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PRESENT AND FUTURE OF SUPER HIGH-EFFICIENCY TANDEM SOLAR CELLS

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ABSTRACT

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. In addition, the terrestrial R&D activities of tandem cells, in the New Sunshine Program of MITI (Ministry of International Trade and Industry) and NEDO (New Energy and Industrial Technology Development Organization) in Japan are reviewed briefly. 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 AM1.5. This paper also reports high-efficiency InGaP/GaAs 2-junction solar cells with a world-record efficiency of 26.9% at AM0, 28°C and radiation damage recovery phenomena of the tandem cell performance due to minority-carrier injection under light illumination or forward bias, which causes defect annealing in InGaP top cells. Future prospects for realizing super-high efficiency and low-cost tandem solar cells are also described.

Keywords: Tandem Solar Cell, III-V, High-Efficiency, Tunnel Junction, Radiation Damage

1. INTRODUCTION

Substantial increase in conversion efficiency can be realized by multi-junction (tandem) solar cells in comparison with single-junction cells. Multi-junction solar cells have been investigated since 1960 [1], as shown in Table I. Although AlGaAs/GaAs tandem cells, including tunnel junctions [2] and metal inter connectors [3], were developed in the early years, a high efficiency close to 20 % was not obtained because of difficulties in making high performance and stable tunnel junctions and the defects related to the oxygen in the AlGaAs materials [4]. A double hetero (DH) structure tunnel junction was found be useful for preventing diffusion from the tunnel junction by the authors [5]. An InGaP material for the top cell was proposed by NREL [6], and a GaInP/GaAs tandem cell with an efficiency of 29.5% but small area of 0.25cm^2 was reported. For the concentrator system, over 30% efficiency was attained by the GaAs/GaSb mechanical stacked cells [7].

Table I. Progress of the III-V tandem cell technologies.

1960	Proposal of multi-junction solar cells	Wolf
1982	Optimal design for high-efficiency	MIT
1982	A 15.1% AlGaAs/GaAs tandem cell	RTI
	A 15.7% AlGaAs/GaAs tandem cell	Varian
1987	A 20.2% AlGaAs/GaAs tandem cell (Double-hetero structure tunnel junction)	NTT
1989	A 27.6% AlGaAs/GaAs tandem cell (Metal-inter-connector)	Varian
1990	A 32.6% GaAs/GaSb tandem cell (Mechanical-stacked x 100 concentrator)	Boeing
	A 27.3% InGaP/GaAs tandem cell	NREL
1994	A 29.5% InGaP/GaAs tandem cell	NREL
1996	A 30.3% InGaP/GaAs tandem cell	J-Energy
1997	First satellite using InGaP/GaAs cells	Hughes Spectrolab

Recently, InGaP/GaAs 2-junction solar cells have drawn increased attention for space applications because of the possibility of high conversion efficiency of over 30%. Recently, Japan Energy Corp. has achieved a world record efficiency of over 30% under one-sun AM1.5 global conditions for the InGaP/GaAs tandem solar cell [8]. In addition, some effort has been made to put such type cells into commercial production for space applications based on the joint WL/PL/NASA Multijunction Solar Cell Manufacturing Technology (Man Tech) Program [9]. In fact, the first commercial satellite (HS 601HP) with 2-junction GaInP/GaAs-on Ge solar arrays was launched in August 1997 [10]. Good following wind may flow to encourage the multi-junction cells further.

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. Future prospects for realizing super-high efficiency and low-cost tandem solar cells are also described.

2. KEY ISSUES FOR REALIZING HIGH-EFFICIENCY TANDEM CELLS

Major problems for higher efficiency are improvements in the top cell material quality and tunnel junction performance for cell interconnection. Key issues for realizing high-efficiency tandem cells are discussed based on our results.

2.1 Top cell property improvements

Selection of top cell materials is also important for high-efficiency tandem cells. As top cell material, InGaP has some advantages such as lower interface recombination velocity, less oxygen problem and good window layer material compared to AlGaAs as shown in Table II.

The top cell characteristics depend on the minority carrier lifetime in the top cell layers. Figure 1 shows change in photoluminescence (PL) intensity of p-InGaP base layer as a function of the minority carrier lifetime. The lowest surface recombination velocity was obtained by introducing the AlInP window layer and the highest minority carrier lifetime was obtained by introducing buffer layer and optimizing the growth temperature. The best conversion efficiency of the InGaP single junction cell was 18.5 %.

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

Items	InGaP	AlGaAs
Interface recombination velocity	<5x10^{3}cm/s	10^4~10^{5}cm/s
Oxygen-related defects	Less problem	Major problem
Window layer (Eg)	AlInP (2.5eV)	AlGaAs (2.1eV)
Other problems	High doping in p-AlInP	Lower eff. (2.6% down)

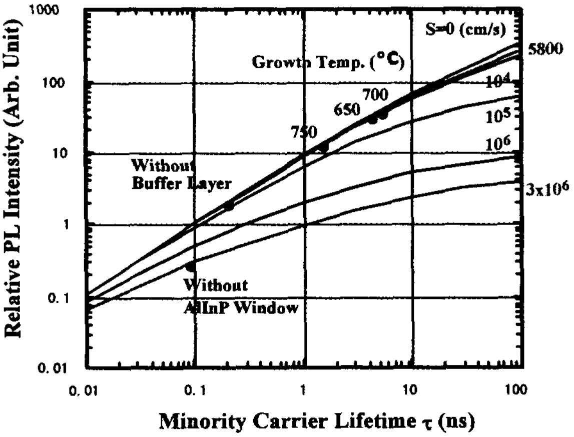

Fig. 1. Changes in PL intensity of the solar cell active layer as a function of the minority carrier lifetime (τ) of the p-InGaP base layer and surface recombination velocity (S).

2.2 Tunnel junction property improvements and effects of tunnel junction on InGaP/GaAs tandem cell properties

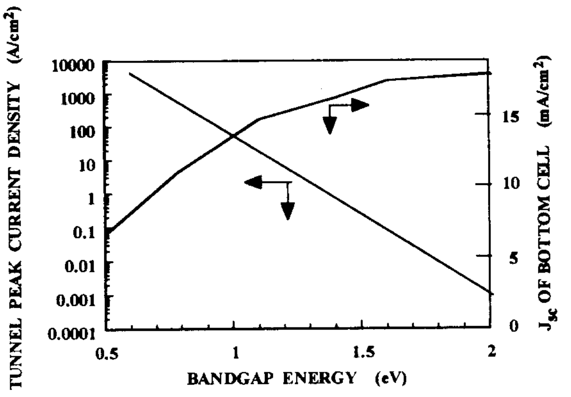

Fig. 2. Calculated tunnel peak current density and short-circuit current density Jsc of GaAs bottom cell as a function of bandgap energy of tunnel junction.

One of the most important issues for realizing high-efficiency monolithic-cascade type tandem cells is the 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 tunneling current decreases exponentially with increase in bandgap energy as shown in Fig. 2.

In addition, impurity diffusion from a highly doped tunnel junction during overgrowth of the top cell increases the resistivity of the tunnel junction. A double hetero (DH) structure was found to be useful for preventing diffusion by the authors [5]. More recently, an InGaP tunnel junction has been for the first time tried for an InGaP/GaAs tandem cell in this work [8]. Peak tunneling current of the InGaP tunnel junction is found to increase from 5mA/cm^2 up to 300mA/cm^2 by making a DH structure with AlInP barriers as shown in Fig. 3. Furthermore, higher tunneling current up to 2A/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 for obtaining high tunneling current, and DH structure has also been confirmed to be useful for preventing diffusion as the authors have found [5].

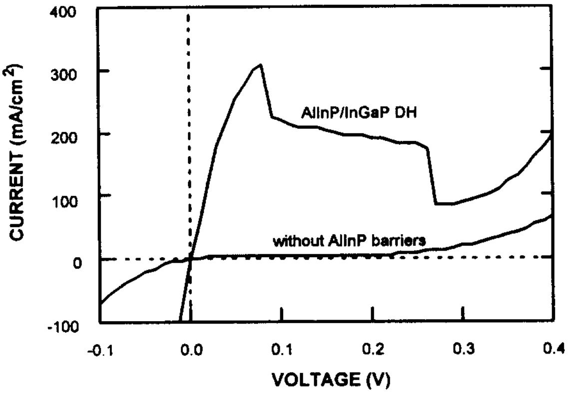

Fig. 3. Changes in I-V characteristics of the InGaP tunnel junction by introducing the DH structure.

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 (GaAs tunnel junction with InGaP barriers), AlInP/GaAs (GaAs tunnel junction with AlInP barriers), and AlInP/InGaP (InGaP tunnel junction with AlInP barriers) DH structures has been compared by using spectral responses of the tandem cells as shown in Fig. 4. The upper barrier layer of

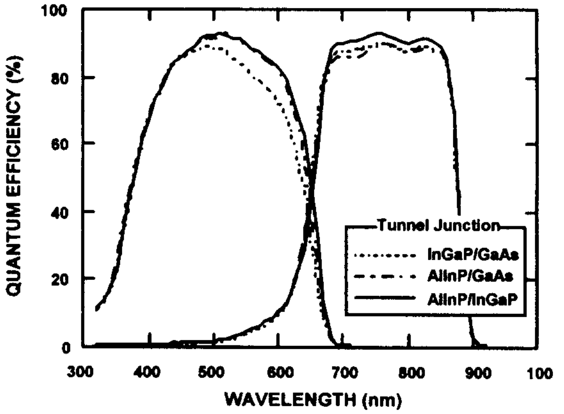

Fig. 4. Spectral response of the InGaP/GaAs tandem cells dependent on their tunnel junction structure. All the tunnel junctions have DH structure.

3. SUPER HIGH-EFFICIENCY TANDEM CELL R&D PROGRAM IN JAPAN

Table III. 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	AM1.5	25.4	Hitachi Cable	1996
		4	AM0	22.5	Mitsubishi Electric	1987
	InP bulk	0.25	AM1.5	21.4	NTT	1986
Thin-film	GaAs-on-Ge	1	AM1.5	23.2	Hitachi Cable	1996
	GaAs-on-Si	1	AM1.5	20.0	NTT	1989
Tandem	InGaP/GaAs 2-Junction	4	AM1.5	30.3	Japan Energy	1996
		9	AM1.5	30.6	Japan Energy	1998
		4	AM0	26.9	Japan Energy Toyota Tech. Inst.	1997
	AlGaAs/GaAs2-Junction	0.25	AM1.5	20.2	NTT	1987
		1	AM1.5	28.8	Hitachi Cable	1996
	GaAs/InGaAs Mechanically Stacked	1	AM1.5	28.8	Sumitomo Electric	1996
	AlGaAs/Si 2-Junction	0.25	AM0	21.2*	Nagoya Inst. Tech.	1996
	InGaP/GaAs/InGaAs MS 3-Junction	1	AM1.5	33.3	Japan Energy Sumitomo Electric	1997
Concen. Tandem	InGaP/GaAs 2-Junction	1	AM1.5 (x 5.1)	31.2	Toyota Tech. Inst. Japan Energy	1998

*** active-area efficiency**

the tunnel junction also takes the part of the BSF of the top cell. A large reduction in quantum efficiency in wavelengths between 500 and 650 nm has been observed with the InGaP/GaAs tunnel junction cells. This reduction is thought to be caused by the diffusion of zinc during epitaxial growth.

The C-V measurement indicates that the broadening of the carrier concentration profile due to the diffusion of Zn dose not occur in the cells with an AlInP barrier layer as shown in Fig. 5. Furthermore, an increase in the quantum efficiency of the bottom GaAs cell due to the elimination of absorption loss in the GaAs tunnel junction has been confirmed in the cell with InGaP tunnel junction as shown in Fig. 4.

Finally, the optimal conditions for current matching between the top InGaP and bottom GaAs

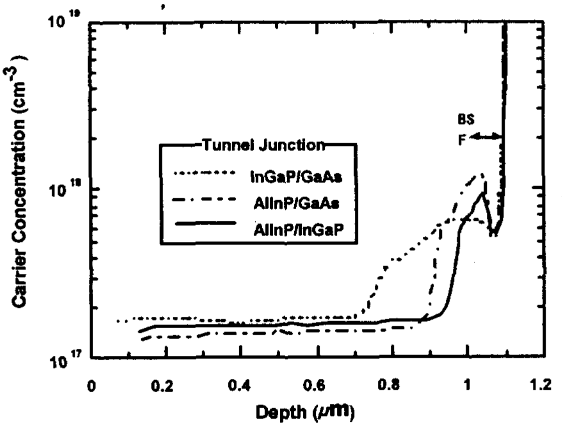

Fig. 5. Carrier concentration profile in the layers above the tunnel junction measured by the etching C-V method.

cells have been examined by changing the base layer thickness of the top cells.

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

The super-high solar cell R&D project started in FY 1990 [11]. The objectives of the project is conversion efficiencies about twice the 1990 values at the laboratory level by the beginning of the 21st century and production of such cells by 2010. Especially, multi-junction solar cells show potential for super-high efficiency cells with efficiencies of 36~40% due to their wide-band photo-response, although the theoretical efficiency for single-junction GaAs and InP cells is 27~28%. Concentrator operation of 2-junction cells and 3-junction cells is also effective not only in improving efficiency (more than 40%) but also in lowering cost. Thin-film compound solar cells fabricated on inexpensive substrates such as Ge, Si and polycrystalline materials would be useful as low-cost cells.

More recently, monolithically grown InGaP/GaAs 2-junction solar cells with a 1-sun AM1.5 conversion efficiency of 30.6% have been successfully fabricated by Japan Energy Corp. The mechanically stacked 3-junction cells of monolithically grown InGaP/GaAs 2-junction cells and InGaAs bottom cells have reached the highest efficiency of 33.3% [12] at 1-sun AM1.5 following joint work by Japan Energy Corp. and Sumitomo Electric Corp.

Figures 6 and 7 show a schematic cross-section and I-V characteristics of a high-efficiency mechanically stacked 3-junction cell under AM1.5G illumination.

4. WORLD-RECORD AM0 EFFICIENCY ATTAINMENT

As a by-product of these results, the same cells are being developed for space applications, because about 90% of the values of AM1.5 efficiencies are expected to be attained at AM0, and the InGaP/GaAs 2-junction cells have shown unique radiation-resistant properties under light illumination condition [13].

Figure 8 shows a schematic cross-section of an InGaP/GaAs 2-junction cell used in this study. InGaP/GaAs cell layers were grown on GaAs substrates by the metalorganic chemical vapor deposition (MOCVD) method. The top and bottom cells were connected by an AlInP-InGaP double-hetero (DH) structure tunnel junction.

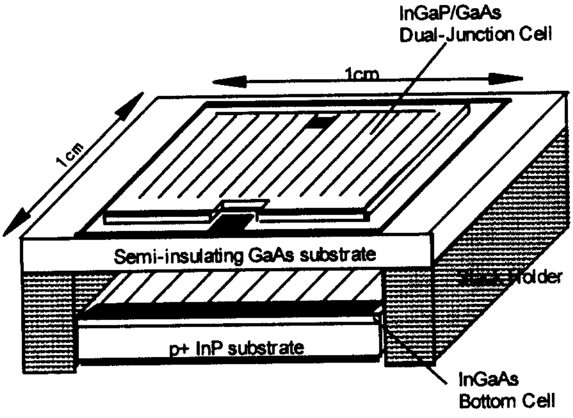

Fig. 6. Schematic illustration of the mechanically stacked triple-junction cell.

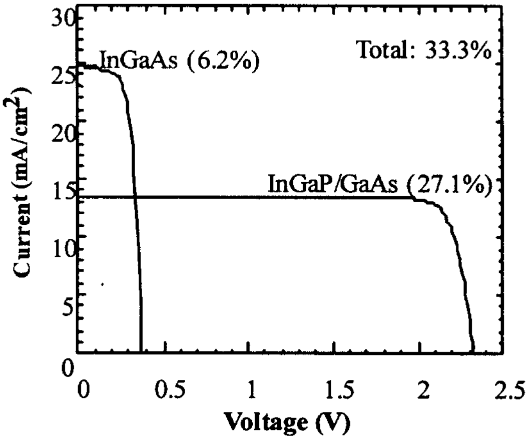

Fig. 7. I-V curves of the triple-junction cell component under AM1.5G illumination measured by the JQA.

A world-record efficiency of 26.9% (Voc=2.451V, Isc=67.4mA, FF=88.1%) at AM0, 28°C, which has been measured at NASDA using a one light source simulator, has been obtained for 4 cm^2 InGaP/GaAs tandem cells, as shown in Fig. 9.

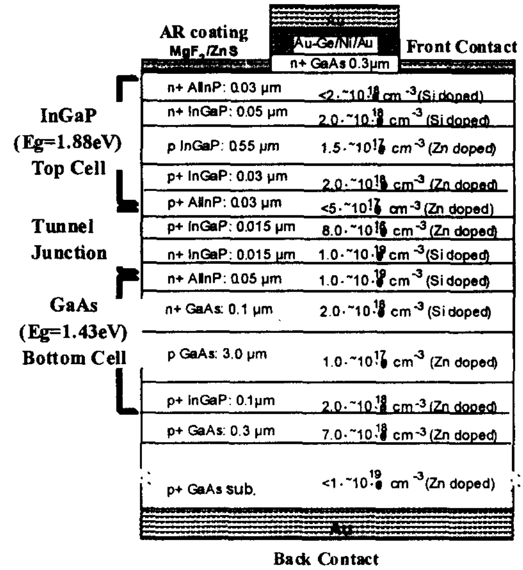

Fig. 8. Schematic of a high-efficiency InGaP/GaAs 2-junction cell structure.

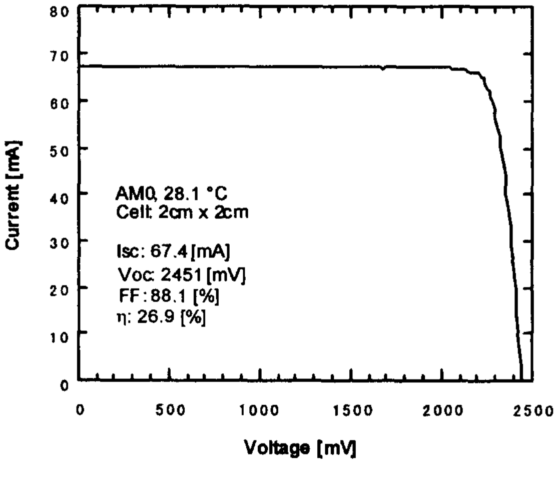

Fig. 9. I-V curve of an InGaP/GaAs tandem cell with a conversion efficiency of 26.9% (AM0), which has been measured by NASDA using a one light source simulator.

Figure 10 shows the radiation resistance of InGaP/GaAs tandem cells against 1 MeV electron irradiation with fluences in the range from $3x10^{14}$ to $1x10^{16}$ cm^{-2}, in comparison with those of InP, InGaP and GaAs-on-Ge solar cells. The radiation resistance of our tandem cell is similar to a GaAs-on-Ge cell. Degradation in our tandem cell performance is thought to be mainly attributed to large degradation in the GaAs bottom cell with a highly doped base layer.

5. UNIQUE RADIATION-RESISTANT PROPERTIES OF InGaP/GaAs TANDEM CELLS

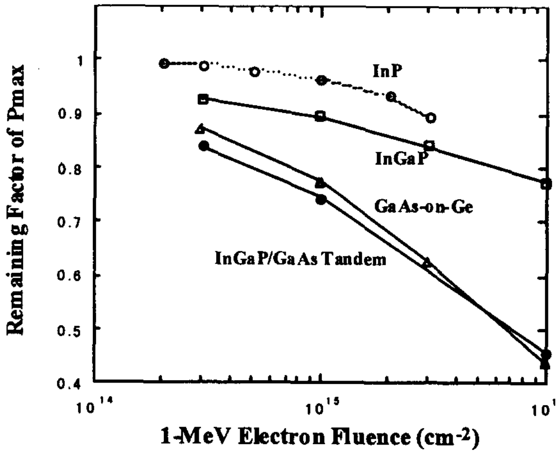

Fig. 10. Radiation resistance of InGaP/GaAs tandem cells against 1 MeV electron irradiation, in comparison with those of InP, InGaP and GaAs-on-Ge solar cells.

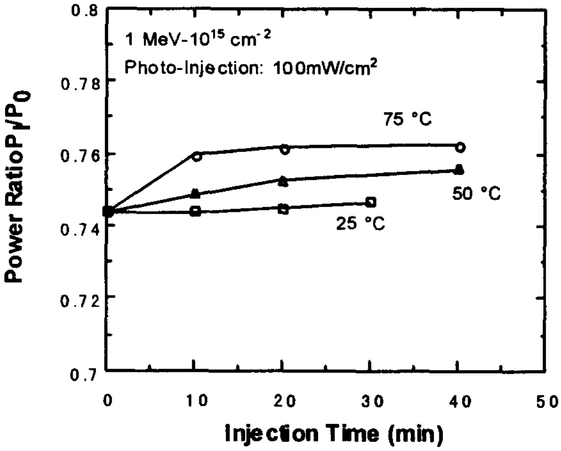

Fig. 11. The maximum power recovery of the InGaP/GaAs tandem cell due to light illumination at various temperatures.

Figure 11 shows the maximum power recovery due to photo injection of 100 mW/cm^2 at various temperatures for the tandem cells. The ratios of maximum power after injection P_I to maximum power before irradiation P_0 are shown as a function of injection time. The recovery ratio increases with an increase in ambient temperature within the operating range for space use. The power recovery due to current injection under forward bias was also observed [13].

Since similar effects in GaAs cells occurred at higher temperatures of 150-200°C [14], the remarkable recovery of a the tandem cell, as shown in Fig. 11, is thought to be caused by the photoinjection-enhanced annealing of radiation damage to the InGaP cell. Although the power recovery of the InGaP/GaAs tandem cell is much smaller than that of the single-junction InGaP cell (because the degradation of the tandem cell is dominated by that of the GaAs bottom cell), optimal design of the tandem cell structure might enhance the recovery and improve the radiation resistance of the tandem cells.

6. FUTURE PROSPECTS FOR OBTAINING 40% EFFICIENCY

In order to apply super high-efficiency cells widely, it is necessary to improve their conversion efficiency and reduce their cost. In this paper, the possibility of obtaining super high-efficiency of over 40% by using multi-junction cell structure and thin-film technologies on inexpensive substrates such as Si and polycrystalline materials are discussed.

Figure 12 shows theoretical and realistically expected conversion efficiencies of single-junction and multi-junction solar cells reported by Fan et al. [15], Wanlass et al. [16] and Kurtz et al. [17] in comparison with experimentally realized efficiencies. Therefore, concentrator 3-junction and 4-junction solar cells have great potential for realizing super high-efficiency of over 40%. As a 3-junction combination, GaInP/GaAs/Ge cell on a Ge substrate will be widely used because this system has been already developed. The 4-junction combination of an AlGaInP (Eg=2.0eV) top cell, a GaAs second-layer cell, a material third-layer cell with a bandgap of 1.05eV made of, for example, GaInAsP and GaInAsN, a Ge bottom cell is lattice-matched to Ge substrates and has a theoretical 1-sun AM0 efficiency of about 42%. This system has also potential of over 45% under 500-suns AM1.5 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.

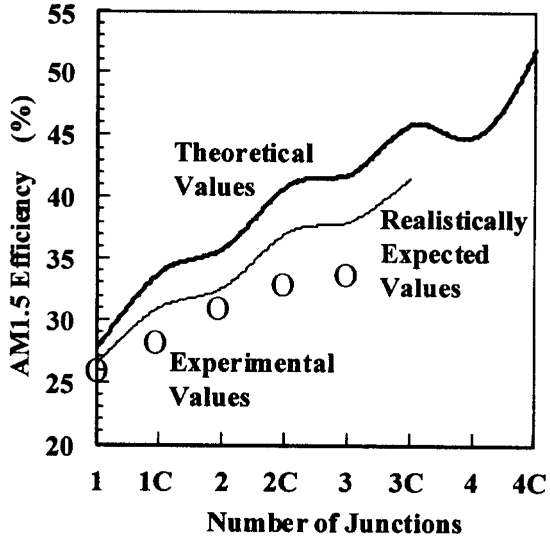

Fig. 12. Theoretical and realistically expected conversion efficiencies of single-junction and multi-junction solar cells reported by Fan et al. [15], Wanlass et al. [16] and Kurtz et al. [17] in comparison with experimentally realized efficiencies. C indicates concentration.

Figure 13 shows calculated grain size d and dislocation density N_d dependencies of AM1.5 conversion efficiencies for GaAs single-junction cells, 2-junction cells and concentrator 2-junction cells in comparison with experimental values.

The calculations have been carried out using our previous model [18] as follows:

$$1/L^2 = 1/L_0^2 + \cdot\ \pi^3 N_d/4, \qquad (1)$$

$$1/L^2 = 1/L_0^2 + 4S/Dd, \qquad (2)$$

where L is the minority-carrier diffusion length in solar cell active layers, L_0 is the radiative recombination limited L, S is the surface recombination velocity at the edge of the grain boundary depletion region and is assumed to be 5×10^6 cm/sec in the case of GaAs, and D is minority-carrier diffusion coefficient.

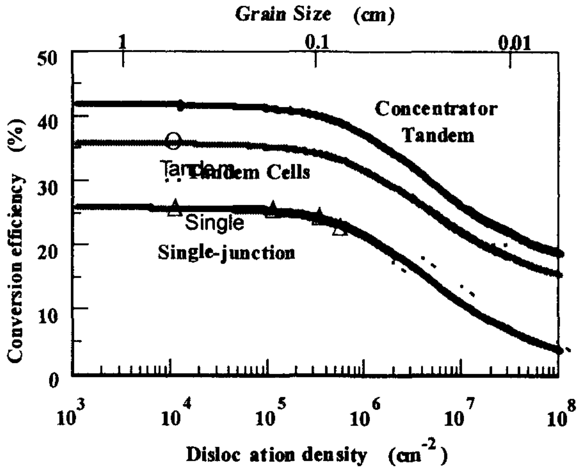

Fig. 13. Calculated grain size d and dislocation density N_d dependencies of AM1.5 conversion efficiencies for GaAs single-junction cells, 2-junction cells and concentrator 2-junction cells in comparison with experimental values.

Therefore, 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 an efficiency of more than 35% and low-cost cells if one can reduce the dislocation density to less than 5×10^5 cm^{-2} and increase the grain size to more than 0.1 cm.

7. SUMMARY

Present status of super high-efficiency tandem solar cells was reviewed. In addition, the terrestrial R&D activities of tandem cells, in the New Sunshine Program of MITI and NEDO in Japan were reviewed briefly.

InGaP/GaAs tandem solar cells with newly recorded efficiency of 30.6% at AM1.5 (1-sun) were achieved 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 hetero-structure tunnel junction with AlInP barriers. The mechanical stacked 3-junction 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 AM1.5.

This paper also reported high-efficiency InGaP/GaAs 2-junction solar cells with a world-record efficiency of 26.9% at AM0, 28°C and radiation damage recovery phenomena of the tandem cell performance due to minority-carrier injection under light illumination or forward bias, which caused defect annealing in InGaP top cells. These results confirm the great potential of the InGaP/GaAs tandem cells for space applications.

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

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