its toxicity. A twofold increase in thickness of Al_2O_3 (from 0.5 to 1 mm) also ensured unimpeded heat dissipation.

MACOR has the lowest thermal conductivity, which restricts significantly the use of ceramics with passive cooling of the module. Flow-through water cooling and the use of thin substrates reduce converter overheating and make it possible to prevent output power losses and premature module degradation. Extrapolation of experimental data reveals that MACOR substrates with a thickness of 0.5, 1.0, and 1.5 mm raise the PVC temperature by $\Delta T = 35$, 45, and 67 °C, respectively, in the high-current operating mode. In light of the low bending strength and the need to form a step for shingling assembly and to maintain satisfactory thermal parameters, the recommended thickness of MACOR ceramic bases is 1 mm. Previous studies have demonstrated that when temperature-stable contacts are deposited, the heating of GaSb-based PVCs to $T \sim 80\,°C$ is not critical [15].

A prototype module of four photovoltaic converters was assembled in a shingled series-parallel arrangement (see the inset in Fig. 3) and tested. The module was fabricated in order to optimize its design and assess the applicability of MACOR ceramics. PVCs were mounted on a ceramic base with a top conductive layer (Fig. 2, *b*). With a converter thickness of $\sim 450\,\mu$m, the step height of the terraced substrate was $\sim 500\,\mu$m. The dependences of parameters of the fabricated module under illumination by a xenon flash

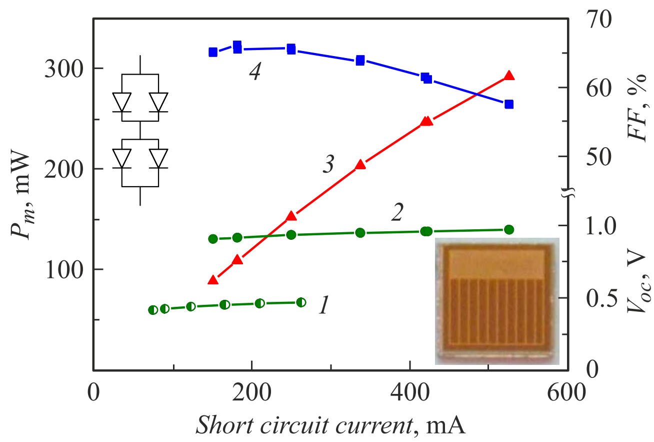

Figure 3. Electrical parameters of the converter 4×4 mm in size (curve *1*) and the shingled module (curves *2–4*) with a ceramic base. *1*, *2* — Open-circuit voltage (V_{oc}), *3* — power at optimum load (P_m), and *4* — fill factor (FF). The insets show the arrangement of PVCs in the module and the photographic image of the fabricated converter.

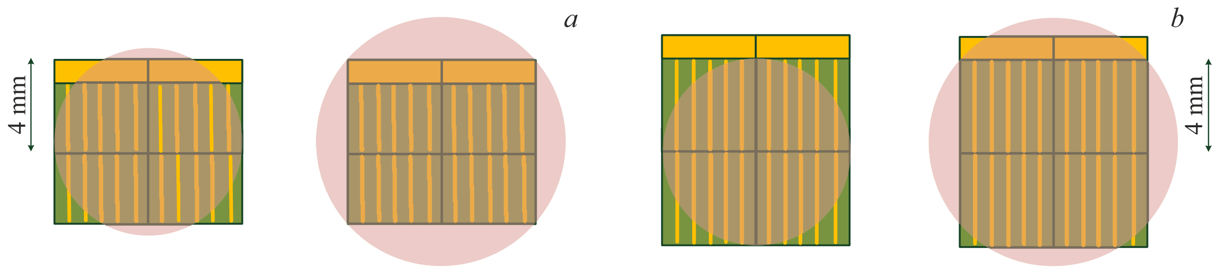

Figure 4. Losses in irradiation of PVC modules of different geometries. *a* — Current geometry (square PVCs with a rectangular photosensitive surface); *b* — planned geometry (rectangular PVCs with a square photosensitive surface).

lamp (with a pulse duration of 1 ms) on the short-circuit current are shown in Fig. 3 (curves *2–4*). IV measurements were carried out within a single light pulse. The IV behavior could be examined within a wide illumination intensity range by adjusting the distance from the lamp to the PVC. At a current of 0.5 A, the power of the module at the point of optimum load (P_m) reached $\sim$ 300 mW.

A commercial photovoltaic module will feature more converters, which should help increase the output voltage and reduce the shading coefficient. The results of experiments demonstrated that the overall square PVC geometry should be changed to a rectangular one (Fig. 4). Longer cells and an equilateral photosensitive surface of the module will help reduce optical losses (most notably, the losses due to radiation missing the module, which dominate over the losses due to incomplete illumination) under illumination by a beam with a circular intensity distribution [16]. Figure 4 presents two scenarios of module irradiation: with a focused laser beam and with a defocused one. The modified geometry turns out to be preferable in both cases.

Thus, general approaches to the design of multicell shingled modules based on GaSb were formulated, and ways to improve them were identified. The relevance of MACOR two-level ceramic substrates, which are lightweight, allow for mechanical processing with tight tolerances, and offer satisfactory thermal (with water cooling of the module) and insulation characteristics, was demonstrated.

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Conflict of interest

The authors declare that they have no conflict of interest.

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