Japan programs on novel concepts in PV

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Japanese R&D activities in photovoltaics (PV) and our R&D activities of III–V compound multijunction (MJ) solar cells are presented. We have realized high-efficiency InGaP/InGaAs 3-junction solar cells with an efficiency of 36.5–37% (AM1.5G, 200 suns) and concentrator 3-junction solar cell modules of an outdoor efficiency of 27% as a result of designing grid structure, developing low optical loss Fresnel lens and homogenizers, and designing low thermal conductivity modules. We are now challenging to develop low-cost and high output power concentrator MJ solar cell modules with an output power of 400 W/m^2 for terrestrial applications.

1. PV R&D programs in Japan

Table 1 shows photovoltaics (PV) roadmap until 2030 (long-term targets for developing large-scale PV power generation technology in Japan). The target by 2039 is to develop PV technology for realizing an electricity cost of 5–6 Japanese yen/kWh, which corresponds to the electricity generation cost of the present nuclear and fossil fuel power generation systems in Japan. Recently, METI (Ministry of Economics, International Trade and Industry in Japan) revised the New Energy Supply Outlook based on an interim report by the New Energy Subcommittee for the Advisory Committee for Energy. The latest target for PV installation in FY (fiscal year) 2010 is 4.82 GW. To accomplish the target, greater effort to for PV technology to realize about one order higher PV module production and PV system installation are necessary.

To achieve these long-term targets, a new five-year PV R&D program was started since FY 2001 aiming at achieving targets. The new PV R&D program consists of four projects, namely, „Development of Advanced Manufacturing Technology“ (budget in FY 2003 is 7.9 million euro), „Development of Advanced Solar Cells and Modules“ (21.7 million euro), „Investigation for Innovative PV Technology“ (11.1 million euro) and „Technology Development for Future Mass Deployment“ (8.5 million euro).

The project „Development of Advanced Solar Cells Modules“ consists of three R&D theme: 1) Si-based thin film solar cell modules, 2) CIS-based thin film solar cell modules, and 3) Super-high efficiency compound solar cells. The target of this project is to develop advanced solar cell module technologies to reduce mass production costs of PV modules to less than 100 yen/W. The target of R&D for „Si-based thin film solar cell modules“ is to realize 12% efficiency with 3600 cm^2 module until the end of FY 2005. Kaneka and Mitsubishi Heavy Industries join this R&D. The target of R&D for „CIS-based thin film solar cell modules“ is to realize 13% efficiency with 3600 cm^2 module. Showa Shell Sekiyu and Matsushita Electric join this R&D. The target of R&D for „Super-high efficiency compound solar cells and modules“ is to realize 40% efficiency under concentrator operation. Sharp, Daido Steel and Daido Metal join this R&D.

The aim of the project „Investigation for Innovative PV Technology“ is to develop innovative PV technologies to realize a drastic reduction in manufacturing cost of solar cell modules as low as 15 yen/kWh. This project is seeds investigations consisting of 1) novel materials, 2) novel structures, and 3) novel manufacturing processes and about 20 themes are investigated. For novel materials, SiGe, $FeSi_2$, carbon, organic semiconductor, wide-band-gap chalcopyrite and new nitride material solar cells are investigated. As novel structures, nano-structure Si, spherical Si, advanced light-trapping thin film, wide-band-gap micro-crystalline SiC and dye-sensitized solar cells are also studied. In addition, Si cell technology with CAT-CVD, CIS thin film cell by electroplating and Si thin film cells by lateral growth are investigated for novel manufacturing processes.

2. R&D background of multijunction solar cells

Multijunction (tandem) solar cells have the potential for achieving high conversion efficiencies of over 40% and are promising for space and terrestrial applications. One of the authors has started his researches on AlGaAs/GaAs 2-junction solar cells since 1982 and his group has

Table 1. Japanese PV roadmap until 2030

	2000	2005	2010	2020	2030
Manufacturing cost of modules (yen/W)	140	100	75	50	30
Technology development (assuming 100 MW/year production)	–	140	100	75	50
Generation cost of electricity(yen/kWh)	70	30	25	10–15	5–10
PV systems installed (cumulative) (GW)	–	–	4.82	23–35	52–82

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demonstrated 20.2% efficiency by proposing double heterostructure tunnel junction as a sub cell interconnection in 1987 [1]. In Japan, based on such an activity, R&D project for „Super-high efficiency MJ solar cells" has been conducted under support by NEDO since FY 1990 [2] as a long-term target to the early 21st century, in which challenges and efforts are made in the development of super-high efficiency solar cell technology, aiming at a dramatic increase in conversion efficiency of over 40% and developing innovational technologies. We have proposed AlInP–InGaP double heterostructure (DH) top cell, wide-band-gap InGaP DH tunnel junction for sub-cell interconnection, and lattice-mathced InGaAs middle cell. As a result of the above technology developments, the mechanically stacked InGaP/GaAs/InGaAs 3-junction cells ($1\,cm^2$) have reached the highest (1-sun world-record) efficiency of 33.3% at 1-sun AM1.5G following joint work by Japan Energy Co., Sumitomo Electric Co. and Toyota Technical Institute [3]. Since FY 2001, such an R&D project has been shifted to the project for „Concentrator MJ Solar Cells and Modules".

In this paper, more recent results for high-efficiency III–V compound multijunction (MJ) solar cells, concentrator MJ solar cells and modules conducted under the New Sunshine Project in Japan are presented. Future prospects for super high-efficiency and low-cost MJ and concentrator cells and modules are also presented.

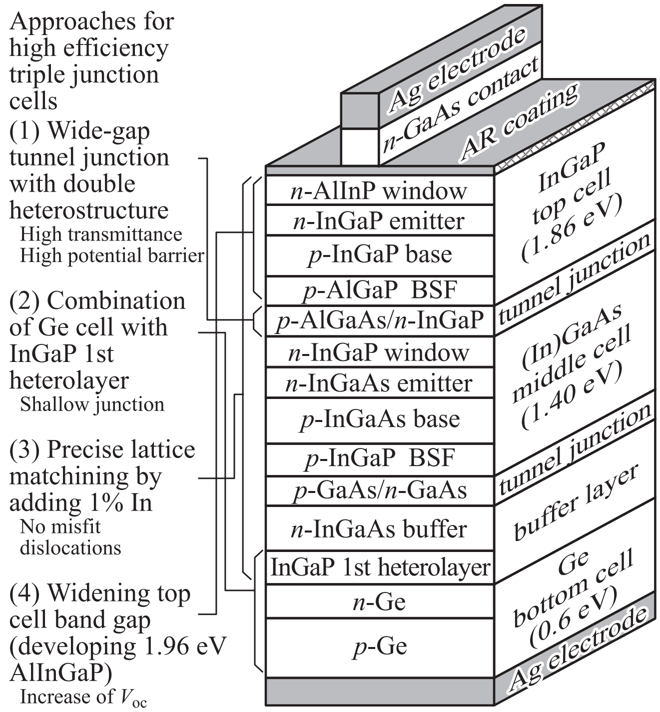

Figure 1. Schematic illustration of a triple-junction cell and approaches for improving efficiency of the cell. BSF — back surface field.

3. High-efficiency multijunction solar cells

Conversion efficiency of InGaP/GaAs based multijunction solar cells has been improved by the following technologies. A schematic illustration of the InGaP(In)GaAs/Ge triple-junction solar cell and key technologies for improving conversion efficiency is shown in Fig. 1.

3.1. Wide band-gap tunnel junction

A wide band-gap tunnel junction which consists of *p*-Al(Ga)InP/*p*-AlGaAs/*n*-(Al)InGaP/*n*-Al(Ga)InP double heterostructure increases incident light into the (In)GaAs middle cell and produces effective potential barriers for both minority carriers generated in the top and middle cells. The wide band-gap tunnel junction without absorption and recombination losses improves both V_{oc} and I_{sc} of the cells. It is difficult to obtain high tunneling peak current with wide gap tunnel junction, so thinning depletion layer width formation of highly doped junction is quite necessary. Since impurity diffusion is occurred during growth of the top cell [4], carbon and silicon, which have low diffusion coefficient, are used for *p*-type AlGaAs and *n*-type (Al)InGaP, respectively. Furthermore, the double heterostructure supposes to suppress impurity diffusion from the highly doped tunnel junction [5]. The second tunnel junction between middle and bottom cells consists of *p*-InGaP/*p*-(In)GaAs/*n*-(In)GaAs/*n*-InGaP which have wider band-gap than middle cell materials.

3.2. InGaP/Ge heteroface structure bottom cell

InGaP/GaAs cell layers are grown of *p*-type Ge substrate. $P-N$ junction is formed automatically during MOCVD growth by diffusion of V group atom from the first layer grown on the Ge substrate. So, the material of the first heterolayer is important for the performance of Ge bottom cell. An InGaP layer is thought to be suitable material for the first heterolayer, because phosphor has lower diffusion coefficient in Ge then arsenic and indium has lower solubility in Ge than gallium. Quantum efficiency of the Ge bottom cell was improved by the InGaP hetero-growth layer. In the case of GaAs hetero-growth layer, junction depth was measured to be around $1\,\mu$m. On the other hand, thickness of *n*-type layer produced by phosphor from the InGaP layer was $0.1\,\mu$m. An increase in Ge quantum efficiency was confirmed to be due to a reduction in junction depth.

It was found that the absorption edge of the InGaP top cell shifted to the longer wavelength region, by using the InGaP first heterolayer. Band gap of the InGaP top cell reduced from 1.86 eV to 1.81 eV by changing the hetero-growth layer from GaAs to InGaP. The fact that the band gap increased with the growth temperature increased indicated this phenomenon was due to the ordering effect in the InGaP material [6]. Since the band-gap narrowing of the top cell decreases V_{oc} of the triple-junction cell, an approach for growth of less ordering InGaP should be necessary. As a matter of a fact, conversion efficiency has been improved up to 30% (AM0) by increasing top cell band gap up to 1.89 eV [7].

3.3. Precise lattice matching to Ge substrate

Although 0.08% lattice mismatch between GaAs and Ge was thought to be negligibly small, misfit dislocations were generated in thick GaAs layers and deteriorated cell performance. By adding about 1% indium into the InGaP/GaAs cell layers, all cell layers are lattice-matched precisely to the Ge substrate. As a result, cross-hatch pattern caused by misfit dislocation due to lattice mismatch was disappeared in the surface morphology of the cell with 1% indium. The misfit dislocations were found to influence not to I_{sc} but to V_{oc} of the cell. V_{oc} was improved by eliminating misfit dislocations for the cell with 1% indium. In addition, wavelength of the absorption edge became longer and I_{sc} of both top and middle cells increased, by adding 1% indium.

3.4. Widening of top cell band gap by AlInGaP

Now, we are developing AlInGaP top cells in order to improve V_{oc} of the triple-junction cells. Current matching between top and middle cells should be done by controlling the top cell band gap instead of thinning the top cell. In this case, V_{oc} of the cell can be increased with keeping the maximum current. An AlInGaP cell with 1.96 eV band gap and 2.5 μm thickness was found to attain high V_{oc} of 1.5 V with keeping the same I_{sc} as the conventional InGaP top cells under AM1.5G condition. For AM0 condition, further increase in band gap up about 2.0–2.03 eV is required for the AlInGaP cells, although that is depended on the current matching requirement from the beginning of life (BOL) to the end of life (EOL).

The best data of the triple-junction cells in our laboratory are summarised in Table 2. Technologies described above (**3.1**–**3.3**) were applied to fabrication of the triple-junction cells. Band gap of the InGaP top cell of about 1.82 eV is still low. By using AlInGaP top cell with 1.96 eV, higher V_{oc} close to 2.72 V is predicted. Fig. 2 shows AM0 $I-V$ curve of an InGaP/InGaAs/Ge solar cell fabricated. We have demonstrated 31.5–32% at 1-sun AM1.5G and 29.2–30% at 1-sun AM0 with InGaP/InGaAs/Ge 3-junction solar cells [8]. Conversion efficiencies over 33% (AM1.5G) and close to 31% (AM0) will be expected for the (Al)InGaP/InGaAs/Ge triple-junction cells.

Table 2. Characteristics and predicted efficiencies (Eff) of the triple-junction cells

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Eff (%)	Condition
InGaP ($E_g = 1.82$ eV)				
2567	14.1	0.87	31.5	AM1.5G, 25°C
2568	17.9	0.86	29.2	AM0, 28°C
AlInGaP ($E_g = 1.96$ eV)				
2720	14.1	0.87	33.3	AM1.5G, 25°C
2721	17.9	0.86	31	AM0, 28°C

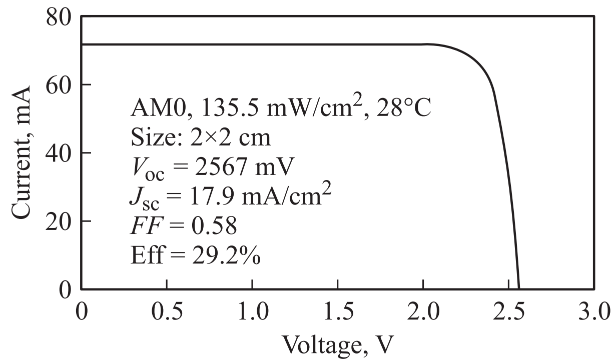

Figure 2. AM0 $I-V$ curve of InGaP/InGaAs/Ge 3-junction solar cell.

For the next generation multijunction cell approaches, one way is an optimization of band gaps for utilizing solar energy with wide energy range above Ge band gap. A lattice-mismatched AlInGaP(1.8 eV)/InGaAs(1.2 eV)/Ge(0.65 eV) 3-junction cell and a lattice-matched AlGaInP(2.0 eV)/GaAs(1.4 eV)/GaInNAs(1 eV)/Ge(0.65 eV) 4-junction cell are challenging structures. Another way is an increase of junctions for utilizing high-energy range. Many thin junctions with contiguous band gaps can reduce energy loss due to difference between photon energy and band-gap energy. AlInGaP and InGaAsP lattice-matched to GaAs provides various band gaps and might establish the high-efficiency cells.

4. High-efficiency concentrator multijunction solar cells

The previous R&D project for high-efficiency MJ solar cells is now taken over by Sharp Co., Daido Steel Co. and Daido Metal Co. and targeted to concentration application also supported by NEDO. The new target is 40% efficiency under 500-sun concentration by the end of March 2006.

In order to apply a high-efficiency multijunction cell developed for 1-sun condition to a concentrator cell operating under $\sim$ 500-sun condition, reduction in energy loss due to series resistance is the most important issue. Cell size was determined to be 7×7 mm with considering total current flow. Grid electrode pitching, height and width were designed in order to reduce series resistance. Fig. 3 shows FF of the cell with various grid pitching under 250 suns. Grid electrode with 5 μm height and 5 μm width was made of Ag. Grid pitching influences lateral resistance between two grids (R_L) and total electrodes resistance (R_E). Series resistance of the cell (R_S), R_E and R_L are also shown in Fig. 3. R_E was measured directly after removing electrode from the cell by chemical etching. R_L was calculated by using sheet resistance of window and emitter layers. Based on the data in Fig. 3, the grid pitching is determined to be

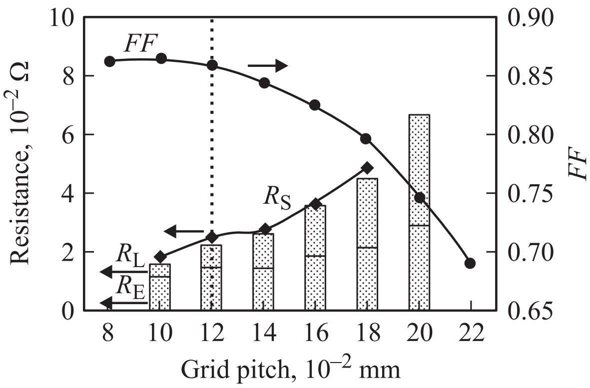

Figure 3. FF of the concentrator cells with various grid pitching under 250-sun light. Series resistance (R_S), lateral resistance (R_L) and total electrodes resistance (R_E) are also shown.

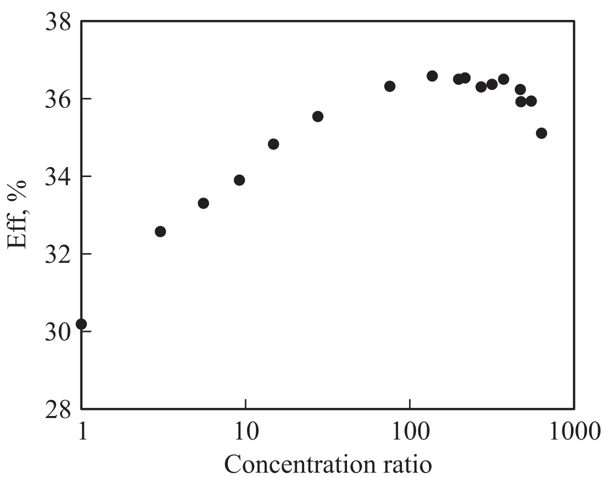

Figure 4. Efficiency of an InGaP/InGaAs/Ge concentrator 3-junction cell as a function of concentration ratio.

0.12 mm at this time. In order to reduce series resistance down to 0.01 Ω and obtain high FF under 500 suns, grid height should be increased to be twice. High eficiency under $<$ 500 suns is thought to be obtained by the optimal grid design without modification of the cell layer structure such as emitter thickness and tunnel junction thickness from the cell developed for 1-sun condition.

Fig. 4 shows efficiency of a concentrator cell as a function of concentration ratio. The concentration ratio is defined by the increase in I_{sc}, I_{sc}/I_{sc}(1-sun) ratio. High conversion efficiency over 36% is measured under concentrated light with concentration ratio ranging from 100 to 500 suns. At concentration ratio of 200 suns, conversion efficiency was measured to be 36.5%. Decrease in efficiency is due to decrease in FF, so a reduction in series resistance is necessary to obtain high FF under high-concentration ratio. A little decrease in V_{oc} under concentrated light over 100 suns is caused by increase in cell temperature during irradiation of the light.

5. High-efficiency and low-cost concentrator multijunction cell modules

R&D in Japan on III–V concentrator cells is now done mainly with 3-junction monolithic module. Besides the cells, extensive studies are done in (1) Non-imaging Fresnel concentrator, (2) Homogenizers, (3) New and simple module design [9].

A 400× and 7000 cm^2 concentrator module was fabricated with 36 pieces of the randomly selected receivers connected in series and the same number of the newly developed dome-shape Fresnel lens. The module wall and no heat sinks dissipated the heat or no external cooling utilities were used.

The efficiency in a hot summer day (35°C of ambient temperature) was 27.0% [10]. This value was well above on the record efficiency of 22.7% established by Fraunhofer Institute (Germany) in October 2002 with 1 order less area (768 cm^2). This achievement resulted from several new technologies:

1. High-pressure and vaccum-free lamination of the solar cell that suppress temperature rise only to 8° under 400× geometrical concentration illumination of sunbeam.

2. Direct and voids-free soldering technologies of fat metal ribbon to solar cells that suppress hot spots and resistance by 300 times higher output current than normal non-concentration operation.

3. A new encapsulating polumer that survives exposure of high concentration UV light and heat cycles.

4. Beam-shaping technologies that illuminates square aperture of the solar cells from round concentration spot.

5. Homogenizer technologies giving uniform flux and prevent from conversion loss stemmed from chromatic aberrations and surface voltage variation.

6. Allowing as large as 1.75 mm assemble tolerance. There is no need of special optical alignment. Even local mechanical industries can assemble the main body.

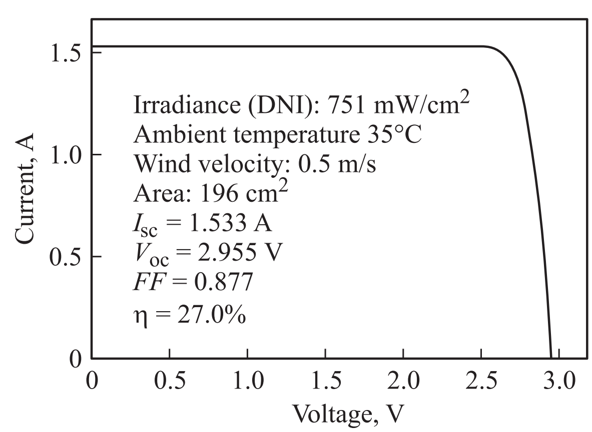

Figure 5. Outdoor evaluation of $I - V$ with a plastic Fresnel lens (including loss in concentrator optics and temperature rise).

Table 3. Roadmap table of more than 31% efficiency module

	Technologies				
	in Nov. 2002	**in Aug. 2003**	in Mar. 2004	in Mar. 2005	in Mar. 2006
Cell efficiency (1 sun) (%)	30.1	**30.3**	32	–	–
Concentrator cell efficiency (%)	34.4	**35.3**	37	–	40
Lens efficiency (%)	72.4	**85.4**	85.8	–	91
Homogenizer efficiency (%)	94.4	**96.3**	97.5	97.5	97.5
Ohmic loss in circuit (%)	0.1	**0.1**	0.1	0.1	0.1
Spectrum mismatching loss (%)	5.3	**5.1**	3	–	–
Current mismatching loss (%)	3.7	**3.7**	2	2	2
Loss by temperature rise (%)	1.2	**1.3**	1.3	–	1
Total efficiency (%)	21.7	**27.0**	29	> 29	> 31

7. Shaped Fresnel lens designed by non-imaging optics theory and made by low-cost injection mold that gives tight variation of optical efficiency as narrow as 0.5% (see also Fig. 5).

The technological roadmap toward 31% efficient module is shown in Table 3 [10]. Since we have identifield detailed technological problems and how to solve them, the target will be achieved well in advance.

6. Future prospects

Multijunction (MJ) solar cells will be widely used in space because of their high conversion efficiency and better radiation–resistance. In order to apply super high-efficiency cells widely, it is necessary to improve their conversion efficiency and reduce their cost. Concentrator 3-junction and 4-junction solar cells have great potential for realizing super high-efficiency of over 40% [11]. As a 3-junction combination, InGaP/InGaAs/Ge cell on a Ge substrate will be widely used because this system has been already developed. The 4-junction combination of an $E_g = 2.0$ eV top cell, a GaAs second-layer cell, a material third-layer cell with an E_g of 1.05 eV, and 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.

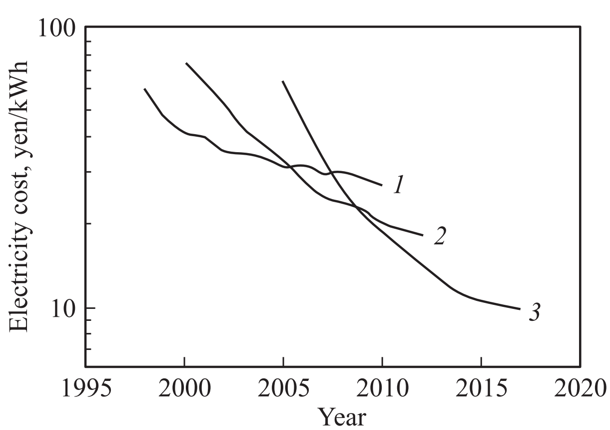

Figure 6. Scenario of electricity cost reduction by developing concentrator solar cells. The type of solar cell: *1* — Si-crystal, *2* — thin film, *3* — concentrator.

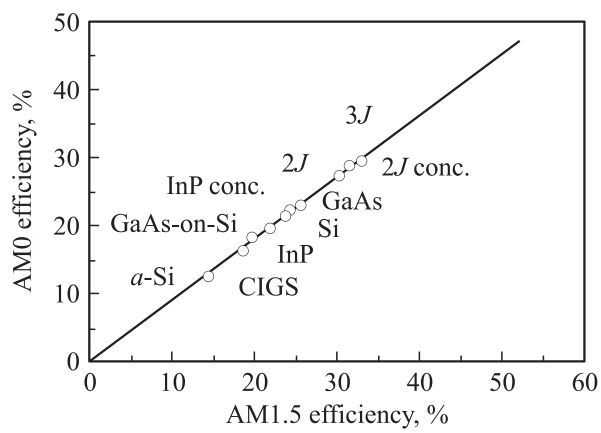

Figure 7. Correlation between AM0 and AM1.5 efficiencies for various solar cells.

We are now challenging to develop low–cost high output power concentrator MJ solar cell modules with an output power of 400 W/m^2 for terrestrial applications.

Concentrator operation of the MJ cells is essential for their terrestrial applications. Since the concentrator PV systems have potential of cost reduction, R&D on concentrator technologies including MJ cells is started in Japan. Therefore, concentrator MJ and Si-crystal solar cells are expected to contribute to electricity cost reduction for widespread PV applications as shown in Fig. 6 [12].

Fig. 7 shows correlation between AM0 and AM1.5 efficiencies for various solar cells. Therefore, high-efficiency MJ solar cells developed for terrestrial use can be applied into space solar cells. We are also now challenging to develop high-efficiency, light-weight and low-cost MJ solar cells for space applications.

7. Summary

Conversion efficiency of InGaP/InGaAs/Ge cells has been improved up to 31–32% (AM1.5) and 29–30% (AM0) as a results of technologies development such as double wide band-gap tunnel heterojunction, InGaP–Ge heterostructure bottom cell, and precise lattice-matching of InGaAs, middle cell to Ge substrate by adding indium into the conventional GaAs layer. For concentrator applications, grid structure has been designed in order to reduce the energy loss due to series resistance, and 36.5–37% (AM1.5G, 200 suns) efficiency has been demonstrated. In addition, we have realized high-efficiency concentrator InGaP/InGaAs/Ge 3-junction solar cell modules of an outdoor efficiency of 27% as a result of developing high-efficiency InGaP/InGaAs/Ge 3-junction cells, designing grid contact with low series resistance, developing non-imaging Fresnel lens and 2nd optics (homogenizers) with low optical loss, and designing modules with low series resistance and low thermal conductivity.

Future prospects are also presented. We have proposed concentrator III–V compound MJ solar cells as the 3rd generation solar cells in addition to 1st generation Si-crystal solar cells and 2nd generation thin-film solar cells. We are now challenging to develop low-cost and high output power concentrator MJ solar cell modules with and output power of 400 W/m^2 for terrestrial applications and high-efficiency, light-weight and low-cost MJ jolar cells for space applications.

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