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

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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

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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 $4 \times 4\ cm^2$. 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

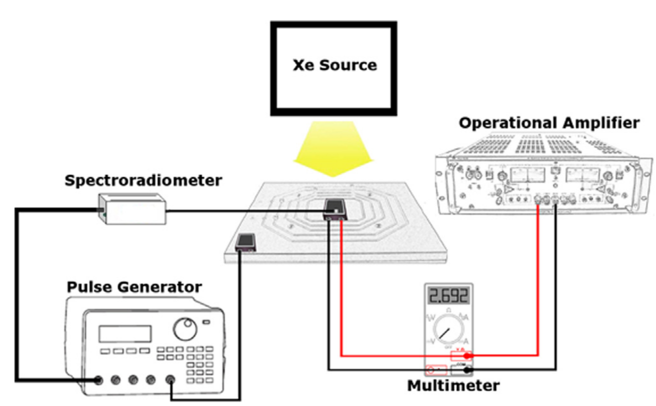

Fig. 1. Schematic of the sun simulator set-up.

taken in the presence of the blue light source only. The relation between PL emission and the power of the blue light source appears to be linear as shown in Fig. 2(a). In this case the top InGaP junction is strongly forward biased and the radiative recombination created at the band-gap edge of the top junction leads to coupling current directed towards the middle InGaAs junction. The increase of the current inside the middle junction could be detected if this were the limiting junction. Such a procedure is performed and explained in detail elsewhere [8].

Subsequently, in the presence of a fixed blue light intensity, a NIR source of varying intensity was used and the PL signal from the band-edge of the top junction was captured at each irradiance value. The integrated PL emission intensity of the top junction was found to decrease approximately linearly with increasing irradiation power of the NIR light as shown in Fig. 2(b). PL quenching of the signal at the band-gap edge of the top junction is induced from the decreased forward voltage in the InGaP top junction, originating from the photovoltaic effect in the InGaAs middle junction. The NIR illumination produces a photovoltage which acts as an applied bias to the InGaP top junction. As the illumination power of the NIR light increases, the induced voltage in the InGaP junction increases also thus reducing its forward bias voltage. These results confirm that the junctions are coupled electrically and optically and luminescent coupling effects between the top and middle junction appear to have a strong correlation with the external photocurrents of the top and middle junctions. In the case where the NIR light at 808 nm increases, the reduction of the PL emission of the top junction is accompanied by an increase of the PL emission of the middle junction as shown in Fig. 3(a). Since the PL emission of the top junction decreases then subsequently the amount of photons directed to the middle InGaAs junction due to coupling effects decreases. The same holds with the PL emission of the middle junction. NIR light enhances the radiative recombination at the band-gap edge of the middle junction and thus the amount of photons directed towards the bottom Ge junction is expected to increase. Consequently, while luminescent coupling effects between top and middle junctions decrease, luminescent coupling effects between middle and bottom ones increase. Specifically a linear decrease is observed in the radiative signal of the middle InGaAs junction as the radiative signal from the top InGaP junction increases (see Fig. 3b). The reduction of the radiative signal at the band-edge of the top and therefore the

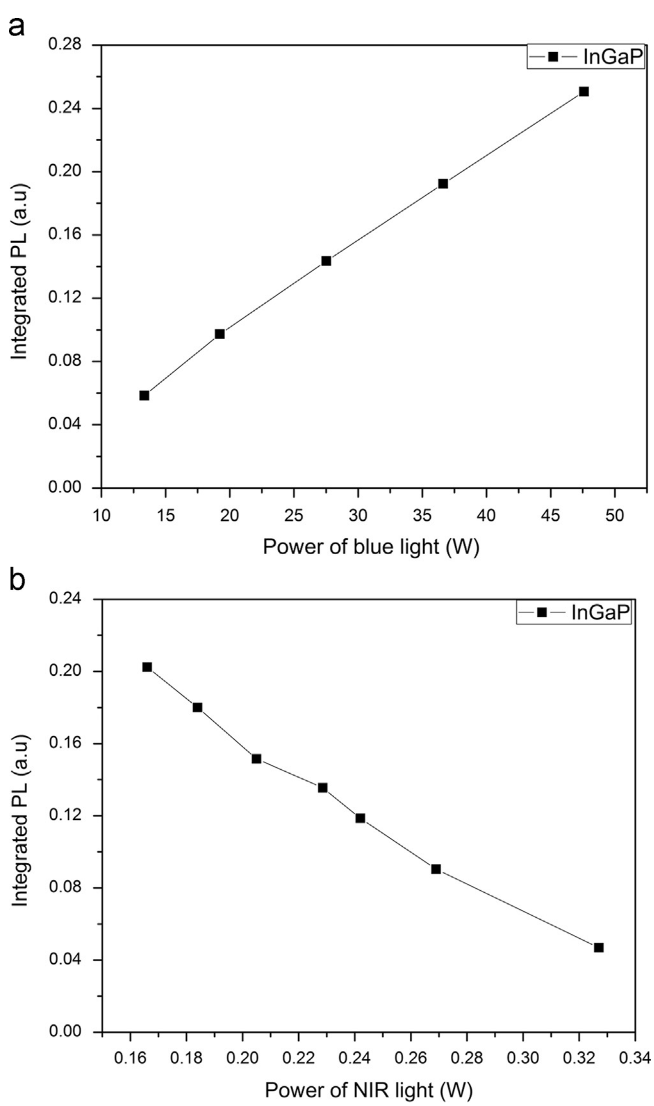

Fig. 2. (a) Integrated PL intensity of the radiative signal from the top InGaP junction against the power of the blue light source applied on the device. (b) Integrated PL intensity of the top InGaP junction against the power of the NIR light source. The measurements were taken in the presence of a fixed blue light intensity of 40 W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

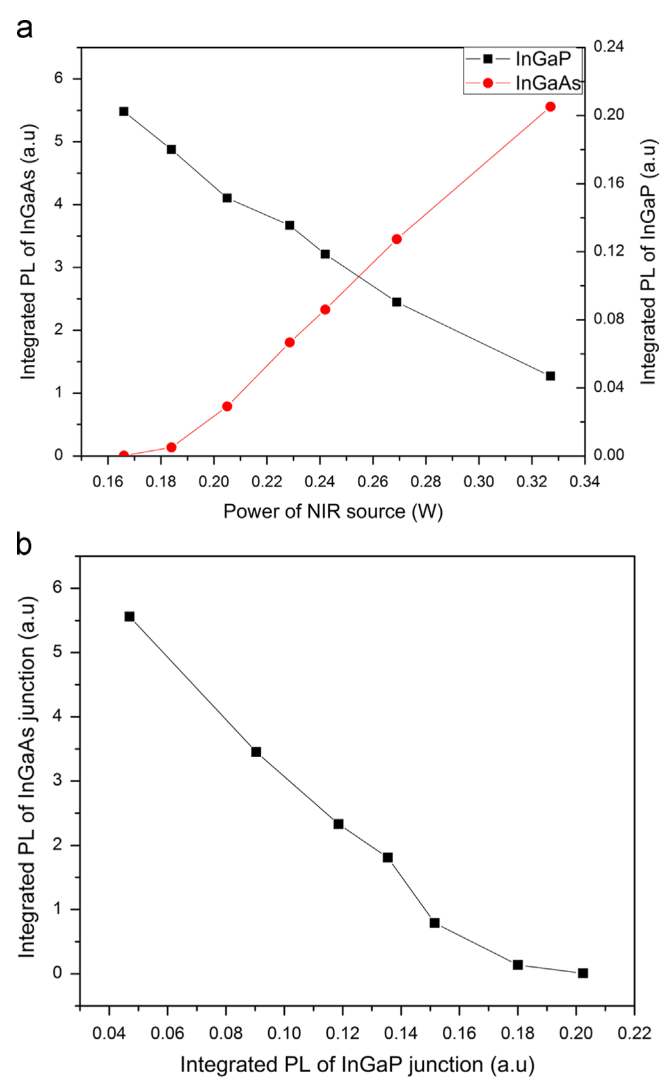

Fig. 3. (a) Integrated PL emission from the top and the middle junctions in the presence of fixed blue light intensity and varying NIR intensity and (b) relationship between the radiative signals from the junctions at the same light bias conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reduction of the coupling current directed to the middle junction in the presence of a light source outside the region of response of the top junction is in agreement with previous theoretical calculations [9] which predict that the coupling current density depends on the externally induced photocurrents and also on the density of the coupling currents between other junctions in the multi-junction device. Presence of photocurrents in all the junctions of the tandem as well as presence of coupling currents between other junctions causes reduction to the coupling current density. Therefore, in a triple-junction solar cell the coupling current between top and middle junctions depends on the external photocurrents of the junctions as well as on the coupling current between middle and bottom junction.

The bottom Ge junction was not taken into consideration in the above explanation. This junction produces a very small photocurrent since no illumination in its response region was applied to the device in this case. Since the voltage of that junction is very small the change in applied spectrum will not cause differences in the forward voltage of the Ge and thus will not have significant influence on the floating potential between the top and middle junctions.

The excitation power dependent PL measurements indicate that a polychromatic light bias significantly reduces radiative emission from junctions in multi-junction devices. The reduction of the radiative emission was observed in the presence of voltage. Therefore, the presence of radiative recombination is expected to be very low or completely absent under polychromatic light bias. Furthermore, recent results have shown that reduction of the electroluminescence (EL) emission from a junction occurs in the presence of a light bias outside the region of response of the junction [10]. In the next sections examination of the luminescent emission from the solar cells will be carried out under a solar simulator indoors and solar irradiation outdoors in order to investigate the extend of radiative emission.

3.2. *Luminescent emission using a high intensity pulsed solar simulator*

In order to investigate the presence of luminescent emission at different sun concentration levels, the emission of the cell was measured using the pulsed sun simulator set-up over a broad range of wavelengths and concentration levels. At each concentration level, the device was investigated at different voltage bias and temperature in order to extract the impact of these parameters on the luminescent signal. The detection of the signal from the device is a non-trivial task due to the high reflection of the Xenon lamp spectrum from the surface of the cell which obscures the actual emitted signal. To have a clear indication of the luminescent emission from the cell, the short-circuit current emission was initially captured. Due to the absence of voltage at short-circuit conditions, the emitted signal is very low and differs from the emitted signal taken in the presence of voltage. For that reason the short-circuit spectrum taken from the device was set as the background signal and then the spectrum from the device was taken in the presence of voltage. Thus, the recorded signal is not the raw luminescent signal from the device but the difference between the emission of the device in the absence (short-circuit) and in the presence of voltage. Therefore, it should be noted that the actual emitted signal from the device is higher than the emission reported here since the difference between emissions at different voltages is lower compared to the actual signal.

3.2.1. *Impact of voltage bias*

The luminescent emission from the device was investigated at different voltage biases and at a constant temperature in order to establish the impact of voltage bias. A broad range of concentration levels was used, between 200 and 1000 sun. Before performing the optical measurements, the electrical parameters of the device were measured to determine the maximum power point of the device in each case and therefore the voltage region at which the cell should be investigated optically. The electrical characteristics of the device at nominal concentrations of the sun simulator of 400 sun and 1000 sun are given in Table 1. The temperature of the device was set to 20 °C.

After performing these measurements, the voltage bias applied to the device was varied between 2.6 and 2.9 V to specifically include the maximum power point voltage at each concentration level within the range. Voltage dependent emission spectra were then recorded from the triple-junction cell under test at various voltages at 400 and 1000 sun concentration and at a temperature of 20 °C. The results are depicted in Fig. 4. Two emission peaks are present at the band-edges of the two top junctions at 1.33 eV and 1.82 eV at all voltage biases and for both concentrations under investigation. Specifically the InGaP peak corresponds to the peak at 1.82 eV while the InGaAs peak corresponds to the peak at 1.33 eV. During light excitation of the cell, radiative recombination of carriers creates photons that can be either emitted from the surface or directed towards the bottom junctions where they can be reabsorbed. The emission signals observed correspond to the portion of photons that finally escape from the cell. According to previous work a small number of photons is expected to be emitted from the surface since the escape cone of photons at the front of the cell is relatively small. Thus, the vast majority of photons are actually emitted and reabsorbed into the lower junctions causing coupling effects [4]. The large amount of photons emitted from the band-gap edges of the top and middle junctions in our measurements give an indication of the possibility of the presence of coupling effects in the device. Specifically strong radiative recombination at the band-gap edge of the top InGaP might lead to reabsorption of photons from the middle InGaAs junction and coupling effects. Similarly, strong emission from the InGaAs junction may lead to reabsorption of photons in the bottom Ge junction. Here it should be noted that the presence of strong radiative recombination under white light application was not an expected result since the excitation dependent PL in Section 3.1 showed that white light reduces radiative recombination. Thus, even if the white light excites all junctions of the tandem and luminescent emission is an expected behavior, the presence of polychromatic light strongly reduces that emission for the reasons explained in the previous sections. The observation of a strong radiative signal in Fig. 4 from both junctions at maximum power point voltage for both concentrator levels gives evidence that coupling effects may occur during outdoor operation of the device in these conditions. Fig. 4 also shows that the emission at the maximum power point becomes higher at higher concentration levels due to the higher carrier concentration generated. This is discussed further in the next sections. Furthermore, higher radiative emission is observed at higher voltages as indicated in Fig. 4 since the voltage bias increases the amount of recombination in the device.

As depicted in Fig. 4, the radiative emission created by the middle InGaAs junction is considerably higher compared to the

Table 1
Electrical parameters of the device under examination at different nominal concentration levels. The temperature of the sample was set to 20 °C.

Nominal concentration level (sun)	V_{oc} (V)	I_{sc} (A)	P_{MPP} (W)	FF (%)	V_{MPP} (V)	I_{mpp} (A)
400	3.06	1.89	4.95	85.20	2.69	1.83
1000	3.15	5.12	13.51	82.40	2.77	4.87

amount of luminescent emission produced by the InGaP top junction. The difference in luminescent signals is believed to be attributed to the thickness of the InGaAs middle junction. Middle junction is two times thicker than the top one and thus the number of energy states excited in this junction is higher. This is in agreement with the EL emission of the device which shows that the emission signal from the middle junction is higher than the signal emitted by the top [11]. Here it should be noted that the radiative signal at 1.33 eV should be a superposition of the actual luminescent emission from the middle junction and the radiative recombination of carriers of the top junction. Specifically, the photons emitted from the top junction are directed towards the middle one via optical interactions and coupling effects. The excited carriers produced by the injected photons are relaxed to ground states and finally to the band-gap edge contributing to the radiative emission at 1.33 eV.

Furthermore, the radiative emission at different voltages shows that the application of higher voltage biases causes shifting of the peak wavelength. This redshift is tentatively attributed to heating of the sample leading to band-gap narrowing effects. Even if the sample temperature was set to 20 °C, lattice temperature rises due to excess carrier density apparent in the device as a result of high biases. The redshift is more pronounced in the case of applied voltage value of 2.9 V where the forward bias is higher. At open-circuit conditions redshift of the spectrum was not observed indicating that the temperature rise is very low in those conditions may be due to the absence of current in the device. At sun concentrations of 400 in Fig. 4(a) the band-gap shrinkage of the top junction in the investigated voltage range was measured to be 10.8 meV while the reduction of the band-gap for the middle was 1.2 meV. Similar reduction of the band-gap was observed at even lower sun concentrator levels (200). The band-gap shrinkage at a concentration level of 1000 sun was found to be 4.8 meV for the top and 1 meV for the middle junction. The peak wavelengths against voltage bias for both concentration levels are depicted in Fig. 5. Larger redshift of the top junction at both concentration levels appears indicating the higher sensitivity of that junction to the applied voltage and thus to the temperature. Higher sensitivity of the top junction with temperature is a material dependent property and is attributed to the higher temperature coefficient of the InGaP material. This is confirmed by the temperature measurements presented in the next section.

Fig. 4 also shows that the emission taken at open-circuit conditions is higher than the emission taken at maximum power

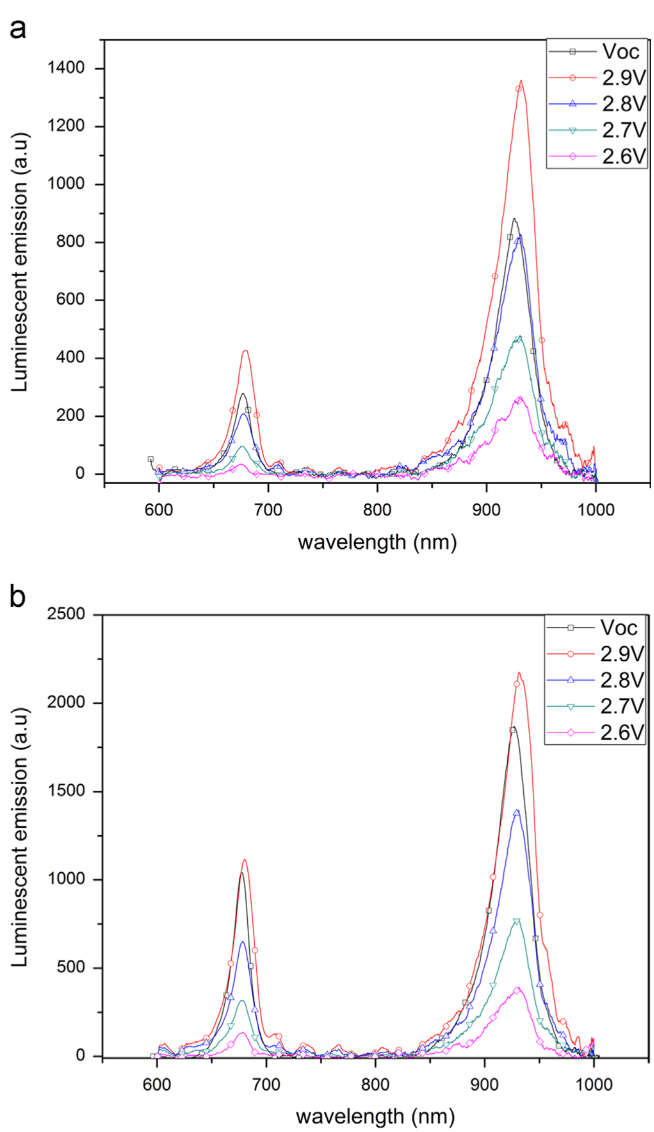

Fig. 4. Luminescent emission from the device at different voltage biases at a temperature of 20 °C. The spectrum was taken at (a) 400 and (b) 1000 sun. The maximum power point of the device in those conditions is 2.69 V and 2.77 V, respectively.

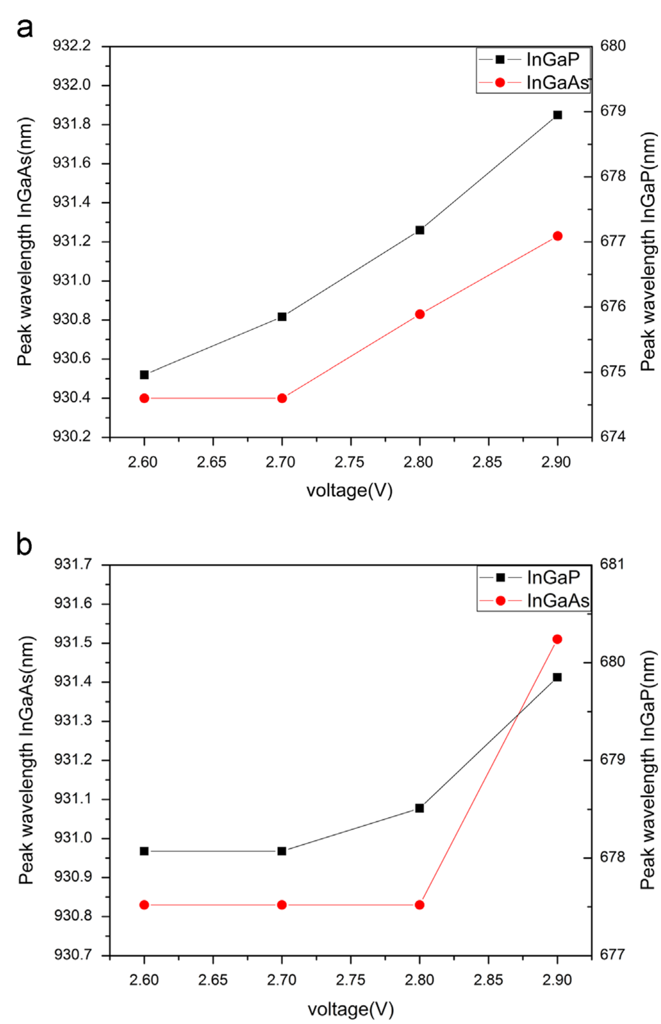

Fig. 5. Peak wavelengths against voltage bias at a temperature of 20 °C. The dependence of the peak wavelengths with voltage was investigated at (a) 400 and (b) 1000 sun. Redshift of the peaks are more pronounced in the top InGaP junction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

point voltage. Under open-circuit conditions, the emission is expected to be higher compared to the one taken at maximum power point voltage since in the absence of current, all the energy of the device is dissipated as emission [12]. Previous works have shown that the open-circuit voltage can be derived from the luminescent properties of the device [13]. One important observation that arises from Fig. 4 is that the emission taken at open-circuit conditions is lower compared to the radiative signal emitted from the device in the presence of voltage bias of 2.9 V. So for the conditions investigated here even if the open-circuit voltage value is above 3 V the luminescence emitted is lower than the emission at voltage bias of 2.9 V. This observation indicates that the luminescent intensity emitted at open-circuit conditions is not related linearly with the luminescence arising when we apply voltage to the device. The result shows that with voltage bias application of 2.9 V, the carriers created in the device are higher in number compared to the carriers created due to light only (open-circuit conditions). Therefore, although a lower radiative recombination is expected in the presence of voltage (2.9 V) due to current generation, the high number of excited carriers results in significant luminescent emission. Consequently, the emission seems to depend non-monotonically on the bias. However, in the presence of voltage a proportional relation between luminescent intensity and voltage exists. The integrated luminescent signal was found to increase with increasing applied voltage since the presence of voltage moves the operating point of the device towards the forward bias region where the recombination rate increases as mentioned before. The integrated luminescent emissions of the InGaP and InGaAs against voltage at low and high sun concentrations are depicted in Fig. 6. The dependence of the integrated emission against voltage is exponential for both junctions and concentrations under investigation. From the literature it is known that the emission is proportionally related to the coupling current [14] and the coupling current has an exponential dependence with voltage according to the diode equation [15,16]. Thus, the emission signal is expected to be exponentially related to the applied voltage. Fitting of the curves with an exponential function was performed and showed very good agreement with the measured emission curves. Fig. 6 also shows that the increase of the emission with voltage is more pronounced in the top junction at lower concentration levels (400 sun). The higher sensitivity of the top junction to voltage could be attributed to the higher sensitivity of that junction to temperature as discussed in the previous paragraph. Higher voltage bias applied on the device leads to increased lattice temperature, heating of the sample and thus band-gap reduction. Band-gap shrinkage causes decrease of the open-circuit voltage of a junction and increase of the photocurrent [17]. The photocurrent becomes higher due to increased absorption from the lower energy states close to the band-gap edge. Reduction of the open-circuit voltage also occurs due to heating in both junctions and thus the operating voltage comes closer to open-circuit conditions, enhancing the recombination within the device. Since band-gap narrowing is higher in the top junction as indicated by the higher redshift of the PL peak, photocurrent and optical absorption as a function of voltage increases more compared to the middle junction leading to a higher increase in radiative emission. Furthermore, open-circuit reduction is more pronounced in the top junction and thus the operating voltage comes closer to open-circuit voltage resulting also in higher recombination in the top junction. Another factor that may explain the higher sensitivity of the top junction to voltage could be the dependence of the potential of each junction on applied voltage. Higher voltage biasing of the device could affect the top junction bias to a greater degree (shifting it closer to open-circuit voltage) than the middle junction and thus increased recombination is observed. Overall, a combination of the above effects may also take place resulting to a higher sensitivity of the top junction to voltage. The above effects are more pronounced at lower concentrations.

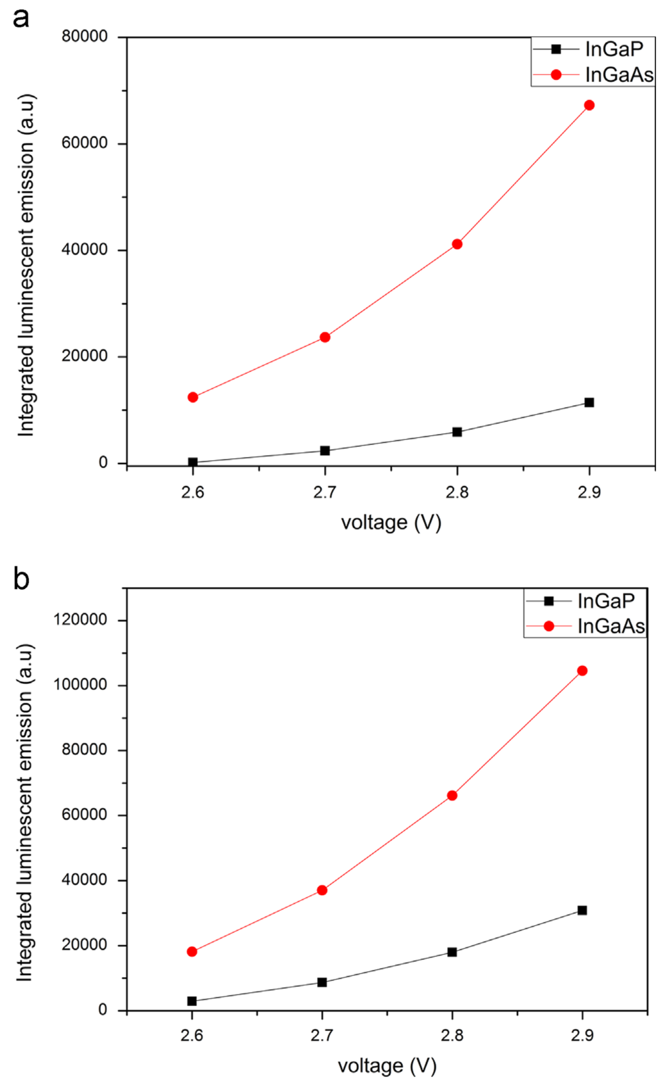

Fig. 6. Integrated luminescent emission against voltage bias for both top InGaP and InGaAs junction at sun concentrations of (a) 400 and (b) 1000. The temperature of the sample was set to 20 °C.

Table 2
Wavelength position of the peaks apparent in the vicinity of the middle junction at different nominal concentration levels. The voltage bias applied on the device was 2.9 V.

Nominal concentration level (sun)	Wavelength (nm)	Wavelength (nm)	Wavelength (nm)	Wavelength (nm)
200	710.0	738.0	768.0	–
400	708.7	737.0	765.0	–
800	708.0	736.5	766.0	809.2
1000	707.8	736.5	765.8	806.2

In the high voltage region (2.9 V) multiple small peaks are apparent at wavelengths between 700 and 832 nm. The peaks were present in the high voltage regime indicating that their existence is related to voltage bias. The exact wavelength positions of the peaks at different concentration levels and at a voltage bias of 2.9 V are given in Table 2.

The small peaks are tentatively attributed to defect luminescence in the top junction. They are apparent at the high voltage regime in all the concentration levels under examination and become more pronounced at high light biases where the junctions become even more forward bias. The forward bias in those conditions is so strong that has the potential to excite mid-gap states in the junctions. The wavelength of the peaks was found to 'blueshift' at higher irradiance concentrations due to band filling effects. The sensitivity of the spectroradiometer used was limited at 1000 nm and therefore the presence of similar peaks in the wavelength region of the middle InGaAs junction could not be observed.

3.2.2. *Impact of temperature*

To examine the impact of the temperature on the radiative emission, the emission spectrum from the device was captured at various temperatures. The temperature control of the sample was achieved with a Peltier element with measurement uncertainty of 4%. Initially the electrical characteristics were measured at temperatures of 40 °C and 60 °C and at nominal concentration of 1000 sun as depicted in Table 3. The maximum power point voltage at these temperatures is lower compared to that at lower temperatures (20 °C) investigated earlier. In an attempt to indicate differences between luminescent emissions at high and low temperatures, the emission at a specific concentration (1000 sun) and at maximum power point was plotted for three different temperatures 20 °C, 40 °C, 60 °C (Fig. 7a). Furthermore for comparison purposes, the radiative emission at open-circuit voltage conditions was also plotted at different temperature levels (Fig. 7b). Integrated luminescent emission against temperature is plotted in Fig. 7(c) and (d), respectively, in order to demonstrate the trend of the emission with temperature at maximum power point voltage and open-circuit conditions.

It is observed that luminescent emission from the device is still apparent at 40 °C and 60 °C indicating that significant radiative recombination takes place in the device and therefore coupling effects may occur at even higher temperatures. Higher temperatures are expected to significantly reduce radiative recombination from the junctions since non-radiative paths become dominant at

Table 3
Electrical parameters of the device under examination at different temperatures. The nominal concentration level is 1000 sun.

Temperature (°C)	V_{oc} (V)	I_{sc} (A)	P_{MPP} (W)	FF (%)	V_{MPP} (V)	I_{mpp} (A)
40	3.08	5.16	12.93	80.70	2.65	4.89
60	3.01	5.24	12.44	78.90	2.52	4.95

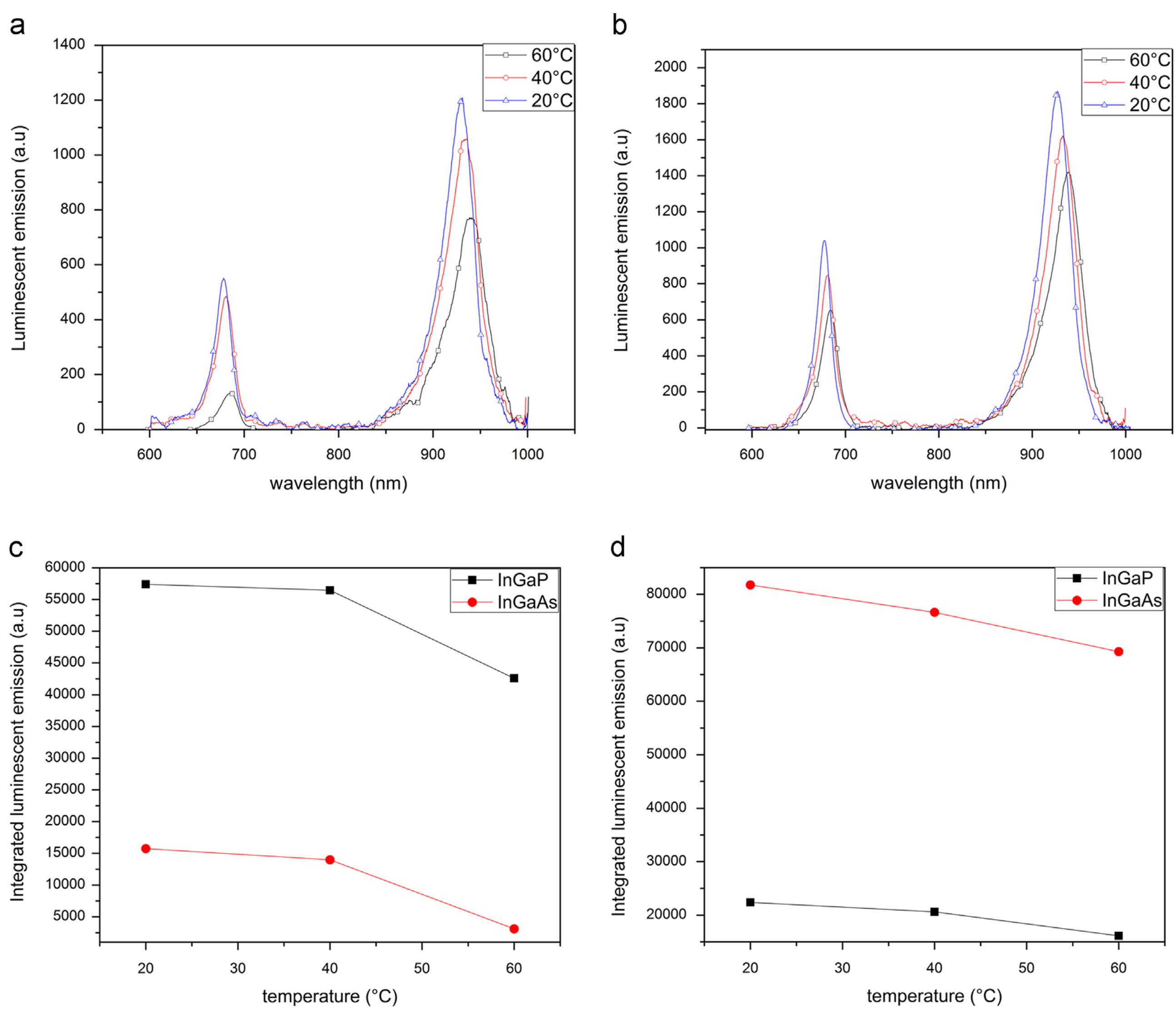

Fig. 7. Luminescent emissions of the InGaP/InGaAs/Ge device at a concentration of 1000 sun for three different temperatures at (a) maximum power point and (b) at open-circuit conditions. Integrated PL against temperature at maximum power point and open-circuit conditions are depicted in Fig. 6(c) and (d), respectively.

these conditions [11,18]. Due to the reduction of the radiative recombination the coupling current directed towards the bottom junctions is likely to be affected significantly [8].

A linear redshift of the luminescent peaks with temperature is apparent during measurements at open- circuit conditions and in the presence of voltage. The shift of the emission is attributed to heating resulting in band-gap shrinkage effects of the junctions. A linear decrease of band-gap energy with increasing temperature is a typical behavior of semiconductors for temperatures above roughly 100 K [19,20]. The band-gap shrinkage of the InGaP due to heating at open-circuit conditions (Fig. 7b) is 21.4 meV while the corresponding one for the middle junction is 19.6 meV. The corresponding band-gap narrowing per degree Celsius for each junction is 5.3×10^{-4} eV/°C and 4.9×10^{-4} eV/°C which are in good agreement with previous measurements [21]. As temperature increases, the absorption band energy of the top junction shifts more than that of the middle causing a rise in the current density ratio of top to middle (J_T/J_M) with temperature. The shift to higher J_T/J_M with temperature is advantageous given that higher J_T/J_M is generally more difficult to achieve. Integrated luminescent emission against temperature (Fig. 7c and d) demonstrates that the radiative emission of the top junction reduces more than the emission of the middle in both maximum power point and open-circuit conditions as a function of temperature. This indicates the higher sensitivity of the top junction emission with temperature. It is well known that the decrease of the energy gap of the device due to temperature effects leads to reduction of the open-circuit voltage [17]. Since the band-gap reduction of the top junction is higher, the open-circuit voltage drop is larger in that junction. Therefore, the luminescent emission of the top InGaP junction at open-circuit conditions will exhibit a higher intensity drop compared to the middle InGaAs in agreement with the observed results. This holds for the luminescence at maximum power point voltage conditions.

Besides the energy shift of the luminescence with temperature, another major characteristic of the emission peaks is the exponentially dropping edges. The energetically lower slope remains constant against temperature while the higher one gets flatter with increasing temperature. This is in agreement with recently published results and is attributed to temperature independent density of states below band-gap and Boltzmann distributed carrier emission above that [20].

3.2.3. *Impact of concentration*

The luminescent emission at the maximum power point was measured at different concentration levels in order to study the effect of concentration upon radiative emission from the device (see Fig. 8a). The integrated emission as a function of concentration for both junctions (InGaP and InGaAs) is shown in Fig. 8(b). A linear relationship of the integrated luminescent emission against concentration is apparent for the InGaAs junction in the investigated concentration range. The measurements were conducted under high carrier injection conditions where radiative recombination is the dominant mechanism [22]. The linear relationship is not apparent for the top InGaP junction probably due to the existence of multiple peaks at the low energy band tail of the junction described above which overestimates the integrated emission at 1000 sun. The increasing rate of the integrated emission of the middle junction against concentration is much higher than the rate observed for the top junction since a higher number of carriers is excited in that junction due to the larger thickness. In summary, the presence of higher concentration and light biases increases radiative recombination emitted from each junction.

Redshift of the PL peak was obtained with increasing sun concentration indicating an increase of the sample temperature

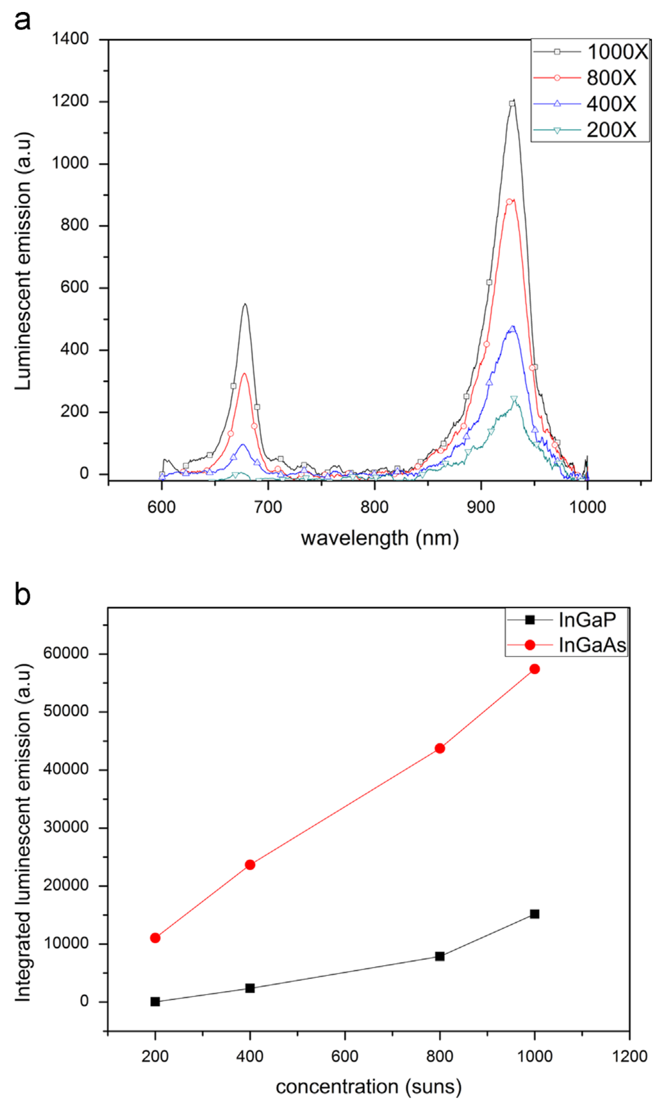

Fig. 8. (a) Luminescent emission of the InGaP/InGaAs/Ge device at maximum power point conditions and at sun concentration between 200 and 1000. The temperature of the device was set to 20 °C. (b) Integrated PL of the top InGaP and middle InGaAs junction against concentration at the same voltage and temperature conditions.

due to higher injection levels. The observed redshift fluctuates between 1 and 6 meV depending on the applied temperature with the higher shift present at lower temperatures (20 °C) and at the top junction. Redshift of the middle junction is very small and almost negligible. The observed redshift is in agreement with recent published results and may be attributed to enhanced carrier–carrier and carrier–lattice collisions [20,23].

3.3. *Luminescent emission under outdoor solar irradiance*

Outdoor measurements were also performed for the observation of radiative emission under open- circuit and in real solar irradiance conditions. The device was placed on a solar tracker that followed the sun to within an error of 0.1°. The temperature of the cell during the optical measurements was measured to be 30 °C. The measurements were performed under open-circuit conditions at midday since at that time the solar irradiation is higher and stable. An irradiance concentration of 6 sun on the device was achieved with a Fresnel lens. The Direct Normal Irradiance taken from the pyrheliometer at the time of the measurement was 777 W/m^2 while the Global Irradiance measured from the pyranometer was 996 W/m^2.

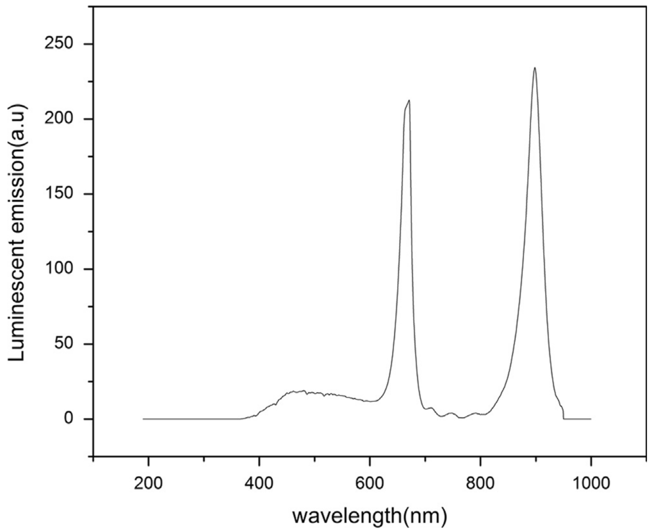

Fig. 9. Outdoor emission of the InGaP/InGaAs/Ge under 6 sun. The measurements were performed during midday and under open-circuit conditions.

The emission was captured by a fiber optic cable used to direct light to a Silicon-CCD spectroradiometer. The outdoor radiative emission spectrum as seen in Fig. 9 under concentrated solar irradiation shows clearly the significant radiative recombination of the carriers at the band-edges of the top and middle junctions which indicates that photons are likely to be directed towards and reabsorbed by middle (InGaAs) and bottom (Ge) junctions, respectively. The peak from the Ge is not shown in the graph since it is beyond the sensitivity of the spectroradiometer. The strong emission from the device shows clearly that radiative emission is significant under concentrated solar irradiation and open-circuit conditions confirming the indoor results using the sun simulator. An important observation is that under outdoor illumination the InGaP radiation peak is relatively increased compared to the InGaAs peak. This is probably attributed to the higher outdoor irradiation below 680 nm compared to the Xenon lamp illumination.

Indoor and outdoor tests of the samples have shown that despite the fact that polychromatic light reduces radiative recombination as demonstrated in Section 3.1, the presence of radiative emission is still occurring under broadband solar irradiance and high intensity sun simulator. The results suggest that triple-junction devices used for CPV applications have significant radiative effects that affect the energy yield of the modules and these have to be taken into account.

4. Conclusions

Excitation power dependent PL was performed in order to investigate radiative recombination from the top junctions and thus coupling effects between top–middle and middle–bottom junctions in InGaP/InGaAs/Ge devices. Measurements showed that the presence and the intensity of radiative emission from a junction depend on the photocurrents of the junctions in the tandem as well as on the radiative emission from the remaining junctions of the device. A linear decrease of the radiative signal from the top InGaP junction occurs in the presence of fixed blue light and increased NIR light excitation. Furthermore a linear relationship exists between radiative signals from the two top junctions in the presence of varying NIR light conditions. These results showed that a polychromatic light bias reduces radiative emission and thus coupling effects on multi-junction devices.

The presence of luminescent emission in InGaP/InGaAs/Ge was observed under a high intensity pulsed solar simulator indoors and under broadband solar irradiance outdoors. The emission indoors was investigated at different concentration levels, voltage bias and temperature. Radiative signals from the band-gap edges of the top InGaP and middle InGaAs are clearly observed at high and low concentration and are more pronounced at high concentration levels. The emission signal from the device under the sun simulator was measured at the maximum power point of the cell in order to mimic the operating conditions outdoors. The emission signal in a multi-junction device was obtained also at high temperatures (60 °C). Furthermore, the results showed that voltage bias determines the intensity of luminescent emission. Higher voltage bias applied on the device causes higher luminescent emission. Outdoor measurements were also performed under solar irradiance in order to validate the results from indoor testing. Outdoor measurements confirmed the presence of radiative emission at open-circuit conditions and at low concentration levels (6 sun) indicating the importance of radiative effects at even lower concentrations. Indoor and outdoor testing of luminescent emission indicates that significant radiative recombination occurs in the devices under examination and thus there is a strong likelihood of an occurrence of luminescent coupling in real operating conditions despite the potential for quenching of the luminescent emission under polychromatic light as excitation power PL measurements showed.

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