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Chapter

High-Efficiency GaAs-Based Solar Cells

Masafumi Yamaguchi

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Abstract

The III-V compound solar cells represented by GaAs solar cells have contributed as space and concentrator solar cells and are important as sub-cells for multi-junction solar cells. This chapter reviews progress in III-V compound single-junction solar cells such as GaAs, InP, AlGaAs and InGaP cells. Especially, GaAs solar cells have shown 29.1% under 1-sun, highest ever reported for single-junction solar cells. In addition, analytical results for non-radiative recombination and resistance losses in III-V compound solar cells are shown by considering fundamentals for major losses in III-V compound materials and solar cells. Because the limiting efficiency of single-junction solar cells is 30-32%, multi-junction junction solar cells have been developed and InGaP/GaAs based 3-junction solar cells are widely used in space. Recently, highest efficiencies of 39.1% under 1-sun and 47.2% under concentration have been demonstrated with 6-junction solar cells. This chapter also reviews progress in III-V compound multi-junction solar cells and key issues for realizing high-efficiency multi-junction cells.

Keywords: solar cells, GaAs, InP, InGaP, III-V compounds, multi-junction, tandem, high efficiency, radiation-resistance

1. Introduction

The III-V compound solar cells represented by GaAs solar cells have advantages such as high-efficiency potential, possibility of thin-films, good temperature coefficient, radiation-resistance and potential of multi-junction application compared crystalline Si solar cells. The III-V compound solar cells have contributed as space and concentrator solar cells and are important as sub-cells for multi-junction solar cells. As a result of research and development, high-efficiencies [1, 2] have been demonstrated with III-V compound single-junction solar cells: 29.1% for GaAs, 24.2% for InP, 16.6% for AlGaAs, and 22% for InGaP solar cells. **Figure 1** shows historical record-efficiency of GaAs, InP, AlGaAs and InGaP single-junction solar cells along with their extrapolations [3].

The data can be fitted with the Goetzberger function [4]:

$$\eta(t) = \eta_{limit}[1 - \exp.(t_0 - t)/c], \tag{1}$$

where $\eta(t)$ is the time-dependent efficiency, η_{limit} is the practical limiting efficiency, t_0 is the year for which $\eta(t)$ is zero, t is the calendar year, and c is a characteristic development time. Fitting of the curve was done with three parameters which are given in **Table 1**. The extrapolations show that the progress of

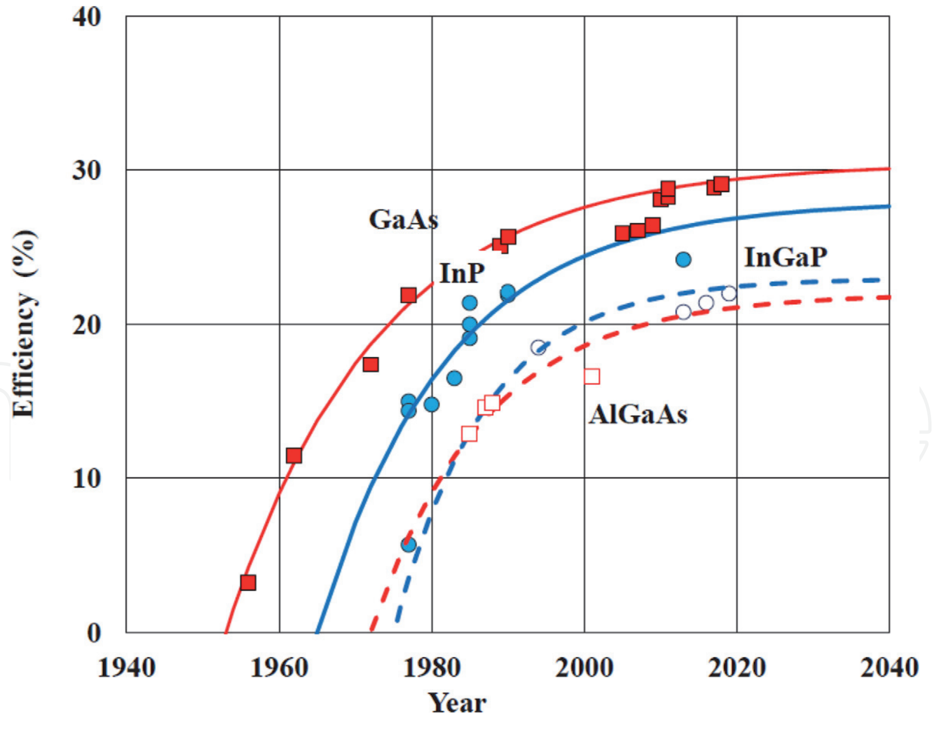

Figure 1.
World record efficiencies of GaAs, InP, AlGaAs and InGaP single-junction solar cells over years. Solid and dashed lines are the fitted trajectories using Eq. (1).

Solar cells	η_{limit}	c	t_0
GaAs	30.5	20	1953
InP	28	17	1965
AlGaAs	22	15	1972
InGaP	23	12	1975

Table 1.
Fitting parameters for various solar cells.

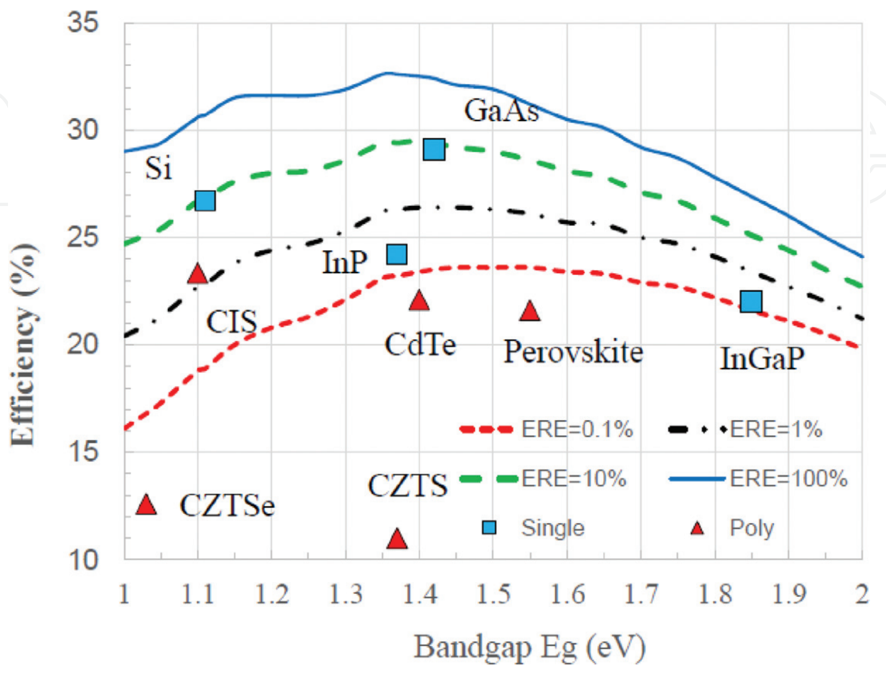

Figure 2.
Calculated and obtained efficiencies of single-junction single-crystalline and polycrystalline solar cells.

efficiencies is converging or will converge soon, which is mainly bounded by the Shockley-Queisser limit [5].

Figure 2 shows calculated and obtained efficiencies of single-junction single-crystalline and polycrystalline solar cells [6]. Because the limiting efficiency of single-junction solar cells is 30-32% as shown in **Figure 2**, multi-junction solar cells have been developed and InGaP/GaAs based 3-junction solar cells are widely used in space. Recently, highest efficiencies of 39.2% under 1-sun and 47.1% under concentration have been demonstrated with 6-junction solar cells [7].

This Chapter reviews progress in III-V compound single-junction solar cells such as GaAs, InP, AlGaAs and InGaP cells. In addition, analytical results for non-radiative recombination and resistance losses in III-V compound solar cells by considering fundamentals for major losses in III-V compound materials and solar cells. This chapter also reviews progress in III-V compound multi-junction solar cells and key issues for realizing high-efficiency multi-junction cells.

2. Analysis of non-radiative recombination and resistance losses of single-junction solar cells

By using our analytical model [8, 9], potential efficiencies of various solar cells are discussed. This model considers the efficiency loss such as non-radiative recombination and resistance losses, which are reasonable assumption because conventional solar cells often have a minimal optical loss. The non-radiative recombination loss is characterized by external radiative efficiency (ERE), which is the ratio of radiatively recombined carriers against all recombined carriers. In other words, we have ERE = 1 at Shockley-Queisser limit [5]. EREs of state-of-the-art solar cells can be found in some publications such as references [2, 10–13]. In this chapter, the EREs of various solar cells are estimated by the following relation [14]:

$$V_{oc} = V_{oc:rad} + (kT/q)\ln(ERE), \tag{2}$$

where V_{oc} the measured open-circuit voltage, k the Boltzmann constant, T the temperature, and q the elementary charge. $V_{oc:rad}$ the radiative open-circuit voltage and is expressed by the following Eq. [15]

$$V_{oc,rad} = (kT/q)\ln\left[J_{ph}\right]V_{oc,rad})/J_{o,rad} + 1], \tag{3}$$

where $[J_{ph}]V_{oc,rad}$ is the photocurrent at open-circuit in the case when there is only radiative recombination and $J_{o,rad}$ the saturation current density in the case of radiative recombination.

0.28 V for E_g/q - $V_{oc;rad}$ value reported in [15–17] were used in our analysis. Where E_g is the bandgap energy. The second term on the right-hand side of Eq. (2) is denoted as $V_{oc;nrad}$, the voltage-loss due to non-radiative recombination and is expressed by the following Eq. [15].

$$\Delta V_{oc;\,nrad} = V_{oc:rad} - V_{oc} = (kT/q)\ln\ [J_{rad}(V_{0c})/J_{rec}(V_{oc})] = -(kT/q)\ln(ERE), \tag{4}$$

where $J_{rad}(V_{0c})$ is the radiative recombination current density and $J_{rec}(V_{oc})$ is the non-radiative recombination current density.

Figure 3 shows open-circuit voltage drop compared to band gap energy (E_g/q – V_{oc}) and non-radiative voltage loss ($V_{oc,nrad}$) in GaAs, InP, AlGaAs and

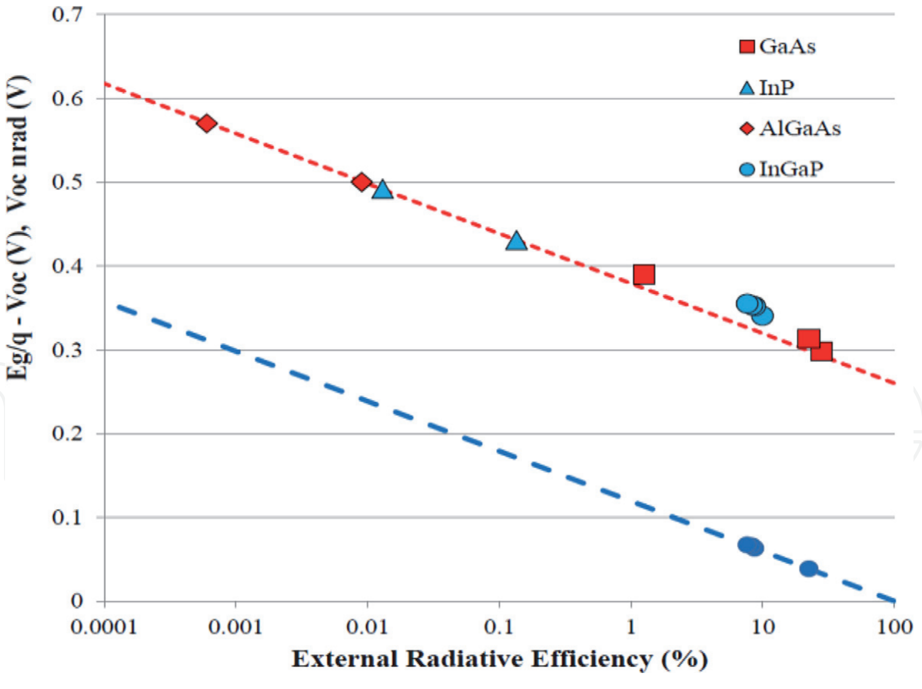

Figure 3.
Open-circuit voltage drop compared to band gap energy ($E_g/q - V_{oc}$) and non-radiative voltage loss ($V_{oc,nrad}$) in GaAs, InP, AlGaAs and InGaP solar cells as a function of ERE.

InGaP solar cells [2, 8–13, 17] as a function of ERE. High ERE values of 22.5% and 8.7% have been observed for GaAs and InGaP, respectively compared to InP (0.1%) and AlGaAs (0.01%).

The resistance loss of a solar cell is estimated solely from the measured fill factor. The ideal fill factor FF_0, defined as the fill factor without any resistance loss, is estimated by [18].

$$FF_0 = (v_{oc} - \ln(v_{oc} + 0:71))/(v_{oc} + 1), \qquad (5)$$

where v_{oc} is

$$v_{oc} = V_{oc}/(nkT/q). \qquad (6)$$

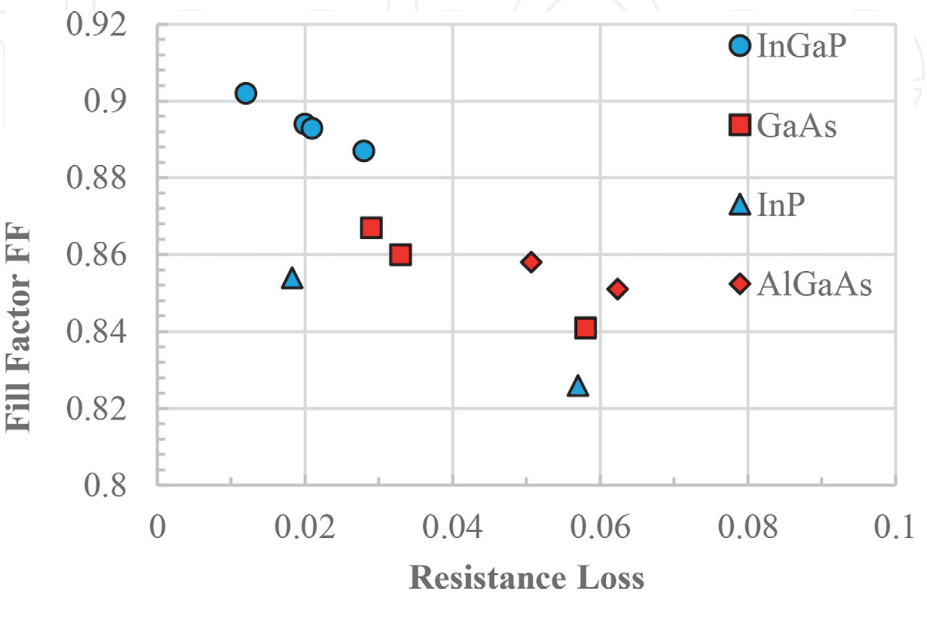

Figure 4.
Correlation between fill factor and resistance loss in GaAs, InP, AlGaAs and InGaP solar cells.

The measured fill factors can then be related to the series resistance and shunt resistance by the following Eq. [18]:

$$FF \approx FF_0(1 - r_s)\left(1 - {r_{sh}}^{-1}\right) \approx FF_0\left(1 - r_s – {r_{sh}}^{-1}\right) = FF_0(1 - r), \quad (7)$$

where r_s is the series resistance, and r_{sh} is the shunt resistance normalized to R_{CH}. The characteristic resistance R_{CH} is defined by [18]

$$R_{CH} = V_{oc}/J_{sc}, \quad (8)$$

r is the total normalized resistance defined by $r = r_s + {r_{sh}}^{-1}$.

Figure 4 shows correlation between fill factor and resistance loss [2, 8–13, 17] in GaAs, InP, AlGaAs and InGaP solar cells. Lower resistance losses of 0.01-0.03 have been realized for GaAs, InP and InGaP solar cells compared to 0.05 for AlGaAs.

3. Historical progress and key issues for high-efficiency III-V compound single-junction solar cells

Table 2 shows major losses, their origins and key technologies for improving efficiency [6]. There are several loss mechanisms to be solved for realizing high-efficiency III-V compound single-junction solar cells. (1) bulk recombination loss, (2) surface recombination loss, (3) interface recombination loss, (4) voltage loss, (5) fill factor loss, (6) optical loss, (7) insufficient –energy photon loss. Key

Losses	Origins	Technologies for improving
Bulk recombination loss	Non radiative recombination centers (impurities, dislocations, grain boundary, other defects)	High quality epitaxial growth Reduction in density of defects
Surface recombination loss	Surface sates	Surface passivation Heteroface layer Double hetero structure
Interface Recombination loss	Interface states Lattice mismatching defects	Lattice matching Inverted epitaxial growth Window layer Back surface field layer Double hetero structure Graded band-gap layer
Voltage loss	Non radiative recombination Shunt resistance	Reduction in density of defects Thin layer
Fill factor loss	Series resistance Shunt resistance	Reduction in contact resistance Reduction in leakage current, Surface, interface passivation
Optical loss	Reflection loss Insufficient absorption	Anti-reflection coating, texture Back reflector, photon recycling
Insufficient-energy photon loss	Spectral mismatching	Multi-junction (Tandem) Down conversion Up conversion

Table 2.
Major losses, their origins of III-V compound cells and key technologies for improving efficiency.

technologies for reducing the above losses are high quality epitaxial growth, reduction in density of defects, optimization of carrier concentration in base and emitter layers, double-hetero (DH) structure junction, lattice-matching of active layers and substrate, surface and interface passivation, reduction in series resistance and leakage current, anti-reflection coating, photon recycling and so forth.

Solar cell efficiency is dependent upon minority-carrier diffusion length (or minority-carrier lifetime) in the solar cell materials as shown in **Figure 5**.

Radiative recombination lifetime τ_{rad} is expressed by

$$\tau_{rad} = 1/BN \tag{9}$$

where N is the carrier concentration and B is the radiative recombination probability. The B value for GaAs reported by Ahrenkiel et al. [19] is B = 2 X 10^{-10} cm^3/s. Effective lifetime τ_{eff} is expressed by

$$1/\tau_{eff} = 1/\tau_{rad} + 1/\tau_{nonad} \tag{10}$$

where τ_{nonrad} is non-radiative recombination lifetime and given by

$$1/\tau_{nonrad} = \sigma v N_r \tag{11}$$

where σ is capture cross section of minority-carriers by non-radiative recombination centers, v is minority-carrier thermal velocity, and Nr is density of non-radiative recombination center.

Therefore, improvement in crystalline quality and reduction in densities of defects such as dislocations, grain boundaries and impurities that act as non-radiative recombination centers are very important for realizing high-efficiency solar cells.

In this chapter, analytical results for historical progress in efficiency of GaAs single-junction solar cells are shown. **Figures 6** and **7** show analytical results for progress in ERE and resistance loss of GaAs single-junction solar cells.

The first GaAs solar cells reported by Jenny et al. [20] were fabricated by Cd diffusion into an n-type GaAs single crystal wafer. Efficiencies of 3.2-5.3% were quite low due to deep junction. Because GaAs has large surface recombination velocity S of

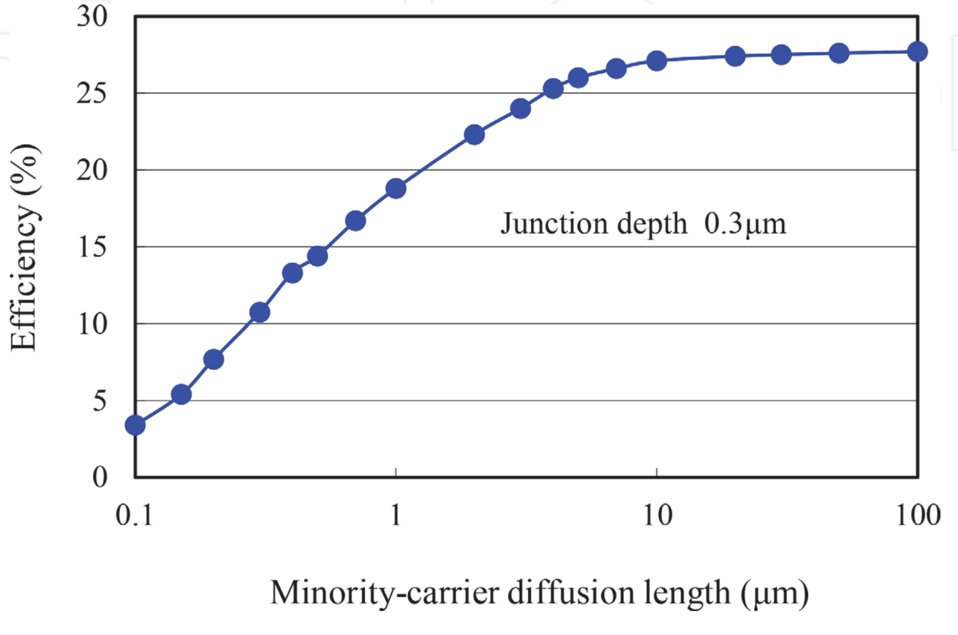

Figure 5.
Minority-carrier diffusion length dependence of GaAs solar cell characteristics.

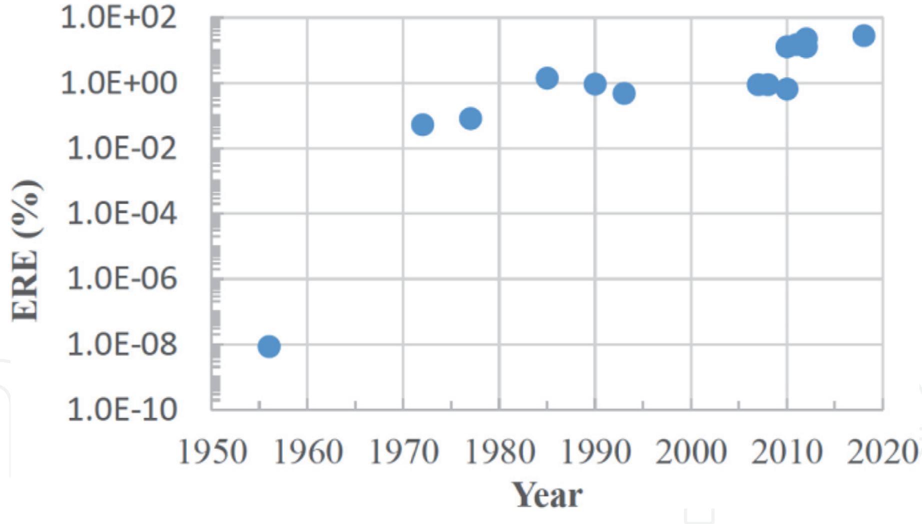

Figure 6.
Analytical results for ERE progress of GaAs single-junction solar cells.

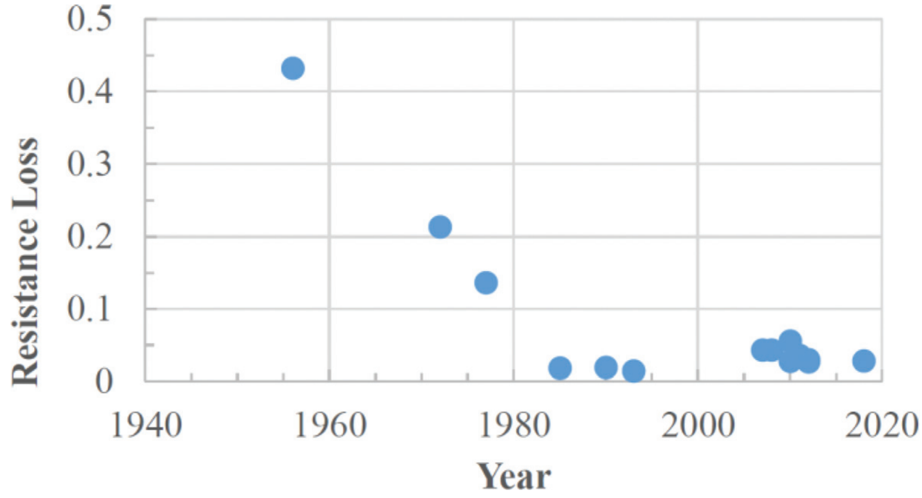

Figure 7.
Analytical results for resistance loss progress of GaAs single-junction solar cells.

around 1 × 10^7 cm/s [6, 21], formation of shallow homo-junction with junction depth of less than 50 nm is necessary to obtain high-efficiency. Therefore, hetero-face structure AlGaAs-GaAs solar cells have been proposed by Woodall and Hovel [22] and more than 20% efficiency has been realized [22] in 1972 as shown in **Figure 1** as a result of ERE improvement from 10^{-8}% to 0.05% as shown in **Figure 6**. Double-hetero (DH) structure AlGaAs-GaAs-AlGaAs solar cell with an efficiency of 23% has been realized by Fan's group in 1985 [23] as a result of ERE improvement from 0.05% to 1.4% as shown in **Figure 6**. Now, DH structure solar cells are widely used for high-efficiency III-V compound solar cells including GaAs solar cells.

Figure 8 shows device structures of GaAs solar cells developed historically. As mentioned above and shown in **Figure 8**, device structures of GaAs cells were improved from homo-junction, to heteroface structure, finally to DH structure. Now, InGaP layer is mainly used as front window and rear back surface field (BSF) layers instead of AlGaAs layer. The reasons are explained in the part of multi-junction solar cells.

Figure 9 shows the chronological improvements in the efficiencies of GaAs solar cells fabricated by LPE (Liquid Phase Epitaxy), MOCVD (Metal-Organic Chemical Vapor Deposition) and MBE (Molecular Beam Epitaxy). LPE was used to fabricate AlGaAs-GaAs heteroface solar cells in 1972 because it produces high-quality

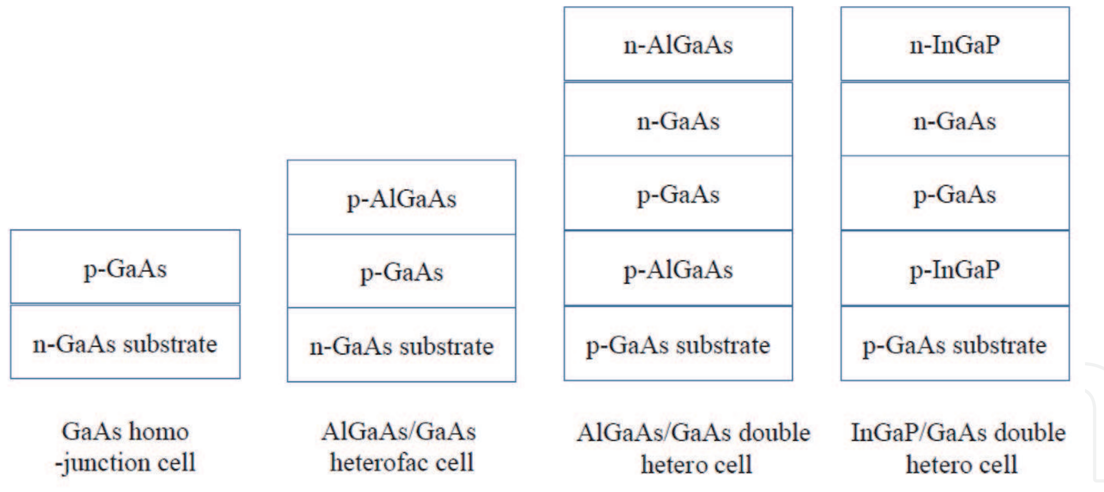

Figure 8.
Device structures of GaAs solar cells developed historically.

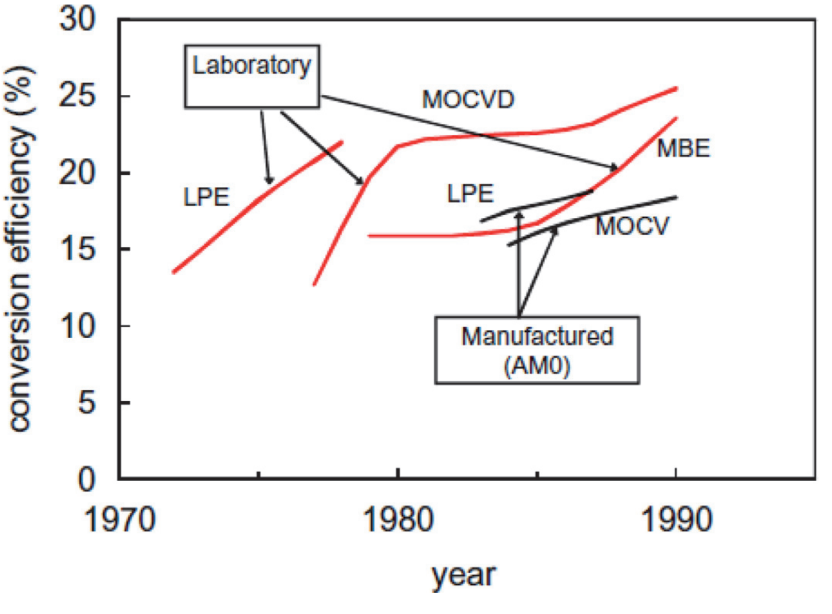

Figure 9.
Chronological improvements in the efficiencies of GaAs solar cells fabricated by the LPE, MOCVD and MBE methods.

epitaxial film and has a simple growth system. Homo-junction structure and heteroface structure GaAs solar cells shown in **Figure 8** were fabricated by LPE. However, it is not as useful for devices that involve multilayers because of the difficulty of controlling layer thickness, doping, composition and speed of throughput. Since 1977, MOCVD has been used to fabricate large-area GaAs solar cells by using DH structure shown in **Figure 8** because it is capable of large-scale, large-area production and has good reproducibility and controllability.

Regarding the differences of surface recombination velocities in semiconductor materials, differences of point defect behavior are thought to be one of the mechanisms. For example, because nearest-neighbor hopping migration energies (0.3 eV and 1.2 eV) of V_{In} and V_P in InP [24] are lower than those (1.75 eV) of V_{Ga} and V_{As} in GaAs, better surface state may be formed on InP surface compared to GaAs surface.

In addition to improvement in surface recombination loss, as a result of technological development, resistance loss has been improved as shown in **Figure 7**. In parallel, bulk recombination loss and interface recombination loss have been

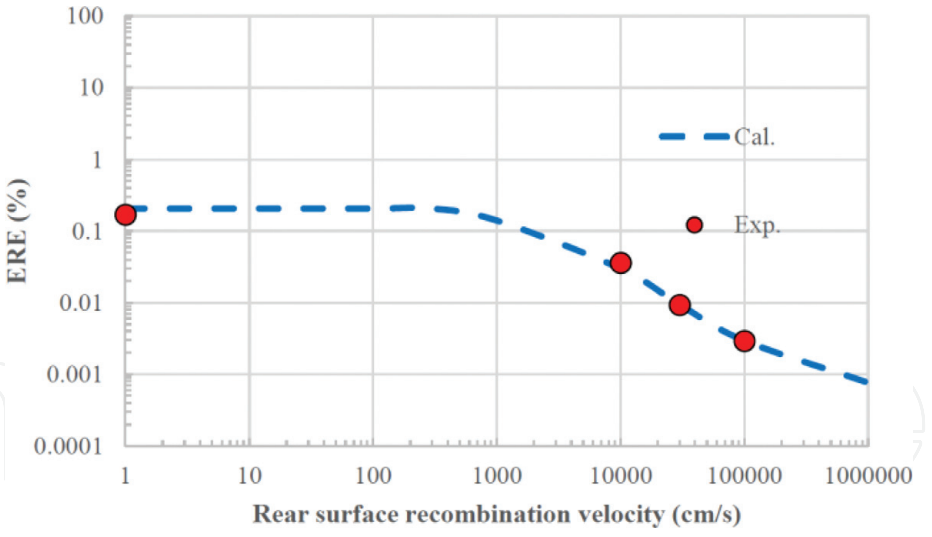

Figure 10.
Correlation between ERE and interface recombination velocity in InGaP single-junction solar cells.

improved as shown in **Figure 6**. Recently, efficiency of GaAs solar cells reached to 29.1% [2] by realizing ERE of 22.5% as a result of effective photon recycling [1].

Lattice mismatching also degrades solar cell properties by increase in interface recombination velocity as a result of misfit dislocations and threading dislocations generation. By using interface recombination velocity S_I as a function of lattice mismatch ($\Delta a/a_0$) for InGaP/GaAs heteroepitaxial interface [25], lattice mismatch ($\Delta a/a_0$) dependence of interface recombination velocity (S_I) is semi-empirically expressed by [16].

$$S_I\ [\mathrm{cm/s}] = 1.5 \times 10^8 \Delta a/a_0 \tag{12}$$

As one of example for effects of interface recombination loss upon solar cell properties, analytical results for correlation between ERE and interface recombination velocity in InGaP single-junction solar cells are shown in **Figure 10**.

4. Historical progress and key issues for high-efficiency III-V compound multi-junction solar cells

While single-junction cells may be capable of attaining AM1.5 efficiencies of up to 30-32% as shown in **Figure 2**, the multi-junction (MJ) structures [26, 27] were recognized early on as being capable of realizing efficiencies of up to 46% as shown below. **Figure 11** shows the principle of wide photo response using MJ solar cells for the case of a triple-junction cell. Solar cells with different bandgaps are stacked one on top of the other so that the cell facing the Sun has the largest bandgap (in this example, this is the InGaP top cell). This top cell absorbs all the photons at and above its bandgap energy and transmits the less energetic photons to the cells below. The next cell in the stack (here the GaAs middle cell) absorbs all the transmitted photons with energies equal to or greater than its bandgap energy, and transmits the rest downward in the stack (in this example, to the Ge bottom cell). As shown in **Figure 12**, the spectral response for an InGaP/GaAs/Ge monolithic, two-terminal triple-junction cell shows the wideband photo response of multijunction cells. In principle, any number of cells can be used in tandem.

As a result of research and development, high-efficiencies have been demonstrated with III-V multi-junction solar cells: 37.9% under 1-sun and 44.4% under

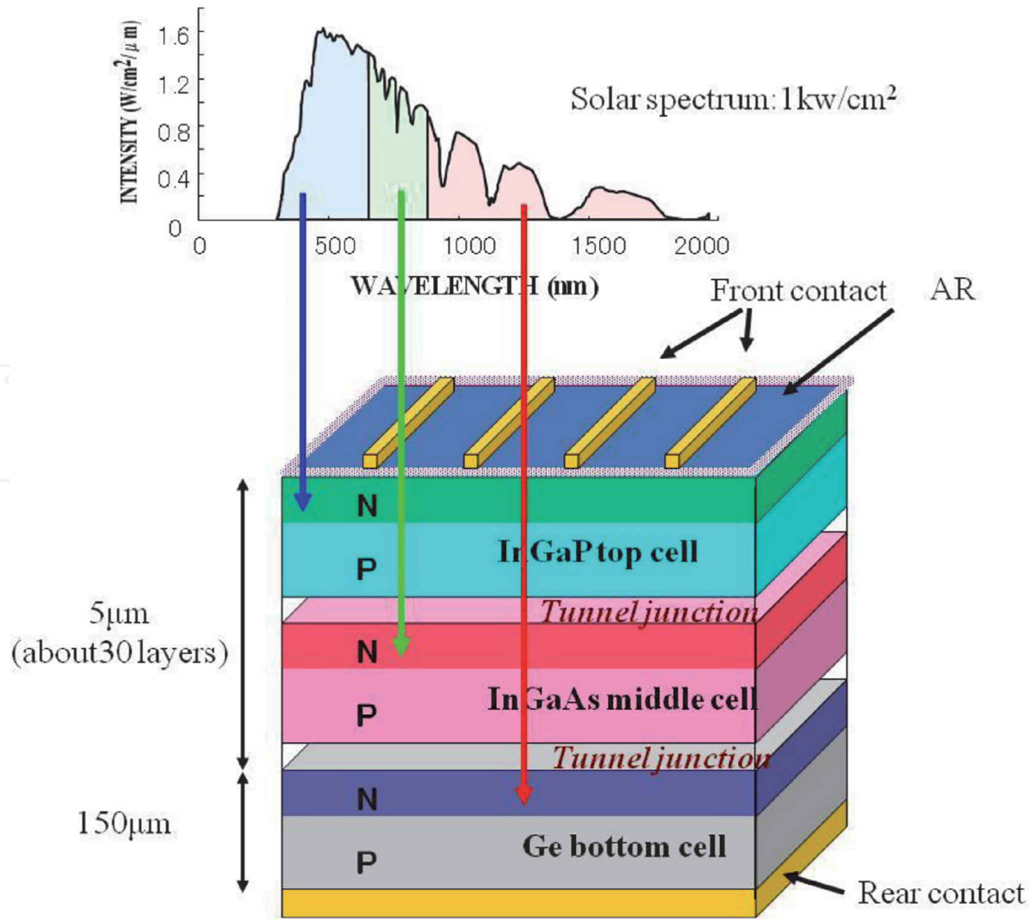

Figure 11.
Principle of wide photo response by using a multijunction solar cell, for the case of an InGaP/GaAs/Ge triple-junction solar cell.

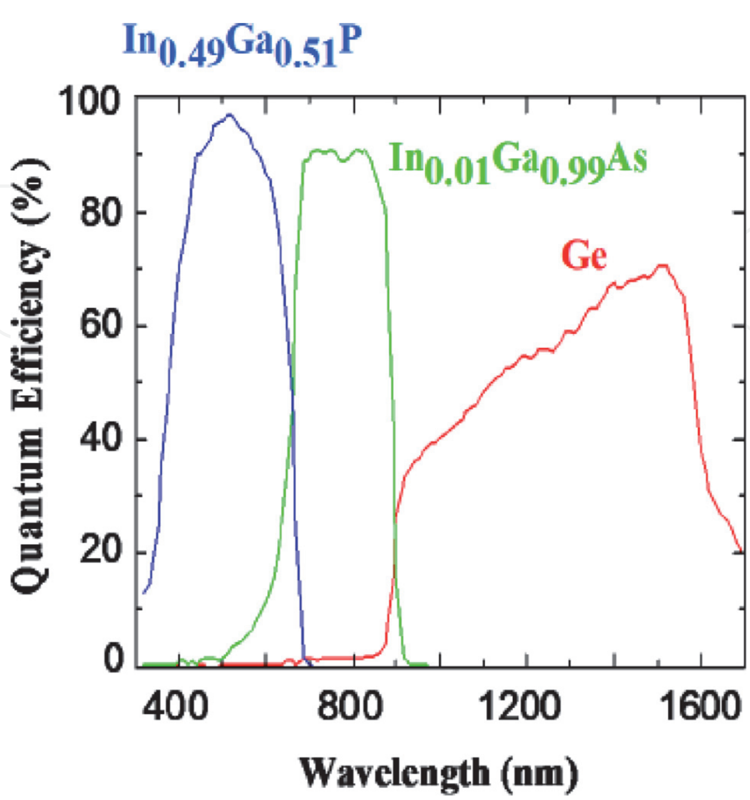

Figure 12.
Spectral response for an InGaP/GaAs/Ge monolithic, two-terminal three-junction cell.

concentration for 3-junction cells [28] and 39.2% under 1-sun, 47.1% under concentration for 6-junction solar cells [7]. **Figure 13** shows historical record-efficiency of III-V multi-junction (MJ) and concentrator MJ solar cells in comparison with 1-sun efficiencies of GaAs and crystalline Si solar cells, along with their extrapolations [3].

Table 3 shows key issues for realizing super high-efficiency MJ solar cells. The key issues for realizing super-high-efficiency MJ solar cells are (1) sub cell material selection, (2) tunnel junction for sub cell interconnection, (3) lattice-matching, (4) carrier confinement, (5) photon confinement, (6) anti-reflection in wide wavelength region and so forth. For concentrator applications by using MJ cells, the cell front contact grid structure should be designed in order to reduce the energy loss due to series resistance (resistances of front grid electrode including contact resistance, rear electrode, lateral resistance between grid electrodes) by considering shadowing loss attributed to grid electrode, and tunnel junction with high tunnel peak current density is necessary. Because cell interconnection of sub-cells is one of the most important key issues for realizing high-efficiency MJ solar cells in order to reduce losses of electrical connection and optical absorption, effectiveness of double hetero structure tunnel diode is also presented in this chapter.

Selection of sub-cell layers by considering optimal bandgap and lattice matching of materials is one of key issues for realizing super high-efficiency MJ cells. **Table 4** shows one example for selection of top cell material and comparison of InGaP and AlGaAs as a top cell material. InGaP that has better interface recombination velocity, less oxygen-related defect problems and better window material AlInP compared to those of AlGaAs has been proposed as a top cell material by NREL group [29]. As described above, InGaP materials are now widely used as front widow and back surface filed layers of solar cells instead of AlGaAs.

Figure 14 shows the connection options for two-junction cells: the two cells can be connected to form either two-terminal, three-terminal or four-terminal devices. In a monolithic, two-terminal device, the cells are connected in series with an optically transparent tunnel junction intercell electrical connection. In a two-terminal structure, only one external circuit load is needed, but the photocurrents in

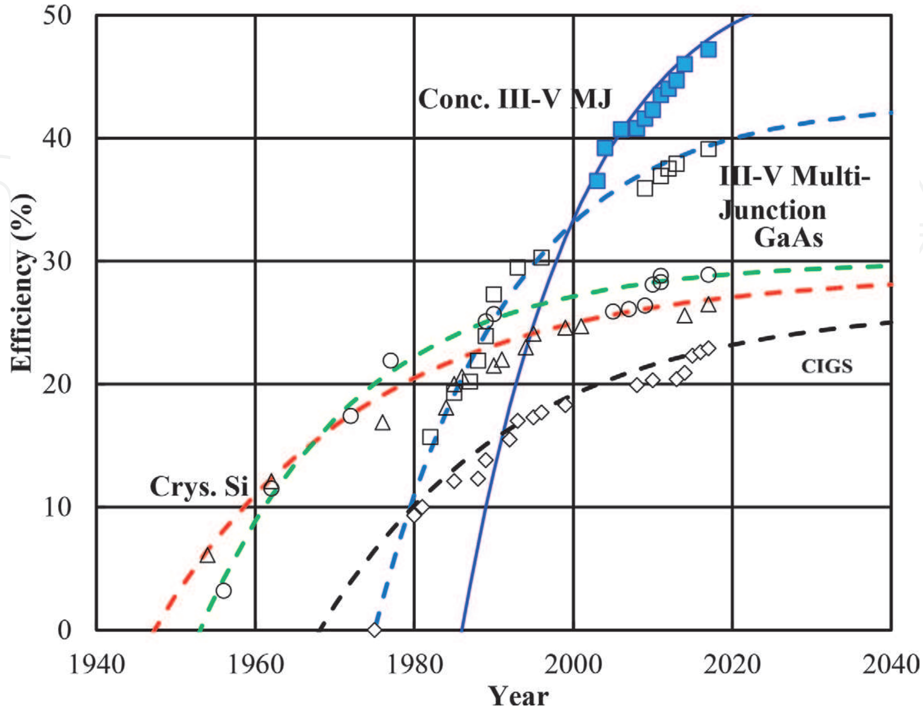

Figure 13.
Historical record-efficiency of III-V multi-junction (MJ) and concentrator MJ solar cells in comparison with 1-sun efficiencies of GaAs and crystalline Si solar cells, along with their extrapolations.

Key issue	Past	Present	Future
Top cell materials	AlGaAs	InGaP	AlInGaP
Middle cell materials	None	GaAs, InGaAs	GaAs, quantum well, quantum dots, InGaAs, InGaAsN etc.
Bottom cell materials	GaAs	Ge, InGaAs	Si, Ge, InGaAs
Substrate	GaAs	Ge	Si, Ge, GaAs, metal
Tunnel junction (TJ)	Double hetero structure-GaAs TJ	Double hetero structure-InGaP TJ	Double hetero structure-InGaP or GaAs TJ
Lattice matching	GaAs middle cell	InGaAs middle cell	(In)GaAs middle cell
Carrier confinement	InGaP-BSF	AlInP-BSF	Wide-gap-BSF Quantum dots
Photon confinement	None	None	Back reflector, Bragg reflector, quantum dots, photonic crystals, etc.
Others	None	Inverted epitaxial growth	Inverted epitaxial growth, epitaxial lift off

Table 3.
Key issues for realizing super-high-efficiency III-V compound multi-junction solar cells.

	InGaP	AlGaAs
Interface recombination velocity	$<5 \times 10^3$ cm/s	10^4–10^5 cm/s
Oxygen-related defects	Less	Higher
Window Layer (Eg)	AlInP (2.5 eV)	AlGaAs (2.1 eV)
Other problems	High doping in p-AlInP	Lower efficiency (2.6% lower)

Table 4.
Comparison of InGaP and AlGaAs as a top cell material.

the two cells must be equal for optimal operation. Key issues for maximum-efficiency monolithic cascade cells (two-terminal multijunction cells series connected with tunnel junction XE “tunnel junctions”) are the formation of tunnel junctions of high performance and stability for cell interconnection, and the growth of optimum bandgap top- and bottom-cell structures on lattice-mismatched substrates, without permitting propagation of deleterious misfit and thermal stress-induced dislocations.

As shown in **Table 3**, cell interconnection of sub-cells is one of the most important key issues for realizing high-efficiency MJ solar cells. DH structure has been found to effectively prevent from impurity diffusion from tunnel junction and high tunnel peak current density has been obtained by the authors [30, 31]. **Figure 15** shows annealing temperature (equivalent to growth temperature of top cell layers) 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 [30, 31]. It has also been found that the impurity diffusion from the tunnel junction is effectively suppressed by the wider bandgap material tunnel junction with wider bandgap material-double hetero (DH) structure [32]. These results are thought to be due to the lower diffusion coefficient for impurities in the wider band gap materials such as the AlInP barrier layer and InGaP tunnel junction layer [32].

As a result of developing high performance tunnel junction with high tunnel peak current density, high efficiency MJ solar cells have been developed [30, 33, 34].

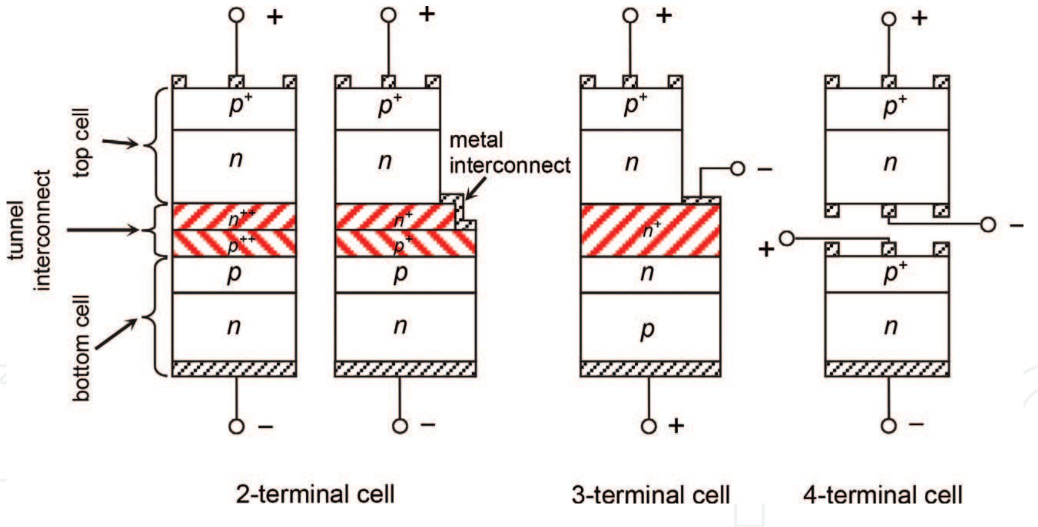

Figure 14.
Schematic diagrams of various configurations of two-junction cells.

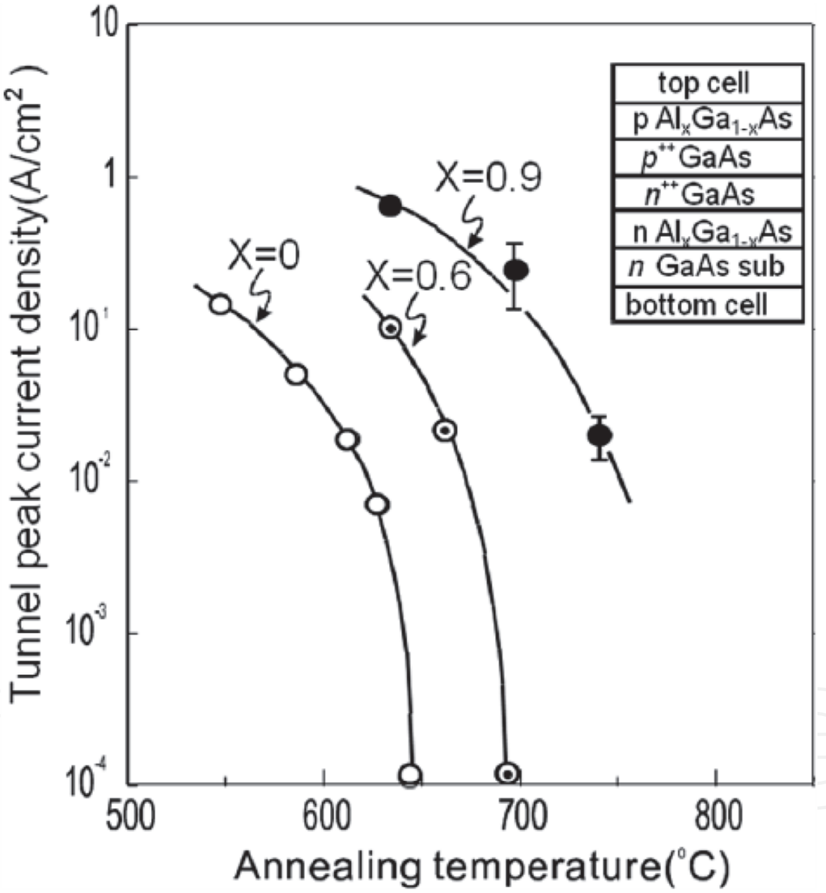

Figure 15.
Annealing (growth) temperature dependence of tunnel peak current densities for double hetero structure tunnel diodes. X is the Al mole fraction in $Al_xGa_{1-x}As$ barrier layers.

Figure 16 shows a structure and light-illuminated (AM1.5G 1-sun) I-V characteristics of InGaP/GaAs/InGaAs 3-junctuon solar cell. 37.9% efficiency under AM1.G 1-sun and 44.4% under 300-suns concentration have been demonstrated with InGaP/GaAs/InGaAs 3-junction solar cell by Sharp [35]. Spectrolab has achieved 38.8% efficiency under 1-sun with 5-junction solar cells [36]. FhG-ISE has demonstrated 46.0% under 58-suns concentration with 4-junction solar cells [37]. Most recently, 39.2% under AM1.5 1-sun and 47.1% under 144-suns have been realized with 6-junction cell by NREL [7].

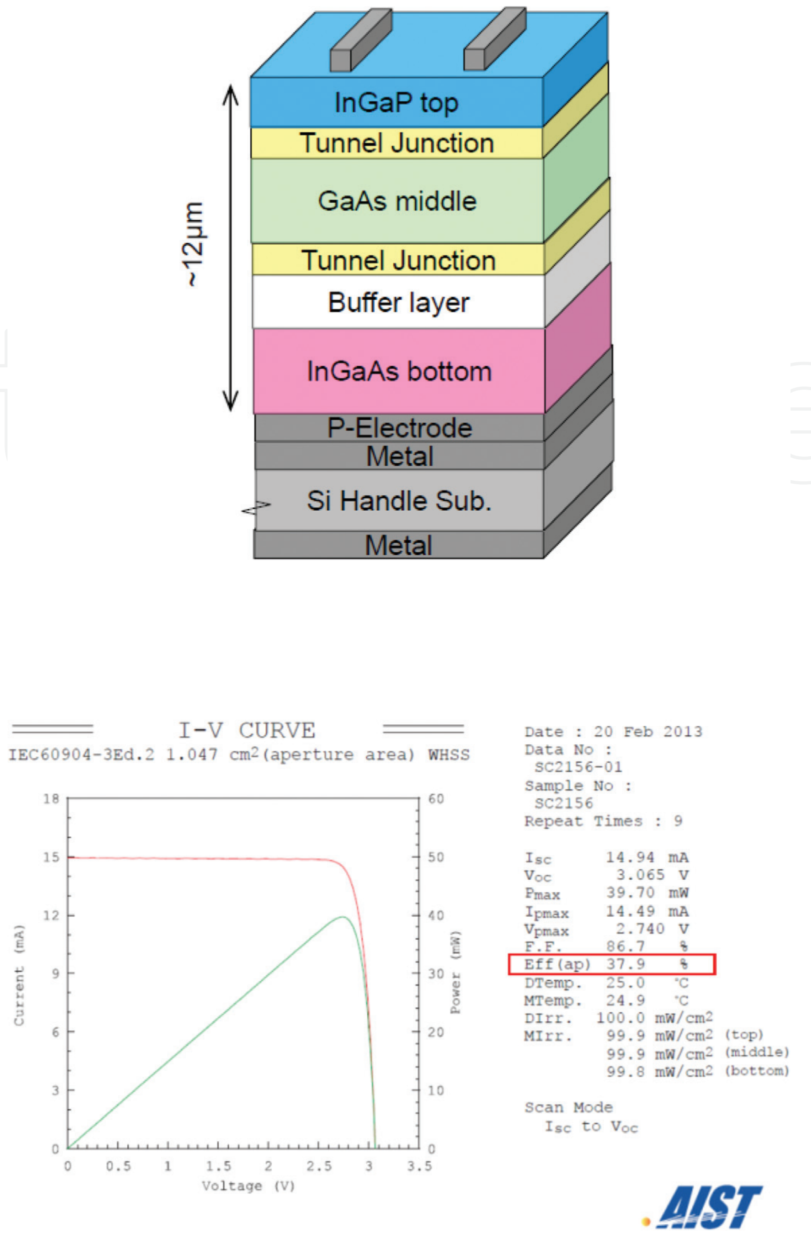

Figure 16.
A structure and light-illuminated I-V characteristics of InGaP/GaAs/InGaAs 3-junctuon solar cell.

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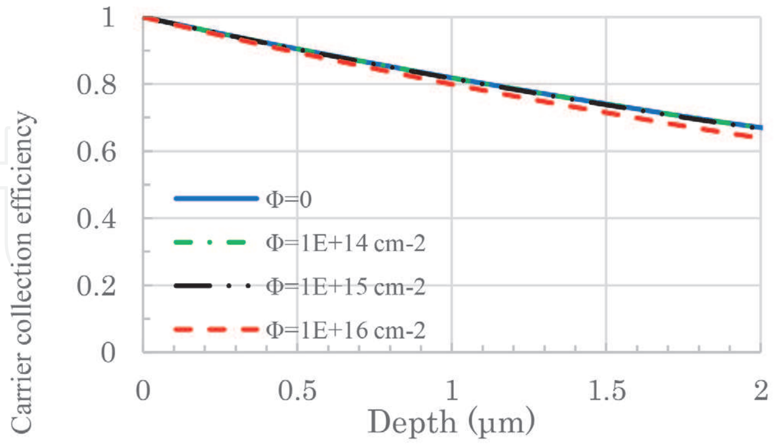
5. Radiation resistance and space applications of III-V compound single-junction and multi-junction solar cells

Development radiation-resistant solar cells is necessary for space application because solar cells degrade due to defect generation under radiation environment in space. Recombination centers tend to affect the solar cell performance by reducing the minority carrier diffusion length L in solar cell active layer from a pre-irradiation value L_0 to a post-irradiation value L_φ through Eq.

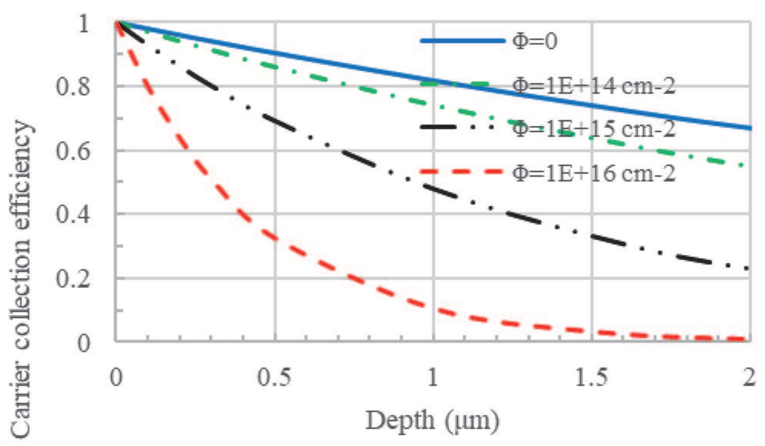
$$1/L_\varphi^2 - 1/L_0^2 = \Sigma I_{ri}\sigma_i v_{th}\varphi/D = K_L\varphi, \quad (13)$$

where suffixes 0 and φ show before and after irradiation, respectively, I_{ri} is introduction rate of i-th recombination center by electron irradiation, σ_i the capture cross section of minority-carrier by i-th recombination center, v_{th} the thermal velocity of minority-carrier, D the minority-carrier diffusion coefficient, K_L the damage coefficient for minority-carrier diffusion length, and φ the electron fluence.

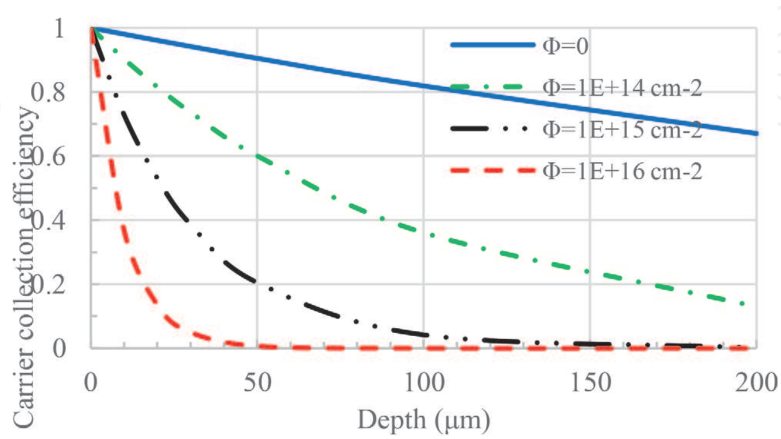
The III-V compound solar cells have better radiation tolerance compared to crystalline Si cells because many III-V compound materials have direct band gap and higher optical absorption coefficient compared to Si with in-direct bandgap. In addition, InP-related materials such as InP, InGaP, AlInGaP, InGaAsP are superior



(c)



(b)



(a)

Figure 17.
Calculated depth × distribution of carrier collection efficiency in (a) Si, (b) GaAs and (c) InP under 1-MeV electron irradiation, calculated by using our experimental values [40–42] and Eq. (11), and by assuming carrier collection efficiency as a function of exp.(−x/L).

radiation-resistant compared to Si and GaAs and have unique properties that radiation-induced defects in InP-related materials are annihilated under minority-carrier injection such as light-illumination at room temperature or low temperature of less than 100 K [38, 39].

Figure 17 shows calculated depth x distribution of carrier collection efficiency in Si, GaAs and InP under 1-MeV electron irradiation, calculated by using our experimental values [40–42] and Eq. (13), and by assuming carrier collection efficiency as a function of exp.($-x/L$). It is clear from **Figure 17** that GaAs has better radiation-tolerance and InP has superior radiation tolerance compared to Si.

Figure 18 shows changes in efficiency of Si single-junction, GaAs single-junction and InGaP/GaAs/Ge 3-junction space solar cells as a function of 1-MeV electron

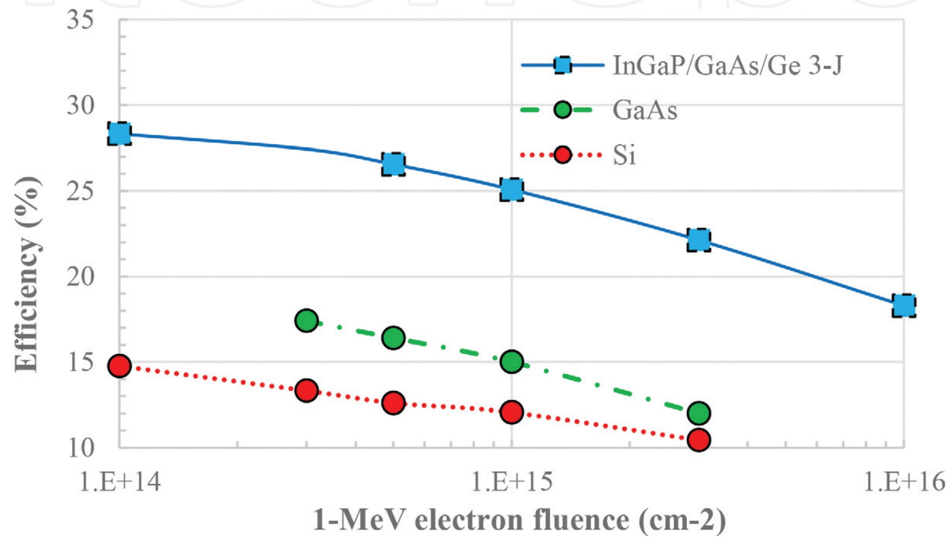


Figure 18.
Changes in efficiency of Si single-junction, GaAs single-junction and InGaP/GaAs/Ge 3-junction space solar cells as a function of 1-MeV electron fluence.

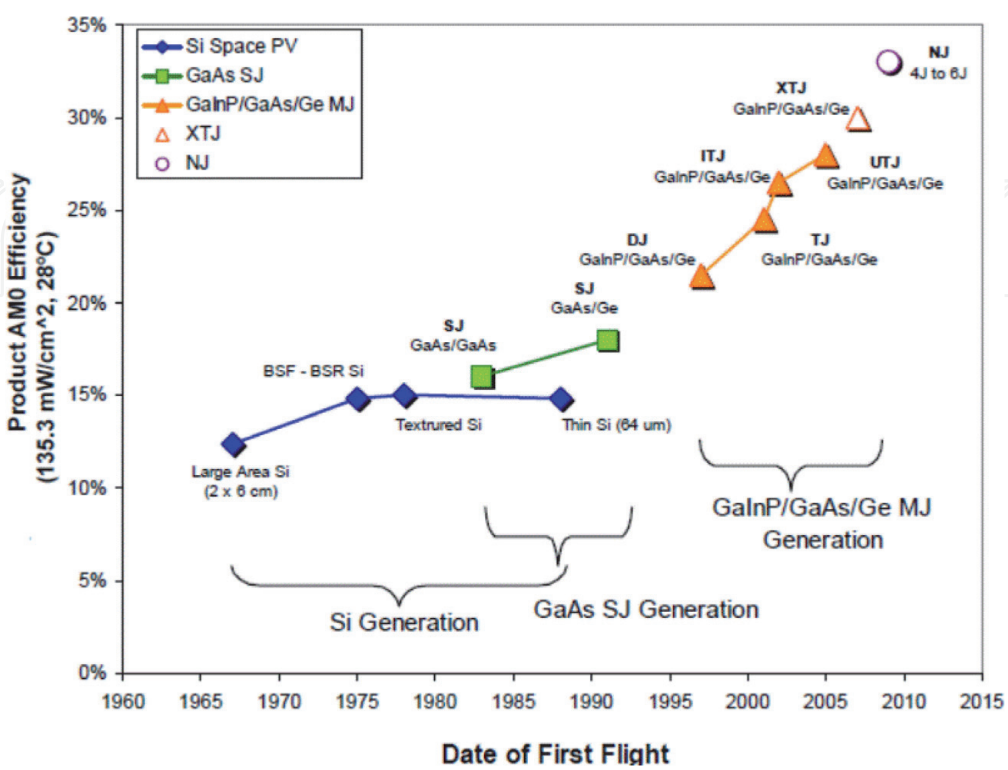


Figure 19.
Historical product efficiency of space solar cells against date of first flight. Open points are for planned products and estimate flight dates.

fluence. The InGaP/GaAs/Ge 3-junction solar cells is now mainly used for space as shown below because they are radiation-resistant and are highly efficient compared to Si and GaAs space solar cells [43].

Because GaAs single-junction solar cells and III-V compound multi-junction solar cells have high-efficiency and radiation-resistance compared to Si solar cells, III-V compound solar cells are mainly used in space as shown in **Figure 19** [44].

6. Future prospects

The multijunction solar cells will be widely used in space because of their high conversion efficiency and good radiation resistance. However, in order to apply super-high-efficiency cells widely on Earth, it will be necessary to improve their conversion efficiency and reduce their cost. **Figure 20** summarizes efficiency potential of single-junction and multi-junction solar cells, calculated by using the similar procedure presented in Section 2, in comparison with experimentally realized efficiencies under 1sun illumination. Altough single-junction solar cells have potential efficiencies of less than 32%, 3-junction and 6-junction solar cells have potential efficiencies of 42% and 46%, respectively.

The concentrator PV (CPV) systems [45] with several times more annual power generation capability than conventional crystalline silicon flat-plate systems will open a new market for apartment or building rooftop and charging stations for battery powered electric vehicle applications. Other interesting applications are in agriculture and large-scale PV power plants.

The multi-junction solar cells are greatly expected as high-efficiency solar cells into solar cell powered electric vehicles. **Figure 21** shows required conversion efficiency of solar modules as a function of its surface area and electric mileage to attain 30 km/day driving. A preferable part of the installation is the vehicle roof. Because of space limitation for passenger cars, development high-efficiency solar cell modules with efficiencies of more than 30% is very important as shown in **Figure 21** [46, 47].

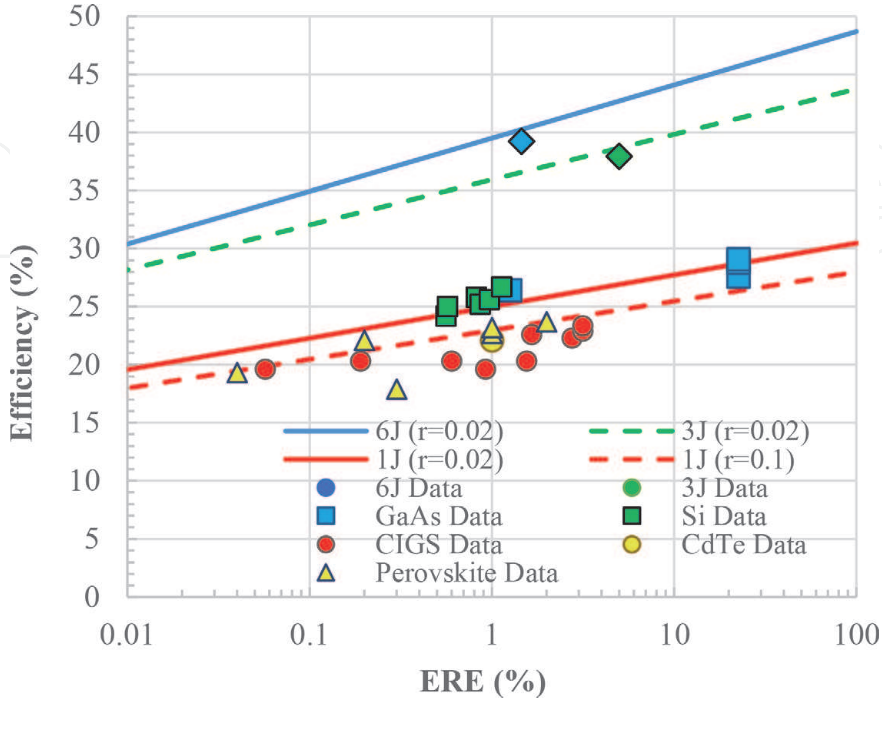


Figure 20.
Calculated conversion efficiencies of various single-junction, 3-junction and 6-junction solar cells, calculated by using the similar procedure presented in Section 2, in comparison with experimentally realized efficiencies under 1-sun illumination.

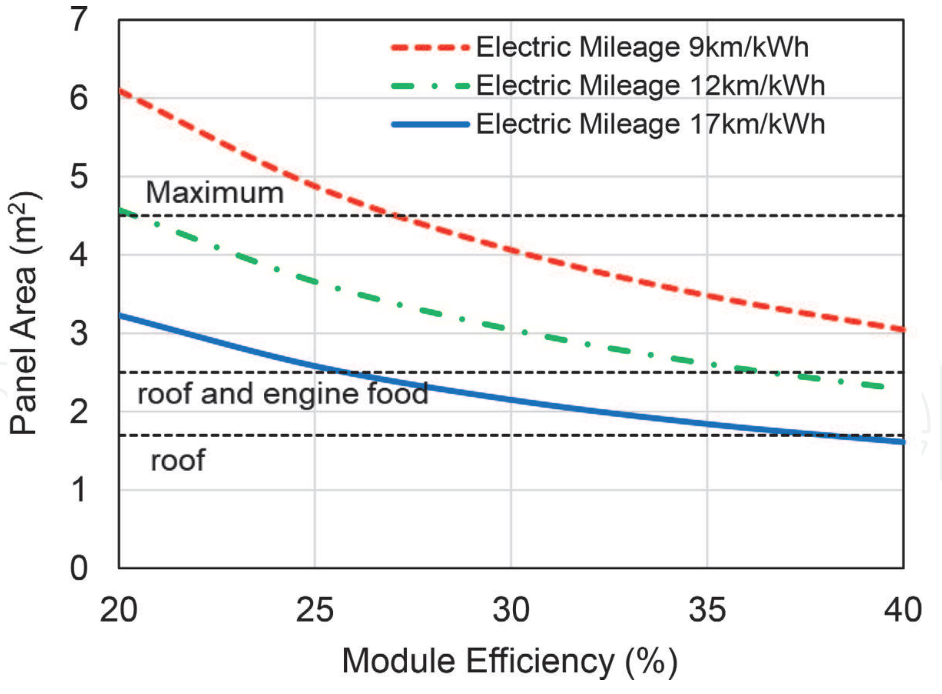


Figure 21.
Required conversion efficiency of solar modules as a function of its surface area and electric mileage to attain 30 km/day driving. A preferable part of the installation is the vehicle roof.

In addition to high-efficiency, cost reduction of solar cell modules is necessary. Therefore, further development of high-efficiency and low-cost modules is necessary.

7. Conclusion

This chapter reviewed progress in GaAs-based single junction solar cells and III-V compound multi-junction solar cells and key issues for realizing high-efficiency solar cells. The III-V compound solar cells have contributed as space and concentrator solar cells and are expected as creation of new markets such as large-scale electric power systems and solar cell powered electric vehicles. Regarding single-junction solar cells, especially, GaAs solar cells have shown 29.1% under 1-sun illumination, highest ever reported for single-junction solar cells. In addition, analytical results for non-radiative recombination and resistance losses in III-V compound solar cells are shown by considering fundamentals for major losses in III-V compound materials and solar cells. Because the limiting efficiency of single-junction solar cells is 30-32%, multi-junction junction solar cells have been developed and InGaP/GaAs based 3-junction solar cells are widely used in space. The InGaP/GaAs/InGaAs 3-junction solar cells have recorded 37.4% under 1-sun and 44.4% under concentration. Recently, highest efficiencies of 39.1% under 1-sun and 47.2% under 144-suns concentration have been demonstrated with 6-junction solar cells. The 3-junction and 6-junction solar cells potential efficiencies of 42% and 46% under 1-sun, respectively. Further development of high-efficiency and low cost solar cells and modules is necessary in order to create new markets.

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Conflict of interest

The author declares no conflict of interest.

Author details

Masafumi Yamaguchi
Toyota Technological Institute, Nagoya, Japan

*Address all correspondence to: masafumi@toyota-ti.ac.jp

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