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DESIGN OF HIGH-EFFICIENCY, RADIATION-HARD, GaInP/GaAs SOLAR CELLS[1]

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SUMMARY

Record air mass zero efficiency values are reported for $Ga_{0.5}In_{0.5}P$/GaAs devices before and after irradiation by 10^{15} cm^2 1 MeV electrons. The two-terminal, two-junction devices are grown monolithically with a high-conductance, GaAs tunnel-junction interconnect and an area of 0.25 cm^2. A device optimized for beginning-of-life (BOL) performance achieved BOL 25.7% (25.4%) efficiency, while devices optimized for end-of-life (EOL) performance achieved EOL efficiencies of 19.6% (19.8% and 20.0%). (The efficiencies noted in parentheses were measured at NASA Lewis) The effects of the thickness of the top cell and the doping level of the bottom cell were investigated in this study. A range of top-cell thicknesses and bottom-cell doping levels gave respectably high (greater than 18%) EOL efficiencies.

INTRODUCTION

In recent years, $Ga_{0.5}In_{0.5}P$/GaAs cells have drawn increased attention both because of their high efficiencies and because they are well suited for space applications. They can be grown and processed as two-junction devices with roughly twice the voltage and half the current of GaAs cells. They have low temperature coefficients, and have good potential for radiation hardness. We have previously reported the effects of electron irradiation on test cells which were not optimally designed for space. (ref. 1) From those results we estimated that an optimally designed cell could achieve 20% after irradiation with 10^{15} cm^{-2} 1 MeV electrons. Modeling studies predicted that slightly higher efficiencies may be achievable. (ref. 2) Record efficiencies for EOL performance of other types of cells are significantly lower. Even the best Si (ref. 3) and InP (ref. 4) cells have BOL efficiencies lower than the EOL efficiency we report here. Good GaAs cells have an EOL efficiency of 16%. (ref. 5) The InP/$Ga_{0.5}In_{0.5}As$ two-junction, two-terminal device has a BOL efficiency as high as 22.2% (private communication from M. Wanlass), but radiation results for these cells were limited. (ref. 6)

In this study we use the previous modeling and irradiation results to design a set of $Ga_{0.5}In_{0.5}P$/GaAs cells that will demonstrate the importance of the design parameters and result in high-efficiency devices. We report record AM0 efficiencies: a BOL efficiency of 25.7% for a device optimized for BOL performance and two of different designs with EOL efficiencies of 19.6% (at 10^{15} cm^{-2} 1MeV electrons). We vary the bottom-cell base doping and the top-cell thickness to show the effects of these two important design parameters. We get an unexpected result indicating that the dopant added to the bottom-cell base also increases the degradation of the top cell.

EXPERIMENTAL DETAILS

A schematic of the device structure is shown in Fig. 1. The devices were grown from trimethyl gallium, trimethyl indium, trimethyl aluminum, arsine, and phosphine in a hydrogen carrier gas. The dopant sources were diethyl zinc, hydrogen selenide, disilane, and carbon tetrachloride. Zinc and selenium were the p- and n-type dopant sources unless otherwise noted. The bottom-cell base doping levels were 1, 3, and 8 X 10^{16} cm^{-3}, referred to hereafter as low, medium, and high, respectively. These doping levels could not be measured directly on the finished devices, but are estimated from calibration layers grown with similar diethyl zinc fluxes. Other details of the device structure and processing can be found elsewhere. (ref. 7, 8)

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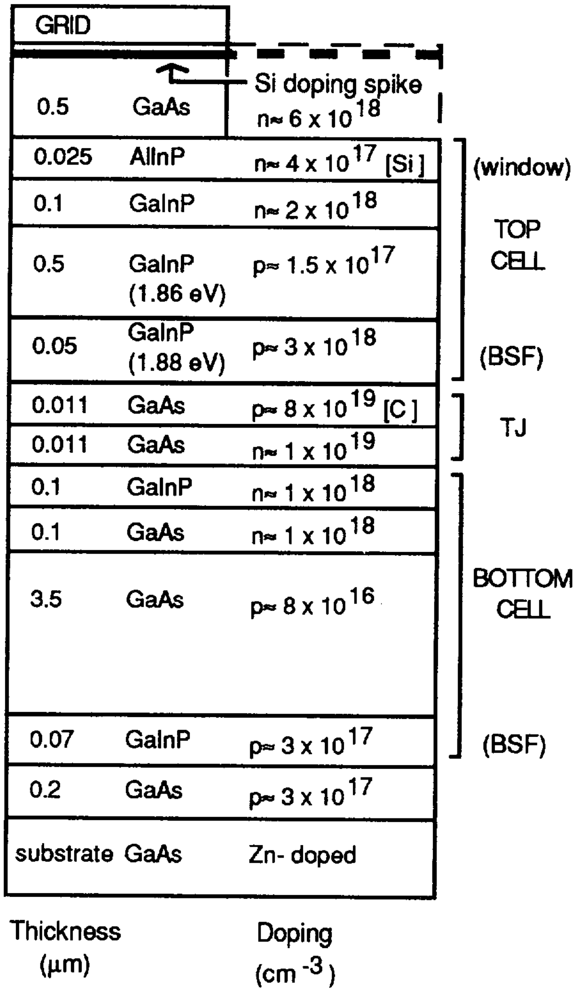

Fig. 1. Device structure for the cell with high bottom-cell base doping, 0.65 μm-thick top cell and a BOL efficiency of 25.7%. The total top-cell thickness of 0.65 μm was varied by decreasing the thickness of the top-cell base layer (layer with 1.5 X 10^{17} cm^{-3} doping). The BSF layers serve to passivate the back surface of each individual cell and the TJ is a tunnel junction that makes an ohmic connection between the top and bottom cell.

All of the devices were measured before and after irradiation on the fiber-optics, two-source simulator in B. Sopori's lab at NREL. The efficiencies were measured by adjusting the simulator to obtain the correct currents on two (top and bottom) reference cells. The top- and bottom-cell photocurrents were measured by shining a NIR or visible laser, respectively, on the device in addition to the simulator light. The spectral responses of the top and bottom cells were measured using red and blue bias lights, respectively. The record efficiencies reported in Table I were measured by K. Emery and coworkers at NREL, then sent to NASA Lewis for confirmation. In most cases the efficiencies agree within 2% (relative). All of the cells are small: 5 mm X 5 mm. The cells are close to champion quality except that the anti-reflection (AR) coats were not well controlled and some variation was observed in the window layer of the top cell. EOL efficiencies of more than 20% would have been achieved if the AR coats had been optimal. The electron irradiation was done at JPL by Bruce Anspaugh and his staff.

RESULTS

A summary of the highest efficiency measurements is shown in Table I. A complete summary of all of the measured efficiencies, before and after irradiation, is shown in Fig. 2. Most of the data points in

Table I. Summary of measurements on highest efficiency devices. All measurements were completed using the AM0 spectrum and a cell temperature of 25°C.

Cell design Base doping	Top-cell thickness	Irradiation (elec/cm^2)	Measurement place	V_{oc} (V)	J_{sc} (mAcm^{-2})	FF (%)	Efficiency (%)
high	0.65 μm	None	NREL	2.393	16.55	88.7	25.7
		None	NASA	2.398	16.39	88.2	25.4
medium	0.45 μm	10^{15}	NREL	2.221	14.53	82.9	19.6
		10^{15}	NASA	2.226	14.58	83.3	19.8
low	0.55 μm	10^{15}	NREL	2.198	14.72	83.0	19.6
		10^{15}	NASA	2.198	14.90	83.4	20.0

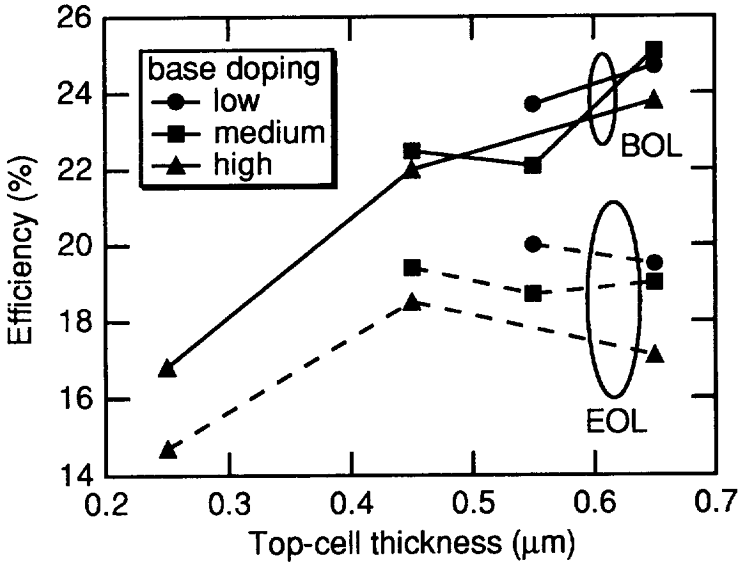

Fig. 2. The AM0 efficiencies of the devices before and after irradiation, as measured at NREL on the Sopori simulator.

Figs. 2–4 represent the averaged values for four 5 mm X 5 mm devices. Data is not included for a few cells that were badly shunted or damaged. The bottom-cell base doping had little effect on the BOL efficiency. The top-cell thickness has a very large effect on the efficiency because the thinner top cells generate less photocurrent and the device is limited by this smaller photocurrent. After irradiation, the cells with lower bottom-cell base doping tend to show higher efficiencies. The optimal top-cell thickness decreases after irradiation. This is because the current of the thick bottom cell usually degrades more than the current of the thin top cell. Fig. 2 shows that respectably high efficiencies (greater than 18%) are obtained for top-cell thicknesses between 0.45 and 0.65 μm when the bottom-cell base doping is not too high.

The degradation of the photocurrents is shown in Figs. 3 and 4. The as-grown top-cell photocurrents show a very strong dependence on thickness, as expected. The device with top-cell thickness of 0.55 μm has a lower photocurrent primarily because of a poor blue response, implying that some oxygen or carbon may have contaminated the window layer. After irradiation, the top-cell photocurrent shows a very significant dependence on bottom-cell base doping. This effect will be discussed below in more detail. The bottom-cell photocurrent decreases with top-cell thickness since a thinner top cell allows more light to penetrate to the bottom-cell junction. The larger decrease in photocurrent with higher base doping was expected from previous studies that showed the damage coefficient to increase with doping. The degradations of the V_{oc} and the FF ranged from 6%–9% and 2%–4%, respectively. The V_{oc} showed a slightly greater degradation (8%–9%) for the cells with the low bottom-cell base doping compared with those with high doping (6%–7%). This difference is not great enough to compensate for the opposite trend in bottom-cell photocurrent degradation (10%–11% degradation for the lightly doped and 21%–23% for the highly doped cells).

In order to better understand the degradation of the photocurrents we plot the spectral response of the bottom and top cells in Figs. 5 and 6. The primary loss mechanism in both cases is a decreased minority-carrier diffusion length. The increase in damage coefficient with base doping for the GaAs bottom cells was reported previously.(ref. 1, 9) Similar changes in the degradation of the spectral response curve as a function of base doping have also been reported for InP n-on-p cells.(ref. 4) The increased radiation hardness of the $Ga_{0.5}In_{0.5}P$ top cell for low bottom-cell base doping is unexpected because no deliberate change was made in the top-cell doping. The similarities between the degradation of the top- and bottom-cell spectral responses imply that a memory or diffusion effect caused an unintentional change in the top-cell base doping. We are currently trying to confirm this hypothesis by using secondary mass ion spectroscopy to quantify the zinc levels in the top cells.

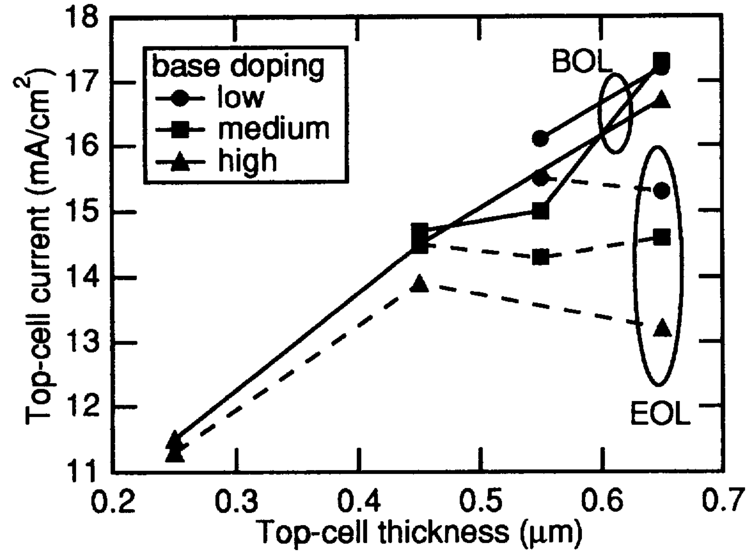

Fig. 3 Top-cell photocurrent before and after irradiation.

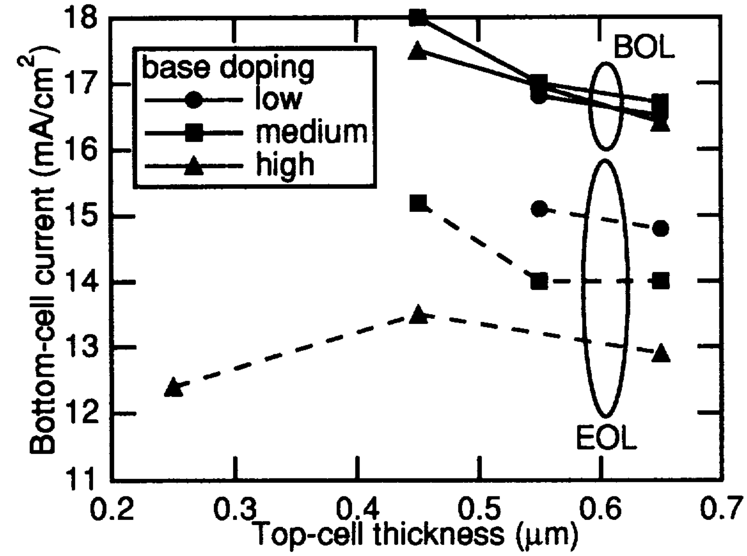

Fig. 4 Bottom-cell photocurrent before and after irradiation.

The results of this study are very consistent with our previous study(ref. 1) in which we predicted an EOL efficiency of 20% for an EOL optimized device. However, our previous study differed in one significant way: the photocurrent for a 0.75 µm-thick top cell degraded by only 2%, compared with 11% for the 0.65 µm-thick top cell with low bottom-cell base doping in this study. The results of both studies together may imply that the base doping of the 0.75 µm top cell was lower than that used in this study. Thus, if we had used a lower top-cell base doping in this study, we should have seen improved radiation resistance of the top cell, and, hence, of the tandem cell. A decreased doping of the top cell might increase the degradation of the V_{oc}. However, this is a small effect, and can be viewed as negligible since our previous study (with apparent low top-cell base doping) gave almost identical degradation of the V_{oc} compared with this report. Thus, we conclude that the device can be even further optimized for EOL efficiency.

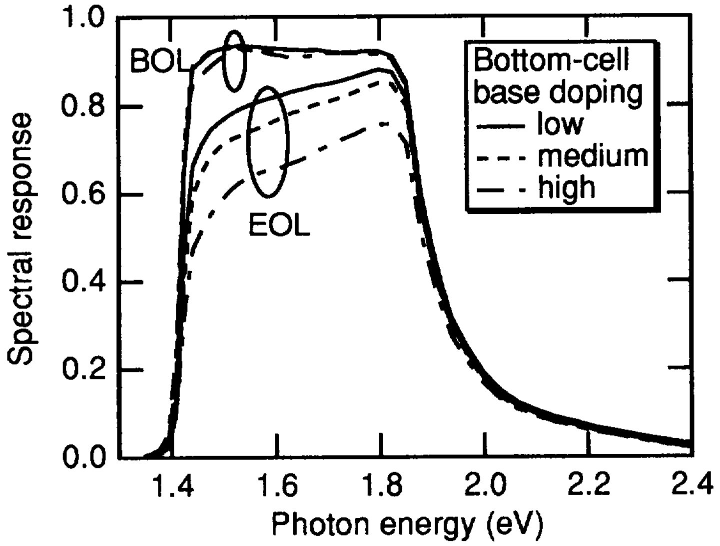

Fig. 5. The bottom-cell spectral response of tandem cells with 0.65 µm-thick top cells before and after irradiation.

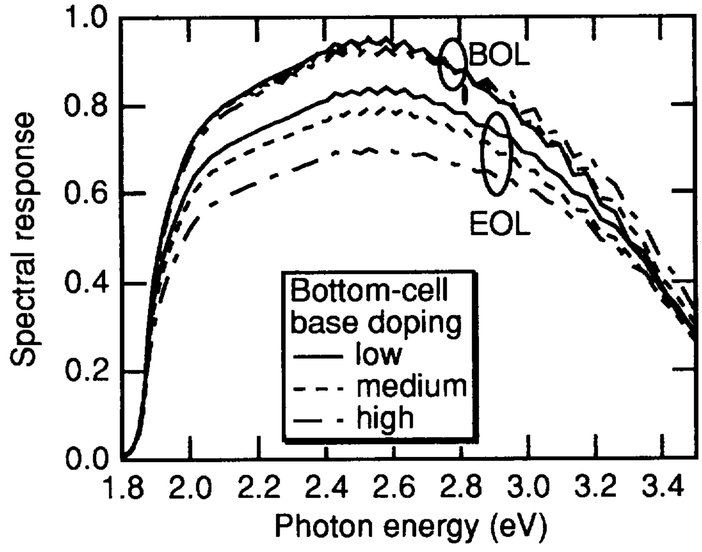

Fig. 6. The top-cell spectral response of tandem cells with 0.65 µm-thick top cells before and after irradiation. The small variations in the blue response may be caused by contaminates in the window layer of the top cell.

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