MONOLITHIC SERIES-CONNECTED GALLIUM ARSENIDE CONVERTER DEVELOPMENT

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ABSTRACT

We report the development of monolithic GaAs photovoltaic devices intended to convert light generated by a laser or other bright source to electricity. The converters described here can provide higher operating voltage than is possible using a single-junction converter, owing to use of a monolithic circuit that forms a planar series-connected string of single-junction sub-cells. This planar monolithic circuit is arranged to deliver the desired voltage and current during operation at the maximum power point. The paper describes two-, six-, and twelve-junction converters intended for illumination by a laser diode with a wavelength of 0.8 μm . Design and characterization data are presented for optical power in the range of 100 mW to 1 W. The best conversion efficiency exceeds 50%.

INTRODUCTION

The delivery of electric power to remote locations via optical fibers is of increasing interest, owing to electrical isolation and other advantages inherent to fiber optic cable. In such a power transmission system optical energy from a laser or other light source is coupled into a fiber, transmitted through the fiber, and converted to electric energy at the exit end of the fiber. The exit energy conversion can utilize an ordinary photovoltaic (PV) device (such as a concentrator solar cell) but many applications require higher voltages than can be obtained with ordinary Si or GaAs cells. One approach to this requirement is to combine modulation of the laser (or chopping of the photon flux) on the entry side of the fiber with a cell and transformer on the exit side to boost the voltage. However, the loss of the DC component of the cell output and further transformer losses require entry laser power that is often beyond the state of the art. A more efficient approach comprises the use of a series-connected PV array at the fiber exit.

The efficient operation of a miniature series-connected array intended for fiber optic receptacles imposes several design requirements, including uniform illumination of the sub-cells, encapsulation in a fiber cable connector or receptacle, and accurate spacing between the converter and the fiber end surface. Compatibility with conventional fiber optic

components requires an array diameter that is typically only a few millimeters (although larger diameters can be used in special cases). For these reasons, the use of series connection of discrete PV cells is not feasible; rather, the cells must be formed monolithically using microelectronic processing techniques to interconnect the cells. The use of such a technique is reported here.

The various device design features that will result in highly efficient GaAs cells for both space and terrestrial applications have been known for some time (1-5) and will not be reviewed here. The first reported work on series connection of multiple junctions of GaAs on the same chip was that of Borden (6,7). The cell consisted of four 1 mm x 5.5 mm segments, separated by electrical isolation grooves, and connected in series by a metal patterning scheme located in the grooves. The efficiency of Borden's first cell was low owing to low fill factors (0.625 under a simulated AM2 spectrum), which were attributed to contact resistance (67 Ω). Further highly-successful work on a similar approach has been carried out at VS Corporation (8).

DEVICE DESIGN

The design of the series-connected PV converter requires special consideration of the optical flux, as well as the manner in which the series string is monolithically interconnected. For conversion of light from conventional optical fibers, the light receiving area should be round and have angular symmetry so that an equal flux is incident on each sub-cell. Fig. 1 shows a photograph of a twelve-segment converter formed in this work. Each segment subtends an arc of approximately 30°. The special features of the design are discussed below.

Flux Considerations

The cells to be described are intended for conversion in the incident power range of 0.1 W to 1 W. The typical core diameter of the fiber that will deliver the optical power is about 400 μm ; thus the optical power density is in the range of 80 W/cm² to 800 W/cm² at the exit of the core. By comparison, the AM1 spectrum power density is about 89 mW/cm². Thus, for 1 W at the fiber exit, the power density is equivalent to about 9000 suns.

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FIGURE 1. PHOTOGRAPH OF A TWELVE-SEGMENT CONVERTER.

In the design to be discussed, the light-receiving surface of the converter is circular, with a diameter of 3 mm, which is intentionally much larger than the fiber core diameter. The light exiting the fiber spreads in a cone with a characteristic angle specified as the numerical aperture (NA) of the fiber; a typical value of NA is 0.4. As a result of this spreading, the converter surface can be fully illuminated. Thus, if the converter is positioned 3.4 mm from the end of 0.4-NA fiber, the light will broaden to a 3 mm diameter spot. The power density is then 14 W/cm², and the equivalent concentration in terms of power at the converter surface is about 100 suns.

In order to compare grid design requirements for these converters to similar requirements for concentrator cells, we provide an analysis in Table I that shows pertinent photon density for a 1 W laser ($\lambda=0.8\mu\text{m}$) spectrum and the AM1 spectrum. In terms of photons per second absorbed (which relates directly to J_{sc} and is therefore the most important comparison for grid design), the equivalent concentration is approximately 320 suns. Thus, a concentrator cell grid design is quite appropriate for this photon density.

Series-circuit Factors

Series-connected PV converters of two, six, and twelve sub-cells have been fabricated using monolithic processing techniques. The diameter of the light-receiving area is 3 mm for all three types, as noted above. Current is collected from the front surface by a conventional grid. The busbar from each sub-cell grid is connected monolithically to the back of the next sub-cell in the string, with the endpoints of the string connected to pads for Au wire bonding. The sub-

cells are separated by an etch that forms an isolation channel between segments of the array. The monolithic interconnection of the devices is made possible by substrate removal and two-sided processing; this process is more fully described in ref. 9.

TABLE I
PHOTON FLUX ANALYSIS

Input Spectrum	Power Density ¹ (W/cm ²)	Photon Density ¹ (/s·cm ²)
Laser at $\lambda=0.8\mu\text{m}$	14.1	5.7×10^{19}
AM1 full spectrum	0.089	3.9×10^{17}
AM1/GaAs ²	0.059	1.8×10^{17}

Notes:

1. Power and photon density at the converter.
2. AM1/GaAs is that portion of the AM1 spectrum absorbed by GaAs (i.e. $E_{ph} > 1.43\text{eV}$).

The optimization of the device design requires not only consideration of the conventional sheet resistance, grid pattern resistance, contact resistance, and shadow loss, but also the area sacrificed to the channel used for segment isolation. Table II shows the optical loss that results from shadowing by the metal lines and from sacrifice of active light receiving area for formation of the isolation channels. The increased total shadowing percentage for the six junction cell reflects the fact that it is a more recent design intended to operate at high input photon fluxes. The low isolation area loss indicates the improvement in the etch process that has recently been obtained.

TABLE II
OPTICAL DESIGN DETAILS

Number of Sub-cells	Input (mW)	Metal Grid Shadowing (%)	Isolation Area Loss (%)
2	500	5.4	1.8
6	1000	18.5	0.3
12	500	5.2	9.4

FABRICATION

The GaAs active layers were grown epitaxially on multiple three-inch-diameter GaAs substrates using low-pressure organo-metallic chemical vapor

deposition (OMCVD); the epitaxy also included layers intended to make possible substrate removal and back-surface processing. The front surface of the wafer was processed conventionally to form metallization, isolation and anti-reflection coatings, and was then bonded to a temporary support structure.

Next, the substrate was removed to reveal the back side of the epitaxial films; this permits back-side processing, including the rear metallization and interconnection of the devices. Since the epitaxial films are only a few microns thick, step heights are small enough to permit good microelectronic processing of the back, as well as alignment to the front side metallization. After back side processing, the devices were mounted on a permanent substrate, and the temporary support structure was removed. The devices were then separated by conventional dicing techniques.

Substrate removal and backside processing permit the attainment of a number of design advantages. For example, the back of each sub-cell can be fully metallized, thus obviating the need for lateral current flow in the thin base, which would otherwise constitute a second sheet resistance loss; i.e. in this design there is no need for a thick heavily doped epitaxial layer beneath the cell to support lateral flow. Since the epitaxial layers are thin, there are no step coverage problems in the subsequent processing. Additionally, the thermal resistance of the inactive substrate is removed. The result of this type of backside processing is low series resistance, high fill factor, and reasonable conduction of heat to a sink.

DEVICE PERFORMANCE

Current-voltage characteristics were obtained from the cells in a conventional manner using a computer controlled measurement system. Briefly, under illumination from a laser diode at 808 nm wavelength, the converter bias was swept from reverse bias to forward bias by a Kepco bipolar/operational amplifier. The input to the Kepco was provided by a linear ramp voltage from an Exact pulse generator of about 500 ms duration. The voltage across the cell and a current viewing resistor were digitized by a dual channel HP54111D digitizer. Approximately 200 current/voltage pairs were obtained in this 500 ms sweep. Each set of data at a given illumination level was transferred to a HP9000 series 300 computer for manipulation.

Fig. 2a shows the I-V curves for the two-segment device under illumination levels from 0.2 W to 1.2 W at 808 nm from an optical fiber coupled to a laser diode. Fig. 2b is a plot of device efficiency against load resistance R_L , derived from the illuminated I-V characteristic ($R_L = V/I$). As can be seen from Fig. 2b the optimum load ranges from 70 Ω at 100 mW optical input to 15 Ω for 0.5 W. The efficiency exceeds 50% over the range 100 mW to 400 mW.

(a)

(b)

FIGURE 2. CHARACTERIZATION OF A TWO-SEGMENT CONVERTER. (a) Current-voltage curves (b) Efficiency versus load resistance.

We include the load resistance plot because it shows the importance of matching the load to the maximum power point impedance, for a given illumination level. Relative to a conventional cell of the same diameter, an n-segment cell will have roughly n times the single junction open circuit voltage, and $1/n$ times the short circuit current. It should be apparent that increasing the number of segments (thus increasing voltage and decreasing current) will require an increase in the load impedance necessary to obtain

approximately the same power conversion levels. In applications involving remote regions where there is no power to operate an active load, it will be critically important to properly match the load to the converter maximum power impedance.

We have included load resistance information on the I-V plots. The dashed curves are constant electric power (I-V) contours. Thus, the product of current and voltage everywhere along a given dashed contour is a constant. Similarly, there exists a family of lines emanating from the origin with various slopes (slope=I/V) that we have

termed constant load lines (not plotted in the figures). Each line represents a load value that is equal to the inverse of the slope of the line. The scale at the top and right sides of the plots represent the endpoints of load lines emanating from the origin and intersecting the axis tick mark; the value plotted along the top and right comprises the inverse slope (V/I) for the load line. This scale can be used to obtain the load resistance for any point on the I-V curves as follows: Select the desired point or interval on the I-V or power contour curve, then extend a load line from the origin, through the desired point or interval, and read the load range on the top or right scale.

(a)

(a)

(b)

(b)

FIGURE 3. CHARACTERIZATION OF A SIX-SEGMENT CONVERTER. (a) Current-voltage curves (b) Efficiency versus load resistance.

FIGURE 4. CHARACTERIZATION OF A TWELVE-SEGMENT CONVERTER. (a) Current-voltage curves (b) Efficiency versus load resistance.

Figure 3 shows the I-V characteristics and efficiency versus load for the six-segment converters. Note that the optimum load resistance in this case ranges from about 450 Ω at 200 mW optical input to about 70 Ω at 1.2 W, reflecting the fact that we have roughly tripled the voltage and reduced the current by about 1/3. According to the argument presented above this should produce a factor of 9 increase in optimum load resistance, in approximate agreement with the data for the 2-segment cell.

Fig. 4 shows the I-V plots and efficiency versus load for the 12-segment converters. The optimum load for this converter at 0.5 W optical input is about 3 k Ω . The performance of this 12-segment converter ($\eta=40\%$) is limited by series resistance, and resultant reduced fill factor, as well as by area sacrificed to the isolation channel (see Table II). The high series resistance is due to a metal grid on each sub-cell that is designed to operate over a more limited range of 200 mW to 500 mW (as can be seen in Fig. 1). A grid design with more closely spaced lines would allow this device to operate at higher incident photon flux.

CONCLUSION

We have reported on the fabrication and testing of multi-segment single bandgap series connected cells. The efficiency of laser light to electric energy conversion exceeds 50% for the best devices. These devices are expected to have applications in optical power delivery systems.

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