A 32.6% efficient lattice-matched dual-junction solar cell working at 1000 suns

I. García, I. Rey-Stolle, B. Galiana, and C. Algora
Instituto de Energía Solar, Universidad Politécnica de Madrid, Avda Complutense s/n, 28040 Madrid, Spain
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Photovoltaic conversion efficiencies of 32.6% and 30% at concentrations of 1000 and 3500 suns, respectively, are achieved in monolithic GaInP/GaAs dual-junction solar cells grown lattice matched on a GaAs substrate by metal-organic vapor-phase epitaxy. The tunnel-junction design, based on an (Al)GaAs/GaAs heterojunction, is found to be a key factor for achieving this efficiency at such high concentrations. Moreover, the thorough design and joint optimization of the front grid and the top-cell emitter, using quasi-three-dimensional distributed models, also plays a major role. Efficiencies of over 40% at 1000 suns should be achieved by extending this approach to triple-junction devices. © 2009 American Institute of Physics. [DOI: 10.1063/1.3078817]

Monolithic dual-junction solar cells based on the GaInP/GaAs system were first proposed by Olson et al. in 1985. Since then, such cells have proven to be a successful approach to obtain high efficiencies, mainly due to the ease with which high electronic quality in the GaInP compound can be achieved, as compared to other ternary compounds such as AlGaAs. Over the years, the evolution of this type of device for terrestrial concentrator applications gave rise to a record efficiency of 30.2% at 300 suns, which was achieved in 2001 for a GaInP/GaInAs metamorphic dual-junction solar cell. In this paper, we present a GaInP/GaAs lattice-matched dual-junction solar cell with an efficiency of 32.6% at 1000 suns—the highest efficiency reported so far for a monolithic dual-junction solar cell. Special emphasis has been placed on the design of the device for ultrahigh-concentration operation, the nominal target concentration being 1000 suns during the whole optimization process. However, in a concentrator system, the irradiance distribution is not uniform over the entire solar cell. Such a system shows a maximum irradiance that is significantly higher than the nominal (average) concentration level. Therefore, the efficiency decrease in the solar cell for concentrations above the nominal level should be as small and steady as possible to minimize the drop in conversion efficiency produced when working under a nonuniform light profile. The dual-junction solar cell presented in this paper also meets this requirement, as its efficiency still exceeds 30% at 3500 suns.

The most important aspects that have been dealt with in order to maximize the conversion efficiency of the solar cells at high concentrations are the tunnel-junction performance, the photocurrent and current matching, and the series resistance. The two last parameters are directly related to the tunnel junction, which makes its design the most influential for our purposes. Our tunnel-junction approach for the dual-junction solar cell consists of an (Al)GaAs:C/GaAs:Te semiconductor structure with AlGaAs barrier layers. The I-V curves of tunnel-junction devices fabricated with these structures show peak current densities of 2000 and 300 A/cm² for the as-grown and annealed devices, respectively. Since the annealing time applied is twice the time required to grow the uppermost layers in the dual-junction solar-cell structure, the peak current density obtained in a tunnel junction inside the complete structure will be well over 300 A/cm², which is equivalent to an operation at a concentration of 20 000 suns in a solar cell with a short-circuit current of 15 mA/cm² at 1 sun. Also, the voltage drop is below 10 mV up to a current density equivalent to 2500 suns. This behavior makes this type of tunnel junction very suitable for applications in multijunction solar cells designed to work under ultrahigh-concentration conditions. Furthermore, the use of GaAs in the tunnel junctions is not optimum in terms of photocurrent generation in the dual-junction devices because of the absorption in this material. To reduce this absorption, the GaAs in the anode of the tunnel junction was replaced with AlGaAs. The reduced absorption was made apparent by performing external quantum efficiency (EQE) measurements and the electrical properties of the tunnel junction did not appear to be affected by this modification, as shown in the concentration measurements presented below.

To maximize the short-circuit current of the dual-junction device, the GaInP top cell needs to feature a high photocurrent; that is, it should have an appropriate thickness to achieve a minimum absorption and allow a high photocurrent also in the bottom cell, while always meeting the current-matching condition. This is especially important in the case of the device studied herein, where the tunnel junction absorbs a considerable quantity of light as compared to other high-band-gap systems. A key issue here is the band gap obtained for the lattice-matched GaInP material in the top cell. Due to ordering phenomena, its value can vary for the same composition which, in our lattice-matched device, directly influences both the maximum achievable efficiency and the design of the top cell. Maximum disordering, that is, a band gap of 1.91 eV, is desirable to obtain maximum efficiencies in the GaInP/GaAs dual-junction devices. However, a compromise must be reached between the ordering and the electronic properties of the material. This can be achieved by choosing adequate growth conditions. In our case, the optimization gave rise to a GaInP material with a band gap of 1.85 eV. The possibility of increasing the band gap by using antimony as a surfactant was not explored in this study. Finally, the GaAs bottom cell must also be optimized to obtain the highest conversion efficiency in the dual-junction device but this only requires small modifications of
the thickness and the doping levels with respect to the already developed GaAs single-junction concentrator solar cells.

The semiconductor structure of the dual-junction device is schematically depicted in Fig. 1. This structure was grown in a horizontal reactor—by means of a low-pressure metalorganic vapor-phase epitaxy—on a (001) GaAs substrate with a miscut angle of 2° toward the nearest (111)A plane. The precursors were arsine and phosphine for the group-V elements, and trimethyl gallium, trimethyl aluminum, trimethyl indium, ditertiarybutylensilane, carbon tetrabromide, diethyl telluride, and dimethyl zinc for the group-III and dopant elements. The compounds [GaInP and (Al)GaInP] in the top cell were grown lattice matched to GaAs within Δa/a = ±7.5 × 10^{-4}. The structure was then processed, by using photolithography techniques to define the front grid, and the metal was deposited by means of thermal evaporation. The wet mesa etching process applied to isolate the devices and minimize the perimeter recombination consisted of an optimized sequence of etching processes using acid and basic solutions. An antireflecting coating (ARC) was finally deposited on the devices, which were encapsulated.

The EQEs of the devices were determined using a laser light bias to measure each junction, and the results were corroborated by the Calibration Laboratory of the Fraunhofer Institute for Solar Energy Systems (ISE, Freiburg, Germany). The results are plotted in Fig. 2 for devices with and without ARC. The reflectivity of the ARC-coated devices is also plotted. The apparently poor blue response of the GaInP top cell is a consequence of the emitter design, which is optimized to maximize the efficiency at 1000 suns by reducing its series-resistance component, as explained below. This leads to the necessity of using a thickness and a doping level in this layer that produce such an EQE response. The short-circuit current densities (J_{sc}) calculated by means of the convolution of the EQE values obtained for ARC-coated devices with the standard solar spectrum AM1.5D low aerosol optical depth (AOD), show values of 14.3 and 13.5 mA/cm² for the top and bottom cells, respectively, meaning that there is a current mismatch of 6%. This result is partly due to the deposited ARC layer, which is not negligibly reflective in the near-IR region, as shown in Fig. 2. Although this current mismatch gives rise to an increased fill factor (FF), the loss in short-circuit current produces a net conversion efficiency that is lower than that in a current-matched device. This means that there is still room for improvement in this dual-junction device, by simply adjusting the current matching—via fine-tuning of the thickness of the top-cell base layer—and by using an appropriate ARC coating thickness and material quality.

Regarding the series resistance, the metallization front grid plays a major role in minimizing the series resistance when working under concentration. The main parameters that influence the design of the optimum front grid are the top-cell emitter sheet resistance and the short-circuit current of the device (through the shadowing factor). The emitter sheet resistance, the photocurrent, and the characteristics of the front grid are coupled parameters in this design process. Therefore, it is necessary to perform a multivariable optimization, bearing in mind that the merit figure to be maximized is the conversion efficiency of the solar cell.

By using quasi-three-dimensional models based on distributed circuit units (which have been shown to be a suitable tool in this type of analysis),11,12 a front-grid design based on the inverted square topology13 was carried out. Such a design is particularly appropriate for operation under concentration. In addition, the finger pitch was kept constant through the front grid because this approach has been demonstrated to give similar results as those obtained with the current-balanced design for uniform light profiles and is clearly advantageous for nonuniform light profiles. The solar-cell active area used was 1 mm², which, in accordance with the compromise situation imposed by the series resistance, perimeter recombination, and heat dissipation for an operation of the device at 1000 suns, is close to the optimum value.14 The metal in the front grid is based on the AuGe/Ni/Au system and a description of its properties can be found elsewhere.11 The optimization performed using all these input parameters for the operation of the device at 1000 suns showed that the optimum solution was to use eight 3 μm wide fingers. The resulting geometrical dimensions of the device make it appropriate to use the “LED-like...
approach\textsuperscript{14} for the postgrowth processing of the semiconductor structure.

Certified concentration measurements on these devices were performed at the Calibration Laboratory of the Fraunhofer ISE. The solar spectrum used is the standard AM1.5D low AOD solar spectrum. The authors are deeply indebted to J. Bautista for his continuous technical support, to C. Domínguez, I. Antón, and the I.S.I. group for assistance with the concentration measurements and for useful discussions, and to Dr. A. Bett and G. Sieffer from the FhG ISE for the certified EQE and concentration measurements. Funding for this research was provided by the European Commission under Contract No. SES6-CT-2003-502620 (FULLSPECTRUM project), by the Spanish Ministry of Education and Science (Ministerio de Educación y Ciencia) through projects GENESIS-FV (part of the CONSOLIDER-INGENIO 2010 program), Contract Nos. TEC2004–22300-E, TEC2005–27245, and TEC2007–29630-E, and by the Regional Government of Madrid (Comunidad de Madrid) under Contract No. S-505/ENE/0310 (NUMANCIA program).

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FIG. 3. $V_{oc}$, FF, and efficiency of the dual-junction device measured as a function of the concentration under the standard AM1.5D low AOD solar spectrum.