Comparison of InAs/GaAs and InGaAs/GaAs Quantum Dot Solar Cells and Effect of Post-Growth Annealing on Their Optical Properties

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***Abstract*- We have reported InAs/GaAs and InGaAs/GaAs quantum dot solar cells (QDSCs) and the effect of rapid thermal annealing (RTA) on their optical properties. A thermal stability was observed up to 700°C, and further increase in temperature results in a blue shift in photoluminescence (PL) emission peak. A maximum open circuit voltage (V_{OC}) of 0.33V was obtained for the InGaAs/GaAs solar cell (SC), whereas a maximum short circuit current (J_{SC}) of 20 mA/cm^2 was obtained for the InAs/GaAs SC. A fill factor (FF) of 0.31, and 3.0758% efficiency was obtained for the InGaAs/GaAs SC which is higher than the InAs/GaAs QDSC.**

Keywords: QDSC, MBE, photoluminescence, fill factor.

I. Introduction

Theoretically QDSCs with quantum dots (QDs) grown in the active absorption region is expected to have higher efficiency of solar-energy conversion [1-3]. The expected reason for this higher efficiency is the creation of intermediate-level energy bands. Most experimental studies have been extensively carried out on these QDSCs, but some have reported a decrease in efficiency due to the recombination of carriers in the QDs and wetting layers. The highest value of the activation energy reported for InAs/GaAs QDSCs is in the range of 94-115 meV [4-5]. InGaAs/GaAs QDSCs have hardly been investigated.

In this paper, both InAs/GaAs and InGaAs/GaAs QDSCs have been reported having higher activation energies than the previous works [4-5]. However, we have obtained higher activation energy for the InGaAs/GaAs SC compared to the InAs/GaAs SC. This indicates a better confinement in the former one. The photocurrent and J-V characteristics have also been reported. Both SCs were grown by solid source molecular beam epitaxy (SSMBE).

II. Experiment

The self-assembled InAs/GaAs and InGaAs/GaAs quantum dot solar cell (QDSC) samples were grown on GaAs (100) substrate by solid-source molecular beam epitaxy (SSMBE). The heterostructures for the two samples are shown in Fig. 1.

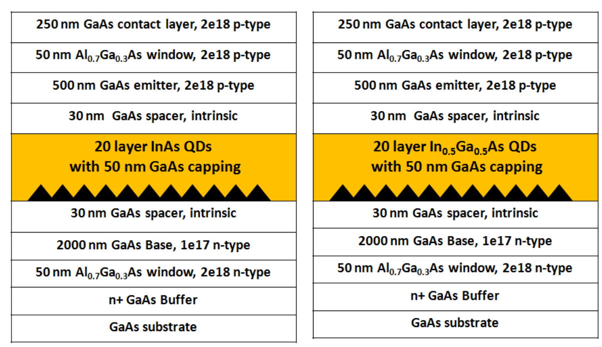


Fig. 1. Heterostructures of (a) InAs/GaAs, and (b) InGaAs/GaAs QDSC

A buffer layer of n+ GaAs was grown on the substrate, followed by a 50 nm of n-doped $Al_{0.7}Ga_{0.3}As$ window layer and then a 2000 nm of n-doped GaAs base contact layer. Similarly, a top emitter layer of 500 nm, p-doped GaAs layer, followed by a 50 nm, p-doped $Al_{0.7}Ga_{0.3}As$ window layer was grown, and the sample growths were terminated with a top p-doped, 250 nm of GaAs layer. In between the n- and p-type layers, an active layer of InAs/GaAs QDs (Fig. 1a) and InGaAs/GaAs QDs (Fig. 1b) were grown to form a complete p-i-n type QDSC structure. The active layer of the QDSCs contains 20 layers of InAs or InGaAs dots with a 50 nm, GaAs capping layer in between two dot stacks. The dots were grown at a substrate temperature of 490°C.

Then the samples were subjected to post growth annealing at 650, 700, 750, and 800°C for 30s in an argon ambient using the AnnealSys (As-One 150) RTP system. Temperature-dependent photoluminescence (PL) measurements were performed for as grown as well as annealed samples, using a focused beam of 25 mW, 532 nm diode-pumped, solid-state laser. During the PL measurement, the samples were mounted on a closed cycle He-cryostat, where temperature can be varied between 19-300K, and the detector used was a liquid nitrogen cooled InGaAs array detector.

The solar cells were fabricated using mesa lithography and lift-off technique for 0.8 x 0.8 cm^2 devices. The n- and p-metal stacks of AuGe/Ni/Au and Au/Zn were deposited using an e-beam evaporator; no anti-reflection coating was used. The non-metallized part was removed by wet etching. The back contact was annealed at 407°C for 6 minutes**.**

The current density versus voltage (J-V) characteristics of the solar cells (SCs) were measured by a Keithley multimeter under irradiance of 100 mW/cm2 (AM 1.5 simulated illuminations, Photo Emission Tech). The fill factor (FF) and power conversion efficiency (η) were determined by the following equations (1) and (2), respectively.

$$FF = V_M J_M / V_{OC} J_{SC} \quad (1)$$

$$\eta = V_{OC} J_{SC} (FF) / P_{in} \quad (2)$$

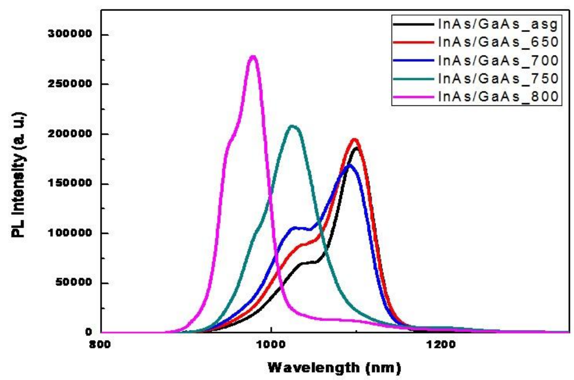
where V_M and J_M are the voltage and current density at the maximum power output, respectively. V_{OC} and J_{SC} are the open-circuit photovoltage and short-circuit photocurrent density, and P_{in} is the intensity of the incident light (100 mW/cm^2).

The wavelength-dependent short-circuit photocurrent density (J_{SC}) was measured at different wavelengths (λ) using a homemade setup with a Bentham monochromator and dual light (tungsten and xenon) sources.

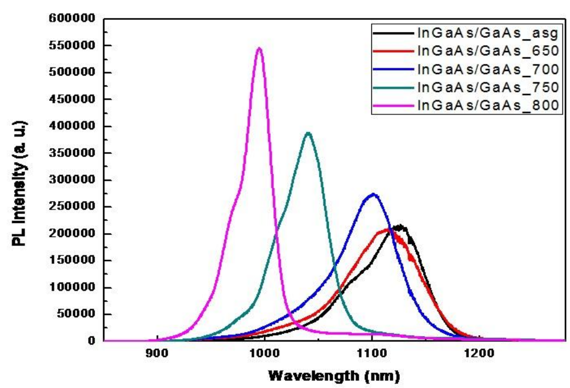
III. Result and discussion

Fig. 2 compares the PL spectra before and after the RTA treatment. The as grown InAs/GaAs SC shows a relative weak emission peak at 1099nm, whereas that for the InGaAs/GaAs SC it is at 1125nm. The red shift for the InGaAs/GaAs SC confirms a larger dot size. An improvement in the intensity is observed for both the SCs at annealing temperature of 650 and 700°C, but with a negligible spectral shift. Further increase in the temperature results in a considerable blue shift and increased intensity. The improvement of the PL emission after RTA treatment is observed probably due to the suppression of non-radiative recombination centers, which are formed due to point defects occurred during the growth [6]. As the sample heterostructures were grown at different temperatures for dot layer and the capping layer, there may be some defects during the formation of GaAs capping layers. When the temperature was ramped up from 490 to 590°C during the growth transition of GaAs layers from the dot layer, some part of the GaAs thin film grows at a lower temperature at which Ga adatom movement on the surface may differ and hence form the defects as discussed above. The full-width half-maximum (FWHM) of both the samples (~37nm) is similar to that of the as grown sample up to 700°C, which indicates that there is no significant change in the homogeneity and the composition of QDs. A blue shift occurs in the PL emission peak at 750°C, which may be due to the intermixing of materials, and it leads to a compositional change.

There is also a reduced quantum confinement in the QDs after the RTA, which can be confirmed by



(a)



(b)

Fig. 2. PL results of as grown and post-RTA treatment of (a) InAs/GaAs, (b) InGaAs/GaAs SCs

calculation of the activation energy from the temperature-dependent PL results. According to the calculations, there is a 27% decrease in the activation energy of InAs/GaAs QDs (i.e. from 180.19meV to 131.26meV) after a high temperature annealing. A similar trend was observed for the InGaAs/GaAs QDs with a decrease of 30% (311.66meV to 215.95meV). The higher activation energy for the InGaAs/GaAs QDs compared to the InAs/GaAs

QDs reveals a better confinement in the former one, which leads to a lower thermal escape of carriers. Hence, RTA can probably be used to change the QD absorption.

Fig. 3 shows the wavelength dependent photocurrent response for the QDSCs discussed in this paper. The band-to-band absorption of GaAs is observed below 873nm, and the spectra above the GaAs bandgap correspond to the QD states. The photons with energies corresponding to sub-band gap transitions captured by the QDs give rise to the photocurrent response of QDs above GaAs bandgap.

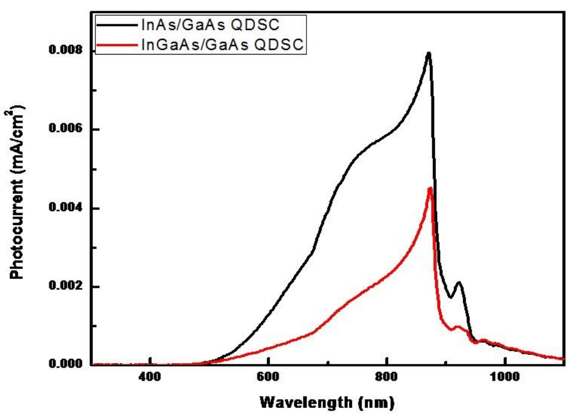


Fig. 3. Photocurrent comparison of InAs/GaAs and InGaAs/GaAs QDSCs

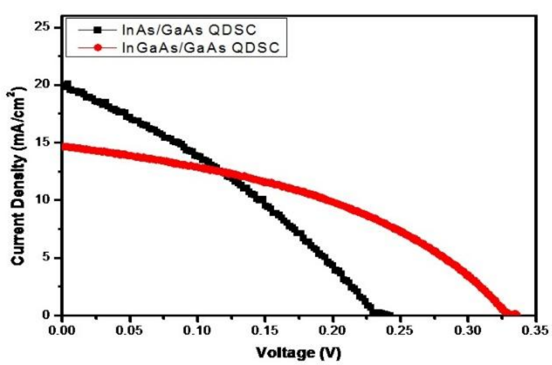


Fig. 4. J-V characteristics of InAs/GaAs and InGaAs/GaAs QDSCs

The response above the GaAs bandgap is effectively reduced for both samples, which is attributed to the reduction in carrier lifetime due to the formation of strain-related defects. The J-V characteristics for both SCs is shown in Fig. 4. The highest J_{SC} obtained for the InAs/GaAs cell is 20 mA/cm^2, whereas the InGaAs/GaAs cell has a value of 14.7 mA/cm^2. The V_{OC} obtained for the InGaAs/GaAs (0.33V) cell is higher than that of the InAs/GaAs (0.23V) cell. Photons with lower energies than the bandgap do not get absorbed, which limits the current, and the higher energy photons can quickly thermalize to the band edges, reducing the voltage. This trade-off between the V_{OC} and J_{SC} is obtained between the SCs. We obtained higher FF in InGaAs/GaAs SC (0.4), compared to the InAs/GaAs SC (0.31). The InGaAs/GaAs SC also has higher efficiency (3.0758%) than the InAs/GaAs counterpart (2.357%).

IV. Conclusion

We have reported the growth, fabrication, and characterization of two QDSCs with InAs and InGaAs QDs. We have compared the change in PL emission after RTA treatment, and obtained a thermal stability up to 700°C. Then we have measured the photocurrent and J-V response of the as grown QDSCs. We have obtained a maximum current density (J_{SC}) of 20mA/cm^2 for the InAs/GaAs QDSC and a maximum V_{OC} of 0.33V for the InGaAs/GaAs QDSC. Higher FF and efficiency also obtained for the InGaAs/GaAs SC. By optimizing the number of dot stacks and the capping layer thickness, we can get a better result for both the QDSCs.

V. Acknowledgement

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VI. References

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