SUNS-VOC AND MINORITY CARRIER LIFETIME MEASUREMENTS OF III-V TANDEM SOLAR CELLS

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ABSTRACT

Quasi steady state photoconductance (QSS-PC) and the “Suns- V_{oc}” technique have been extensively used for characterizing silicon solar cells. QSS-PC has been used to determine the minority carrier lifetime, saturation current and surface recombination velocity. In this paper, we use both techniques to measure III-V tandem solar cells and III-V material, demonstrating the utility of the Suns- V_{oc} for tandem devices and the ability to apply the QSS-PC measurements to the III-V materials, including GaAs and GaN. PC1D modeling is used to explain the experimental results.

INTRODUCTION

Two techniques often used to characterize silicon solar cell are photoconductance measurements (either transient or quasi-steady state) and examination of the open circuit voltage with light intensity (illumination- V_{oc}, also often called Suns- V_{oc}). While these techniques utilize different effects and have different analysis, they are united in that they can both be measured using the same equipment, and hence both techniques, which have different advantages and uses, are examined in this paper.

Quasi-steady-state photoconductance (QSS-PC) [1,2] has several potential benefits when applied to III-V materials and devices. One advantage is that the short lifetimes encountered in some III-V materials can be characterized without the need for ultra-fast optics or electronics. This is particularly critical for newer materials such as the dilute nitrides or the III-nitride material systems which may have minority carrier lifetimes in the 10 to 100 picosecond (ps) range. Furthermore, since the measurements are fast with no set-up, lifetime measurements in these materials can be routine. Moreover, the lifetime measured by the QSS-PC system represents a weighted average over particular region. In cases where the material may not be homogeneous, such as in the III-nitride materials where phase separation may occur, the average lifetime is more representative of the impact of lifetime on device performance than from other techniques such as photoluminescence. Finally, the QSS-PC is calibrated with respect to illumination level. Overall, the QSS-PC technique allows accurate, repeatable and routine measurements of minority carrier lifetime while reducing the costs and time associated with measuring the lifetime. While photoconductance approaches have previously been used for III-V materials [3,4], the technique is not presently commonly used, and this paper demonstrates the ability to apply current technology and analysis to the III-V material system.

A second class of advantages relates to the use of QSS-PC or Suns-Voc for series connected tandem solar cells rather than layers or single junction devices. In monolithic tandem devices, the individual solar cells are internally connected via tunnel junctions. These internal connections make the characterization of the individual solar cells in the tandem more difficult. Quantum efficiency measurements can be used to probe the individual solar cells collection properties. QSSPC or Suns-Voc can be used to probe the individual junction in a monolithically-connected tandem solar cell. For QSS-PC, no contacts are needed.

In the Suns-V_{oc} technique, a voltage is measured as a function of light intensity, and each light intensity & voltage point is transformed into a (current, voltage) point of an IV curve. Since no current is extracted from the device during measurements, the requirement for an ohmic contact is substantially relaxed. Further, while the same technique can be implemented on an IV tester, the use of a separate reference for determining the light intensity (so that current in never extracted from the device under test) as well as the speed of measurements mean that the technique can be routine. Further, the flash lamp allows for a greater variation of light intensities.

The paper uses the WCT-100 [5] for two sets of measurements which demonstrate that both Suns-V_{oc} and QSSPC can be used with III-V materials. The following section presents Suns- V_{oc} results for a two junction monolithic GaInP/GaAs tandem, showing the use of Suns- V_{oc} curves in analyzing the performance of the solar cell. The next section uses QSS-PC to measure GaAs substrates and GaN layers.

USING SUNS- V_{oc} FOR TANDEM SOLAR CELLS

The Suns- V_{oc} technique can be used for several aspects in measuring tandem devices. The most straight forward use of Suns-V_{oc} is to measure the pseudo-IV curve of the solar cell, which differs from the conventional IV curve in that the FF is not affected by series resistance. A two-junction monolithic tandem [6] consisting of a top cell of GaInP (Eg=1.8eV) and a bottom GaAs (Eg = 1.43 eV) solar cell on a GaAs substrate was measured under these conditions, with the V_{oc} matching the V_{oc} measured under standard IV tests. The pseudo-IV curve is shown in Figure 1.

By using filters over the flash lamp, the Suns-V_{oc} technique can be modified to probe individual junctions in the tandem by using light in the wavelength ranges such that only one solar cell in the multi-junction stack is excited. For the upper stack, light only above the band gap of the upper cell is passed to the tandem, while for a middle cell a notch filter is used. The present results use filters only with the Suns- V_{OC} technique, but the same approach can be applied to measurement of lifetime using QSS-PC. For QSS-PCD, the conductivity is then attributed to only one junction in the device, and hence the parameters, such as minority carrier lifetime, of one of the junctions can be measured.

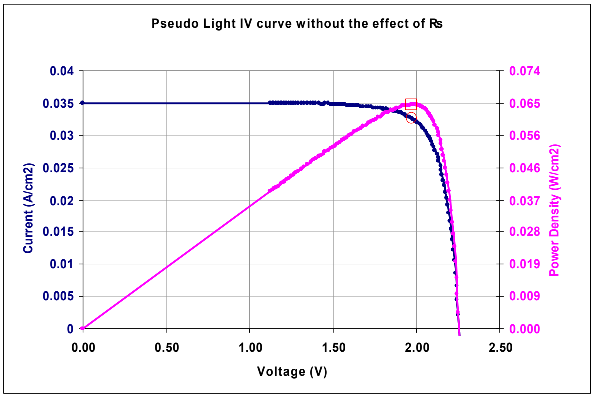

Figure 1: Suns-Voc for the top cell (GaInP) of the tandem using the Voc-measurement system

In order probe each junction individually, filters are places over the flash lamp. In the first cases, a notch filter is used which passes low energy light, in the range 750 to 850 nm. The pseudo-IV curve is shown in Figure 2 and V_{OC} as a function of light intensity is shown in Figure 4.

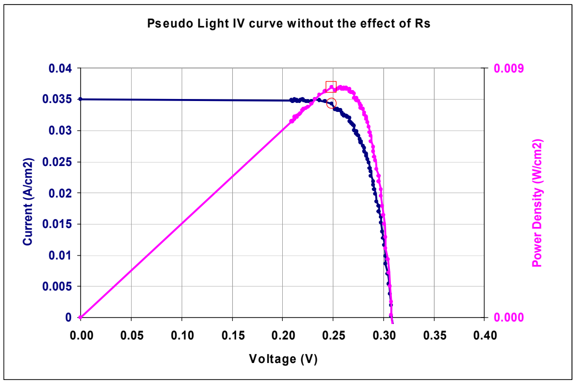

Figure 2: Pseudo-IV curve of the tandem using a low-pass filter which excites the GaAs junction.

The V_{OC} of the tandem with only the GaAs junctions excited, is just over 0.3V. The low V_{OC} is not due to an intrinsic low V_{OC}, but rather due to the excitation of the tunnel junction, which is a GaAs tunnel junction. In the equivalent circuit diagram, shown in Figure 3, the top GaInP solar cell is “off”, since it is not illuminated. Any current or voltage generated by the tunnel junction may be in opposition to the GaAs bottom solar cell, if the tunnel junction does not act like a low-resistance path. Since the tunnel junction is both much thinner than the GaAs bottom cell and is optimized not for high open circuit voltage, the current and voltage of the GaAs bottom cells is larger, particularly at low to moderate illumination levels, giving rise to an apparent low V_{OC}.

As the illumination increases, the tunnel junction may develop a substantial current and voltage in opposition to the GaAs bottom cell. The effect is seen by plotting the voltage as a function of light intensity as in Figure 4. At high illumination, the voltage of the tunnel junction increases more rapidly with illumination than the GaAs junction, since in a junction with shunting components, the effect of these reduces as light intensity increases. Thus, as the illumination increases, the voltage across the tunnel junction increases more rapidly than across the bottom tandem junction, as the overall voltage decreases. These effects, which may be difficult to determine via other techniques, are readily identified using Suns- V_{OC}.

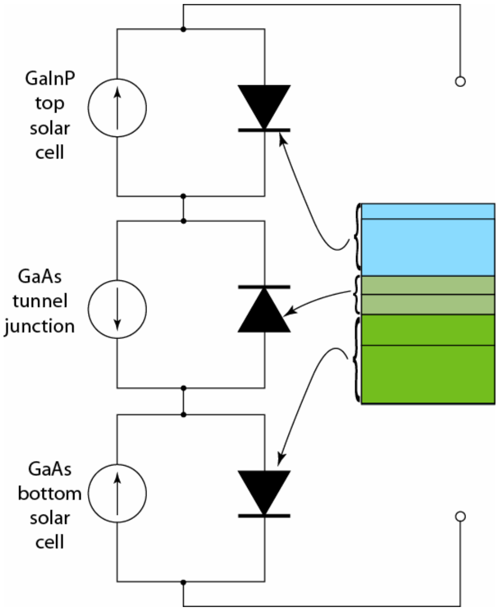

Figure 3: Equivalent circuit for a two-junction tandem solar cell connected via a tunnel junction.

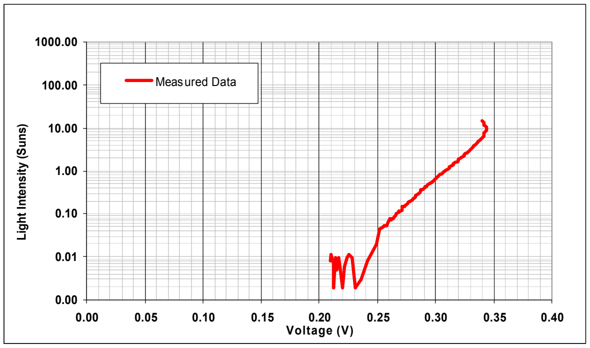

Figure 4: Voc as a function of light intensity as determined from pseudo-IV measurements.

The ability to tailor the relative bias and current of junctions provides additional flexibility in determining the operation of the device. For example, biasing the top GaInP solar cell with a constant light source (in this case it is done with room lights, but combinations of filters or other light sources give increased control), allows interaction between the three junctions to be measured. The voltage light intensity plot is shown in

Figure 5, and shows greater “bend-back” than before. The top cell is biased under constant illumination, while the bottom cells have varying illumination. Since the voltage of the GaInP is the largest but does not increase with the illumination (since its light source is fixed), as the illumination increases, the overall voltage decreases even low illumination levels. The point at which the bend-back occurs allows further information about the top cell to be determined.

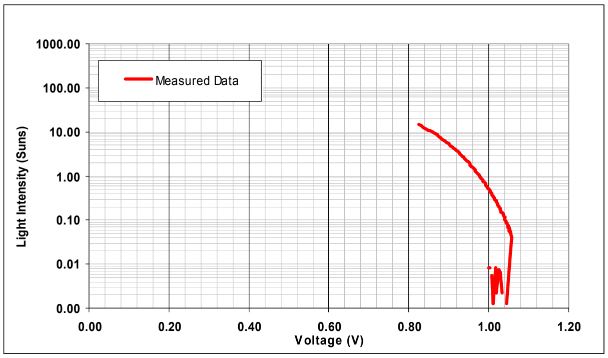

Figure 5: Implied voltage of the tandem using the Voc measurement system, with the top GaInP at low (constant) light bias.

QSS-PC FOR III-V AND III-N MATERIALS

When light of energy greater than band gap (E_g) is absorbed in a semiconductor material an electron hole pair (EHP) is created. This EHP increases the conductivity (σ) of the material by increasing the excess carrier density in the valence band and conduction band, giving rise to photoconductance.

Photoconductance measurements can be made and analyzed in several modes, including transient photoconductance decay, quasi-steady state measurements, or a generalized photoconductance, which incorporates elements from both [7,8]. The choice of technique depends on the lifetime and other recombination mechanisms in the device. For the application to III-V materials, the quasi-steady state technique is used to avoid the need for fast electronics. For example, in the GaN materials, the lifetimes can be on the order of ps, and hence would require electronics capable of measuring these levels. Consequently, only quasi-steady state techniques are considered [9].

The central issue in the application of the QSS-PC technique to III-V is that the change in the conductivity of the sample must be large enough to be readily detectable in a robust fashion, that the mobility of the material must be well-characterized, and that the effect of traps, surfaces or non-idealities must be able to be compensated for in the calculations of bulk lifetime from the effective lifetime [10]. Mobilities in III-Vs are typically well characterized, even for relatively new material systems such as the nitride material system [11]. The requirement that the bulk recombination be at least measurable if not dominant also exists in the application of the technique to silicon. While the easy application of surface passivation does not exist as readily in the III-Vs as in silicon, the use of high band gap passivation layers is common. By exciting the layers with light below the high band gap passivation layers, the photoconductivity only of the active layers can be measured.

The final issue in the application of the QSS-PC technique is the magnitude of the photoconductivity signal from III-V materials. Due to a combination of typically higher band gaps and dramatically lower lifetimes, the $\Delta\sigma$ from such materials is expected to be significantly lower than from silicon materials.

To determine the range of expected $\Delta\sigma$, GaAs and GaN layers are modeled in PC1D, and the $\Delta\sigma$ is determined. The parameters of the GaAs and GaN devices are shown in Table 1. The mobilities of GaN deliberately use conservative values of mobilities. The surface recombination velocity and minority carrier lifetime are varied.

Table 1: Parameters of GaN and GaAs devices used in simulation of PC1D.

Parameters	GaN	GaAs
Electron Mobility (max)	440 cm^2/Vs	8569 cm^2/Vs
Hole Mobility (max)	10 cm^2/Vs	408 cm^2/Vs
Dielectric Constant	8.9	13.18
Band Gap	3.45 eV	1.424 eV
Intrinsic Conc. at 300K	4.455e-11 cm^{-3}	2.59e6 cm^{-3}
P-type background doping	1e16 cm^{-3}	1e17 cm^{-3}
1st front diffusion	4e18 cm^{-3} N-type	1e19 cm^{-3} N-type

In order to measure repeatable, accurate results, a minimum $\Delta\sigma$ in the nS range is selected. Given the high absorption, and advanced state of the GaAs material system, even lifetimes as low 0.1 ns gave conductivities of 20 nS, and hence, unsurprisingly, GaAs can be readily used for the QSS-PC.

The QSS-PC measurements are particularly desirable for materials such as the III-nitrides, where the low minority carrier lifetimes can make measurements difficult. For different intensities of excitation, we varied the bulk lifetime throughout an expected range, for example for GaN the range we assumed was 2ps to 2ns. As GaN has a high absorption coefficient, the device thickness was set to 0.5μm in order to maximize V_{oc} while still being thick enough for nearly total absorption. Using this thickness and varying the surface recombination shows that the surface recombination does not strongly affect the ability to measure the photoconductance. The simulations show that the lifetimes as fast as 200ps will be measurable through conductance in the nS range with a light source intensity of 100X. Light intensities of 100X are readily achieved with the system used. However, higher $\Delta\sigma$ could be readily achieved by increasing the UV content of the incident spectrum, since the existing flash spectrum and incident solar radiation have relatively low levels of the UV light needed to excite carriers in GaN.

To experimentally demonstrate that QSS-PC can be used for lifetime measurements in the III-Vs, particularly newer material such as the III-nitrides, two cases, expected to be at opposite extremes of the conductivity range are measured, consisting of an "intrinsic" GaAs wafer, and thin layers of GaN grown on sapphire. For the GaN sample, a photoconductance signal, although a noisy one, was measured. The current system uses a lamp that has a glass protective cover which inadvertently filters most of the UV portion of the light. For solar cell measurement, several avenues can be taken to increases the signal strength including: Use of InGaN layers rather than GaN (since at Eg = 3.4 eV the band gap is too large for photovoltaic applications); the use of a UV light source rather than one which mimics the solar spectrum; and an amplifier circuit for the measured conductance signal.

In addition to the GaN layers grown on sapphire, an undoped, unpassivated GaAs wafer was also measured to determine the $\Delta\sigma$. Since the wafer is thicker than the thin layers modeled in PC1D, the $\Delta\sigma$ signal is higher (in the mS range) as expected.

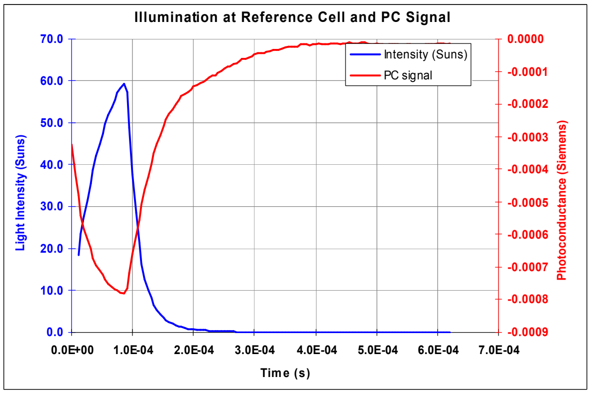

Figure 6: PC Decay of undoped GaAs at 60 Suns Vs the light intensity using the lifetime measurement system.

CONCLUSION

While the QSS-PCD and Suns-Voc techniques have been extensively applied to silicon solar cells, both techniques have substantial advantages for their use in III-V multiple junction tandem solar cells. Simulation results of III-V and III-nitride solar cells show that the techniques are applicable to these material systems, since they allow conductivities in the nS range, and hence can be measured using existing PCD systems with only minor modifications. The paper also presents a new application for the Suns-Voc method, by which it can be used to measure the series-corrected IV curve of an individual solar cell in a tandem stack. Experimental results show that the QSS-PC technique can be used with III-V layers, and further demonstrates the utility of the Suns- V_{oc} technique in characterizing multiple junction solar cells by allowing examination of individual solar cells and the effects of the tunnel junctions.

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