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Photoluminescence analysis of coupling effects: The impact of shunt resistance and temperature

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ABSTRACT

In multi-junction devices, due to the series connection of junctions, recombination current from the top junctions can be directed to the bottom ones affecting their electrical characteristics. Recently, luminescence coupling effects during External Quantum Efficiency (EQE) measurements at very intense light bias conditions indicated high recombination current flowing towards the bottom junctions of the cells. In an attempt to find the magnitude of coupling current as well as the factors affecting the optical interactions between junctions, excitation and voltage dependent Photoluminescence (PL) measurements of GaInP/GaInAs/Ge have been carried out. An investigation using junctions with different shunt resistances has been conducted to identify the impact of shunts on the coupling current. Furthermore the impact of temperature on the coupling current has been considered. Our results show that a maximum of 2.3% of the recombination current of the top junction is converted to coupling current in the middle junction depending on the devices under examination. The coupling efficiency depends on the shunt resistance of the top junctions as well as on the temperature. Furthermore a physical model of the current limiting junction was built taking into consideration the impact of local ohmic shunts in the solar cell device and used to validate the experimental data taken.

1. Introduction

III–V monolithic multi-junction solar cells reach efficiencies exceeding 40% and have applications in space and terrestrial concentrator systems [1]. Multi-junction solar cells typically consist of monolithically integrated junctions epitaxially grown on a substrate where the junctions are connected in series by tunnel diodes leading to a conventional two terminal contact. These monolithic devices have the benefit of simplifying the connection between the cells, but are more susceptible to reduced performance due to spectral mismatch. As a consequence of the series connection of the cells, recombination current from the top junctions can be directed to the bottom one. Previous studies have shown that under certain operating conditions significant radiative recombination can take place in the top junctions of a multi-junction device causing luminescence coupling effects [2,3]. Specifically, under high bias conditions in high quality materials, radiative recombination centers can be created at the top junctions and can become of major importance. Higher carrier recombination causes emission of photons that can be absorbed by the bottom junctions thereby enhancing the current output of the bottom junction. Strong recombination occurs near the band gap edge of the top junctions and therefore photon energy emission is expected to be observed at the end of the response region of the top junctions and close to their band gap. The rate of band-to-band recombination is higher for direct band gap materials and thus coupling effects are expected to have significant influence in GaInP/GaInAs tandem devices resulting in a considerable change of junction photocurrents. These effects can be important during EQE and PL measurements of multi-junction solar cells at high bias conditions and have the potential to affect the measured current-ratio of the junctions. The junctions may operate far from current matching conditions since the current of the device is limited by the current limiting junction thus lowering the performance of the

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triple junction device. Previous calculations showed that under optimal conditions (the spectrum conditions at which the junctions were designed to be current matched) monolithic tandem devices without radiative coupling perform marginally better [4]. However, under non-optimal conditions the stack with coupling performs reasonably well compared to the tandem without coupling. Furthermore optical coupling can also be used as an identification method for a quality assessment of semiconductor materials [5].

Previous studies have demonstrated the effect of surface passivation and light bias on coupling effects using the EQE method [6]. However, many of the factors affecting the optical interactions between junctions are still unclear. In this paper, excitation power dependent PL and voltage dependent PL measurements of GaInP/GaInAs/Ge solar cell devices of different materials quality and structure were performed in order to demonstrate the effect of shunt resistance and temperature on luminescence coupling effects. Dark EQE has been used to indicate the leakage current and the shunt resistance of each junction of the device. Furthermore, analysis of the circuit model in the case of luminescence coupling is also presented and used to explain the experimental observations. A physical model of devices have been developed taking into consideration the impact of local ohmic shunts. The model was used for the simulation of the luminescence emission of the different shunt resistance devices. Spatially resolved EL technique has been used in order to observe the number and the dimensions of local ohmic shunts which then used to feed the physical model.

2. Experimental procedure

To observe luminescent coupling effects, PL measurement under varying light intensity was performed upon a number of triple junction devices under high intensity bias light in the wavelength region of the top junction (300–660 nm). During excitation power dependent PL measurements the samples were excited by the 450 nm LED that excites the top GaInP junction. The blue LED output was varied and produced a bias photocurrent of 1–5.7 mA/cm^2 at a voltage bias of 1.2 V. In those light bias conditions the shunt current leakage is eliminated and coupling effects start to be present. In an attempt to investigate the coupling effects at higher light bias conditions a green laser module with fixed intensity was added. In that case the bias photocurrent of the top junction fluctuated between 5.4 and 9 mA/cm^2. The PL signal was captured by a silicon (Si) based spectroradiometer which covers the ultraviolet and visible region. In addition an infrared laser module (IR) at 980 nm was used for the saturation of the bottom Ge junction and for the current limitation of the middle GaInAs junction. The light bias of the IR laser which caused saturation of the Ge bottom junction was kept constant and was of much higher intensity compared to the other light sources. During excitation power dependent PL measurements, a fixed voltage bias was applied to the solar cell devices whilst the luminescence and bias current outputs were measured. All the measurements were carried out at room temperature. For the investigation of the effect of temperature, voltage dependent PL was performed at a fixed light intensity of the blue and infrared light sources.

The dark EQE measurement set-up system consisted of a steady-state Quartz-Tungsten-Halogen light source in series with a monochromator in order to obtain a monochromatic light input which is then chopped at 75 Hz and measured by digital lock-in-amplifiers. The monochromatic light was separated by a beam splitter and allowed simultaneous measurement of the test and a reference device of known absolute EQE. The reference device used was a NIST traceable calibrated Si photodiode which is sensitive across the visible and into the near infrared spectrum. No bias light was applied to the cell during dark EQE in order to indicate the current leakage through shunts and the magnitude of shunt resistance of each junction.

The cells under investigation were concentrator GaInP/GaInAs/Ge triple junction devices with the same dimensions but different shunt resistances and structural parameters. Two different series of triple junction devices have been investigated (labeled as A, S). In all devices the top GaInP and middle GaInAs were grown on a *p*-type Ge substrate. The specifications of the cells can be found elsewhere [7,8]. Comparison between the measurements in the lattice-matched series A and S devices was performed in order to indicate the effect of coupling efficiency on different shunt resistance devices.

3. Model of coupling effects

3.1. Electrical model of GaInP/GaInAs in the absence of shunts

The equivalent circuit of a two junction device under bias light conditions during PL measurements, which takes into account the radiative coupling effects, is presented in Fig. 1. For simplicity the model ignores the Ge bottom layer because the main interaction under investigation is between the GaInP and GaInAs subcells. Voltage bias is required to reduce the impact of shunt resistance. Therefore, with the application of appropriate voltage bias the effect of the shunt can be eliminated.

The circuit corresponds to the case where the top junction is saturated due to strong bias light and the middle one exhibits coupling effects due to excess recombination current flowing towards the GaInAs. In order to cause saturation of the top junction, a blue bias light was applied to the device. The currents shown in the circuit are the dark (recombination) current for the top junction ($I_{rec,top}$), the GaInP junction photocurrent ($I_{bias,top}$) due to light bias and the output current of the solar cell (I_{out}). The GaInAs junction photocurrent ($I_{bias,mid}$) corresponds to the stray light from the environment applied on the middle junction but is very weak so it can be neglected ($I_{bias,top} \gg I_{bias,mid}$). A portion of the recombination current of the top junction is absorbed by the GaInAs junction and generates the photocurrent I_{LC}.

The dark-recombination current of the top junction contains a radiative and a non-radiative part. Band-to-band radiative and non-radiative processes in the neutral region and at high forward

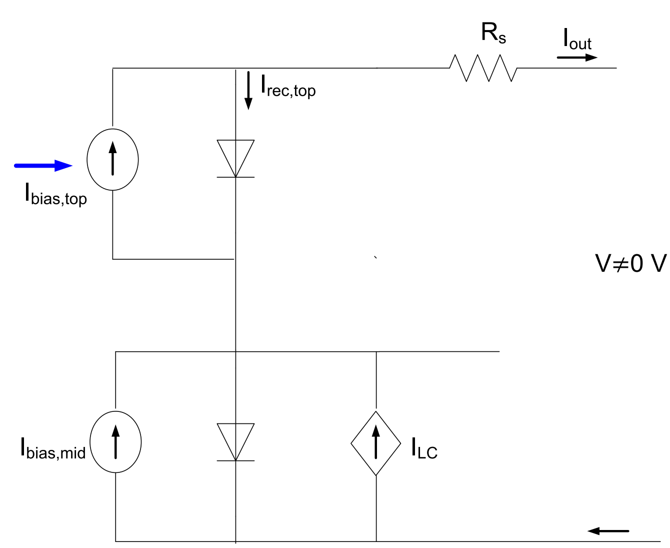

Fig. 1. Circuit model of the GaInP/GaInAs in the absence of shunt resistance.