Solar Energy Materials & Solar Cells 134 (2015) 175–184

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Luminescent emission of multi-junction InGaP/InGaAs/Ge PV cells under high intensity irradiation

Vasiliki Paraskeva [a,*], Matthew Norton [a,b], Maria Hadjipanayi [a], Mauro Pravettoni [c], George E. Georghiou [a]

[a] FOSS Research Centre for Sustainable Energy, PV Technology, University of Cyprus, 75 Kallipoleos St., Nicosia 1678, Cyprus
[b] European Commission, DG JRC, Institute for Energy and Transport, Renewable Energy Unit, TP450, 21027 Ispra (VA), Italy
[c] Institute of Applied Sustainability to the Build Environment, University of Applied Sciences and Arts of Southern Switzerland, Canobbio CH-6952, Switzerland

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form
25 October 2014
Accepted 25 November 2014
Available online 13 December 2014

Keywords:
Multi-junction
Voltage bias
Luminescent coupling
Photoluminescence
Electroluminescence

ABSTRACT

Combined electroluminescence (EL) and photoluminescence (PL) measurements were conducted in order to investigate the presence of luminescent emission of InGaP/InGaAs/Ge at different operating conditions of the tandem. Luminescent emission from cell samples was observed at different sun concentrations, voltage biases and temperatures. A high intensity pulsed solar simulator was used to photoexcite the device which exhibited strong radiative recombination from both the top InGaP and middle InGaAs junctions. Luminescent emission from the device was investigated under a range of voltage biases and was clearly observed at the maximum power point voltage of the sample under test indicating its presence during typical operating conditions of the solar cells. Investigation of the emission was also performed at relatively high temperatures (up to 60 °C) in order to mimic the outdoor operating conditions of a solar cell device. Luminescence was detected at high temperatures indicating that significant radiative recombination is present at even higher temperatures. Outdoor measurements under actual solar spectrum demonstrated the presence of luminescent emission in agreement with indoor testing. The significant amount of radiative recombination at the band-gap edges of the top junctions observed in our measurements gives evidence that optical coupling to the lower ones may occur. Finally, excitation power dependent PL was performed using monochromatic laser sources in order to investigate the impact of externally induced photocurrents of different intensity upon the radiative signal of each junction.

1. Introduction

III–V compound multi-junction solar cells have the potential for attaining solar energy conversion efficiencies of well over 40% and are promising candidates for the third generation space and terrestrial concentrator photovoltaic (CPV) applications [1]. Most of III–V materials are direct band-gap semiconductors where radiative recombination is the dominant carrier recombination mechanism. The existence of significant radiative recombination may result to coupling effects in a tandem device. Luminescent coupling effects are referred to as the phenomenon in which an amount of radiative recombination in the top junctions can be reabsorbed by the lower band-gap ones contributing to the photocurrent of the latter junctions [2–5]. It should be noted that experimental observation of radiative emission at high concentration solar spectrum has not been achieved to date. As a result further investigation is needed to improve our understanding of the luminescent emission and thus radiative coupling effects under actual operating conditions outdoors and to provide cell designers with an additional tool with which to optimise their device performances.

The major goal of the paper is to investigate the presence of luminescent emissions of the InGaP/InGaAs/Ge tandem device at different concentrations, voltage bias and temperatures. The samples were tested both outdoors using an outdoor test setup with a lens and indoors using a high intensity pulsed solar simulator. High luminescent emission observed from the device at different operating conditions gives evidence of the probability of the presence of coupling effects in the tandem device. Significant recombination at the band-gap edge of the top InGaP junction suggests that coupling current is likely to be directed towards the middle InGaAs junction. In the same way, strong

* Corresponding author. Tel.: +357 22 894398; fax: +357 22 895370.
E-mail address: vparas01@ucy.ac.cy (V. Paraskeva).

http://dx.doi.org/10.1016/j.solmat.2014.11.047
0927-0248/

recombination at the band-gap edge of the middle InGaAs junction indicates that photons are likely to be directed towards the bottom Ge junction thus enhancing its photocurrent.

Initially, prior to the indoor and outdoor testing of the sample, the excitation power dependence of the PL emitted from each junction in the solar cell was investigated. For this purpose, monochromatic light sources of variable intensity and spectrum were used. Monochromatic light sources of variable intensity and spectrum provide a means of investigating the radiative recombination and therefore emission from each junction in the multi-junction device individually, and can be used to demonstrate the relationship between them.

The high intensity simulator utilized in this work for the investigation of emission indoors can reach intensities over 1000 times higher than the standard 'one-sun' irradiance defined in IEC 60904-3 and can therefore approximate the light bias conditions applied to a concentrator solar cell within a module under field operation. Luminescent emission from the cell was captured under various concentration levels in a sun simulator. At each concentration level, measurements at different voltage bias and temperature were performed. The applied voltage has a significant impact on the radiative emission and has been investigated. In addition, temperature variations are also expected to influence luminescent emission and for that reason measurements were taken at different temperatures. Temperature effects are significant since CPV cells work far from the standard test conditions and at temperatures that can exceed 80 °C. Moreover, the current–voltage characteristics were measured at the same concentration and temperature levels where the emission was captured in order to extract the maximum power point voltage of the cell in each case.

Finally, outdoor measurements under open-circuit conditions were performed using an appropriate lens in order to demonstrate the existence of luminescent emission under broadband solar irradiance conditions. The measurements outdoors were performed under low concentration.

2. Experimental procedure

For the investigation of excitation power dependent PL measurements, the sample was excited with a 450 nm blue LED and a near infrared light source (NIR) at 808 nm. The PL signal from the device was captured by a Si based spectroradiometer. The blue LED output irradiance varied from 13 W to 48 W while the near infrared laser irradiance was varied between 0.16 W and 0.33 W.

In an attempt to investigate the luminescent emission from the cell at high concentrations indoors, a high intensity pulsed solar simulator installed at the Joint Research Centre (JRC) and manufactured by ScienceTech Inc. was used. The pulsed solar simulator beam can be adjusted to provide concentrations from 200 to 2000 sun intensity. Its light source is a Xenon lamp that delivers 5 ms pulses of light with a spatial non-uniformity of $\pm 2\%$ over an area of 4×4 cm^2. Temperature control of the cells in the temperature range 20–60 °C was achieved by a Peltier element. An operational amplifier was used for the application of voltage bias to the device and for the appropriate current limitation. A Silicon (Si) spectroradiometer unit that covers the visible and near infrared region (300–1000 nm) with a spectral resolution of 0.5 nm was utilized for the detection of the emission of the device during flashing. The Si spectroradiometer can typically detect the emission of the top two junctions of a triple-junction device. The signal from the bottom (typically Ge) junction cannot be observed in the PL spectrum since it is outside the sensitivity region of this spectroradiometer. Automated triggering of the spectroradiometer provided the collection of the PL signal from the device during flashing whilst a fiber-optic cable collected the emission from the cell. This was placed in front of the device and was permitted to shade part of the cell from the simulator flash. At each concentration level, the short-circuit current and the open-circuit voltage were measured using a Yokagawa scopecorder. The short-circuit current was measured over a calibrated load resistor of 0.05 Ω. The 1-sun *I–V* curves of the device were carried out under a 1-sun solar simulator at the JRC. The short-circuit current at 1-sun was used to calculate the irradiance concentration level applied to the device each time. Current–voltage (*I–V*) characteristics were captured also at each concentration and temperature level under examination in order to indicate the maximum power point in each case. *I–V* curves were taken by a custom made *I–V* scan which is part of the sun-simulator system. A Keithely 2430 was used for four-point measurements. The schematic of the set-up is shown in Fig. 1.

For the detection of the luminescent emission under concentrated solar irradiation in the outdoor set-up, the multi-junction device was mounted on an accurate solar tracker and a typical Fresnel lens achieved an irradiance concentration of 6 sun. A Silicon spectroradiometer unit was used for the capture of emission and the measurements were carried out at open-circuit conditions. Calibrated environmental sensors i.e. a pyrheliometer and a pyranometer were mounted on the solar tracker and used for the collection of Direct Normal Irradiance and Global Normal Irradiance at the moment of the measurement. The irradiance conditions were recorded as they are important parameters that influence radiative recombination of the junctions. The outdoor measurements were carried out on a clear non-cloudy day with high Direct Normal Irradiance.

The cells under investigation were concentrator InGaP/InGaAs/Ge triple-junction devices where the top InGaP and middle InGaAs were grown on a p-type Ge substrate. The specifications of the cells can be found elsewhere [6].

3. Results and discussion

3.1. Excitation power dependent PL

The intensity and the spectrum of the light bias applied on the multi-junction devices determine the current limiting junction and give access to each junction separately in the tandem [7]. In order to find a relation between the radiative signal emitted from the device and the light bias applied on the tandem the integrated PL intensity of the radiative recombination at the band-gap edges of the top and middle junction were measured at different light intensities of blue (450 nm) and NIR (808 nm) light sources. The light sources cause excitation of carriers and create photocurrents at different junctions depending on the region of response. All the measurements were carried out in the presence of a voltage bias of 1.2 V. Initially the integrated PL signal from the top junction was

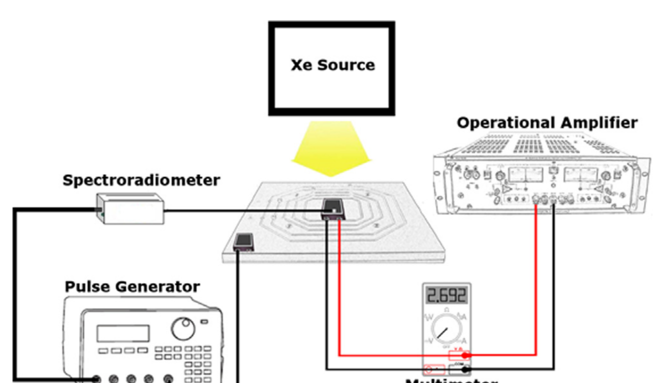

Fig. 1. Schematic of the sun simulator set-up.