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MULTI-STACKED LATERAL QUANTUM DOT MOLECULES FOR PHOTOVOLTAIC APPLICATIONS

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ABSTRACT: Multi-stacked lateral quantum dot molecules are grown by a modified molecular beam epitaxial growth technique using thin-capping and regrowth of quantum dots on n-GaAs (001) substrate. Quantum dot molecules in a single layer has a dot density of 2×10^{10} cm^{-2} which can be increased by growing a stacked structure in order that higher photon absorption in photovoltaic cells can be achieved. Closely-spaced quantum dots in lateral quantum dot molecules improve in-plane carrier conduction which can be beneficial to the overall solar cell performance. Multi-stacked lateral quantum dot molecule solar cells having Schottky structure are fabricated and tested for their I-V characteristics at dark and illuminated conditions. The experimental results are reported and discussed.
Keywords: Quantum dot molecules, Quantum dot solar cells.

1 INTRODUCTION

Self-assembled quantum dots (QDs) have been proved useful for many photonic devices. For examples, QD lasers are found to have low threshold current density, while QD infrared detectors can be designed to respond to long wavelengths [1, 2] and QD transistors can function as high speed nano-electronic devices [3]. Efficient emitting device structures such as heterostructure, and multi-quantum well structure can also be the basis for high performance solar cells. Therefore, using QDs as an active layer of solar cells has a potential to provide devices with greater energy conversion efficiency. In practice, multi-stacked quantum dots are normally inserted in the active part of QD devices in order to increase the effectiveness of QD functionality. In QD solar cells, low lateral dot density is a limiting factor in developing high efficiency device. The contribution of QDs in solar cell output in still doubtful inspite of their ability to emit strong photoluminescence at room temperature [4]. The low QD density probably is a limiting factor.

To achieve high lateral dot density and the resultant increased efficiency, quantum dot molecules (QDMs) were proposed as an active part of solar cell structures [5]. In order to grow a high dot density sample, the conventional molecular beam epitaxy (MBE) process was modified to include thin-capping and regrowth procedures. This results in QDMs which have high dot density, good dot uniformity and quality [6]. In addition, the QDMs grown using the modified MBE technique are aligned along the $[1\bar{1}0]$ crystallographic direction [7]. The anisotropy may prove useful for active photonic devices such as modulators, switches and filters.

The quantum nature of QDMs makes them a potential candidate for novel solar cell structures which can be engineered to absorb more light, particularly at the long wavelength region of the solar spectrum.

In this paper, we report a MBE growth of multi-stacked lateral QDMs for photovoltaic applications. Preliminary electrical characteristics of Schottky-type solar cell structure with embedded QDMs as compared to the control sample without QDM layer indicate that increased efficiency can be achieved.

The growth of self-assembled QDs in a standard MBE process, results in dot density in the range of 10^9-10^{10} cm^{-2}, depending on growth temperature and growth rate, and other parameters [8, 9]. We have developed a modified MBE technique using thin-capping-and-regrowth of QDs to create lateral QDMs having one order of magnitude higher in dot density (10^{10}-10^{11} cm^{-2}) as shown in the atomic force microscope (AFM) images in figure 1 where the densities of QDs grown by a typical MBE technique and by our modified growth technique are compared. In practical device design, multi-stacked QDMs can be introduced in the device structure in order to increase the absorptive dot volume. In the stacking process, the dots are vertically aligned as seen in the transmission electron microscope (TEM) image of figure 2. This is due to the strain fields induced by the underlying QDs.

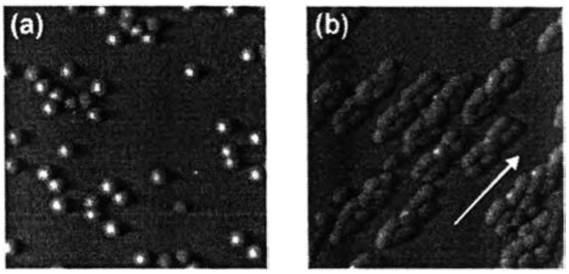


Figure 1 AFM images of (a) self-assembled QDs grown by standard MBE technique, and (b) QDMs grown by a modified MBE technique. The arrow indicates the $[1\bar{1}0]$ crystallographic direction. The scan field is 1×1 μm^2 for both images.

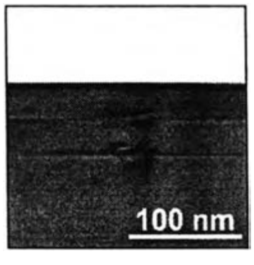


Figure 2 The TEM image of a double-stacked QDs showing vertical alignment

2 SAMPLE PREPARATION

MBE growth of multi-stacked lateral QDMs is conducted using RIBER 32P machine. The MBE growth process starts from a standard InAs QD formation on a buffer layer grown on n-GaAs (001) substrate at 500°C at a growth rate of 0.01 ML/sec. The InAs QDs are then capped with a thin layer of GaAs. The lattice mismatch results in anisotropic strain fields and the subsequent formation of a camel-like nanostructure with nanohole in the middle and an elongation along the $[1\bar{1}0]$ crystallographic direction [10]. The regrowth of QDs 0.6 ML of InAs QDs at 450-470°C (on the nano holes) leads to the formation of nano-propellers. As the regrowth process continues, at 1.2 ML of InAs, lateral QDMs are formed. The strain fields are shifted from the centered dots to the satellite dots, along the perimeter of the nano-propeller's blades on both sides. The dot density of a single-stack layer of QDMs is 3×10^{10} cm^{-2}. Multiple stacks of lateral QDMs are grown by repeating the same process after capping the previous stack of QDMs. The schematic structure of the sample is shown in figure 3.

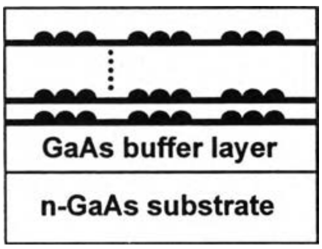


Figure 3 Schematic diagram of a multi-stacked quantum dot molecules.

In order to measure the electrical contribution of the QDMs in a bulk layer, Schottky structure is fabricated. Samples with Au-Schottky contact having an area of 0.25 cm^{-2} with a grid pattern are shown in figure 4.

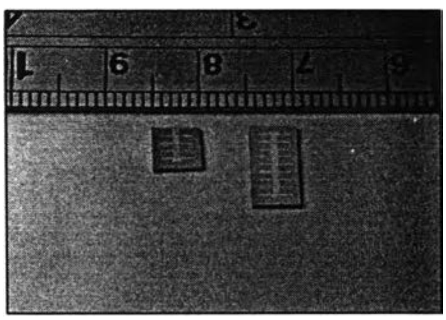


Figure 4 Photograph of the front side of the Schottky device for I-V characterization.

3 EXPERIMENTAL RESULTS AND DISCUSSION

In photovoltaics applications, efficient electronic and optical properties of QDMs are required. In our previous investigation [11], electron mobility in a stacked quantum dots structure is lower than the bulk material as shown in figure 5. Closely spaced quantum dots in lateral QDMs would improve electronic transport and may lead to better lateral current conduction in the solar cell structure.

QDM solar cells with 1 and 5 stacks of embedded QDM layer are tested under AM1, 100 mW/cm^2 solar

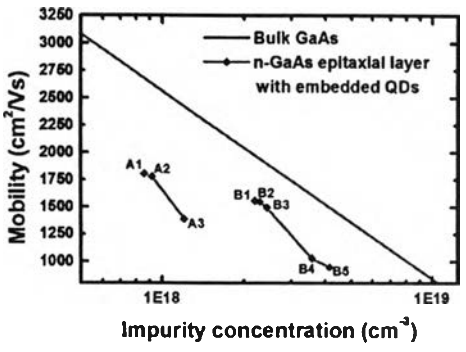


Figure 5 Electron mobility in InAs/GaAs quantum dot samples are shown to be lower than bulk GaAs. Samples "A" have 100 nm thick epitaxial GaAs layer with 0, 1 or 2 embedded QD stacks. Samples "B" have 500 nm thick epitaxial GaAs layer having 0, 1, 2, 4 and 9 embedded QD stacks.

simulator and their I-V characteristics under dark and illuminated conditions are shown in Fig.6. For the 1-stack sample, the results in Fig.6 (a) indicate that the open-circuit voltage is Voc = 0.25V, and the short-circuit current is Isc = 0.75mA. The fill factor for the sample is 0.34. For the 5-stack sample, the results in Fig.6 (b) indicate that the open-circuit voltage is Voc=0.3V, Isc=0.7mA, and the F.F.= 0.37. We attribute the slightly increased F.F. to the lower sheet resistance of the 5-stack QDM solar cell device. However, we cannot observe any clear improvement of PV output by increasing the number of QDM stacks. This proposed multi-stacked QDM solar cell structure still does not reach the critical QD volume for better solar absorption.

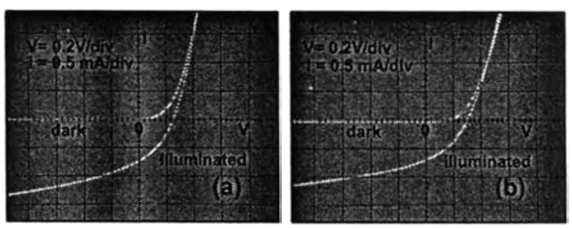
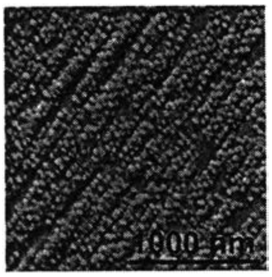
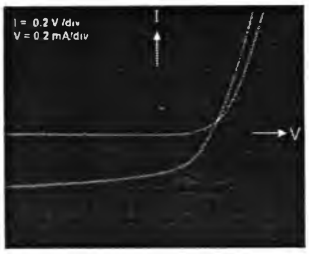


Figure 6 I-V curves of multi-stacked QDM solar cell under dark and illuminated conditions. (a) 1 stack and (b) 5 stacks.

In order to extend the QDM contribution to PV application, we try to grow high density QDMs by repeating our modified MBE process with 5 cycles of thin-capping-and-regrowth. The AFM image of high dot density QDMs is 6×10^{10} cm^{-2} as shown in figure 7. Further investigation of multi-stacked high dot density QDMs for PV application is on-going experimented. Our preliminary result from single stack high dot density QDM solar cell having Schottky structure was reported in 31st IEEE-PVSC [5] confirming that sheet conductivity of high dot density QDMs is improved and provide much better F.F. value of 0.5 comparing to those of normal QDM solar cells.



(a)



(b)

Figure 7 (a) AFM image of high dot density QDMs grown by 5 cycles of thin-capping-and-regrowth process (0.6 ML in the first 4 cycles and 1.5 ML in the last fifth cycle). (b) I-V curves at dark and illuminated conditions of high dot density quantum dot molecule solar cell (reported in 31st IEEE-PVSC).

4 SUMMARY

QDMs are grown by a novel thin-capping-and-regrowth MBE process. Multi-stacked QDMs are subsequently inserted in a solar cell structure having Schottky grid-contact. Electrical measurements of the 1-stack and 5-stack QDM solar cells under AM1 illumination show no significant change in their performance. We cannot prove the increased absorption volume of the stacked quantum dot molecules. Further investigations are needed in order to achieve a higher dot density by using multiple cycles of thin-capping-and-regrowth process where further improvement in terms of efficiency of quantum dot solar cells are expected.

5 ACKNOWLEGEMENTS

The research work on self-assembled quantum dots for nano-photonic and nano-electronic applications is financially supported by the Asian Office for Aerospace Research and Development (AOARD), U.S. Air Force, and Thailand Research Fund (TRF) through the Royal Golden Jubilee Ph.D. Program and TRF's Senior Researcher Award.

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Multi-Stacked High-Density Quantum Dot Molecules as PV Active Layer

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Abstract: Quantum dot molecules (QDMs), are prepared by thin-capping-and-regrowth MBE process. The unique features of QDMs are their high dot density (10^{10}-10^{11} cm^{-2}), specific pattern of dot sets, dot set alignment along the $[1\bar{1}0]$ crystallographic direction, and dot uniformity. These features result in strong photoluminescence (PL) at room temperature. High density QDMs are obtained by repeating cycles of thin-capping-and-regrowth MBE process. In spite of higher dot density, dot uniformity relaxes giving a broader spectral response which is desirable for photovoltaic applications. In order to increase the active volume of QDMs in solar cell structures, we propose to embed the multi-stacked, high-density QDMs in the device's active layer. The device is subsequently characterized and tested for their photovoltaic behaviors. The results show improved solar energy conversion efficiency.

Key Words: Quantum dot molecules, Quantum dot solar cells.

1 Introduction

Solar cell is in principle a shallow junction device having a high aperture area for the collection of a wider solar spectrum. GaAs-based solar cells needs very thin active layer to absorb a portion of photon energies due to GaAs's direct bandgap property and its limited bandgap value of 1.43 eV which corresponds to 0.87 μm of wavelength. However, the GaAlAs/GaAs lattice-matched heterostructure using GaAlAs as an optical window can provide very high conversion efficiency of more than 20% in solar cell performance.(1-4) Narrow bandgap material like Ge (Eg = 0.66 eV) is also used in a tandem cell structure due to its lower cost as an alternation substrate to GaAs.(5-6)

InAs is another semiconducting material with a narrow bandgap (Eg = 0.34 eV) and a direct bandgap but with a lattice mismatch of 7% to GaAs. Epitaxial (2D) growth of InAs on a GaAs substrate, therefore, result in strain in the growing layer. When the growth exceeds a critical thickness, the 3D formation of quantum dots (QDs) results. These self-assembled InAs QDs by the MBE technique is well known as the Stranski-Krastanov growth mode.(7-9) Due to the zero degree of freedom of carriers in the QDs, each carrier has its unique energy level. Multiple carriers then result in quantized discrete energy states, which high rate of transitions among energy levels. Quantum-dot integration to solar cell structure is proposed by Luque et al.(10) With an idea that quantum dots give rise to intermediate bands which result in increased solar energy absorption. However, from the basic understanding of luminescence spectrum of InAs quantum dots, we could expect long wavelength response will result when these zero-dimensional quantum structures are inserted in the active region of solar cells.(11) Variation in dot size can broaden the spectrum response characteristics of quantum dot solar cells.(12)

Self-assembled InAs QDs grown by a standard MBE process give a low dot density in the order of 10^9-10^{10} cm-2.(13) These values of dot density are not significant and the quantum dot contribution to solar cell performance is small.(14) We, therefore, proposed to develop a MBE growth technique by using a thin-capping-and-regrowth process.(15) With this unique growth technique, self-assembled lateral InAs quantum dot molecules are realized with high dot density (10^{10}-10^{11} cm^{-2}) and ordered pattern of dot sets along the $[1\bar{1}0]$ crystallographic direction.(16) In order to obtain a higher aggregate dot volume to be used as an active layer of solar cells of we propose to grow multiple stacks of quantum dot molecules by multiple series of thin-capping-and regrowth MBE process.(17)

In this paper, we further extend our growth technique by the modification of MBE process to prepare high-density quantum dot molecules (10^{11}-10^{12} cm^{-2}). With multiple series of this modified MBE growth, multi-stacked, high-density quantum dot molecules are obtained. We then fabricate Schottky solar cells with this high density QDM layer as the active layer. Electrical (I-V) characteristics of this Schottky (multi-stacked) quantum dot molecule solar cell under solar simulator is reported and discussed in this paper.

2 High Density Quantum Dot Molecules

Quantum dot molecules (QDMs) are grown by a self-assembly technique, specifically the thin-capping-and-regrowth MBE process. All samples are grown on (001) n-GaAs substrates.

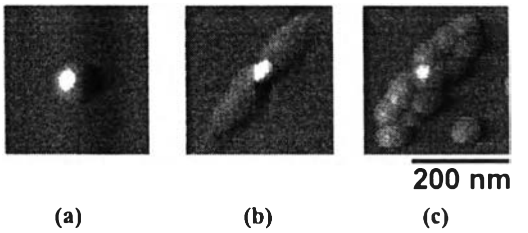


Figure 1 Processing steps for QDMs.

The first step is to start with a standard MBE process for self-assembled quantum dots (QDs) at 500°C as shown in figure 1(a). Then, QDs are capped by 6 ML of GaAs at the temperature of 470°C. The QDs' shape is transformed into a camel-like structure having a nanohole in the middle of the dot. Afterwards, 0.6-ML InAs is regrown at the same temperature. As a result, nanopropeller-shaped QDs aligning along the [1 $\bar{1}$ 0] crystallographic direction are obtained as shown in figure 1(b). When the deposited thickness of regrown InAs QDs increases to 1.2 ML, QDMs are formed as shown in figure 1(c). The number of QDs per each molecule is 10-12 dots.

For the high dot density structure, we repeat the thin-capping-and-regrowth process for 5 cycles with regrown thickness of 0.6 ML in the first 4 cycles and 1.5 ML in the last cycle to obtain one layer of high density QDMs as shown in figure 2. Then we repeat the same 5 cycles several times to obtain multiple layer of QDMs or, in other words, to obtain multi-stacked, high-density QDMs. These multi-stacked, high-density QDMs give strong photoluminescence (PL) at room temperature comparing to those of QDMs and QDs as shown in figure 3. The strong emission from the multi-stacked, high-density QDMs sample reflects the high dot density which will be useful for QD solar cell structure.

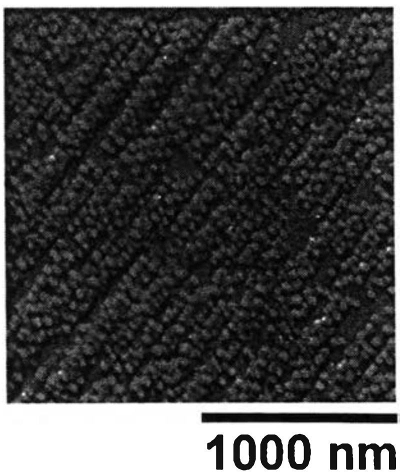


Figure 2 AFM image of high density QDMs

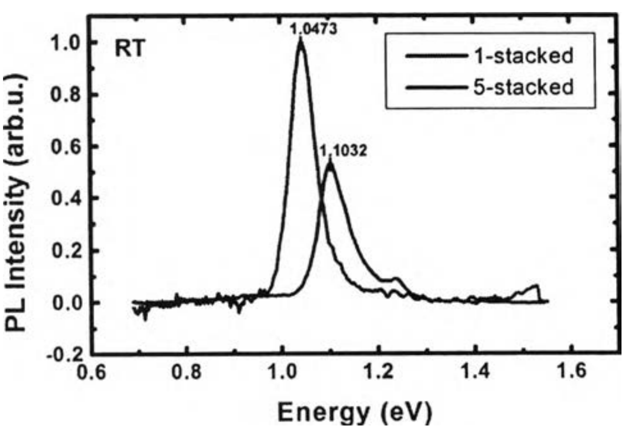
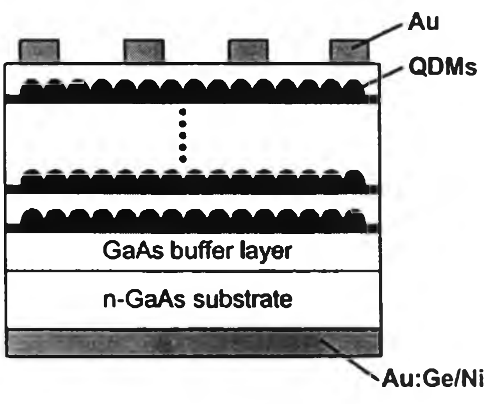


Figure 3 Strong PL spectrum from multi-stacked high density QDMs comparing to that of single stacked sample.

3 Multi-Stacked High Density QDM Solar Cells

A Schottky structure is used in this experiment in order to observe the intrinsic performance of solar cells having zero junction depth. The integration of the multi-stacked, high density QDMs into a solar cell structure is done step by step, by forming the following layer in sequence QDs, nanopropeller QDs, QDMs, to multi-stacked, high-density QDMs. The multi-stacked high-density QDMs give high dot density and layer dot volume (aggregate). When inserted and used in a solar cell structure, significant contribution of the QDs towards the solar cell output is expected.

Schottky solar cells with 1 stack and 5 stacks of high-density QDMs are fabricated. The schematics of the cross-section of the structures is shown in figure 4. Subsequent electrical (I-V) characterization are carried out under AM1 100 mW/cm^2 solar simulator.



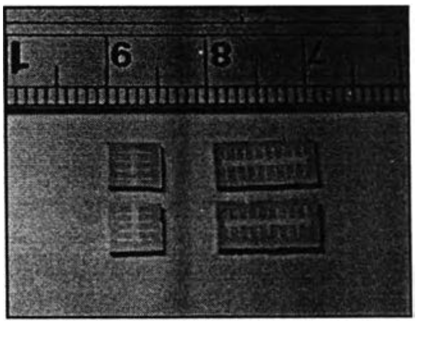


Figure 4 Multi-stacked high density QDM solar cell having Schottky structure.

The cell area of each sample is either 0.5 or 0.25 cm^2 with 10% coverage of the front grid contact by Au evaporation. The results show that Voc = 0.3 V, Isc = 1 mA and the fill factor (F.F.) = 0.5. The experimental results indicate that Isc of 5 stacks high density QDM solar cell gives highest current among other types of QD solar cell previously studied. We achieve Isc = 2 mA/cm^2 from our 0.5 cm^2 solar cells. The high Isc achieved in our multi-stacked QDMs structure is promising, and, with proper designs of PN heterojunction, optical window and AR coating, is likely to develop into high-efficiency QDM solar cells. Further investigation of QDM solar cell is on-going.

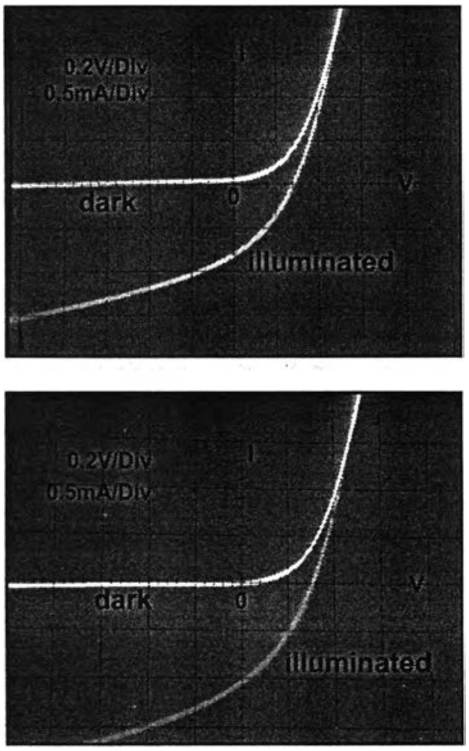


Figure 5 I-V curves at dark and illuminated conditions of multi-stacked high density QDM solar cell comparing with those of single stacked sample. (a) single stacked and (b) 5-stacked

4 Summary

QDMs as an active layer of solar cells is prepared by the thin-capping-and-regrowth MBE process. By repeating the processing steps for several cycles, we can obtain multi-stacked, high-density QDMs structure and utilize the high aggregate dot volume for solar cell structure. The fabricated Schottky solar cells with an embedded layer of multi-stacked, high-density QDMs undergo electrical characterization at a standard condition controlled by a solar simulator: AM1 100 mW/cm2. It is found that, when compared with other structures, the multi-stacked QDM solar cells exhibit a significant increase in short-circuit current which will lead to high efficiency solar cells.

Acknowledgement

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Improvement of PV Performance by Using Multi-Stacked High Density InAs Quantum Dot Molecules

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ABSTRACT

InAs quantum dot molecules (QDMs) are prepared by thin-capping-and-regrowth MBE process. The dot density can be varied between 10^{10} cm^{-2}, for as-grown quantum dots (QDs), to 10^{12} cm^{-2}, for multi-stack QDMs. Photocurrent measurements on 1- and 5-stack high-density QDM layers show that these InAs QDMs when embedded inside a GaAs bulk structure extend photon absorption beyond the 850-nm bandedge limited by GaAs. The results also indicate that the higher the number of stacks the higher the resulting current. The presence of high-density QDMs in solar cells thus extends the absorption region and at the same time increase the output current. Electrical characterisations on homojunction (p-n) solar cells with 1- and 5-stack high-density QDMs embedded between the junction show that the 5-stack sample provides a higher short-circuit current density of J_{sc} = 14.4 mA/cm^2 compared to 9.6 mA/cm^2 provided by the 1-stack sample. The increase is due entirely to the difference in absorptive dot volume accounted for by the difference in the number of stacks of high-density InAs QDMs. The efficiency of homostructure QDMs solar cell is 5.1%.

INTRODUCTION

Solar cells made from semiconductor materials can absorb a limited portion of the solar spectrum determined by the energy gaps of the materials. This leads to the limitation of conversion efficiency when solar cells are made from single bandgap semiconductors. In order to utilize multiple bandgaps of different semiconductors, tandem solar cells can be useful because they can absorb different photon energies from a wider solar spectrum compared to their single bandgap counterparts.[1-3] However, tandem solar cells face many technical difficulties. For example, lattice-matched semiconductors are needed in order to obtain defects-free crystals, essential for tunnel junctions which are required to connect the upper and lower cells of the tandem structure. Therefore, only two- or three-junction cells are used in most tandem structures because having more junctions would make it considerably more difficult to have defects-free structure throughout. In addition, a wide bandgap semiconductor usually forms the uppermost layer in order to avoid short wavelength absorption near the surface. But Ohmic contacts to wide bandgap semiconductors generally have high contact resistivities. Although high efficiency can be achieved, it comes with the expense of complicated design and fabrication.

GaAs, a direct semiconductor with a bandgap of 1.42 eV, is a promising high-efficiency material. It has an absorption edge at 850 nm. We propose that by introducing InAs quantum dots (QDs) into the GaAs bulk structure, it is possible to extend the absorption edge and, hence, to improve the efficiency of GaAs-based solar cells.

Self-assembled InAs QDs could be formed on GaAs substrates by Stranski-Krastanov growth mode due to the 7% lattice-mismatch between InAs and GaAs. The growth of self-assembled InAs QDs on a GaAs substrate in a standard molecular beam epitaxial (MBE) process results in dot density in the range of 10^{9}-10^{10} cm^{-2} as shown in the atomic force microscopy (AFM) image in Fig. 1. The density depends mainly on the growth temperature which controls the growth rates.[4] These as-grown QDs have low dot density and the expected benefits of photon absorption at long wavelengths are minimal. Consequently, our previous QD solar cells did not show noticeable improvements (extended spectrum response and increased conversion efficiency) comparing to typical bulk GaAs solar cells.[5]

It has been proposed that having a high density of ordered, uniform QDs could provide an intermediate energy band in the bandgap of host semiconductor which leads to improved conversion efficiency.[6] In order to increase the density of the InAs QDs, we have developed a modified MBE technique using a thin-capping-and-regrowth process in order to create lateral quantum dot molecules (QDMs). A typical dot density of the QDMs is 10^{10}-10^{11} cm^{-2} as shown in Fig. 2. The QDMs exhibit a specific pattern: the dots are aligned along the $[1\,\bar{1}\,0]$ crystallographic direction and they have good uniformity.[7] Even higher density QDMs are then obtained by repeating the thin-capping-and-regrowth process for several cycles.[8] An AFM image of a sample which underwent five cycles of thin-capping-and-regrowth process with regrowth InAs thickness of 0.6 ML in the first four cycles and 1.5 ML in the last cycle is shown in Fig. 3. The dot density is estimated at 10^{11}-10^{12} cm^{-2}.

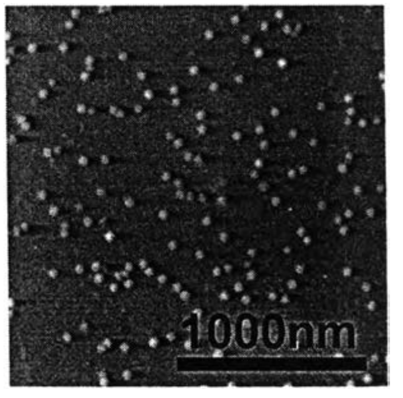

Fig. 1 AFM image of as-grown InAs QDs on GaAs substrate.

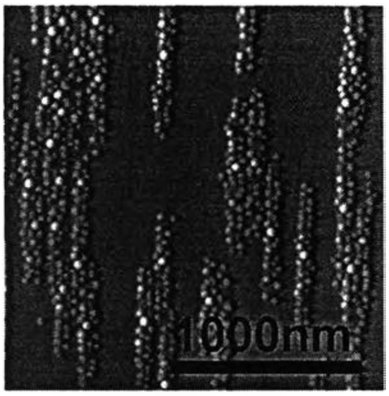

Fig. 2 AFM image of InAs QDMs grown by thin-capping-and-regrowth MBE process.

Fig. 3 AFM image of high-density QDMs grown by repeating the thin-capping-and-regrowth MBE process for five cycles.

We have previously proposed a QD solar cell design, which takes advantage of QD absorption of the solar spectrum outside the normal bulk range, using a Schottky structure. This is followed by similar designs with single stack and multi-stack QDMs as the absorption layer.(9) However, little improvements are found. This is due to an insignificant presence of the QDs as compared to the total absorptive volume. But when the high-density QDM layer, as shown in Fig. 3, is inserted into the Schottky solar cell structure, a significant improvement can be observed, particularly when the QDM layers are stacked on top of one another.(10)

In this paper, we show the first electrical results of QDM solar cell p-n structure, as opposed to the Schottky structure in our previous work. The results are compared between having one- and five stacks of QDM layers. Previous results from Schottky solar cells are also given for comparison purposes. The organisation of the paper is as follows. Next, the properties of the material—multi-stack high-density QDMs—will be explained. Then, the electrical properties of the devices—QDM solar cells—will be given in Section 3, followed by the conclusion in Section 4.

MULTI-STACK HIGH-DENSITY QDMs

The AFM images shown in figures 1 and 2 clearly show that the density of QDMs is at least one order of magnitude higher than those of as-grown QDs. Therefore, one layer of QDMs is equivalent to multiple layers of QDs, in terms of effective dot volume. By the same argument, one layer of high-density QDMs (Fig. 3) is equivalent to multiple layers of QDMs (Fig. 2). Therefore, multi-stack high-density QDMs provide the highest dot volume among other QD and QDM structures, i.e. higher than 10^{12} cm^{-3}.

In addition to the density and morphological information of the QDMs above, we have also characterized the QDMs' optical property by room temperature photoluminescence (PL) measurements using Ar^{+}-laser excitation. The PL results of the 1-stack and 5-stack InAs QDM (embedded in GaAs) samples are shown in Fig. 4. The 5-stack QDM sample provides a higher PL intensity with a broader FWHM comparing to that of the 1-stack sample (80 meV vs. 75 meV). A small blue shift of PL peak (1.053 eV from 1.075 eV) was also observed. These results are due to the higher dot density and a greater degree of size distribution of the 5-stack sample.

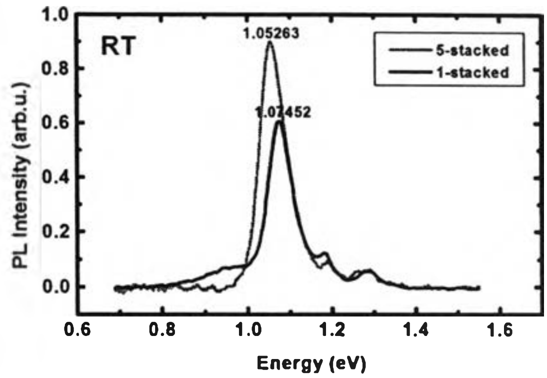

Fig. 4 Room temperature PL spectra of the 1- and 5-stack high-density QDM samples.

MULTI-STACK HIGH-DENSITY QDM HOMOJUNCTION SOLAR CELLS

In our previous work, *Schottky* junction solar cells with embedded layers of multi-stack QDMs and multi-stack high-density QDMs were fabricated and their I-V characteristics reported, as summarized in Table 1. It is typical for a multi-stack *high-density* QDM solar cell with a Schottky structure to give a higher short-circuit current (J_{sc}) than multi-stack QD and QDM solar cells, see Table 1.

In this work, *homo*-junction *high-density* QDM solar cells are fabricated and their I-V characteristics measured. The structure of the 1-stack and 5-stack high-density QDM homojunction solar cells are shown in Figs. 5(a) and 5(b), respectively. P-GaAs substrates are used as the starting material. After the growth of GaAs buffer layer, InAs QDMs are grown by the thin-capping-and-regrowth MBE process. This process is repeated for five cycles in the sample shown in Fig. 5(b). Then, the structures are capped with n-GaAs to form a p-n junction. Au:Ge/Ni and AuZn are used as Ohmic contacts to the front n-GaAs surface and the back p-GaAs substrate, respectively. The current-voltage (I-V) measurements of the solar cells are then carried out in the dark and under illumination.

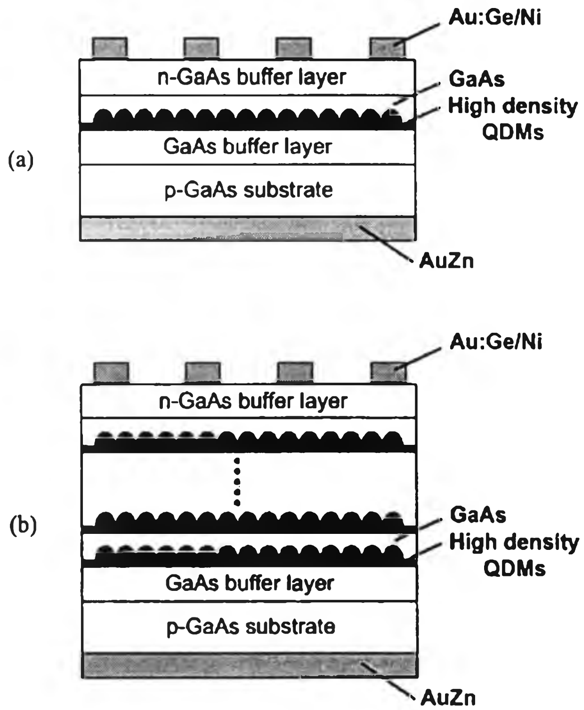

Fig. 5 The schematic of multi-stacked high-density QDM homo-junction solar cells having (a) single-stacked QDMs (b) and 5-stacked QDMs.

From the same batch of homostructure solar cells having 5 stacks of QDMs as active layers, we carefully select better cell with F.F. = 0.67 and J_{sc} = 15.2 mA/cm^2 as shown in Fig.7. The cell efficiency is 5.1%.

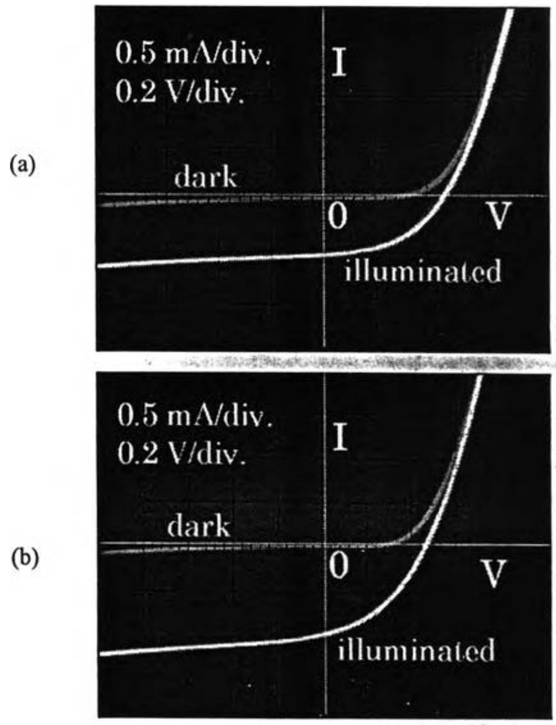

Fig. 6 I-V characteristics of QDM homojunction solar cells measured in the dark and under illumination. Embedded between the junction is a (a) 1-stack or (b) 5-stack QDM layer.

Table 1. Summary of electrical performances of QD and QDM solar cells under 100 mW/cm^2 AM1 solar simulator.

Embedded structures*	Device type	number of QD or QDM stacks	J_{sc} (mA/cm^2)	V_{oc} (V)	F.F.	Ref.
QDs	Schottky	3	0.60	0.24	0.59	[5]
QDMs	Schottky	1	0.68	0.25	0.34	[8]
QDMs	Schottky	5	0.64	0.30	0.37	[8]
High density QDMs	Schottky	1	1.50	0.30	0.50	[10]
High density QDMs	Schottky	5	2.10	0.30	0.50	[10]
High density QDMs	Homojunction	1	9.60	0.50	0.52	This work
High density QDMs	Homojunction	5	14.40	0.50	0.55	This work

In all of the following I-V measurements, the input light is generated from a solar simulator with AM1 solar spectrum and 100 mW/cm^2 input power. The PV output from the 1-stacked QDM solar cell sample exhibits an open-circuit voltage of V_{oc} = 0.5 V and a short-circuit current density of J_{sc} = 9.6 mA/cm^2 as shown in Fig. 6(a). The fill factor of the 1-stacked QDM solar cell is F.F. = 0.52. For the 5-stacked sample, V_{oc} remains constant at 0.5 V but J_{sc} increases to 14.4 mA/cm^2, and the F.F. improves to 0.55 as shown in Fig. 6(b). We attribute the increase in short-circuit current density solely to the higher absorptive dot volume associated with the extra four layers of high-density stacked QDMs. The high-density QDMs also provide a low sheet resistance layer which is a factor in the improvement of the fill factor of the solar cells.

The solar cells are also characterized by spectral response measurements. A tungsten lamp is used as a light source passing through a monochromator having a grating with a resulting sensitivity in the range of 330-1000 nm. The photocurrents generated as a function of incident light with varying wavelengths are recorded. The results for the 1- and 5-stack high-density QDM solar cells are plotted in Fig. 8. The spectral response of GaAlAs/GaAs solar cell without QD integration is also given for comparison. While the wide bandgap of GaAlAs has good response at short wavelength, it is found that the high-density InAs QDM solar cells respond to long wavelengths beyond the band edge wavelength of GaAs, 850 nm.

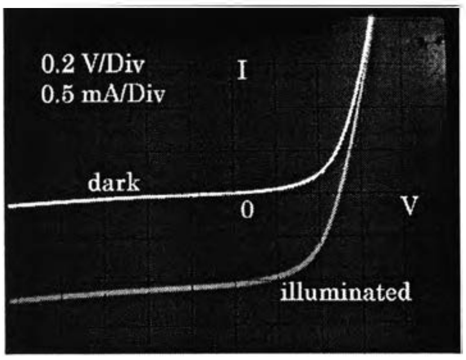

Fig. 7 I-V curves of 5 stack QDM solar cell having better F.F. and leading to an efficiency of 5.1%.

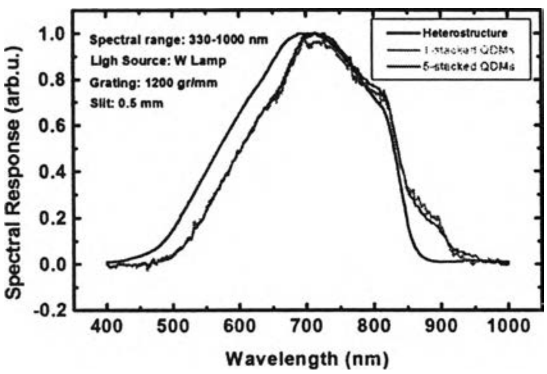

Fig. 8 Photocurrent (PC) spectral responses of 1- and 5-stack high-density InAs QDM solar cells comparing to GaAlAs/GaAs heterostructure solar cell without QD integration.

With the above encouraging results, we are designing multi-stack high-density QDM *hetero*-structure solar cells. Band offsets resulting from heterostructures can provide higher built-in electric fields. We expect to achieve even higher V_{oc} and J_{sc} as compared to homojunction devices.

CONCLUSION

Multi-stack high-density QDMs have been grown by the thin-capping-and-regrowth MBE process. 1- and 5-stack layers of QDMs have been incorporated into homojunction (p-n) solar cells. Spectral response of the QDM solar cells exhibit absorption beyond the GaAs band edge (850 nm). The increased absorption allow high-density multi-stack QDM solar cells to outperform their multi-stack QD and QDM equivalents, both in terms of increased fill factor and short-circuit current. The efficiency of homostructure QDM solar cell is 5.1%.

ACKNOWLEDGEMENT

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Spectral Response and Performance at Concentrated Sunlight of Multi-Stacked High Density InAs Quantum Dot Molecule Solar Cells

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Abstract

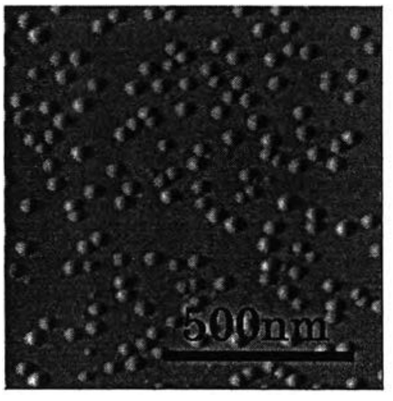
Multi-stacked high density InAs quantum dot molecule (QDM) solar cells were fabricated by multi-cycles of thin-capping-and-regrowth molecular beam epitaxy. One stack of QDMs provides dot density gives as high as 10^{12} cm^{-2}. The high dot density is desirable for effective photon absorption, particularly at long wavelengths of the solar spectrum due to the extended band of quantized energies of InAs quantum dots and good dot size uniformity (better than 70 %). Five stacks of high density QDMs were also grown by a series of GaAs cappings and InAs QDM regrowth utilizing induced strain fields of the underlying layers. Photoluminescence measurement of 5-stacked QDM sample indicates that quantum dot size is larger and dot uniformity worsen as shown respectively by the PL blue shift (from 1.075 eV to 1.053 eV) and a broader FWHM of PL spectrum (from 75 meV to 80 meV) comparing to a 1-stacked QDM sample.

Five-stacked high density InAs QDM solar cells with homojunction of GaAs were fabricated and tested. It is found that this multi-stacked structure of high density InAs QDMs responds to long wavelengths spectral region beyond 850 nm which is the absorption band edge of GaAs. We observed the extension of the absorption up to 1000 nm which is the sensitivity limit of our instruments. Heterostructure of GaAlAs/GaAs solar cell without QD integration was also measured as a reference.

I-V characteristics of five stacked high density InAs QDM solar cells were measured under AM1 100 mW/cm^2 solar simulator. The open-circuit voltage of this homojunction solar cell is 0.5 V while the short-circuit current density is as high as 15.2 mA/cm^2. With a relatively low fill factor of 0.668, the efficiency of this preliminary InAs QDM solar cell is about 5.076%. Due to the low dimensionality of quantum dot structure which is useful for high performance device, this multi-stacked QDM solar cells are also characterized at concentrated sunlight using a focused solar simulator having different light intensities (1~4 suns). The performance of InAs QDM solar cells at high sun numbers is compared to those of GaAlAs/GaAs heterojunction without QD integration.

Extended Abstract

High density InAs quantum dot molecules (QDMs) are grown by multi-cycles of thin-capping-and-regrowth MBE process.[1] Comparing to the initial QD density of 10^{10} cm^{-2}, QDMs provide higher dot density of 10^{12} cm^{-2} as shown in AFM images of figures 1(a) and 1(b) respectively.

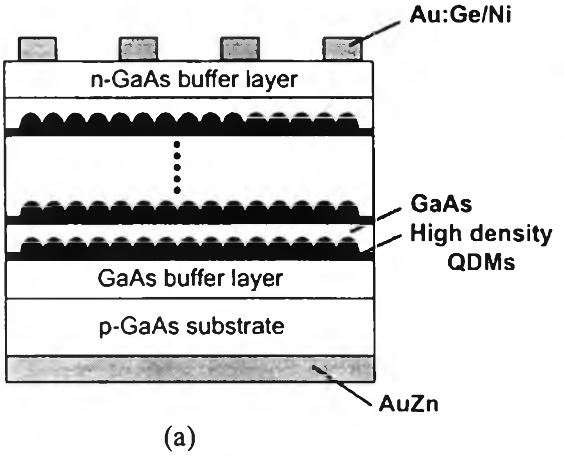


(a)

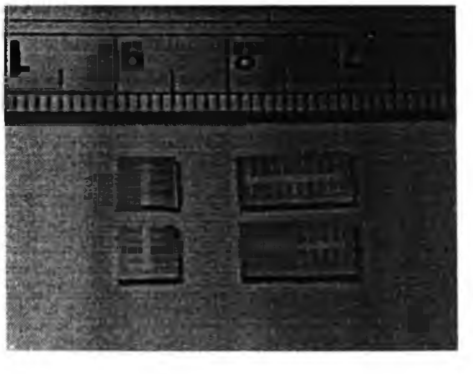
(b)

Fig. 1 AFM images of (a) as-grown QDs and (b) QDMs.

Multi-stacked high density InAs QDMs are inserted into a p-n junction of GaAs as an active part of solar cell structure.[2] Schematic diagram of cell structure is shown in figure 2(a). P-type GaAs substrate is used as the starting material in our experiment. After a GaAs buffer layer, intrinsic high density InAs QDMs are grown and repeated for 5 stacks of QDMs, followed by the capping of n-GaAs for p-n junction. AuZn and Au:Ge/Ni are used as Ohmic contacts to for p-type and n-type GaAs respectively. The actual solar cells having front grid contacts with cell areas of 5×5 and 5× 10 mm^2 are shown in figure 2(b).



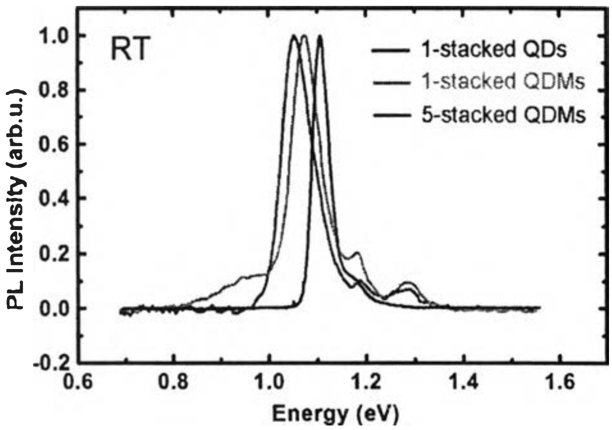
(a)



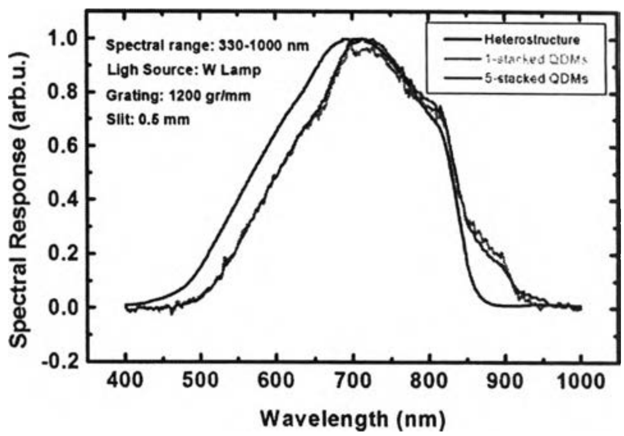
(b)

Fig. 2 (a) Schematic structure of multi-stacked high density QDM solar cells.
(b) Fabricated QDM solar cells.

Good optical properties of multi-stacked high density InAs QDMs are confirmed by PL measurement at room temperature by an excitation of Ar^+ laser.[(3)] Strong PL emission from 5 stacks of QDMs appears at 1.053 eV and broad FWHM of 80 meV. The blue shift of PL peak from those of 1 stacked QDMs and as-grown QDs indicates that the multi-stacked QDMs are composed of larger dots which are not as uniform as the 1-stacked or the as-grown QDs. The latter is attributed to the statistical nature of strain field relaxation during stacking formation. Conventional QDs normally provide PL peak at 1.1 eV and FWHM of 47 meV.[(4)] (see figure 3)



(Fig. 3)



(Fig. 4)

Fig. 3 Normalized PL spectra of 5-stacked QDMs comparing to those of 1 stacked QDMs and as-grown QDs.

Fig. 4 Spectral response at longer wavelengths is found in InAs QDM solar cells comparing to GaAlAs/GaAs heterojunction without QDs.

It is found that both 1-stacked and 5-stacked QDM solar cells give broader spectral response at longer wavelengths beyond 850 nm which is the absorption band edge of GaAs. Figure 4 shows the comparison between InAs QDM solar cells and GaAlAs/GaAs heterojunction solar cell without QD integration in term of spectral response. While the wide bandgap of GaAlAs results in good response at short wavelengths response the response drops sharply above 850 nm. However, QDM solar cells have an extended response up to nearly 1000 nm which is the limit of our measuring instruments.

The multi-stacked QDM solar cells are tested for their I-V curves under AM1 100 mW/cm^2 solar simulator (see figure 5). The homojunction solar cell gives a relatively low open-circuit voltage (V_{oc}) of 0.5V. The short circuited current density (J_{sc}) of this QDM solar cell is 15.2 mA/cm^2 with a fill factor (F.F.) of 0.668. These results lead to an efficiency of 5.076%.

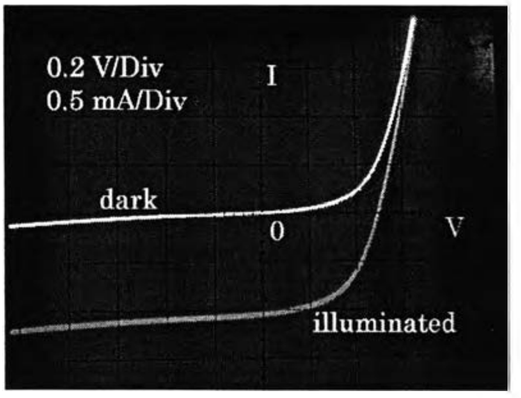
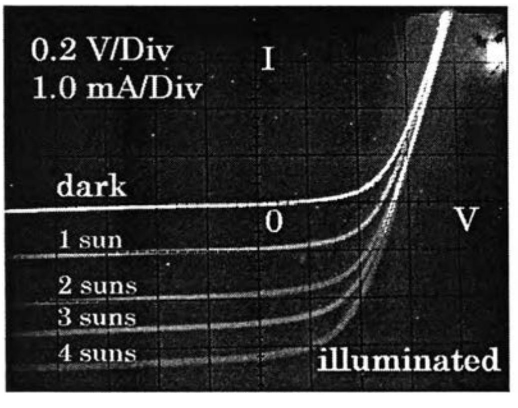
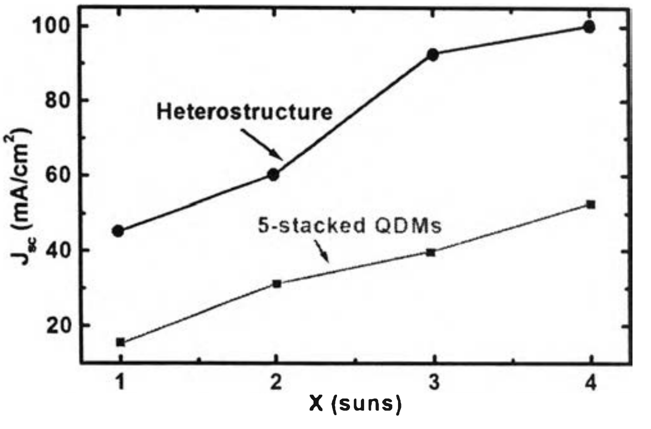


Fig. 5 I-V curves at dark and illuminated conditions of 5-stacked high density InAs QDM solar cells

The QDM solar cells are also tested under concentrated sunlight ranging from 1 sun to 4 suns by using focused beam of solar simulator. At concentrated illumination, V_{oc} improves from 0.5V to 0.55V while the J_{sc} increases with light intensity (see figure 6(a)). The results are plotted in J_{sc}-X as shown in figure 6(b) and compared to those of GaAlAs/GaAs heterojunction solar cell without QD integration.





(a) (b)

Fig 6 (a) I-V curves of InAs QDM solar cell at 1-4 suns.

(b) J_{sc} of 5-stacked QDMs and GaAlAs/GaAs heterojunction without QDs as a function of X (number of suns).

Further improvement of QDM solar cells utilizing GaAlAs/GaAs heterostructure and their performance at high concentrated sunlight are under investigation.

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Long Chains of Self-Assembled InAs Quantum Dot Molecules by Modified MBE Growth Technique

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Abstract

Long chains of self-assembled lateral InAs quantum dot molecules (QDMs) are grown by thin-capping-and-regrowth MBE process.(1) By capping as-grown InAs quantum dots (QDs) with a thin layer (9 MLs) of GaAs at 470°C, we obtain elongated nanostructure which can be used as a template for subsequent growth. When 1.2 ML of InAs is grown on the template, QDMs having 24-30 dots in each molecule (see Fig. 1) are formed. By repeating the above thin-capping-and-regrowth process for 5 cycles, long chains of InAs QDMs can be obtained. The longest chain of QDMs is found to be longer than 5 microns. An average length of the QDMs is 0.7±0.1 microns (see Fig. 2a) while the width is position dependent. Around the central dots, the equivalent cross-sectional InAs waveguide area is 80×7 nm2 (A1-A4 in Fig. 2b). At other positions along the QDM chain, two closely-spaced dots give rise to an approximate area of 150×5 nm2 (B1-B4). These long chains of InAs QDMs have central dots linking adjacent QDMs and may perform useful waveguide and electronic switching functions in nano-devices.

Photoluminescence (PL) measurements on QDMs and long chains of QDMs are conducted at room temperature. The PL spectra show that there is a FWHM broadening (45 to 71 meV) due to less dot uniformity of QDMs comparing to the as-grown QDs (see Fig. 3). Further characterisations are being carried out and PL emission and electron transport properties of the long chain QDMs will be reported.

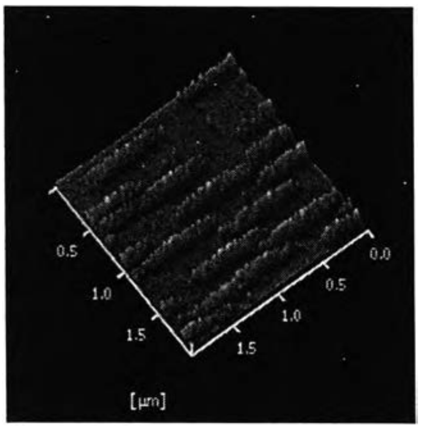
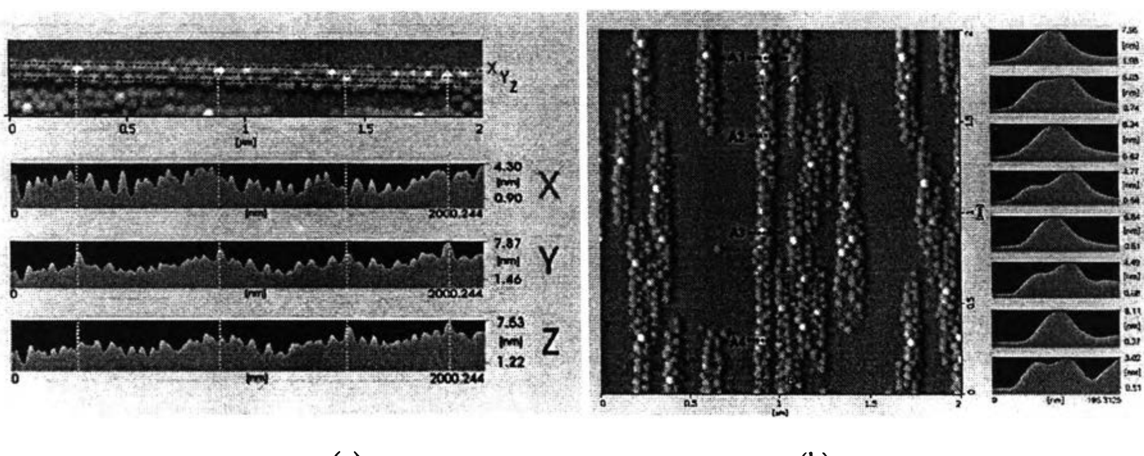


Fig. 1 AFM image of self-assembled QDMs having 24-30 dots in each molecule.



(a) (b)

Fig. 2a AFM images and line scans (a) along and (b) perpendicular to the length of a QDM chain.

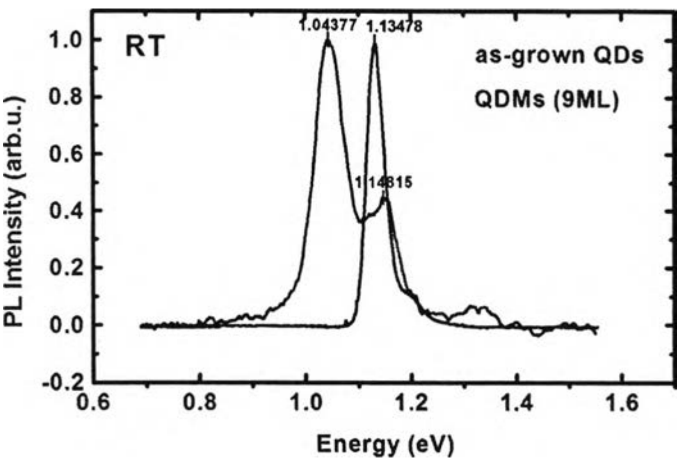


Fig.3 PL spectra of InAs QDMs and as-grown InAs QDs.

[1] S. Suraprapapich, S. Kanjanachuchai and S. Panyakeow, J. Vac. Sci. Technol. B 23, 1217, 2005.

ประวัติผู้เขียนวิทยานิพนธ์

นายศิริชัย เรืองเดช เกิดเมื่อวันที่ 5 พฤษภาคม พ.ศ. 2522 ที่โรงพยาบาลสุพรรณบุรี อำเภอเมือง จังหวัดสุพรรณบุรี ศึกษาชั้นประถมที่โรงเรียนวิทยาศึกษา, ชั้นมัธยมต้นที่โรงเรียนบางปลาม้าสูงสุมารผดุงวิทย์,ชั้นประกาศนียบัตรวิชาชีพที่วิทยาลัยเทคนิคสุพรรณบุรี และชั้นประกาศนียบัตรวิชาชีพชั้นสูงที่สถาบันเทคโนโลยีราชมงคล"วิทยาเขตสุพรรณบุรี"จังหวัดสุพรรณบุรี ได้รับปริญญาวิศวกรรมศาสตร์บัณฑิต สาขาวิศวกรรมอิเล็กทรอนิกส์ จากคณะวิศวกรรมศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง เมื่อปี พ.ศ. 2547 ต่อจากนั้นเข้าศึกษาต่อในหลักสูตรวิศวกรรมศาสตร์มหาบัณฑิต ที่ห้องปฏิบัติการวิจัยสิ่งประดิษฐ์สารกึ่งตัวนำ ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย เมื่อ พ.ศ. 2547