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Analysis for Future Generation Solar Cells and Materials

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Abstract

Efficiency potential of future generation solar cells such as wide bandgap Chalcopyrite, CZTS and CZTSSe solar cells, MQW and QD solar cells is discussed based on ERE (External Radiative Efficiency), open-circuit voltage loss and fill factor loss and non-radiative recombination loss. CZTS and CZTSSe solar cells have efficiency potential of more than 20% by improvement in ERE from around about 0.001% to 1%. MQW and QD cells have efficiency potential of 24.8% and 25.8% by improvements in ERE from around 0.1% to 1% and 10%, respectively.

1. Introduction

Future generation solar cells such as wide bandgap chalcopyrite, CZTS (Cu_2ZnSnS_4), CZTSSe ($Cu_2ZnSn(S,Se)_4$), MQW (Multi Quantum Well) and QD (Quantum Dot) solar cells are very attractive because of high efficiency potential. However, there are non-radiative recombination losses in those materials and solar cells. In this paper, efficiency potential of future generation solar cells is discussed based on ERE, open-circuit voltage loss and fill factor loss and non-radiative recombination losses.

2. Analytical procedure for estimating efficiency potential of future generation solar cells

In order to realize higher efficiency of various solar cells, improvements in short-circuit density Jsc, open-circuit voltage Voc and fill factor FF are substantially necessary.

The open-circuit voltage Voc is given by

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_L}{J_0}+1\right) \quad (1)$$

where k is Boltzmann constant, T is absolute temperature, q is electronic charge, J_L is photon generated current density , and J_0 is saturation current density. In order to increase Voc, decrease in saturation current density J_o is essential.

One of problems to attain the higher efficiency solar cells is the higher minority-carrier lifetime in various materials. Figure 1 shows open-circuit voltage drop compared to bandgap energy (Eg/q-Voc) and non-radiative voltage loss (Voc, nrad) in various solar cells as a function of external radiative efficiency (ERE). Open-circuit voltage is expressed by [1-3].

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

where the second term shows non-radiative voltage loss, and $V_{oc,\,rad}$ is radiative open-circuit voltage and is given by [1-3]

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

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 and 0.28V was used as the $\Delta V_{oc,\,rad} = E_g/q - V_{oc,\,rad}$ value [3] in Fig. 1.

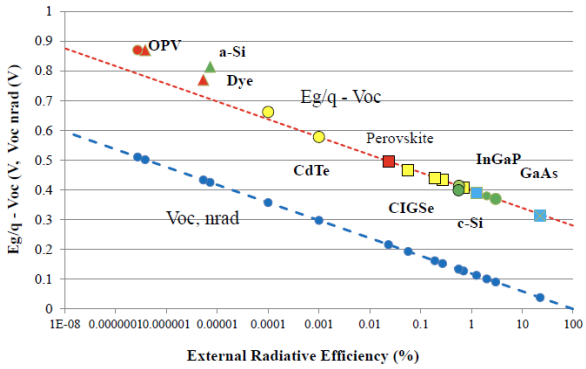

Fig. 1. Open-circuit voltage drop compared to bandgap energy (Eg/q-Voc) and non-radiative Voc (Voc, nrad) in various solar cells as a function of external radiative efficiency (ERE).

As shown in Fig. 1, even crystalline Si solar cells have still non-radiative loss and further improvements in efficiency are thought to be possible by improving minority-carrier lifetime and reducing recombination losses.

Fill factor is dependent upon Voc and ideal fill factor FF_0 used in the calculation is empirically expressed by [4],

$$FF_0 = \frac{v_{oc} - \ln(v_{oc}+0.72)}{v_{oc}+1} \quad (4)$$

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

$$v_{oc} = V_{oc}/(nkT/q) \quad (5)$$

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

$$FF \approx FF_0(1-r_S)(1-1/r_{sh}) \approx FF_0(1-r_S-1/r_{sh}) \quad (6)$$

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

$$r_s = R_S/R_{CH} \quad (7)$$

$$r_{sh} = R_{sh}/R_{CH} \quad (8)$$

The characteristic resistance R_{CH} is expressed by [4]

$$R_{CH} = \frac{V_{oc}}{I_{sc}} \quad (9)$$

In the calculation, highest values obtained were used as Jsc. Voc and FF were calculated by equations (1)-(9) and conversion efficiency potential of various solar cells were calculated as a function of external radiative efficiency (ERE).

3. Analysis for efficiency potential of future generation solar cells

The CZTS and CZTSSe solar cells have drawn worldwide attention due to earth-abundant composition and high-efficiency potential. However, CZTS and CZTSSe solar cells have larger non-radiative recombination loss compared to those in CIGSe and CdTe cells Figure 2 shows calculated efficiency of CZTS, CZTSSe and CIGSe solar cells as a function of ERE [3] and efficiency values for CZTS and CZTSSe cells reported by Solar Frontier [6-8] and IBM [5,9], and CIGSe cells reported by Solar Frontier [5,10], ZSW [2,11,12] and NREL [2,11,12]. At present, although high efficiency of 22.3% and 22.6% has been attained with the CIGSe cells [5,10], CZTSSe cell has shown much lower efficiency of 12.6% [5,9] and thus there are some problems to be solved. In summary, in the CZTS and CZTSSe solar cells, efficiencies over 20% will be realized with $r_s + 1/r_{sh}$ of 0.2 by improvements in ERE into more than 1% from about 0.001% as shown in Fig. 2. In order to improve ERE in CZTS and CZTSSe cells, improvements in non-radiative recombination losses in active layers and interfaces based on understanding defects and interface in those cells.

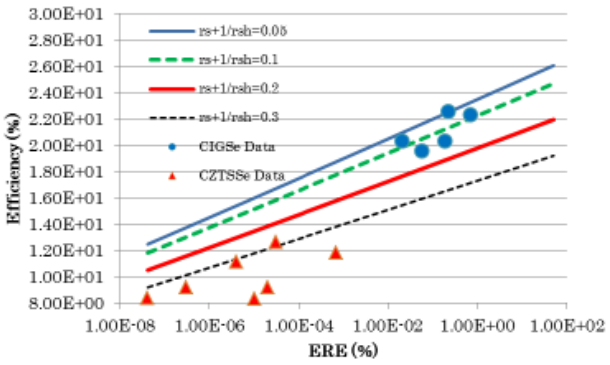

Fig. 2. Calculated efficiency of CZTS, CZTSSe and CIGSe solar cells as a function of ERE and $r_s + 1/r_{sh}$ in comparison with efficiencies of CZTS, CZTSSe and CIGSe solar cells reported.

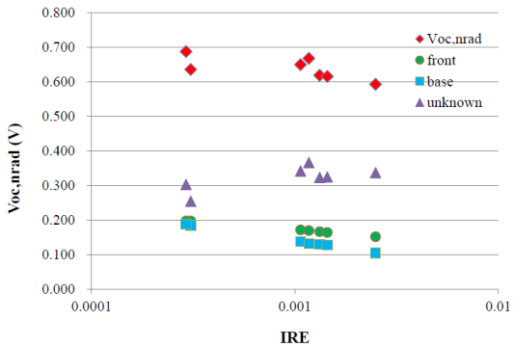

Fig. 3. Voltage losses of CZTS and CZTSe solar cells as a function of internal radiative efficiency and contribution from front, base and unknown part.

Figure 3 shows voltage losses of CZTS and CZTSe solar cells fabricated at the Solar Frontier [8] and AIST [13] as a function of internal radiative efficiency and contribution from front, base and unknown part. Because CZTS and CZTSe cells have larger non-radiative recombination loss compared to those in CIGSe and CdTe cells as shown in Fig. 3, understanding and reducing non-radiative recombination loss in order to improve performance of CZTS and CZTSe cells.

The MQW and QD solar cells have also drawn wild-wide attention due to one of innovative approaches and high-efficiency potential. However, interface recombination is one of problems to be solved for realizing high-efficiency MQW and QD cells. Figure 4 shows calculated efficiency of MQW and QD solar cells as a function of ERE and efficiency values for GaAs solar cells by Alta Devices [2,5,14] and FhG-ISE [2,11,12], and MQW and QD cells reported by Imperial College [15], Ioffe Inst., [16], Rochester Inst. [17], and Univ. Tokyo. [18-20]. as a function of ERE [3]. Although the GaAs solar cells have realized highest ERE of 22.5% [2], MQW and QD solar cells have much lower ERE of less than 0.1%. Further improvement in efficiency are also thought to be possible by improving minority-carrier lifetime and reducing non-radiative recombination losses as a results of increasing ERE and decreasing $r_s + 1/r_{sh}$. In summary, efficiencies over 24 % such as 24.8 % and 25.8 % will be realized with $r_s + 1/r_{sh}$ of 0.1 by improvements in ERE 1% and 10%, respectively from 0.1 % as shown in Fig.4. In this paper, intrinsic losses [21] in MQW and QD solar cells are also discussed as well as non-radiative recombination losses.

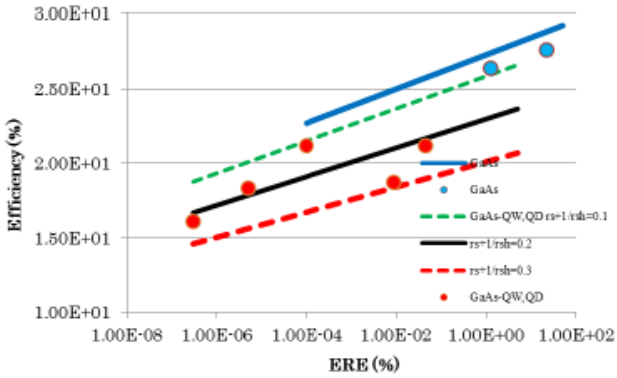

Fig. 4. Calculated efficiency of MQW and QD solar cells as a function of ERE and $r_s + 1/r_{sh}$ in comparison with efficiencies of GaAs solar cells reported by Alta Devices and FhG-ISE and MQW and QD cells reported by Imperial College, Ioffe Inst. Rochester Inst., and Univ. Tokyo.

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