Silicon and Germanium Nanocrystal Electronic Devices

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Outline

• Motivation
• Nanocrystal synthesis
• Nanocrystal characterization
• Nanocrystal thin films
  I: Drop-casting of functionalized Ge NCs
  II: Impaction
  III: Spin-casting of bare Ge NCs
• Hybrid solar cells
• Summary
Motivation

Semiconductor nanocrystal applications

- Transistors
- LEDs
- Photodiodes
- Solar cells


## Motivation

Need >10 TW of carbon-free power by 2050.


<table>
<thead>
<tr>
<th>Source</th>
<th>Theoretical Resources</th>
<th>Practical Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>4.6 TW</td>
<td>1.5 TW</td>
</tr>
<tr>
<td>Wind</td>
<td>2 TW</td>
<td>&lt; 10 TW</td>
</tr>
<tr>
<td>Geothermal</td>
<td>12 TW</td>
<td>&lt; 10 TW</td>
</tr>
<tr>
<td>Biomass</td>
<td>50 TW</td>
<td>&lt; 10 TW</td>
</tr>
<tr>
<td>Solar</td>
<td>120,000 TW</td>
<td>&gt; 50 TW</td>
</tr>
</tbody>
</table>
Motivation

Metric (cost/energy output) is \(~10\)x too large.

Motivation

Little improvement in efficiency. “Breakthrough technology” needed.
Motivation

Nanocrystal solar cells

- Tunable absorption » Multijunction devices
- Large conductivities & mobilities » High efficiencies
- Easily processed » Cost reduction opportunities

Si & Ge nanocrystals (NCs)

- Non-toxic
- Abundant
- Compatible with Si technologies


Motivation

NC seeded crystallization of a-Si:H

NC-only thin films

NC/polymer hybrid solar cells

Song et al., Thin Solid Films, 2006
NC synthesis

Ar → MFC → RF → 25 mm OD quartz → Pressure gauge → P

H₂ → MFC

GeCl₄ or SiH₄ → MFC

5 nm Ge NC recipe

Ar Flow: 42 sccm
GeCl₄ Flow: 2 sccm
H₂ Flow: 30 sccm
Pressure: 2 Torr
Power: 125 W

NC characterization

Si & Ge NC properties

- Spherical
- Freestanding
- Tunable size (3-50 nm)
- Relatively monodisperse (std. dev. 10-15% <d_p>)
- Controllable crystallinity

Film formation I

For devices, need films that have...

- The optical properties of their constituent particles
- Reasonable conductivities/mobilities

Nanocrystals collected on mesh

1-Dodecene
\( C_{12}H_{24} \)

Dissolves in common non-polar solvents

\[ 3 \times 10^{-8} \] to \[ 3 \times 10^{-6} \] (A)

\[ V_g = 40 \text{ V} \]

\[ V_{ds} (V) \]

Ge NCs

SiO\(_2\)

Si

10 nm

X100,000 100 nm WD 10.1 mm
Film formation II

5 nm Ge NC recipe
- Ar Flow: 42 sccm
- GeCl₄ Flow: 2 sccm
- H₂ Flow: 30 sccm
- Pressure: 2 Torr
- Power: 125 W

Ar → MFC → MFC → MFC
H₂ → MFC
GeCl₄

25 mm OD quartz

Pressure gauge → P
NC spray
Substrate → Orifice
Exhaust

Raster arm
Total flow rate = 74 sccm, Pressure ratio ~ 4
Distance from orifice ~10-20 mm, Pressure ratio ~ 4
Total flow rate = 113 sccm, Distance from orifice ~10-20 mm

Film densities approaching 60% bulk value
Average crystallite size of films can be varied from 4-14 nm. Bandgap widens to >1 eV from 4-14 nm.
Conjugated Polymer

- High optical absorption
- Solution based processing
- Large-scale and low-temperature manufacturing

Power Conversion Efficiency(%)
Hybrid solar cells


Si NCs/P3HT Solar Cells

- Light absorption in P3HT and Si NCs
- Exciton dissociation
- Carrier transport
Hybrid solar cells

Hybrid solar cells

Summary

- Nonthermal plasma synthesis of high quality Si & Ge NCs
- Three methods of NC thin film formation
- Tuneable film absorption by altering Ge NC size; optical bandgaps >1 eV
- Field effect mobilities of $\sim 10^{-2} \text{ cm}^2/\text{Vs}$ after annealing
- Si NC/P3HT hybrid solar cells with 0.8 V $V_{oc}$ and 1.5% efficiency

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