# Program (first version, status February 2023)

## 1 Basics of photovoltaics (21.2. Ballif)

- Sun spectrum
- Basic PV and semiconductor properties
- Spectral response, quantum efficiency
- Standard test conditions (STC, NOTC), Watt peak
- Different choices of solar cells
- Efficiency limits
- Space requirements and the challenge for large scale

## 2 Technology, market development and sustainability. (28.3. Ballif)

- A first look into technologies
- Markets and grid/system integration
- Energy pay-back time, CO2 content of PV, contribution to world decarbonisation
- Material bottlenecks and global challenge for the energy transitions (wind, batteries, grid).
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## 3 PV Systems, energy yield (7.3. Ballif)

- **Energy yields** depending on location, orientation and type of technology
- Grid connection of PV, inverters, ancillary services,
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## 4 PV implementation (14.3. Ballif)

- PV system design and exemple of realization for solar parks, BAPV and BIPV (vehicle), VIPV, Field, Floating, Alpine PV
- PV activities from R&D (EPFL and CSEM) to industrialization in Switzerland

# 5 Basic semiconductor properties (21.3. Wolff/Ballif)

- Reminder of essential semiconductor properties
- Thermal equilibrium and doping
- Mobilities

# 6 Absorption and generation (28.3 Wolff/Ballif)

- Direct and indirect band gaps
- Absorption coefficient
- Generation profile

# 7 Recombination (4.4. Haug/Ballif)

- Definition of lifetime, diffusion length
- Recombination processes, Auger
- Shockley – Read - Hall recombination / effect of impurities
- Surface recombination
- Electric field and charges
- How to avoid surface and bulk / or both recombination

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- *Easter Break (11.4.)*

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# 8 Equations for solar cells (18.4 Haug/Ballif)

- Drift- and diffusion current, Poisson equation, continuity equations, boundary conditions
- Infinite p-n diode in darkness and under illumination
- Finite cell and geometry factor
- Role of Auger recombination and bandgap narrowing
- General design rule of solar cells

# 9 Simulations of solar cells with PC1D (25.4, teaching assistants)

- Base material properties
- Definition of recombination/boundary conditions
- Excitation
- Optical properties
- Internal elements
- Shunt resistance, series resistance,
  parallel diode, two diode model

# 10 Silicon and Wafers (2.5. Ballif + beginning of cell processing)

- Crystalline Si standard chain
- Generality crystalline silicon wafers
- Metallurgical grade (MG)
- Purification via the gas phase / Siemens process
- Ingot fabrication
- Wafering
- Alternative approach to wafering

# 11 Silicon cell processing: Al-BSF and PERC (9.5. Ballif)

Generality on design of cells

- **Standard process**

- Etching
- Diffusion
- Antireflection layer
- Screen-printing
- Firing
- Measuring/sorting
- **Perc Process**
  Losses and potential gains
- Analysis of record cell
- Selective emitter
- Backsurface passivation, PERC cells
- Metalisation/plating
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## 12 High efficiency - TOPCON HJT and backcontacted (16.5. Ballif)

- Advantages of high efficiency
  Temperature coefficient
- Passivated contacts
- Tunnel junction cells
- C-Si Heterojunction
- Backcontact interdigitated cells

## 13 Advanced concepts,Thin film and tandem PK on silicon solar cells (23.5. Wolff/Ballif)

- A brief comparison of technologies
- Today's thin film technologies: Chalcopyrites/ CdTe/thin film Silicon (First solar)
- Perovksite solar cells, Perovskite-silicon tandems
- Other concepts (Quantum dots, polymers, organic, dye sensitized)
- III-V solar cells, Epitaxial growth on Si.
- for space and concentration

## 14 Encapsulation/packaging (30.5. Ballif)

- Goals and requirements
- Accelerated aging tests
- Typical assembly and processes
- Encapsulation materials
- Characterization
- Costs for various products
- Final conclusions to the lecture

## Objectives

- Acquire an in-depth, intuitive but sound physical understanding of how PV devices work
- Understand the various materials choices, and device structures
- Be able to perform efficiently simulations of various devices (electrical and optical)
- Understand process manufacturing chain and interlinks
- Understand price / cost issue, asses critically PV as a form of sustainable energy.

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## Prerequisite

- A good understanding of basic semiconductor physics is required.
- **Please read page 13-39** of *Solar Cells*, by M. A. Green. Prentice Hall (1982), Volume 1 (provided)
- To become familiar with all semiconductor concepts presented in the introduction, it is recommended to read pages 5-75 of *Physics of Semiconductor Devices* by S.M. Sze and K.K. Ng (available through Wiley Online Library)

### Exam

- 3 hours written exam, closed book
- multiple choice questions and a set of questions on which to elaborate
- A list of formulae is attached below, a clean copy will be distributed during the exam

## Useful links

- http://pvcdrom.pveducation.org/
- https://www.pvlighthouse.com.au/

### Moocs

- https://ocw.tudelft.nl/courses/solar-energy/ (popular mooc by Arno Smets, TU Delft)

## Some reference books

- *Solar Cells*,
  M. A. Green, Prentice Hall (1982), Volume 1-2-3
- *Photovoltaikanlagen*, Planung, Installation, Betrieb, Christof Bucher, ISBN: 978-3-905711-66-0
- *Solar Energy: The Physics and Engineering of Photovoltaic Conversion, Technologies and Systems*
  A. Smets, O. Isabella, K. Jäger, R. van Swaaij, M. Zeman, UIT Cambridge, ISBN: 978 1 906860 32 5, n.b. a preliminary version can be downloaded at
  https://courses.edx.org/c4x/DelftX/ET.3034TU/asset/solar_energy_v1.1.pdf
- *Sonnenergie: Photovoltaik*
  A. Goetzberger, Teubner, Stuttgart (1997)
- *Crystalline Silicon Solar Cells*
  A. Goetzberger, B. Voss, J. Knobloch, Wiley 1998
- *Photopile solaire - De la physique de la conversion photovoltaïque aux filières, matériaux et procédés*
  A. Ricaud, Cahiers de Chimie, PPUR, 1997
- *Practical Handbook of Photovoltaics (Second Edition) Fundamentals and Applications*
  A. McEvoy, T. Markvart. L. Castaner, ISBN: 978-0-12-385934-1
- Further reading on advanced concepts: *Third generation photovoltaics*
  M. A. Green, Springer

**Essential formulae**

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|---|---|
| **Physical constants** | **Transport equations** |
| Elementary charge: $q = 1.6 \times 10^{-19}$ As | $\vec{j}_{tot}^{drift} = q(n\mu_n + p\mu_p)\vec{E}$ |
| Boltzmann constant: $k_B = 1.38 \times 10^{-23}$ J K$^{-1}$ | $\vec{j}_p^{diff} = q(D_n\vec{\nabla}n - D_p\vec{\nabla}p)$ |
| **Spectral response** | **Injection level and lifetime** |
| $I_{cell} = A\int_{300}^{1200}\Phi(\lambda)SR(\lambda)d\lambda$ | $\Delta n = \Delta p = G \cdot \tau$ (Attention: $\tau = \tau(\Delta n)$) |
| $SR(\lambda) = EQE(\lambda)\frac{q}{E(\lambda)} = EQE(\lambda)\frac{\lambda[nm]}{1240}$ | $\tau_{SRH} = \frac{\Delta n}{U_{SRH}} = \frac{1}{\sigma v_{th} N_t}$ (SRH rec. in bulk) |
| $IQE(\lambda) = \frac{EQE(\lambda)}{1-R(\lambda)}$ | $S_{eff} = \frac{U_S}{\Delta n} = \sigma v_{th} D_{it}$ (SRH rec. at surface) |
| **Intrinsic carrier density (equilibrium)** | $\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}$ |
| $np = n_i^2 = N_V N_C \exp(-E_g/kT)$ | $\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surf}}$ where $\frac{1}{\tau_{surf}} = \frac{2 \cdot S_{eff}}{W}$ |
| $n_i \approx 1.0 \times 10^{10}$cm$^{-3}$ (in Si at 300 K) | **Shockley equation** |
| **Lambert-Beer-Bouguer absorption** | $I(V) = I_D - I_L = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$ |
| $I(x) = I_0\exp(-\alpha x)$, ($\alpha$: absorption coefficient) | $j_0 = j_{0,n} + j_{0,p}$ |
| **Fresnel reflection** | $j_{0,p} = \frac{qD_n n_{p,0}}{L_n} = \frac{qD_n n_i^2}{L_n N_A}$, analogous for $j_{0,n}$ |
| $R = \frac{(1-n)^2+k^2}{(1+n)^2+k^2}$, ($n_{air} = 1$, $n_{medium} = n + ik$) | $L_n = \sqrt{D_n\tau_n}$, analogous for $L_p$ |
| **Field and Potential** | **Solar cell characteristic** |
| $\vec{E} = -\vec{\nabla}\Psi$ | $FF = \frac{P_{max}}{I_{sc}V_{oc}} = \frac{I_{max}V_{max}}{I_{sc}V_{oc}}$ |
| **Poisson equation** | $R_s \approx R_{oc} = \left.\frac{dV}{dI}\right\vert_{V_{oc}}$ |
| $\Delta\Psi = -\frac{\rho}{\epsilon\epsilon_0} = -\frac{q}{\epsilon\epsilon_0}(N_D^+ - N_A^- + p - n)$ | $R_p \approx R_{sc} = \left.\frac{dV}{dI}\right\vert_{V=0}$ |

Useful quantities you should know:

- Values of $E_g$ for the typical semiconductors
- Typical values for $V_{oc}$, $I_{sc}$, and $FF$ for the different technologies
- Intensities of the illumination spectra
- Performance ratio and typical energy yield
- Energy payback times
- Typical price of components of PV systems, and the related solar electricity production costs