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Influence of the mesa electrode position on monolithic on-chip series-interconnect GaAs laser power converter performance

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ABSTRACT

Monolithic on-chip series-interconnect (MOS) technology is the most mature technology for the fabrication of muti-junction laser power converters. In this study, we focused on the effect of mesa electrodes prepared at different positions on the GaAs laser power converter performance. First, an optimized epitaxial structure was prepared, and then, two different structure six-junction MOS laser power converters were separately fabricated. The test results that structure1 which mesa electrode at the base layer has 41.5% efficiency compare to structure2 which at the lateral conduction layer (LCL)has 37.4% efficiency. The characteristic data statistics of the 95 samples with two structures indicated that structure1 produces a higher output power and exhibits better performance characteristics.

According to the theoretical models of the two structures, the root cause is that structure1 has a lower series resistance. Additional simulated results show that when the base doping concentration is higher than 5.1×10^{16} cm^{-3}, structure1 has a smaller series resistance and better performance characteristics. According to the conclusions in this study, we can further improve the output performance of laser power converters, especially in larger area laser power converters.

1. Introduction

Ultra-high photoelectric conversion efficiency can be achieved with photovoltaic cells using monochromatic light instead of wide-spectrum light for different types of semiconductor materials with different band gaps [1–10].

Laser is an ideal monochromatic optical source because it has the characteristics of mono-chromaticity and strong brightness. Using the reflection characteristics of fiber optics, laser energy can be remotely transferred to a laser power converter, and power over fiber technology can be realized. In addition, because the fiber has insulation, anti-corrosion, and non-flammability characteristics, it can be applied in special environments with high voltages power, corrosive surroundings, low pressures (e.g., outer space) and other special circumstances [11–13,20].

Electronic circuits or sensors are typically driven at a relatively high voltage of + 5 V. Thus, a laser power converter must serially connect several sub-cells to fabricate a multi-junction photovoltaic cell to satisfy this high-voltage requirement [9]. Monolithic on-chip series-interconnect (MOS) technology is the most mature technology for the fabrication of multi-junction laser power converters [7–12]. This technology uses an isolation gap to form multiple sub-cells on the semi-insulating (SI) substrate, and the sub-cells are then laterally connected to each other in series. In general, a thicker and heavily doped lateral conduction layer (LCL) is necessary to achieve lateral current movement with a low resistance loss (i.e., more than a few micrometers). In addition, deep etching techniques are essential in the MOS laser power converter to prepare the isolation gap and mesa electrode to realize the coplanar serial connection between each sub-cell. In this paper, we focus on the different positions of the mesa electrode and their influence on the performance of the MOS laser power converter.

2. The MOS laser power converter and mesa electrode

MOS laser power converters based on GaAs materials are commonly used to absorb monochromatic light in the red or near-infrared wavelength range (700–870 nm) [2–8]. The classic multi-junction MOS laser power converter structure, as shown in Fig. 1, is based on the SI substrate and the prepared isolation gap that penetrates to the SI substrate to achieve electrical isolation. Then, the mesa is exposed by etching technology, and the bottom electrode is prepared on the mesa and formed mesa electrodes. The mesa electrodes must be located beneath

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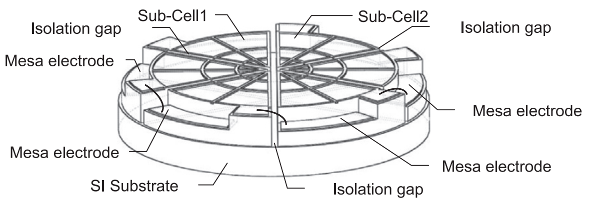

Fig. 1. The classic GaAs-based multi-junction MOS laser power converter structure, which is based on an SI substrate, isolation gap and mesa electrode.

the P/N junction to interconnect with the upper electrodes of the next sub-cell in the string to supply a high-voltage output, as shown in Fig. 1.

In general, two different positions have been used for the mesa electrode in MOS laser power converters in previous studies, as shown in Fig. 2. In the first, the mesa electrode is on the base layer (designated as structure1), as shown in Fig. 2a and described by Peña and Algora [16,17]. In the second, the mesa electrode is on the LCL (designated as structure2), as shown in Fig. 2b and described by Oliva and Wojtczuk [18,19]. Most previous works have suggested that the mesa electrode should be located in the LCL mainly because the layer has a heavy doping concentration and can more easily form ohmic contacts with a lower contact resistance. In fact, the two different mesa electrode positions have different effects on the performance of MOS laser power converters. Prior to this study, a report has not discussed the difference in the output performances of MOS laser power converters with structure1 and structure2. Thus, we discuss this difference based on actual tests and theoretical model with laser power converters with these two structures.

3. Fabrication of laser power converters with two different structures

To better compare the performance differences between the two different structures, six-junction MOS laser power converters were first prepared.

An optimized epitaxial structure was designed, and a classic p-on-n structure for GaAs laser power converter was chosen [21], as shown in Fig. 3. A 0.25 µm thick inner reverse barrier layer was an innovation introduced to further increase the insulation of the SI substrate, and a 3 µm thick GaAs N++ LCL heavily doped ($> 1.8 \times 10^{18}\ cm^{-3}$) with silicon (Si) was grown on the reverse barrier layer. This layer should have a lower sheet resistance to push the high lateral current flow from the mesa electrode to the upper contact grid. A 0.15 µm thick back-surface field (BSF) layer was chosen to reduce the back-surface recombination velocity and improve the efficiency of the MOS laser power converters. A 3.3 µm thick base layer heavily doped ($> 1 \times 10^{17}\ cm^{-3}$) with Si was grown on the BSF layer, and then, a 0.2 µm thick zinc (Zn)-doped GaAs emitter layer with a doping concentration of $> 1.8 \times 10^{18}\ cm^{-3}$ was grown on the base layer. A high-conductivity GaInP window layer, which is required to maintain a low series resistance and to provide transparency for the incident light, was grown on the emitter layer. Finally, a 0.5 µm thick heavily doped cap layer, which forms a better ohmic contact with a doping concentration of $> 1 \times 10^{19}\ cm^{-3}$ with Zn doping, was grown on the window layer. The total thickness of the active layer in optimized epitaxial structure was 8 µm, and this thickness was suitable for the dry etching process.

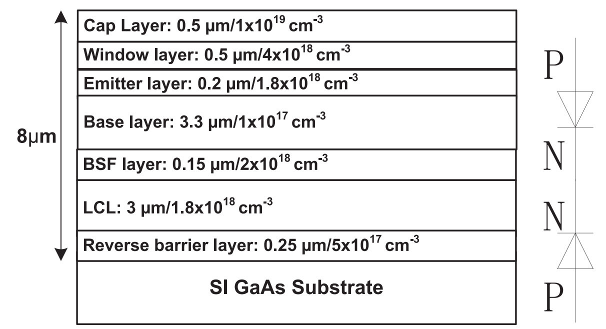

Fig. 3. A classic p-on-n epitaxial structure for the GaAs MOS laser power converter. The total thickness of the active layer was 8 µm. The reverse barrier layer was an innovation introduced to further increase the insulation characteristics of the SI substrate.

Then, the epitaxial structure was prepared in a multi-wafer metal oxide chemical vapor deposition reactor (AIXTRON: CCS6 × 2) on an SI GaAs substrate {100} with a misorientation of 6° towards the {111} plane. With trimethylgallium (TMGa) and trimethylindium (TMIn) and trimethylaluminium (TMAl) as the III compound sources, arsenic trihydride (AsH_3) and PH_3 as the V compound sources, silicon tetrahydride (SiH_4) as the doping source for the N-type material, and diethylzinc (DeZn) as the doping source for the P-type material, the reactor pressure was maintained at 1×10^5 Pa. Hall effect measurements were performed to check the electron concentration and mobility of the Si-doped and Zn-doped layers.

Lastly, the six-junction MOS laser power converters were prepared as shown in the scanning electron microscope (SEM) micrograph in Fig. 4a. The preparation process was complex and required at least seven photolithography processes [17]. The detailed preparation process was similar to the process sequence described by Schubert [18]. In the first photolithographic and dry etch step, the mesa layer was uncovered. Then, the six sub-cells were separated by an isolation gap in a second etching process. Silicon nitride films were used as side passivation to prevent side carrier recombination, and a photo-definable

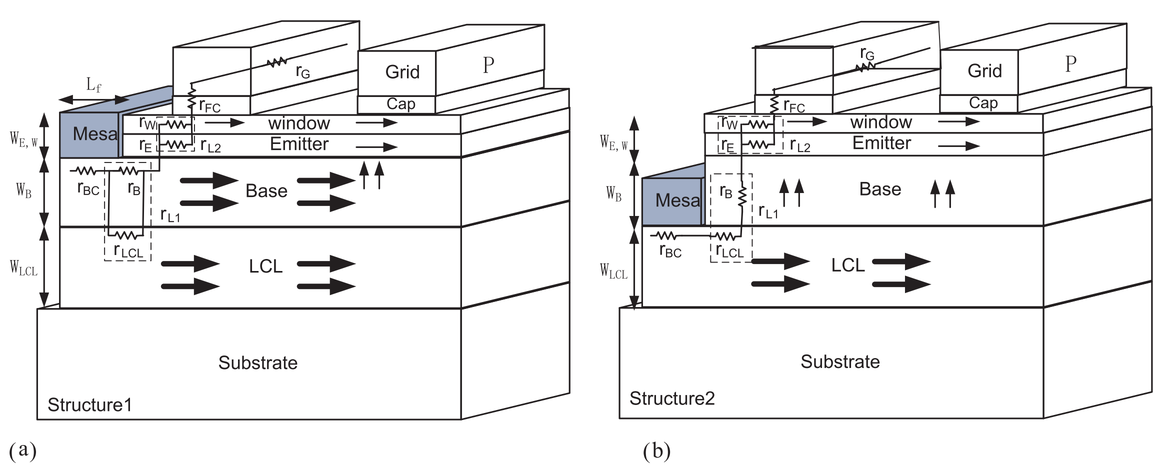

Fig. 2. Two types of mesa electrodes in different positions in a MOS laser power converter. 2a is a mesa electrode at the base layer (designated as structure1), and 2b is the mesa electrode at the LCL (designated as structure2).