論 文 の 内 容 の 要 旨

Thesis Summary

論文題目

Study on limiting factors of efficiency in
InGaP multiple-quantum-well solar cells and their optimum design
（InGaP多重量子井戸太陽電池の変換効率制限要因の検討と最適設計）

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A general design guideline for MQWs toward high-efficiency MJSCs

A general guideline for designing multiple-quantum-wells (MQWs) targeting at a particular optical absorption threshold for high-efficiency multi-junction solar cells (MJSCs) was proposed. We demonstrated a full design flow by designing an InGaP/InGaP strain-balanced MQW for a triple-junction dual-MQW solar cell to replace the bulk $In_{0.49}Ga_{0.51}P$ top cell (1.91 eV). The structural parameters, i.e. the well and the barrier thicknesses, were uniquely defined by the two design constraints firstly. Next, evaluating the effective mobility of the MQW designs, we quantitatively resolved the contributions of each transport mechanisms (the thermal escape process, direct tunneling process, and the thermally-assisted tunneling process) with all possible combinations of the band alignment, i.e. shallow-well, deep-well, high-barrier, and high-barrier deep-well configurations, for the first time. We found that thermal escape is the most dominant mechanism for carrier transport compared with the tunneling process. As a result, the domain with higher effective mobility is localized in the low-barrier constituent domain. The constituent materials for the wells and the barriers were optimized by evaluating their device performance. By estimating the critical mobilities, we derived an optimized SB-MQW design with acceptable degraded carrier transport. On the other hand, based on our new design technique, we discussed the possibility of further improving our previously-developed 1.23 eV-InGaAs/GaAsP MQW for quad-junction solar cells in terms of the constituent materials. We concluded that by reducing the phosphor content in the GaAsP-barrier, the efficiency of the current device can be further promoted because of the facilitated thermal escape process. However, because the required optimum absorber thickness increases, the impacts of the background doping become more critical. We estimated that the background doping must be carefully suppressed to lower than $\sim 10^{14}$ cm^{-3} by an appropriate growth condition so that MQW solar cells could still be considered as an ideal *p-i-n* diode. Experimental demonstrations of facilitated photon-coupling and the improved efficiencies based on the proposed InGaP/InGaP SB-MQW and the InGaAs/GaAsP SB-MQW designs suggest promising future research topics. Our design technique provides insight to explore the optimum combination of constituent materials toward better performance for the first time.

Study on the limiting factors of efficiency in InGaP quantum well solar cells

Solar cells based on multiple quantum wells have attracted a great deal of attention in recent years. Due to the superior radiative nature, the output voltage had been expected to be more ideal over solar cells made of bulk materials. It had been intuitively speculated that there would be a trade-off consideration between the degradation of carrier transport in terms of carrier collection efficiency (*CCE*) and the improvement of radiative efficiency (*ERE*) when designing the optimum constituent materials for quantum well solar cells. However, comparison among quantum-well solar cells had been mainly done based on the devices with different optical absorption edges in the previous research, which implies an unfair comparison. By using the general design framework proposed in Chapter 4, we found that *ERE* was strongly correlated with *CCE*, which causes that the energy conversion efficiency η is strongly correlated with its *CCE* as well. By throughout investigating the significant four scenarios ((1) with degraded carrier transport, (2) with improved crystal quality, (3) with higher absorption, and (4) with a higher concentration ratio), we determined that improving τ_{SRH} over ~57 ns, or when concentration ratio exceeds ~25, the *p-i-n* solar cells begin to reach the radiative limit. In conclusion, by comparing the weakly-confined and highly-confined quantum well solar cells in a fair manner, we concluded that the constituent domain that leads the highest energy yields always converges to the weakly-confined constituent domain with good carrier transport. For prospects, although the several essential assumptions employed in the simulation for the sake of analysis may be difficult to be realized experimentally (e.g., identical SRH-lifetimes for the highly-confined and the weakly-confined quantum-well solar cells, …etc.), the crucial conclusions in this research can be partially proven by demonstrating the dependence of the *ERE* on the *CCE* with any SB-MQW solar cells.

Applications of the general MQW design guideline

In order to demonstrate proof-of-concept, we have grown SB-MQW samples by using Metal-Organic Vapor-Phase Epitaxy (MOVPE) method, fabricated devices, and characterized their device performance. First of all, two double-hetero samples for a 400-nm-thick $In_{0.49}Ga_{0.51}P$ and a 400-nm-thick InGaP/InGaP SB-MQW designed in chapter 4 were grown. As identified by the X-ray diffraction pattern, the samples demonstrated good agreement with the designed parameters. Furthermore, by using a 532-nm laser for PL-measurement, we found that both samples exhibit identical emission peak wavelength at 679 nm (1.83 eV), which proofed an excellent agreement with the model despite the deviation from the targeted wavelength at 649 nm (1.91 eV) due to the atomic ordering effect. This ensured a fair comparison for the InGaP/InGaP SB-MQW design with the $In_{0.49}Ga_{0.51}P$ bulk for the first time. Remarkably, our InGaP SB-MQW design demonstrated higher emission intensities under the same excitation conditions. These results suggested that our SB-MQW design could be a promising candidate for serving as the top cell of the triple-junction dual-MQW solar cell for an enhanced photon-coupling between the top cell and the middle cell. Therefore, its tolerance against the fluctuation of the incoming solar spectrum for space system can be improved, promoting its long-term reliability. A further demonstration of photon-coupling by fabricating a triple-junction dual-MQW solar cell based on the current designs is the next essential stage of this research.

Next, the general design guideline was further applied to designing a photonic power converter (PPC) with a targeted wavelength at 977 nm. Conventional PPCs based on bulk materials suffer from significant relaxation loss. A promising solution to this is to employ an MQW architecture with a matched exciton peak wavelength with the monochromatic light source for power conversion. To ensure satisfactory effective mobility for power conversion, an MQW absorber with carefully-tailored constituent materials and structural parameters targeting at a particular wavelength of an optical power source is necessary. Another critical problem relates to a demanded absorber thickness of up to 20 μm. Without using a highly strain-balanced structure, the heteroepitaxy absorber may severely suffer from a lack of absorption resulting from its limited thickness. Therefore, the proposed general design framework was applicable. Following the similar design flow as introduced in chapter 4, we derived an optimum PPC design based on a 30-periods InGaAs/GaAsP SB-MQW structure. By measuring the external quantum efficiency, we found that the deviation of the exciton peak position 979 nm from the design value of 977 nm was only 2 nm, suggesting an excellent agreement with our targeted PPC device. On the other hand, the open-circuit voltage of the devices was 0.912 V under AM1.5G illumination, for a band gap-voltage offset of 0.345 V which is better than can be expected for any bulk material. Fill factor was 80.1%, and carrier collection efficiency drooped by 4% per volt of bias. We have made the first demonstration of an MQW photonic converter subcell for the 977 nm band, with excellent open-circuit voltage and collection efficiency.

Based on the above results, we have successfully proofed the fidelity of our general design framework for optimizing both the structural parameters and the constituent materials of MQW devices. Our design technique is considered to be applicable not only to QW solar cells but also to most of the optoelectronic devices based on MQWs to explore the optimum combination of constituent materials toward better performance.