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1-MeV Electron Irradiation of GaInAsN Cells

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1-MeV-ELECTRON IRRADIATION OF GaInAsN CELLS

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ABSTRACT

GaInAsN cells are measured to retain 93±3% and 89±4% of their original efficiency after exposure to 5 X 10^{14} and 1 X 10^{15} cm^{-2} 1-MeV electrons, respectively. The rate of degradation is not correlated with the performance at beginning of life (BOL). The depletion width remains essentially unchanged, increasing by < 1%. Temperature-coefficient data for GaInAsN cells are also presented. These numbers are used to project the efficiency of GaInAsN-containing multijunction cells. The GaInAsN junction is not currently predicted to increase the efficiencies of the multijunction cells. Nevertheless, GaInAsN-containing multijunction cell efficiencies are predicted to be comparable to those of the conventional structures, and even small improvements in the GaInAsN cell may lead to higher multijunction cell efficiencies, especially for high-radiation applications and when cell operating temperature is low.

INTRODUCTION

The addition of a 1-eV GaInAsN junction to a GaInP/GaAs/Ge cell has the potential of reaching efficiencies in the 35%-40% range [1]. However, to date, the quality of the GaInAsN cells has been disappointing [2,3]. Using the performance that has been achieved for single-junction GaInAsN cells (and, assuming that that performance will be duplicated in a multijunction structure), modeling has projected [4] that the 4-junction (GaInP/GaAs/GaInAsN/Ge) cell efficiency may approach the three-junction (GaInP/GaAs/Ge) cell efficiency under some conditions, while falling substantially short under other conditions.

The GaInAsN cells contribute less photocurrent and less voltage than expected, but the low photocurrent is the primary problem because these series-connected multijunction cells are limited by the smallest photocurrent. Thinning of the GaInP and GaAs cells allows penetration of extra light to the GaInAsN, increasing its low photocurrent. The top cells' photocurrent that is lost by this thinning is roughly offset by the addition of the GaInAsN cell's photovoltage, resulting in 3- and 4-junction efficiencies that are comparable. Even though the efficiency is not increased, the thinning of the upper junctions may provide a more radiation-resistant device, thus providing a possible motivation for including GaInAsN despite its poor quality.

The evaluation of the benefits of the 4-junction versus the 3-junction structure is complex and very dependent on the design of the respective structures. As a first step in this evaluation, this paper presents radiation-damage and temperature-coefficient data for a set of GaInAsN cells. The projected efficiencies for the 3- and 4-junction cells are then compared.

METHOD

The GaInAsN single-junction cells used unintentionally doped, 2-µm-thick GaInAsN active layers with thin, n-type GaInP emitters, as described in reference [5]. The layers were grown using metal-organic chemical vapor deposition with dimethylhydrazine as the nitrogen source. Four pieces were selected with a range of band gaps (1.007 - 1.08 eV) and device performance. The cells were irradiated twice with 5 X 10^{14} cm^{-2} 1-MeV electrons at the Jet Propulsion Laboratory. Each piece had four 0.25-cm^2 devices with grid density of about 1%. The samples were measured at both NREL and Spectrolab. The two data sets gave similar results. The average of the two data sets is shown here, except when one data set was shown to be superior to the other. The internal quantum efficiency (QE) was calculated from the external QE and the reflectivity, both measured simultaneously on a small part of each sample. The carrier concentrations and depletion widths of the samples were measured with a Bio-Rad Polaron profiler.

The temperature coefficients of the device parameters were measured between 10°C and 65°C for GaInAsN cells that were not irradiated. No effort was made to quantify changes in the spectral correction factor (the simulator intensity was not changed between measurements) so there is a high uncertainty in the temperature coefficient of the short-circuit current.

RESULTS AND DISCUSSION

Fig. 1 summarizes the internal QE before and after irradiation for the four different devices. The cause of the difference in performance between these samples is primarily in the junction depth, with photocarriers collected mostly from the depleted layer and the emitter formed during the anneal rather than from diffusion of minority carriers in the base [5]. When the collection is primarily from a depleted layer, 1-MeV-electron-caused degradation of the minority-carrier diffusion lengths is unlikely to significantly affect the performance of the device, implying that the GaInAsN devices are expected to be radiation hard compared with GaAs devices, and that samples with significant collection from an emitter may degrade faster than those that collect only from the depleted layer. However, the degradation (Fig. 1) is observed to be relatively insensitive to device performance. Although MC973 is shown here to exhibit the largest degradation in current, the difference between it and the other samples is not statistically significant. Further optimization of the devices may increase the sensitivity to radiation if the GaInAsN material quality is improved, especially if long diffusion lengths are achieved. Nevertheless, Figs. 1 and 2 show that there is not currently a correlation between device performance and radiation hardness.

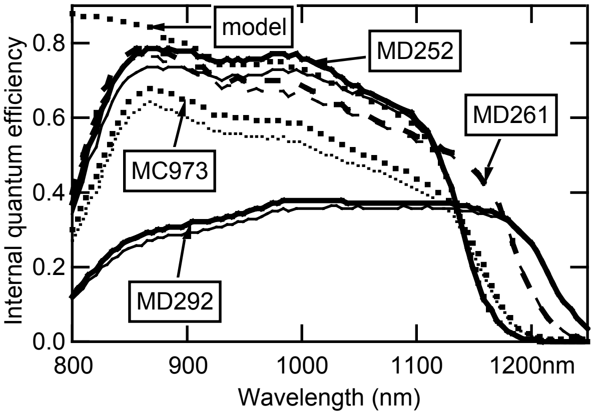

Fig. 1. Internal quantum efficiency before irradiation (bold lines) and after 10^{15} cm^{-2} irradiation with 1-MeV electrons (thin lines) for the four different samples. The dotted line [5] labeled 'model' was used in the modeling.

The degradation of the device parameters is summarized in Fig. 2 and Table 1.

A decrease in Voc is expected to be correlated with an increase in the dark current, as shown in Fig. 3 for two devices. The current-axis intercept has increased after irradiation, indicating a rise in the diode saturation current density. The diode ideality factor, n, however, is little changed from its value of 1.36±0.05 before electron irradiation, as seen from the similarity of the slopes in Fig. 3.

The diode quality factor can be used as an indication of the types of recombination occurring in a diode. High bulk recombination in the base and emitter usually imply a diode ideality factor of unity. Although an n=2 value sometimes implies that the recombination is in the space-charge region, a detailed analysis of Shockley-Read recombination at midgap defects [6-8] determines that n should be between 1 and 2 and may show a voltage dependence. Fig. 4 shows the voltage dependence of n calculated from the measured dark I-V curves for one set of devices. The shape of this curve is consistent with recombination at midgap defects (see Fig. 5.9 of [6]).

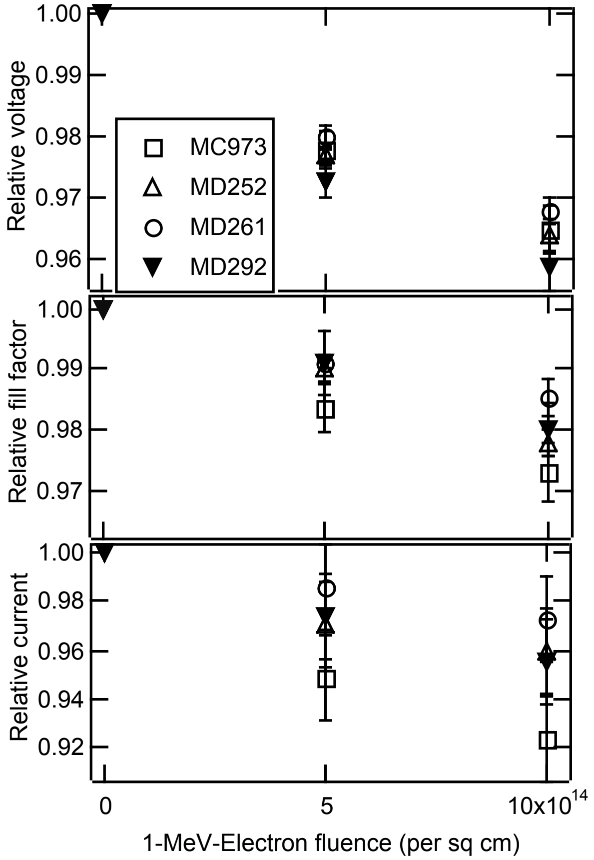

Fig. 2. Degradation of the open-circuit voltage, fill factor, and short-circuit current after irradiation. Each data point represents the average of data for four devices, with the standard deviation indicated by the error bars. The plotted data points were averaged and tabulated in Table 1.

Table 1. Percentage of beginning of life (BOL) GaInAsN device parameters remaining after irradiation with 1-MeV electrons. (See Fig. 2)

Fluence	Voc(%)	FF(%)	Jsc(%)	Power(%)
5 X 10^{14}	97.7±1	98.6±1	97±3	93±3
1 X 10^{15}	96.2±1	97.8±1	95±4	89±4

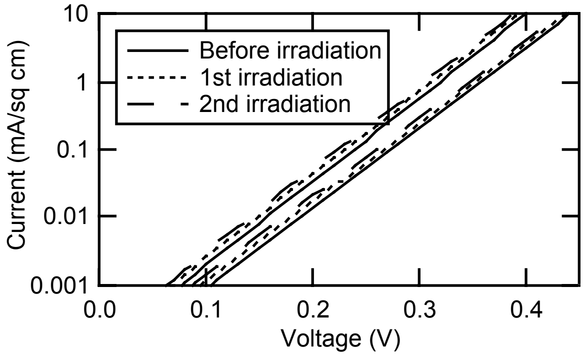

Fig. 3. Dark current for two devices on piece MC973. The degradation is a small effect compared with the sample uniformity.

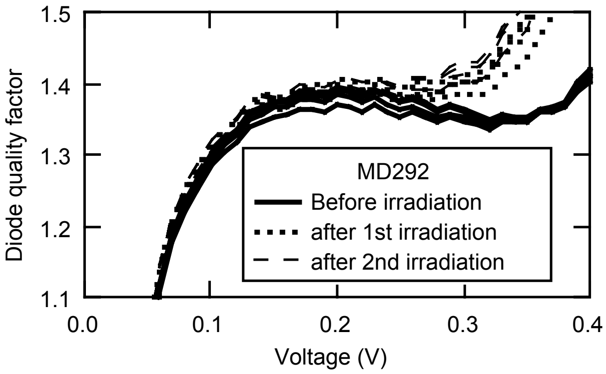

Fig. 4. The diode quality factor derived from the dark I-V curves for the four devices on sample MD292. The increase in the series resistance (evident in the upper right-hand part of the graph) was correlated with loss of grid lines.

These unintentionally doped cells had depletion widths (at short-circuit condition) in the range 0.2 - 0.6 µm. After irradiation, the depletion widths increased by less than 1%. This change correlates with a decrease of less than 2% in the measured carrier concentration, as shown in Fig. 5. Note that the calculation of the carrier concentration assumes an asymmetric junction, giving the smaller of the two carrier concentrations. For these samples the structure of the junction is unknown.

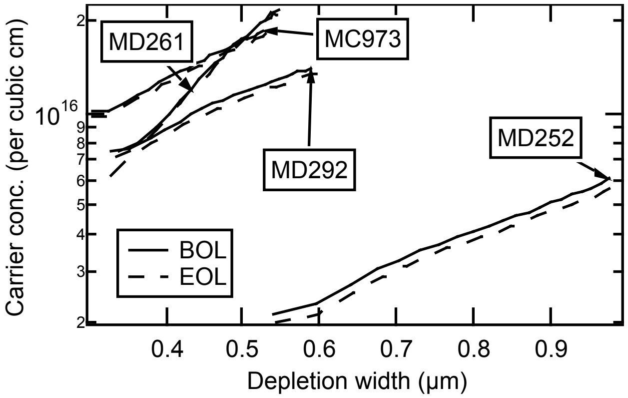

Fig. 5. The carrier concentration measured from capacitance-voltage profiling before irradiation and after 10^{15} cm^{-2} 1-MeV-electron irradiation.

The GaInAsN-cell temperature coefficients are summarized in Table 2. The measured values are close to those of the other junctions.

Table 2. Temperature coefficients in absolute and relative units.

Sample	Voc (mV/ °C)	Voc (%/°C)	Jsc (µA/ cm^2°C)	Jsc (%/°C)	FF (abs%/ °C)	FF (rel%/ °C)
MC337b	-2.1	-0.53	12	0.13	-0.14	-0.21
MC337d	-2.1	-0.53	15	0.16	-0.09	-0.14
MC465a	-2.1	-0.53	11	0.13	-0.15	-0.22

MODEL

The measured I-V and internal QE data for a 1.072-eV GaInAsN cell [5] were incorporated into a model predicting the efficiencies of multijunction cells. The assumptions of the model affect the absolute efficiencies, but are less important for comparing two cells with each other. The GaInAsN-containing cell designs (GaInP- and GaAs-cell thicknesses) were adjusted in each case to optimize the efficiency. These designs required extra photocurrent in the lower junctions, but not as much as if the photocurrents were matched under short-circuit conditions. For calculation of the dark current, the front and back passivation of the junctions was assumed to be perfect. However, the QE was reduced in order to approximately match laboratory results. The germanium junction was assumed to capture light absorbed in the top 80 µm. The combined assumption of an 80-µm-thick active Ge layer and perfect front and back passivation resulted in higher Vocs than are usually obtained, so the dark current for the Ge junction was increased somewhat. The resulting dark current in the germanium junction was such that the Ge junction boosted the tandem Voc by 255 mV at 300 K and by 143 mV at 353 K. This study is very similar to a previous study [4] except: (1) the reduced current is accounted for here by $\lambda<350$ nm, QE=0; $\lambda>400$ nm, QE=0.96, with linear interpolation between these two regions, whereas the previous study assumed QE=0.9 regardless of wavelength; (2) when the thicknesses of the upper cells are reduced, an enhancement in voltage is expected. This effect is included in this calculation, whereas the previous calculation neglected this effect; and (3) The actual shape of a single GaInAsN QE is used in this study, whereas the previous study looked at the effect of variable GaInAsN QE with a quality factor defined as the Jsc(measured)/Jsc(ideal).

The modeling results are summarized in Table 3. The device structures using GaInAsN are calculated to have efficiencies that are 0.9% and 1.7% (absolute) lower than their GaInAsN-free counterparts designed for maximum beginning-of-life (BOL) efficiency (J-ratio = 1.0) at 300 K. The difference is larger, 2% to 2.7%, at 80°C (353 K). However, when the GaInAsN-containing designs are compared with designs for radiation-hard GaInP/GaAs/Ge devices, the efficiencies are roughly equal even at BOL. The end-of-life (EOL) efficiencies, η, were estimated from

$$\text{EOL } \eta = [0.84 \times (P_1+P_2+P_4)/P + 0.89 \times P_3/P] \times \text{ BOL } \eta \quad (1)$$

where P_1, P_2, P_3, and P_4 are the powers generated by the GaInP, GaAs, GaInAsN, and Ge subcells, respectively, and P is the sum of these. The 0.84 factor was taken from the ratio of EOL/BOL for GaInP/GaAs/Ge cells at a fluence of 10^{15} electrons/cm^2 [9].

The EOL efficiencies at 300 K actually show a small (but insignificant) advantage for the GaInP/GaAs/GaInAsN cell over the GaInP/GaAs cell. Given the relative immaturity of the GaInAsN technology, it seems probable that further improvements can be made. These further

Table 3. Calculated AM0 device parameters for the various structures at 300 K and 353 K. The device designs were optimized at each temperature. The EOL efficiency, η, was calculated from eq. 1. The thicknesses for the GaAs layers of designs 5 and 6 were 0.63μm at 300 K and 0.55μm at 353 K.

Structure	η(%) @300K	Voc(V) @300K	Jsc (mA/cm^2) @300K	EOL η(%) @300K	η(%) @353K	Voc(V) @353K	Jsc (mA/cm^2) @353K
1. GaInP/GaAs	28.8	2.500	17.4		26.3	2.279	17.9
2. GaInP/GaAs/Ge	31.8	2.755	17.4		27.9	2.422	17.9
3. GaInP/GaAs *	27.9	2.505	16.5	23.4	25.6	2.284	17.0
4. GaInP/GaAs/Ge *	30.8	2.760	16.5	25.9	27.1	2.428	17.0
5. GaInP/GaAs/GaInAsN	27.9	2.938	14.9	23.6	24.3	2.616	14.9
6. GaInP/GaAs/GaInAsN/Ge	30.1	3.178	14.9	25.5	25.2	2.742	14.9

*Radiation-hard design is designed with JGaInP/JGaAs=0.9.

improvements can be expected to lead to new record efficiencies, especially for radiation-hard designs.

CONCLUSIONS

After irradiation with 1 X 10^{15} cm^{-2} 1-MeV electrons, GaInAsN cells retained 89±4% of their original conversion efficiency. Thus, their radiation resistance is currently superior to that of the GaInP/GaAs/Ge cell, which is reported to retain 84% [9] of its conversion efficiency after a similar irradiation. Much-needed improvements in the GaInAsN quality may reduce the radiation hardness, but the range of structures explored in this study did not show a correlation between device performance and radiation hardness. The depletion widths of the devices increased less than 1%, corresponding to a decrease in the measured carrier concentration of less than 2%. The temperature coefficient is dominated by the open-circuit voltage, which decreases with increasing temperature at a rate of 2.1 mV/°C.

Estimation of the efficiencies of multijunction structures containing a GaInAsN subcell implies that its addition does not yet lead to higher efficiencies. The 4-junction structures exhibit an especially high Voc temperature coefficient. Further research should result in improvements in the GaInAsN cells, and even small improvements may lead to attractive applications of these cells, especially for high-radiation and low-temperature missions. At that time, further radiation testing must be completed to see if the changes have increased or decreased the radiation hardness.

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