論文の内容の要旨

論文題目　Research on improvement of MQWs solar cell's performance through development of growth technology and novel tunneling-assisted structure

（結晶成長法の改善とトンネル援用構造の導入による多重量子井戸太陽電池の特性改善に関する研究）

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The research into photovoltaic renewable energy source is more and more intensive due to the rapid increase of worldwide power consumption. In order to achieve high efficiency solar cells, one strategy is the utilization of the multi-junction. Unfortunately, one important factor limiting the efficiency of III–V/Ge multi-junction solar cells is the current mismatch among sub-cells, especially the low current density in the GaAs middle junction. One effective method to achieve better current balancing and higher performance is the extension of the absorption edge of the GaAs middle cell by implementing a lower band gap InGaAs material. However, the lattice constant of InGaAs is larger than that of GaAs and the lattice mismatch causes the growth to be quite difficult. To avoid accumulating strain in InGaAs layers that induces crystal defects and thus degrades the efficiency of a solar cell, a strain compensating structure such as InGaAs/GaAsP multiple quantum wells (MQWs) is a favorable option. However, up to now, the current mismatch for the III–V/Ge multi-junction solar cells still hasn't been solved successfully due to the insufficient photocurrent from MQWs part.

Under this background, in this work, the methods of improving MQWs solar cell's performance have been investigated from two aspects. One is reduction of the photon-generated carriers' recombination rate through improving the crystal quality of MQWs structure. The other one is facilitation of the photon-generated carriers' escape from deep wells by inducing a novel tunneling-assisted structure.

This research has revolved around these two targets. For the improvement of MQWs' crystal quality, the strain accumulation in MQWs structure and the rough hetero-interfaces are two critical points. The accumulated strain in MQWs will induce defects and deteriorate the crystal quality. To solve this problem, an in-situ strain monitoring method has been developed to achieve strain-balance more precisely and efficiently. On the other hand, in order to achieve current match in multi-junction solar cell, a high amount of indium has to be incorporated in the well layers. At the same time, high phosphorus content in barrier layers is also necessary for strain compensation. This induces abrupt lattice constant difference between well and barrier layers with risks of rough hetero-interfaces and defects. Also the atomic diffusion between InGaAs and GaAsP may induce unintended atomic content, which make it difficult to control the strain accumulation. A smart hetero-interfaces management by optimizing gas-switching sequence has been successfully developed to achieve good crystal quality.

For the facilitation of carrier escape, the key point is reducing the photon-generated carrier escape time from wells. In the MQWs system, deep well supplies wide absorption range. But simultaneously, the large band offset would increase the thermionic escape time exponentially. To overcome this obstacle, a novel asymmetric MQWs structure, in which a thin well is implemented next to the deep well, has been designed for assisting the carrier escape by resonant tunneling effect. The process of this sequential thermionic excitation and tunneling has been simulated and optimized, the solar cell with this tunneling-assisted structure has been fabricated, and the characteristics of it have been investigated thoroughly.

This dissertation consists of seven chapters. In chapter 1, the background and basic knowledge of solar cells has been introduced, followed by the detailed descriptions of MQWs solar cell. The motivations and objectives of this dissertation have also been given in this chapter.

The chapter 2 starts with the introduction of main characteristics of photovoltaic cells. Then the efficiency limitation for single junction solar cell has been derived by detained balance method. Depending on this method, the proper band gap for middle subcell of III–V/Ge multi-junction has been calculated to be 1.20 eV, which is an important parameter for the design of MQWs structure. After that, the laboratory equipments generally used in this work have been described, such as growth equipment of metal organic vapor phase epitaxy (MOVPE), structure detector of X-ray diffraction (XRD), photoluminescence (PL) and so on.

In chapter 3, the high-resolution wafer curvature measurement has been proved to be a very effective method for the in situ strain monitoring during the growth of InGaAs/GaAsP strain-compensated MQWs in MOVPE. The first observation of the clear curvature periodic oscillations following the InGaAs/GaAsP MQWs' growth has been achieved by stopping the satellite rotation. With the help of this in-situ strain monitoring method, we can adjust growth conditions instantaneously on the basis of in-situ signal from the layer structure and can obtain strain-balance conditions just in one trial growth. Also, the curvature simulation model has been developed by implementing with thermal expansion and lattice relaxation effects to improve the simulation accuracy and application sphere. The simulations by this model fit the curvature transients covering a whole range of averaged strain with less deviation than before.

In chapter 4, the interfacial management for InGaAs/GaAsP MQWs structures with thin wells and barriers and large number of hetero-interfaces has been investigated. By means of XRD measurement and high-accuracy in-situ curvature measurement, it has been found that the hetero-interfaces with substantial lattice mismatch tend to generate interfacial defects, which can be mitigated by the insertion of ultrathin GaAs interlayers. However, an inadequate gas-switching sequence induces unintended atomic content near the hetero-interfaces and in the GaAs insertion layers, which influences the average strain of the structure. It has been proved that extending the stabilization time for the arsenic and phosphorus mixture before GaAsP barrier growth to 3 s and inserting a 1 s hydrogen purge after InGaAs well growth are quite effective to remove the unwanted strain. Static photoluminescence (PL) and time-resolved photoluminescence (TRPL) results have also been used to evaluate the crystal quality of grown structures.

Chapter 5 has introduced a novel tunneling-assisted structure for InGaAs/GaAsP MQWs to facilitate the carrier escape from deep well. The novel structure has been designed to implement a thin well next to the deep well after a thin barrier. Through optimizing of confinement energy levels and barrier thickness, a sequential thermionic excitation and tunneling process have been achieved. By breaking up one direct thermionic escape process from fundamental state into two thermionic escape processes, the collection time of photon-generated carriers has been calculated to be significantly dropped from several nanoseconds to a few hundreds picoseconds compared with conventional MQWs. Therefore, this novel tunneling-assisted structure has been expected to facilitate carrier escape and improve the cell performance effectively.

In chapter 6, firstly, the fabrication of solar cell with the designed tunneling-assisted structure has been introduced. Static PL measurement has proved the absorption band gap of new structure is 1.2 eV as designed. After that, the room temperature time-resolved PL measurement has confirmed that the tunneling-assisted structure has faster carrier escape time than a conventional MQWs structure. Then, the external quantum efficiency (EQE) and I-V curve have been detected and the results have revealed that the solar cell with novel tunneling-assisted structure has larger EQE and higher short-circuit current than the conventional MQWs structure with almost constant open-circuit voltage. Also, the characteristics of bias dependence and temperature dependence for the tunneling-assisted structure have been investigated.

In chapter 7, the whole dissertation has been concluded and the main improvements in this work have been summarized. At last, the suggestions on future investigation have been introduced.