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Japanese R&D Activities of High Efficiency III-V Compound Multi-Junction and Concentrator Solar Cells

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Abstract

This paper reviews Japanese R&D activities of III-V compound multi-junction (MJ) and concentrator solar cells. As a result of advanced technologies development for high efficiency cells and discovery of superior radiation-resistance of InGaP based materials, InGaP-based MJ solar cells have been commercialised for space use in Japan. A new world-record efficiency of 35.8% at 1 sun has been achieved with InGaP/GaAs/InGaAs 3-junction solar cell. MJ solar cells composing of multi-layers with different bandgap energies have the potential for achieving high conversion efficiencies of over 50% and are promising for space and terrestrial applications due to wide photo response. In order to solve the problems of difficulties in making high performance and stable tunnel junctions, a double hetero (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. An InGaP material instead of AlGaAs for the top cell was proposed by NREL. As a result of advanced technologies development for high efficiency cells and discovery of superior radiation-resistance of InGaP-based materials by the authors, InGaP-based MJ solar cells have been commercialised for space use even in Japan since 2002. Most recently, world-record efficiency (35.8%) at 1-sun AM1.5G has been realised with inverted epitaxial grown InGaP/GaAs/InGaAs 3-junction cells by Sharp. Since the concentrator modules have been demonstrated to produce roughly 1.7 to 2.6 times more energy per area per annum than the 14 % multicrystalline silicon modules in most cities in Japan, concentrator PV (Photovoltaics) as the 3rd PV technologies in addition to the 1st crystalline Si PV and the 2nd thin-film PV technologies are expected to contribute to electricity cost reduction for widespread PV applications.

Keywords: Solar cells; high efficiency; III-V compounds; multi-junction; concentrator

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1. Introduction

By earthquake and tsunami occurred on March 11th 2011, Fukushima nuclear power plant No.1 has generated severe accidents to emit high level radiations and to contaminate foods, water and others with radio isotopes as shown in Fig. 1.

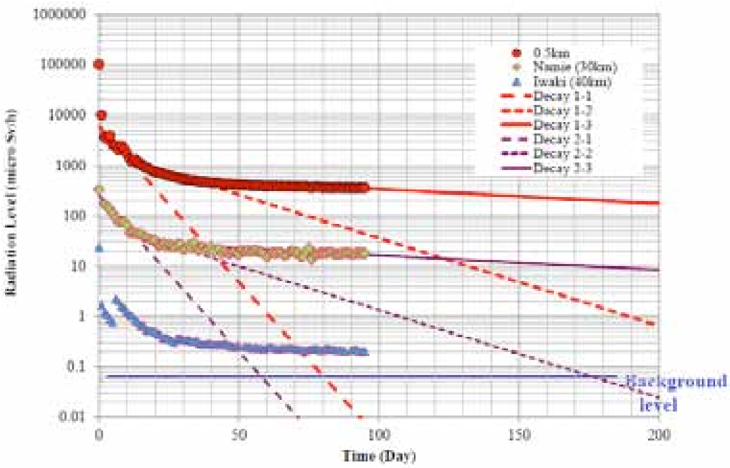

Fig. 1. Decay of radiation level in Japan due to accident of the Fukushima nuclear power plant No. 1

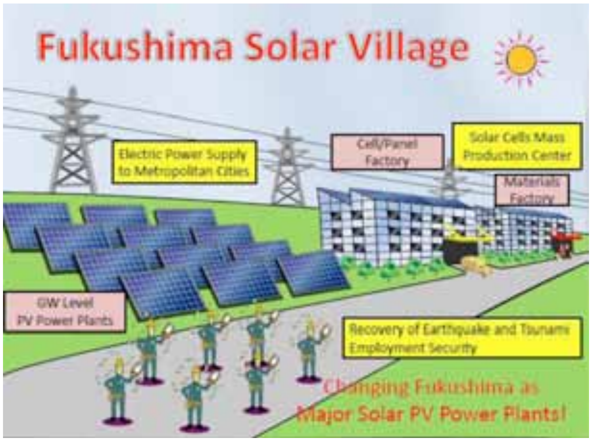

Fig. 2. Proposal of “Fukushima Solar Village” plan

Such an accident has given us very important messages such as serious concerns for safety and cost effectiveness of nuclear energy and importance of clean renewable energies including photovoltaics (PV) instead of nuclear energy. The accidents by the Fukushima nuclear power plants suggest difficulty of further installation of new nuclear power plants in Japan. An idea such as the “Fukushima Solar Village” plan has been proposed to attain employment security, to maintain power supply from those areas to metropolitan cities and to overcome several problems occurred by nuclear power plant accident as shown in Fig. 2.

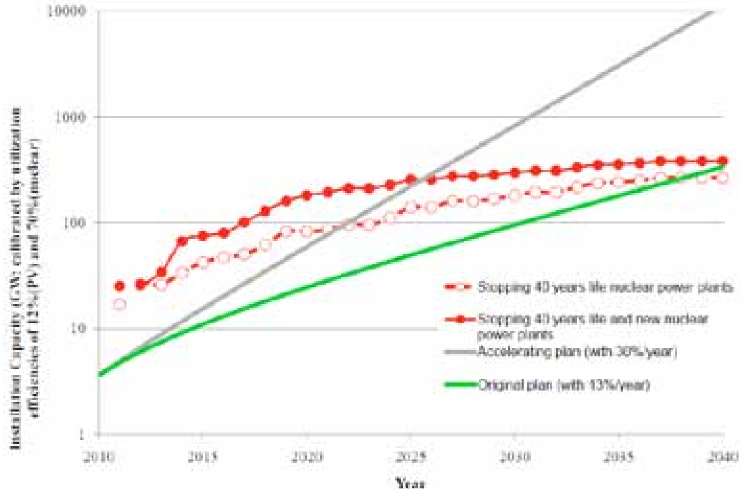

Fig. 3. Proposal of further installation of photovoltaic (PV) power generation systems instead of further installation of new nuclear power plants in Japan

As a result of discussion at the Committee for the 2030 PV Road Map in Japan organised by the New Energy and Industrial Technology Development Organization (NEDO) and METI (Ministry of Economy, Trade and Industry), we expect about 100 GW cumulative installed capacity [1], about 10% of Japanese electricity consumption by 2030. Accelerating plan such as further installation of photovoltaic power generation systems in Japan has also been proposed in order to overcome several problems resulting from Fukushima nuclear power plant accident.

Large-scale PV systems are necessary to develop in order to realise installation targets of PV systems shown in PV roadmaps. These suggest that concentrating PV systems can play a very important role for a growing PV market and large-scale productions of PV systems when cost effectiveness against flat plate arrays is demonstrated.

This paper reviews our R&D activities of III-V compound MJ, space and concentrator solar cells.

2. High-efficiency potential and R&D activities of III-V compound multi-junction solar cells

Multi-junction (MJ) solar cells composing of multi-layers with different bandgap energies have the potential for achieving high conversion efficiencies of over 50% and are promising for space and terrestrial applications due to wide photo response. Figure 4 shows theoretical conversion efficiencies of single-junction and MJ solar cells in comparison with experimentally realised efficiencies [2]. MJ solar cells were proposed in 1955 by Jackson and in 1960 by Wolf. MIT group encouraged R&D of tandem cells based on their computer analysis. Although AlGaAs/GaAs tandem cells, including tunnel junctions and metal interconnections, were developed in the early years, a high efficiency close to 20% was not obtained. This is because of difficulties in making high performance and stable tunnel junctions, and the defects related to the oxygen in the AlGaAs materials.

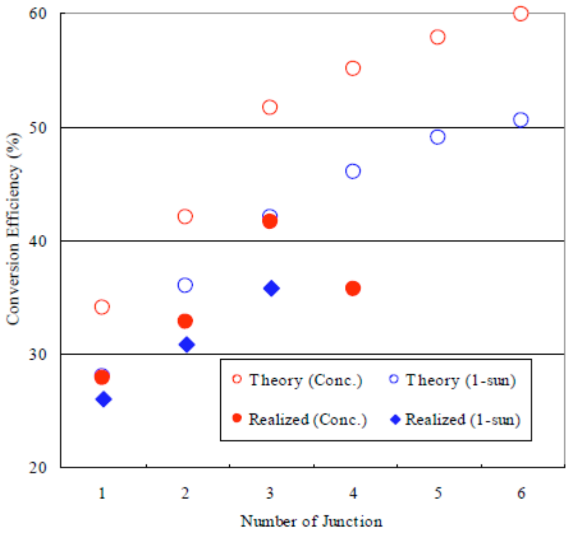

Fig. 4. Theoretical conversion efficiencies of single-junction and MJ solar cells in comparison with experimentally realised efficiencies [2].

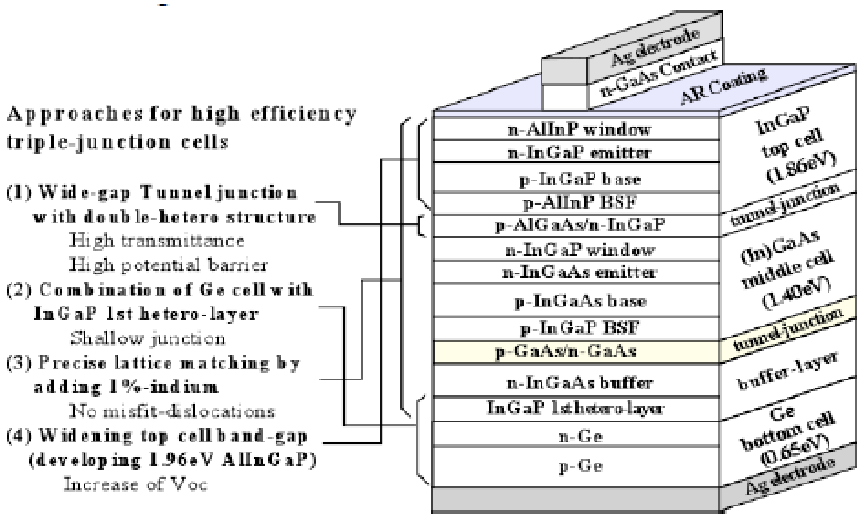

Fig. 5. Schematic illustration of a triple-junction cell and approaches for improving efficiency of the cell.

A schematic illustration of the InGaP/(In)GaAs/Ge triple junction solar cell and key technologies for improving conversion efficiency are shown in Fig. 5. A double hetero (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 [3] as shown in Fig. 6. The authors also demonstrated 20.2% efficiency AlGaAs/GaAs 2-junction cells [4]. An InGaP material for the top cell was proposed by NREL group [5].

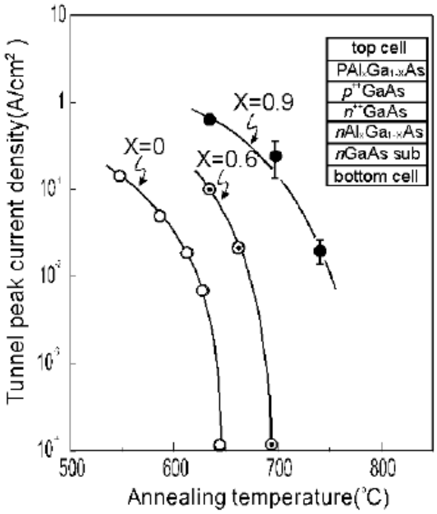

Fig. 6. Annealing temperature dependence of tunnel peak current densities for double hetero structure tunnel diodes. X is the Al mole fraction in $Al_xGa_{1-x}As$ barrier layers.

Conversion efficiency of InGaP-based 3-junction solar cells has been improved by the following technologies:

(i) Selection and high-quality growth of InGaP as a top cell material
(ii) Proposal of double-hetero structure and wide-band gap tunnel junction for cell interconnection
(iii) Precise lattice matching of InGaP top cell and InGaAs middle cell with Ge substrate
(iv) Proposal of AlInP as a back surface field layer for the InGaP top cell
(iv) Proposal of InGaP-Ge heteroface structure bottom cell

Table 1. Key issues for realising super high-efficiency multi-junction solar cells

Key Issue	Past	Present	Future
Top cell materials	AlGaAs	InGaP	AlInGaP
3rd layer materials	None	Ge	InGaAsN etc.
Substrate	GaAs	Ge	Si
Tunnel junction	DH-structure GaAs tunnel junction (TJ)	DH-structure InGaP TJ	DH-structure InGaP or GaAs TJ
Lattice matching	GaAs middle cell	InGaAs middle cell	(In)GaAs middle cell
Carrier confinement	InGaP-BSF	AlInP-BSF	Widegap-BSF Quantum dots (QDs)
Photon confinement	None	None	Bragg reflector, QDs, etc.
Others	None	Inverted Epi.	Inverted Epi. Epitaxial Lift off

As a result of the above proposals and performance improvements, we have demonstrated a world-record efficiency (33.3% at 1-sun AM1.5G) InGaP/GaAs/InGaAs 3-junction solar cell [6] in 1997. The key point is the transfer to Ge substrate for the 31.7% InGaP/(In)GaAs/Ge 3-junction solar cell [8]. Recently, 41.1% efficiency at 454 suns has been attained with GaInP/GaInAs/Ge 3-junction solar cell by Bett *et al.* [7] and 41.6 ± 2.5 % at 173 suns has been achieved with GaInP/GaInAs/Ge 3-junction solar cell by King *et al.* [8]. Table 1 summarises key issues of realising super-high-efficiency MJ solar cells.

3. Space application of MJ solar cells

InGaP/GaAs-based MJ solar cells have drawn increased attention for space applications because superior radiation-resistance of InGaP top cells and materials have been discovered by the authors [9] and those have the possibility of high conversion efficiency of over 30%. High efficiency of 29.2% at 1-sun AM0 and 31.7% at 1-sun AM1.5 has been achieved for InGaP/GaAs/Ge triple junction cell [10]. Superior radiation-resistance of InP-based material and solar cells has been discovered by the authors [9, 11]. Figure 7 shows the maximum power recovery due to forward bias injection of 100 mA/cm^2 at various temperatures for 1-MeV electron-irradiated InGaP single-junction 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. Even at room temperature, forward bias or photo injection-enhanced annealing of radiation damage to InGaP single-junction cells and InGaP/GaAs tandem cells has been observed [9]. Therefore, the results show that InGaP single-junction cells and InGaP-based tandem cells under device operation conditions have superior radiation-resistant properties.

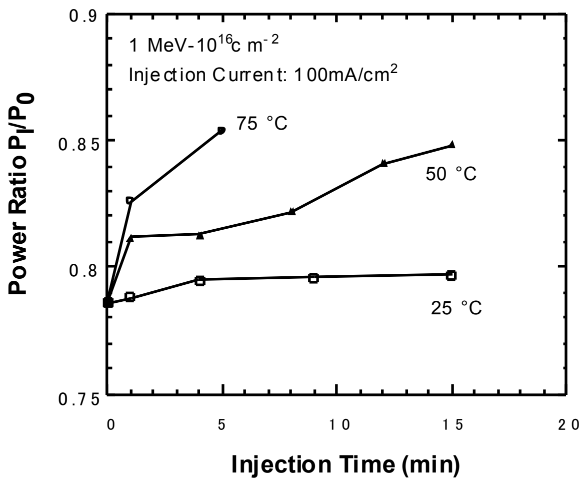

Fig. 7. The maximum power recovery of the InGaP single-junction cell due to forward bias injection (100 mA/cm^2) at various temperatures.

We have also confirmed superior radiation-resistance of InGaP-based multijunction cells by space flight demonstration of InGaP / GaAs 2-junction cells by using the Mission Demonstration test Satellite-1 launched in 2002 [12]. As a result of advanced technologies for high-efficiency cells and the discovery of the superior radiation resistance of InGaP-based materials, InGaP/GaAs/Ge 3-junction solar cells have been commercialised for space use in Japan since 2002 [10, 12].

4. Low-cost potential and R&D activities of concentrator MJ solar cells

Concentrator operation is very effective for cost reduction of solar cell modules and thus that of PV systems. Concentrator operation of the MJ cells is essential for their terrestrial applications. Since the concentrator PV systems using MJ solar cells have great potential of cost reduction as shown in Fig. 8 [2], R&D on concentrator technologies including MJ cells is started in Japan.

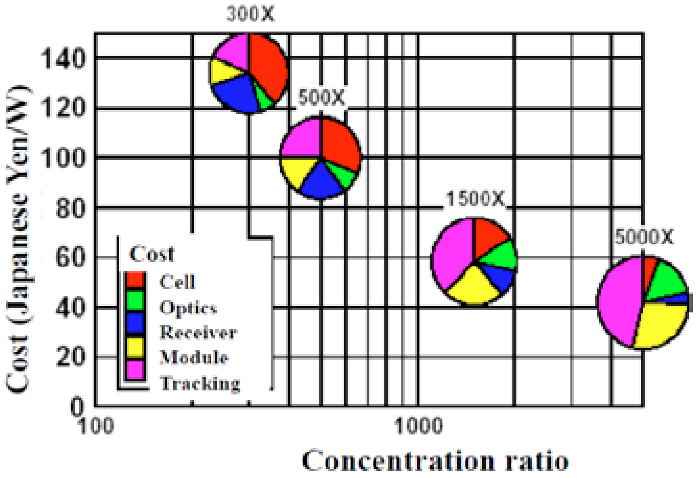

Fig. 8. Summary of estimated cost for the concentrator PV systems vs. concentration ratio [2].

As one of the Sunshine Program in Japan, an R&D project for super high-efficiency MJ solar cells was started based on our results in 1990. Conversion efficiency of InGaP/GaAs based multijunction solar cells has been improved by the following technologies: (i) Selection and high quality growth of InGaP as a top cell material, (ii) Proposal of double-hetero structure and wide-band gap tunnel junction for cell interconnection, (iii) Precise lattice matching of InGaP top cell and InGaAs middle cell with Ge substrate, (iv) Proposal of AlInP as a back surface field layer for the InGaP top cell, (v) Proposal of InGaP-Ge heteroface structure bottom cell. In 1997, we demonstrated a world-record efficiency (33.3% at 1-sun AM1.5G) InGaP/GaAs/InGaAs 3-junction cell. The conversion efficiency of InGaP/(In)GaAs/Ge triple-junction solar cells has been improved to 31.7% (AM1.5G) [10].

Since 2001, the R&D project for super high-efficiency concentrator MJ solar cells and modules was initiated in Japan. For concentrator applications, the grid structure has been designed in order to reduce the energy loss due to series resistance. We have successfully fabricated high efficiency concentrator InGaP/InGaAs/Ge 3-junction solar cells designed for 500-sun application. The efficiencies by in-house measurement are 39.2% at 200-suns and 38.9% at 489-suns [8]. The concentrator InGaP/InGaAs/Ge 3-junction solar cell modules were also developed using new technologies [13]. The peak uncorrected efficiency for the 7,056 cm^2 400 X and 5,445 cm^2 550 X module with 36 and 20 solar cells connected in series was 26.6% and 28.9%, respectively, measured in house. The concentrator modules have been demonstrated to produce roughly 1.7 times more energy per area per annum than the 14% multi-crystalline silicon module in most cities in Japan.

Innovative photovoltaics R&D program with which we intend to realise 40% efficiency and lower the electricity cost of less than 7 Japanese Yen/kWh has been initiated in Japan since FY2008. Concentrator III-V compound MJ solar cells are thought to be more realistic for attaining more than 40% efficiency and lower cost of less than 7JPY/kWh. We are now challenging higher efficiency of more than 45% with concentrator cells and 35% with concentrator modules until the end of FY 2014. 40.0% efficiency under 1,100-suns has been realised with InGaP/InGaAs/Ge 3-junction cells by Sasaki *et al.* [14]. Most recently, world-record efficiency has been demonstrated with InGaP/GaAs/InGaAs 3-junction solar cell with 35.8% and 42.1% at 1-sun and 230-suns, respectively by Sharp [15]. Figure 9 shows I-V curve of the world-record efficiency (35.8% at 1-sun AM1.5G) InGaP/GaAs/InGaAs 3-junction solar cell fabricated by inverted epitaxial growth. From 20.2% with AlGaAs/GaAs 2-junction cell in 1987 by NTT and 33.3% with InGaP/GaAs/InGaAs 3-junction cell in 1997 by Japan Energy, Sumitomo Electric and Toyota Tech. Inst., new world-record efficiency of 35.8% has been achieved with InGaP/GaAs/InGaAs 3-junction solar cell.

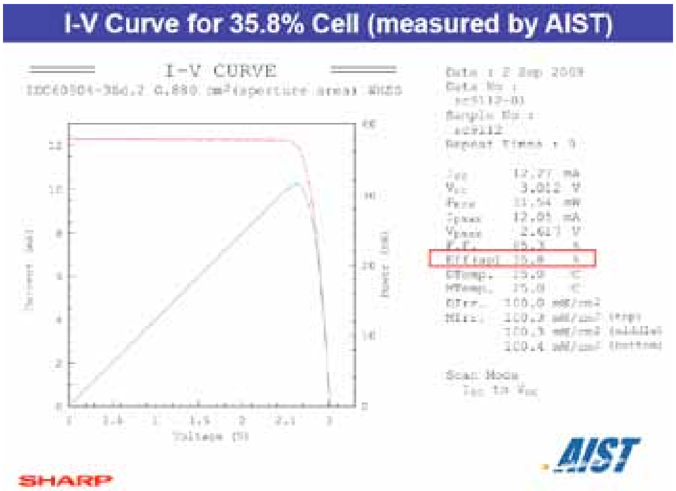

Fig. 9. I-V curve of the world-record efficiency (35.8% at 1-sun AM1.5G) InGaP/GaAs/InGaAs 3-junction solar cell.

5. Future Prospects

The new Concentrator PV system with two times more annual power generation than the conventional crystalline silicon flat-plate system will open a new market for apartment or building rooftop applications. Another interesting application is what we call the tree planting PV and large-scale PV power plant applications. Now, we are approaching 42.1% efficiency by developing concentrator MJ solar cells. Concentrator 4-junction or 5-junction solar cells have great potential for realising super high-efficiency of over 50%. Since concentrator MJ and crystalline Si solar cells are expected to contribute to electricity cost reduction for widespread PV applications, we would like to contribute to commercialisation of concentrator PV technologies as the 3rd PV technologies in addition to the first crystalline Si PV and the 2nd thin-film PV technologies. Concentrator PV is expected to contribute to one-thirds (40 GW) of solar cell module production in 2030 as reported by the European Commission's PV experts in the Strategic Research Agenda for Photovoltaic Solar Energy Technology [16].

Figure 10 shows scenario of electricity cost reduction by developing concentrator solar cells. The electricity cost target of PV (1/3 and 1/6 compared to present PV cost of about 40 Japanese Yen/kWh by 2020 and 2030, respectively) that Mr. Kan, Japanese Prime Minister, has made announced is equivalent to our target of PV electricity cost (less than 7 Japanese Yen/kWh by 2030) as shown in Fig. 10.

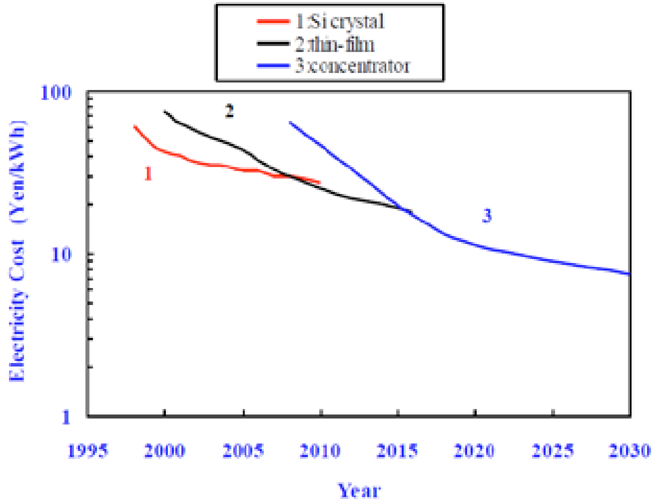

Fig. 10. Scenario of electricity cost reduction by developing concentrator solar cells

6. Conclusion

As a result of advanced technologies development for high efficiency cells and discovery of superior radiation-resistance of InGaP based materials, InGaP-based MJ solar cells have been commercialised for space use in Japan. 42.1% efficiency at 230-suns AM1.5G has been realised with InGaP-based 3-junction solar cells. Most recently, a new world-record efficiency of 35.8% at 1 sun has been achieved with InGaP/GaAs/InGaAs 3-junction solar cell. A new 400X and 550X (geometrical concentration ratio) are developed and show the highest efficiency in any types of PV as well as more than 20 years of accelerated lifetime. The new concentrator system is expected to open a door to a new age of high efficiency PV.

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