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III-V Coupled Quantum Well Solar Cells: Predicted Performances and Growth Challenges

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1. Introduction

A quantum well (QW) solar cell including InGaAs wells is a promising candidate for the purpose of current matching in InGaP/GaAs/Ge tandem solar cells, because it allows narrowing of the bandgap of a middle cell while keeping lattice matching to a Ge substrate. For such QW cells, the extended edge of quantum efficiency to longer wavelengths is due to photo-absorption inside of the wells and escape of the carrier from the well to the barrier, and finally to the n and p regions, by thermal excitation as shown in **Fig. 1(a)**. At the same time, this structure holds an increased chance of carrier trap inside of wells and recombination of carriers, both radiative and non-radiative, just as the case of light-emitting devices using QWs. Therefore, a significant shunt resistance will degrade an efficiency of QW cells if carrier escape from the wells to the barriers is not sufficient.

A possible solution for preventing the recombination of carriers inside of the wells is the reduction of barrier thickness enough for carriers inside of a well to tunnel to a neighboring well, leading to minibands inside of multiple QWs as shown in **Fig. 1(b)**. We call such a QW cell as a coupled QW (CQW) cell. The merit of CQW cells is the delocalization of carriers inside of QWs and thus reduced chance of recombination between electrons and holes. Transport of carriers inside of QWs will be, of course, enhanced. These factors will lead to an increased efficiency of a CQW cell by the reduction of shunt resistance.

In this paper, as a preliminary step for the fabrication of such a CQW cell, we have predicted the performance of a CQW cell using a simulation of carrier transport. At the same time, we have assessed critical issues for the growth of CQW structure by metal-organic vapor phase epitaxy (MOVPE) which we believe is the most suitable growth method for QW structures of III-V semiconductors with the productivity required for solar cells.

2. Simulated performance of a CQW cell

We used a commercial software APSYS [4]. All the elementary steps regarding photons and carriers inside of a III-V layer structure are taken into account including tunneling which is essential for the simulation of a CQW cell, although we have not yet optimized all the physical parameters for quantitatively accurate simulation of the performance of a CQW cell. We assumed 10 pairs of InGaAs wells (4 nm) and GaAsP barriers (9 nm for a QW cell and 4 nm for a CQW cell). The atomic content of these layers were determined so that absorption edge is 1 μm and the total strain inside of QWs is completely compensated. The QWs are non-doped and are sandwiched between GaAs n and p regions. As a reference, we also assumed a GaAs pin junction cell. The total thickness of the i region was the same for all the cells to keep the same built-in field.

As shown in **Fig. 2**, for the QW cells, the quantum efficiency exists at longer wavelengths than the band gap of GaAs. The absolute value of the efficiency, however, was smaller than the measured value by a factor of roughly 10, probably due to smaller photo-absorption coefficient inside of the wells that is incorrectly modeled in the simulation.

The open circuit voltage is the most important feature of the CQW cell. As shown in **Fig. 3**, the conventional QW cell suffers from decreased current when the voltage increases, that is, when the effect of built-in field is small. This is indeed due to carrier recombination inside of the wells. The CQW cell, on the other hand, exhibits the current-voltage characteristic that is close to the simple pin junction. This is an indication of enhanced carrier transport due to the formation of minibands inside of the QWs.

3. Growth challenge for the implementation of CQW cells

The heart of CQW cells is thin barriers to allow tunneling. It has been pointed out that hetero-interfaces of quantum wells fabricated by MOVPE have transient layer of atomic content [5]. For the case of the InGaAs/GaAsP QWs, thin barrier that satisfies strain balance contains P more than As, and we have to care both In/Ga transition and As/P transition in the atomic content at the hetero interfaces. As shown in **Figs. 4 and 5**, detailed analysis of the atomic content at InGaAs/GaAsP interface in a conventional QW cell revealed (1) tailing of indium from InGaAs to the overlying GaAsP and (2) P penetration from GaAsP to underlying InGaAs. These phenomena should be suppressed in order to implement the band lineup as depicted in Fig. 1(b), for which we have to improve source supply sequences during the growth of InGaAs/GaAsP interfaces based on the kinetic model of the growth surface.

References

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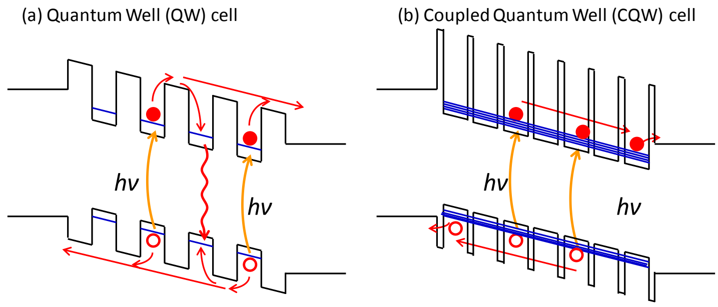

Figure 1 Schematic of the band lineup of (a) a conventional quantum-well solar cell and (b) a coupled quantum well solar cell. The filled and open circles indicate electrons and holes, respectively.

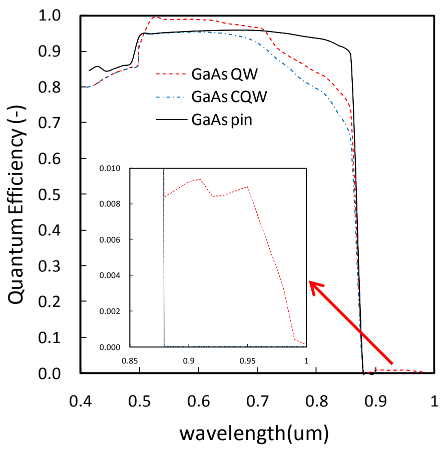

Figure 2 Simulated quantum efficiency curves as a function of photon wavelength for a GaAs bulk pin cell, an InGaAs (4 nm)/GaAsP (9 nm) 10 QW cell and an InGaAs (4 nm)/GaAsP (4 nm) 10 CQW cell. The QW cells has GaAs n and p regions at both ends and the same total thickness of i region to keep the same built-in field. The inset is the magnification at the longer wavelengths.

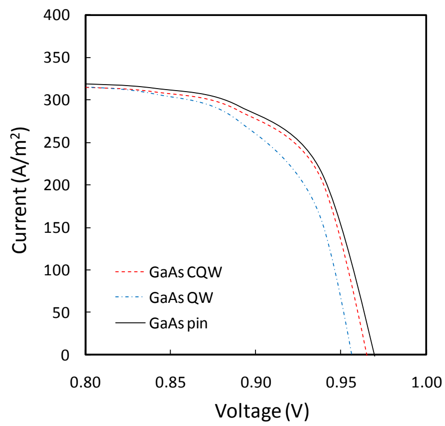

Figure 3 Current-voltage characteristics of the cells in Fig. 2. Note that the current starts from non-zero value in order to exaggerate the open-circuit voltages.

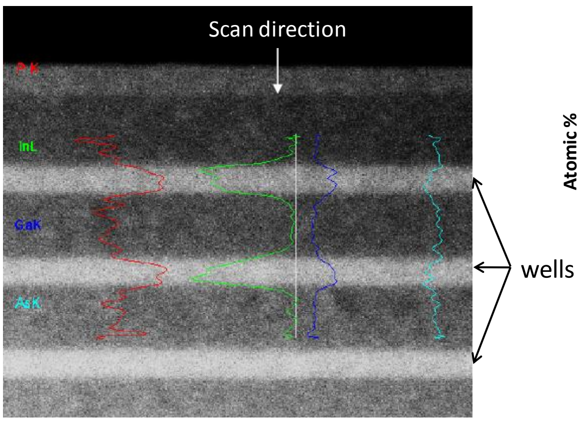

Figure 4 A STEM cross section of InGaAs/GaAsP QWs with the atomic content profiles obtained by nano-spot EDX.

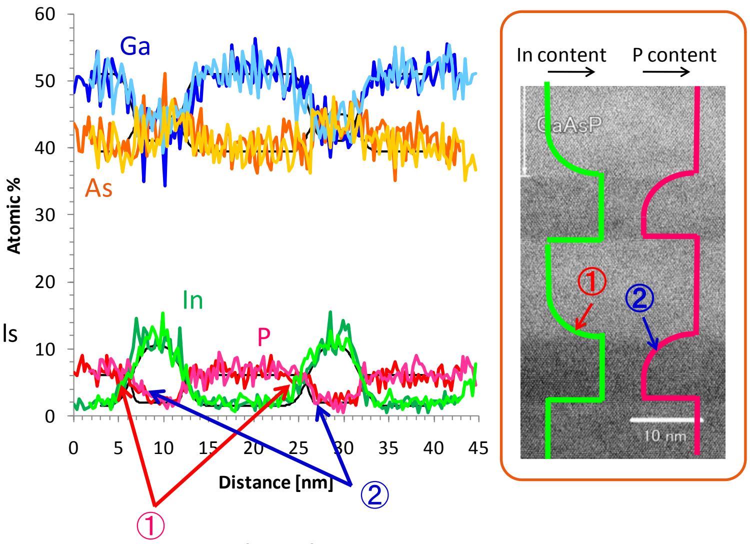

Figure 5 The profiles of atomic contents corresponding to Fig. 4. The black curves are simulated values assuming completely abrupt content profile and spreading by EDX measurement. Tailing of the atomic contents are observed as indicated by (1) and (2), which are exaggerated in the inset.