Physics and technologies of super-high-efficiency tandem solar cells

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In this paper, present status of super-high-efficiency tandem solar cells has been reviewed and key issues for realizing super-high-efficiency have also been discussed. The mechanical stacked 3-junction cells of monolithically grown InGaP/GaAs 2-junction cells and InGaAs cells have reached the highest efficiency achieved in Japan of 33.3 % at 1-sun AM 1.5. Future prospects for realizing super-high-efficiency and low-cost tandem solar cells are also discussed.

1. Introduction

Substantial increase in conversion efficiency (efficiency values over 30%) can be realized by multi-junction (tandem) solar cells due to their wide-band photoresponse in comparison with single-junction cells. Tandem solar cells have been studied since 1960 [1]. Although AlGaAs/GaAs tandem cells, including tunnel junctions and metal interconnectors, were developed in the early years, high efficiency values close to 20% were not obtained [2]. This is because of difficulties in making high performance and stable tunnel junctions, and the defects related to oxygen in AlGaAs [3]. A double heterostructure (DH structure) tunnel junction was found to be useful for preventing diffusion from the tunnel junction and improving the tunnel junction performance by the authors of [4]. InGaP as a material for the top cell was proposed by NREL [5]. As a result of performance impovements in a tunnel junction and a top cell, over 30% efficiency has been obtained with InGaP/GaAs tandem cells [6]. Recently, InGaP/GaAs 2-junction solar cells have drawn increased attention for space applications because of the possibility of high conversion efficiency over 30%. In fact, the first commercial satellite (HS 601HP) with 2-junction GaInP/GaAs on Ge solar arrays was launched in August 1997 [7].

In this paper, present status and future prospects of super-high-efficiency tandem solar cells has been reviewed and key issues for realizing super-high-efficiency have also been discussed.

2. Key issues for realizing high-efficiency tandem cells

Key issues for realizing high-efficiency tandem cells are discussed based on our results.

Selection of top cell materials is also important for high-efficiency tandem cells. As a top cell materials lattice-matched to GaAs or Ge substrates, InGaP has some advantages such as lower interface recombination rate, less oxygen problem and good window layer material compared to AlGaAs, as shown in Table 1.

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The top cell characteristics depend on the minority carrier lifetime in the top cell layers. Fig. 1 shows changes in photoluminescence intensity (I_{PL}) of the solar cell active layer as a function of minority carrier lifetime (τ) of the p-InGaP base layer grown by MOCVD and surface recombination rate (S). The lowest surface recombination rate was obtained by introducing an AlInP window layer and the highest minority carrier lifetime was obtained by introducing a buffer layer and optimizing the growth temperature. The best conversion efficiency of the InGaP single junction cell was 18.5%. Another important issue for realizing high-efficiency monolithic-cascade-type tandem cells is achievement of optically and electrically low-loss interconnection of two or more cells. A degenerately doped tunnel junction is attractive because it only involves one extra step in the growth process. To minimize optical absorption, formation of thin and wide-bandgap tunnel junctions is necessary, as shown in Fig. 2. However, the formation of a wide-bandgap tunnel junction is very difficult, because the tunnel peak current density (J_t) decreases exponentially with increase in bandgap energy (E_g).

In addition, impurity diffusion from a highly doped tunnel junction during overgrowth of the top cell increases the resistivity of the tunnel junction. A DH structure was found to be useful for preventing diffusion [4]. More recently, an InGaP tunnel junction has been tried for the first time for an InGaP/GaAs tandem cell in [6]. As p-type and n-type dopants, Zn and Si were used, respectively. Peak tunneling current of the InGaP tunnel junction is found to increase from 5 up to 300 mA/cm^2 by making the DH structure with the AlInP barriers. Furthermore, higher tunneling current

Table 1. Comparison of top cell materials (InGaP and AlGaAs)

Items	InGaP	AlGaAs
Interface recombination rate	$< 5 \cdot 10^3$ cm/s	$10^4 \div 10^5$ cm/s
Oxygen-related defects	Less problem	Major problem
Window layer (E_g)	AlInP (2.5 eV)	AlGaAs (2.1 eV)
Other problems	High doping in p-AlInP	Lower efficiency (2.6% down)

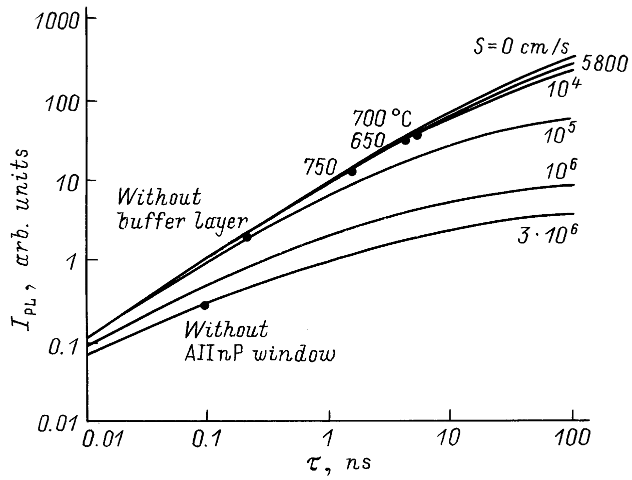

Figure 1. Changes in photoluminescence intensity ($I_{\rm PL}$) of the solar cell active layer as a function of the minority carrier lifetime (τ) of the *p*-InGaP base layer and surface recombination rate (S). Values of the growth temperature and the surface recombination rate are shown.

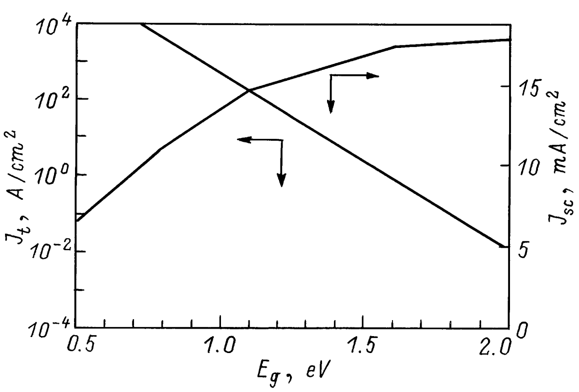

Figure 2. Calculated tunnel peak current density (J_t) and short-circuit current density of GaAs bottom cell ($J_{\rm sc}$) as a function of bandgap energy (E_g) of the tunnel junction.

up to 2 A/cm^2 has been obtained by increasing the doping density in the junction. Therefore, the InGaP tunnel junction has been observed to be very effective to obtaine high tunneling current, and DH structure has also been confirmed to be useful for preventing diffusion as the authors of [4] have found.

The impurity diffusion from a highly doped tunnel junction also degrades the top cell performance. The dependence of the tandem cell characteristics on the tunnel junction structure such as InGaP/GaAs, AlInP/GaAs, and AlInP/InGaP DH structures has been compared by using spectral responses of the tandem cells as shown in Fig. 3. The upper barrier layer of the tunnel junction also takes the part of the back surface field (BSF) of the top cell. A large reduction in quantum efficiency at wavelengths between $\lambda = 500$ and 650 nm due to the diffusion of Zn during epitaxial growth has been observed with the InGaP/GaAs tunnel junction. On the other hand, an increase in the quantum efficiency of the bottom GaAs cell due to the elimination of absorption losses in the GaAs tunnel junction has been confirmed in the cell with an InGaP tunnel junction. In the case of using an AlInP/InGaAs DH structures tunnel junction, the AlInP upper barrier layer of the tunnel junction is found not only to suppress the Zn diffusion but also to produce the effective BSF due to the band discontinuity with InGaP.

DH structure effect on suppression of impurity diffusion from the tunnel junction has been examined. Fig. 4 shows formation and migration enthalpy of group III-vacancies versus bond-gap energy of the materials. Effective suppression of Zn diffusion from tunnel junction by the InGaP tunnel junction with the AlInP DH structures is thought to be attributed to the lower diffusion coefficient for Zn in the wider bandgap energy materials such as the AlInP barrier layer and InGaP tunnel junction layer.

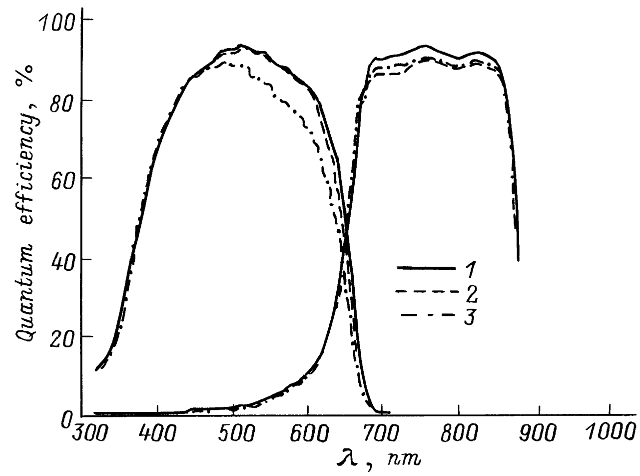

Figure 3. Spectral response of the InGaP/GaAs tandem cells dependent on their tunnel junction structures: *1* — AlInP/InGaP, *2* — AlInP/GaAs, *3* — InGaP/GaAs. All the tunnel junctions have DH structure.

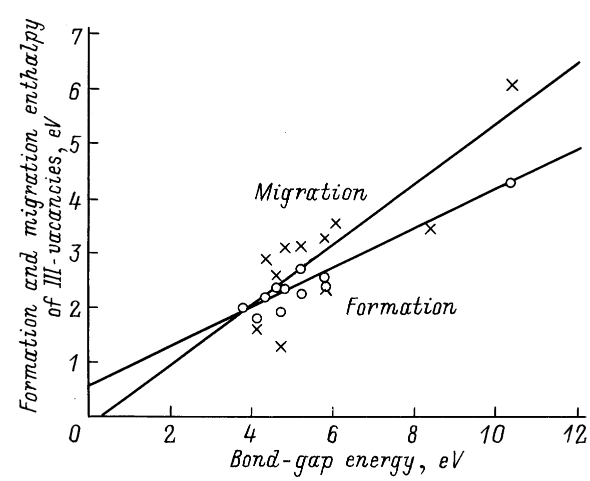

Figure 4. Changes in formation and migration energies of III-group element vacancies as a function of bond-gap energy of III–V compound materials.

Table 2. Summary of research activities of III−V compound solar cells in Japan

Solar cells		Area, cm^2	AM	Efficiency, %	Organization	Year
Bulk	GaAs bulk	0.25 4	AM 1.5 AM 0	25.4 22.5	Hitachi Cable Mitsubishi Electric	1996 1987
	InP bulk	0.25	AM 1.5	21.4	NTT	1986
Thin-film	GaAs on Ge GaAs on Si	1 1	AM 1.5 AM 1.5	23.2 20.0	Hitachi Cable NTT	1996 1989
Tandem	InGaP/GaAs 2-junction	4 9 4	AM 1.5 AM 1.5 AM 0	30.3 30.6 26.9	Japan Energy Japan Energy Japan Energy Toyota Tech. Inst.	1996 1998 1997
	AlGaAs/GaAs 2-junction	0.25 1	AM 1.5 AM 1.5	20.2 28.8	NTT Hitachi Cable	1987 1996
	GaAs/InGaAs Mechanically stacked	1	AM 1.5	28.8	Sumitomo Electric	1996
	AlGaAs/Si 2-junction	0.25	AM 0	21.2*	Nagoya Inst. Tech.	1996
	InGaP/GaAs/InGaAs MS 3-junction	1	AM 1.5	33.3	Japan Energy Sumitomo Electric	1997
Concentrator tandem	InGaP/GaAs 2-junction	1	AM 1.5 (×5.1)	31.2	Toyota Tech. Inst. Japan Energy	1998

* Active-area efficiency.

3. Super-high-efficiency tandem cells

Fig. 5 shows a schematic cross-section on the high-efficiency InGaP/GaAs 2-junction cell. The InGaP/GaAs cell layers were grown on the GaAs substrate by the MOCVD method. The top and bottom cells were connected by the InGaP tunnel junction. Fig. 6 shows the light current−voltage ($I-V$) curve of the high-efficiency InGaP/GaAs tandem cell. The high-efficiency has been realized by introducing DH structures in the InGaP top cell, InGaP tunnel junction and GaAs bottom cell.

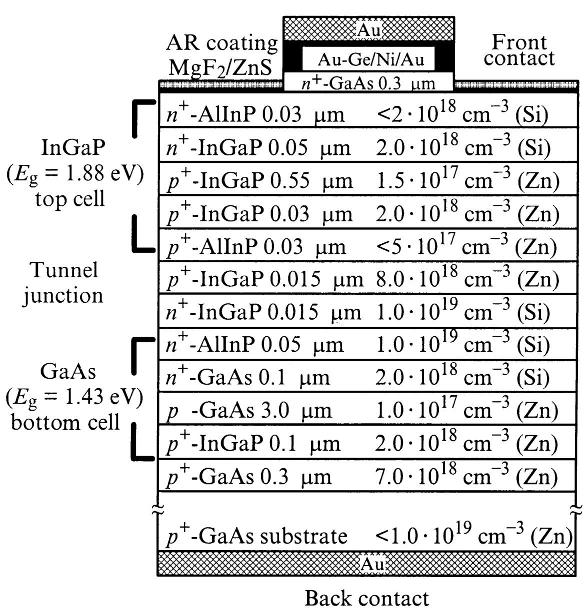

Figure 5. A schematic cross-section of the high-efficiency InGaP/GaAs 2-junction cell.

More recently, monolithically grown 3 × 3 cm^2 InGaP/GaAs 2-junction solar cells with 1-sun AM 1.5 efficiency of 30.6% have been successively fabricated by improvements in InGaP top cell and GaAs bottom cell properties as results of improvements in epitaxial growth and introduction of the C-doped AlGaAs/Si-doped InGaP heterostructure tunnel junction with AlInP barriers by Japan Energy Co. This value is the highest ever reported for the 2-junction cells under 1-sun illumination. The mechanically stacked 3-junction cells of monolithically grown InGaP/GaAs 2-junction cells and InGaAs bottom cells have reached highest efficiency of 33.3% [8] at 1-sun AM 1.5 following joint work by Japan Energy Co. and Sumitomo Electric Co.

Table 2 summarizes research activities of III−V compound solar cells in Japan.

4. Future prospects for obtaining 40% efficiency

Some effort has been made to put this type cells into commercial production for space applications based on the Multi-junction Solar Cell Manufacturing Technology

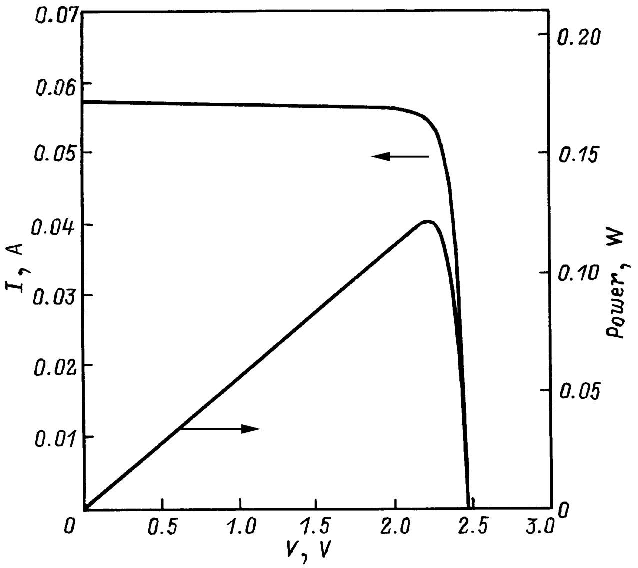

Figure 6. Light current–voltage and power–voltage curves of the high-efficiency InGaP/GaAs tandem cell measured at the Japan Quality Assurance Organization: cell area 4 cm^2, AM 1.5, 100 mW/cm^2, 25.3°C, short-circuit current $I_{sc} = 56.88$ mA, open-circuit voltage $V_{oc} = 2.488$ V, fill-factor $FF = 85.6\%$, efficiency 30.3%.

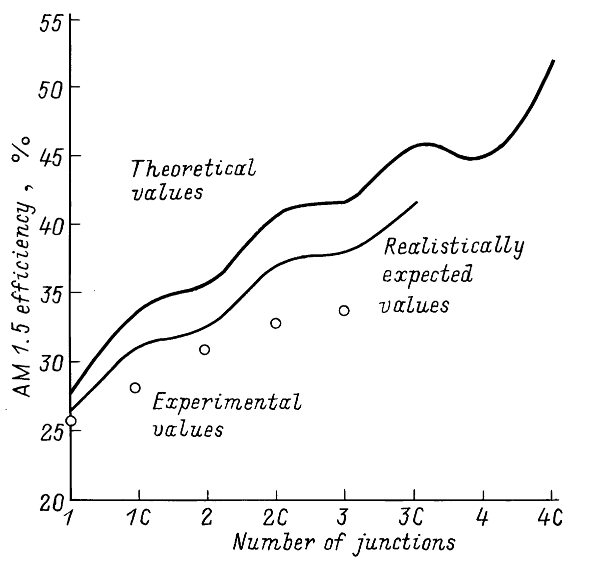

Figure 7. Theoretical and realistically expected conversion efficiencies of single-junction amd multi-junction solar cells in comparison with experimentally realized efficiencies. C indicates concentration.

Program [9]. In fact, the first commercial satellite with 2-junction GaInP/GaAs on Ge solar arrays was launched in August 1997 [7]. Therefore, tandem solar cells will be widely used in space.

In order to apply super-high-efficiency cells widely, it is necessary to improve their conversion efficiency and reduce their cost. Fig. 7 shows theoretical and realistically expected conversion efficiencies of single-junction and multi-junction solar cells in comparison with experimentally realized efficiencies. Therefore, concentrator 3-junction and 4-junction solar cells have great potential for realizing super-high-efficiency over 40%. As a 3-junction combination, GaInP/GaAs/Ge cell on Ge substrate will be widely used because this system has been already developed. The 4-junction combination of the AlGaInP ($E_g = 2.0$ eV) top cell, the GaAs second-layer cell, the third-layer cell made of a material with 1.05 eV bandgap, for example GaInAsP or GaInAsN, and the Ge bottom cell is lattice-matched to Ge substrates and has theoretical 1-sun AM 0 efficiency of about 42%. This system has also potential of over 45% under 500-suns AM 1.5 condition. Although this system is ideal for maximum theoretical efficiency, the selection of third-layer cell materials and improvement in the material quality are problems to overcome.

There are 3-junction cells on Si or metal substrates, as approaches for realizing low cost. There must be also 3-junction cells on metal substrates as one of future targets. Concentrator thin-film multi-junction solar cells fabricated on inexpensive substrates such as Si and polycrystalline materials have great potential for realizing high-efficiency (with efficiency more than 35%) and low-cost cells if one can reduce the dislocation density to less than $5 \cdot 10^5$ cm^{-2} and increase the grain size to more than 0.1 cm [10].

5. Summary

Present status of super-high-efficiency tandem solar sells was reviewed. InGaP/GaAs tandem solar cells with newly recorded efficiency of 30.6% at AM 1.5 (1-sun) were achieved by improvements in InGaP top cells and AlGaAs/InGaP DH structure tunnel junctions with AlInP barriers. The mechanical stacked 3-junctuin cells of monolithically grown InGaP/GaAs 2-junction cells and InGaAs cells reached the highest efficiency achieved in Japan of 33.3% at 1-sun AM 1.5.

Key technologies and basic physics for realizing super-high-efficiency and low-cost multi-junction solar cells were also discussed.

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