Tuning of laser power converters efficiency by means of temperature

M Z Shvarts, V M Emelyanov, D A Malevskiy, M A Mintairov, S A Mintairov, M V Nakhimovich, P V Pokrovskiy, R A Salii, N A Kalyuzhnyy

Ioffe Institute, St. Petersburg, 194021, Russia
e-mail: shvarts@scell.ioffe.ru

Abstract. The results of studying the In$_{x}$Ga$_{1-x}$As laser power converters with the indium percentage of 18% and of 23% are presented. In the mode of 1064 nm laser radiation conversion the photovoltaic parameters dynamics with raising temperature is discussed.

1. Introduction

The temperature effect on operation efficiency of various photovoltaic (PV) converters ranging from solar cells (SCs) to detector-transducers of laser radiation (LR) has been widely discussed in the literature [1-7]. A SC, especially one converting a concentrated sunlight, is characterized by the operating temperatures increased up to +50 ÷ +90 °C, which the most notably leads to decrease in open circuit voltage, a change in current balance (in the multi-junction SCs), and a general decrease in the devices efficiency [1-4].

When transmitting laser energy by fiber optic lines, a photovoltaic detector-transducer operates under conditions similar to that of a concentrator SCs: a high power density on a small-sized device. For a laser power converter (an LPC) of 50-60% record-breaking efficiency, a significant fraction of the absorbed light energy is still converted into heat leading to overheating the LPC and changing its photovoltaic parameters. It should be noted here that, in practice, the maximum efficiency level for an LPC is achieved at spectral matching between the LPC maximum spectral response (SR) with an LR wavelength. The LR wavelength choice is determined by two main factors: the existence of powerful lasers and the ability to transfer energy over a long distance without loss. Here, the LR wavelength of 1064 nm is of the greatest interest. At this wavelength, there are high-power industrial lasers. Besides, this spectral line corresponds to both optical windows - the atmospheric transparency maximum (energy transfer by open channels through the atmosphere) - and the silica fiber absorption minimum [8, 9].

The LPC with extreme SR at 1064 nm can be fabricated based on such a narrow-gap A3B5 semiconductor materials as either GaSb or Ge and the InGaAsP quaternary compounds solution matched by the lattice parameter to InP, as well as based on the crystalline silicon [8, 10-14].

However, the listed above A3B5 materials have a very narrow bandgap (0.66–0.73 eV), which limits their efficiency due to high thermalization energy loss at the conversion of ~1.17eV (1064 nm) photons. For a Si-based LPC, such a loss is practically absent. Because of the spectral sensitivity maximum shifted towards the 1020-1040 nm wavelengths, there is a considerable loss in the light-to-current conversion process [15]. Some additional restrictions come from the high series resistance in converting light fluxes of a high density and a low voltage of the Si-based LPC, as well as from a strong degradation of the photovoltaic characteristics with increasing operating temperature.
The wavelength range of 1000–1100 nm can be overlapped by the LPC formed on the basis of the InGaAs strained metamorphic structures [16-18]. In such structures, the concept of a smooth decrease in the bandgap with an increase in the percentage of In in the InₓGa₁₋ₓAs solid solution could be implemented.

By varying the indium fraction within x ≈ 0.12-0.23 and tuning the photoactive layers thickness (to ensure complete absorption of radiation), it is possible to achieve the most efficient collection of photogenerated charge carriers for radiation of a given spectral range. Achievement of a high spectral sensitivity and a high LPC voltage simultaneously with the optimal percentage composition of indium has allowed the authors to demonstrate the In₀.₂₃Ga₀.₇₇As LPC with an efficiency of more than 50% when converting 1064 nm LR [18].

An LPC operation in the high-density LR conversion conditions leads inevitably to an increase in the device temperature [19, 20]. The fundamental processes coming next that lead to a shift in the red absorption edge of the material, a change in the spectral sensitivity at the LR wavelength, in the operating voltage, and the LPC efficiency as a whole [6]. Accordingly, one can choose such a composition of the InₓGa₁₋ₓAs material with x ≤ 0.24 for the LPC, with which at the standard temperature (+25°C) the edge of the spectral sensitivity will only partially “touch” the laser wavelength (see Figure 2 below). Thus, the maximum value of SR will be in the range of shorter wavelengths relative to the target LR line at 1064 nm. The use of the InₓGa₁₋ₓAs material with a wider bandgap will give an increase in the LPC voltage at +25°C. When the LPC switches to the operating temperature conditions (+50÷+100°C) the LR conversion efficiency will be determined by two processes caused by the shift of the fundamental absorption edge: an increase in SR with a corresponding rise in the photocurrent and a voltage drop. Therefore, at a certain temperature, a maximum efficiency should be expected for the InₓGa₁₋ₓAs LPC with a low In percentage.

The results of studying the temperature dynamics of the InₓGa₁₋ₓAs LPC (indium percentage of 18% and 23%) output parameters at converting 1064 nm high-power LR are presented below.

2. Experiment

Metamorphic InₓGa₁₋ₓAs structures were grown by the MOVPE on AIXTRON 200/4 reactor. The peculiarities of the technology were previously described in [21, 22] regarding the formation of metamorphic buffer layers on GaAs substrates. To study the temperature dependences of the photovoltaic parameters, the LPCs of two types were fabricated. The first type was based on the InₓGa₁₋ₓAs structure with x = 0.23 and efficiency of more than ~ 50% (25 °C, SR₁₀₆₄(ₜₚ) = 0.77A/W), and the second – on the structure with x = 0.18 and efficiency of ~ 42% (25 °C, SR₁₀₆₄(ₜₚ) = 0.54A/W), with the LR power of 2 - 7 W/cm² (see Figure 2 below). The LPC designated illumination area (DIA) was of 2.8 mm x 2.8 mm in size.

It should be noted that the presented efficiency values were obtained when recording the LPC I-V curves in the conditions of the pulse laser power supply mode. The time parameters of light pulses were the following: the duration of 200 μs, the duty cycle of 250, and the time of raising the light power along the leading edge of less than 50 μs. Pairs of current-voltage values for I-V curves were registered at the 10⁸th microsecond from the beginning of the pulse. To plot one complete I-V dependence, up to 50 light pulses were required. The mentioned above conditions excluded an uncontrolled increase in the LPC temperature due to radiation heating by a high-power LR. The principal diagram of the experimental setup for recording the LPC I-V curves in the pulsed LR conditions is shown in Figure 1.

In the experiment:
- the LPC being studied is installed at a thermostatically controlled base using a Peltier unit;
- the LR is fed to the LPC via 300 μm optical fiber with the terminal optical homogenizer providing a uniform distribution of light power density within the DIA of the sample;
- the controller sets the required thermal mode for the LPC within the temperature range +2 ∆ +125°C with an accuracy of +/-1°C monitored by the Pt100 temperature detector;
- the control driver of the laser provides an adjustment of the integrated light power at the LPC during the pulse period from 0.1 to 5 Watts.

Studying the LPC photosensitivity spectral dependences in the temperature range \(+2 \div +125^\circ\text{C}\) were carried out at a setup. The functional parameters of the setup are described in [23].

**Figure 1.** The principal diagram of the experimental setup for recording the LPC I-V under pulsed laser radiation and a controlled temperature conditions of samples.

**3. Results and discussion**

The spectral dependences of the photosensitivity of the In\(_{0.18}\)Ga\(_{0.82}\)As and In\(_{0.23}\)Ga\(_{0.77}\)As LPC samples for a discrete set of temperatures are shown in Figure 2. At +25°C, the SR value for the In\(_{0.23}\)Ga\(_{0.77}\)As LPC reaches its maximum at the LR wavelength of 1064 nm and practically does not change over the entire range of temperatures considered, remaining within 0.77 \(\div\) 0.78 A/W. Having a wider bandgap, at +25°C, the In\(_{0.18}\)Ga\(_{0.82}\)As LPC has an extremely low initial index for SR\(_{1064\text{nm}}\) = 0.54 A/W, which gradually increases with temperature to 0.75 \(\div\) 0.77 A/W at +75 \(\div\) +125°C. The latter means that for the In\(_x\)Ga\(_{1-x}\)As samples being studied, which differ from each other in the percentage of In by 5%, at elevated temperature they have equal light-to-current conversion coefficients.

**Figure 2.** Spectral response dependencies for In\(_{0.18}\)Ga\(_{0.82}\)As and In\(_{0.23}\)Ga\(_{0.77}\)As LPCs within 0 \(\div\) +125°C temperature range.
As for the values of the open circuit voltage ($V_{oc}$) and the fill factor ($FF$) of I–V curve, the same dynamics of the indicated parameters degradation with the coefficients “-1.54 mV/°C” and “-0.07 %/°C” is recorded for both samples, respectively.

After writing the LPC efficiency at a given LR power in the form

$$\eta(T) = SR(T) \cdot V_{oc}(T) \cdot FF(T)$$

(1)

it is getting evident that the nature of the change in the efficiency with temperature will be determined only by the SR (T) dependence: the In$_{0.23}$Ga$_{0.77}$As LPC efficiency monotonically decreases with increasing temperature, while for the In$_{0.18}$Ga$_{0.82}$As the LPC efficiency firstly increases to a maximum value at $T=+50 \div +75°C$ and then decreases in accordance with the course of the dependence $\sigma V_{oc}(T) \cdot FF(T)$ (Figure 3). As a result, the In$_{0.18}$Ga$_{0.82}$As LPC efficiency values turn out to be higher than the same values for the In$_{0.23}$Ga$_{0.77}$As LPC in the temperature range above +50°C typical for operating the devices during the conversion of high-power continuous or pulsed laser radiation.

![Figure 3](image)

**Figure 3.** Temperature dependencies of open circuit voltage $V_{oc}$ (a) and efficiency (b) of LPC at conversion of 1064 nm laser light. Integral laser power for 2.8x2.8 mm$^2$ LPC is 175 mW (2.5W/cm$^2$).

4. Conclusion

The results of studying the metamorphic In$_x$Ga$_{1-x}$As LR LPC (1064 nm) characteristics at elevated temperatures were presented. It has been shown that the decrease in the LPC efficiency due to the fundamental processes occurring in the semiconductor In$_x$Ga$_{1-x}$As material can be effectively used (shift of the absorption edge) or compensated (reduction of the open circuit voltage) by selecting the percentage of In. A relatively wider bandgap of the In$_{0.18}$Ga$_{0.82}$As ($E_g \approx 1.25$eV at +25°C) material (versus that of the In$_{0.23}$Ga$_{0.77}$As with $E_g \approx 1.09$eV at +25°C) allows one to obtain higher voltages in the LPCs. The temperature drift of the absorption edge to the long-wavelength region simultaneously provides an increase in the spectral response at a laser wavelength of 1064 nm. The combination of these processes allows, at a certain temperature (within +50 ÷ +100°C) of the In$_{0.18}$Ga$_{0.82}$As LPC, to guarantee its maximized efficiency. Moreover, that value overcomes the same PV parameter for the In$_{0.23}$Ga$_{0.77}$As LPC, which is more effective at +25°C.

Acknowledgments

The reported study was funded by RFBR, project number 19-08-00881.
References

[1] Garcia I, Victoria M, and Antón I, 2016 Handbook on Concentrator Photovoltaic Technology, ed. C Algora and I Rey-Stolle (Chichester, West Sussex, UK: John Wiley & Sons, Ltd) p 245

[2] Fernández E, Siefer G, Schachtner M, Garcia Loureiro A and Pérez-Higueras P 2012 AIP Conf. Proc. 1477 189

[3] Siefer G and Bett A 2012 Prog. Photovolt. Res. Appl. 22 515–524

[4] Helmers H, Schachtner M, Bett A 2013 Sol. Energy Mater. Sol. Cells 116 144-152

[5] Mukherjee J, Jarvis S, Perren M and Sweeney S 2013 J. Phys. D: Appl. Phys. 46 264006

[6] Höhn O, Walker A, Bett A, and Helmers H 2016 Appl. Phys. Lett. 108 241104

[7] Guangji L, Chengmin W, Jian L and Hongchao Z 2019 AIP Advances 9 095053

[8] Pena R, Algara C 2005 Proc. of the 20th EUPVSEC 488–491

[9] Summerler L and Purcell O 2009 Concepts for wireless energy transmission via laser Europeans Space Agency (ESA)-Advanced Concepts Team

[10] Jomen R, Tanaka F, Akiba T, Ikeda M, Kiryu K, Matsushita M, Maenaka H, Dais P, Lu S and Uchida S 2018 Jpn. J. Appl. Phys. 57 08RD12

[11] Andreev V, Khvostikov V, Kalinovsky V, Grikhes V, Rumyantsev V, Shvarts M, Fokanov V, Pavlov A 2003 Proc. of WCPEC-3 3P-B5-33

[12] Khvostikov V, Sorokina S, Khvostikova O, Levin R, Pushnyi B, Timoshina N, and Andreev V 2016 Semiconductors 50 1338-43

[13] Emelyanov V, Mintairov S, Sorokina S, Khvostikov V, Shvarts M 2016 Semiconductors 50 125-131

[14] Emelyanov V, Sorokina S, Khvostikov V, Shvarts M 2016 Semiconductors 50 132-137

[15] Green M, Zhao J, Wang A, and Wenham S, 1992 Electron Device Lett. 13 (6) 317–318.

[16] Kalyuzhnyy N, Emelyanov V, Mintairov S and Shvarts M, 2018 AIP Conf. Proc. 2012 110002

[17] Kim Y, Shin H-B, Lee W-H, Jung S, Kim C, Kim H, Lee Y, Kang H 2019 Sol. Energy Mater. Sol. Cells 200 109984.

[18] Kalyuzhnyy N, Emelyanov V, Evstropov V, Mintairov S, Mintairov M, Nahimovich M, Salii R and Shvarts M 2019 AIP Conf. Proc. 2149 050006

[19] Panchak A, Pokrovskiy P, Larionov V, Malevskiy D and Shvarts M 2018 AIP Conf. Proc. 2012 040009

[20] Mintairov M, Evstropov V, Mintairov S, Shvarts M, Kalyuzhnyy N 2018 J. Phys. Conf. Ser. 1135 012070

[21] Rybalchenko D, Mintairov S, Salii R, Shvarts M, Timoshina N and Kalyuzhnyy N 2017 Semiconductors 51 93-99

[22] Kalyuzhnyy N, Mintairov S, Nadtochiy A, Nevedomskiy V, Rybalchenko D, Shvarts M 2017 Electron. Lett. 53 (3) 173-175.

[23] Levina S, Emelyanov V, Filimonov E, Mintairov M, Shvarts M, Andreeev V, 2020 Sol. Energy Mater. Sol. Cells 213 110560.