Overview of Concentrator Solar cells and Analysis for their Non-radiative Recombination

Masafumi Yamaguchi, Kan-Hua Lee, Daisuke Sato, Kenji Araki, Nobuaki Kojima and Yoshio Ohshita

Toyota Technological Institute, Nagoya (Japan)

Abstract

Concentration photovoltaics have great potential of higher efficiency and lower cost compared to conventional crystalline Si and thin-film solar cells. Although excellent results for concentrator solar cells such as 27.6%, 30.5%, 44.4% and 47.1% with Si, GaAs, InGaP/GaAs/InGaAs 3-junction and AlGaInP/AlGaAs/GaAs/GaInAs/GaInAs/GaInAs 6-junction concentrator cells have been demonstrated, there are still problems to be solved. This paper overviews concentrator solar cells. In addition, this paper presents analytical results for efficiency potential of concentrator solar cells based on analysis of non-radiative recombination loss in concentrator solar cells. Concentrator Si, GaAs, CIGS and InGaAs/InGaAs 3-junction solar cells have efficiency potential of more than 34%, 36% 31% and 50%, respectively, by realizing external radiative efficiency of 20% and reducing series resistance. This paper also presents our recent approaches for photovoltaic-powered vehicle applications and static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module with efficiency of 32.84%, and so forth.

Keywords: Solar Cells, Concentrator, Efficiency, Si, GaAs, multi-junction, non-radiative recombination

1. Introduction

The development of high-performance solar cells offers a promising pathway toward achieving high power per unit cost for many applications. Substantial increases in conversion efficiency can be realized by using concentrating solar cells rather than solar cells under one-sun operation (Yamaguchi and Luque, 1999). According to overview by Swanson (2003), work on concentrating photovoltaics as a means to reduce cost began in the early 1960s. However, the critical issues to be solved are 1) reducing series resistance to enable efficient handling of the large currents involved, and 2) to maintain low-enough temperature rise by heat dissipation. As a results of conducting R&D Programs under DOE, EC, and NEDO, conversion efficiencies of concentrating solar cells were improved significantly as shown Fig. 1.

In this paper, we describe potential of high-efficiency and low-cost of concentrating solar cells and key technologies for realizing high-efficiency concentrating solar cells. In this paper, our recent approaches for photovoltaic-powered vehicle applications, especially static low concentration photovoltaics are also presented.

2. Overview for concentrator Si, GaAs, CIGS and InGaP/GaAs-based multi-junction solar cells

Figure 1 summarizes chronological improvements in conversion efficiencies of Si, GaAs, CIGS and III-V compound multi-junction solar cells measured under 1-sun operation by using the global AM1.5 spectrum (1000 W/m^2) at 25_^{0}C (IEC 60904-3: 2008 or ASTM G-173-03 global) (NREL) and measured under concentration operation by using the ASTM G-173-03 direct beam AM1.5 spectrum at a cell temperature of 25 ^{0}C (NREL) and future efficiency predictions of those solar cells (original idea by Professor Goetzberger et al. (2002) and modified by Yamaguchi et al. (2018)). The function chosen here (eq. 1) is derived from the diode equation):

$\eta(t) = \eta_L\{1\text{-}\exp[(a_0 - a)/c]\}$. (eq. 1)

where $\eta(t)$ is the time-dependent efficiency, η_L limiting asymptotic maximum efficiency, a_0 is the year for which $\eta(t)$ is zero, a is the calendar year and c is a characteristic development time. Fitting of the curve is done with three parameters which are given in Table 1. For example, 55% for η_L, 15 for a_0 and 1986 for c were used in the case of III-V compound multi-junction solar cells for terrestrial use. The function can be fitted relatively

doi:10.18086/swc.2021.05.03 Available at http://proceedings.ises.org

well to the past development of best laboratory efficiencies of various solar cells under 1-sun and concentrator conditions, although no fitting parameters for concentrator CIGS solar cells are listed in Table 1 because of a few present data.

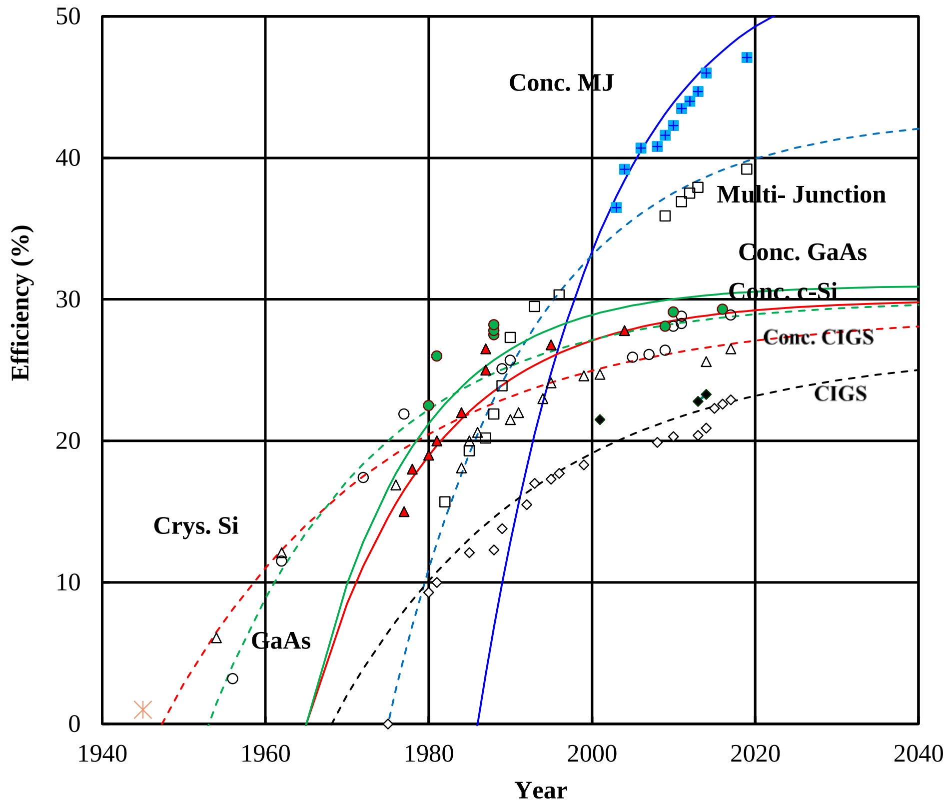


Fig. 1: Chronological efficiency improvements of crystalline Si, GaAs, III-V compound multi-junction solar cells and CIGS solar cells under 1-sun and concentrator conditions.

Table 1: Fitting parameters for different technologies

Solar cell	Illumination condition	η_L	c	a_0
Single-crystal Si	1-sun	29	26.8	1947.2
Single-crystal Si	concentration	30	15	1965
GaAs	1-sun	30	20	1953
GaAs	concentration	33	20	1960
CIGS	1-sun	26.5	25	1968
CIGS	concentration	-	-	-
III-V multi-junction	1-sun	43	17	1975
III-V multi-junction	concentration	55	15	1986

3. Analysis for efficiency potential and non-radiative recombination of concentrator Si, GaAs CIGS and III-V 3-junction solar cells

Figure 2 shows concentration dependence of 27.6% efficiency Si concentrator solar cell reported by Amonix (Slade and Garbousgain, 2005), 44.4% efficiency InGaP/GaAs/InGaAs 3-junction concentrator solar cell reported by Sharp (Sasaki et al., 2013, Yamaguchi et al., 2016), 28.8% efficiency GaAs concentrator solar cell reported by FhG-ISE (Schilling et al., 2018) and 23.3% efficiency CIGS concentrator solar cell reported by NREL (Ward et al., 2014), and calculated by using eqs. 2 – 6. Although quite good agreement between calculated and experimental efficiency results of Si, GaAs and InGaP/GaAs/InGaAs 3-junction concentrator solar cells under concentrator condition of less than 100-suns, reduction in conversion efficiency of concentrator solar cells under high concentrator condition is thought to be occurred due to series resistance and temperature rise. In the case of CIGS concentrator solar cells, under high concentrator condition of more than 20-suns, fill factor degrades because of higher series resistance.

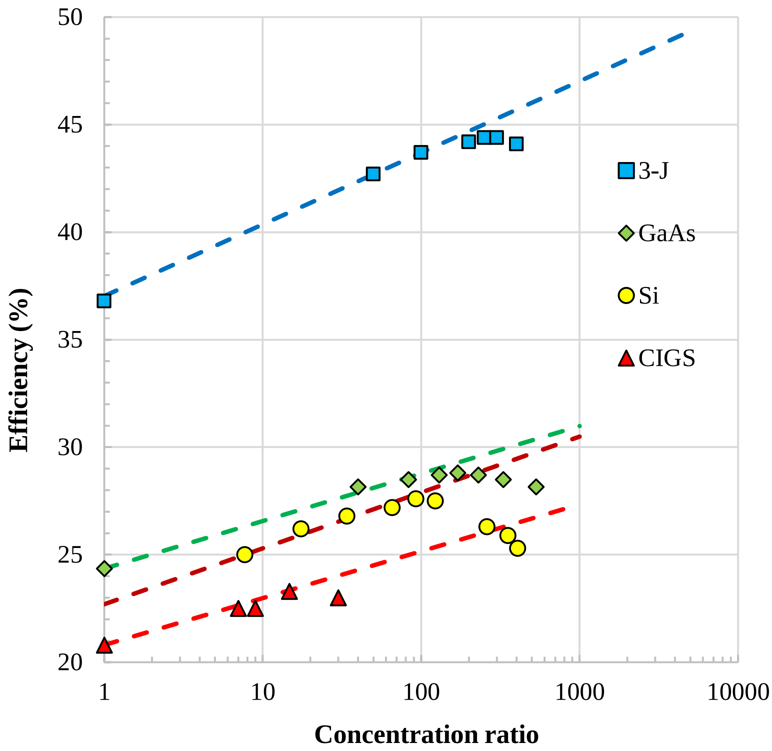


Fig. 2: Comparison of calculated and experimental efficiencies of Si concentrator solar cell reported by Amonix, InGaP/GaAs/InGaAs 3-junction concentrator solar cell reported by Sharp, GaAs concentrator solar cell reported by FhG-ISE and CIGS concentrator solar cell reported by NREL as a function of concentration ratio.

In order to realize higher efficiency of concentrator solar cells, improvements in short-circuit density Jsc, open-circuit voltage Voc and fill factor FF are substantially necessary. One of problems to attain the higher efficiency solar cells is the higher minority-carrier lifetime in various materials. Non-radiative recombination loss of various solar cells were evaluated by external radiative efficiency (ERE) and open-circuit voltage Voc is expressed by (Rau 2007, Green, 2012, Yao et al., 2015, Yamaguchi et al., 2017, 2018a).

$$V_{oc} = V_{oc,rad} + (kT/q)\ln(ERE), \quad \text{(eq. 2)}$$

where the second term shows non-radiative voltage loss, and $V_{oc,rad}$ is radiative open-circuit voltage.

Resistance loss of various solar cells were estimated by fill factor FF

$$FF \approx FF_0(1-r_s)(1-1/r_{sh}) \approx FF_0(1-r_s-1/r_{sh}), \quad \text{(eq. 3)}$$

where r_s are normalized series resistance and normalized shunt resistance r_{sh}, respectively and given by

$$r_s = R_s/R_{CH}, \ (6) \quad r_{sh} = R_{sh}/R_{CH}, \quad \text{(eq. 4)}$$

The characteristic resistance R_{CH} is expressed by (Green, 1998)

$$R_{CH} = V_{oc}/I_{sc}. \quad \text{(eq. 5)}$$

Ideal fill factor FF_0 used in the calculation is empirically expressed by (Green, 1998),

$$FF_0 = [v_{oc} - \ln(v_{oc} + 0.72)]/(v_{oc} + 1), \quad \text{(eq. 6)}$$

where v_{oc} is normalized open-circuit voltage and is given by

$v_{oc} = V_{oc}/(nkT/q)$, (eq. 7)

In the calculation, highest values obtained were used as Jsc. Voc and FF were calculated by equations eq. 2 – eq. 7 and conversion efficiency potential of various solar cells were calculated as a function of ERE.

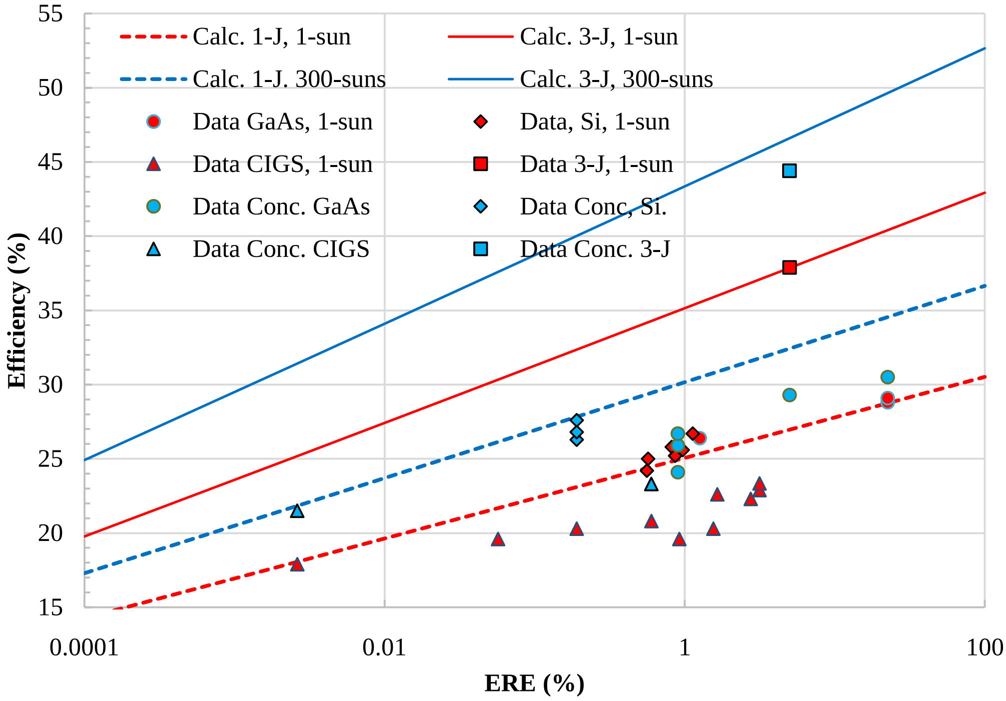


Fig. 3: Calculated efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun and concentrator operations as a function of ERE (external radiative efficiency) in comparison with state-of-the-art efficiencies of those solar cells under 1-sun and concentrator operations.

Figure 3 shows calculated efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs 3-junction solar cells as a function of EREs in comparison with state-of-the-art efficiencies of Si, GaAs, CIGS and InGaP/GaAs/InGaAs solar cells under 1-sun and concentrator operations (Sasaki et al., 2013, Yamaguchi et al., 2016, Green et al., 2021).

Si concentration solar cells have efficiency potential of more than 34% by realizing ERE of 20% from about 0.2%.

Efficiencies of 26.7% and 27.6% (Green et al., 2021) have been demonstrated with single-crystalline Si solar cells under 1-sun and 92.3-suns concentrator operations, respectively. Si solar cells have potential efficiencies of more than 28.5% (ERE: from 5% to 20%) and 34% (ERE: from 0.2% to 20%) under 1-sun and concentrator operations, respectively,.

Efficiencies of 29.1% and 30.5% (Green et al., 2021) have been demonstrated with GaAs solar cells under 1-sun and 258-suns concentrator operations, respectively. GaAs solar cells have potential efficiencies of more than 30% (ERE: from 22.5% to 50%) and 36% (ERE: 1-5% to 50%) under 1-sun and concentrator operations, respectively.

Efficiencies of 23.35% and 23.3% (Green et al., 2021) have been demonstrated with CIGS solar cells under 1-sun and 14.7-suns concentrator operations, respectively. CIGS solar cells have potential efficiencies of more than 26.5% (ERE: from 5% to 30%) and 31% (ERE: from 1-5% to 30%) under 1-sun and concentrator operations, respectively.

Efficiencies of 37.9% and 44.4% (Sasaki et al., 2013, Yamaguchi et al., 2016, Green et al., 2021) have been demonstrated with InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun and 302-suns concentrator operations, respectively. The 3-junction solar cells have potential efficiencies of more than 42% (ERE: from 5% to 40%) and 50% (ERE: from 5% to 40%) under 1-sun and concentrator operations, respectively.

Figure 4 shows calculated result for concentration ratio at maximum efficiency as a function of area series resistance product of GaAs single-junction and InGaP/GaAs/Ge 3-junction concentrator solar cells (Green et al., 2021, Yoshida et al, 1983, Partain, 1995) Designing low series resistance of concentrator solar cells with area series resistance product of less than 50mΩcm², 15mΩcm² and 5mΩcm² at 100-suns, 300-suns and 1000-suns, respectively is necessary for realizing high efficiency.

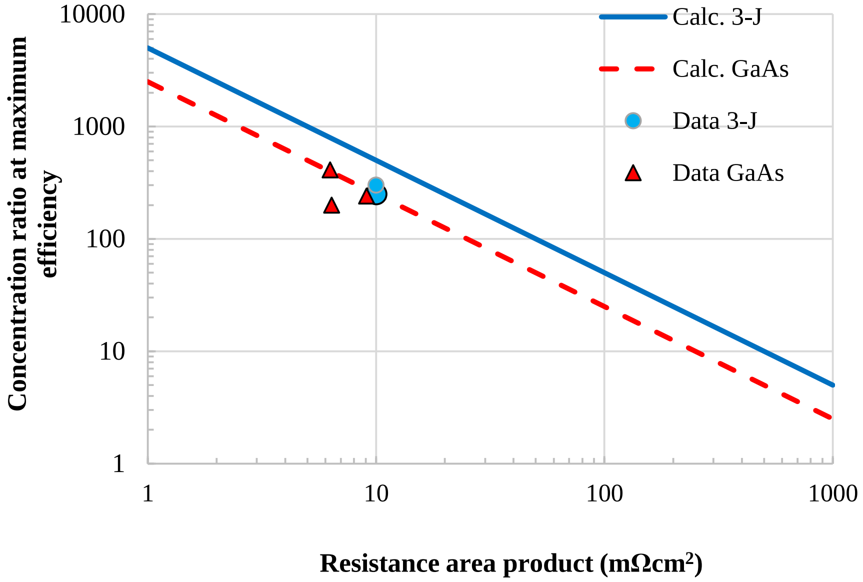


Fig. 4. Calculated result for concentration ratio at maximum efficiency as a function of series resistance of GaAs single-junction and InGaP/GaAs/Ge 3-junction concentrator solar cells.

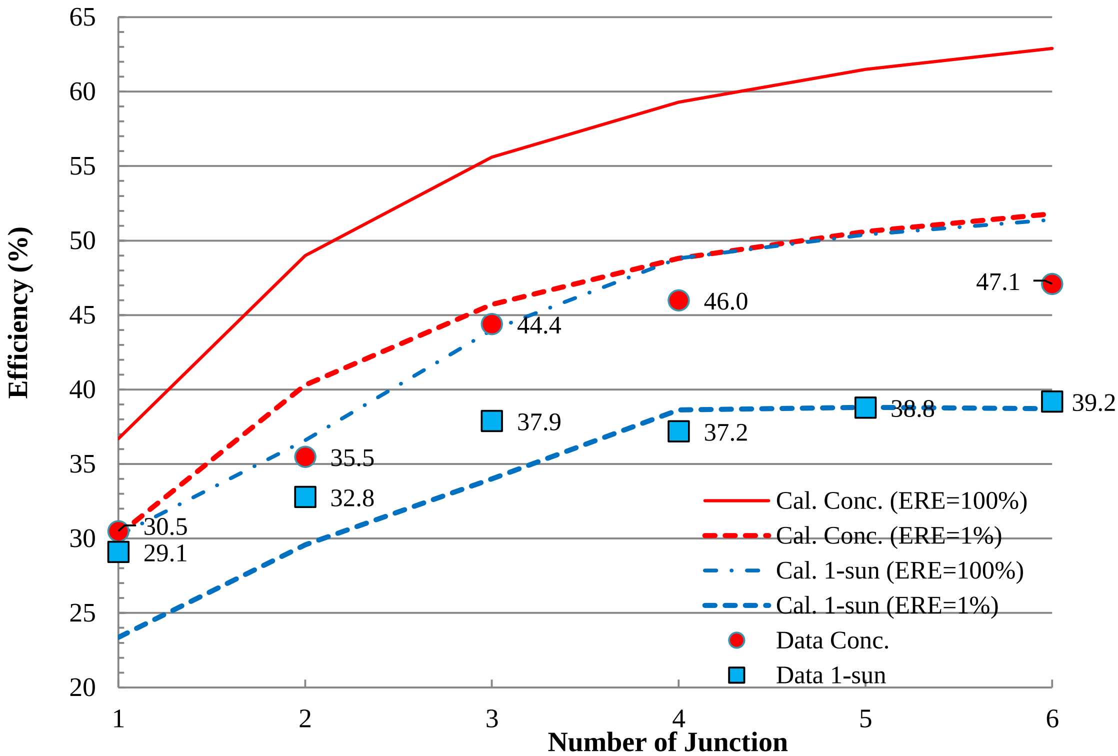


Fig. 5: Possible conversion efficiencies of single-junction and multi-junction solar cells calculated in the case of external radiative efficiebcy (ERE) of 100% and 1% in comparison with experimentally realized efficiencies for 1-sun intensity and under concentration.

Figure 5 summarizes efficiency potential (Phillips and Bett, 2014, Yamaguchi etal., 2021b) of single-junction and multi-junction solar cells calculated in the case of external radiative eficiency (ERE) of 100% and 1% in comparison with experimentally realized efficiencies (best efficiencies reported) (Green et al., 2021) for 1sun intensity and under concentration. In the ideal case (ERE=100%), efficiency of 40%, 61% and 69% under concentration is expected with single-junction, 3-junction and 6-junction solar cells, respectively. Because concentrator solar cells show relatively lower ratio between 68% and 76% of the ideal values compared to those (between 76% and 90%) of solar cells under 1-sun operation, further studies of concentrator solar cells are necessary.

4. Our recent approaches for PV-powered vehicle application

Development of high-efficiency solar cell modules and new application fields are significant for the further development of PV and the creation of new clean energy infrastructure based on PV. Notably, the development of PV-powered vehicle applications is desirable and very important for this end. This paper also presents our recent approaches for PV-powered vehicle applications: Demonstration car using Sharp's high-efficiency III-V 3-junction solar cell modules has shown longer distance driving compared to vehicles installed with Si solar cell modules. Figure 6 shows practical data regarding the driving distance of Toyota Prius 2017 (Yamaguchi et al, 2021a), Toyota Prius 2019 demonstration car (Yamaguchi et al, 2021a) and Sono Motors Sion (Sono Motors)as a function of module efficiency and solar irradiance in comparison with calculated results of driving distance by assuming electric mileage of 9.35km/kWh and system charging efficiency of 81.2% without cell temperature correction.

The results suggest importance of high-efficiency solar cell modules, module nominal power and longer electric mileage (that is light-weight car) because Toyota demonstration car installed with III-V 3-junction solar cell module of about 30.9% efficiency has demonstrated 29.1km/day driving (Yamaguchi et al, 2021a) at an average solar irradiance of 4.1kWh/m^2/day, contrary to Sono Motor Sion installed with Si back contact solar cell module of about 22% efficiency that has shown 18-19 km/day driving (Sono Motors) at the similar solar irradiance as seen in Fig. 6. However, cost reduction in III-V 3-junction solar cell modules is necessary.

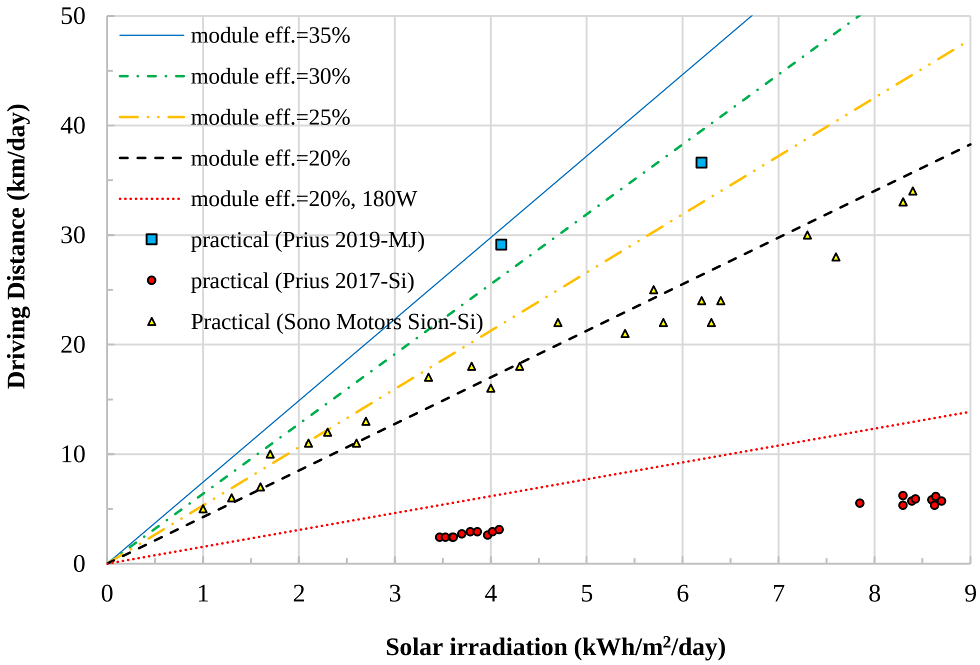
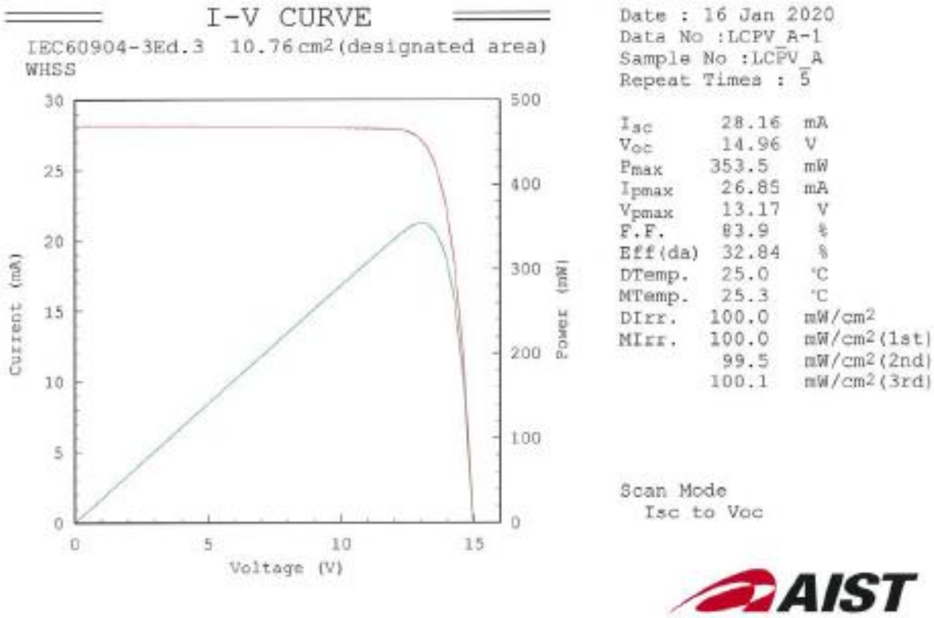


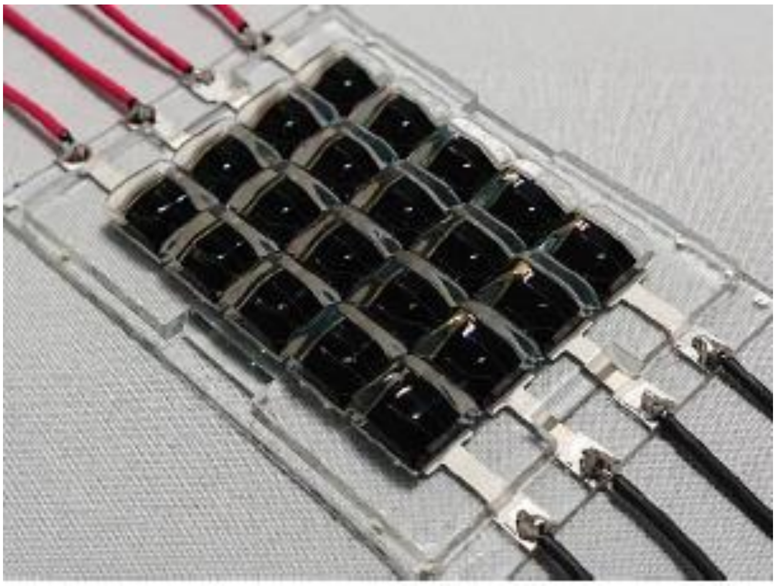
Fig. 6: Practical data regarding the driving distance of Toyota Prius 2017, Toyota Prius 2019 (demonstration car) and Sono Motors Sion as a function of module efficiency and solar irradiance in comparison with calculated results of driving distance by assuming electric mileage of 9.35km/kWh and system charging efficiency of 81.2%.

As an approach for cost reduction of high-efficiency multi-junction solar cells, we are studying on static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module. Most recently, we have achieved 32.84%

efficiency with static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module (area of 10.76 cm^2) as shown in Fig. 7 (Sato et al, 2020)].



(b)



(a)

Fig. 7: (a) Photo and (b) current-voltage curve of prototype static low concentrator module with III-V based triple-junction solar cell.

5. Summary

This paper overviews concentrator photovoltaic (CPV) cells such as crystalline Si CPV cells, GaAs CPV cells and III-V compound multi-junction CPV cells. In addition, this paper presents analytical results for efficiency potential of CPV cells based on analysis of non-radiative recombination loss in CPV cells.

1) Si concentration solar cells have efficiency potential of more than 34% by realizing external radiative efficiency (ERE) of 20% from about 0.2%.

2) GaAs concentration solar cells have efficiency potential of more than 36% by realizing ERE of 50% from

about 1 - 5%.

3) InGaP/GaAs/InGaAs 3-junction concentration solar cells have efficiency potential of more than 50% by realizing ERE of 40% from about 5%.

4) CIGS concentrator solar cells have efficiency potential of more than 31% by realizing ERE of 20% from about 1-5%.

This paper also presented our recent approaches for photovoltaic-powered vehicle applications. Demonstration car using Sharp's high-efficiency III-V 3-junction solar cell modules, As an approach for cost reduction of high-efficiency multi-junction solar cells, we are studying on static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module. Most recently, we have achieved 32.84% efficiency with static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module (area of 10.76 cm^2).

Acknowledgments

The authors thank members in the NEDO, METI and EC, and to Prof. A. Luque, Prof. Y. Okada, Prof. M. Sugiyama, Dr. A. Bett, Dr. T. Takamoto, Dr. G. Sifer, Dr. Y. Hishikawa, Prof. G. Sala Prof. N.J. Ekins-Daukes and other collaborative researchers who have contributed to the "EU-Japan Collaborative Research on Concentrator Photovoltaics". In addition, MY thanks to Prof. A. Yamamoto, Dr. H. Sugiura, Prof. K. Ando, Dr. C. Amano, Prof. S. Katsumoto, and other former members of the NTT labs., Dr. M. Al-Jassim and Dr. R. Ahrenkiel, NREL, and Dr. M. Yang, Dr. M. Imaizumi, Dr. S. Taylor, Dr. A. Kahn and Dr. N. Dharmarasu, former membrs of the Toyota Tech. Inst. Drs. E. Ikeda, T. Agui, H. Kurita and M. Ohmori, Japan Energy, Drs. T. Yamada, T. Tanabe, Matsubara and S Takagishi, Sumitomo Elec., Drs. K. Takahashi and T. Unno, Hitachi Cable, Drs. M. Kondo and H. Uozumi, Daido Steel, Prof. Y. Kemmoku, Toyohasi Sozo College, Dr. T. Egami, T. Hisamatsu and Y. Miyazaki, Daido Metal for their contribution to intitial stage of studies.

References

Goetzberger, A., Luther, J., Willeke, G., 2002. Solar cells: past, present, future. Sol. Energy Mater. Sol. Cells, 74**,** 1. https://doi.org/10.1016/S0927-0248(02)00042-9.

Green, M.A., 1998. Solar Cells (UNSW, Kensington) p.96. ISBN-13: 978-0138222703, ISBN-10: 0138222703.

Green, M.A., 2012. Radiative efficiency of state-of-the-art photovoltaic cells. Prog. Photovolt. 20, 472. http://doi.org/ 10.1002/pip.1147.

Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., Hao, X., 2021. Solar cell efficiency tables (version 58). Prog. Photovolt. 29, 657. http://doi.org/10.1002//pip.3444.

NREL, https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html

Partain, L.D., 1995. L.D. Partain ed. "Solar cells and their applications" (Wiley) p.1. ISBN-0471574201.

Phillips, S.P., Bett, A.W., 2014. III-V multi-junction solar cells and concentrator photovoltaic (CPV) systems. Adv. Opt. Tech. 3, 469. http://doi.org/10.1515/aot-2014-0051.

Rau, U., 2007. Reciprocity relation between photovoltaic quantum efficiency and electroluminescent emission of solar cells. Phys. Rev. B76, 085303. http://doi.org/ 10.1103/PhysRevB.76.085303.

Sasaki, K., Agui, T., Nakaido, K., Takahashi, N., Onitsuka,, R., Takamoto, T., 2013. Development of InGaP/GaAs/InGaAs inverted triple junction concentrator solar cells. AIP Conference Proceedings Volume l556, (AIP Publishing) p.22. http://proceedings.aip.org.

Sato, D., Araki, K., Takamoto, T., Juso, H., Yamada, N., Masuda, T., Yamaguchi, M., 2020. Nearly 30%-efficient low-concentration static photovoltaic modules with IMM triple-junction solar cells. Appl. Phys. Express 13**,** 077001. https://doi.org/10.35848/1882-0786/ab970f.

Schilling, C.L., Hohn, O., Micha, D.N., Heckelmann, S., Klinger, V., Oliva, E., Glunz. S.W., Dimroth, F., 2018. Combining photon recycling and concentrated illumination in a GaAs heterojunction solar cell. IEEE J. Photovolt. 8, 348. http://doi.org/ 10.1109/JPHOTOV.2017.2777104.

Slade, A., Garboushain, V., 2005. 27.6% Efficient Silicon Concentrator Solar Cells for Mass Production. Technical Digest of the 15th International Photovoltaic Science and Engineering Conference, Shanghai, China, p 701. publication at: https://www.researchgate.net/publication/267779112..

Sono Motors, https://sonomotors.com/

Swanson, R.M., 2003. Photovoltaic concentrators, In Book "Handbook of photovoltaic science and engineering" A. Luque and S. Hegedus eds. (Wiley) pp.449. http://doi.org/10.1002/0470014008.

Ward, J.S., Egaas, B., Noufi, R., Contreras, M., Ramanathan, R., Osterwald, C., Emery, C., 2014. Cu(In,Ga)Se 2 solar cells measured under low flux optical concentration. Proceedings of the 40th IEEE Photovoltaic Specialists Conference (IEEE, New York) p.2934. http://doi.org/10.1109/PVSC.2014.6925546

Yamaguchi, M., Luque, A., 1999. High efficiency and high concentration in photovoltaics. IEEE Trans. Electron Devices. ED-46, 2139. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=792009.

Yamaguchi, M., Takamoto, T., Araki, K., Kojima, N., 2016. Recent results for concentrator photovoltaics in Japan. Jpn. J. Appl. Phys. 55, 04EA05. http://doi.org/10.7567/JJAP.55.04EA05.

Yamaguchi, M., Yamada, H., Katsumata, Y., Lee, K-H., Araki, K., Kojima, N., 2017. Efficiency potential and recent activities of high-efficiency solar cells. J. Mater. Res. Volume 32, 3445. https://doi.org/10.1557/jmr.2017.335.

Yamaguchi, M., Lee, K-H., Araki, K., Kojima, N., Yamada, H., Katsumata, Y., 2018a. Analysis for efficiency potential of high-efficiency and next-generation solar cells. Prog. Photovolt. 26, 543. https://doi.org/10.1002/pip.2955.

Yamaguchi, M., Lee, K-H., Araki, K., Kojima, N., 2018b. A review of recent progress in heterogeneous silicon tandem solar cells, J. Phys. D: Appl. Phys. 51, 133002. https://doi.org/10.1088/1361-6463/aaaf08.

Yamaguchi, M., Masuda, T., Araki, K., Sato, D., Lee, K-H., Kojima, N., Takamoto, T., Okumura, K., Satou, A., Yamada, K., Nakado, T., Zushi, Y., Ohshita, Y., Yamazak, M., 2021a, Development of high-efficiency and low-cost solar cells for PV-powered vehicles application. Prog. Photovolt. 29**,** 684. http://doi.org/10.1002/pip.3343.

Yamaguchi, M., Dimroth, F., Geisz, J.F., Ekins-Daukes, N.J., 2021b. Multi-junction solar cells paving the way for super high-efficiency. J. Appl. Phys. 129, 240901. https://doi.org/10.1063/5.0048653.

Yao, J., Kirchartz, T., Vezie, M.S., Faist, M.A., Gong, W., He, Z., Wu, H., Troughion, J., Watson, T., Bryant, D., Nelson, J., 2015. Quantifying losses in open-circuit voltage in solution-processable solar cells. Phys. Rev. Applied. 4, 014020. http://doi.org/10.1103/PhysRevApplied.4.014020.

Yoshida, S., Mitsui, K., Oda, T., Yoshida, M., Yukimoto, Y., 1983. Series resistance effects and cell performances in GaAs concentrator solar cells. Transactions on Electronics, Information and System, C103, 53. (in Japanese). https://doi.org/10.11526/ieejeiss1972.103.53.