OPTOELECTRONICS LETTERS Vol.13 No.1, 1 January 2017

A six-junction GaAs laser power converter with different sizes of active aperture*

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(Received 7 September 2016; Revised 18 October 2016)

We investigate a novel GaAs-based laser power converters (LPCs) grown by metal-organic chemical vapor deposition (MOCVD), which uses a single monolithic structure with six junctions connected by tunnel junctions to obtain a high output voltage. The LPCs with diameters of active aperture of 2 mm and 4 mm were fabricated and tested. The test results show that under an 808 nm laser, two LPCs both show an open circuit voltage of above 6.5 V. A maximum power conversion efficiency of 50.2% is obtained by 2 mm sample with laser power of 0.256 W, and an output electric power of 1.9 W with laser power of 4.85 W is obtained by 4 mm sample. The performances of the LPCs are deteriorated under illumination of high flux, and the 4 mm sample shows a higher laser power tolerance.

Document code: A **Article ID:** 1673-1905(2017)01-0021-4

DOI 10.1007/s11801-016-6193-8

In the laser power converter (LPC) system, the laser transmits wirelessly or through an optical fiber and is received by the LPC which then converts the optical energy into electrical energy for remote use[1,2]. The LPC system shows advantages of high temperature tolerance, good electrical insulation, strong anti-interference ability and low optical power transmission loss, making it extremely suitable to be used in the place of anti-electromagnetic interference or where needs electronic devices under ambient conditions applied for isolation[3-5].

Many kinds of photovoltaic devices, such as Si and CdTe cells, have been applied for LPC system, while these kinds of LPCs exhibit low power conversion efficiency. Unlike above materials, GaAs with a bandgap of 1.43 eV can absorb the light with wavelength between 800 nm and 850 nm supplied by the commonly high power laser with an internal quantum efficiency as high as 95%, which makes GaAs become the optimal material used for obtaining high power conversion efficiency of LPCs[6]. Besides, GaSb and InP based LPCs were also used for converting the laser power at 1 550 nm, while this kind of laser has a relatively low optical power compared with that of the GaAs based lasers, which limits the maximum converted electrical power of LPC, and the output voltage was around 0.55 V due to the small bandgap of the materials in the active region[7,8].

The single junction GaAs based LPC has an open circuit voltage of about 1 V[9], while the electronic systems usually need a high driving voltage, such as 6 V. To obtain a high output voltage, one choice is to connect multiple GaAs cells together by metal wire to sum their voltages. An output voltage of 4 V has been realized for LPCs by connecting four single AlGaAs/GaAs and AlGaAs/AlGaAs cells[10], and 5 V has been obtained by connecting four single GaAs cells[11]. While this type of LPC shows a large light receiving area, adding difficulty in the application of LPC system based on fiber, and the space between each cell cannot contribute for absorbing the laser power, which caused a power loss of the entire system. Another design to obtain a high output voltage is to divide the active area into multiple pie-shaped cells on chip. Each cell is electrically isolated by deep isolation trenches, and then metalized to connect adjacent cells in-series. It was reported that a six pie-shaped cells show an output voltage of 6 V[12]. However, the deep etching will inevitably introduce some damages to the edge of

* This work has been supported by the National Natural Science Foundation of China (Nos.61376065 and 61604171), and Zhongtian Technology Group Co. Ltd.

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device, and may cause a current leakage. And the trench region will reduce the total light receiving area of the LPC, resulting in larger optical power loss.

In this work, we investigate a novel design of GaAs-based LPC to convert the laser power at 808 nm into electrical power, which uses a single monolithic structure with six junctions to increase the power conversion efficiency and the output voltage. Unlike the multiple GaAs cells connected together by metal wire, this novel LPC can be easily fabricated with a small light receiving area, which facilitates the utilization of the fiber based system. Compared with pie-shaped LPCs, the sub cell does not have to be isolated by deep etching and connected by the electrode climbing, which shows a much simpler process and a reduced production cycle time and cost. Besides, LPCs with sub cells connected by junction has a smaller series resistance, which improves the quantum efficiency and increases the fill factor (*FF*) of the device.

The epitaxial structure of the LPC was grown on GaAs substrates by a metal-organic chemical vapor deposition (MOCVD) system (Aixtron 200/4) at 675 °C. Trimethylgallium (TMGa) and trimethylaluminum (TMAl) were used as III group precursors, and arsine (AsH_3) was used as V group sources. Diethylzinc (DEZn) and carbon tetrabromide (CBr_4) were used as p and n type doping sources, respectively. Ultra high purity hydrogen (H_2) was used as the carrier gas in the reactor. Fig.1 shows the basic structure of the LPC. Six sub cells using GaAs as the active region were connected by $Al_{0.37}Ga_{0.63}As$/GaAs tunnel junctions, and these sub cells have different thicknesses depending on their positions. The laser can be absorbed by GaAs as $I=I_0\exp(-\alpha x)$, where I is the transmitted laser power, I_0 is the laser power at the surface of the GaAs, α is the absorb coefficient, and x is the transmitted depth of laser from the surface. In this work, the thickness of the sub cell was designed to absorb 15% of the incident laser power. A cap layer of 50-nm-thick n-doped GaAs was deposited on the surface to form the ohmic contact with metal.

The device fabrication started by etching a 35-μm-wide trench by inductively coupled plasma (ICP) etching using positive photo resist AZ4620 with a thickness of 7 μm as a mask. The Cl_2/BCl_3 mixture gases were utilized as the etching gas at flow rates of 6/14 cm^3/min, respectively. The cross section of the LPC after ICP etching was measured by scanning electron micrograph (SEM) as shown in Fig.2. It shows that the etching depth is about 6 μm which is deep enough to expose the entire active region of the LPC. The sidewall angle is about 75°, which is beneficial for the subsequent sidewall passivation realized by depositing 200-nm-thick SiN by plasma enhanced chemical vapor deposition (PECVD).

After passivation, AuGe/Ni/Au with a total thickness of 300 nm was evaporated on the top of the mesa by electron beam evaporation to form the N-type contact. In this work, two kinds of electrode structures are utilized for LPC with different light receiving areas as shown in Fig.3. All samples both have light receiving areas with circle shape, and the diameters of the circles for samples A and B are 2 mm and 4 mm, respectively. For both samples, the grid lines have a width of 6 μm and distribute parallelly with each other by a distance of 100 μm. The perpendicular lines are also introduced to reduce the resistance of the metal grid lines for these two samples.

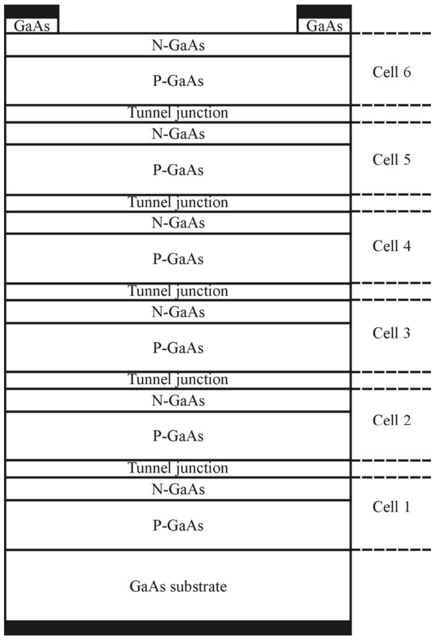

Fig.1 Schematic diagram of the cross section of the fabricated LPC

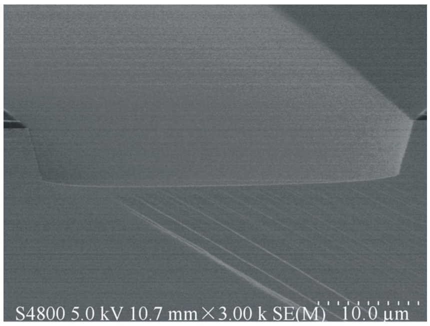

Fig.2 SEM image of the cross section of the LPC after ICP etching

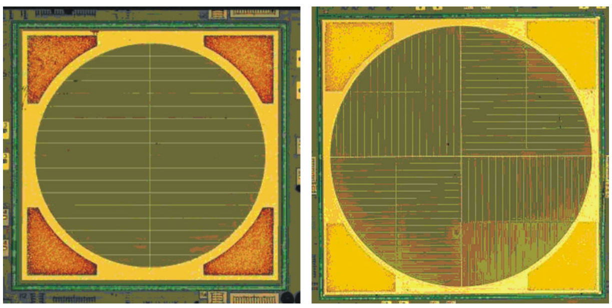
(a) (b)

Fig.3 Microscope images of (a) sample A with the diameter of the active aperture of 2 mm and (b) sample B with the diameter of the active aperture of 4 mm

To further decrease the series resistance of the device, the electrode was thickened by Ag-Au with a thickness of 2 μm. Then the LPC was thinned to 200 μm at the back side, and the AuGe/Ni/Au with a total thickness of 250 nm was evaporated to form the N-type contact. After that, the samples were annealed in N_2 environment at 420 °C for 90 s to form the ohmic contacts.

The cap layer between the grid lines was etched away using wet etching method, and then an antireflection (AR) coating of double layers were evaporated on the surface of the samples. The materials chosen for the AR coating were SiO_2/TiO_2, and the thicknesses of the double layers were 90/60 nm which was optimized for minimum reflectivity under illumination of 808 nm laser. The reflectance spectra of the LPCs with and without AR coating are measured by a spectrometer, and the results are shown in Fig.4. The reflectance of LPC without AR coating is about 45%, and it is reduced to about 20% after depositing the AR coating, since the area of the optical spot is about 5 mm×5 mm, some of the optical power can be reflected by the electrode. To eliminate the effect of electrode on the reflectivity, a test sample without electrode is also measured. The result shows that the reflectivity is below 3% at the wavelength around 810 nm, indicating that the designed AR coating is effective to reduce the reflectivity.

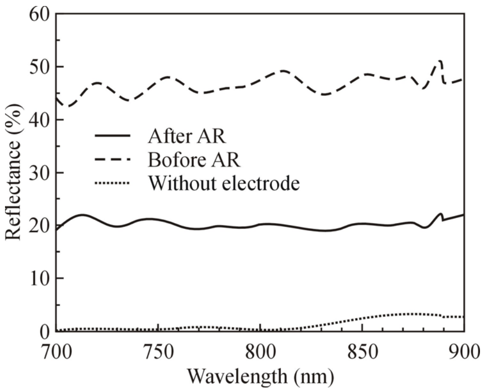

Fig.4 Reflectance spectra of the LPCs with and without AR coating and without electrode

After the fabrication process, the current-voltage (*I-V*) characteristic curves of the two samples with different active apertures are measured under 808 nm laser at room temperature. Fig.5(a) shows the *I-V* characteristics of sample with an aperture diameter of 2 mm, and it can be seen than the light induced current of the LPC increases to 0.29 A by increasing the laser power from 0.256 W to 3.840 W. An output electric power of 1.12 W is obtained under illumination of 3.840 W as shown in Fig.5(b). Besides, Fig.5(b) shows that the maximum *FF* and power conversion efficiency of the LPC are 86% and 50.2%, respectively, which are both obtained at 0.256 W. The maximum output electric power, *FF* and power conversion efficiency of this LPC are much higher than those of six-pie shaped LPC which also have an aperture diameter of 2 mm[12].

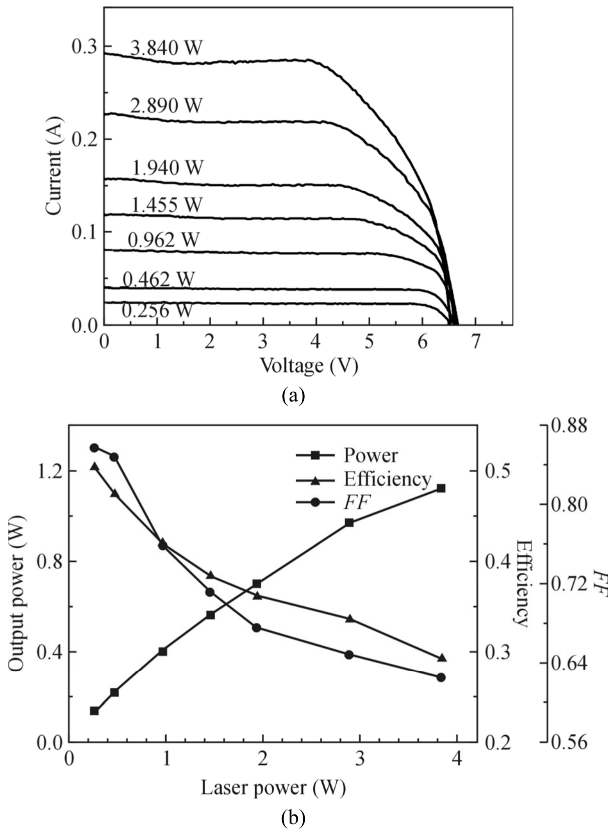

Fig.5 The photoelectric properties of sample with the aperture diameter of 2 mm: (a) *I-V* characteristics; (b) output power, *FF* and power conversion efficiency as function of laser power

Under a high laser power, the *I-V* curve exhibits a slow roll-off at a low bias voltage. *FF* and the conversion efficiency both decrease accordingly with the increase of laser power. The slow roll-off of the *I-V* curve in multijunction solar cells is usually caused by a current leakage, while this is not the main reason for our LPC, since the slow roll-off of the *I-V* curve cannot be seen under a low laser power[13]. The slow roll-off of the *I-V* curve indicates that the dominant performance limiting factor in this sub cell under high illumination is series resistance which results in an enhanced losses at high flux[14]. Besides, the open circuit voltage of the LPC is around 6.5 V and increases as increasing the laser power at low flux, while it begins to decrease at high flux due to a temperature rising[15].

Fig.6(a) shows the *I-V* characteristics of sample B with an aperture diameter of 4 mm, and the open circuit voltage of the LPC is above 6.5 V. An obviously difference with the sample with an aperture diameter of 2 mm is that the sample with an aperture diameter of 4 mm sample does not show a slow roll-off, which is attributed to the reduced laser power density because of a larger active aperture of the LPC. Besides, the 4 mm sample exhibits a higher laser power tolerance, since the *FF* and power conversion efficiency decrease much slower with increasing the laser power. A tip appears in the *I-V* curve of 4 mm sample when the laser power is above 4.08 W, indicating a current confinement by tunnel junction when the light induced current is above the peak current of the tunnel junction[16] and the performance of this LPC can be further improved by increasing the peak current of tunnel junction. Fig.6(b) shows that the 4 mm sample has a maximum electric power of 1.9 W at a laser power of 4.85 W, which is the maximum power that the laser can afford in our test. It is beneficial for the system to be charged quickly using the LPC with a high output power. The *FF* and power conversion efficiency shown in Fig.6(b) are much higher than those in the 2 mm sample under high illumination, indicating an improved performance of LPC obtained by increasing the active aperture.

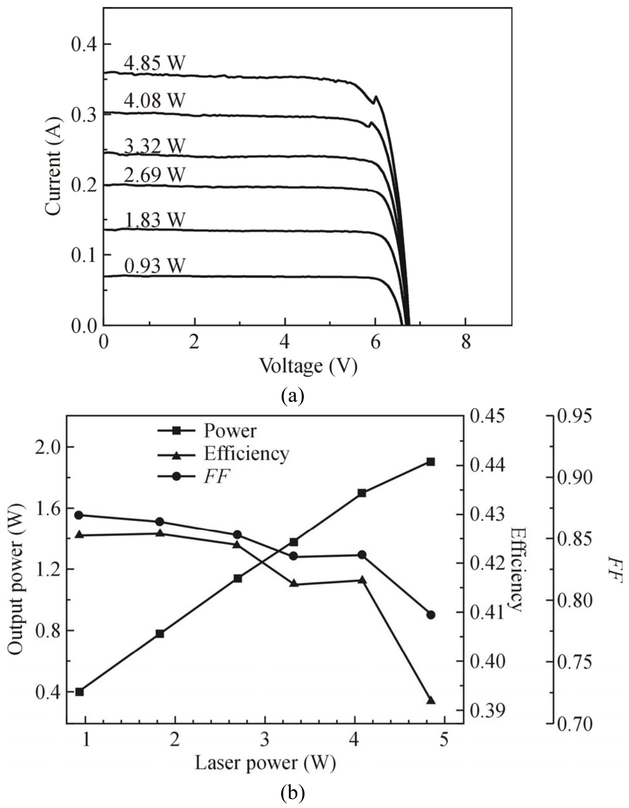

Fig.6 The photoelectric properties of sample with the aperture diameter of 4 mm: (a) *I-V* characteristics; (b) Output power, *FF* and power conversion efficiency as a function of laser power

The AlGaAs/GaAs and GaAs cells connected together by metal wire both show high output voltage (both above 4 V) and high output power (7 W for AlGaAs/GaAs cell and 1 W for GaAs cells), while the light receiving area are much bigger compared with our LPCs, which are 400 mm^2 and 40.8 mm^2 for AlGaAs/GaAs and GaAs cells, respectively. At the same incident power density, our LPCs also show a higher *FF* than the AlGaAs/GaAs and GaAs cells, which can be attributed to a reduced series resistance loss by using tunnel junctions[10,11]. The high output voltage, small light receiving area, high incident power density, improved *FF* make our LPC become an optimal device using the fiber based charging system.

In conclusion, a novel design of six-junction GaAs-based LPC which is used to convert 808 nm laser power to electric power is grown by MOCVD. The *I-V* curves of the LPCs with diameters of active aperture of 2 mm and 4 mm are measured at a series of laser powers, and the LPCs show an open circuit voltage of above 6.5 V. A maximum power conversion efficiency of 50.2% is obtained by the 2 mm sample under 0.256 W laser, and an output electric power of 1.9 W under 4.85 W laser is obtained by the 4 mm sample. Under high illumination, the performance of the LPC can be improved by increasing its active aperture.

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