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High Intensity Low Temperature (HILT) Performance Of Space Concentrator GaInP/GaInAs/Ge MJ SCs

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Abstract: In the work, the results of an investigation of GaInP/GaInAs/Ge MJ SCs intended for converting concentrated solar radiation, when operating at low temperatures (down to -190 °C) are presented. A kink of the cell I-V characteristic has been observed in the region close to V_{oc} starting from -20ºC at operation under concentrated sunlight. The causes for its occurrence have been analyzed and the reasons for formation of a built-in potential barrier for majority charge carriers at the *n*-GaInP/*n*-Ge isotype hetero-interface are discussed. The effect of charge carrier transport in *n*-GaInP/*n-p* Ge heterostructures on MJ SC output characteristics at low temperatures has been studied including EL technique.

Keywords: multi-junction solar cells, potential barrier, heterointerface, electroluminescence
PACS:, 88.40.hj, 88.40.jp.

INTRODUCTION

Beginning in the mid-1990s, a number of space experiments with modules based on Fresnel lens concentrators (mini-dome point focus module for PASP Plus mission [1], flat-plate point focus module for "Molnija 3K" spacecraft [2], SCARLET linear – focus array [3] for DS1, SLA (Stretched Lens Array) for TacSat-4 satellite [4]) and reflecting CellSaver systems [5] have been successfully conducted. Currently, researchers are preparing space tests with an improved Stretched Lens Array SquareRigger (SLASR) system [6].

The success of previous experiments and promising in equipping new types of space concentrator modules with highly-efficient multijunction (MJ) solar cells (SCs) open prospects for the development of the concentrator trend in space solar power engineering, especially for use of such modules in advanced spacecrafts including those, which have to be sent into deep space. Such space missions involve high-intensity low-temperature (HILT) conditions for SC operations. Therefore, investigations of the concentrator MJ SC behavior at moderate and deep negative temperatures are important.

A number of works on the behavior of photovoltaic characteristics of space and terrestrial TJ SCs at high illuminations and temperatures (HIHT) and low illuminations and temperatures (LILT) have been published [7, 8]. However, data on concentrator MJ SCs functioning at moderate and deep negative temperatures are practically absent.

The estimates show that the temperature of a SC, which operates at radiation concentration ratios of 70 – 100 in a photovoltaic module with Fresnel lenses [2] moving from the Sun to distances greater than 3 A.U., will fall below -50ºC (Fig.1).

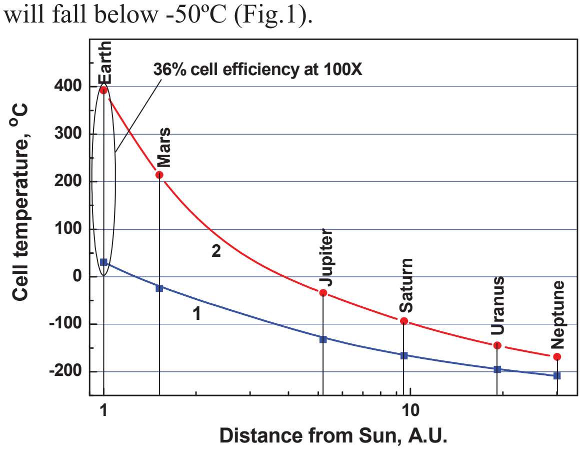

FIGURE 1. TJ SC temperature in concentrator module as a function of distance from the Sun in the presence (1) and absence (2) of effective heat dissipating coating on a thermoconducting board with MJ SCs. For operating temperature estimations the SC of 36% (AM0, 100 X) efficiency is assumed.

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Theoretically, for spacecraft separation distances from the Sun of 5-7 A.U., the emissivity (degree of blackness) of a sink, on which the SCs are arranged, can change the temperature of the SCs. In the case of a spacecraft flight on the way from Earth's orbit to Mars, SCs will operate at relatively high temperatures (+200ºC). Therefore, precautions must be taken to prevent SCs from overheating, or TJ SC operational characteristics must be adjusted to accommodate the temperature change [8].

Herein, we present the results on GaInP/GaInAs/Ge MJ SCs, intended for conversion of concentrated solar radiation and operating at low temperatures. A kink in the cell's I-V characteristic has been observed in the region close to V_{oc} starting from -20ºC at operation under concentrated illumination. The causes for this occurrence have been analyzed. The reasons for the built-in potential barrier for the majority charge carriers at the *n*-GaInP/*n*-Ge isotype interface have been determined. Finally, the effect produced by a change in the charge carrier transport for *n*-GaInP/*n-p* Ge heterostructures on MJ SC output characteristics at low temperatures has been studied including EL technique.

I-V EXPERIMENTAL DETERMINATION

The kink in the MJ SC load I-V characteristic in the region of V_{oc} has been attributed to the influence of the parasitic potential barrier for majority charge carriers at the *n*-GaInP/*n*-Ge interface in the bottom Ge subcell [9]. At low temperatures, the S-shaped dark I-V characteristics with the hopping voltage variation effects have been observed in the control mode of the current flow through the cell.

Our measurements of the I-V characteristics of TJ SCs demonstrate that at temperatures below -20 ºC to - 50 ºC, the knee-shaped feature in the I-V curve occurs close to V_{oc} (Fig. 2). Once this feature forms, the dependence of the V_{mpp} voltage on temperature upon further cooling becomes nonlinear. The values of V_{mpp} fall sharply, whereas V_{oc} continues to grow linearly with decreasing temperature (Fig. 3). At the same time, a simultaneous drop in the FF of the I-V characteristic, P_{max} and the efficiency of SC are observed.

In some cases, registration of the typical voltage jump in the dark I-V characteristic (S-shape) upon cooling appeared to be difficult (because of the impossibility to pass large forward currents through a tested specimen due to technical limitations of measurement equipment), whereas the kink in the vicinity of V_{oc} was clearly observed in the load I-V characteristic.

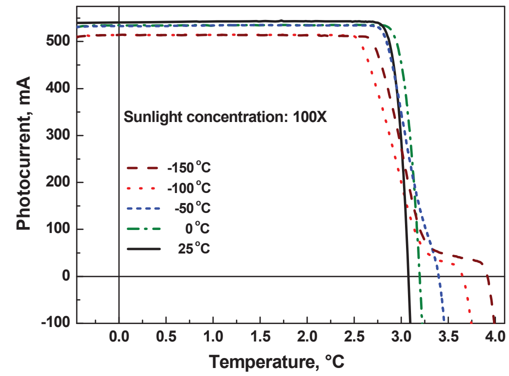

FIGURE 2. IV curves recorded at 100X sunlight concentration for TJ SC at negative temperatures.

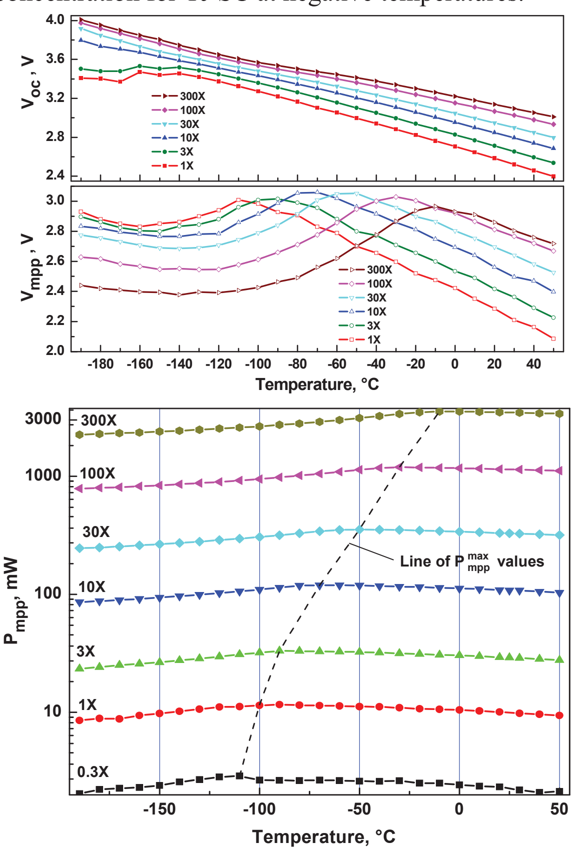

FIGURE 3. Temperature dependencies for V_{oc} and V_{mpp} (top plots) and for P_{max} obtained at different sunlight concentrations.

It has been established that, the temperature, at which the I-V characteristic kink becomes detectable, decreases with decreasing illumination level.

Thus, in designing the concentrating optics for space solar arrays intended for use in deep-space missions, it is necessary to select an illumination level for SC operation under the normal kink-free I-V characteristic regime. This ensures the correlation between the gradual reduction of SC illumination and the corresponding freezing of the cell.

GAINP/GE INTERFACE IN GE COMPONENT CELL AND IN TJ SC

By nature, the occurrence of an undesired potential barrier for majority charge carriers at the *n*-GaInP/*n*-Ge interface is determined by the peculiarities of the diffusion of *P* (V group element), Ga, and In (III group elements) from GaInP into a Ge (IV group element) substrate. Larger solubility limits and smaller diffusion coefficients of Ga relative to those of P result in the prevalence of the local p-type doping. This phenomenon should be taken into account, when considering a wide class of materials, and in studying properties of the interfaces between III-V compounds and IV group elements.

Especially in the case of *n*-GaInP/*n*-Ge hetero-interface, the effects of diffusion into the substrate of both the V group elements (in this case *P*), which form the n-region of the photoactive p-n junction in Ge, and the III group elements (Ga, In), which creates the inverse conduction, should be present. The solubility limit of Ga in Ge ($4.5\cdot10^{20}$ cm^{-3}) is substantially higher than that of P ($5\cdot10^{19}$ cm^{-3}) [10, 11]. Given that the diffusion coefficient of P in Ge ($\sim2.4\times10^{-11}$ cm^2/sec) [12] is much larger than that of Ga ($\sim3.5\times10^{-13}$ cm^2/sec) at temperatures of MOCVD growth, one can expect the appearance of a region with an inverse type conduction (*p*-Ge:Ga layer) near the *n*-GaInP/*n*-Ge interface (within *n*-Ge:P layer) (Fig. 4). Inversion of the conduction type in this region in the vicinity of the interface creates a potential barrier for electrons, which affects the charge carrier transport in the Ge SC. In the photovoltaic regime, the shift in this region corresponds to the inverse voltage bias.

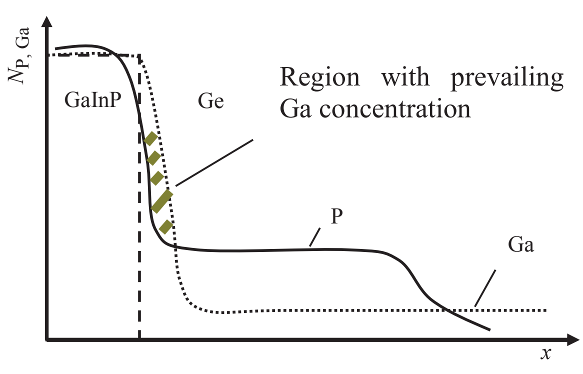

FIGURE 4. A schematic profile of the concentration distribution for P and Ga in a Ge substrate.

A schematic of the forbidden gap diagram with a potential barrier in the *n* GaInP/*n-p* Ge heterostructure is presented in Fig. 5. The potential barrier value of ~ 0.05-0.1 eV has been determined in [9] using temperature volt-capacitance measurements (spectroscopy of total conduction). The success of this method to identify potential barriers to the hetero-interface has been demonstrated in [13].

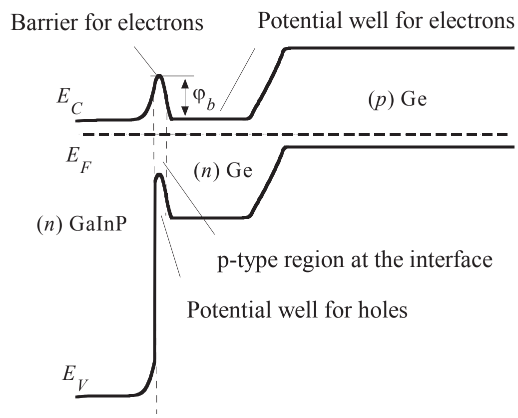

FIGURE 5. A schematic band diagram for the *n* GaInP/*n-p* Ge heterostructure.

TJ SC DARK IV AND ELECTROLUMINESCENCE

The computer simulation of the Ge subcell structure I-V characteristics featuring a typical band diagram and one having a potential barrier has shown that the barrier with a height of 0.1eV describes well the dark I-V curve both at 25 °C, at which the barrier disappears, and at -190 °C (Fig. 6). The dark I-V curves for *n* GaInP/*n-p* Ge heterostructures were simulated using the AFORS-HET software [14].

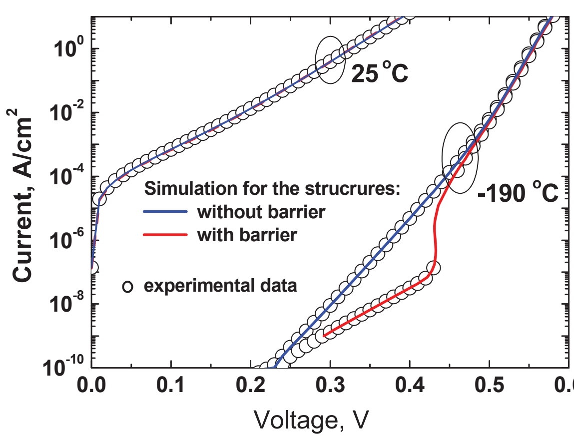

FIGURE 6. Simulated I-V curves for the heterostructures with and without a potential barrier at the *n*-GaInP/*n*-Ge interface at 25 °C and -190 °C.

At some critical value of the injected charge carrier concentration, a decrease in the potential barrier and, as a consequence, a drastic rise in a current flowing through the structure is observed. Accumulation of charge carriers can be stimulated by illuminating the structure. The rise in the light intensity results in an increase of the non-equilibrium charge carrier concentration at the *n*-GaInP/*n*-Ge interface and in the drop of the potential barrier height. In the photovoltaic regime, this region is under a reversed voltage bias, which explains the observed decrease in the "switching-in" voltage value with the light flux intensity at certain negative temperature (see fig.3).

The investigations of the TJ SC dark I-V characteristics with simultaneous registration of the electroluminescence (EL) have shown that, in taking the *n* GaInP/*n-p* Ge heterostructure to the break-down regime, a fast transition of EL distributed over the surface to a localized regime can be observed, which indicates a change in the current flow mechanism through the structure. In the presence of a reverse biased *p-n* junction in the *n* GaInP/*n-p* Ge structure, such a transition has evidence of thermal break-down, which usually have been observed on different reverse biased p-n junctions. The current flowing in the break-down region heats the "current channel", which can additionally enhance the local thermal break-down.

According to the surface non-homogeneity of the *n* GaInP/*n-p* Ge heterostructure and the potential barrier value, different scenarios of the EL transition to the local state were observed. So, the low temperature "break-down" can be characterized by both the insignificant redistribution of EL over the SC surface and the "point" localization (Fig.7).

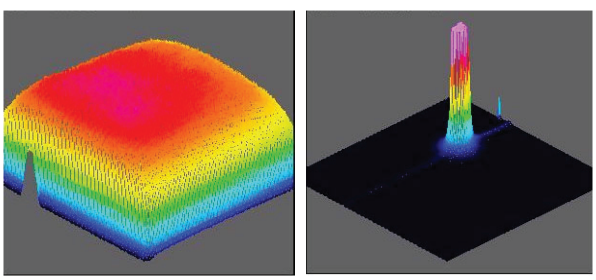

FIGURE 7. Uniform (left) and localized (right) EL distribution over the SC surface (-190 ^{o}C).

Thus, the results of the investigation confirm that according to a technological regime of growing *n* GaInP/*n-p* Ge heterostructures in TJ SCs, a potential barrier for photo-generated electrons can be formed. From the perspective of shape-formation of the TJ SC load I-V characteristics, this barrier plays a role of a p-n junction switched in the reverse direction, having properties that affect the temperature dependencies of the output photovoltaic parameters of concentrator SCs assigned for operation at high-intensity low-temperature (HILT) conditions. Moreover, the proposed electroluminescent method of control can then be used to determine the surface non-homogeneity in *n* GaInP/*n-p* Ge heterostructures.

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