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Analysis of Depletion-Region Collection in GaInNAs Solar Cells

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Analysis Of Depletion-Region Collection In GaInNAs Solar Cells

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ABSTRACT

We provide qualitative insight into depletion-region collection in GaInNAs cells to (1) understand the effect of diffusion length L on the QE; and (2) describe the magnitude of L required to get adequate current from the cell. We use Wolf's equations for the QE including a drift field E, and model E as being equal to the junction built-in voltage distributed uniformly across the depletion region. This allows us to calculate the QE as a function of L and depletion width W_D. We show that if L is sufficiently small, increasing W_D can actually decrease the QE. To determine how long L needs to be in a practical GaInNAs junction, we calculate from the QE the short-circuit current density as a function of W_D and L. This allows us to estimate that $L_{ambipolar}$ needs to be greater than roughly 1 μm in order to obtain enough photocurrent for the 4-junction application, giving guidance to the experimental effort to develop such cells.

INTRODUCTION

Considerable effort has been spent on developing 1-eV GaInNAs junctions for future-generations of high-efficiency multijunction devices [1-5]. However, the poor diffusion lengths in this material result in unacceptably low quantum efficiencies (QE): as-grown pn junctions typically show QE < 20%.

With the introduction of a wide depletion region, i.e. a pin structure, to collect photocarriers, greatly improved QEs > 70% have been achieved [2]. Considerable progress has been made in five- and six-junction structures for which this magnitude of QE is sufficient, due to the reduced current-density requirements on the GaInNAs junction for current-matching in these structures [4,5]. However, for application in the simpler GaInP/GaAs/GaInNAs or GaInP/GaAs/GaInNAs/Ge structures, QE>90% is required. Such QEs have not been achieved for 1-eV GaInNAs grown by MOVPE, although significant progress has recently made using MBE growth [6]. One problem has been the difficulty of obtaining sufficiently large depletion widths W_D. However, merely obtaining large W_D is not sufficient.

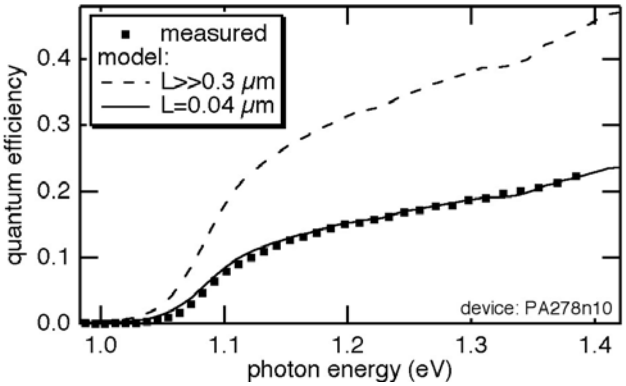

Fig. 1. Dots: measured QE of a GaInNAs junction with W_D=0.3 μm. Dashed line: modeled QE assuming complete collection in the 0.3 μm depletion region. Solid line: Modeled QE assuming incomplete collection (see text).

The drift field in the depletion region helps move the photocarriers to the junction, resulting in an effective collection length L_C for photocarriers which is enhanced compared to the (zero-field) diffusion length L. It is conventionally assumed that every photocarrier in the junction depletion region is swept to the junction by the drift field and collected; i.e. that $L_C > W_D$. For this to be the case, it is necessary for the photocarriers to live long enough for the field to sweep them to the junction. However, if the diffusion length L is very low, even the enhancement in L_C provided by the drift field may not be enough to get the required $L_C > W_D$.

The consequence would be a QE lower than if there were complete collection of carriers from the depletion region. Figure 1 gives an experimentally observed example. It shows the measured QE for a GaInNAs junction whose W_D = 0.3 μm as determined by capacitance-voltage profiling. For comparison, the dashed line is what the QE would be for complete collection in the depletion region, showing that in this cell a significant fraction of the photocarriers generated in the depletion region are not being collected. In contrast, if we get rid of the oversimplified assumption of complete collection in the depletion region, we can account for the measured QE as shown by the solid line, to be discussed in more detail below.

Here we focus exclusively on collection in the depletion region. The collection of photocarriers in the "flat-band" regions of GaInNAs solar cells is discussed by Kurtz [7].

OBJECTIVE

Because the minority-carrier diffusion lengths in GaInNAs are low, in order to understand collection in the depletion region well enough to take advantage of the drift-field enhancement, it is necessary to account for the dependence of the collection length L_C on the diffusion length and on the drift field. Our objective here is to provide this understanding by modeling the effect of the enhanced collection in GaInNAs junctions, so that we can (1) explain the observed phenomenon (illustrated qualitatively in Fig. 1) that increasing W_D sometimes results in decreasing, rather than increasing, QE; and (2) understand and describe what magnitude is required for L in order to get the required current from the cell. Our approach is not intended to be a fully quantitative description of the junction, the detailed complexities of which (e.g. ambipolar transport, trapping by localized states, etc) would be difficult to treat analytically.

APPROACH

In order to gain insight into the characteristics of drift collection in these devices, we use an idealized model of the junction shown in Fig. 2 to capture the essential features. The junction is assumed to be fully depleted, with a uniform field $E=V_{bi}/W_D$.

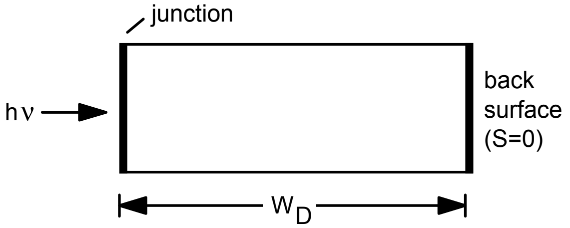

Fig. 2. Schematic of the model for the junction.

Wolf [8] provides the quantum efficiency of the illuminated junction including the field, as:

$$QE=\frac{\alpha}{G}\cdot\frac{1}{b^2-1}\cdot\left[b-1+\frac{(1-a)e^{-Gd}+(a-b)e^{-bGd}}{\cosh Gd+a\sinh Gd}\right] \quad (1)$$

where

$$F\equiv eE/2kT\,, \quad (2a)$$

$$b\equiv(\alpha-F)/G\,, \quad (2b)$$

$$G\equiv\sqrt{F^2+1/L^2}\,, \quad (2c)$$

$$a\equiv\frac{F}{G}+\frac{S}{GD}\,, \quad (2d)$$

$\alpha=\alpha(\lambda)$ is the absorption coefficient, $d=W_D$ is the base thickness, S is the back surface recombination velocity, $D=k_BT\mu/e$ is the diffusion coefficient at temperature T, and $L=(k_BT\mu\tau/e)^{1/2}$ is the diffusion length. The carrier mobility μ and lifetime τ are assumed to be independent of field. We take V_{bi}=0.75V for a 1-eV-bandgap junction, and for simplicity assume S=0. These equations then allow us to calculate the QE as a function of W_D and L.

RESULTS

Using our model, we can now derive insight into the effects of diffusion length and field (or cell thickness) in determining the QE. Figure 3 compares the QE calculated for three different combinations of L and W_D. For L=1 μm and W_D=1 μm, most of the carriers are collected. Increasing W_D to 3 μm increases the QE because the cell is thicker. However, the situation changes qualitatively when we now consider a much lower diffusion length. At L=0.1 μm and W_D=1 μm, the carrier collection is much less than at L=1μm; i.e., the field is no longer adequate to sweep all the carriers to the junction before they recombine. If we now increase W_D to 3 μm, the QE actually decreases, rather than increasing as was the case for the larger L=1 μm. This is because for small L, the detrimental effect of lowering the field (by a factor of 3 in this example) outweighs the effect of the increased thickness of the region where light is being absorbed. Thus, the QE can either increase or decrease with increasing W_D, depending on the magnitude of L. This is the central theme of this paper, taking us beyond the simple approximation in which increased W_D necessarily results in enhanced QE.

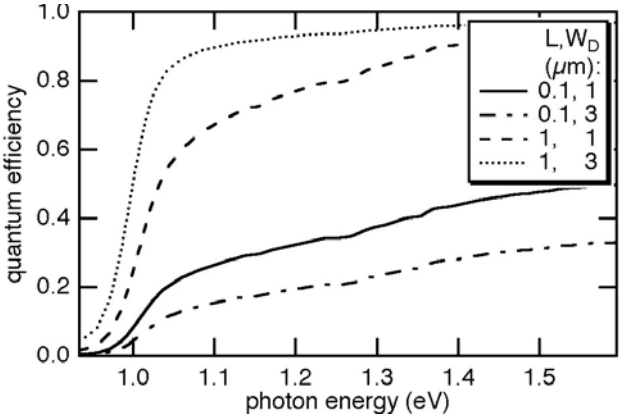

Fig. 3. QEs calculated for several combinations of W_D and L, for the fully depleted structure of Fig. 2.

We can now go back to the data of Fig. 1 and, given the measured W_D of 0.3 μm in that device, see what value of L gives a QE consistent with the measured data. The figure shows that L=0.04 μm is consistent with the measured QE.

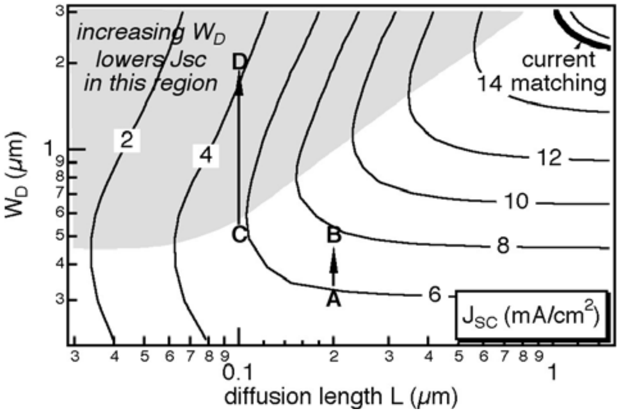

Fig. 4. Contours of J_{SC} as a function of W_D and L for the low-AOD spectrum, for the model junction of Fig. 2. In the grey region, increasing W_D decreases J_{SC}. Note that L is the diffusion length, not the collection length L_C.

Clearly, for practical devices, we cannot permit L to be arbitrarily small. To quantify this, we calculate from the QE the short-circuit current density J_{SC} as a function of W_D and L necessary to obtain the current needed in the multijunction application. Figure 4 shows $J_{SC}(L,W_D)$ for the low-AOD spectrum. To illustrate the effect of L on whether increasing W_D is useful, consider two cases. (1) As shown by the arrow from A to B in Fig. 4, we set L=0.2 µm, and increase W_D from 0.3 µm to 0.5 µm. In this case, increasing W_D increases J_{SC}. (2) As shown by the arrow from C to D in Fig. 4, we set L=0.1 µm, and increase W_D from 0.5 µm to 2 µm. In this case, increasing W_D decreases J_{SC}.

The second case is an example of a general feature of J_{SC}: there is a region of W_D and L, shaded in grey in the figure, in which increasing W_D decreases J_{SC}. To understand why this region exists, we need to understand in more detail the effect of the drift field. The drift field results in a collection length $L_C = 1/(G-F)$, which is always greater than or equal to L; i.e. the field enhances the collection length. For zero field, L_C becomes $L_C=L$, while in the limit of high field L_C approaches $L_C=\mu\tau E$. As long as $L_C > W_D$, all the photocurrent generated in the depletion region is collected. However, if L_C is reduced so that $L_C < W_D$, collection in the depletion region is no longer complete. A key point in our analysis is that the drift field decreases with increasing W_D because the same voltage is distributed over a longer distance; and hence L_C decreases as well. As long as $L_C > W_D$, this will not have a significant effect on the photocurrent collection, which is determined by the smaller of L_C and W_D. But, under conditions where increasing W_D reduces L_C to less than W_D, the current collection will decrease rather than increase. The crossover from W_D-limited to L_C-limited J_{SC} is given by the boundary of the grey region in Fig. 4.

For current-matching the 1.0-eV GaInNAs junction under GaInP/GaAs junctions, for the low-AOD spectrum a J_{SC} of 15.8 mA/cm^2 is needed for ideal top and middle cells. The J_{SC}=15.8 mA/cm^2 contour is indicated in bold in Fig. 4, and defines the minimum values of W_D and L required to achieve this current for a fully depleted cell. The contour shows that not only do we need W_D>2 µm; we also need L > 1 µm. In contrast, current matching for the six-junction structure [4,5] is about 8 mA/cm^2. The corresponding contour in Fig. 4 shows that for this current, the requirements on W_D and L are greatly reduced to roughly W_D > 0.5 µm and L > 0.2 µm.

For application in a GaInP/GaAs/GaInNAs three-junction structure, it may be worth considering GaInNAs band gaps below 1 eV as a strategy to increasing the GaInNAs current. Figure 5 compares the E_g=1 eV contours of J_{SC} from Fig. 4 with J_{SC} contours calculated for E_g=0.95 eV. Reducing E_g from 1 to 0.95 eV reduces the values needed for both W_D and L, making this appear to be a promising approach. Unfortunately, other studies [9] indicate that the minority-carrier properties of GaInNAs degrade so rapidly with decreasing E_g that achieving L=0.5 µm at E_g=0.95 eV is probably even more difficult than achieving L=1 µm at E_g=1 eV.

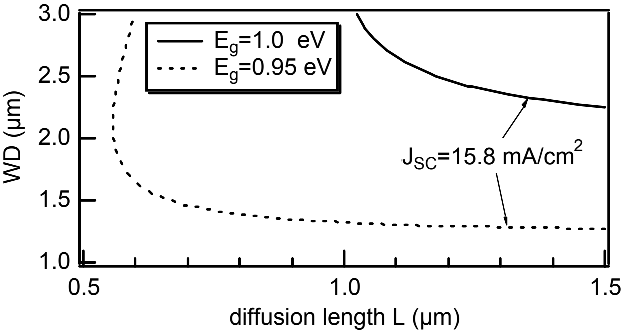

Figure 5. Contours of J_{SC} calculated as for Fig. 4, but for E_g=0.95 eV as well as E_g=1.0 eV.

Furthermore, obtaining large W_D in practice also appears to be increasingly difficult with decreasing band gap. Figure 6 plots the required depletion width W_D (assuming L_C>W_D) as a function of junction band gap E_g for current-matching under GaInP/GaAs junctions. The figure also shows the depletion widths we have obtained to date on MOVPE-grown GaInNAs junctions, measured by capacitance-voltage profiling. At E_g=1 eV, the achieved depletion widths are within a factor of three of the needed depletion width. However, the achieved depletion widths fall off rapidly with decreasing band gap, presumably due to an increase in the concentration of either doping impurities or defects with increasing nitrogen concentration (i.e. decreasing band gap). The achieved depletion widths shown in Fig. 2 decrease more rapidly with E_g than the needed depletion width decreases, weakening the motivation for going to bandgaps below 1 eV.

However, it may still be possible to achieve the needed depletion widths by growing the junctions with solid-source molecular-beam epitaxy (MBE) [6]. Using our model, we can estimate the diffusion length in the MBE-grown long-depletion-width junctions of Ptak [6]. Figure 7 compares the QE measured for one of these MBE devices (the W=2.7 µm device of Ref. [6]'s Fig. 2) with a family of QE curves generated by our model as a function of diffusion length. For the absorption coefficient for this E_g=1.28 eV device, we use the GaAs absorption coefficent

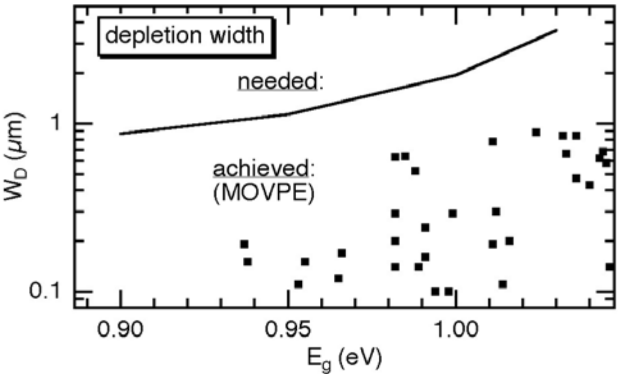

Figure 6. Depletion width needed to match the GaInNAs third junction's current to the GaInP and GaAs top two junctions in a GaInP/GaAs/GaInNAs three-junction cell. Also shown (dots) are the depletion widths that have actually been achieved for MOVPE-grown GaInNAs junctions to date.

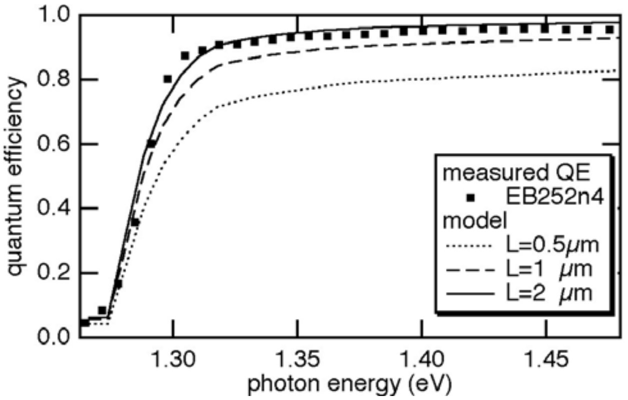

Figure 7. Measured QE for MBE-grown device EB252n4, compared to calculated QE curves from our model with various diffusion lengths.

translated down in energy to match the 1.28-eV band edge, as discussed by Kurtz [7]. The results of Fig. 7 suggest that the diffusion length in the base of this device is at least 1–2 μm. The next development step would be to achieve similar L and W_D in a E_g=1.0-eV device.

SUMMARY

We have modeled drift collection in idealized fully depleted 1-eV GaInNAs solar cells to provide insight into the dependence of the QE on the diffusion length L and depletion width W_D. We find that, roughly, L>1 μm as well as W_D > 2 μm are required for current-matching in the 3- or 4-junction application. The E_g=1.28-eV MBE-grown device of Fig. 7 [6] appears to satisfy these criteria, although not yet with a 1.0-eV band gap. Lowering the band gap from 1.0 to 0.95 eV lowers the requirements on W_D and L, although in practice it may be harder to obtain the required W_D and L at E_g= 0.95 eV than at 1 eV. Alternatively, for the six-junction structure [4,5], a much less demanding L>0.2μm and W_D>0.5 μm are required, an encouraging result for this device structure as these paramaters should be obtainable with MOVPE-grown material.

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