論文の内容の要旨

An Investigation on Strain-balanced Stepped-potential Quantum Well Solar Cells for Higher Efficiency

（高効率化に向けた歪み補償階段ポテンシャル量子井戸太陽電池に関する研究）

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(Abstract)

This work has focused on strain-balanced quantum well and stepped quantum well solar cells. The unique points of this work from previous reports and publications are as followed:

1. Stepped quantum well structure is an outstanding point of this work, since at the present time all of publications related to normal quantum well solar cell. Through the research work in this thesis, we know there is some other choice, allowing us to improve solar cell performance better.
2. Not only solar cell performances like IV and QE were measured, but also carrier escape kinetics and recombination losses were investigated by time-resolved PL, temperature-dependent PL and bias-dependent PL. It is beneficial to provide a clear way to understand how to optimize the structure in order to improve efficiency.

The experiments in this thesis have been carried out step-by-step from the investigation of strained InGaAs/GaAsP quantum well solar cell, strain-balanced (SB) InGaAs/GaAsP quantum well solar cell, strain-balanced InGaAs/GaAs/GaAsP stepped quantum well solar cell and deep stepped quantum well solar cell.

In chapter 3, it has related to the epilayer growth of InGaAs/GaAsP MQWs by metal-organic vapor-phase epitaxy (MOVPE). In the absence of lattice matched l.2 eV material, strained InGaAs was used as the quantum well material. However strained quantum wells introduce misfit dislocations into the structure that dominate the recombination of the cell. The associated loss in short-circuit-current and open-circuit-voltage is shown to be too large to allow strained GaAs/InGaAs QW cells to realistically match GaAs in terms of power conversion efficiency. Strain-compensation (SC) is exploited to surmount the limitations imposed by strain. GaAsP tensile strain compensation layers were introduced into QW solar cell to compensate compressive strain from InGaAs quantum wells. Actually the more strain accumulated in the QWs, the worse crystal quality, which can be characterized by *ex-situ* XRD and photoluminescence.

Furthermore, strained and strain-compensated MQW solar cells have been fabricated to check out the contribution of MQW. As strained QW and strain-compensated QW show such significant difference in crystal quality, we fabricated the strained QW solar cell and the strain-compensated (SC) QW solar cell by MOVPE to make a comparison. Under simulated 1 sun AM1.5 conditions, IV and QE results have demonstrated the effectiveness of strain-compensation for improving the performance of quantum well solar cells. The SB InGaAs/GaAsP QW solar cell shows an increase both in short-circuit-current and open-circuit-voltage compared with the strained InGaAs/GaAs solar cell owing to reduced minority carrier recombination. The increased Voc can be related to a reduction in recombination current through the dependence of Voc on both Jsc and dark current.

In chapter 4, stepped MQW structure was designed to lessen large mismatch at the interface and promote carrier escape outside the QWs. The fundamental principle of a quantum well solar cell is that MQWs are inserted in the undoped region of p-i-n cell so that it can absorb photons with energy below host material’s bandgap. In this way, the short-circuit current can be increased depending on the well material with lower bandgap. However, there is still a risk of trapping carriers inside QWs and promoting radiative and non-radiative recombination which leads to an increase in dark current and a reduction in open circuit voltage, although it is possible to minimize the negative effect by strain-compensated technology. With the aim of promoting carrier escape from quantum wells, we introduce $In_{0.16}Ga_{0.84}As/GaAs/GaAs_{0.79}P_{0.21}$ strain-compensated multiple stepped quantum wells (SC-MSQWs). We describe and contrast QWSCs with and without GaAs step layer between the InGaAs well and the GaAsP barrier. The effect of the GaAs step layer was evaluated by atomic force microscopy (AFM) and XRD. The MSQW cell shows a smoother surface with smaller RMS measured by AFM. The total net strain in the QW structure seems to be reduced by inserting GaAs strain-reducing layer. The MSQW cell exhibits higher Jsc (19.29 mA/cm2) than the normal MQW cell (16.85 mA/cm2). The enhanced FF for the MSQW cell suggests that carrier transport was improved through the emitter and intrinsic region.

In chapter 5, we investigate the relationship between strain distribution and the GaAs step layer thickness. The accumulated strain decreases inside the QWs with the increasing

GaAs step layer, the main reason improving the crystal quality. Furthermore, we also studied the absorptance spectra, sub-GaAs-bandgap quantum efficiencies, IV curves, and their relationship with the GaAs step layer thickness. As the InGaAs absorber layer thickness keeps the same, the absorption doesn’t show much difference. Sub-GaAs-bandgap increases with the increasing GaAs step layer, and it is related to the increasing collection efficiency, rather than the absorption. However, no matter carrier escape rate or collection efficiency, they become saturated when the GaAs step layer reaches 8 nm. The conclusion is the optimal GaAs step layer thickness is 8 nm.

In previous chapters, shallow wells (16% Indium) have been shown to increase the short circuit current of strain-balanced quantum well solar cells (SB-QWSCs) with a comparatively small loss in open circuit voltage and are thus able to enhance efficiency relative to comparable conventional cells. These shallow well solar cells extend the photon absorption edge to 960 nm in the solar spectrum. An improvement in three-junction solar cell efficiency is expected for deeper wells with a band edge beyond 1000 nm. However, fabrication of abrupt heterointerface in InGaAs/GaAsP systems is difficult by metal organic vapor phase epitaxy (MOVPE). This is mainly due to Indium diffusion and surface segregation, especially in the case of high Indium content. In chapter 6, deep stepped quantum well solar cell with the double step layer InGaAs/GaAs was developed. The diffusion of indium between InGaAs/GaAsP interfaces and InGaAs/GaAs step interfaces was investigated in MQW solar cell. The absorptance spectra in the wavelength region of 900nm to 1000nm have been measured to check how much light is absorbed by the effective absorber layer InGaAs. The Indium diffusion between InGaAs/GaAsP interfaces can kill photon absorption. It will also degrade sub-GaAs bandgap QE of solar cells. The sub-GaAs bandgap QE for the deep MSQW cell is higher than that of the normal MQW cell.

This thesis has clearly demonstrated the potential and capability of stepped quantum well structure. The strong absorption and carrier collection ability has been successfully realized.