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Overview and Efficiency Potential Analysis of Concentrator Solar Cells

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Abstract

Concentration photovoltaics (CPV) has great potential of higher efficiency and lower cost compared to conventional crystalline Si PV and thin-film PV. Although excellent results for CPV cells such as 27.6%, 29.3%, 44.4% and 46.1% with Si, GaAs, InGaP/GaAs/InGaAs 3-junction and InGaP/GaAs/InGaAsP/InGaAs 4-junction concentrator cells have been demonstrated thorough DOE, EC, NEDO and R&D projects of Europe-Japan Collaborative Research Project on Concentrator Photovoltaics, there are still problems to be solved. This paper overviews concentrator solar cells such as concentrator crystalline Si, GaAs, CIGS and III-V compound multi-junction solar-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. 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 ERE (external radiative efficiency) of 20% and reducing series resistance. This paper also presents our recent approaches for PV-powered vehicle applications: Demonstration car (Toyota Prius PHV) by using Sharp's high-efficiency III-V 3-junction solar cell modules (output power of 860W), static low concentrator InGaP/GaAs/InGaAs 3-junction solar cell module with efficiency of 32.84%, and so forth.

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 [1]. According to overview by R. M. Swanson [2], 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) maintain low-enough 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 the presentation, our recent approaches for PV-powered vehicle applications, especially static low concentration PV 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 under 1-sun operation and concentrator operation and future efficiency predictions of those solar cells (original idea by Professor A. Goetzberger et al. [3] and modified by M. Yamaguchi et al. [4]). The function chosen here (Eq. (1)) is derived from the diode equation):

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

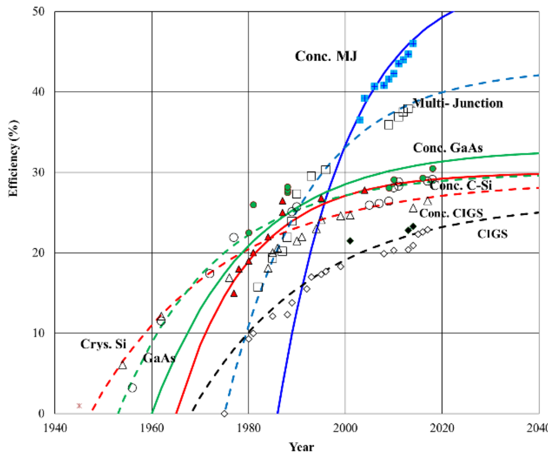

Fig. 1. Chronological efficiency improvements of crystalline Si, GaAs, III-V compound multi-junction (MJ) solar cells and CIGS solar cells under 1-sun and concentrator conditions.

3. Analytical procedure for estimating efficiency potential of concentrator solar cells

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. Open-circuit voltage is expressed by [5-9].

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

where the second term shows non-radiative voltage loss, and $V_{oc,\,rad}$ is radiative open-circuit voltage and is given by [5-9]

$V_{oc,\,rad} = (kT/q)\ln(J_L(V_{oc,rad})/J_{0,rad} + 1)$, (3)

where $J_L(V_{oc,rad})$ is photo-current at open-circuit in the case of only radiative recombination and $J_{0,rad}$ is saturation current density in the case of only radiative recombination. $\Delta V_{oc,\,rad} = E_g/q - V_{oc,\,rad}$ value [9].

Fill factor is dependent upon Voc and ideal fill factor FF_0 used in the calculation is empirically expressed by [10],

$FF_0 = [v_{oc} - \ln(v_{oc} + 0.72)]/(v_{oc} + 1)$, (3)

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

$v_{oc} = V_{oc}/(nkT/q)$, (4)

The fill factor is decreased as in crease in series resistance R_S and decrease in shunt resistance R_{Sh} of solar cell increases and approximated by

$FF \approx FF_0(1-r_s)(1-1/r_{sh}) \approx FF_0(1-r_s-1/r_{sh})$, (5)

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

$r_s = R_s/R_{CH}$, (6)

$r_{sh} = R_{sh}/R_{CH}$, (7)

The characteristic resistance R_{CH} is expressed by [10]

$R_{CH} = V_{oc}/I_{sc}$. (8)

In the calculation, highest values obtained were used as Jsc. Voc and FF were calculated by equations (1)-(8) and conversion efficiency potential of various solar cells were calculated as a function of ERE.

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

In this paper, analytical results for efficiency potential of Si, GaAs, CIGS and III-V 3-junction solar cells under 1-sun and concentrating illumination conditions are presented. Figure 2 shows calculated efficiencies of InGaP/GaAs/InGaAs 3-junction solar cells as a function of EREs in comparison with state-of-the-art efficiencies of InGaP/GaAs/InGaAs solar cells under 1-sun operation [5,6,13,14], and InGaP/GaAs/InGaAs 3-junction concentrator solar cells [5,6,13,14]. Highest efficiencies of 37.9% [13,14] and 44.4% [13,14] have been demonstrated with InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun and concentrator operations, respectively. InGaP/GaAs/InGaAs 3-junction solar cells under 1-sun operation have efficiency potential of more than 42% by realizing ERE of 10% from about 0.06% and normalized resistance of less than 0.025 from around 0.05 [5]. On the other hand, InGaP/GaAs/InGaAs 3-junction concentration solar cells have efficiency potential of more than 50% by realizing ERE of 10% from about 0.05%.

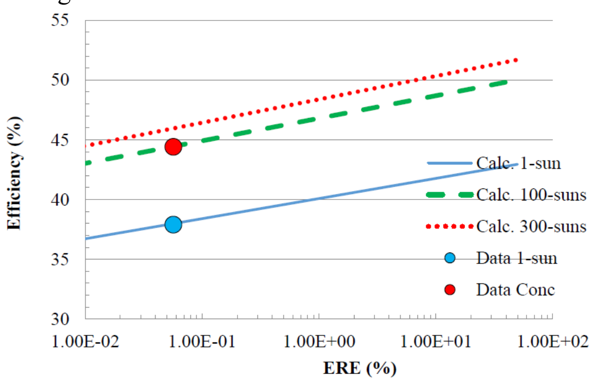

Fig. 2. Calculated efficiencies of InGaP/GaAs/InGaAs 3-junction solar cells as a function of ERE in comparison with state-of-the-art efficiencies of InGaP/GaAs/InGaAs solar cells under 1-sun and concentrator operations.

5. Our 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, 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).

6. Summary

This paper overviews concentrator solar cells such as crystalline Si, GaAs, CIGS and III-V compound multi-junction 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. Concentrator Si, GaAs, CIGS and InGaP/GaAs/InGaAs 3-juncton solar cells have efficiency potential of more than 34%, 36%, 31% and 50% by increasing ERE and reducing resistance losses.

Although high performance CPV is very promising, there are some problems to be solved:

1) Development of much higher efficiency CPV cells >50%, modules >40%.
2) Development of low-cost and highly reliable CPV cells, modules and systems,
3) Field test, energy generation forecast and energy management of CPV systems and hybrid systems with storage battery.
4) Development of automobile, agriculture, large-scale PV applications and so forth.

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