JAPANESE ACTIVITIES OF R&D ON III-V CONCENTRATOR SOLAR CELLS AND MODULES

M. Yamaguchi, T. Takamoto(1), T. Agui(1), M. Kaneiwa(1), K. Araki(2), M. Kondo(2), H. Uozumi(2), M. Hiramatsu(3), Y. Miyazaki(3), T.Egami(3), Yoshishige Kemmoku(4), N. J. Ekins-Daukes
Toyota Technological Institute 2-12-1 Hisakata, Tempaku, Nagoya 468-8511 Japan
(1)SHARP Corporation, 282-1, Hajikami, Shinjo-cho, Kitakaturagi-gun, Nara, 639-2198 Japan.
(2)Daido Steel Co., Ltd. 2-30 Daido-cho, Minami, Nagoya 457-8545 Japan
(3)Daido Metal Co., Ltd., Tendohshinden Maehara Inuyama Aichi 484-0061 Japan
(4)Toyohashi Sozo College, 20-1 Matsushita, Ushikawa-cho, Toyohashi 440-8511 Japan

ABSTRACT: A 3-junction solar cell with InGaP top junction was developed and 38.9 % efficiency was measured at 498 sun AM1.5G irradiance. A new Fresnel concentrator lens designed by non-imaging optic theory made by injection molding was developed and achieved 85.4 % optical efficiency at 400 X geometrical concentration ratio. A new packaging structure for III-V concentrator solar cells was proposed. A 7,056 cm2 concentrator module using above new technologies was fabricated and tested. The measured peak efficiency was 28.1 % (26.8 plus or minus 1.5 percent considering possible DNI measurement errors).
Keywords: III-V Semiconductors, Concentrator Cells, Concentrators, Encapsulation, High-Efficiency, Multijunction Solar Cell, Optical Losses, PV Module, PV System

1 INTRODUCTION

Concentrator modules using high efficiency multi-junction solar cells are expected to reduce the cost of PV significantly [1]. Recently various kinds of concentrator module structure were proposed and implemented using 3J monolithic multi-junction solar cells. Recently, Fraunhofer ISE achieved 22.7 % by 768 cm^2 and 510 X module [2] and 24.9 % by smaller size module [3]. In US, O'neill reported >30 % efficiency by a 10 X outdoor experiment [4].

The purpose of this study is to demonstrate a higher efficiency for the concentrator module of practical size and demonstrate ways for manufacturing the module with various new technologies as well as summarize recent R&D activities on concentrator solar cells and concentrator optics.

2 CONCENTRATOR SOLAR CELL

We have successfully fabricated high efficiency concentrator InGaP/InGaAs/Ge 3-junction solar cells designed for 500 sun application. The efficiency by in-house measurement peaked at 489 sun and 38.9 % (see Fig. 1 and Fig. 2).

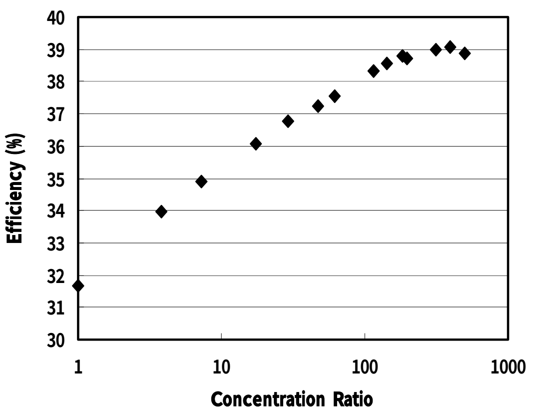

Figure 1: Efficiency of the cell vs. Number of suns

The solar simulator was equipped with both Xe lamp and halogen lamp and adjusted AM1.5G spectrum. The chromatic aberrations of the simulator was evaluated by single junction Ge, InGaAs and InGaP cells with pin-holes [5]. The error due to the chromatic aberration was analyzed by multi-unit SPICE model [6]. The actual efficiency under uniform illumination is thought to be approximately one percent lower.

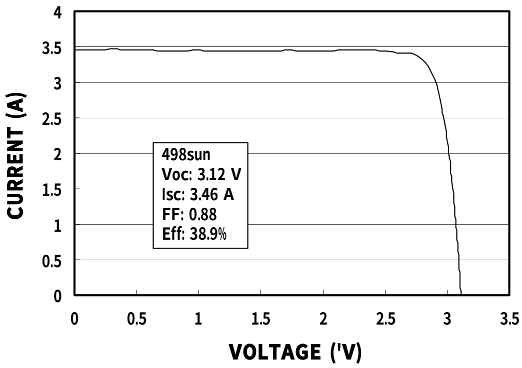

Figure 2: I-V curve of the 3J cell at 498 sun irradiation

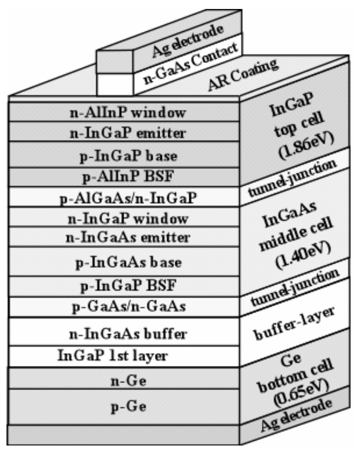

Figure 3 Structure of the 3J concentrator cell

The new concentrator solar cell had wide-gap tunnel junction with double-hetero structure that enables only 1 mΩ resistance at 500 sun of current density (see Fig. 3) [7].

3 CONCENTRATOR OPTICS

A new concentrator optics was introduced, consist of a non-imaging dome-shaped Fresnel lens [8][9][10], and a kaleidoscope homogenizer [10][11]. The non-imaging Fresnel lens allowed wide acceptance half angle with keeping the same optical efficiency with minimum chromatic aberration. The homogenizer reshaped the concentrated into square solar cell aperture, mixed rays to uniform flux (see Fig. 4).

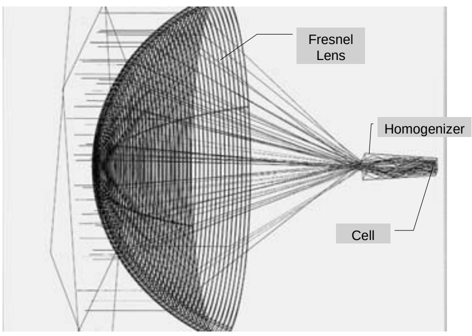

Figure 4: Concentrator Optics

For three decades the developers of Fresnel lens concentrators have viewed injection molding as the “holy grail” for inexpensive lenses [12]. A new molding technology for spherical Fresnel lenses was developed and reached 85.4 % peak efficiency at 400 X geometrical concentration ratio after a 3 year development period (see Fig. 5).

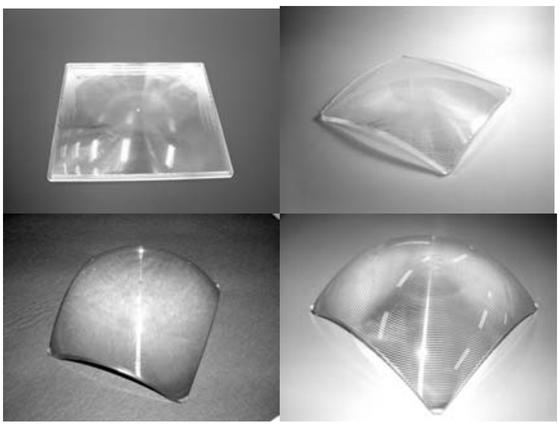

Figure 5: Generations of injection-molded Fresnel lenses
Top-left: 1st generation flat design (400 X, 77.3 % of peak efficiency, 2001)[8]
Top-right: 2nd generation half-dome design (400 X, 81.5 % of peak efficiency, 2002)[9]
Bottom-left: 3rd generation full-dome design made by collapsible molding die (400 X, 85.4 % of peak efficiency)[10]
Bottom-right: 4th generation full-dome design made by collapsible molding die (556 X, 91 % of theoretical efficiency)

The conventional approach of curving or thermal pressing, are both precise but not productive. Injection molding, however, is capable of manufacturing thousands of lenses in a single day and by a single machine. The drawback of this method is it was difficult to create precise prism angle and flat facets. The distribution of optical efficiency in lens surface was measured. The maximum efficiency was a little above 80 % and overall efficiency was 73 % (see Fig. 6). After improvement of the process conditions, the averaged efficiency raised to 85.4 % with the best efficiency exceeded 90 % (see Fig. 7).

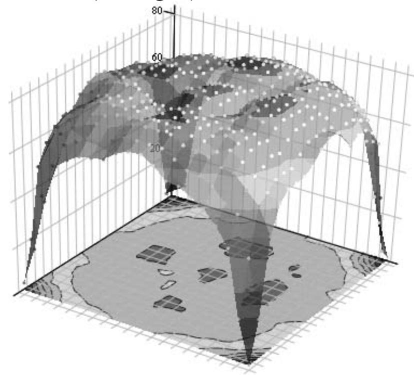

Figure 6: Distribution of 140 mm square 400 X Fresnel lens optical efficiency made by injection molding **before improvement**

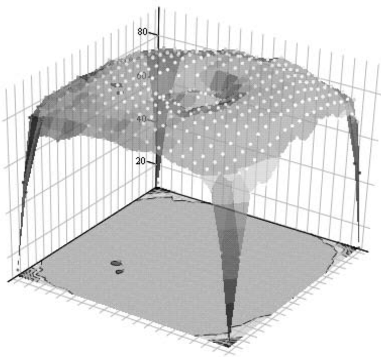

Figure 7: Distribution of 140 mm square 400 X Fresnel lens optical efficiency made by injection molding **after improvement**

4 MODULE AND PACKAGING TECHNOLOGY

The original design came from a 21.7 % -efficient (averaged outdoor efficiency in clear sky day) concentrator module presented in the last WCPEC3 [13]. The transfer efficiency, optical and electrical losses were independently measured and analyzed. As the improved prototype, we design each component’s efficiency as described in Table 1 (final page) and set ambitious targets, jumping to 27 % efficiency with practical size and structure.

This was an ambitious target. However, we had confidence that each component was evaluated accurately and the development target of each component was reasonable. As a result, most of components overcame the technological barriers and met the target value, leading to the achievement of the 27 % of the module efficiency goal.

The new concept introduced to this module was packaging every difficult technology into a receiver package as one of a black box of the device so that every mechanical engineers can easily design their own high performance concentrator module without worrying various difficulties related to concentrator technologies (Fig. 9).

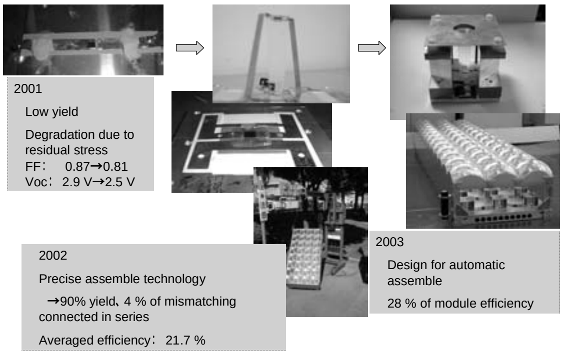

Figure 8: History of 3-year's development in packaging

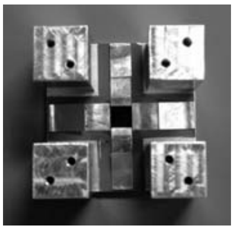

Figure 9: Top view of the concentrator receiver after lamination process.

New technologies were developed, including;

- Super-high pressure and vacuum-free lamination of the solar cell that suppress temperature rise only to 8 degree under 400 X geometrical concentration illumination of sun beam.
- 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.
- A new encapsulating polymer that survives exposure of high concentration UV and heat cycles.

5 OUTDOOR EVALUATION

Outdoor evaluation was done in two sites in Japan (see Fig. 10 and Fig.11).

Figure 10: Field test in Inuyama Site 25 km North from sea, 3 km South from a big river constructed on sunken place, little wind

The averaged outdoor efficiency in Inuyama in summer time was 26.3 %, corresponding 28.1 % after the module temperature compensation (5 to 15 K above the ambient) to 25 C. The averaged efficiency in Toyohashi in autumn was 27.9 %, corresponding 28.1 % after the module temperature correction as well. The 28.1 % of efficiency was confirmed in both Inuyama and Toyohashi sites. Considering possible measurement error of DNI, the probable efficiency lies 26.8 ± 1.5 percent. It was shown that the remarkable efficiency boost resulted from elaborated design after recognition of technological key to concentration operation (see Fig. 12 and Fig. 13).

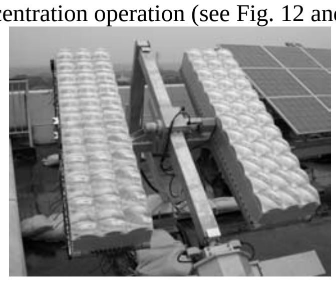

Figure 11: Field test in Toyohashi site, Rooftop of the building and rekatively strong wind, 5 km North from sea

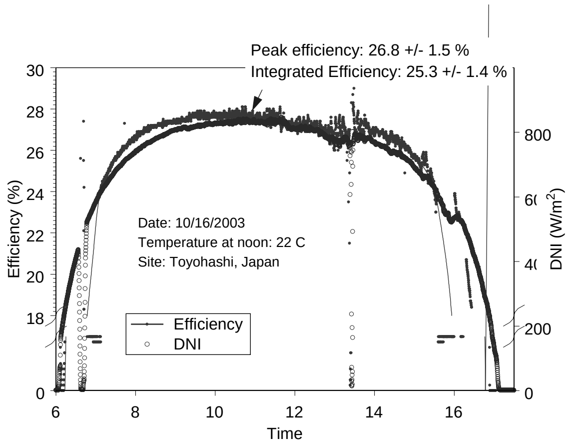

Figure 12: Power generation in a course of the day – clear sky day

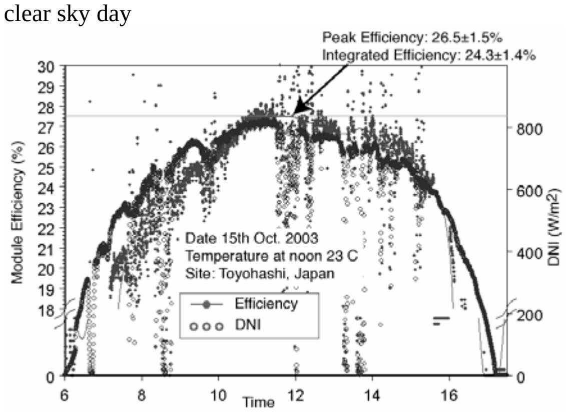

Figure 13: Power generation in a course of the day – sunny day with thin clouds

Power generation trend was compared with the commercial flat-plate crystalline silicon module (see Fig. 14). The newly developed concentrator module produced 2.9 times more power per area.

Continuous observation of power generation was done in Toyohashi site (See Fig. 15). As expected, the integrated efficiency over the course of the day decreased during the winter period. However, the average power generation was comparable to the non-tracking flat-plate module with the same rating power, in spite of the fact, the prototype system had experienced many troubles and output power was lost in this period associated with challenges of new technologies.

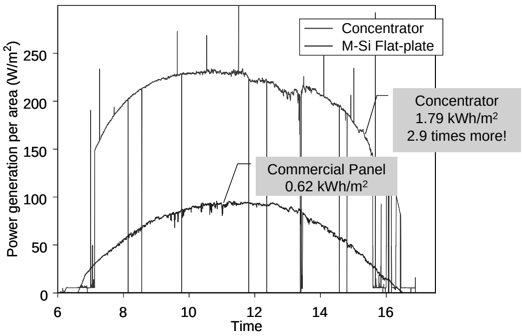

Figure 14: Comparison to a commercial flat-plate crystalline silicon module

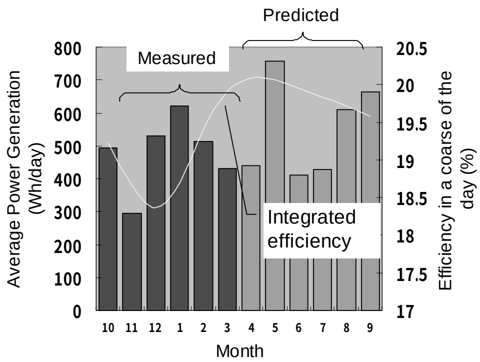

Figure 15: Power generation in each month

6 CONCLUSION

Research and development on concentrator solar electricity in Japan showed remarkable progress in these 3 years, including high-efficiency 3J concentrator solar cells, injection-molded Fresnel lens, new practical module technologies.

7 ACKNOWLEDGEMENT

This work was supported by the Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO) under Ministry of Economy, Trade and Industry (METI).

This work is partially supported by the Ministry of Education, Culture, Sports, Science and Technology as a Private University Academic Frontier Research Center Program "Super High-Efficiency Photovoltaic Research Center"

REFERENCES

[1] M. Yamaguchi and A. Luque, IEEE Trans. Elec. Dev. 46 (10), (1999), 2139
[2] A. W. Bett et al., 3rd WCPEC, (2003), 634
[3] A. W. Bett et al., SCC2003, (2003)
[4] M. J. O'Neill et al., ,28th IEEE PVSC, (2000), 1161
[5] K. Nishioka et al., 3rd WCPEC, (2003), 869
[6] K. Nishioka et al., Jpn. J. Appl. Phys. Vol. 43, No. 3 (2004), 882
[7] T. Takamoto et al., 3rd WCPEC, (2003), 581
[8] R. Leutz et al., (2001) Nonimaging Fresnel Lenses: Design and Performance of Solar Concentrators; Springer Verlag, Heidelberg
[9] M. Hiramatsu et al., 3rd WCPEC, (2003), 2379
[10] K. Araki, SCC2003, (2003)
[11] R. Leuts et al., Proc. ISES, (2001)
[12] B. McConell, SCC2003, (2003)
[13] K. Araki et al., 3rd WCPEC, (2003), 630

Daido Steel Co., Ltd.
attn. Kenji Araki
Tel. +81-52-611-9426, Fax + +81-52-611-2199
E-mail: k-araki@ac.daido.co.jp

Table 1. Roadmap table leading to a >31 % efficiency module

		Technologies in Nov. 2002	Achievement in Mar. 2004	Technologies in Mar. 2005	Technologies in Mar. 2006
A	Cell Efficiency @ 1sun	30.1 % (AVG)	31.0 % (AVG)		
B	Cell Efficiency 400 X	34.4 %(Direct)	35.3 % (Direct) 37.3 % (Global)		40 %
C	Lens Efficiency	72.4 %(Peak)	85.4 % (Peak) 81.0% (AVG)	Anti-fog coating	91 %
D	Homogenizer Efficiency	94.4 % (Typ.)	96.3 % (Typ.)	97.5 %	97.5 %
E	Ohmic Loss in Circuit	0.1 % (Typ.)	0.1 % (Typ.)	0.1 %	0.1 %
F	Spectrum Mismatching Loss	5.3 % (Typ.)	5.3 % (Typ.)		
G	Current Mismatching Loss	3.7 % (Peak)	2 – 4 %	2 %	2 %
H	Loss by Temperature Rise	1.2 % (Typ.)	1.3 % (Typ.)		1 %
I	Total Efficiency	21.7 % (Peak)	28 % (Peak)	> 29 %	> 31 %