Mater. Res. Soc. Symp. Proc. Vol. 1211 © 2010 Materials Research Society 1211-R03-02

GaAs Based InAs/InGaAs Quantum Dots-in-a-Well Solar Cells and Their Concentration Applications

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ABSTRACT

We report the dark and illuminated I-V curves and spectral response characteristics of six-stack InAs/InGaAs quantum dots-in-a-well (DWELL) solar cells. The short circuit current density, open circuit voltage, and external quantum efficiency of these cells under air mass 1.5G at 100 mW/cm^2 illumination are presented and compared with a GaAs control cell. The InAs DWELL cells show higher short circuit density and better efficiency compared to the control cells, confirmed by spectral response measurements. It is found that the trend in the quantum dot (QD) cell ideality factor with voltage is opposite that of the control cell making the quantum dot devices attractive for high concentration. By comparing the dark current density for the QD cell and GaAs control cell, we have conservatively estimated the concentration level at which the QD solar cells would surpass the open circuit voltage of conventional GaAs devices.

INTRODUCTION

Quantum dot (QD) solar cells have been actively investigated recently since they have been theoretically shown to have the potential to realize high power conversion efficiencies (>60%) with an optimized intermediate band design or increase the short circuit current by extending the absorption edge further into the infrared [1-5]. However, very little research has analyzed the effect that the dots have on the transport or recombination effects in the device. In this paper, the I-V characteristics for 6-stack InAs/InGaAs "dots-in-a-well" (DWELL) [6-8] solar cells are discussed and compared to GaAs cells. The test data collected for the QD samples consistently show that the ideality factor of the QD cells is competitive with the typical values of GaAs control cells. Furthermore, it is found that the trend in the QD cell ideality factor with voltage is opposite that of the control cell making the quantum dot devices attractive for high concentration. By comparing the dark current density [9] for the 6-stack QD cell and GaAs control cell, we have conservatively estimated the concentration level at which the QD solar cells would surpass the open circuit voltage (V_{oc}) of conventional GaAs devices.

EXPERIMENT

The QD solar cells were grown by molecular beam epitaxy (MBE) using the DWELL technique [6] that features InAs self-assembled QDs embedded in InGaAs QW layers that are separated by 27 nm GaAs spacer layers. This method allows for improved dot density and bandgap control than growing dots directly on GaAs. The InAs QDs were grown by self-assembly with a slow growth rate of ~0.1 monolayer/s, which provides high dot quality and large dot size. The DWELL structure was grown on a 3-μm thick p-GaAs base layer and then capped with n-GaAs and wide band gap n-AlGaAs. The overall solar cell structure is a *pin* diode, with a 200 nm *i*-layer in which the DWELL layers are situated. The control cell structure is similar to the DWELL one except that there are no InAs dots or surrounding InGaAs quantum wells. As for DWELL structure shown in the schematic diagram in Fig. 1, there are six layers of InAs quantum dots with a bandgap of ~1100 nm grown within the undoped *i*-region. The epi structures were grown on p+ type 2" wafers. The total QD density for the DWELL cells is ~6×10^{11} cm^{-2}.

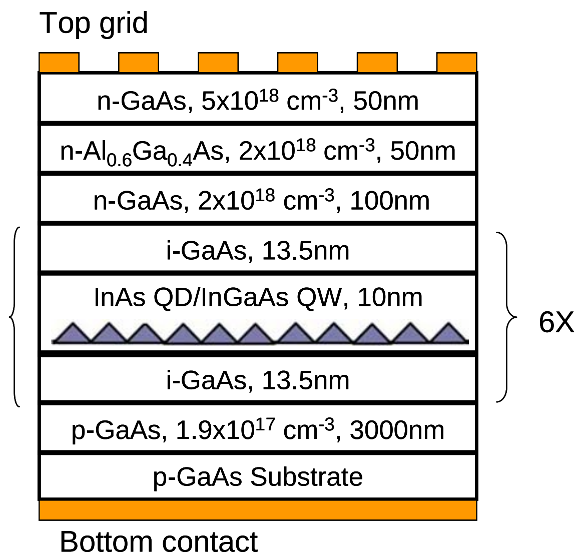

Figure 1. Schematic diagram of the DWELL solar cell containing six-stack InAs QDs.

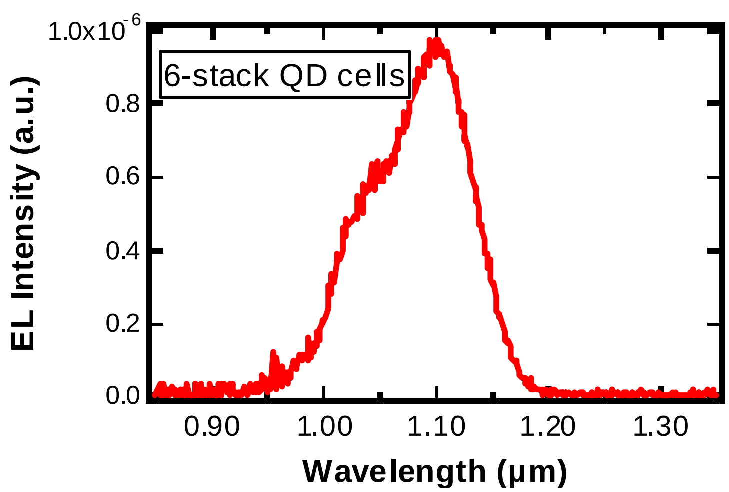

Figure 2. Electroluminescence spectrum for the 6-stack QD sample.

The electroluminescence (EL) spectra of the DWELL samples were measured using an optical spectrum analyzer along with a focal lens and a fiber bundle. This measurement tests the photon emission of the QDs inside the *i*-layer of the solar cell structures. The light emission spectrum for the 6-stack QD cell is shown in Fig. 2. The 6-stack QD cell demonstrates an EL response at longer IR wavelengths (~1.1 μm) compared to the EL peak of 0.86 μm for the GaAs control cell. The measured EL peak width is ~80 nm for the 6-stack QD samples. As can be seen in the Fig. 2, the 1st excited state emission peak of the dots is seen as a shoulder at a shorter wavelength ~1.05 μm. The EL data indicate that the QD size distribution and associated inhomogeneous broadening are typical for this MBE-based DWELL technology.

The control and DWELL solar cells were fabricated simultaneously to keep all the processing similar. The devices are fabricated with three different areal dimensions (5×5mm^2, 3×3mm^2, 2×2mm^2). After patterning, the samples are placed in an e-beam evaporator for a top *n*-metal contact of Ge/Au/Ni/Au. After lift-off, the samples are placed back into the e-beam evaporator for the bottom *p*-metal contact of Ti/Au. A 1.5 μm deep mesa is dry-etched by an inductively coupled plasma (ICP) etcher to the intrinsic region to separate neighboring solar cells. Finally, an anti-reflective coating (ARC) layer is deposited using plasma enhanced chemical vapor deposition to the front surface for reducing the reflection loss of the incident photons and improving the surface passivation. The ARC layer is 80-nm thick Si_xN_y with a refractive index ~2.0.

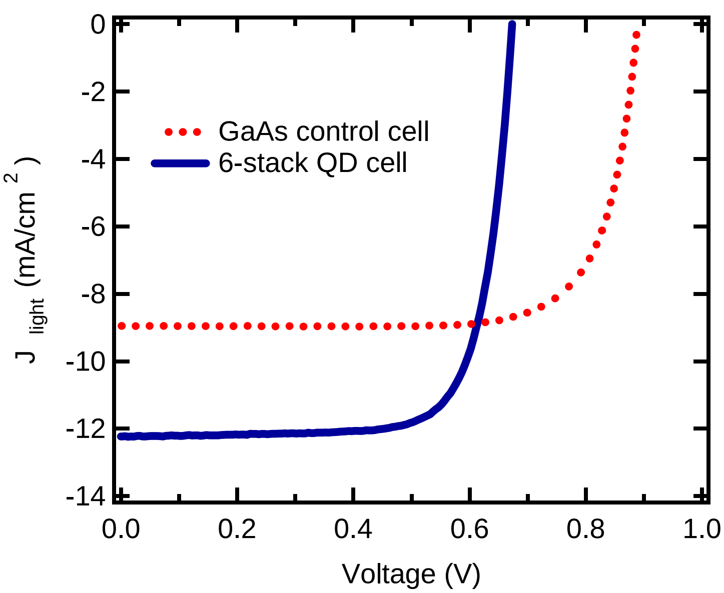

Figure 3. Measured light I-V characteristics of the GaAs control (red dotted line) and the 6-stack InAs/InGaAs DWELL solar cells (blue solid line) under AM 1.5G at 100 mW/cm^2 illumination.

RESULTS AND DISCUSSIONS

Fig. 3 shows the I-V characteristics for the 3×3 mm^2 GaAs control cell and the 6-stack DWELL cells measured under AM1.5G at 100 mW/cm^2 illumination. The control cell (red dotted line) has an open circuit voltage (V_{oc}) of 0.89V and a short circuit current density (J_{sc}) of 9.1 mA/cm^2. The InAs/InGaAs QD solar cell (blue line) has a V_{oc} of 0.68 V and a J_{sc} of 12.2 mA/cm^2. The QD cells have about a 33% larger short circuit current density compared to the GaAs control cell, which is mainly due to the higher photon absorption rate related to the DWELL structure.

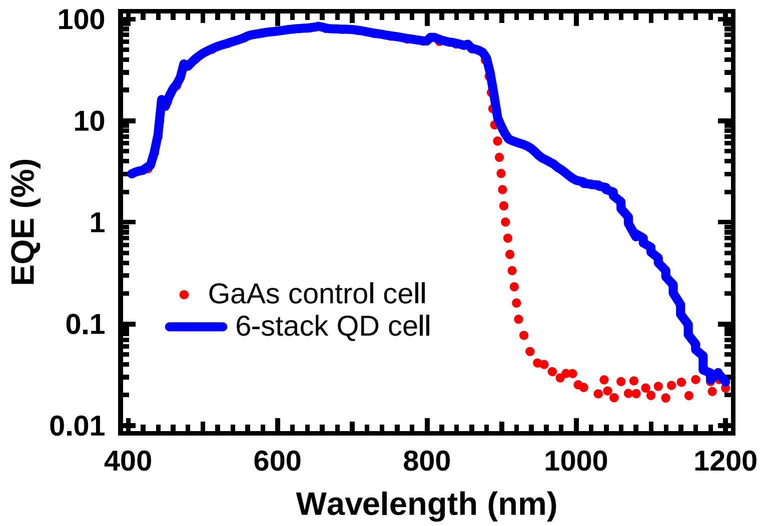

Figure 4. The EQE spectrum for the GaAs control (red dotted line) and the 6-stack InAs/InGaAs DWELL (blue solid line) solar cells.

The spectral response of the DWELL solar cell, as well as the reference cell, is measured by using a tungsten halogen lamp filtered through a Spectra Pro-275 monochromator. Fig. 4 shows the external quantum efficiency (EQE) spectrum for the GaAs control (red dotted line) and the 6-stack InAs/InGaAs DWELL (blue solid line) solar cells. The spectral response data show that the GaAs control and QD cells have similar EQE in the visible to near-IR range (400-870nm). Beyond the GaAs absorption edge (870 nm), the DWELL cell shows extended response with much higher measured EQE up to ~1200 nm (IR wavelength range). This is strong evidence of the contribution from the InAs QDs and InGaAs QWs, the latter being the primary contributor to the increased short circuit current density due to significant absorption between 900 to 1060 nm. The absorption of photons with the wavelengths longer than 870 nm can be further increased by adding more DWELL layers if the cumulative strain is controlled.

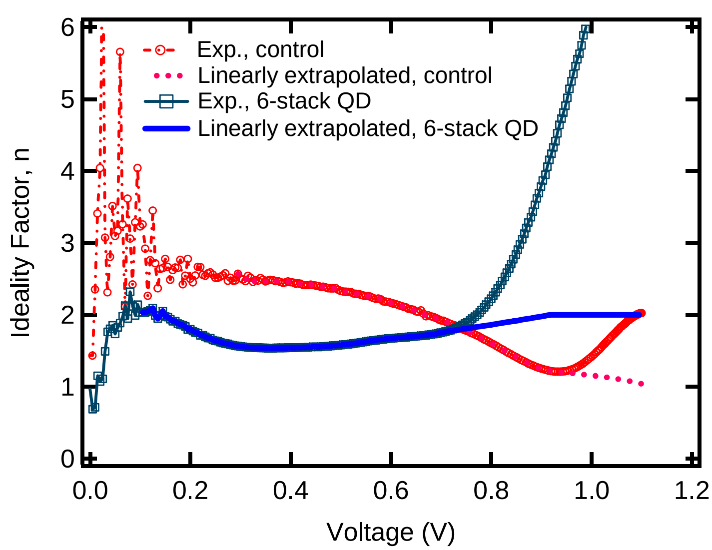

Figure 5. The measured and extrapolated local ideality factors for the GaAs control cell (red dotted line) and 6-stack InAs/InGaAs DWELL (blue solid line) solar cells.

The dark currents have been measured at 25ºC on solar cell structures ranging from 2x2 to 5x5 mm^2 and the ideality factor *n* was studied by using a single diode model to extract the voltage varying *n* and reverse saturation current from dark IV. The two parameters are not constant because the diffusion current with ideality factor 1 is coupled with the recombination component with ideality factor 2. We calculated the "local" ideality factor from the measured dark IV data, and then substituted it into a single diode equation to get the "local" reverse saturation current. Neglecting the series resistance effect, the ideality factor indicates whether junction current is dominated by diffusion or recombination. Whereas the GaAs control shows the typical monotonically decreasing ideality from 0.3 to 0.8 V, a linearly increasing ideality is observed in the DWELL cell as shown in Fig. 5. Based on the measured dark currents, and neglecting series resistance, we extrapolated the IV curves to higher voltages (Fig. 6) and found that they intercept at $\sim 2\times10^4$ mA/cm^2. Dividing the intercept point J_{dark} by the J_{sc} of the QD cell conservatively estimates the light concentration (~1400×) above which the QD cell would have a higher V_{oc} than the GaAs cell assuming additivity applies [10].

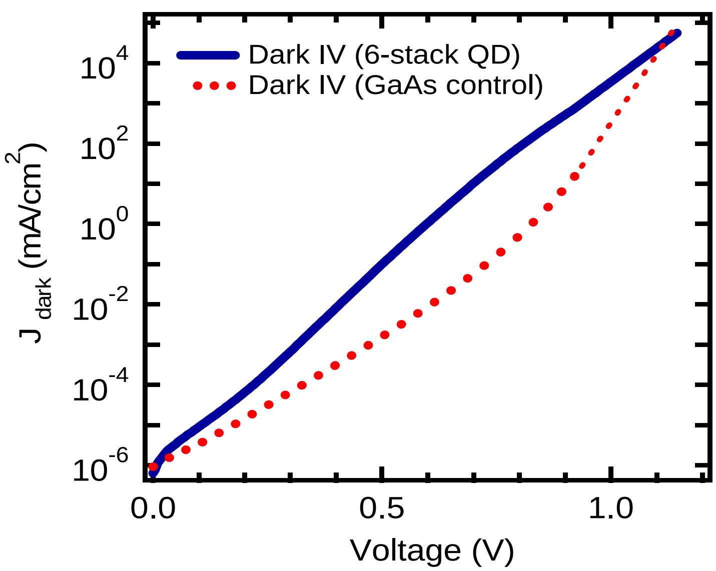

Figure 6. Extrapolated intercept for the measured dark-currents of the GaAs control (red dotted line) and 6-stack DWELL (blue solid line) solar cells up to the high current density region.

CONCLUSIONS

In conclusion, we report the dark and illuminated I-V characteristics, and spectral response characteristics of solar cells grown by the InAs/InGaAs DWELL technique and compared them with GaAs control cells. The QD cells show higher short circuit density and better long-wavelength efficiency compared to the control cell. By comparing the dark current behaviors of the QDs cells to the GaAs control cells, it is shown that above about 1400X concentration, the V_{oc} of the DWELL cell would be superior to that of GaAs control cell. This result is mainly attributed to the unique carrier transport properties that are introduced into solar cell devices that utilize QDs.

ACKNOWLEDGMENTS

This work was supported in part by the Air Force Office of Scientific Research FA9550-06-1-0407, and the Army MAST program.

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