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Fundamentals of Photovoltaic Conversion and Solar Cell Performance

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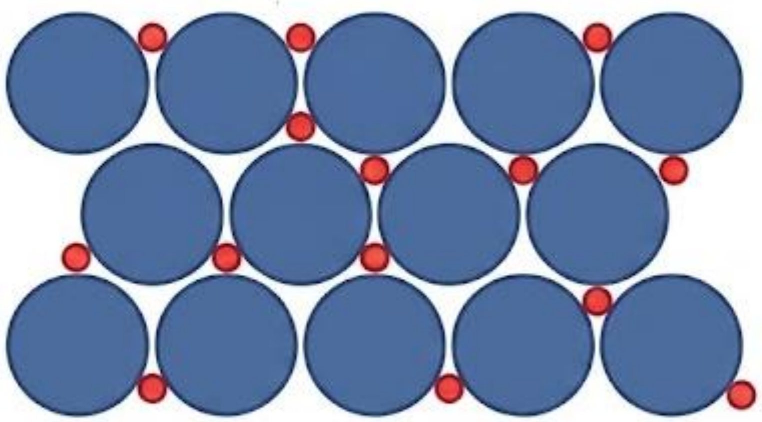
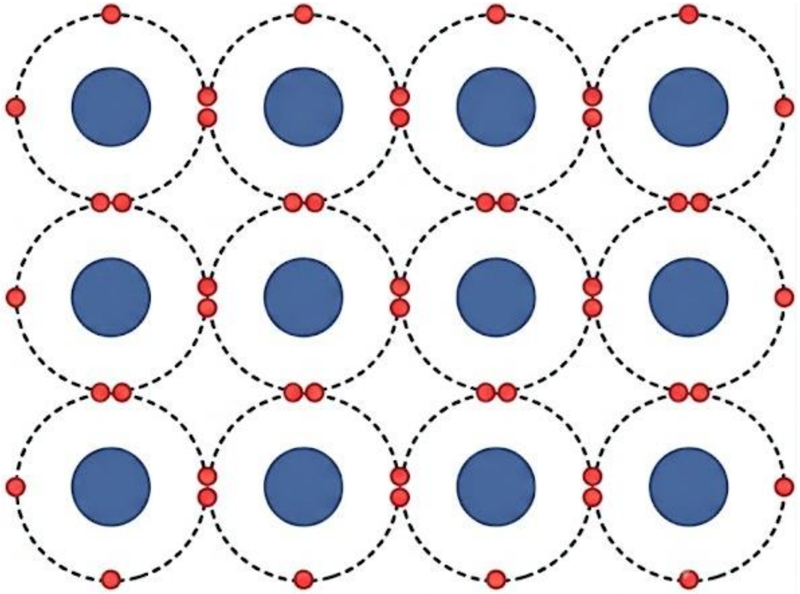
Outline

1. Structure and operating principles of the basic semiconductor p-n junction.
2. Mechanisms of charge carrier generation and extraction under sunlight.
3. Key electrical parameters used to evaluate solar cell performance.
4. Primary optical and electrical loss mechanisms that limit overall efficiency.

Semiconductors

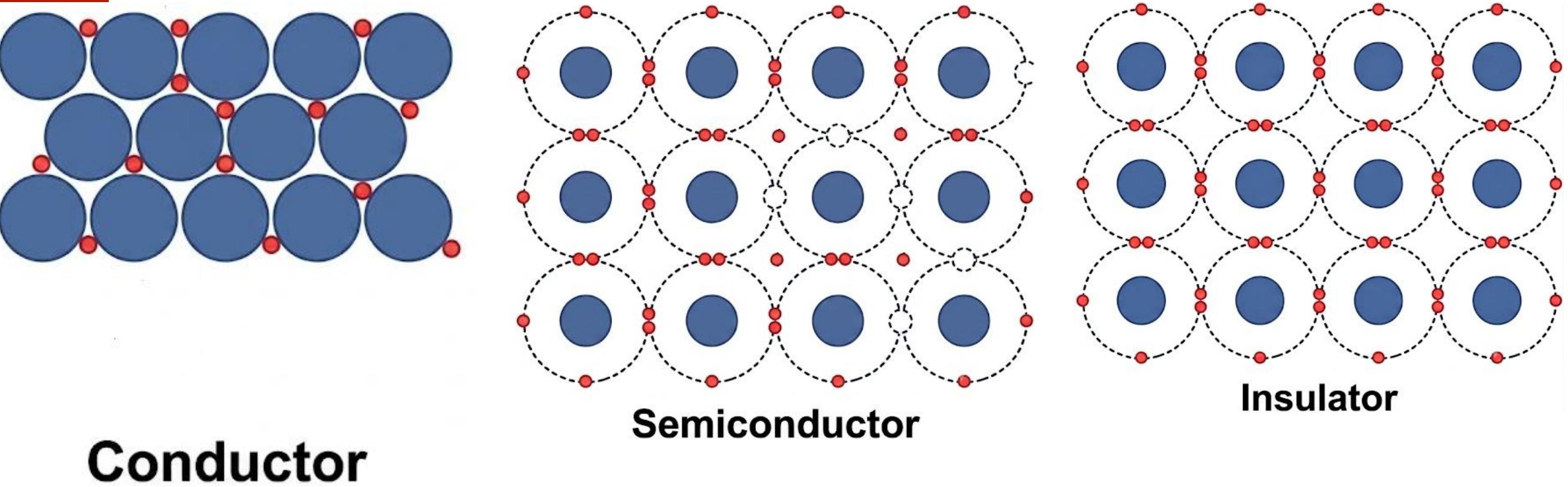


Conductor



Insulator

Semiconductors



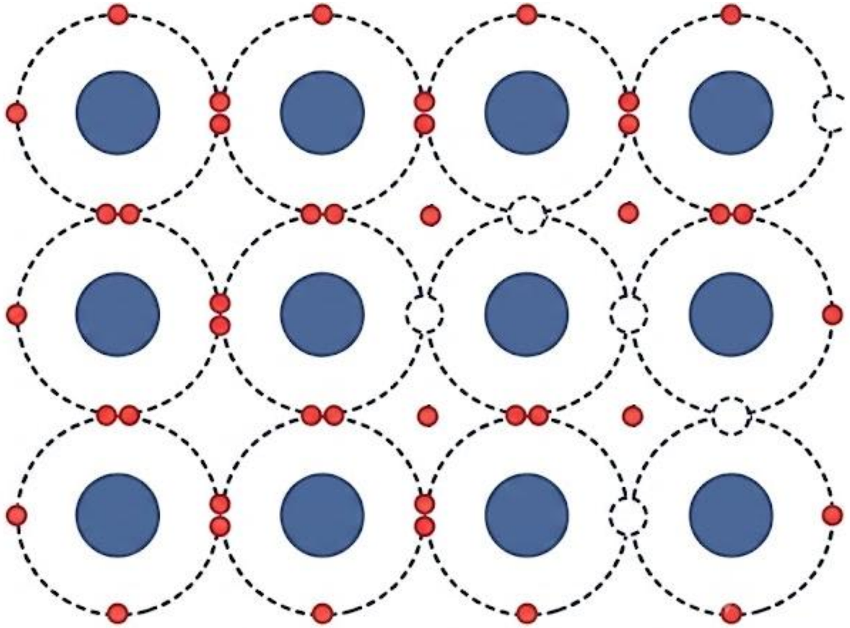
Semiconductors

More free electrons:

Temperature

Light

Doping



Semiconductor

Semiconductors

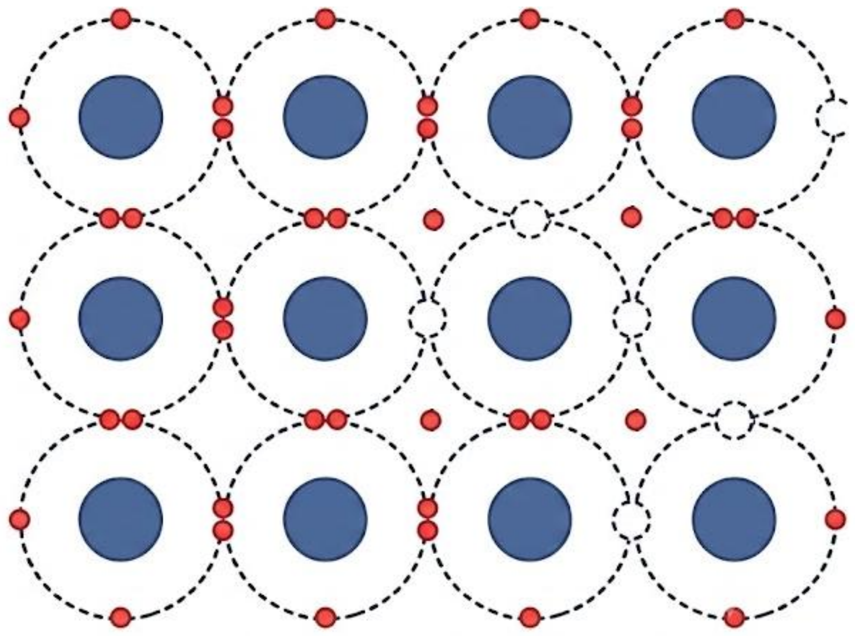
More free electrons:

Temperature

Light

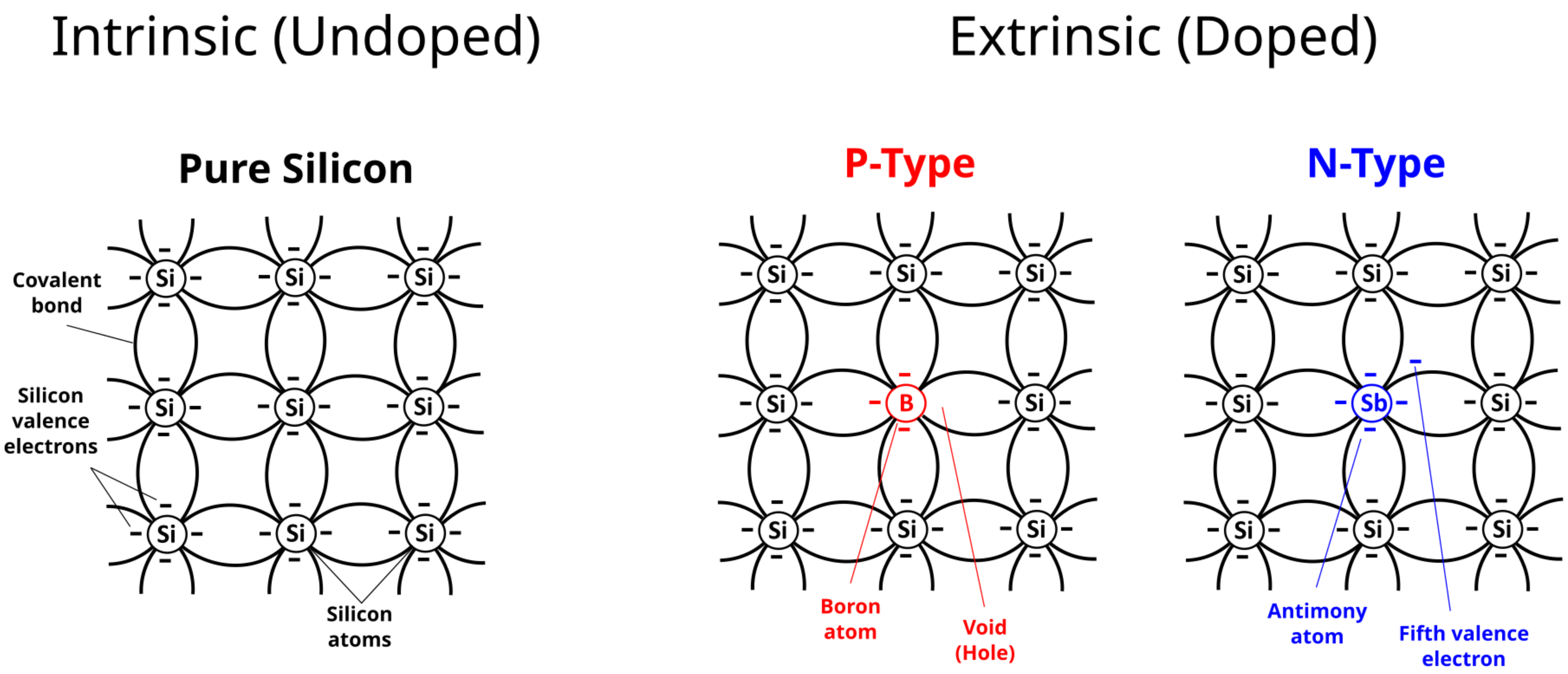
Doping

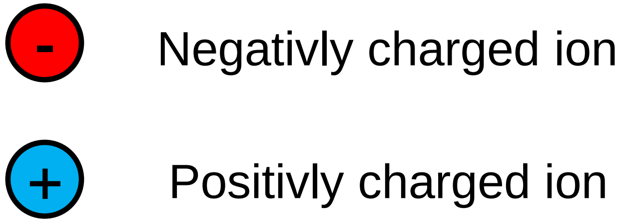
Energy of the photon must be higher than the energy gap of the semiconductor.



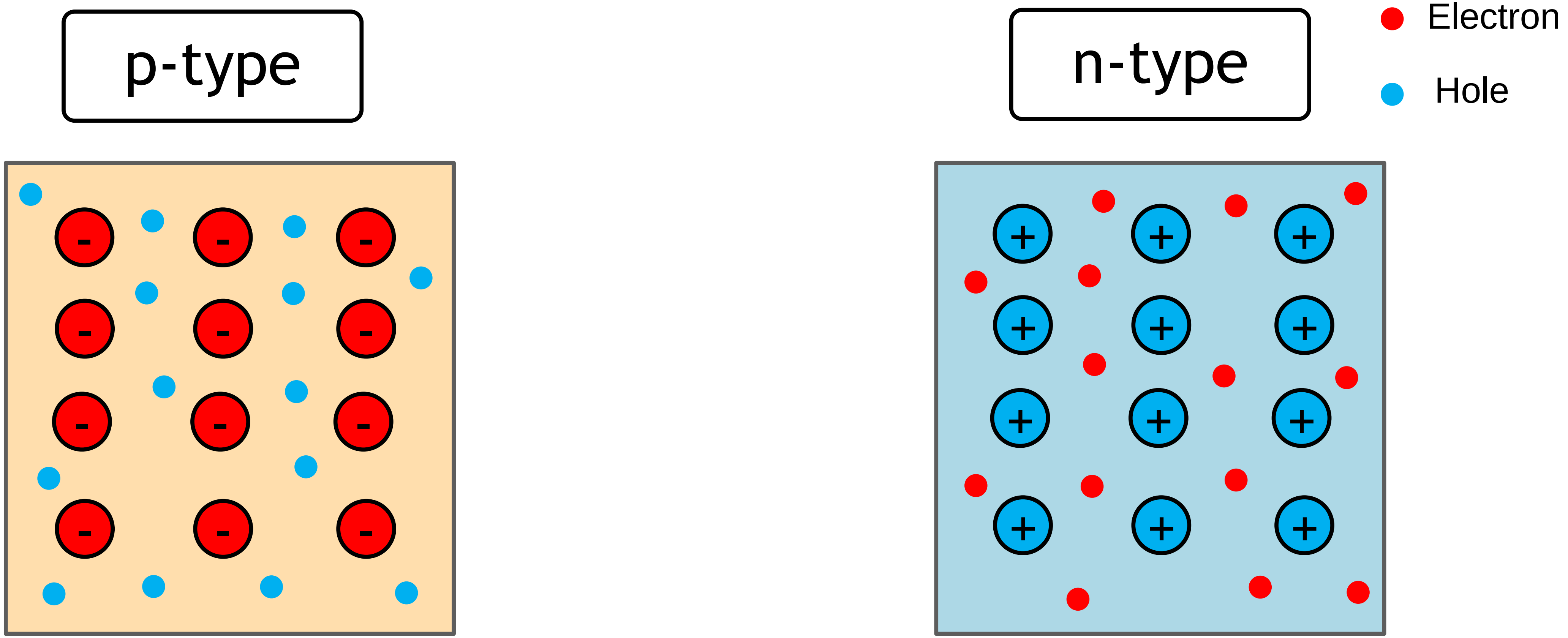
Semiconductor

Doping


Intrinsic (Undoped)
Extrinsic (Doped)
Pure Silicon
Covalent bond
Silicon valence electrons
Silicon atoms
Si
P-Type
Boron atom
Void (Hole)
B
N-Type
Antimony atom
Fifth valence electron
Sb


-
Negativly charged ion
+
Positivly charged ion

P-n junction


p-type
n-type
Electron
Hole

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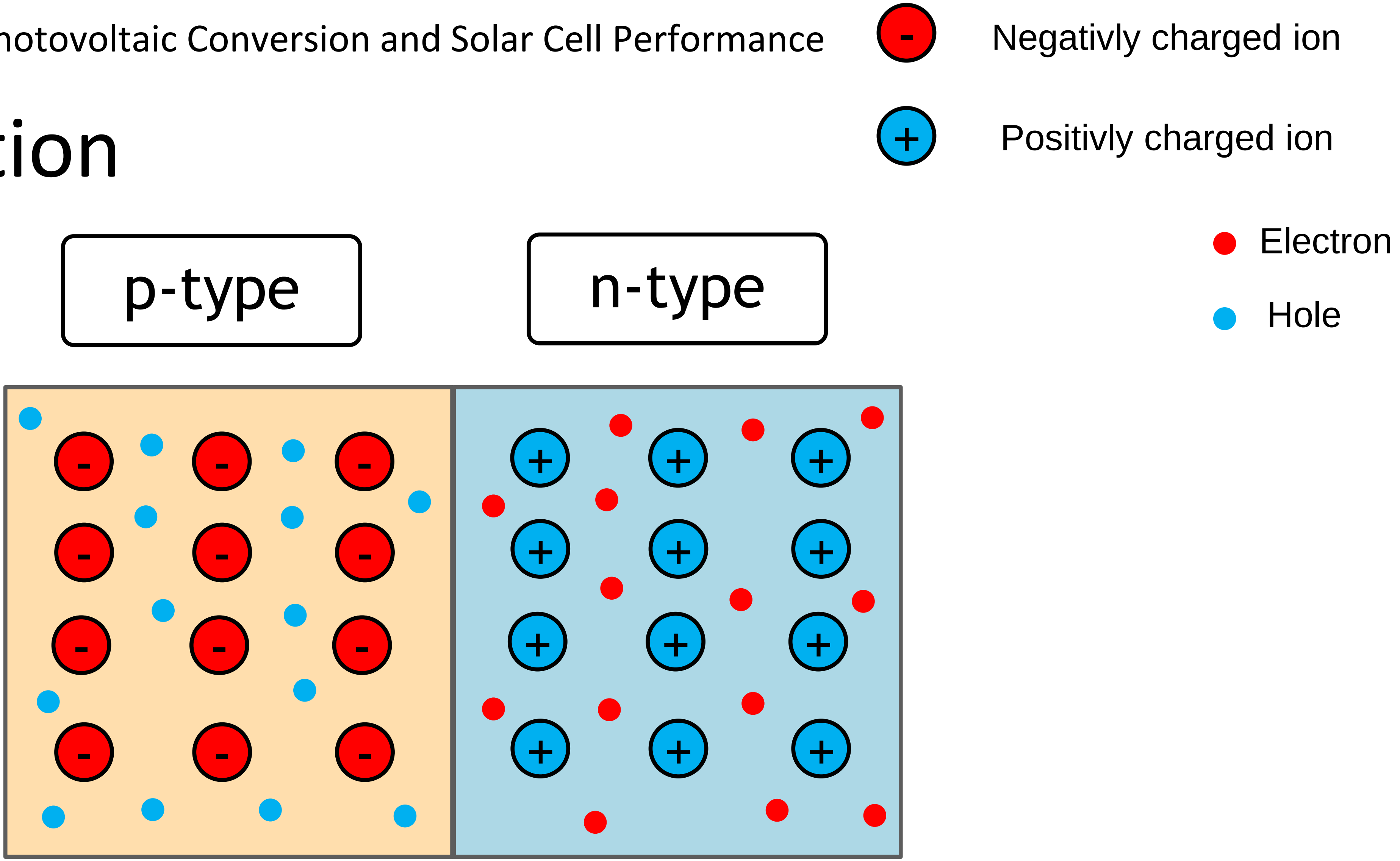
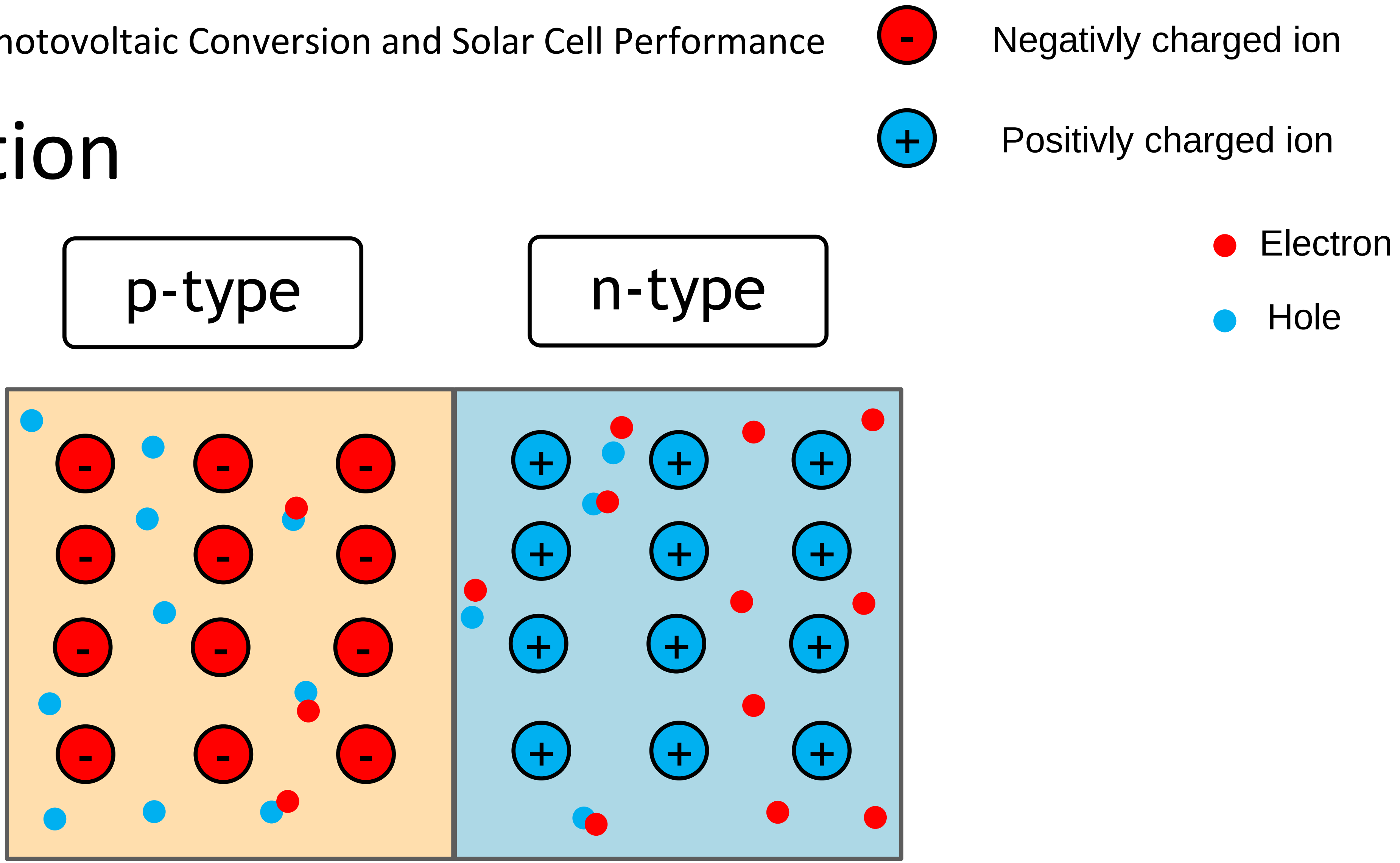
P-n junction

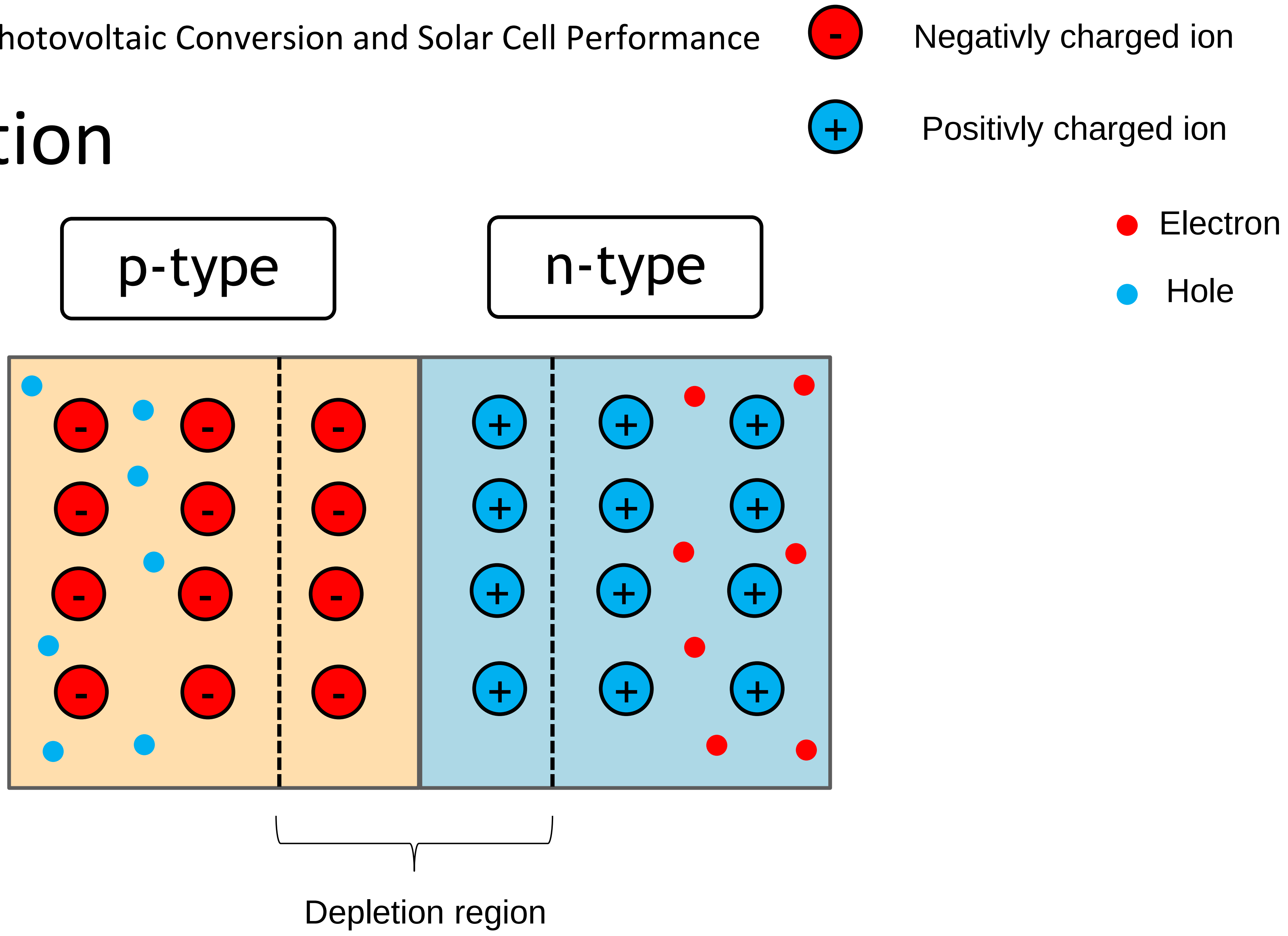


P-n junction

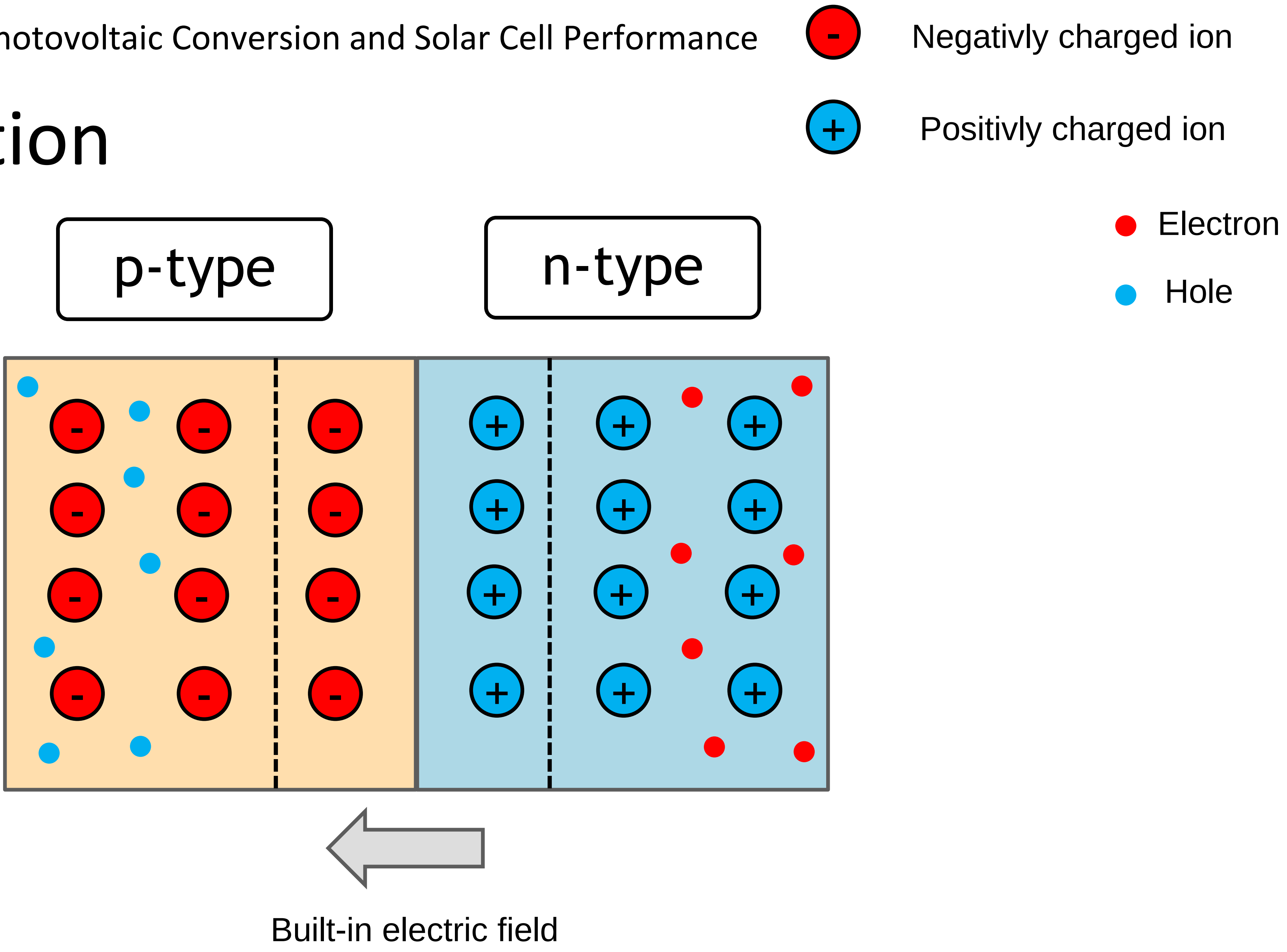


Negativly charged ion
Positivly charged ion
Electron
Hole
p-type
n-type

P-n junction


Negativly charged ion
Positivly charged ion
Electron
Hole
p-type
n-type
Depletion region

P-n junction


-
Negativly charged ion
+
Positivly charged ion
Electron
Hole
p-type
n-type
Built-in electric field

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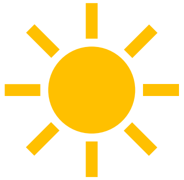
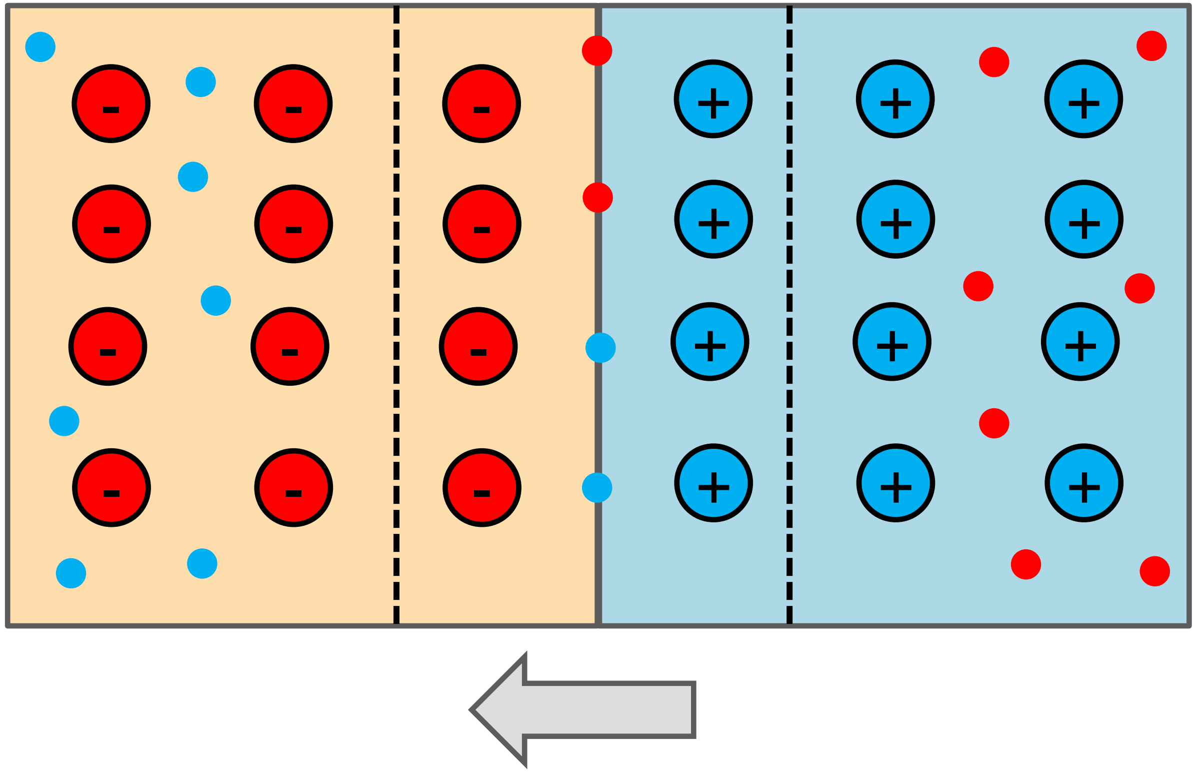
P-n junction - light

- Negativly charged ion
+ Positivly charged ion

Electron

Hole





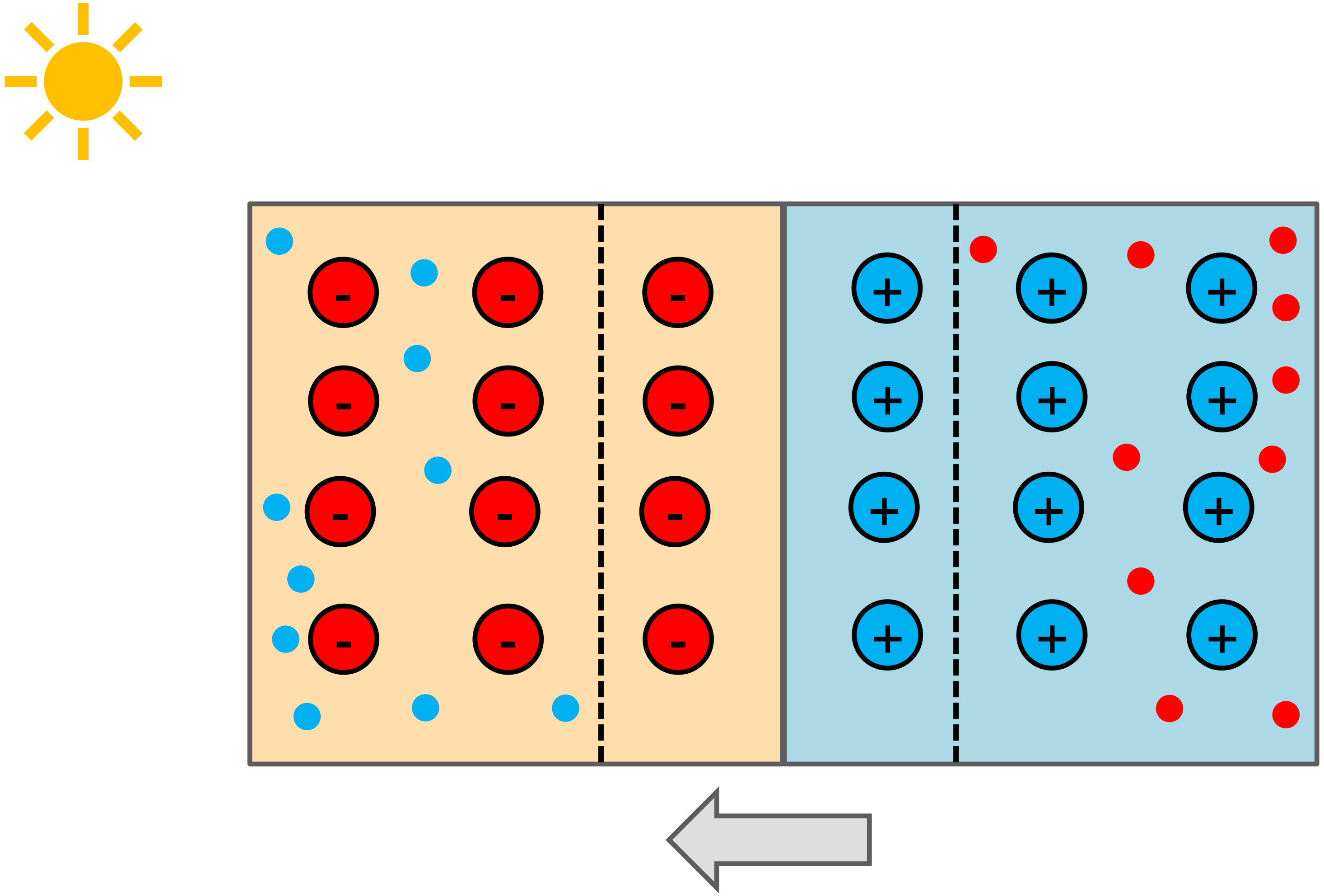
P-n junction - light

Negativly charged ion

Positivly charged ion

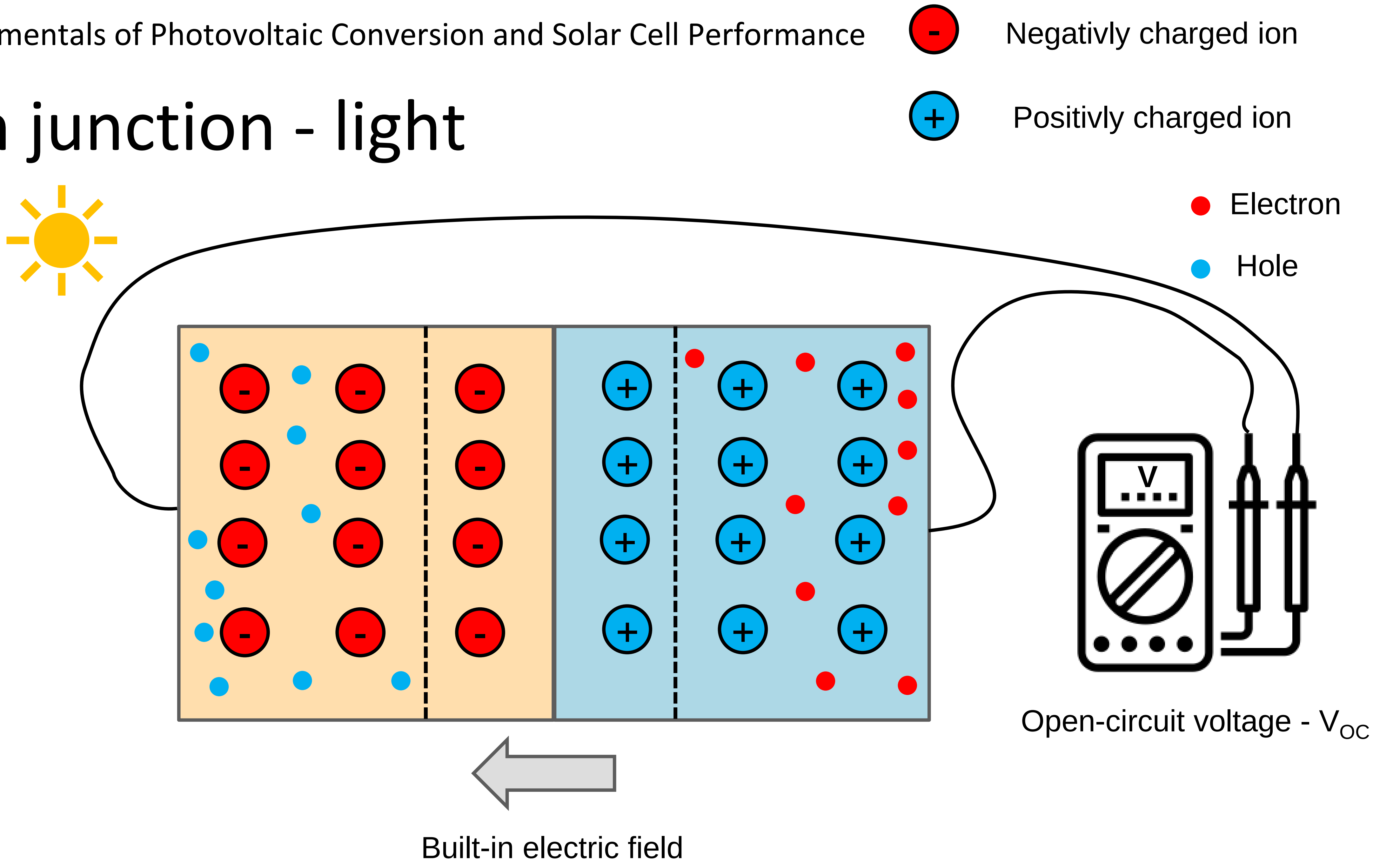
Electron

Hole

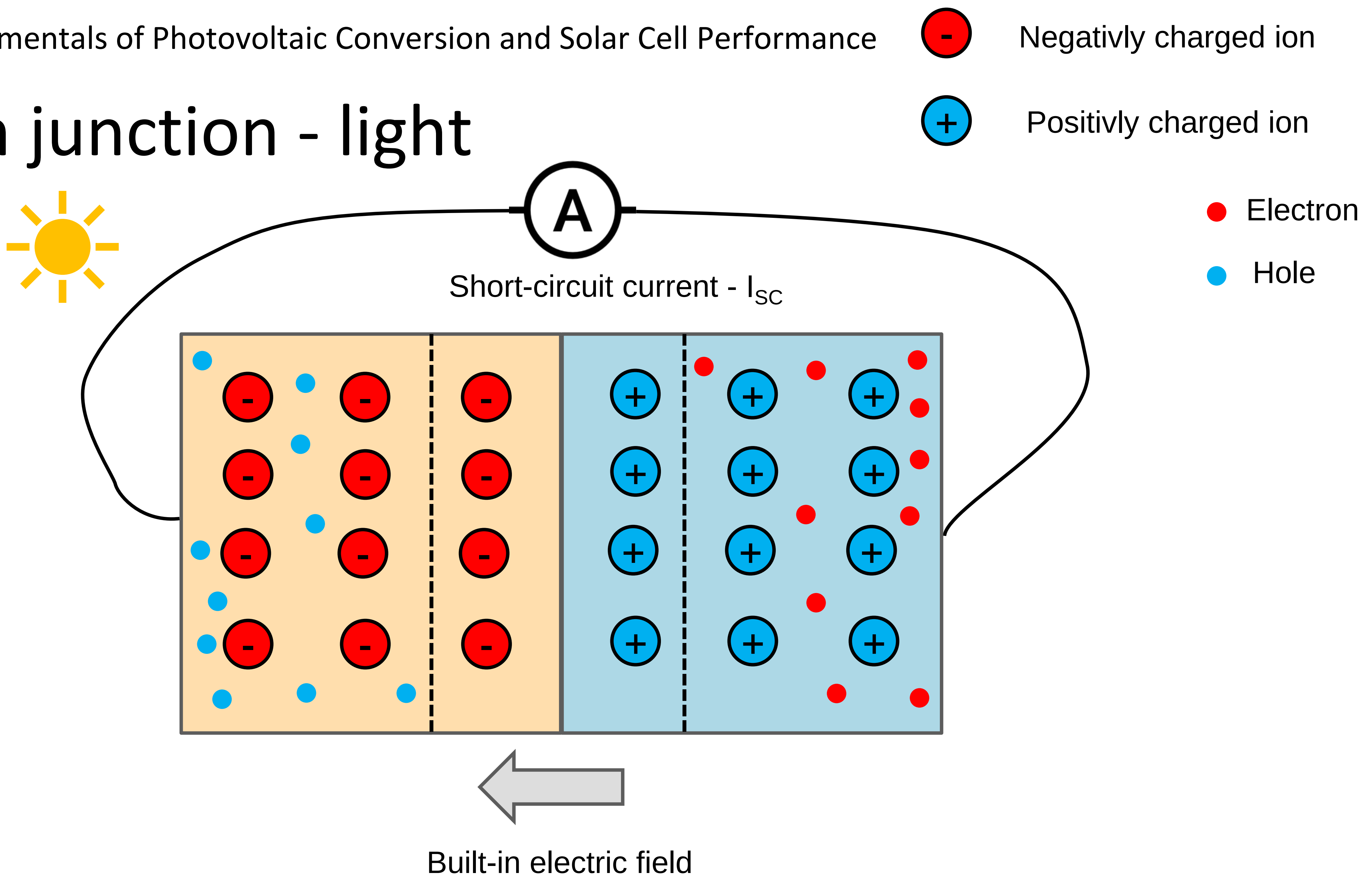


Built-in electric field

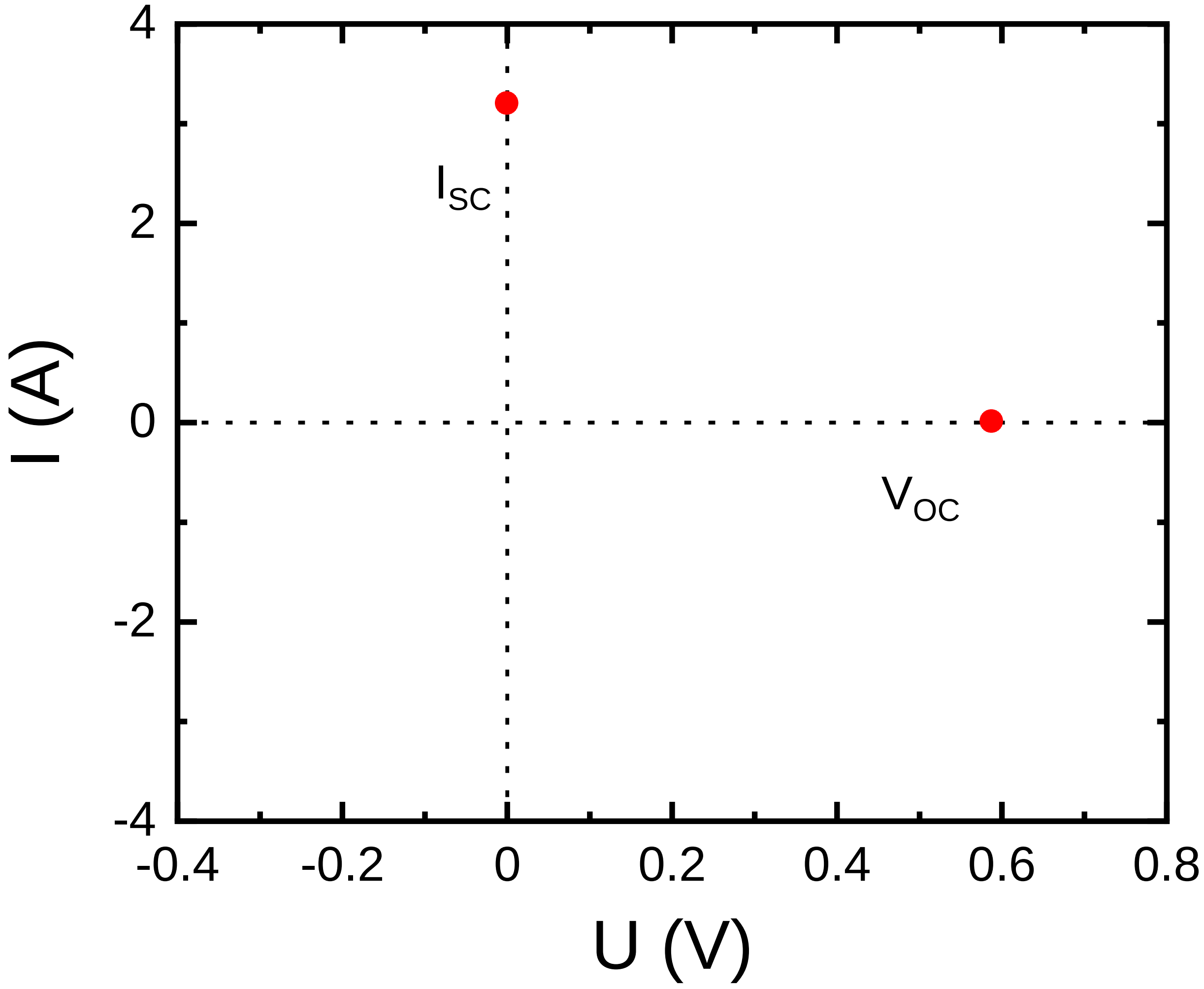
P-n junction - light



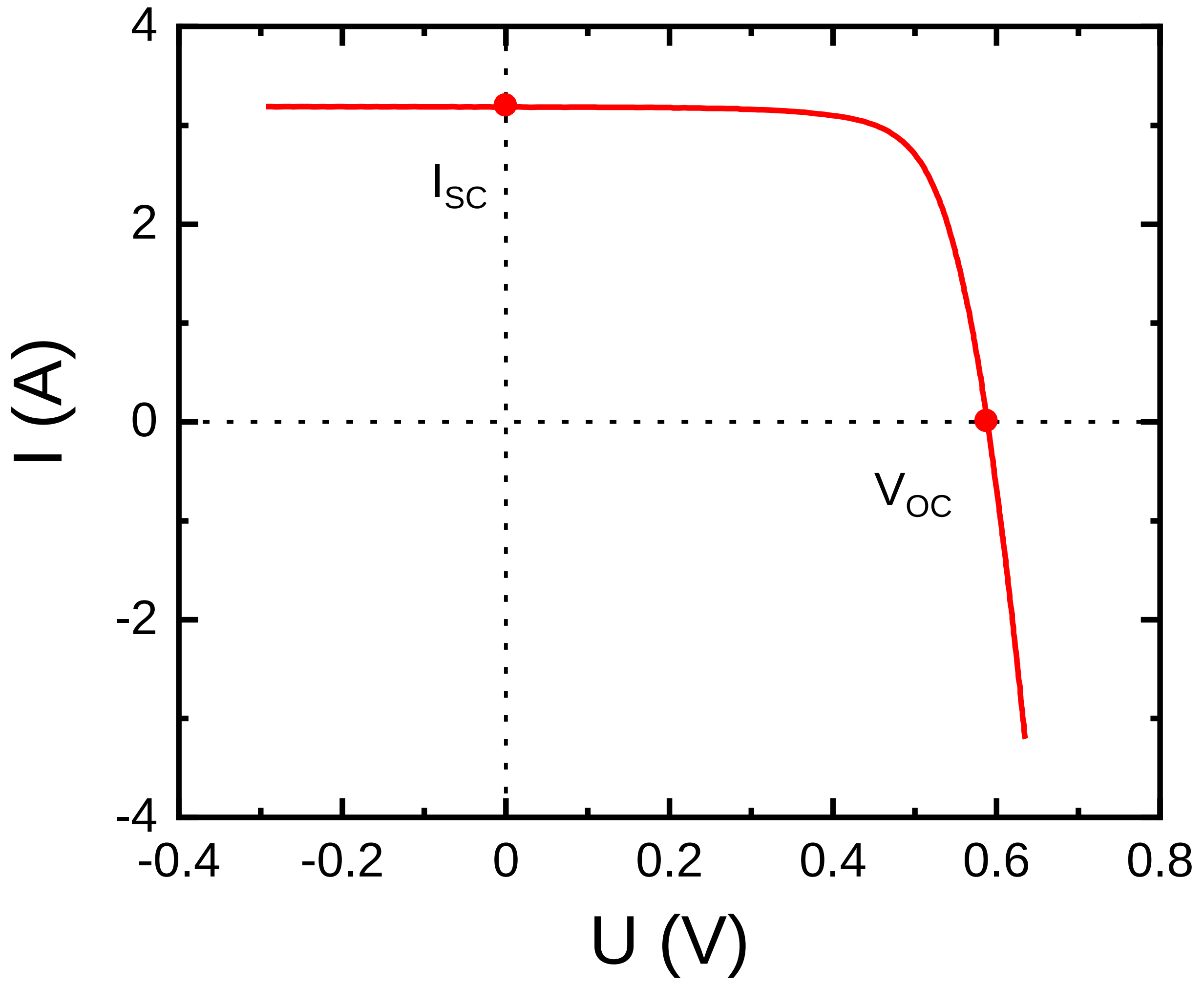
P-n junction - light



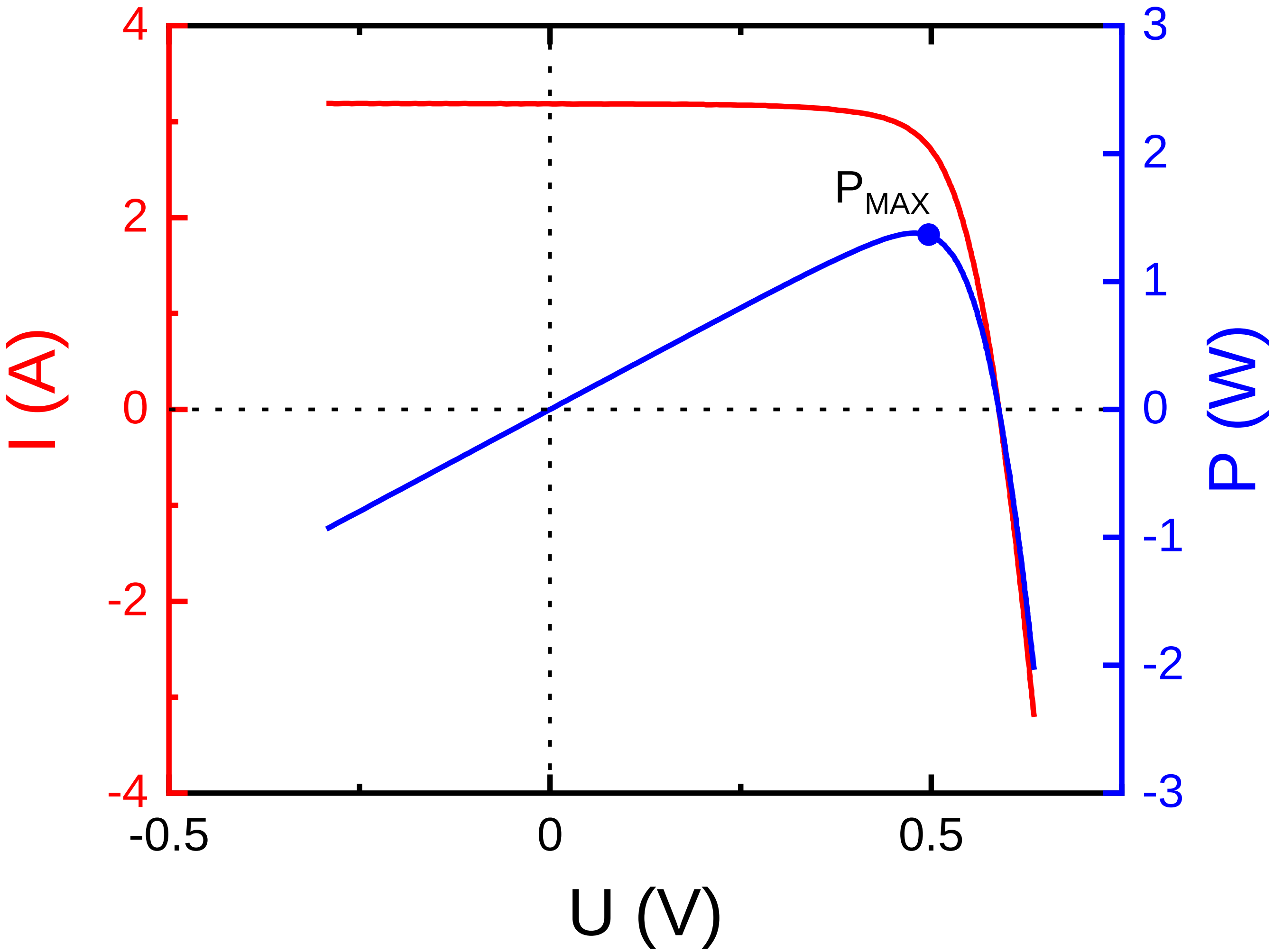
I-V curve



I-V curve



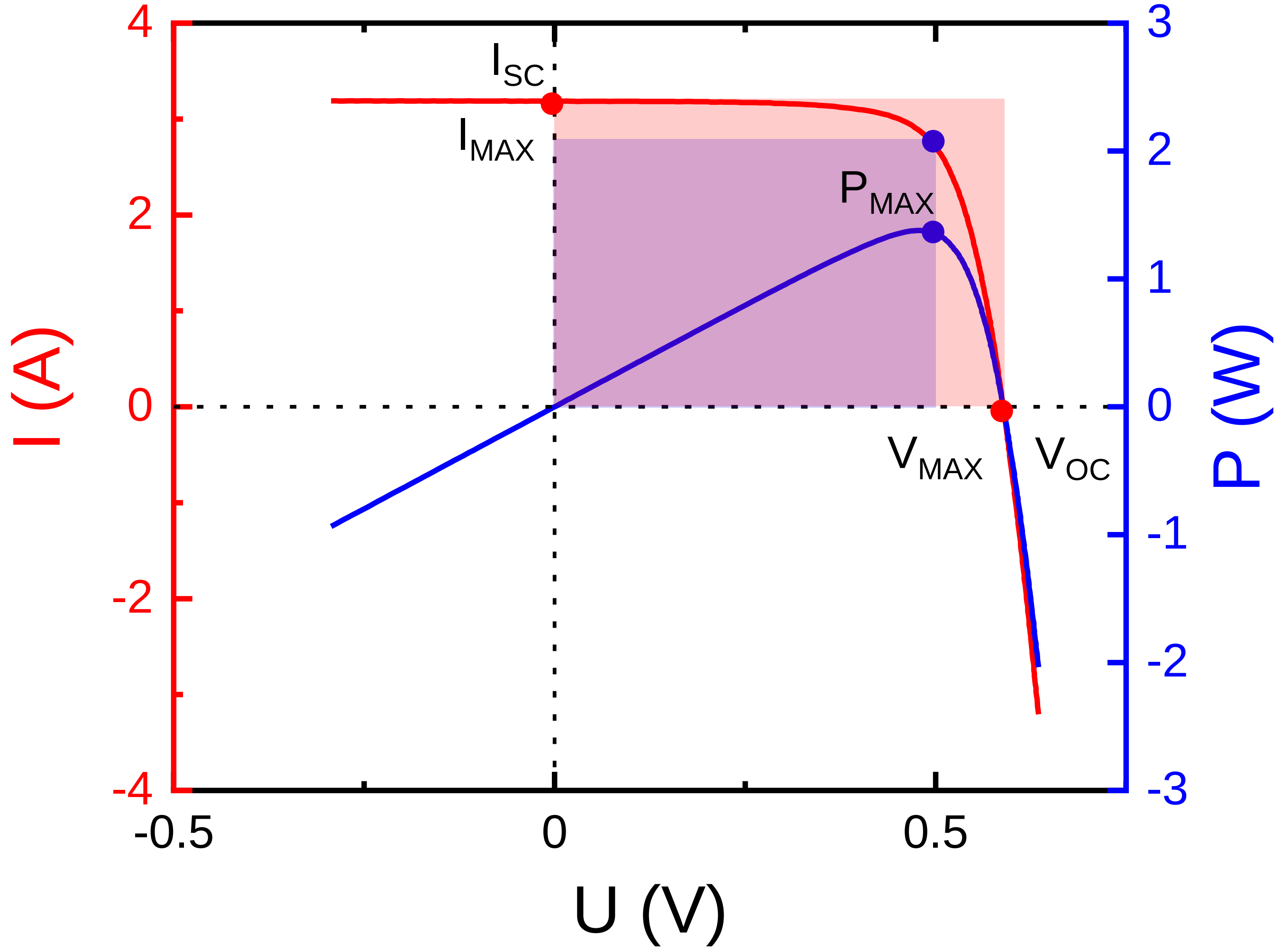
I-V curve



$$P = U \times I$$

$$P_{MAX} = U_{MAX} \times I_{MAX}$$

I-V curve

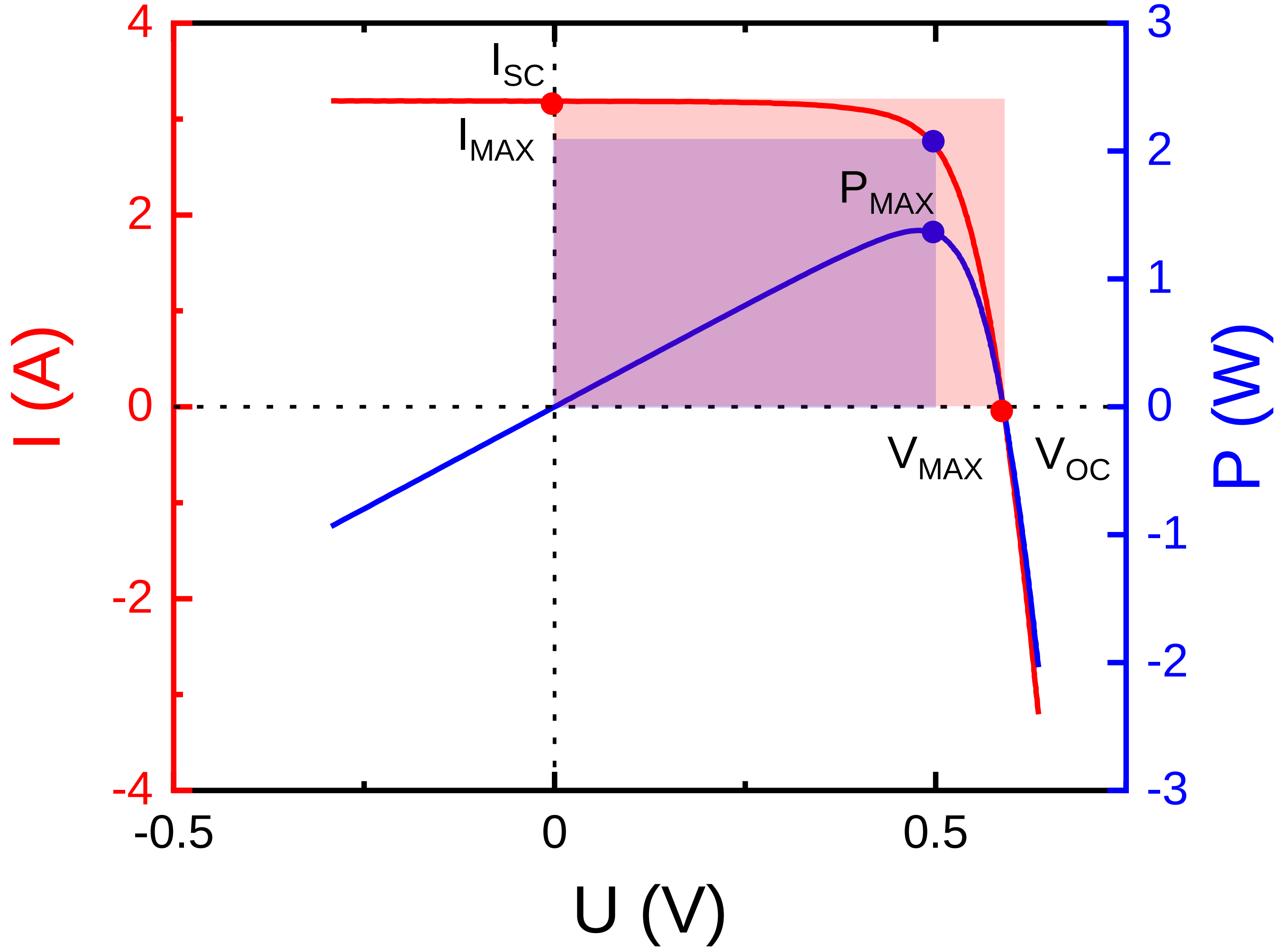


$$P = U \times I$$

$$P_{MAX} = V_{MAX} \times I_{MAX}$$

$$Fill\ Factor = \frac{I_{MAX} \times V_{MAX}}{I_{SC} \times V_{OC}}$$

Efficiency



$$P = U \times I$$

$$P_{MAX} = V_{MAX} \times I_{MAX}$$

$$FF = \frac{I_{MAX} \times V_{MAX}}{I_{SC} \times V_{OC}}$$

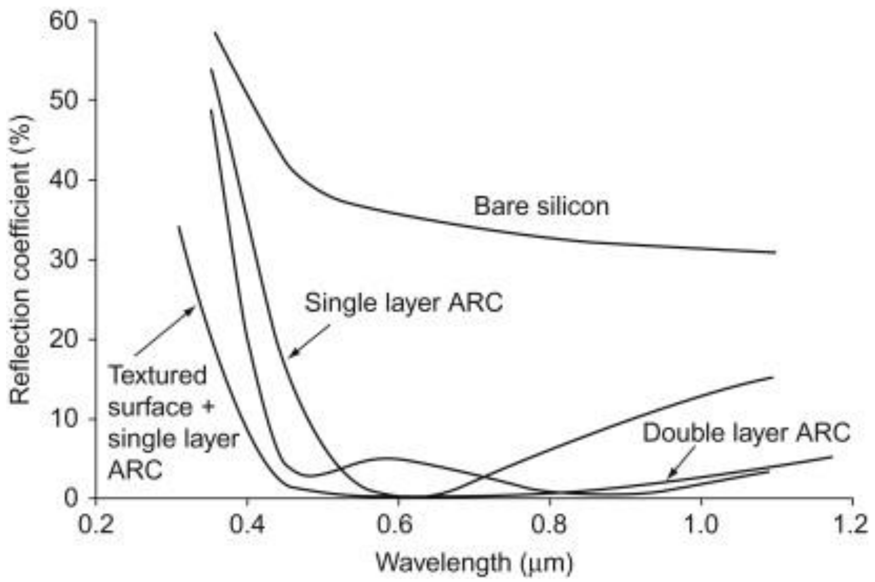
$$\eta = \frac{FF \times I_{SC} \times V_{OC}}{P_{in}}$$

Efficiency - losses

Optical

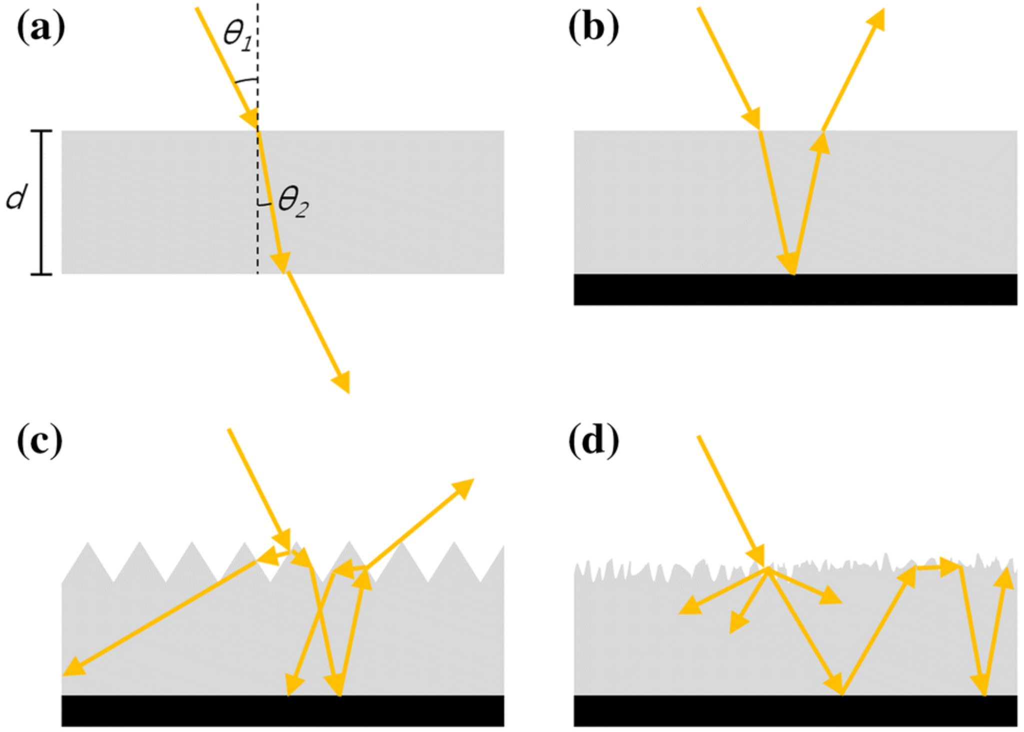
Electrical

Efficiency - losses



https://www.pveducation.org/pvcdrom/design-of-silicon-cells/anti-reflection-coating-color

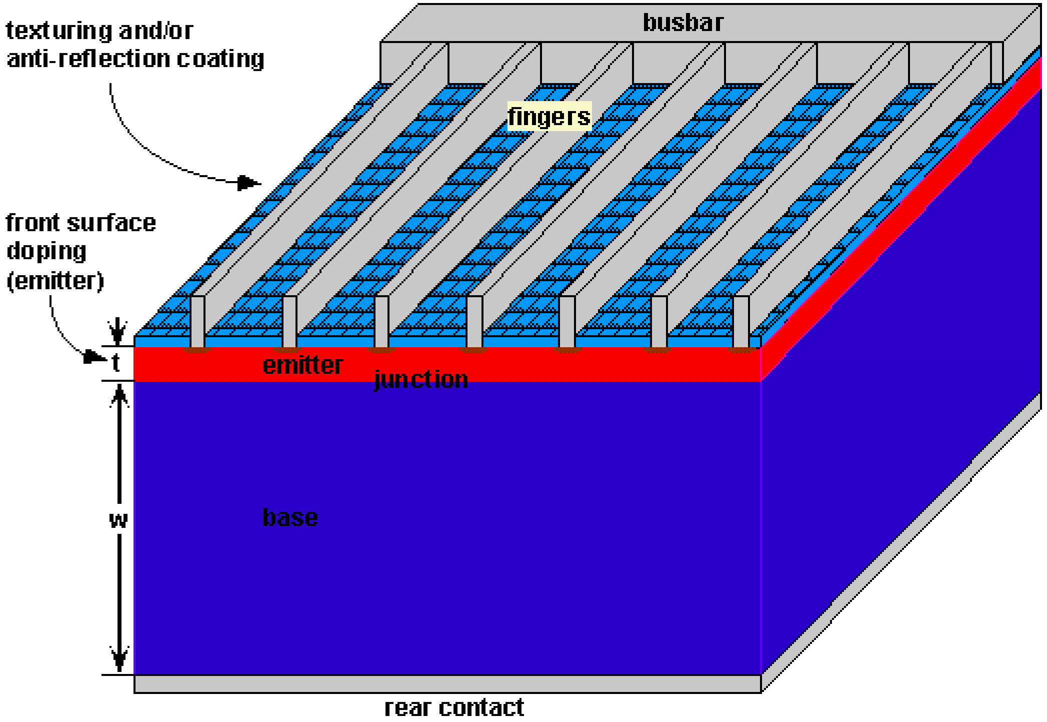
Optical	Electrical
Reflection	



Kim, M.S., Lee, J.H. & Kwak, M.K. Review: Surface Texturing Methods for Solar Cell Efficiency Enhancement. *Int. J. Precis. Eng. Manuf.* **21**, 1389–1398 (2020). https://doi.org/10.1007/s12541-020-00337-5

Efficiency - losses

Optical	Electrical
Reflection	
Shadowing	



https://www.pveducation.org/pvcdrom/design-of-silicon-cells/silicon-solar-cell-parameters

https://upload.wikimedia.org/wikipedia/commons/9/90/Solar_cell.png

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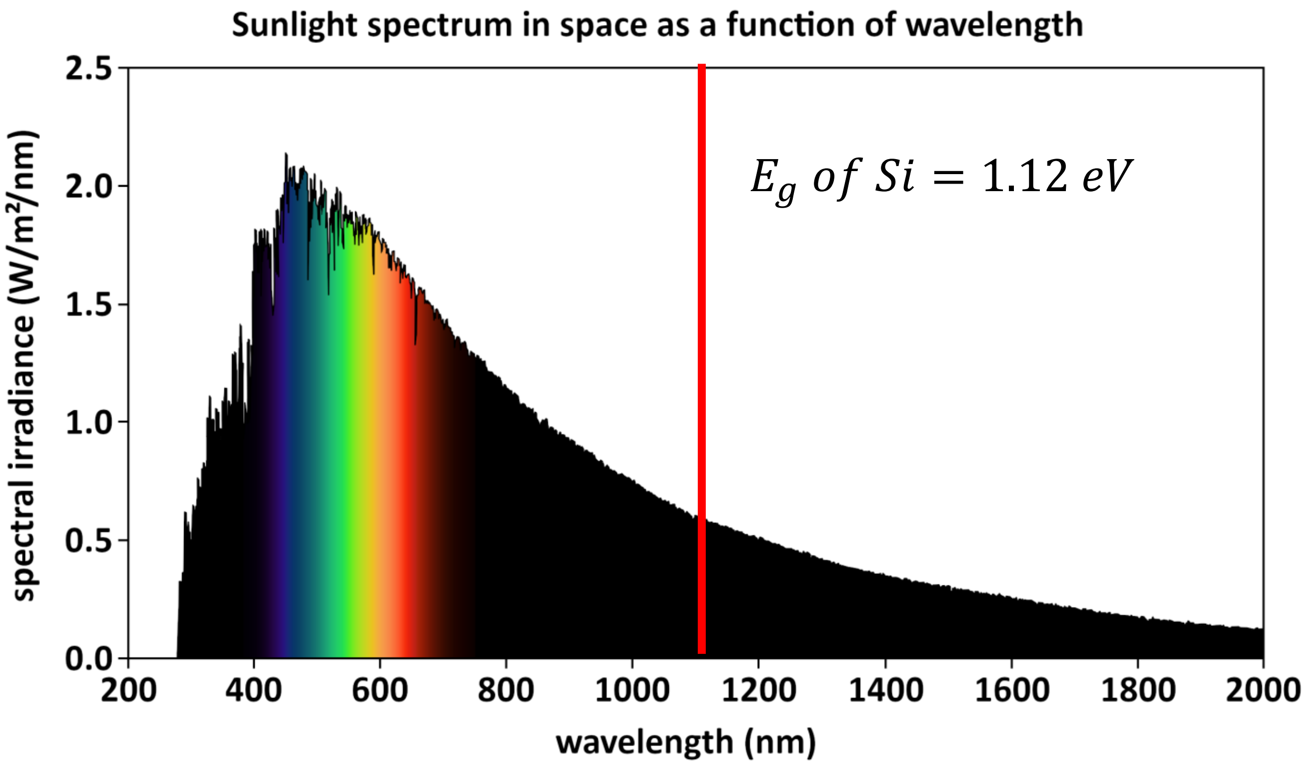
Efficiency - losses

Optical

- Reflection
- Shadowing
- **Incomplete absorption**

Electrical



https://www.wtamu.edu/~cbaird/sq/images/sunlight_wavelength.png

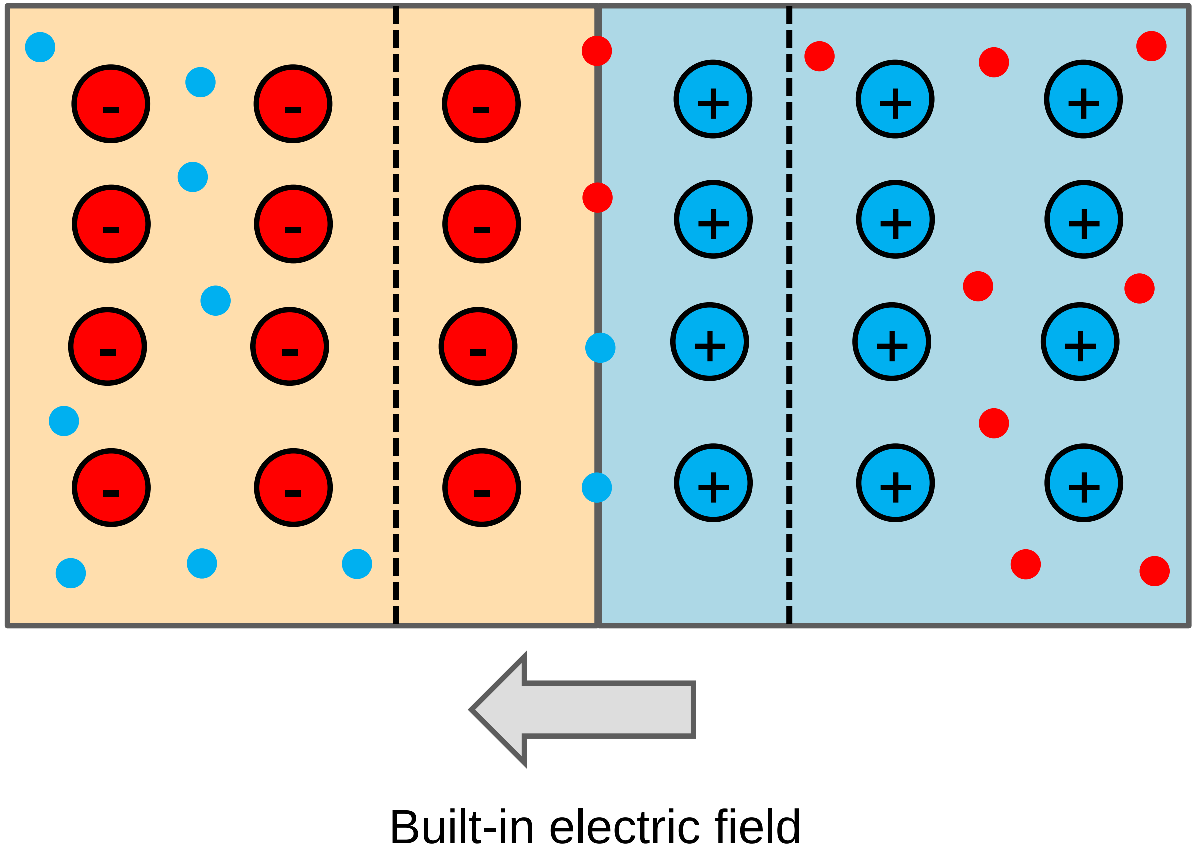
Efficiency - losses

Optical

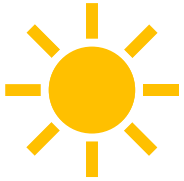
- Reflection
- Shadowing
- Incomplete absorption

Electrical

- **Recombination**



Efficiency - losses

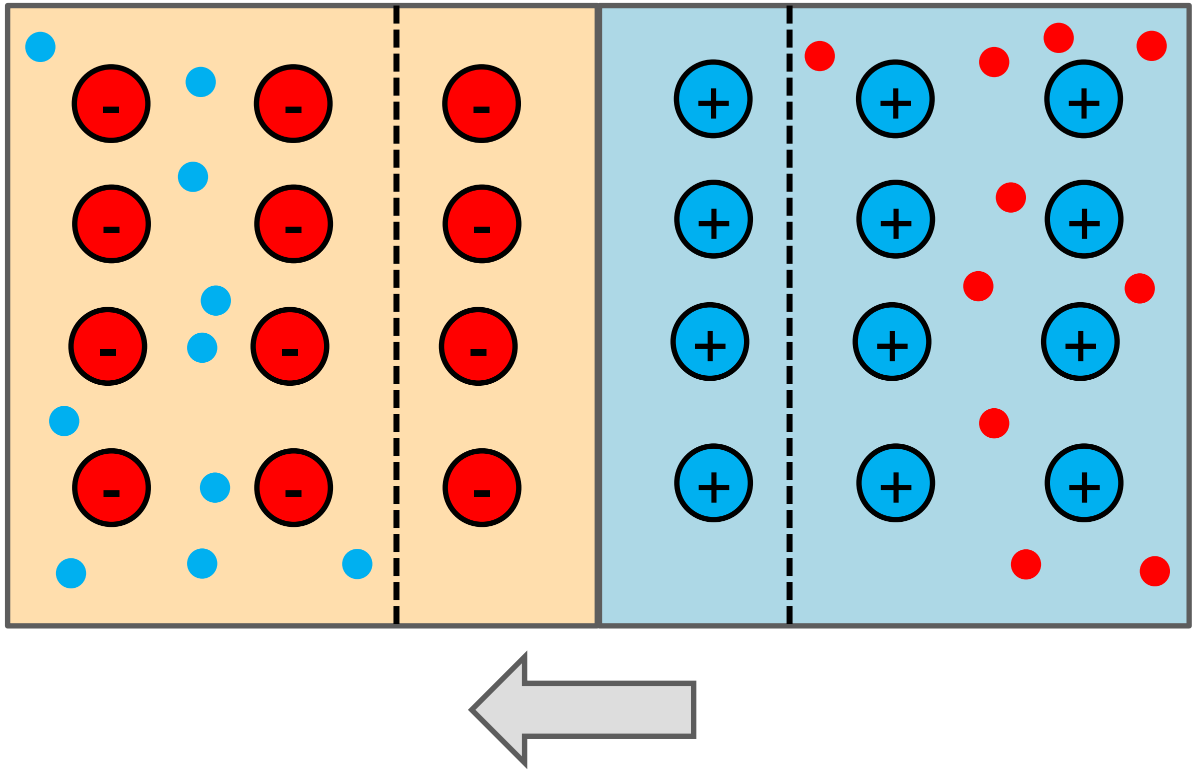


Optical

- Reflection
- Shadowing
- Incomplete absorption

Electrical

- **Recombination**



Built-in electric field

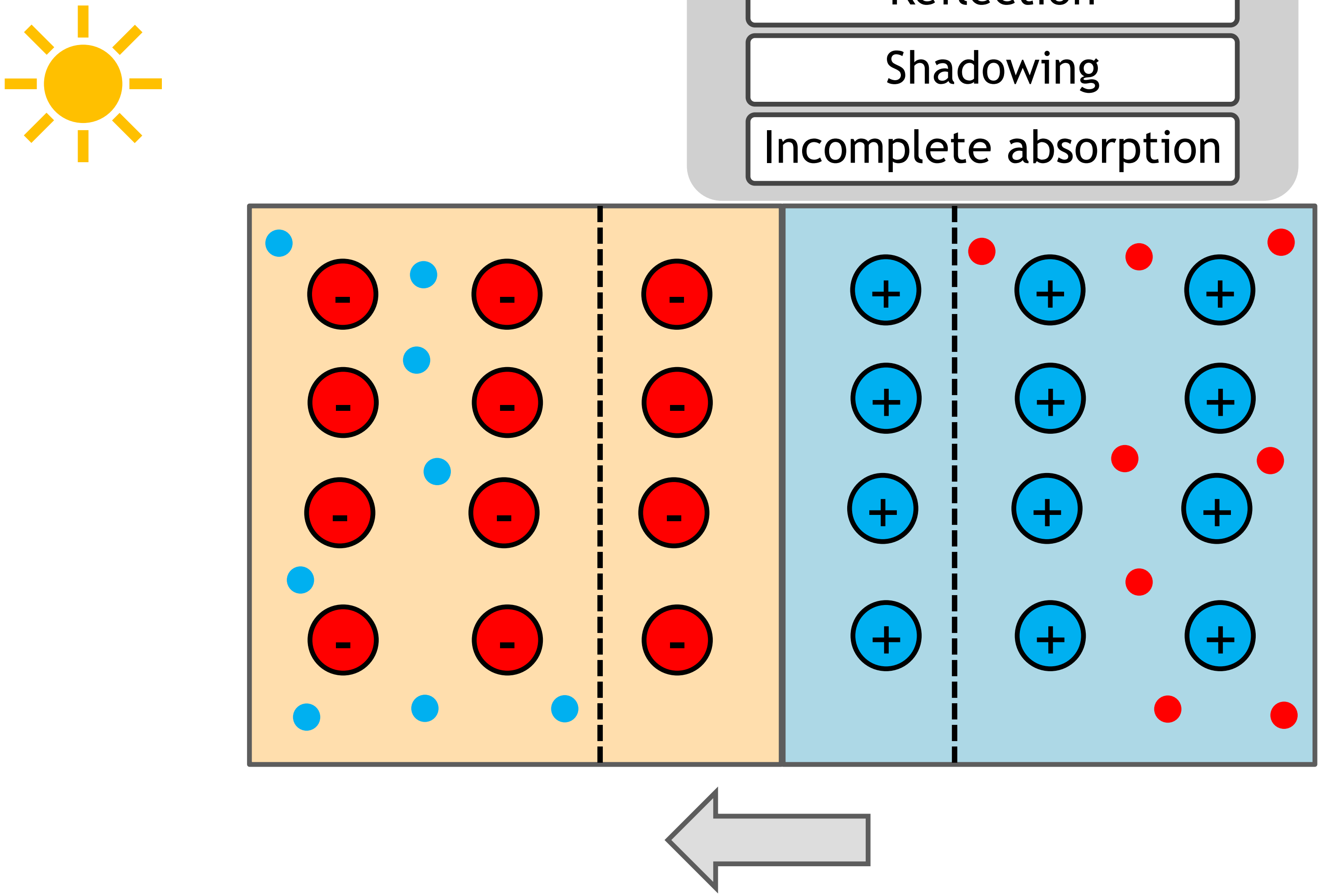
Efficiency - losses

Optical

- Reflection
- Shadowing
- Incomplete absorption

Electrical

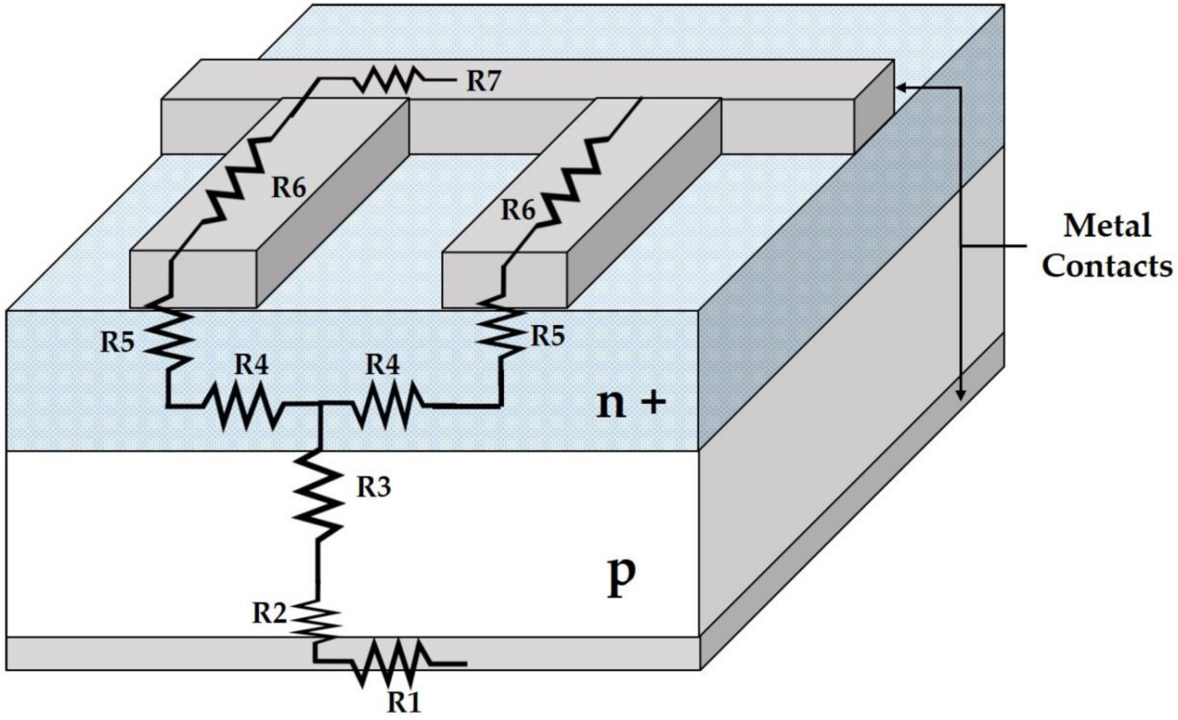
- **Recombination**



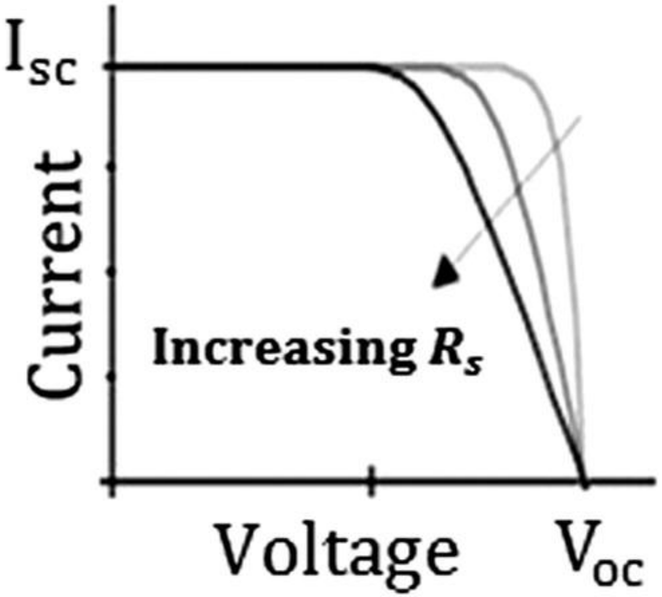
Built-in electric field

Efficiency - losses

Optical	Electrical
Reflection	Recombination
Shadowing	**Series resistance**
Incomplete absorption	



Energies **2024**, *17*(7), 1520; https://doi.org/10.3390/en17071520



Koffi, H. A., A. A. Yankson, A. F. Hughes, K. Ampomah-Benefo, and J. K. A. Amuzu. 2020. "Determination of the Series Resistance of a Solar Cell through Its Maximum Power Point." *African Journal of Science, Technology, Innovation and Development* 12 (6): 699–702. doi:10.1080/20421338.2020.1731073.

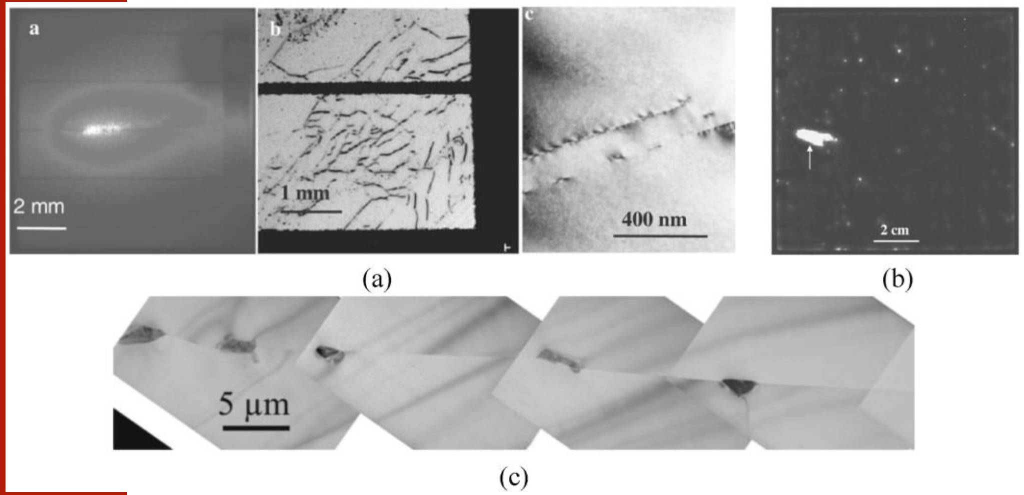
Efficiency - losses

Optical

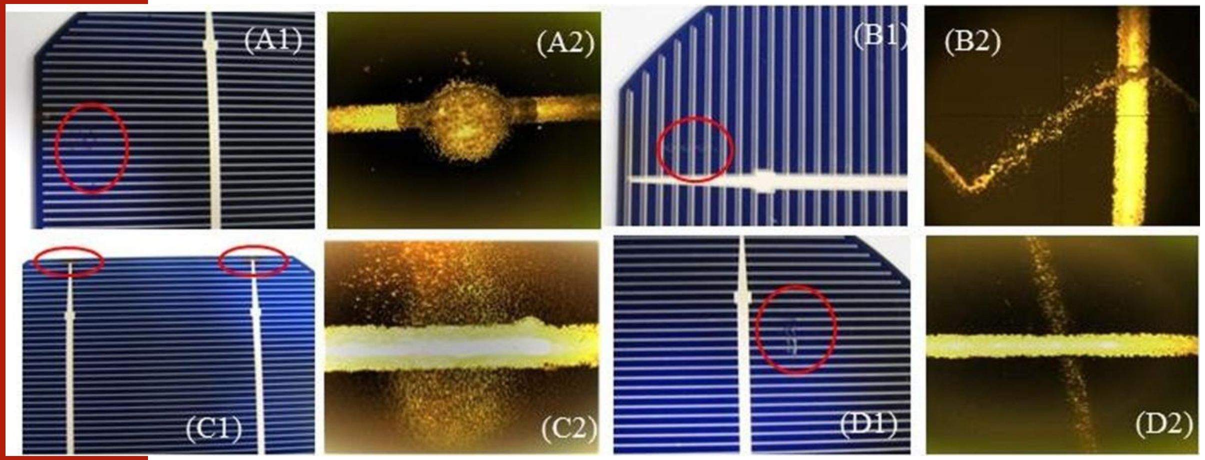
- Reflection
- Shadowing
- Incomplete absorption

Electrical

- Recombination
- Series resistance
- **Shunt resistance**



Ravi Kumar, Rajesh Gupta, Shunts in crystalline silicon PV modules: A comprehensive review of investigation, characterization, and mitigation, Solar Energy Materials and Solar Cells, Volume 277, 2024, 113121, https://doi.org/10.1016/j.solmat.2024.113121.



María Cruz López-Escalante, Francisco Martín Jiménez, Mercedes Gabás Pérez, Dietmar Leinen, José Ramón Ramos Barrado, Shunt resistance criterion: Design and implementation for industrial silicon solar cell production, Solar Energy, Volume 206, 2020, Pages 269-278, https://doi.org/10.1016/j.solener.2020.05.092.

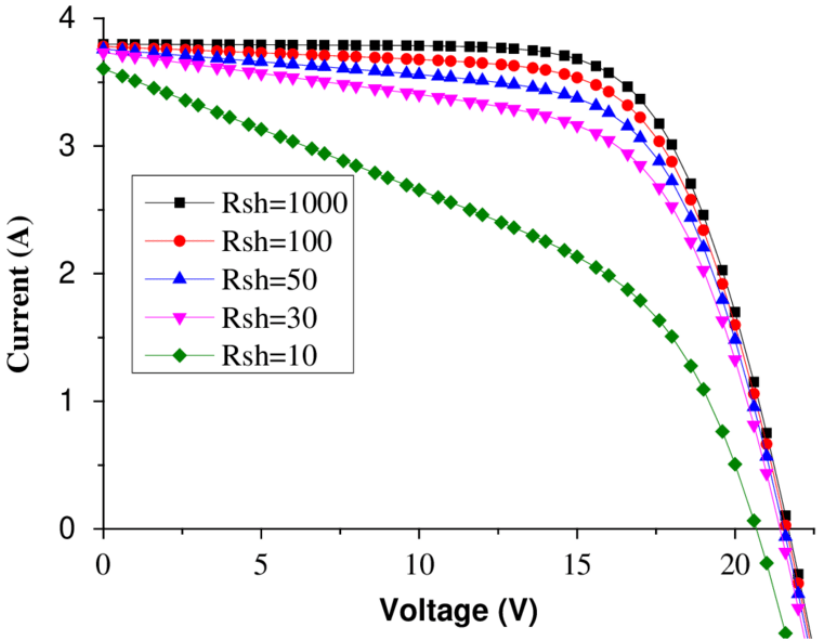


Fig. 9. Influence of quality of the shunt resistance on I (V)

L. Zaghba, M. . Khennane, A. . Borni, and A. Fezzani, "Investigation of the major internal and external factors that affect photovoltaic modules energy production and systems performance", *J. Ren. Energies*, vol. 24, no. 1, pp. 121 – 151, Jun. 2021, doi: 10.54966/jreen.v24i1.976.

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Thank you for your attention!

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