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Photovoltaic Cells with Increased Voltage Output for Optical Power Supply of Sensor Electronics

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Abstract

An elegant solution for the power supply of sensor electronics is the application of power-by-light technology. With this technology several challenges related to conventional copper wiring are inherently overcome; benefits are galvanic isolation, the suppression of electromagnetic interference, and the possibility to combine power and bidirectional data transmission in a single fiber link.

In order to power sensor electronics efficiently, a supply voltage in the range 3 to 12 V is typically required. This paper deals with the photovoltaic laser power converter used to convert the transmitted optical power back into electricity. The advanced cell concepts of multi-junction and multi-segment cells are discussed which both aim at an increased output voltage on the device level, thereby eliminating the need for additional DC/DC conversion. Modeling and experimental results of GaAs based cells are presented, namely of single-junction 2- to 12-segment cells as well as of a dual-junction single-segment structure. A discussion of the pros and cons of the different concepts is given, focusing on the consequences of misalignment and temperature changes.

Key words: Laser power converter, misalignment, multi-junction, multi-segment, photovoltaic cell, power by light, temperature, voltage.

Introduction

One important aspect in sensor design is the power supply. Besides conventional copper wiring, an elegant solution is to power the sensor electronics optically. This can be realized by optical power transmission of laser light from the base station to a photovoltaic receiver located at the sensor which converts the monochromatic laser light back into electricity.

With such power-by-light technology several challenges related to conventional copper wiring are inherently overcome, such as electromagnetic interference, the risk of short circuits and sparks, or susceptibility to corrosion. Furthermore, it provides galvanic isolation, lightning protection, weight reduction, the possibility of wireless powering, and the compatibility with rotating systems. An additional benefit is the possibility to combine power and bidirectional data transmission into a single fiber link. Fields of application are manifold: Examples are structural health monitoring of wind turbines [1, 2], fuel gauges in aircraft wings [3], monitoring of high voltage power lines [4, 5], optical powering of automotive sensors [6], biosensors in smart implants [7-9], monitoring of passive optical networks [10], and fully optical sensor networks [11, 12].

In order to power sensor electronics efficiently, a supply voltage in the range 3 to 12 V is typically required. This paper deals with photovoltaic laser power converters used in power-by-light technology. Two advanced cell concepts, namely multi-junction and multi-segment cells, are discussed which aim at an increased output voltage on the device level, thereby eliminating the need for additional DC/DC conversion. Experimental and modeling results of GaAs based cells are presented, namely of single-junction 2- to 12-segment cells as well as of a dual-junction single-segment cell. The paper concludes with a discussion of pros and cons of these concepts, focusing on the consequences of misalignment and temperature changes.

Photovoltaic Laser Power Converters

With photovoltaic cells as power converters for monochromatic light, very high opto-electrical conversion efficiencies can be achieved because the semiconductor material's bandgap can be well matched to the energy of the photons. With III-V compound semiconductors, a broad range of bandgap energies from below 0.3 to 2.5 eV is covered, corresponding to laser wavelengths in the range 0.5 to 4 µm. With an adjusted design, thermalization and transmission losses, as the main loss mechanisms in solar cells, can be minimized due to the matching of bandgap and photon energy. A plot of the monochromatic efficiency of an idealized laser power converter is shown in Fig. 1 as a function of laser wavelength for different irradiances. The curves are calculated in the detailed balance limit [13] under the assumptions of monochromatic irradiance, a semiconductor bandgap E_g that matches the laser wavelength λ ($E_g=hc/\lambda$), full absorption of the incident photons, each absorbed photon contributes one charge carrier to the photo current ($IQE=EQE=1$), and radiative recombination only [14]. As can be seen in the plot, the ideal conversion efficiency in the detailed balance limit evaluates to values above 80% for an irradiance of 100 W/cm². It is remarked that for practical devices somewhat lower values are expected. However, a comparison with the detailed balance limit for an ideal single-junction solar cell under one sun illumination, which is 33% [15], reveals the possibilities of monochromatic light conversion.

A semiconductor material that is frequently used for laser power converters is GaAs. With a bandgap of 1.42 eV it is well matched for the 800-850 nm wavelength range. Due to its vast use in micro- and optoelectronics, it is a well-known material and available in excellent quality. At Fraunhofer ISE, a conversion efficiency of 57.4% was achieved with a GaAs based photovoltaic laser power converter under 805 nm laser light at an irradiance of 124.0 W/cm². For comparison, the highest reported opto-electrical conversion efficiency of a solar cell is 46% under concentrated light [16, 17].

A drawback of photovoltaic cells, however, is the output voltage of a single cell. For a GaAs based photovoltaic cell it is about 1 V. In contrast, to power sensor electronics efficiently, supply voltages in the range 3 to 12 V are required. To overcome this limitation, photovoltaic laser power converter devices with an increased voltage output were developed. An increased output voltage can be achieved by connecting several subcells in series. That way the output voltage of the string corresponds to a multiplication of the single cell voltage with the number of subcells. A monolithic series connection can be implemented by vertical stacking of subcells (multi-junction cells) or by lateral segmentation (multi-segment cells, also known as monolithic interconnected modules, MIMs) [18]. In the following section these two concepts are introduced.

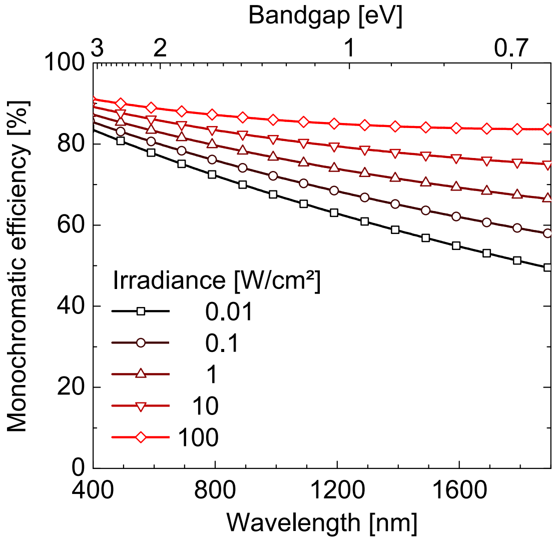

Fig. 1. Detailed balance calculation of the monochromatic efficiency of ideal laser power converters in the radiative limit. Assumptions: Monochromatic irradiance, $E_g=hc/\lambda$, full absorption of the incident photons, each absorbed photon contributes one charge carrier to the photo current (IQE=EQE=1), dark current determined by radiative recombination only. After Ref. [14].

Cell Concepts for Increased Voltage Output

To realize vertically interconnected stacks, the subcells are grown monolithically on top of each other on a conductive substrate [18]. Fig. 2 shows a cross section of a dual-junction structure as an example. In between each pair of subcells a tunnel junction is implemented to establish a low-loss series connection. The contacts to the device are established by metallization of front and back side of the device. To improve lateral conduction to the front grid fingers, a transparent lateral conduction layer can be implemented above the top cell [18, 19]. Due to the growth of several subcells of different thicknesses and the necessity of tunnel diodes in between, the epitaxial growth of multi-junction cells is rather complex. The manufacturing, however, is similar to single-junction cell processing.

To realize multi-segment cells or monolithic interconnected modules (MIMs) [20], the photovoltaic cell structure is grown on semi-insulating substrate. Fig. 3 illustrates the interconnection scheme. The electrical separation of the individual subcells is created by etching isolation trenches through the

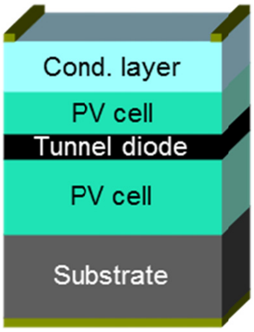

Fig. 2. Cross section of a symmetry element of a stacked dual-junction structure. The two subcells are interconnected via a tunnel diode. An upper conduction layer improves the lateral conduction to the front grid metallization.

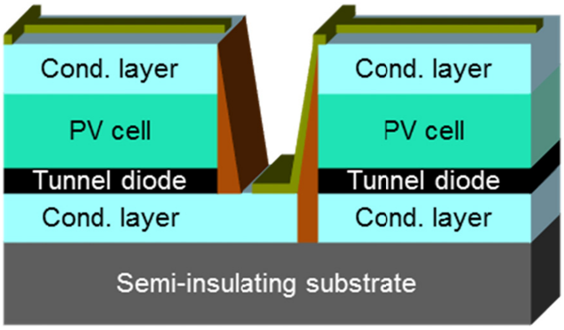

Fig. 3. Schematic illustration of the interconnection scheme of monolithic interconnected modules to realize multi-segment cells.

structure into the semi-insulating (non-conductive) substrate [18, 21]. Below the photovoltaic cell, a highly conductive lateral conduction layer is implemented and connected with a tunnel diode. To contact the back side of the subcells this layer is partially exposed during manufacturing. The flanks of the etched trenches are protected using a dielectric material. The series connection is finally realized via a front metallization which interconnects the lower conduction layer as the back contact of one subcell with the front grid of the adjacent subcell. Similar to multi-junction cells a transparent lateral conduction layer above the photovoltaic cell improves conduction to the front contact. In total, the epitaxial structure for multi-segment cells is of moderate complexity. However, the manufacturing is rather complex: At least six photolithography steps are required which is twice as much as is required for conventional single-segment processing.

Due to the series connection, in both concepts the subcell that generates the lowest photo current limits the current of the full device. For that reason, the devices must be carefully designed to achieve equal current generation in each subcell. For multi-junction cells, current-matching is achieved by precisely tuning the thicknesses of the stacked subcells in a way, that each subcell absorbs the same fraction of the incident monochromatic light. Due to Beer-Lambert law of exponential absorption this means that the cell thickness decreases from bottom to top cell, and the upmost cell thickness decreases with increasing number of junctions. For multi-segment cells, current matching is achieved by proper design of the geometry of the subcell segments with respect to the profile of the light spot. Since the light spot usually features circular symmetry, a pie-shaped design is common.

Investigated Test Cells

Single-junction multi-segment cells based on GaAs were manufactured in different designs. The realized designs differ in the number of segments, the size, and the front grid metallization. Regarding segmentation, multi-segment cells with *N*=2, 4, 6, and 12 segments were realized. For all *N*, cells with a radius of 1.04 mm were realized; in addition, the 2, 4, and 6 segment designs were also realized with smaller radii of 0.75 mm and 0.5 mm. Fig. 4 shows microscope pictures of example cell designs in different configurations: (a) small 2-segment cell, (b) medium 4-segment cell, (c) large 6-segment cell, (d) large 12-segment cell. Each design was further realized with varying front grid designs to optimize for shading and series resistance losses. It is noted that the designs shown in Fig. 4 feature no front grid to minimize shading loss.

As a test structure for the vertically stacked multi-junction approach, dual-junction GaAs/GaAs cells in single-segment design were investigated.

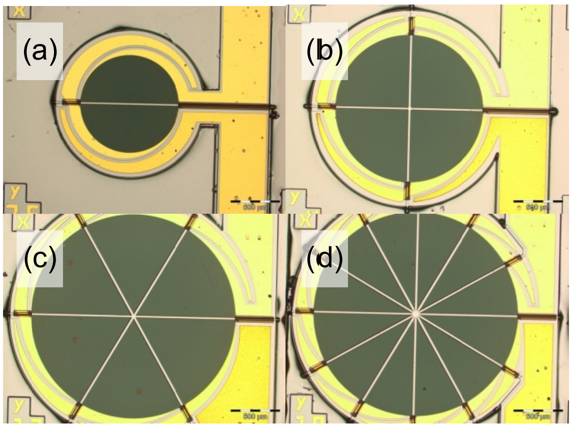

Fig. 4. Microscope pictures of experimentally realized multi-segment designs. Designs with 2, 4, 6, and 12 segments were realized in different sizes with radii of the active area of 0.5, 0.75, and 1.04 mm. All designs feature large metal pads for easy contacting of the front (top right) and back (bottom right) contacts at the right side of the chip.