Optics of Solar Cells

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and Sol Ideas Technology Development

OSA’s 93rd Annual Meeting - San José, CA, USA,
Frontiers in Optics (FiO) 2009/Laser Science (LS)
25th Conference
Optics for Renewable Energy

Keynote Speaker: FMB1, Optics of Solar Cells, Greg P. Smestad, Monday, October 12, from 1:30 PM - 2:15 PM

- Systems Approach
- Optical view of Solar Cells and Photovoltaics
- Literature
- What else is it good for?
- Solar Energy Grid Interconnection Systems (SEGIS)
- Solar R&D Plan
- Where we go from here?
What are Systems?

- A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole.
- Systems are everywhere:
  - the R&D department in your organization,
  - the circulatory system in your body,
  - a photovoltaic cell or PV system.
Systems Thinking is

- a framework that is based on the belief that the **component** parts of a **system** can best be understood in the context of relationships between components and with other systems, rather than in isolation.
- It seeks an understanding of a system by examining the linkages and interactions between the elements that comprise the whole system.
- **Let’s look at a solar cell as a thermo-dynamic system**
Solar Cells can be simple, but...
they can also be complex.

Courtesy of Dick Swanson, SunPower
Band Diagrams are useful, but

![Diagram of band structure](image)

Conduction Band

Light Input

Current Extracted by Contacts

Load Resistor

Valence Band

Efp

qV

Efn

+ -

Courtesy: G.P. Smestad
recombination determines efficiency.

Courtesy: G.P. Smestad
Diode Equation

\[ I(V) = I_{SC} - I_0 \left[ \exp\left( \frac{qV}{\gamma kT} \right) - 1 \right] \]

Device Electrical Characteristics

Courtesy: Alexis de Vos
System Properties

- **Energy**, **material** and **information** are among the different elements that comprise the system and these flow to and from the surrounding environment via semi-permeable membranes, **barriers** or boundaries.

- Systems are often composed of entities seeking equilibrium and can exhibit **exponential** behavior.

- **Entropy** - the amount of disorder or randomness present in any system.
Senge Diagram
Photovoltaic Cell

- Electron-hole Generation and Recombination
- Absorption and Luminescence
- Charge-Transport
- Carrier Extraction (Electricity)
- Other processes
- Changes in Chemical Potential
- Light Input and Output
- Sun
- Traps
- Delay

Courtesy: G.P. Smestad
The Planck Equation describes solar radiation, but...

Courtesy: G.P. Smestad
absorptivity describes what is absorbed.

\[ a(e) = (1 - T_i) \cdot \sum_{i=0}^{\infty} \left[ (1 - 1/n^2)T_i \right]^i \approx \frac{\alpha}{1 \cdot 4t \cdot n^2 + \alpha \left(1 - \frac{1}{n^2}\right)} \]

E. Sacks/MIT/1366 Technologies;
Veeco Instrument Inc. Optical Profiler
Generalized Planck Equation

\[ \mu = e \left(1 - \frac{T_0}{T_S}\right) \]

\[ \frac{e - \mu}{kT_0} = \frac{e}{kT_S} \]

\[ L_x(e, \mu, T_0) = \varepsilon(e) \frac{2}{h^3} \frac{n^2}{c^2} \frac{e^3}{\exp\left(\frac{e - \mu_x}{kT_0}\right) - 1} \]
Planck Describes Rad. Recombination

Silicon Photoluminescence

- Predicted: $\mu = 0.63$ eV
- Measured: $\lambda_{\text{exc}} = 514$ nm

Luminescent output $\times 10^{-18}$ [Photons/(s m$^2$ eV)]

Phonon Energy (eV)
Define and Integrate

\[ L_x'(e, \mu, T_0) = \frac{L_x(e, \mu, T_0)}{e \cdot \varepsilon(e)} \]

Ideal Spectral Flux

\[ a(e) = \varepsilon(e) \]

Quantum Kirchhoff's law

\[ \Gamma_0 = \int_{0}^{\infty} \varepsilon(e) \pi L_0' \, de \]

Photons (Particles)
Detailed Balance

\[ \Phi_{\text{OC}}(\mu, T_0) \equiv \Phi = \frac{\text{Radiative Recombination}}{\text{Total Recombination}} \]

Ambient Incident + Solar Incident =
Luminescent Photons + Phonons or Heat + Current extracted

\[ \Phi = \frac{\Gamma_0 \text{R} - \Gamma_0}{\Gamma_s} \approx \frac{\Gamma_0 \exp(\mu/kT_0) - \Gamma_0}{\Gamma_s} \]
Diode Equation emerges from Planck

\[ \Gamma = \Gamma_S - \frac{\Gamma_0}{\Phi} \left( \exp\frac{\mu}{kT_0} - 1 \right) \]

max. chemical potential \( \equiv \mu_{\text{max}} \approx kT_0 \ln \frac{\Gamma_S}{\Gamma_0} + kT_0 \ln \Phi \)
Radiative Recombination

![Graph showing luminescence and chemical potential relationship with photoluminescence efficiency for different materials: a-Si, GaAs, Si, PbS.](image)

Courtesy: G.P. Smestad
Detailed Balance Efficiencies


- 5800 K
- AM1.5G
- AM 1.5D

Graph showing efficiency as a function of energy (E_g in eV) with different temperature conditions.
All from a Systems Approach to a Photovoltaic Cell

1. Sun
2. Light Input and Output
3. Absorption and Luminescence
4. Carrier Extraction (Electricity)
5. Charge-Transport
6. Changes in Chemical Potential
7. Electron-hole Generation and Recombination
8. Other processes
9. traps
10. delay

Other processes include:
- Absorption
- Luminescence
- Carrier Extraction (Electricity)
- Charge-Transport
- Changes in Chemical Potential
- Electron-hole Generation and Recombination
- Other processes
- traps
- delay
A Solar Cell is a System

- The performance of solar cells is determined by how its materials absorb, reflect and even emit light.
- The voltage produced can be described using the Planck equation rather than the Fermi-Dirac equation.
  - In other words, solar conversion can be viewed from the standpoint of the photon rather than the electron.
- Such an optical Systems Approach can be useful for understanding solar cell-device designs and the fundamental limitations to conversion efficiency for a given absorption.
Want More on this Optical Perspective?

- Look for publications by:
  - Shockley and Queisser
  - Harald Ries
  - P. Wuerfel (Würfel)
  - E. Yablonovitch and G. Cody
  - R. T. Ross
  - T. Markvart
  - T. Trupke
  - PV Optics Computer Program: B. Sopori

www.nrel.gov/pv/measurements/computational_modeling.html
and (yes) Greg P. Smestad


What else is it good for?

- Systems thinking techniques may be used to study any kind of system: natural, scientific, engineered, human, or conceptual.

- *Systems Analysis* for solar R&D can identify key positive reinforcements that can accelerate the adoption of solar technologies. It can identify constraints that can decelerate solar technology adoption, as well as points of leverage where investment and R&D can have the most positive impact.
PV Module Systems

Residential Systems

Smart Grid - Solar Energy Grid Interconnection Systems (SEGIS)
http://www.sandia.gov/SAI/

Courtesy: Ron Smestad
The Solar Advisor Model (SAM) evaluates several types of financing (from residential to utility-scale) and a variety of technology-specific cost models for several and, eventually, all solar technologies.

https://www.nrel.gov/analysis/sam/
SEGIS Dynamics needs Real-Time Data
Solar Resource Monitoring

Book by Stuart Bowden and Christiana Honsberg;
http://pvcdrom.pveducation.org/

Courtesy: NREL Photos
The Solar Industry:
- Similar to automobile industry in ultimate scale—and hence,
- Expect large companies designing complete systems from integrated subsystems delivered by a network of suppliers.
- Can get “there” from “here” via —

The Energy Internet:
- Will evolve from today’s grid
- Can use the Information Internet as model for development
- Key elements include: standards, consumers and producers, a network and an infrastructure for transport and storage
- Can start with —

How do these relate?

Global Solar Industry Value Creation

“Smart Grid” Infrastructure Development

Courtesy: Joe Morabito, Alcatel-Lucent, DOE/SETP March 2009
Senge Diagram —
System-Focused Solar Industry Development

Global Solar Industry Value Creation

Market Supply-Chain Transformation

"Smart Grid" Infrastructure Development

Federal Energy Policy (Congress)

System-Dynamics Modeling

SEGIS

Innovation

National Labs Industry & Universities

Solar Industry Supply-Chain Consortium

Industry Associations

Public & Private Investments

Manufacturing Scale-up

Technology Innovation

Market Growth

Sustainable Profit

Unanticipated & Expanding Applications

Delay

Analysis

Delay

Delay

Delay

Delay

 Courtesy: Joe Morabito, Alcatel-Lucent, DOE/SETP March 2009
Powering the Solar Innovation Engine

- Interconnected systems reinforce the innovation process.
  - Positive Reinforcement spins the wheels faster!
- Feedback loops create virtuous cycles.
Conclusions

- Solar Cells can be viewed from a purely optical perspective.
- Solar Energy R&D and Industry Drivers should be considered in the context of **Systems Thinking**.
- Such perspectives lead to a multidisciplinary, collaborative approach.
- This can reduce the product development interval and facilitate technology transfer to more rapidly spin the Solar Innovation Engine.
Thank you

Visit http://www.solideas.com/ for further information, references and links.

Greg P. Smestad, Ph.D.
Solar Energy Materials and Solar Cells
Sol Ideas Technology Development
OSA Science Educators Day

Thursday, October 15, 2009
5:30 p.m.-8:00 p.m.
McCaw Hall, Frances C. Arrillaga Alumni Center,
Stanford University
326 Galvez St.
Stanford, CA
Tel.: +1 650.723.2021

Solar Cell Educational Kits

www.frontiersinoptics.com/SpecialEvents/default.aspx
How does the Systems Approach in the Senge Diagram relate to OSA?

OSA is one of many organizations that feed into the policy and supply chain aspects of PV. One recommendation from the approach is collaboration, coordination, and integration between such organizations.
Questions & Answers

- With PV technologies and systems so diverse, how can the Systems Approach be used?
  - All installed PV systems must adhere to national and international standards of performance, longevity and stability. Earlier PV technologies can set the stage for new solar technologies as they enter the market.
Questions & Answers

- How was the approach developed?
  - It was developed by several reviewers for DOE, but does not represent the views of the U.S. Department of Energy.
  - We developed this analysis by substantial participation in the DOE Solar Energy Technologies Program’s 2009 Annual Program Peer Review held in March, 2009.
  - More information is available (in the Past Meetings section) on the DOE website at: www1.eere.energy.gov/solar/review_meeting/