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N95- 20517

CALCULATION OF NEAR OPTIMUM DESIGN OF $InP/In_{0.53}Ga_{0.47}As$ MONOLITHIC TANDEM SOLAR CELLS

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SUMMARY

An analysis of InP/InGaAs tandem solar cell structures has been undertaken to allow for maximum AM0 conversion efficiencies (space applications) while still taking into account both the theoretical and technological limitations. The dependence of intrinsic and extrinsic parameters such as diffusion lengths and generation-recombination (GR) lifetimes on N/P and P/N devices performances are clearly demonstrated. We also, report for the first time the improvement attainable through the use of a new patterned tunnel junction as the inter cell ohmic interconnect. Such a design minimizes the light absorption in the interconnect region and leads to a noticeable increase in the cell efficiency. Our computations predict 27% AMO efficiency for N/P tandems with ideality factor γ=2 (GR lifetimes $\approx$ 1μs), and 36% for γ=1 (GR lifetimes $\approx$100μs). The method of optimization and the values of the physical and optical parameters are discussed.

INTRODUCTION

The use of monolithic $InP/In_{0.53}Ga_{0.47}As$ tandem solar cells for space applications is still at the research stage. It has already been demonstrated that their band gap values are particularly adapted for maximum AMO performance levels (ref. 1) in addition to their particularly high resistance to radiation damage (ref. 2). Using chemical beam epitaxy (CBE) and new device processing techniques, we have already shown in our laboratory that high quality materials and devices can be obtained (ref. 3). Therefore, a detailed theoretical simulation is required in order to further optimize and refine the structures now possible with this new technology so that photovoltaic (PV) devices with maximum efficiencies can be achieved.

Regarding both top and bottom cell emitter and base thicknesses and doping levels, we calculate the conditions for maximum photocurrent matching. The dark current is evaluated from the intrinsic limitation where the saturation current is dominant (giving ideality factor γ=1), to the extrinsic limitation where GR current due to trap levels in the depleted region dominates (ideality factor γ=2). The trap level density, which is highly correlated to the epilayer quality, yield effective GR lifetimes in the microsecond range (ref. 4). Thus, their participation in the recombination processes of photo-excited carriers is negligible compared to band to band recombinations and does not affect minority carrier diffusion lengths. This is why most of actual photovoltaic devices show performances limited by the open circuit voltage and fill factor while still exhibiting an excellent photocurrent characteristic (ref. 5).

The present study is undertaken to set a near optimum design for a maximum internal efficiency. The effect of grid shadowing and light reflection which are directly relevant on technological processing are not taken into account.

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METHOD OF CALCULATION

The values of the radiative recombination coefficient and minority carriers mobility versus doping levels in high quality InP and GaInAs epilayers were extracted from references 6 and 7.
The expressions of the equations describing photovoltaic multi-junctions are well known (ref. 8) and will not be recalled here. Nevertheless, it is important to summarize those describing the bottom cell response and the dark current.
Let us write J_t and J_b as the top and bottom cell photocurrent. J_b is a single InGaAs solar cell response J_{InGaAs} (E) reduced by the absorption of the top cell and the tunnel diode.

$$J_b = \int e^{-(\alpha_e(E)x_e + \alpha_b(E)x_b + \alpha_t(E)x_t)} J_{InGaAs}(E)\phi(E)d(E) \qquad 1$$

Where x_e, x_b, x_t are the emitter, base and tunnel diode thicknesses; $\alpha_e(E)$, $\alpha_b(E)$ and $\alpha_t(E)$ are their absorption coefficients varying with doping levels, and $\phi(E)$ is the solar spectrum.
The top and bottom cell photocurrent matching is achieved by an appropriate choice of the individual layer thicknesses.
The expression of the dark current related to such diodes, is set by considering the saturation current I_s (ref. 8), the tunnel current I_{tun} (ref. 10), and the GR current I_{gr} (ref. 8) with $I_{gr} = qn_iW/\tau_{gr}$. Where q is the electron charge, n_i the intrinsic carrier density, W is the depletion region width, and τ_{gr} is the effective GR lifetime.

The I-V characteristic of a single cell is then expressed by (ref. 8),

$$I = J_{cc} - I_s(e^{V/u_t} + 1) - I_{gr}(e^{V/2u_t} + 1) - I_{tun} - V/R_{sh} \qquad 2$$

Where u_t=0.026V at room temperature, $V=V_0-R_sI$ (R_s: series resistance), and R_{sh} is the shunt resistance.
The output voltage of the tandem under illumination is the sum of that from the individual constituent cells reduced by the voltage drop in the tunnel junction. The tandem photocurrent however is controlled by the cell generating the lower photocurrent.

RESULTS AND DISCUSSION

Table 1 shows the parameters required to achieve a near optimum design of N/P and P/N tandem solar cells respectively.
The calculated performances are:

n=1	n=2
Jcc= 33.3 mA	Jcc= 33.3 mA
Voc_{InP}= 1.17V	Voc_{InP}= 0.97V
Voc_{InGaAs}=0.64 V	Voc_{InGaAs}=0.5 V
η= 36.24%	η= 27%

for a N/P structure and

n<2 (τ_{gr}=100ms)	n=2 (τ_{gr}=1ms)
Jcc= 28 mA	Jcc= 28 mA
Voc_{InP}= 1.1V	Voc_{InP}= 0.9V
Voc_{InGaAs}=0.62 V	Voc_{InGaAs}=0.5 V
η= 30.5%	η= 22%

for a P/N structure (because of a high series resistance we can not assume a idealiy factor equals to unity).

OPTIMIZATION

P/N or N/P ?

A priory P/N junctions may seem to be more suitable than N/P structures so as to take advantage of the absorption shift present in p doped compounds (ref. 9). N doped layers however have a lower sheet resistance and p type $In_{0.53}Ga_{0.47}As$ compounds show much better minority carriers mobilities (ref. 7). Furthermore the relatively low absorption coefficients in these materials will necessitate the use of thicker junction layers (of 4-5μm) to minimize transparency losses. Thus a N/P structure is required for good carrier collection before recombination.

In this work the surface recombination velocities (SRV) values used are those found in InGaAs/InP double heterostructures and InPmonolayer.

Emitters

The top cell emitter thickness is calculated to allow an optimum performance through a compromise between a minimization of the surface recombination rate and a reduced sheet resistance (ref. 11).

The bottom cell emitter thickness is derived to achieve the best carrier collection before recombination. There is no sheet resistance and the SRV is small due to the presence of a window layer. Figures 2 shows for comparison the performances expected in the case of P/N and N/P tandems versus emitter width with optimum doping and base width shown in table 1. We can see that the different values of minority carrier mobilities versus doping level lead to a difference of 6% of absolute efficiency if a N/P rather than P/N structure is considered. Also p doped emitters need to be thicker due to high sheet resistance. Consequently, the base is required to be thin in order to allow the photocurrent matching. Therefore the optimum design of P/N tandem is a top cell inverted structure (emitter thicker than the base).

Bases

The base participation in the tandem performance can also be optimized by adjusting the width and the doping level. The high electron mobility in p doped InGaAs allows the use of a thicker bottom cell base without significant carrier recombination. The top cell base is therefore critical due to photocurrent matching constraints.

Figures 3 and 4 show the variation of the photocurrent and efficiency as a function of the InP base thickness assuming a perfect case of $\gamma=1$ ($\tau_{gr}=100$ μs). We can see that light absorption in the InP base leads to an increase of the top cell photocurrent and a decay of the bottom cell photocurrent. The condition of equal currents (top cell thickness: 0.3μm) corresponds precisely to the optimum conversion efficiency of the tandem shown in figure 4 (36% AM0). The high correlation between the photocurrent matching condition and the multi-junction efficiency is clearly demonstrated. Figure 4 shows also the case where a 100% internal efficiency is assumed in order to emphasize the influence of SRVs, lifetimes and diffusion lengths on the photo-response. These combined intrinsic and extrinsic limitations result in a 20% change in absolute efficiency between the two models.

The calculated internal spectral response of the near optimum design tandem solar cell is presented on figure 5. It emerges clearly that the device limitations are mainly due to the bottom cell characteristics. The limited values of diffusion lengths and low absorption do not permit better expectations.

Dark current

As mentioned previously, the dark current is controlled by three different processes. First the saturation current Is which varies with the square of the intrinsic carrier concentration (ref. 4) leads to an intrinsic limitation. Second is the band to band tunneling current which becomes non negligible only in highly doped junctions. Third is the Generation-Recombination current which is the main factor to be minimized by the growth technique. The density of trap levels in the bandgap is taken into account in the I-V characteristics as an effective GR lifetime (equation 2). To describe the effect of this latter parameter on the cell performance, we have drawn in figure 6 the variation of the conversion efficiency of a tandem over a wide range of GR lifetimes yielding ideality factors ranging from 2 to 1. There is a non negligible 8 % in absolute efficiencies enhancement when GR lifetimes vary from 1μs to 20 μs.

Tunnel junction

In the case of a monolithic tandem structure, the electrical interconnect between the two cells is achieved by an InGaAs tunnel junction (ref. 12). An ideal tunnel junction should modify neither the electrical nor the optical properties of the tandem. It has been shown previously (ref. 12) that very thin and extremely low resistivity InGaAs tunnel junctions can be fabricated with CBE. In addition, through patterning of the tunnel junction we can further minimize light absorption in this region (ref. 13). The influence of light absorption in the tunnel junction area on the tandem efficiency is shows in figure 7.

CONCLUSION

The characteristics of an InP/InGaAs monolithic solar cell have been evaluated using a large range of geometric considerations. Our calculations demonstrate the influence of the emitter, base, and tunnel junction layer thicknesses and have allowed us to set a near optimum design for a maximum tandem efficiency. The minority carrier mobilities, especially in InGaAs, seem to suggest the superiority of N/P over P/N structures. Finally it has been demonstrated that photocurrent matching is the principal condition for a near optimum design and that high efficiency tandem solar cells require a low trap level density.

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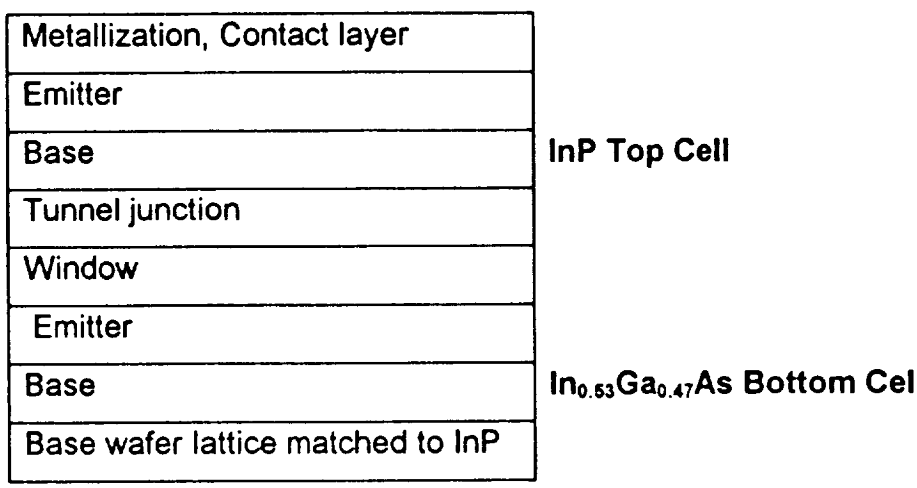

Figure 1: Schematic representation of the monolithic tandem solar cell.

Table 1.

	Top cell InP		Bottom cell $In_{0.53}Ga_{0.47}As$	
	N/P	P/N	N/P	P/N
Emitter				
SRV	10^5 cm^2s^{-1}	10^5 cm^2s^{-1}	10^3 cm^2s^{-1}	10^3 cm^2s^{-1}
Doping	3.10^{18} cm^{-3}	3.10^{18} cm^{-3}	10^{18} cm^{-3}	10^{18} cm^{-3}
Thickness	0.02 μm	0.15 μm	0.5 μm	1 μm
Lifetime	1 ns	1 ns	0.3 ns	0.3 ns
Diff length	0.45 μm	2.5 μm	0.4 μm	2.3 μm
Base				
SRV	10^3 cm^2s^{-1}	10^3 cm^2s^{-1}	10^3 cm^2s^{-1}	10^3 cm^2s^{-1}
Doping	5.10^{17} cm^{-3}	5.10^{17} cm^{-3}	10^{17} cm^{-3}	10^{17} cm^{-3}
Thickness	0.25 μm	0.05 μm	4.5 μm	3 μm
Lifetime	23ns	23ns	19 ns	19 ns
Diff length	13, 8 μm	1.35 μm	7 μm	1.5 μm
Series Resistance	0.97 Ω	2 Ω		
Shunt resistance	10^4 Ω	10^4 Ω		

The near optimum design has been calculated through a systematic variation of all the relevant cell parameters.

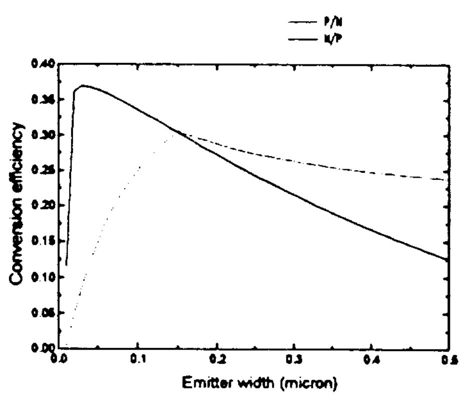

Figure 2 : Conversion efficiency of N/P and P/N tandem solar cell vs. top emitter width with optimum doping and base width.

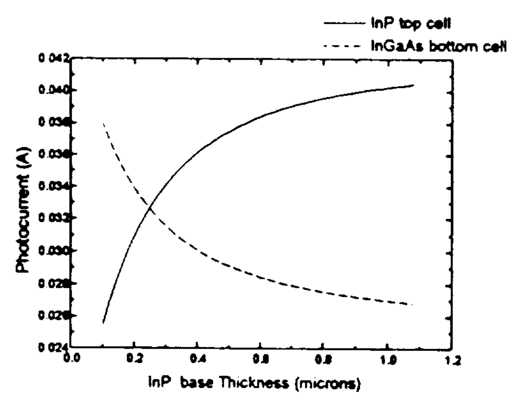

Figure 3: The effect of the top cell base thickness (emitter = 0.05μm) on the photocurrent of a tandem cell with a patterned tunnel junction.

SESSION III

RADIATION DAMAGE

AND

ENVIRONMENTAL TESTING

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