Development of Quantum Dot Solar Cells

Okada Laboratory

Research Center for Advanced Science & Technology
The University of Tokyo
Innovative PV: 50% Efficient Solar Cells

- Efficient absorption by using multiple bandgaps
- Efficient use of high-energy solar radiation

- Multiple junctions (Quantum size effect)
- Intermediate bands (QD superlattice)
- Multiple exciton generation (MEG)
- Hot carriers

- 3 V

- AM1.5 Wavelength
- Efficient use of high-energy solar radiation

- Innovative PV: 50% Efficient Solar Cells
Intermediate Band Solar Cell: Principle

Intermediate Band Solar Cell: Theoretical Efficiencies

\[ \eta = 47\% \text{ (1sun)} \]
\[ \eta = 63\% \text{ (Maximum concentration)} \]

Intermediate Band Realized with 3D Quantum dot Superlattice

**Single QD**

- InAs QD
- GaAs

**3D QD Superlattice**

- GaAs
- InAs QD
- miniband

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**VB**

**CB**
Self-Assembled Growth of Quantum Dots

Frank-van der Merwe

Volmer-Weber

Stranski-Krastanov (S-K)
Molecular Beam Epitaxy (MBE)

- Chamber
- Substrate
- Growing layer
- Shutter
- Source
- K-cell
- Molecular beam
- Vacuum Pump
- H-cracking cell
- $\text{H}_2$
- $\text{N}_2$
- Plasma cell
- $\text{N}_2$
- $\text{H}_2$
- Plasma cell
- H-cracking cell
Self-Organized InGaAs Quantum Dots on (311)B Substrate

QDs on (311)B substrate show:
(1) Better size homogeneity
(2) Higher in-plane density
(3) Ordered periodic structure
(4) Better heterointerface quality

Fabrication of 3D Quantum Dot Superlattice: Strain-Balancing

Accumulation of lattice strain in conventional approach

Strain-compensation growth: Strain/layer is balanced out

Z.R. Wasilewski et al. JCG 201 (1999) 1131
InGaAlAs III-V multijunction solar cells

Strain-Compensation Materials
Self-Organized Stacked InAs QDs on InP(311)B Substrates

Spacer thickness $d = 20$ nm
Number of stacked QDs = 30 layers

Average diameter = 63.2nm
In-plane dot density = $2.7 \times 10^{10} \text{cm}^{-2}$
Size uniformity $\sim 12.3\%$

Y. Okada et al, EU-PVSEC, Barcelona (2005)
InGaAs/GaNAs Quantum Dot Solar Cell: 1 sun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$I_{SC}$ (mA/cm²)</td>
<td>24.26</td>
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<tr>
<td>$V_{OC}$ (V)</td>
<td>0.791</td>
</tr>
<tr>
<td>FF</td>
<td>0.840</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>16.12</td>
</tr>
</tbody>
</table>

Y. Okada, MRS Fall Meeting (Boston, 2008)
IB (3D QD Superlattice) Solar Cell: On-going Developments

InAs/GaAs

IES-UPM
Univ. of Glasgow
A. Luque et al.

InAs/GaAsP

Rochester Institute of Technology
NASA
S. M. Hubbard et al.

InAs/GaAsP

NREL
V. Popescu et al.

InAs/Ga(N)As/GaAs

Univ. of Tokyo
Y. Okada et al.

InAs/AlGaAs

St. Petersburg Russian Academy
Ioffe Institute
S. A. Blokhin et al.
Physics of semiconductor Devices 43, 514 (2009)

η = 15.7% (100) 16.1% (311)B
η = 18.32%
Intermediate Band (Quantum Dot Superlattice) Solar Cell

- Efficiencies > 60% (under concentration) are possible with intermediate band solar cells. Concentrator cells are very cost-effective.
- Fabrication of high-quality 3D quantum dot superlattice is required as a good intermediate band.
  - Good size uniformity (< 10%)
  - High density resulting in higher absorption
  - Close packing resulting in miniband formation (dot spacing < 10nm)
  - Optimization of bandgap energies of materials
- Top-down approaches are attractive for reducing cost.
- Photon management helps increase optical absorption in IB.

This work is supported by NEDO and METI, Japan.