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# InAlAs/InGaAs low-band-gap cell on InP for high efficiency multi-structure solar cell system

Yoshikazu Takeda, Mikio Wakai, Takayuki Ikeoku, and Akio Sasaki

*Department of Electrical Engineering, Kyoto University, Kyoto 606, Japan*

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InAlAs/InGaAs solar cells on InP for a low-band-gap cell have been fabricated. From theoretical simulation it is expected that the optimized InAlAs/InGaAs cell should have photovoltaic characteristic values of $J_{sc} = 21.2$ mA cm$^{-2}$, $V_{oc} = 0.345$ V, FF = 0.745 and $\eta = 4.02\%$ at one sun AM0 without an AR-coating. The best performance achieved by experiment was $J_{sc} = 22.0$ mA cm$^{-2}$, $V_{oc} = 0.320$ V, FF = 0.695, and $\eta = 3.61\%$ without an AR-coating. The uniformity of the characteristics was much improved utilizing the InGaAs cap layer for a low contact resistivity.

## 1. Introduction

To achieve a solar cell efficiency higher than 30% for example, tandem [1], cascade [2], and spectrum-splitting [3] solar cell systems have been proposed and several device structures were fabricated.

For the low-band-gap cells in the spectrum-splitting system with GaAs for the intermediate-band-gap cell ($E_g = 1.43$ eV), several III–V semiconductors such as GaSb, AlGaSb, InGaAs, InGaAsP, and InAsP are candidates from their energy gap values. However, requirement of high quality epitaxial layers on a large area (> 2″) substrate for a near future application reduces the semiconductors to AlGaSb on GaSb substrate, InGaAs on InP substrate, and InGaAsP on InP substrate. Experimental comparison of photovoltaic characteristics between AlGaSb/GaSb and InGaAs/InP solar cells resulted in a better performance of InGaAs/InP [4]. However, since liquid phase epitaxy (LPE) was used to grow InGaAs/InP in the previous experiments [4], the window layer was a thick InP which has a room-temperature energy gap of 1.35 eV that is lower than the energy gap of the GaAs cell. Using molecular beam epitaxy (MBE), higher band gap $In_{0.52}Al_{0.48}As$ can be grown on a large-area InP substrate with the lattice-matching condition. Thus, $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ on InP solar cell structure, with InAlAs as the window layer and InGaAs as the absorption layer, both lattice-matched on InP can be used for the low-band-gap cell covering the solar spectrum from 0.85 μm (GaAs absorption edge) to 1.65 μm ($In_{0.53}Ga_{0.47}As$ absorption edge).

Our calculation shows that the $In_{0.52}Al_{0.48}As/In_{0.67}Ga_{0.33}As_{0.71}P_{0.29}$ cell has a higher efficiency with a higher open-circuit voltage than the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ cell [5]. However, the growth process of the latter structure is much easier by the presently available techniques. We have chosen the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ structure as the first step.

In this paper, we will describe the fabrication of the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ solar cells and the experimental results of the photovoltaic characteristics. $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ will abbreviated as InAlAs and InGaAs hereafter in the text.

## 2. Device structure and wafer characteristics

The layer structure with the InGaAs cap layer and impurity concentrations are shown in fig. 1. The thicknesses of $p^+$-InGaAs and n-InGaAs absorption layers and the impurity concentrations were designed to have the highest conversion efficiency at one sun AM0 [5]. Be and Si were used for acceptor and donor, respectively. The layer thickness uniformity was within ±4% over 40 mm in diameter. Two structures, with and without the $p^+$-InGaAs cap layer, were fabricated.

The X-ray rocking curve of the wafer is shown in fig. 2. The peaks are reflections from InGaAs, InP, and InAlAs from left to right. The lattice-mismatch among the three layers is within $3 \times 10^{-3}$.

The test device structure for the photovoltaic characteristics measurement is shown in fig. 3. In the photolithography process, the circular opening of the InGaAs cap layer was made by etching with $H_2SO_4:H_2O_2:H_2O$ (3:1:1 by volume) at 33°C for 1–2 s, and the mesa-etching was then conducted to the depth

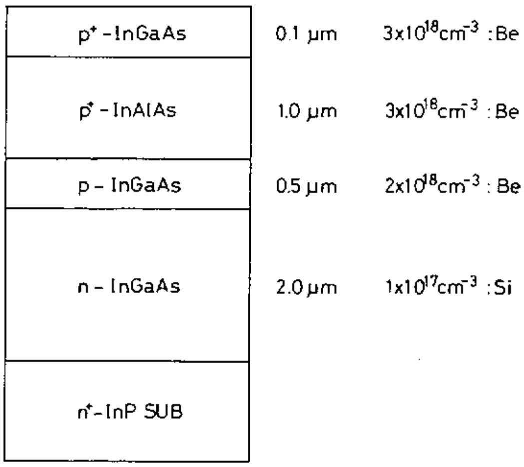


Fig. 1. Layer structure of solar cell wafer with InGaAs cap layer. Thicknesses, impurity concentrations, and dopants are listed on the right hand side.

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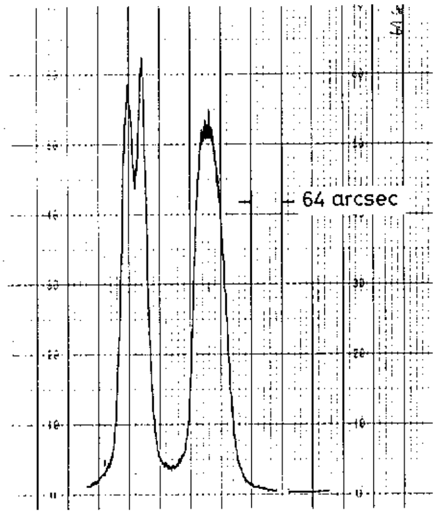


Fig. 2. X-ray rocking curve of the wafer. Peaks are from InGaAs, InP, and InAlAs layers from left to right. Lattice-mismatch among the layers is within $3\times10^{-3}$.

of 2 μm with the same etching solution. The edge portion was covered with polyimide. Ohmic contacts of Au/Zn (10% of Zn by weight) for $p^+$ layer and Au/Sn (10% of Sn by weight) were evaporated and alloyed at 340°C for 1 min in a hydrogen atmosphere. The opening diameter was 629 μm.

## 3. Photovoltaic characteristics and discussion

For the photovoltaic characteristics measurement at one sun AM0, a tungsten lamp solar simulator including an infrared optical filter with the cut-off wavelength at 0.85 μm was adjusted to have the same spectral irradiance as the solar spectrum at AM0 between 0.85 and 1.65 μm.

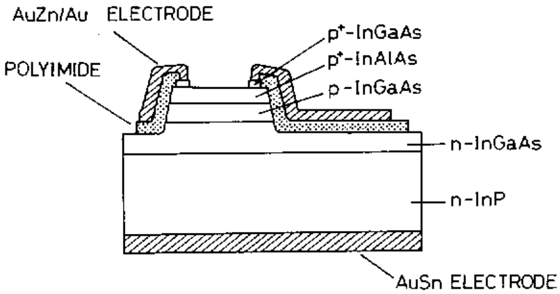


Fig. 3. Test device structure for photovoltaic characteristics measurement. The opening diameter is 629 μm.

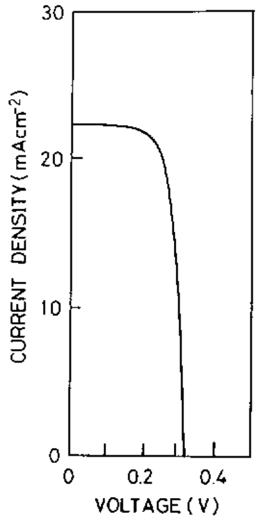


Fig. 4. The best photovoltaic characteristics obtained without AR-coating at one sun AM0; $J_{sc}$ = 22.0 mA $cm^{-2}$, $V_{oc}$ = 0.320 V, FF = 0.695, and $\eta$ = 3.61% without an AR-coating.

Fig. 4 shows the best photovoltaic characteristics at one sun AM0. The AR-coating was not provided but the InGaAs cap layer was used under the ohmic contact ring. The obtained values were $J_{sc}$ = 22.0 mA $cm^{-2}$, $V_{oc}$ = 0.320 V, FF = 0.695 and $\eta$ = 3.61% as listed in table 1. Here, $J_{sc}$ is the short-circuit current, $V_{oc}$ is the open-circuit voltage, FF is the fill factor, and $\eta$ is the conversion efficiency.

The InAlAs/InGaAs cells without the InGaAs cap layer also showed similar photovoltaic characteristics when a good ohmic contact to the InAlAs window layer was obtained. However, in most cases the ohmic contact formation onto InAlAs which has an Al composition of 0.52 was very unreliable and unreproducible. To ensure a low resistivity and reliable ohmic contact, a thin highly doped $p^+$-InGaAs was necessary as it was shown in fig. 1.

Simulated photovoltaic characteristics of the cell with the interface recombination velocity of 10000 cm $s^{-1}$ are as follows: $J_{sc}$ is 21.2 mA $cm^{-2}$, $V_{oc}$ is 0.345 V, FF is 0.745, and $\eta$ is 4.02% at one sun AM0 without an AR-coating [5] as listed in

Table 1
Comparison of experimental and theoretical photovoltaic characteristics at one sun AMO

| | $J_{sc}$ (mA $cm^{-2}$) | $V_{oc}$ (V) | FF | $\eta$ (%) |
|---|---|---|---|---|
| Experiment | 22.0 | 0.320 | 0.695 | 3.61 |
| Calculation ($S_e = S_h$ = 10000 cm $s^{-1}$) [a] | 21.2 | 0.345 | 0.745 | 4.02 |
| Calculation ($S_e = S_h$ = 0 cm $s^{-1}$) | 22.0 | 0.345 | 0.746 | 4.20 |

[a] $S_e$ ($S_h$): interface recombination velocity for electrons (holes).

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## 4. Summary

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PVSEC-3, Tokyo
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table 1. If the interface recombination velocity is assumed to be 0 cm $s^{-1}$, the photovoltaic characteristics become as follows: $J_{sc}$ is 22.0 mA $cm^{-2}$, $V_{oc}$ is 0.345 V, FF is 0.746, and $\eta$ is 4.20% as listed in table 1.

For this simulation, the reflectivity of InAlAs was necessary. The wafer for the solar cell itself was used for the reflectivity measurement. Since in the wavelength region from 0.85 to 1.65 μm the InAlAs is transparent and the InGaAs layer adjacent to the InAlAs is highly absorbing and thick enough, the reflectivity measured is considered equal to the reflectivity of a semi-infinite sample. In that wavelength region the reflectivity was found to be flat and measured to be 0.28. This value was used in the simulation. If a perfect AR-coating is adopted to the present solar cell, $J_{sc}$ and $\eta$ will increase to 30.6 mA $cm^{-2}$ and 5.01%, respectively.

## 4. Summary

InAlAs/InGaAs solar cells on InP for a low-band-gap cell have been fabricated. The best performance achieved by experiment was $J_{sc}$ = 22.0 mA $cm^{-2}$, $V_{oc}$ = 0.320 V, FF = 0.695, and $\eta$ = 3.61% without an AR-coating. The obtained efficiency is 90% of the simulated efficiency. This efficiency corresponds to 5.01% if a perfect AR-coating is provided. The uniformity of the characteristics was much improved utilizing the InGaAs cap layer for a low contact resistivity.

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