

1990

High-efficiency Al_{0.22}Ga_{0.78}As solar cells grown by molecular beam epitaxy

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Melloch, Michael R.; Tobin, S. P.; Bajgar, C.; Keshavarzi, A.; Stellwag, T. B.; Lush, G. B.; Lundstrom, Mark S.; and Emery, K., "High-efficiency Al_{0.22}Ga_{0.78}As solar cells grown by molecular beam epitaxy" (1990). *Department of Electrical and Computer Engineering Faculty Publications*. Paper 85.
<http://dx.doi.org/10.1063/1.103575>

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Citation: **57**, (1990); doi: 10.1063/1.103575

View online: <http://dx.doi.org/10.1063/1.103575>

View Table of Contents: <http://aip.scitation.org/toc/apl/57/1>

Published by the [American Institute of Physics](#)

High-efficiency $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ solar cells grown by molecular beam epitaxy

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(Received 12 February 1990; accepted for publication 24 April 1990)

The quality of *pn* junction photodetectors made of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ has been investigated as a first step in the optimization of tandem solar cells. We have obtained 1 sun AM1.5 efficiencies of 16.1% for 0.25 cm^2 $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ solar cells fabricated from molecular beam epitaxy (MBE) material. This efficiency is 3.2 percentage points higher than the previously best reported efficiency of 12.9% for an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ solar cell fabricated from MBE material.

Single junction solar cells fabricated from GaAs have achieved 1 sun AM1.5 efficiencies of 24.8%.¹ Under 1 sun conditions, solar cells fabricated from Si have demonstrated comparably impressive efficiencies of 22.3%.² While efficiencies will continue to improve in the relatively mature GaAs and Si single-junction solar cells, only modest gains are projected.³ An approach to achieving much higher conversion efficiencies is to cascade a stack of cells of varying band gaps.⁴ In a cascade stack, the cells are arranged in order of decreasing band gap. The top cell is of the widest band gap and therefore only absorbs the most energetic photons. Each successive cell absorbs that portion of the remaining photons which is of energy equal to or greater than its band gap. If the cascaded cells are connected in series, their band gaps have to be chosen such that the photocurrents generated in each cell are the same.

The alloy $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is of considerable interest for cascade solar cell applications because the band gap can be tuned by varying the aluminum mole fraction x and because of the possibility of growing monolithic tandem cell structures. For a two-junction structure, the optimum band-gap combination for the solar spectrum can be obtained with an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ top cell and a Si lower cell. Also of technological importance is the tandem combination of an $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ top cell and a GaAs lower cell because of the ease with which such a tandem structure could be grown.⁵⁻⁷

Molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) are two growth techniques being used to develop high-efficiency GaAs and AlGaAs solar cells for both single and multi-junction applications. Because MBE affords the capability to easily change film structures it is a valuable tool for investigating how changes in solar cell film structure affect performance. However, to be a viable approach, solar cells fabricated from MBE material have to be comparable in performance to those fabricated with material from other growth meth-

ods. Only recently have GaAs solar cells fabricated from MBE material demonstrated performance comparable to those fabricated from MOCVD material.^{1,8} However, there is still a considerable difference in the performance of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ solar cells fabricated from MBE and MOCVD material.⁹⁻¹⁴ In this letter we report a marked improvement in performance of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ solar cells fabricated from MBE material.

The films for this work were grown in a modular Varian GEN II MBE system. An extensive description of the conditioning and preparation of the MBE system and the sources has been reported elsewhere.⁸ Prior to this work, modulation-doped heterojunctions with mobilities of $2 \times 10^6\text{ cm}^2/\text{Vs}$ at 4.2 K and GaAs solar cells with efficiencies of 23.8% under 1 sun AM1.5 conditions have been demonstrated in films grown in this MBE system indicating its capability of producing high quality material.^{8,15}

The film for the $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ solar cell structure was grown on a 2-in.-diam n^+ -GaAs liquid-encapsulated Czochralski wafer. The MBE system had been closed for six months and 62 films had been grown since the initial loading of source material. The wafer was degreased, etched in a 60°C solution of 5:1:1 $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ for 1 min, and placed in a nonindium wafer mount. The sample was then loaded on a carrying trolley and placed into the entry chamber of the MBE system where it was outgassed at 200°C for 2 h. The sample was then moved into the buffer chamber of the MBE system where it was outgassed at 300°C for 1 h immediately before being loaded in the growth chamber. To ensure the highest possible vacuum, liquid nitrogen was circulated through the radial vane and cryoshrouds for 2 h before initiating growth.

The cross section of the film is shown in Fig. 1. The $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ layers were grown at an elevated temperature of 675°C, while the GaAs buffer and cap layers were grown at 600°C (the GaAs surface-oxide desorption temperature was 580°C). The wafers were rotated at five rev-

Cr/Au		
p ⁺ GaAs	A.R. Coating	
p Al _{0.6} Ga _{0.4} As		0.01 μm
p AlAs		0.04 μm
p Al _{0.22} Ga _{0.78} As	2×10 ¹⁸ cm ⁻³	0.25 μm
n Al _{0.22} Ga _{0.78} As	3×10 ¹⁷ cm ⁻³	3.00 μm
n ⁺ GaAs Buffer Layer	1×10 ¹⁸ cm ⁻³	2.00 μm
n ⁺ GaAs Substrate		
Au:Ge/Au Back Contact		

FIG. 1. Cross section of the Al_{0.22}Ga_{0.78}As solar cell.

olutions per minute during most of the film growth to obtain compositional and doping uniformity across the 2 in. substrate. The film growth rates were determined by measuring the frequency of oscillation of the intensity of the specular spot of the reflection high-energy electron diffraction pattern.¹⁶ The growth rates were 1 μm/h for both the GaAs and Al_{0.22}Ga_{0.78}As layers. This was accomplished by lowering the Ga furnace temperature during the growth of the last 200 Å of the GaAs buffer layer. The 100 Å Al_{0.6}Ga_{0.4}As and the 400 Å AlAs layers form the window layer of the cell. The purpose of the window layer is to passivate the top of the p-Al_{0.22}Ga_{0.78}As layer and to be as transparent as possible to the solar spectrum so that most of the solar energy is absorbed below the window layer in the active region of the cell. A window layer of all AlAs was not used because the top p⁺-GaAs cap will be removed to deposit an antireflection coating on the window layer.

After film growth, the wafer was cleaved in half and solar cells were fabricated on one half. Test devices were fabricated and film characterizations were performed on the other half. The post-growth solar cell processing sequence, performed at Spire Corporation, has been described previously¹⁷ and is briefly as follows. First, the epitaxial layer surface was coated with SiO₂. Next a thin AuGe back ohmic contact layer was evaporated and alloyed, followed by an evaporated Au back metallization. Image-reversal photolithography was used to form a pattern for front grid metallization.¹⁸ After etching the SiO₂ in the grid openings, Cr and Au were evaporated for front contacts. The photoresist was dissolved to lift off excess metal, then the contacts were sintered. Photolithography was used to define a pattern for the mesa etch (0.5 cm by 0.5 cm junctions), then a phosphoric acid-based etchant was used to form the mesa. All remaining SiO₂ was removed just prior to a selective cap removal etch (ammonium hydroxide-hydrogen-peroxide system). The etch removed the GaAs cap layer everywhere except under the grid lines and exposed the window layer. Finally, a double-

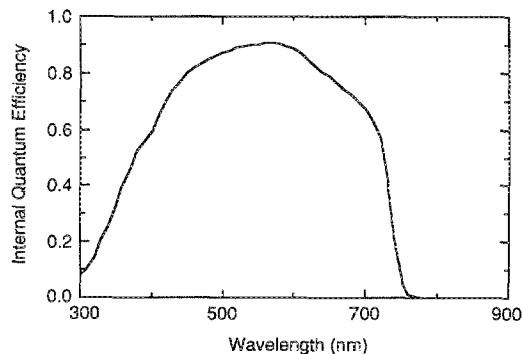


FIG. 2. Internal quantum efficiency for an Al_{0.22}Ga_{0.78}As solar cell fabricated from MBE-grown material.

layer antireflection coating of ZnS and MgF₂ was thermally evaporated over the exposed area of the cell.

The solar cells were measured under 1 sun AM1.5 conditions at the Solar Energy Research Institute. The best performing cell demonstrated an efficiency of 16.1% which is 3.2 percentage points higher than the previously best reported efficiency of 12.9% for an Al_{0.2}Ga_{0.8}As solar cell fabricated from MBE material. This 16.1% efficient cell had an open circuit voltage of 1.22 V, a short circuit current of 16.3 mA/cm², and a fill factor of 81%. The internal quantum efficiency for this cell displayed in Fig. 2 peaks at just over 90% at a wavelength of about 575 nm.

The test devices which were fabricated on the part of the wafer used for diagnostic purposes consisted of a series of mesa-isolated diodes. The mesa-isolated diodes ranged in area from 2.5×10⁻⁵ to 0.25 cm². (Note all the solar cells were of area 0.25 cm².) Displayed in Fig. 3 are typical current-voltage (*I**V*) characteristics for diodes of area 0.25, 0.01, and 10⁻⁴ cm². The small 10⁻⁴ cm² area diodes display the expected dependence of current on the diode voltage of

$$I = (J_{02B}A + J_{02P}P)(e^{qV/2kT} - 1) + J_{01}A(e^{qV/kT} - 1), \quad (1)$$

where J_{02B} is the bulk saturation current coefficient (A/cm²), J_{02P} is the perimeter coefficient (A/cm), J_{01} is the diffusion saturation current coefficient (A/cm²), A is the diode area, and P is the perimeter length. In contrast, each

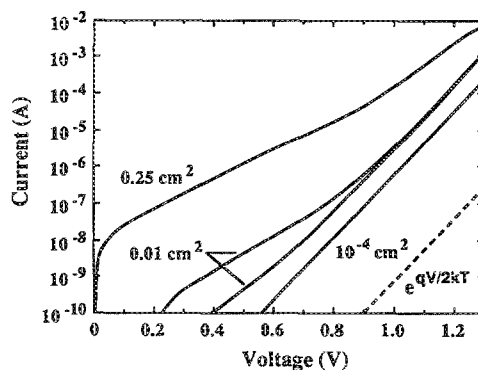


FIG. 3. Comparison of *I**V* characteristics for Al_{0.22}Ga_{0.78}As diodes of area 0.25 cm², 0.01 cm², and 10⁻⁴ cm². *I**V* characteristics for two different 0.01 cm² diodes are shown, one of which exhibits considerable leakage currents and one does not.

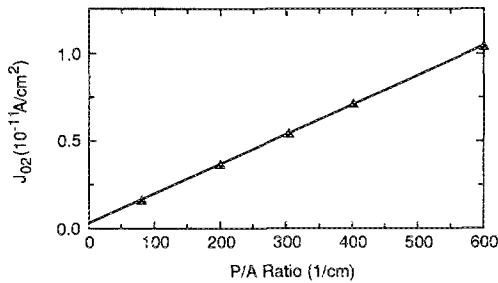


FIG. 4. Plot of extracted J_{02} vs perimeter-to-area ratio for $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ diodes fabricated from MBE-grown material.

of the large area diodes and solar cells exhibit an IV characteristic with considerable leakage current, that is, with diode ideality factors which are greater than 2. For intermediate sizes (0.01 cm^2), some diodes display anomalous leakage currents but others do not. Because of the dependence of the leakage current on diode area, the cause of the leakage currents is attributed to isolated defects in the film. Previously observed leakage currents in very high efficiency solar cells fabricated from MBE GaAs were, in part, attributed to oval defects.⁸ Under 1 sun operation at the maximum power point, this leakage current degrades the fill factor of our solar cells lowering the efficiency by 1 percentage point from 17.1% to 16.1%. These leakage currents become less important as our solar cells are operated at higher biases. Therefore, when operated under concentrated solar conditions such as 500 suns, the leakage current of our cells would not degrade their performance.

From Eq. (1) we can write

$$I_{02}/A = J_{02B} + J_{02P}P/A, \quad (2)$$

where I_{02} is the $q/2kT$ saturation current. By plotting I_{02}/A vs P/A for our series of $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ mesa-isolated diodes, the bulk and perimeter coefficients of the $q/2kT$ current can be determined from the intercept and slope of the plot. From the measured IV characteristics of these test diodes, the $q/2kT$ current was extracted by curve fitting to (1) and plotted as shown in Fig. 4. [This is done only with diodes which did not exhibit leakage currents, that is, diodes whose IV characteristics were well described by Eq. (1).] From the slope and intercept of Fig. 4 one obtains $J_{02P} = 1.7 \times 10^{-14} \text{ A/cm}$ and $J_{02B} = 3.5 \times 10^{-13} \text{ A/cm}^2$, respectively. (When fitting experimental data such as in Fig. 4, it is important to note that small variations in the data will have a much larger effect on the intercept than on the slope. Therefore, there will be a much larger uncertainty in the value of J_{02B} than in the value of J_{02P} determined from the data in Fig. 4.) When the results are scaled to a $0.5 \text{ cm} \times 0.5 \text{ cm}$ cell, one finds that approximately 70% of the $q/2kT$ current is due to the bulk and 30% is due to the perimeter. In contrast, the $q/2kT$ current for $0.5 \text{ cm} \times 0.5 \text{ cm}$ high-efficiency GaAs solar cells

fabricated from MOCVD and MBE material has been observed to be exclusively due to the perimeter.¹

In summary, we have obtained 1 sun AM1.5 efficiencies of 16.1% for 0.25 cm^2 $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ solar cells fabricated from MBE material. This efficiency is 3.2 percentage points higher than the previously best reported efficiency of 12.9% for an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ solar cell fabricated from MBE material.^{13,14} We anticipate that further improvements in the efficiencies of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ solar cells will be possible resulting in performance comparable to cells fabricated from MOCVD material. These improvements will be obtained by further optimization of growth conditions, reduction of oval defect densities, and use of purer source material such as zone-refined aluminum.¹⁹

This work was supported by the Solar Energy Research Institute for the U. S. Department of Energy under subcontracts XL-5-05018-1 (Purdue University) and XL-8-18063-1 (Spire Corporation).

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