The effect of shunt resistance on External Quantum Efficiency measurements at high light bias conditions

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Abstract — Series connection of multi-junction devices can lead to opto-electronic interactions between junctions and thus coupling effects. These effects can be important during External Quantum Efficiency (EQE) measurements of multi-junction devices. In an attempt to find the impact of coupling effects on different shunt resistance devices, EQE measurements have been carried out at high intensity light bias conditions. These measurements showed that in those conditions, the coupling current in high quality materials is considerably higher compared to low quality ones and lead to a higher reduction of the EQE signal. The difference in EQE is, nevertheless, small and it is apparent in all the response region of the material.

Index Terms — electroluminescence, multi-junction solar cell, III-V semiconductors, shunts, spectral response.

I. INTRODUCTION

External Quantum Efficiency (EQE) measurements are essential for the design and performance evaluation of multi-junction solar cells. Previous results have demonstrated that low shunt resistance in a junction can cause reduction of the EQE signal at wavelengths where the junction is expected to respond and increase of the EQE signal in the wavelength region outside the response region of the junction [1]. Apart from measurement artifacts appearing due to the low shunt resistance of a device it has recently been shown that the artifacts in EQE measurements can have different origin [2]: under certain operating conditions significant radiative recombination can be created in the top junctions of a multi-junction device causing luminescent coupling and thus emission of photons that can be absorbed by the junctions underneath. Strong recombination occurs near the band gap edge of the top junctions and therefore photon energy emission is expected to appear at the end of the response region of the top junctions and close to their band gap. These effects can be significant during typical EQE measurements of multi-junction solar cells at very high bias conditions and have the potential to affect the measured current-ratio of the junctions.

In this paper results of EQE measurements are shown in two GaInP/GaInAs/Ge solar cell devices to observe the effects of different shunt resistance on luminescent coupling. The two devices are identical but with top and middle GaInP/GaInAs junctions of different shunt resistances. Different shunts and therefore defect states exist in both devices affecting the measured EQE in the presence of coupling effects [3]. In order to observe the effects of luminescent coupling, high light bias conditions in the region of the top and bottom junctions are applied to the device. The intensity of the light bias controls the amount of recombination current flowing through the top GaInP junction and therefore influences the amount of luminescent current directed to the middle GaInAs junction. It is well known that EQE measurement artifacts depend strongly on both voltage and light bias, which change the operating conditions of junctions. Voltage bias has shown to be the most effective method to correct the measurement artifact due to low shunt resistance. Therefore, application of an appropriate voltage bias offers the possibility to eliminate the shunt current leakage and isolate the effects of luminescent coupling.

The shunt resistance of the middle junction was investigated with spectrally resolved Electroluminescence (EL) and Dark EQE method. EL indicates the radiative recombination in each junction while dark EQE provides information about the current leakage through junctions. The impact of shunts was also investigated through I-V curves of each device at different light bias conditions.

II. THEORETICAL REVIEW OF LUMINESCENT COUPLING

Typical EQE measurements of multi-junction devices are performed as superimposing a chopped monochromatic light to a continuous colored bias light. As a result, the resulting photogenerated current has an AC component from the chopped light and a DC component from the bias. The equivalent DC and AC circuits of a two junction GaInP/GaInAs device at the conditions of EQE measurements for the middle junction which take into account the radiative coupling effects are presented in Fig.1 (a) and (b), respectively. For simplicity the model here ignores the Ge bottom layer and investigates the interaction between the
GaInP and GaInAs subcells. A double junction device is thus considered. The current $I$ represents the DC part of the signal while $i$ represents the AC part. The circuits below express the case when both the top and bottom junctions are saturated and the middle layer is measured. The current components shown in Fig. 1 are the dark currents for the top junction ($I_{d,top}$, $i_{d,top}$), the shunt currents for both junctions ($I_{sh,top}$, $i_{sh,mid}$, $I_{sh,top}$, $i_{sh,mid}$), GaInP subcell photocurrent ($i_{bias,top}$) due to DC light bias (which is assumed to be applied to the top junction only: this is a reasonable assumption with LED bias light), output current of the solar cell ($I_{out}$), small signal photocurrent ($\delta I$) generated in the GaInAs junction from the monochromatic chopped signal. The dark current of the middle junction is not presented in the circuits since the middle junction is in reverse bias conditions. The current $I_{out}$ contains a DC component ($I_{bias,mid}$) from the DC light sources applied on the device ($I_{bias,mid}$) plus an AC bias signal ($i_{out}$) originated by an AC small photocurrent ($\delta I$) due to the chopped monochromator signal. The DC light bias applied to the middle junction is very weak ($I_{bias,mid} << I_{bias,top}$). The recombination current of the top junction is by definition the dark current of the top layer ($I_{rec} = I_{d,top}$). Part of this recombination current is flowing towards the middle GaInAs junction and converted to luminescent current $I_{LC}$. The recombination, shunt and coupling currents contain DC components ($I_{d,top}$, $I_{sh,top}$, $I_{sh,mid}$, $I_{LC}$) as well as small signal components ($i_{d,top}$, $i_{sh,top}$, $i_{sh,mid}$, $i_{LC}$). The coupling current directed towards the middle junction is linearly correlated with the recombination current and can be expressed as a function of the recombination current

$$I_{LC} = a I_{d,top}$$  \hspace{1cm} (1)

The linear form of (1) holds only in the case when the non-radiative Shockley-Read-Hall and Auger recombination are not of major influence in the device. At high forward bias present during the EQE measurements, radiative recombination becomes dominant. The non-radiative processes such as SRH and Auger are assumed to be low. The coefficient $a$ is referred to as coupling efficiency coefficient.

Fig. 1. (a) DC equivalent circuit of a double junction device at the voltage and light bias conditions of EQE measurements for the middle junction and (b) AC equivalent circuit at the same conditions.

Taking into consideration the coupling current given by equation (1) and following the same procedure found elsewhere [4] the general equation for the output current of the current limiting middle junction is

$$I(I + \delta I) = I_{bias,mid} - I_{0,mid} \left[ \exp \left( \frac{q V_{top}}{n k_B T} \right) - 1 \right] + \frac{V_{top}(I)}{R_{sh,mid}} + a I_{d,top} \left[ \exp \left( \frac{q V_{top}}{n k_B T} \right) - 1 \right] + \delta I (1 - x)$$  \hspace{1cm} (2)

where $I_{0,mid}$ is the reverse saturation current of the middle junction, $R_{sh,mid}$ is the shunt resistance of the middle junction, $q$ is the elementary charge, $n$ is the ideality factor, $k_B$ is the Boltzmann constant and $T$ is the absolute temperature.

The lock-in amplifier filters out the dc-component $I_{bias,mid} - I_{0,mid} \left[ \exp \left( \frac{q V_{top}}{n k_B T} \right) - 1 \right] + \frac{V_{top}(I)}{R_{sh,mid}} + a I_{d,top} \left[ \exp \left( \frac{q V_{top}}{n k_B T} \right) - 1 \right]$ and measures only the AC-term $\delta I (1 - x)$. The term $x$ is the reduction of the measured EQE signal and in that case is

$$x = \left( \frac{n k_B T}{q R_{sh,mid}(I_{bias,top} + I_{d,top} - I_{bias,mid} - I_{LC})} \right) \text{shunt resistance term}$$

$$+ \left( \frac{a I_{d,top} \exp \left( \frac{q V_{top}}{n k_B T} \right)}{I_{bias,top} + I_{d,top} - I_{bias,mid} - I_{LC}} \right) \text{coupling term}$$

(3)

The underestimation of the AC measured signal is due to the low shunt resistance (first term) and the luminescent coupling term (second term). Both terms give rise to a decrease of the measured EQE signal at the wavelength the middle junction is expected to respond. The exponential in the coupling term cannot be neglected at room temperature and at high light
biases since the voltage bias of the top junction is not insignificant. At low light bias conditions, the voltage across the top junction is low and the coupling efficiency coefficient $\alpha$ is negligible leading to elimination of the second term. As the light bias of the top junction increases, the first term decreases while the second one increases.

The luminescent coupling current is related to the shunt resistance, with the high quality materials exhibiting higher values of coupling current. Consequently, the coupling term is expected to differ in high and low quality materials. High quality materials are expected to have a higher reduction in EQE at high light bias conditions where the main contribution originates from the coupling term. However, low shunt resistance devices exhibit lower decrease due to lower impact of the coupling current. That difference in coupling currents between different quality materials is expected to cause significant differences on their effect on the EQE. In the next sections, this difference is quantitatively investigated from an experimental point of view.

III. EXPERIMENTAL APPARATUS

A. External Quantum Efficiency (EQE)

The EQE measurement set-up consists of a steady-state Quartz-Tungsten-Halogen light source in series with a monochromator in order to produce the monochromatic light input which is then chopped at 75 Hz, superimposed on the continuous bias light and measured by digital lock-in-amplifiers. The monochromatic light is separated by a beam splitter and allows simultaneous measurement of the test device and a reference cell 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. Both test and reference cell currents are measured in short-circuit conditions. The test device and the reference cell are kept at 25°C temperature. The voltage bias during EQE measurements was applied through the trans-impedance amplifier system.

Due to the series connection of the component junctions, the total incoming spectral irradiance determines which junction limits the total photogenerated current. A set of colored light sources is needed in order to saturate the non-measured junctions and subsequently achieve current limitation in the junction of interest. In the experimental set-up used in this work, a blue and an infrared light source of wavelengths 450 nm and 980 nm respectively have been used for the measurement of the middle junction. In order to detect the luminescence coupling emitted from the device under test, a fiber optic was located in front of the test cell. The fiber optic was placed carefully so as not to shade the device from the incident light. The amount of emitted signal captured by the fiber-optic indicates the amount of coupling effects in the material. High luminescent emission from the surface of the cell demonstrates enhanced coupling effects and optical interaction between junctions. A schematic illustration of the set-up is shown in Fig. 2.

![Fig. 2. External Quantum Efficiency measurement set-up at UCY.](image_url)

When no bias light is applied to the triple junction device, the EQE is here referred to as “dark EQE” and is a useful metric for extracting the impact of the shunt resistance on the EQE measurements [4]. The experimental apparatus is identical with the set-up for light EQE measurements but without light bias.

B. Electroluminescence and current-voltage characterization

The spectral EL experimental set-up consists of a high-precision current source (Keithley 2430) and two spectroradiometers (Si and InGaAs). The current source is used to control the current injected into the solar cell. The light emitted from the cell is directed towards the fiber optic of the spectroradiometer which is connected to a computer. For this purpose two spectroradiometers were used: a Silicon-based spectroradiometer that detects the ultra-violet and visible region and an InGaAs-based spectroradiometer that detects the near infrared region (NIR) of the electromagnetic spectrum.

Finally I-V curves have been performed at different light bias conditions of the component junctions. A varying intensity blue LED that excites the top junction and an infrared (IR) laser module of fixed light intensity that excites the bottom junction were applied on the device. The voltage was varied between -1V and 2V and the current was captured at each point.
IV. EXPERIMENTAL RESULTS

A. Spectroscopic Electroluminescence (EL)

Initially, both devices were examined under EL to study the difference between radiative recombination mechanisms from the top GaInP junction. The magnitude of the radiative recombination in the junctions provides a measure of the material quality of each junction in the photovoltaic device. Consequently, knowledge of the material quality of the junctions can be used to extract conclusions about the correlation of material quality and thus shunt resistance, with luminescent coupling effects. EL results for the two devices are presented in Fig. 3.

![EL emission from two different samples](image1)

Fig. 3. Spectroscopic EL emission from two different samples. The difference in radiative recombination between the two samples is clearly observed.

Two main peaks are apparent in the EL spectrum and indicate the band gap region of the two top junctions GaInP and GaInAs. Fig. 3 demonstrates that the radiative recombination in device C2 is considerably higher compared to the radiative signal emitted by cell C1 highlighting the higher material quality of sample C2. The radiative signal from the top GaInP junction will determine the magnitude of the coupling current directed towards the middle GaInAs junction. Since higher radiative current is apparent in sample C2, larger coupling current is expected to be present in that sample. The presence of significant non-radiative recombination in a device and lower shunt resistance causes additional paths for the current and lowers the coupling signal.

B. “Dark” External Quantum Efficiency

Dark EQE measurements have been carried out also in an attempt to extract the relative value of the shunt resistance of each junction in the devices. Dark EQE of the two selected devices is shown in Fig. 4. Previous investigation of dark EQE has shown that dark EQE measurements of the devices in Fig. 4 refer to the case of high shunt resistance in the top junction and low shunt resistance in the middle and bottom junction. The dark EQE of the device is a consequence of current leakage through GaInAs and Ge, giving rise to an increased EQE in the wavelength region of the top junction due to low shunt resistance of the middle and bottom junction. Detailed description of dark EQE measurements and results can be found elsewhere [4]. The EQE signal from C2 is lower compared to C1 indicating lower leakage current and thus higher shunt resistance in both –top and middle- junctions.

![EQE from two different samples](image2)

Fig. 4. Dark EQE from two different samples.

C. I-V Curves

In order to directly measure the coupling current in the two devices, the characteristic I-V curves of the devices were measured at various light bias conditions (Fig. 5a and 5b). The samples were excited by a 450 nm LED that excites the top GaInP junction and a laser module at 980 nm that excites the bottom Ge junction as mentioned earlier. Under these conditions the output current of the device is the limiting current of the reversed biased middle GaInAs junction. The current is actually the sum of the coupling current directed towards the junction and the shunt current of the junction. The I-V curves in Fig. 5(a) were measured under light bias conditions that produce photocurrents of the top junction around 1.7 mA/cm². The measured output generated photocurrent for cell 1 is 15 μA/cm² while the measured output generated photocurrent for cell 2 is 12 μA/cm². The output current of C1 is higher at reverse bias conditions due to the higher shunt current in the device. Under these light bias conditions, coupling effects start to become evident. The top junction photocurrent is the measured output current of the solar cell when a light bias is applied in the response region of the GaInAs junction (808 nm) in order to cause the GaInP junction to be current limiting.
The characteristic I-V curves in Fig. 5(b) were measured at higher light bias conditions. In this case, light bias conditions produce photocurrent of the top junction roughly 12 mA/cm$^2$. The output generated photocurrent for cell 1 is 0.55 mA/cm$^2$ while for cell 2 is 0.77 mA/cm$^2$ at a voltage bias of the device of 1.2 V. Fig. 5(b) shows that the transition towards higher light bias causes a significant increase of the output current and thus of coupling current especially in the high quality material. The current of the high quality material C2 is higher at all voltage biases indicating that the coupling effects are dominant at all applied voltages while the shunt resistance effects are eliminated. The data show that cell C2 is more affected by coupling and for that reason coupling effects are expected to be enhanced in high quality material devices. Therefore, higher coupling current directed towards GaInAs is expected to cause more pronounced measurement artifacts during EQE measurements.

The shunt resistance value of the middle GaInAs junction for both devices can be extracted by the I-V curves of the tandem device at normal light bias conditions. The I-V curves presented above were taken under dark conditions of the middle GaAs junction. In the dark the shunt resistance of the middle junction is given by Ohm’s law according to the relationship:

$$R_{sh} = \frac{V}{I}$$  \hspace{1cm} (4)

In the absence of voltage bias of the tandem device the voltage of the GaInAs junction is negative since the junction is in reverse bias conditions. Specifically the voltage across the junction according to past measurements is roughly -1.2V [5]. This voltage seems to move the operating point of the middle GaInAs junction close to short circuit conditions (see I-V curves of Fig. 5). In the absence of voltage bias, the output current equals the shunt current since in that region the impact of shunts is higher. Therefore the shunt resistance of the middle junction in the presence of a voltage of 1.2 V and output currents of 3 µA for C2 and 5 µA for C1 (as demonstrated by Fig. 3a) according to (4) were estimated to be $4 \times 10^5 \Omega$ and $0.24 \times 10^5 \Omega$, respectively.

**D. EQE Measurements**

At the same light bias conditions of Fig. 5(a) the EQE measurements of the middle GaInAs junction in both devices were almost identical. This indicates that in those conditions the effects of the shunt and coupling are negligible due to the use of appropriate light and voltage biasing [5]. The EQE of both devices was then measured under higher light bias conditions in order to examine the impact of shunt resistance on coupling effects. The light bias conditions used in that case are the ones used earlier in the I-V curves of Fig. 5(b). EQE measurements were taken in the presence of 0.6 V voltage bias. The results are depicted in Fig.6. In these conditions strong coupling effects exist as indicated by the I-V curves of Fig. 5(b). The EQE signal in the high shunt device is marginally lower compared to the signal of the lower shunt device. This occurs in all wavelengths within the response region of the GaInAs junction. The difference between both signals is around 2.5% and it is believed to be attributed to different coupling effects present in both materials. Another indication of coupling effects during EQE measurements is the overestimation of the signal in wavelengths outside the region of response of the junction under examination. In the case of the EQE measurement of GaInAs, an overestimation of the signal was expected to be observed at around 550 nm. However no change was observed in that region and we tentatively attribute this to the very low EQE signal in the region. During EQE measurements the emission from the two devices was captured by the fiber-optic. Luminescent measurements indicated that the signal emitted by C2 is considerably higher compared to the signal of C1 indicating that coupling effects in higher quality materials are more severe which confirms the EQE and I-V measurements.
V. DISCUSSION

In order to evaluate the simple theoretical model of section II using the experimental results, we add all the measured values in equation (3) and estimate the EQE reduction due to the coupling term in different shunt resistance devices. We measure the values when no voltage bias is applied to the device (V=0V). The $I_{LC}$ values for both materials according to experiments are 0.17 mA for C1 and 0.23 mA for C2. The shunt resistance values for the two devices were estimated to be $0.24 \times 10^5 \Omega$ for C1 and $4 \times 10^5 \Omega$ for C2. The bias photocurrent of the top junction of the devices at the given high light bias conditions was measured to be 4 mA. The photocurrent of the middle junction is assumed to be zero. The voltage across the top junction in those conditions is around 1 V according to previous measurements [5]. Therefore, voltage of 0.99 V across C1 and 1.055 across C2 are reasonable assumptions. The coupling efficiency term in both devices was measured to be around 1%. The reverse saturation current for the devices was set to be $10^{-15}$ mA for C1 and $10^{-16}$ for C2 respectively. These values were not measured but are reasonable approximations. Putting those values into equation (3) gives $x=0.093$ for C1 and 0.116 for C2. These results are in good agreement with the experimental results thus validating the model. The underestimation of the middle junction EQE due to the shunt term according to the model is very small, of the order of $10^{-5}$ and its contribution to the EQE reduction is negligible.

VI. SUMMARY

EL, I-V, EQE results on different shunt devices shows quantitatively the effect of shunt resistance on coupling current. The radiative recombination mechanisms of the two devices were investigated with spectroscopic EL, indicating large differences on the intensity of the radiative recombination in the samples. Measurement of the I-V curves at the light bias conditions where EQE is performed indicate the output current produced by the junction under investigation and furthermore the amount of luminescent coupling effects directed towards it. EQE measurements indicated a larger reduction of the signal in high quality material devices due to coupling. Exceeding the appropriate light bias conditions during EQE measurements in the presence of high shunts in a junction leads to higher measurement artifacts. However even if the difference in DC-currents is large, the impact of the shunt resistance on EQE results during coupling is small.

ACKNOWLEDGMENTS

This work has been co-financed by the European Regional Development Fund and by Republic of Cyprus in the framework of the project ‘Spectrally Tuned Solar Cells for Improved Energy Harvesting’ with grant number ΤΕΧΝΟΛΟΓΙΑ/ΕΝΕΡΓ/0311(BIE)/13.

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