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Numerical prediction of InGaAs/GaAs MQW solar cell characteristics under concentrated sunlight

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Abstract

The characteristics of InGaAs/GaAs multi-quantum well (MQW) solar cells under concentrated sunlight were analyzed by self-consistent numerical calculation and were compared with GaAs p–i–n cells that have the same structure except for the QWs. Prior to the calculations, the absorption coefficients of the InGaAs MQW cell were determined by fitting the calculated quantum efficiencies to experimental ones. In the simulation, mainly the influences of concentrated sunlight and temperature were investigated. Results of the simulation showed that the rate of the conversion efficiency and open-circuit voltage (V_{oc}) of MQW cells increased faster than that of p–i–n cells as the light intensity increased, while the rate of efficiency of the MQW cell decreased a little slower than that of the p–i–n cell with the temperature increase. MQW cells compensate for the disadvantage of lower efficiency and V_{oc} than p–i–n cells in a concentrated sunlight system.

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1. Introduction

In 1990, multi-quantum well (MQW) solar cells were first proposed by Barnham and Duggan [1]. According to their explanation, the output voltage is primarily determined by the wider band gap bulk material while spectral response is determined by the width and depth of the narrower band-gap material, QWs. Thus, if the current and voltage are independently optimized, the MQW cell conversion efficiency can exceed the efficiency limit of a single-band-gap cell. Photo-response enhancement of

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the cell has been observed in the long-wavelength region so far [2]. Nowadays, the MQW solar cell study focuses on whether higher open-circuit voltage (V_{oc}) and higher conversion efficiency can be achieved [3, 4].

Numerical analysis is very useful in this research because it is possible to simulate MQWs with fewer defects. We applied self-consistent numerical analysis to the MQW cell structure, where Poisson equation and current continue equations were simultaneously solved, to predict exact MQW cell I–V characteristics under a normal sunlight incident. This analysis showed that improvement in MQWs enables MQW cell performance to exceed that of the single-band-gap cell though it is difficult for the V_{oc} of MQW cells to exceed that of the single-band-gap cell [5].

It is very difficult to make radical improvement in the hetero-epitaxial technology for the MQWs. However, despite their shorter carrier lifetime, it is expected that the MQW cells under concentrated sunlight can compensate for the disadvantage of lower open-circuit voltage than the ordinary p–i–n cells. Of course, the use of the cells under higher light concentration has another merit; it reduces the amount of high-cost materials. We analyzed the performances of InGaAs/GaAs MQW solar cells under concentrated sunlight by using self-consistent numerical calculation. In this article, the effectiveness of concentrated sunlight and the influence of temperature are evaluated and discussed.

2. Modeling and calculating method

2.1. Cell Structure

We experimentally investigated the MQW cell [6]. The simulation was performed on the basis of the experimental data. Our MQW cell structure is shown in Fig. 1. The cell constists of MgF_2/ZnS double anti-reflection layers, an $Al_{0.7}Ga_{0.3}As$ window-layer, a GaAs p-layer, an MQW layer, a GaAs n-layer, and a GaAs n-substrate. The MQW layer was assumed to have five $In_{0.15}Ga_{0.85}As$ wells in the undoped GaAs

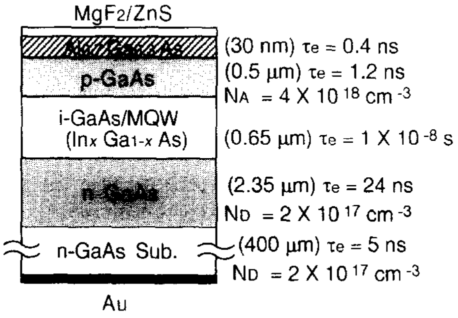

Fig. 1. The cross-section of MQW cell. The MQW layer has 5 InGaAs wells in the undoped GaAs region. Each well width is 20 nm and the thickness between wells is 90 nm. 'x' indicates the content of Indium in the InGaAs layers.

region. Each well width was 20 nm and the thickness between wells was 90 nm. As reference cells, p–i–n GaAs cells with the same structure except for the MQWs were simulated to compare with the cell performance of MQW cells. These parameters are typical of our fabricated cells.

2.2. Simulation method and absorption coefficient

The calculations were performed on a two-dimensional hetero-junction device simulator, HIHEART, to which we specially added a photo-generation function to simulate solar-cell activity. This simulator can give the exact reflectance, transmission, and absorption of each layer by solving the characteristics matrix [6]. Ordinarily, this characteristics matrix method cannot be used to calculate the reflectance and transmission for lower absorption material such as in the long-wavelength region of indirect semiconductor, because the reflectance and transmission vibrate as a function of wavelength. We eliminated the vibration by introducing a calculation algorithm of an averaging method. The calculated reflectance obtained from our simulator was in good agreement with the experimental data.

The absorption coefficients of the InGaAs MQW cell were determined by fitting the calculated quantum efficiencies to experimental ones [7]. For the fitting, the effective lifetime of each layer had to be decreased about one order of magnitude from that in Fig. 1. The fabricated MQW cells presumably have layers with these effective lifetimes. Fig. 2 shows the extinction coefficient calculated from the obtained absorption coefficient. These coefficients generally agree with reference coefficient [8]. Peaks caused by exiton absorption are observed in the figure. Thus, this simulation considers the subband effect with regard to light absorption. With regard to electric conduction, this simulator uses a drift-diffusion model,which means the tunnel effect cannot be treated. However, it seems reasonable to neglect tunnel current because of the thick walls between wells.

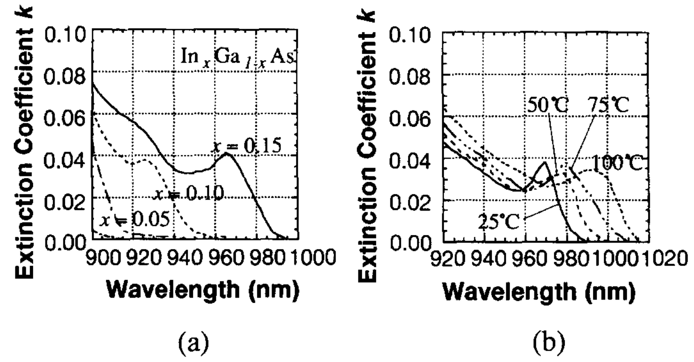

Fig. 2. Extinction coefficients obtained by fitting numerical quantum efficiencies to experimental photoresponse. (a) $In_xGa_{1-x}As$ MQWs, (b) Several temperatures.

3. Results and discussion

3.1. *Influence of concentrated sunlight*

Calculations were performed using the absorption coefficients stated above. Fig. 3 shows the conversion efficiency and the V_{oc} of the InGaAs/GaAs MQW cell and those of the GaAs p–i–n cell as a function of light intensity for four Indium contents (x). The effective lifetime of MQW layers and the i-layer is assumed to be 1.0×10^{-8} s. Based on the experimental quantum efficiency, the effective lifetimes assumed for all layers would be about one order of magnitude higher than those of our fabricated cell. As the light intensity increases, all cells' efficiencies and open-cicuit voltages increase. In particular, the rate of increase in efficiency for the MQW cell is larger than that of the p–i–n cell. The increase of Indium content enhances this effect. The efficiency of the MQW cell with Indium content of 0.05 exceeds that of the p–i–n cell at ~ 1000 suns. These effects are attributed to the variation of V_{oc} which is proportional to the logarithm of the light-generated current. In this case, it should be noted that the difference of the light-generated current between the cells expands exponentially because the light intensity increases exponentially on the x-axis.

An investigation of carrier recombination is useful in understanding the above discussion. Fig. 4 shows the carrier recombination distribution under 1 sun and 1000 suns at the open-circuit voltages of the MQW cell. Solid lines are $In_{0.15}Ga_{0.85}As$/GaAs MQW cells and dashed lines are GaAs p–i–n cells. In the MQW cell, the generation rate and the recombination rate are higher in the wells as shown in the figure. Under 1 sun, the recombination rate of the MQW cell is higher than that of the p–i–n cell when the distance from the surface is 0.9 to 1.2 μm. This reduces the V_{oc} of the MQW cell. Actually, the cumulative carrier recombination of

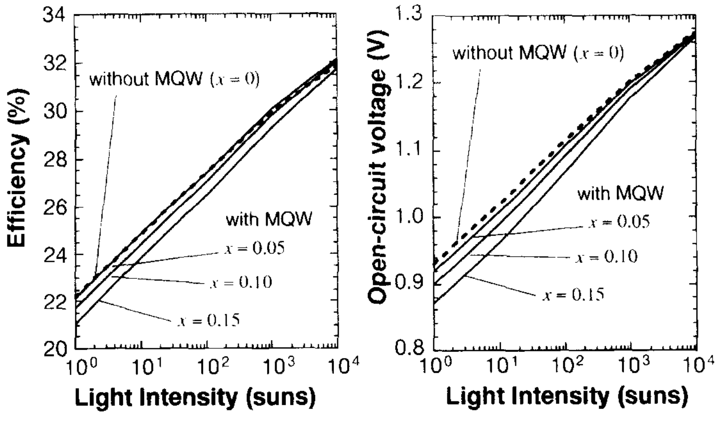

Fig. 3. Conversion efficiency and open-circuit voltage as a function of light intensity for several Indium contents at the MQW effective lifetime of 1.0×10^{-8} s. Solid lines are $In_xGa_{1-x}As$/GaAs MQW cells and dashed lines are GaAs p–i–n cells.

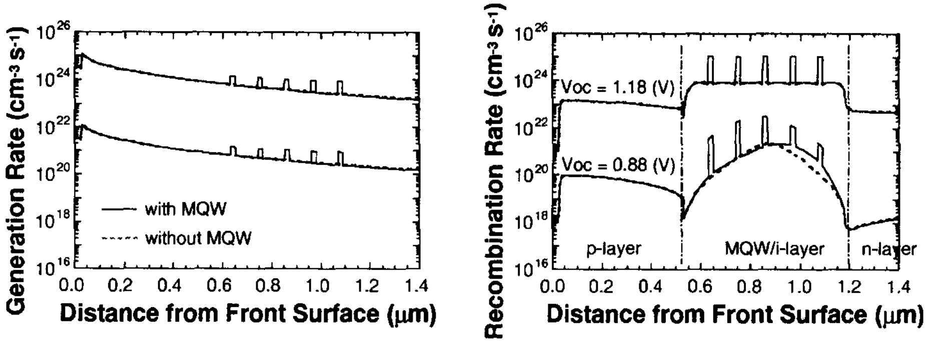

Fig. 4. Generation/Recombination rate distributions for $In_{0.15}Ga_{0.85}As/GaAs$ MQW cell and GaAs p–i–n cell under MQW cell open-circuit conditions under 1 sun and 1000 suns. Each well is positioned on the peaks.

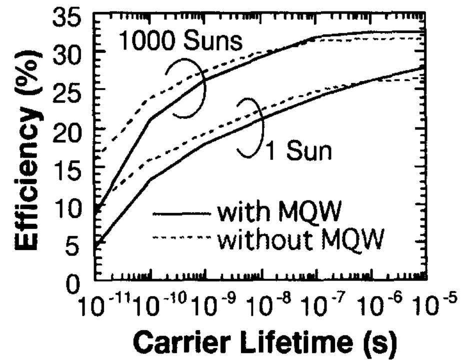

Fig. 5. Conversion efficiency as a function of effective carrier lifetime of $In_{0.15}Ga_{0.85}As/GaAs$ MQW layers for two light intensities. Solid lines are $In_{0.15}Ga_{0.85}As/GaAs$ MQW cells and dashed lines are GaAs p–i–n cells.

the MQW cell is equal to the cumulative carrier generation of it while the cumulative carrier recombination of the p–i–n cell is less than the cumulative carrier generation at the V_{oc} of the MQW cell. Under 1000 suns, the difference of recombination between both cells disappears except at the wells. This reduces the difference in the V_{oc} of both cells.

When the effective lifetime of the MQW layers is 1.0×10^{-8} s, the light intensity required to surpass the single-band-gap cell performance is about 10,000 suns for the MQW cell. This is very difficult to achieve. Fig. 5 compares the efficiency of the MQW cells with that of p–i–n cells under 1 and 1000 suns as a function of effective lifetime in the MQW layer (in the case of p–i–n cells, the i-layer). In the longer lifetime region, the efficiency of MQW exceeds that of the p–i–n cells. Fig. 5 also shows that the lifetime where the efficiency of the MQW cells reaches that of the p–i–n cells is shorter under 1000 suns than under 1 sun. This is mainly due to the improvement in the V_{oc} under concentrated sunlight, as stated above. For MQW cells to perform better than p–i–n cells, the MQW layer requires a lifetime of ~ 100 ns under 1000 suns. This lifetime value will be achieved with slight progress in hetero-epitaxial technology.

3.2. *Influence of cell temperature*

In a concentrated sunlight system, the cell temperature is a very important factor. Ordinarily, its increase causes the rapid drop of V_{oc}. Fig. 6 shows the calculated solar cell performances as a function of temperature from 25°C to 100°C under 1000 suns. The MQW cell performances, except for the short-circuit current (J_{sc}), worsen as the temperature increases.

The increase of J_{sc} is due to the extinction coefficient shifting to the infrared region as shown in Fig. 2. The absorption coefficients of both types of cells increase in the whole wavelength region and the absorption edge of them shifts to the infrared region due to band-gap narrowing with increasing temperature. In the QWs, the escape of carriers is enhanced by thermal contribution. The J_{sc} increasing rater of the MQW cell is consequently a little more than that of the p–i–n– cell.

On the other hand, the V_{oc} and fill factor (FF) rates of decrease in the MQW cell are a little lower than those of the p–i–n cell. Although we have not fully investigated the reason, it seems that the recombination in the depletion-region influences the V_{oc} and FF.

As a result, as temperature increases, the rate of decrease in efficiency of the MQW cell is a little less than that of the p–i–n cell at the MQW effective lifetime of 1.0×10^{-8} s. This indicates that the increase of temperature does not greatly harm the MQW cell performances, as compared with p–i–n cells.

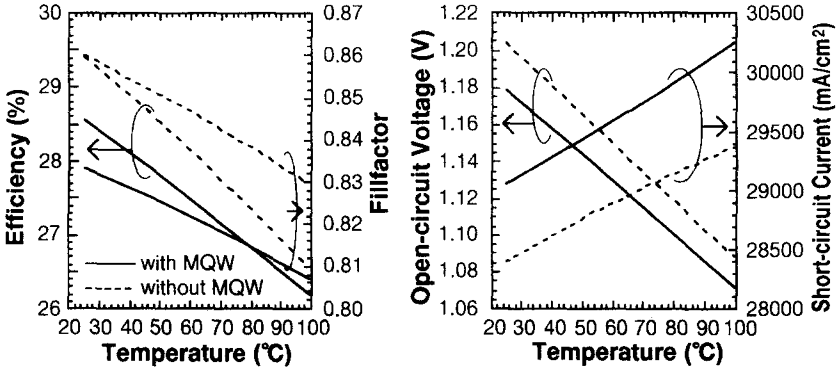

Fig. 6. Solar cell performances as a function of temperature for $In_{0.15}Ga_{0.85}As$/GaAs MQW cell and GaAs p–i–n cell under 1000 suns. The MQW effective lifetime is 1.0×10^{-8} s.

4. Conclusions

We have used numerical analysis to analyze InGaAs/GaAs MQW solar cells under concentrated sunlight. The absorption coefficients of the InGaAs MQW cell were determined by fitting the calculated quantum efficiencies to experimental ones.

The calculated results show that the rate of efficiency and V_{oc} of MQW cells increases faster than that of p–i–n cells as the light intensity increases. Also, the MQW cell performances except for J_{sc} worsen as the temperature increases although the efficiency of the MQW cell degrades slower than that of the p–i–n cell. This means that the increase of temperature does not greatly harm the MQW cell performances, as compared to p–i–n cells. The results indicate that, under a concentrated sunlight system, MQW cells compensate for the disadvantage of lower efficiency and V_{oc} and the performance of MQW cells could exceed that of p–i–n cells with slight progress in hetero-epitaxial technology.

Acknowledgements

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