Emerging thin film photovoltaic inorganic materials: kesterite and beyond

S. Giraldo[1], Y. Sánchez[1], M. Placidi[1], Z. Jehl[1], V. Izquierdo-Roca[1],
A. Pérez-Rodríguez[1,2], and **E. Saucedo[1,3,*]**

[1]Catalonia Institute for Energy Research (IREC), Sant Adrià del Besòs-Barcelona, Spain
[2]IN2UB, Departament d'Electrònica, Universitat de Barcelona, Barcelona, Spain
[3]Electronic Engineering Department, Polytechnic University of Catalonia (UPC), Barcelona, Spain
*e-mail: esaucedo@irec.cat

OUTLINE

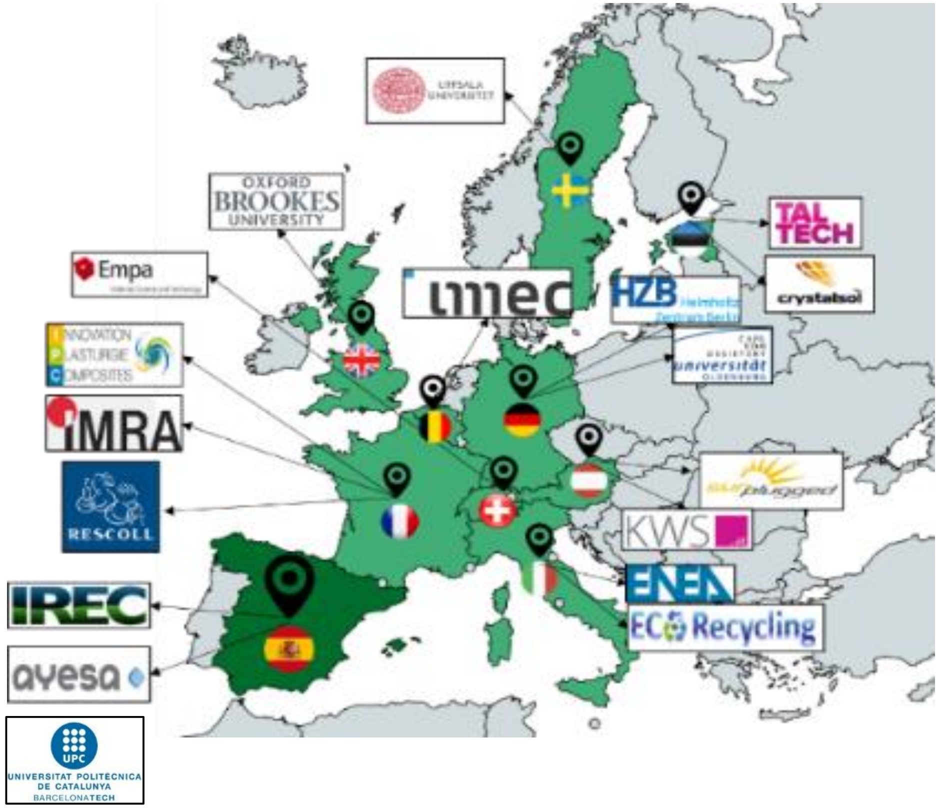
Presentation of CUSTOM-ART project

1. Introduction
2. Characteristics and challenges of kesterite
3. Doping and alloying strategies
4. Beyond kesterites
5. Conclusions and perspectives

CUSTOM-ART – H2020-LC-SC3-2020-RES-IA-CSA-952982
Disruptive kesterite-based thin film technologies customized for challenging architectural and active urban furniture applications

Main Objective: CUSTOM-ART will demonstrate that the new generation of CZTS -based solutions developed and tested during the project, will become the most robust and cost-effective thin-film technology in the EU for challenging and demanding architectural and urban furniture applications.

Partners:



Main characteristics:

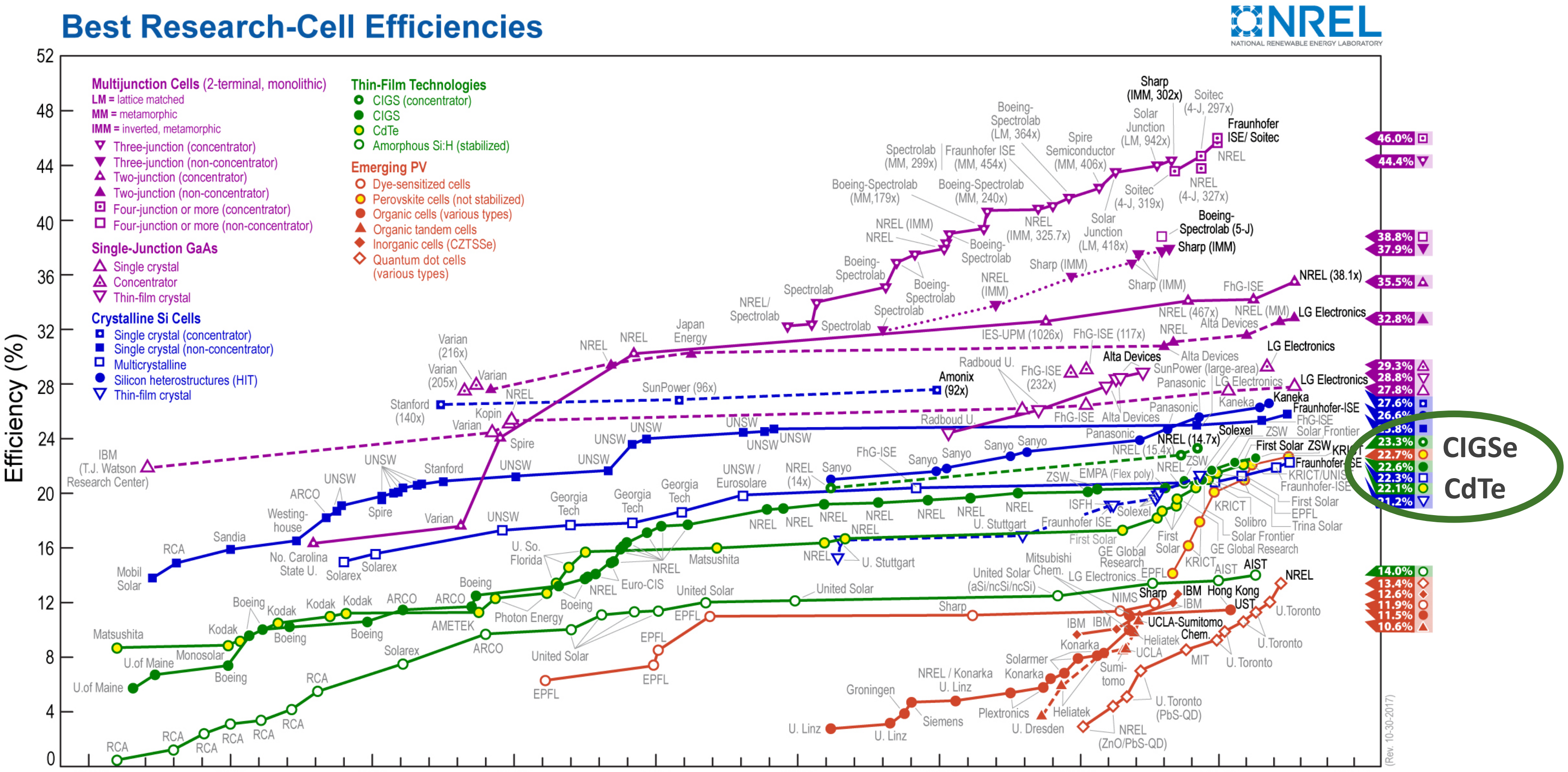
- ✓ Demonstration at solar cell level of a performance $\eta \geq 20\%$ and at module level of a $\eta \geq 16\%$.
- ✓ Fabrication of large size module prototypes: 1) Monograin module (20x20 cm^2; 6.4Wp)) and 2) Micro-crystalline module onto steel (5x10 cm^2; 0.8Wp).
- ✓ Demonstration in 4 DEMO-Sites (curved façades, curved tiles, bus canopy and urban furniture)

Seville
Spain

Innsbruck
Austria

Coordinator: Prof. Dr. Edgardo Saucedo (UPC and IREC)
Duration: 09/2020 – 02/2024
Total budget: 6.999.745,25 €
www.custom-art-h2020.eu

OUTLINE



- **Main commercially available thin film PV technologies: CdTe and CIGSe**
- **In, Ga and Te identified by the European Commission as critical raw materials**

JPhys Energy

TOPICAL REVIEW • OPEN ACCESS

Emerging inorganic solar cell efficiency tables (Version 1)

Lydia H Wong[1], Andriy Zakutayev[2], Jonathan D Major[3], Xiaojing Hao[4], Aron Walsh[5,6], Teodor K Todorov[7] and Edgardo Saucedo[8,9]

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Material	Eff. (%)	V_{OC} (V)	J_{SC} (mA/cm^2)	F.F. (%)	Area (cm^2)	E_g (eV)	Institutions
Cu_2ZnSnS_4 (CZTS)	11.0±0.2	0.731	21.74	69.3	0.2339	1.5	UNSW.[3]
Cu_2BaSnS_4 (substrate)	1.7	0.698	5.3	46.9	0.2	2.01	Central South University, UNSW, Shen Zhen University, Xiamen University.[19]
Cu_2BaSnS_4 (superstrate)	2.0	0.933	5.1	42.9	0.2	2.04	The University of Toledo.[20]
Cu_2FeSnS_4	3.0	0.610	9.3	52.0	0.1	1.5	Indian Association for the Cultivation of Science.[21]
$Cu_2CdSn(S_{0.xx}Se_{0.yy})_4$	2.8	0.356	18.8	41.6	0.405	1.55	Changchun Institute of Applied Chemistry, Chinese Academy of Sciences.[22]
$Cu_2BaSn(S_{0.xx}Se_{0.yy})_4$	5.2	0.611	17.4	48.9	0.425	1.55	Duke University, IBM.[23]
$Cu_2ZnGe(S_{0.xx}Se_{0.yy})_4$	6.0	0.617	NA	NA	0.25	1.47	ZSW, CNRS.[24]
$Cu_2ZnGeSe_4$	7.6	0.558	22.8	59.0	0.5	1.36	CNRS, IMEC.[25]
$Ag_2ZnSnSe_4$	5.18	0.504	21.0	48.7	0.45	1.35	IBM, UCSD.[26]
$Cu_2(Zn_{0.6}Cd_{0.4})SnS_4$	11.0	0.650	25.5	66.1	0.22	1.38	University of New South Wales, Australia; National Renewable Energy Laboratory, United States; Central South University, China.[27]
$(Ag_{0.05}Cu_{0.95})_2(Zn_{0.75}Cd_{0.25})Sn_4$	10.1	0.650	23.4	66.2	0.16	1.4	NTU, Singapore; HZB, Germany.[29]

Several kesterite type materials at the forefront of the emerging thin film photovoltaic materials

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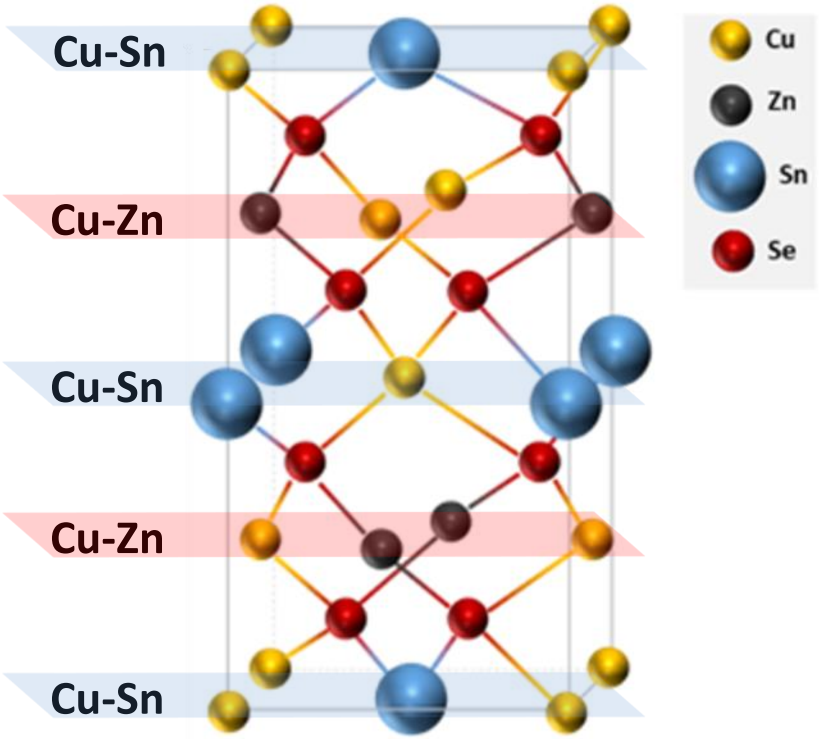
Kesterite: emerging thin film PV materials

Tetragonal structure (I4 space group)

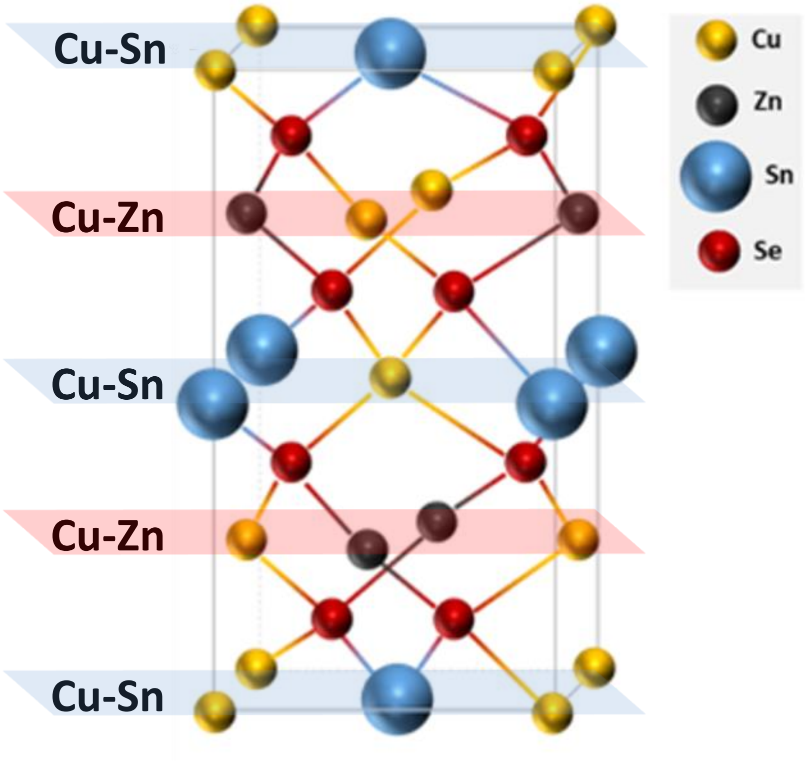


Advantages of kesterites:

- Exclusively formed by **low-toxicity** and earth **abundant elements**.
- **P-type conductivity** naturally due to intrinsic point defects.
- **Direct band-gap** semiconductor with a **high absorption** coefficient (~10^4 cm^{-1}).
- Easily **tunable band-gap**, either controlling the S/Se ratio or with cation substitution.
- Highly **compatible** with **CIGS** technology.

Kesterite: emerging thin film PV materials

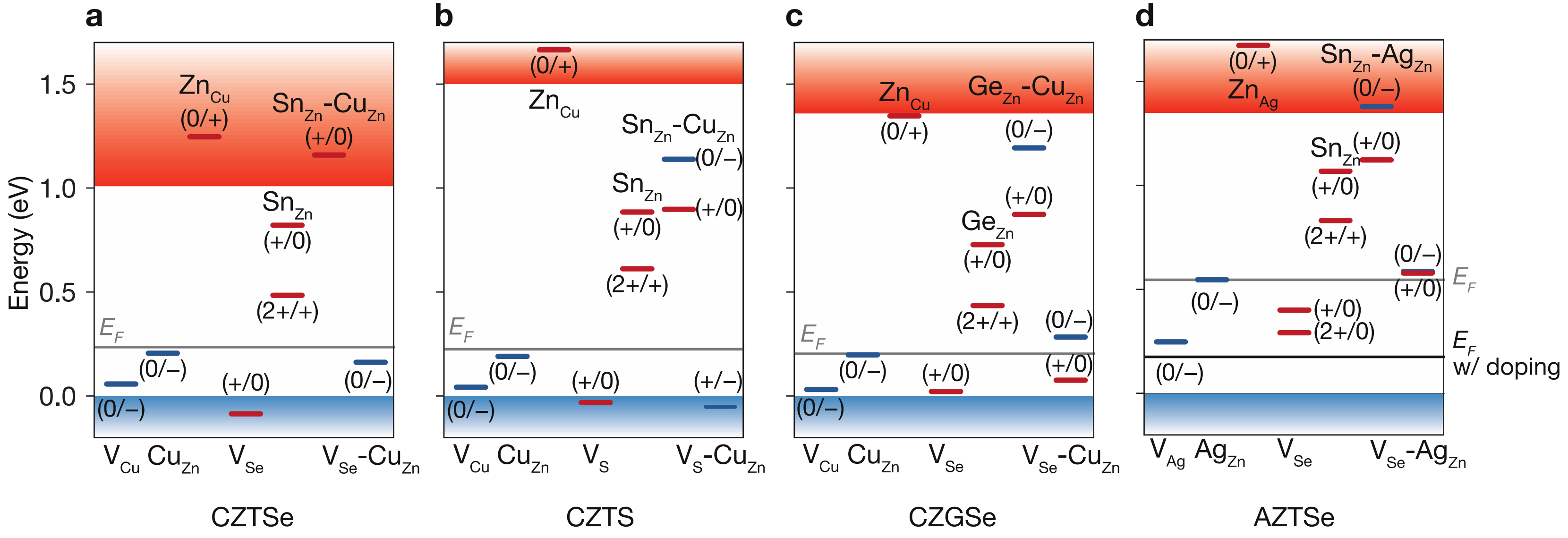
Tetragonal structure (I4 space group)

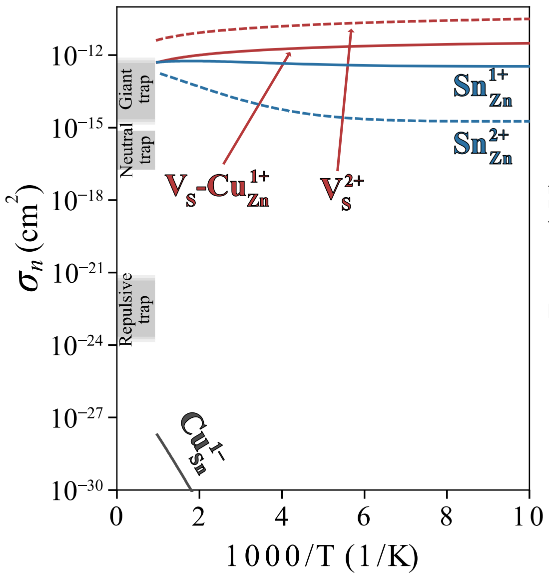


Challenges of kesterites:

- **Cu** and **Zn** are **iso-electronic elements**: easy exchange in the lattice (anti-sites defects formation: Cu_{Zn}, Zn_{Cu}).
- **Sn** forms **volatile species** with **Se** and **S:** Sn exchange with the annealing atmosphere, Sn loss.
- **Sn** is a **multi-valent element (Sn^{+2}** and **Sn^{+4}):** formation of defects related to Sn valence.
- **Sn** strongly **interacts** with **alkaline** elements.
- **Zn** is a relatively **volatile** element.

How can we solve this issue?





Recent materials modelling results show that*:

- Sn_{Zn} related anti-sites introduces deep defects
- All of them are giant recombination traps

Most plausible origin of the high non-radiative recombination and low carriers life-time

*Results obtained by Prof. A. Walsh Group (ICL) in STARCELL, Unpublished.

How can we solve this issue?

How to avoid Sn related anti-sites?*

$$Sn_{Zn}^{2+}$$

~~⊖ Zn-rich~~

Additional Zn forms ZnS/ZnSe.

~~⊖ Sn-poor~~

The Cu-rich secondary phases are conductive.

~~⊖ hole poor (n-type)~~

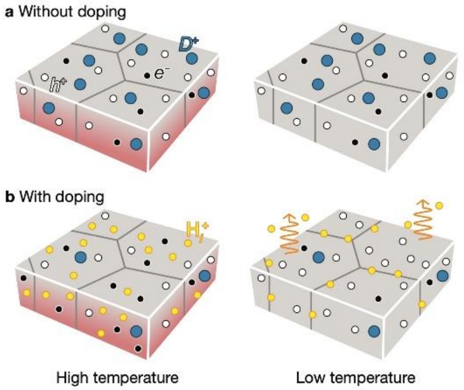
The acceptor (Cu_{Zn}) are too many.

Partial substitution by Ge:

- Ge related defects are less detrimental
- Higher efficiencies theoretically predicted

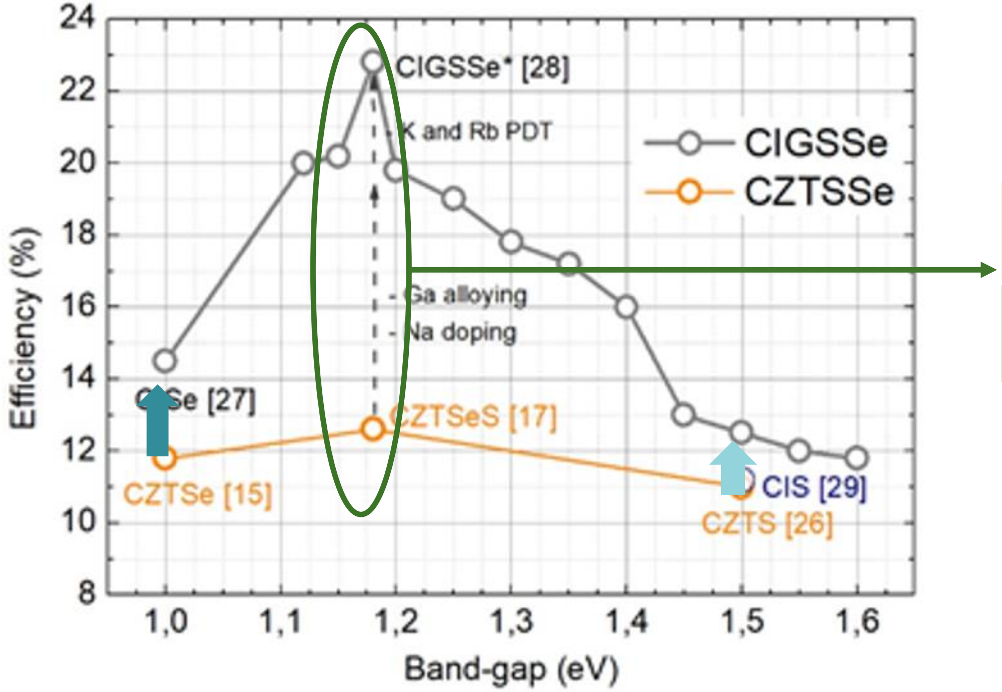
Doping with H_i^+:

- Removes free e-
- Reduce recombination



Results obtained by Prof. A. Walsh Group (ICL) in STARCELL, Unpublished.

We can learn several things from CIGS…



“Progress and Perspectives of Thin Film Kesterite Photovoltaic Technology: A Critical Review”, Sergio Giraldo, Zacharie Jehl, Marcel Placidi, Victor Izquierdo-Roca, Alejandro Pérez-Rodríguez, Edgardo Saucedo, Advanced Materials, Volume 31, Issue 16, 201806692, 2019.

Doping

Alloying

- $CuInSe_2$ and $Cu_2ZnSnSe_4$ – About 2% efficiency difference
- $CuInS_2$ and Cu_2ZnSnS_4(Cd) – About 1% efficiency difference
- **$Cu(In,Ga)Se_2$ and $Cu_2ZnSn(S,Se)_4$ – About 10% efficiency difference**

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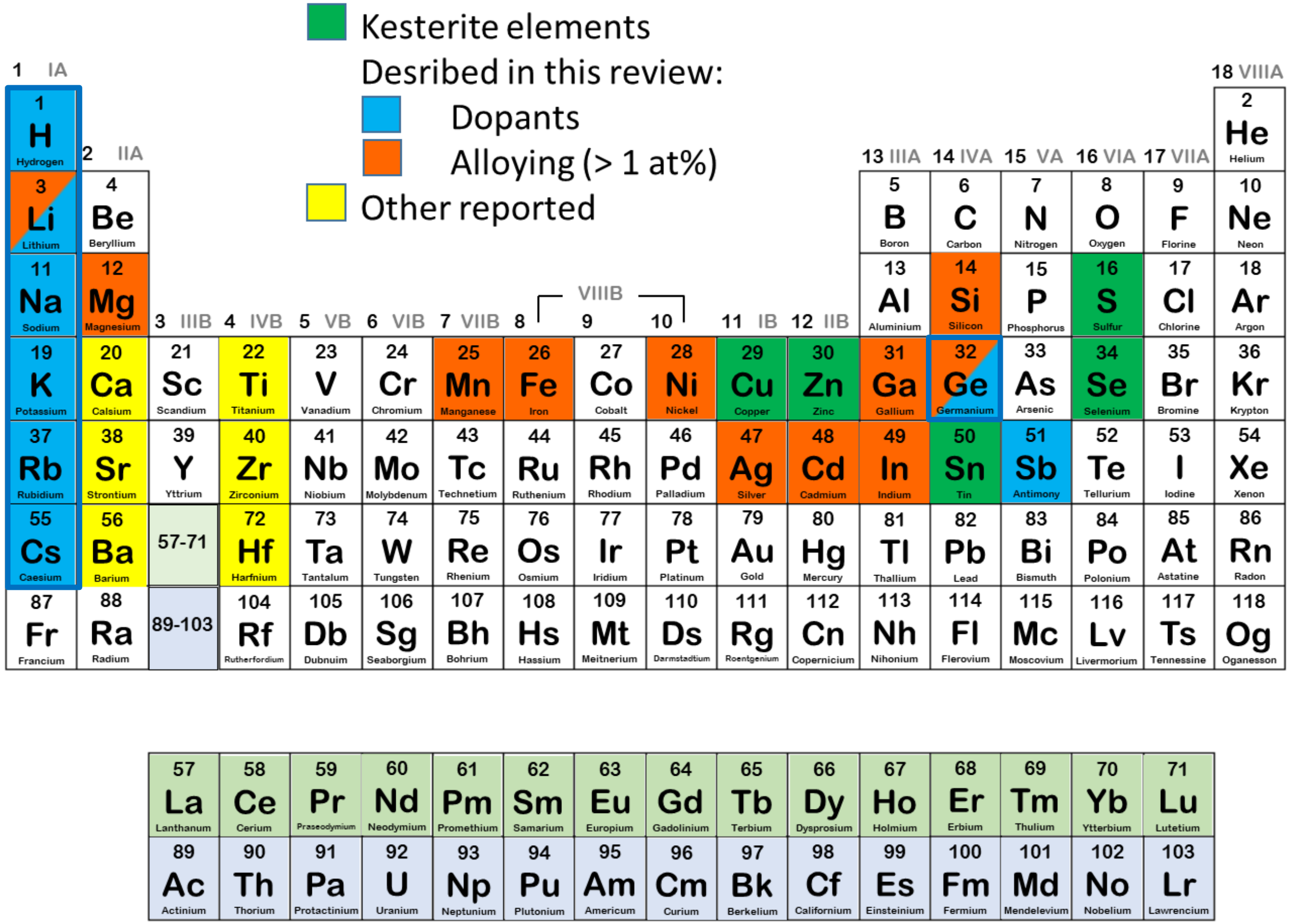
Extrinsic Doping



🟩 Kesterite elements

Desribed in this review:

🟦 Dopants

🟧 Alloying (> 1 at%)

🟨 Other reported

“Doping and alloying of kesterites”, Yaroslav Romanyuk, Stefan Haass, Sergio Giraldo, Marcel Placidi, Devendra Tiwari, David Fermin, Xiaojing Hao, Hao Xin, Thomas Schnabel, Marit Kauk-Kuusik, Paul Pistor, Stener Lie and Lydia Helena Wong, J. Physics Energy 2019 (DOI: 10.1088/2515-7655)

Most relevant

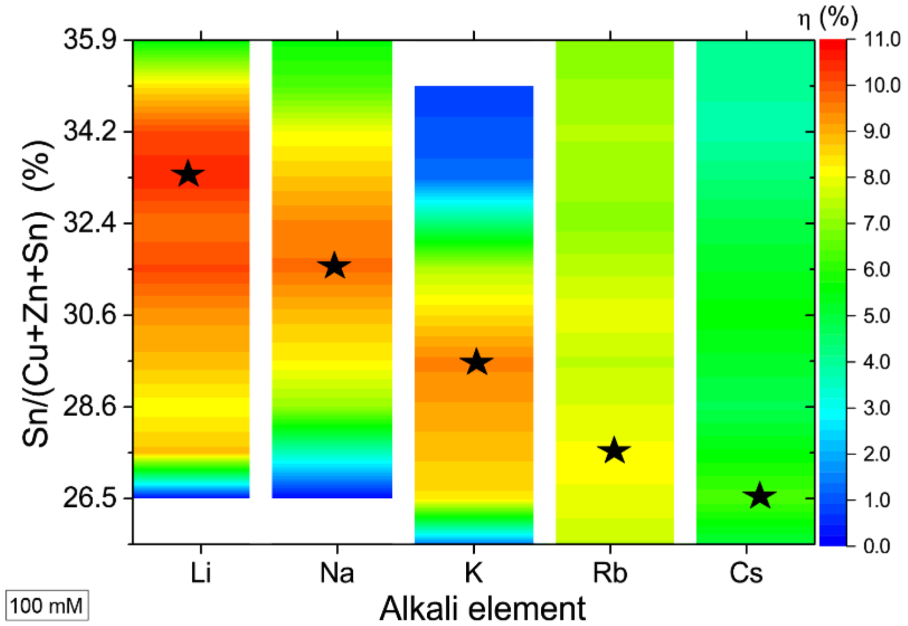
Doping: alkali elements and Ge

What is the best alkaline dopant?

Author	Order of performance improvement
Mule et al. Thin Solid Films 2016	Na > Cs > K > Rb > Li
Hsieh et al. Adv. Energy Mater. 2016	K > Rb > Na > Li > Cs
Altamura et al. Scientific Reports 2016	Li > Na > Rb
López-Marino et al. J. Mater. Chem. A 2016	K > Na
S. Haass et al. Adv. Energy Mater. 2017	Li > Na > K > Rb > Cs

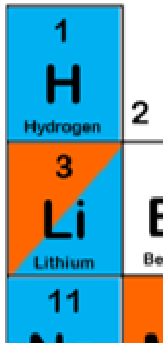
- ✓ Some discrepancy in the literature about the most efficient alkaline
- ✓ Effect on morphology quite well documented
- ✓ Role of each of them is still matter of intensive research
- ✓ PAT (or doping before/during the annealing) more effective than PDT for the moment
- ✓ Lighter elements more effective than heavier elements for the moment

Brief review on alkaline doping…

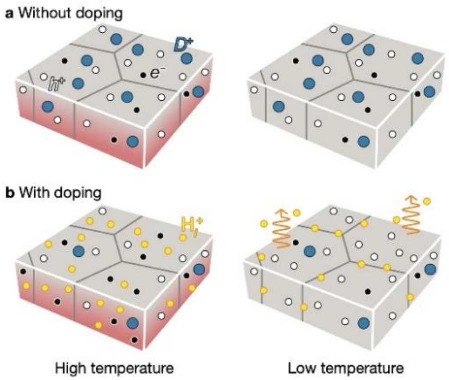


- ✓ For each alkali metal adjustment of Sn content and alkali concentration is mandatory!*
- ✓ Strong interaction with Sn
- ✓ This is something very particular of kesterites, and no yet understood
- ✓ Li > Na > K > Rb > Cs

*Stefan G. Haass et al., Adv. Energy Mater. 2018, 8, 1701760.

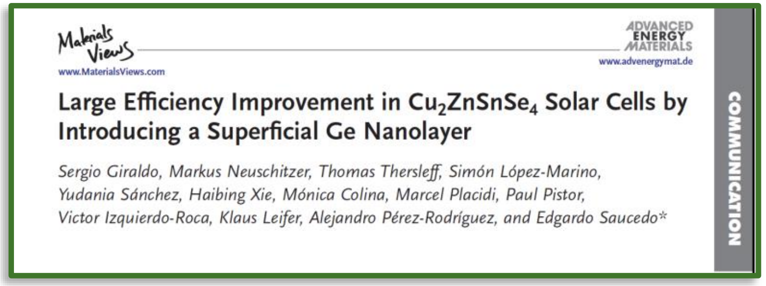


- ✓ Li has been demonstrated as a relevant doping and alloying element to improve kesterite efficiency
- ✓ Li^+ is the most similar cation to H^+



Is this related to the technological solution proposed by ICL in STARCELL????

I have no idea!!!! But at least is very promising!!!



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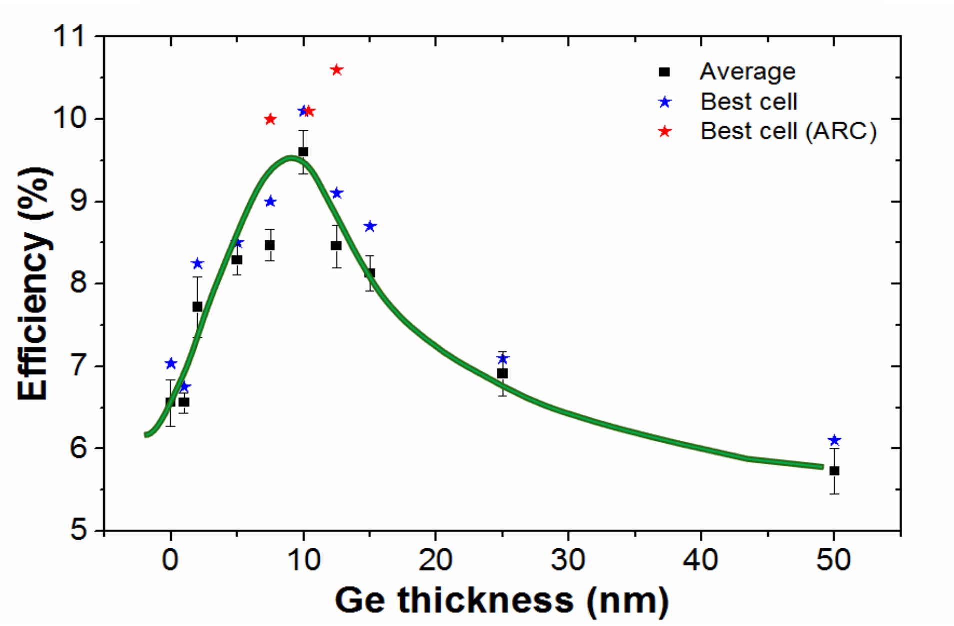
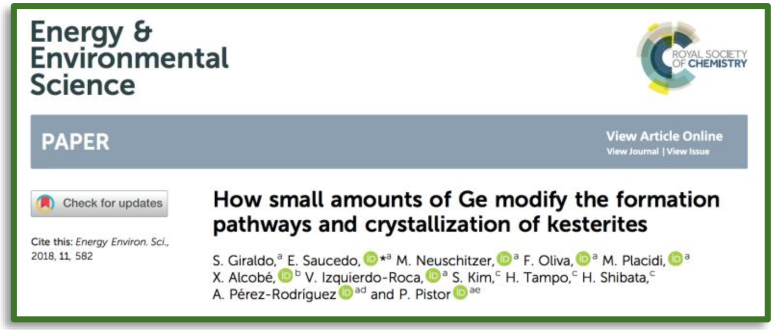
COMMUNICATION

Large Efficiency Improvement in $Cu_2ZnSnSe_4$ Solar Cells by Introducing a Superficial Ge Nanolayer

*Sergio Giraldo, Markus Neuschitzer, Thomas Thersleff, Simón López-Marino, Yudania Sánchez, Haibing Xie, Mónica Colina, Marcel Placidi, Paul Pistor, Victor Izquierdo-Roca, Klaus Leifer, Alejandro Pérez-Rodríguez, and Edgardo Saucedo**



S. Giraldo et al., Adv. Ener. Mater. 5, 2015, 1501070.



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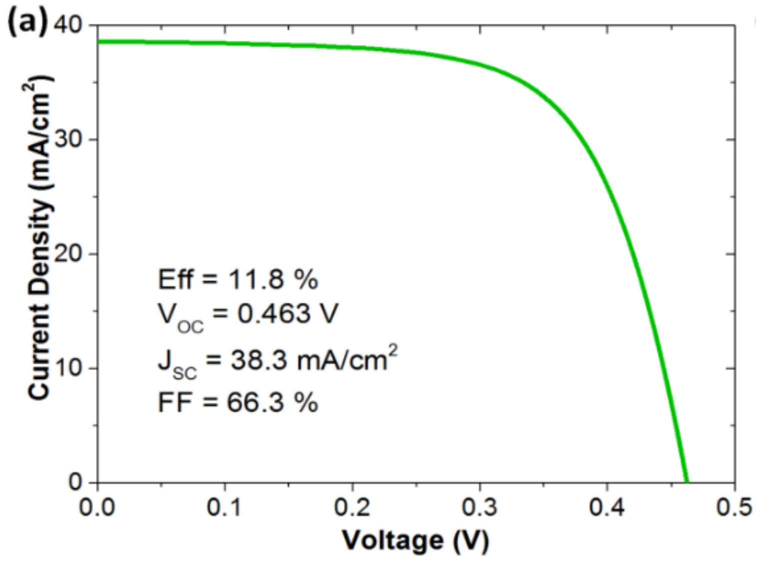
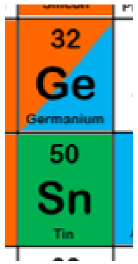
Cite this: *Energy Environ. Sci.*, 2018, 11, 582

How small amounts of Ge modify the formation pathways and crystallization of kesterites

S. Giraldo,[a] E. Saucedo,[*a] M. Neuschitzer,[a] F. Oliva,[a] M. Placidi,[a] X. Alcobé,[b] V. Izquierdo-Roca,[a] S. Kim,[c] H. Tampo,[c] H. Shibata,[c] A. Pérez-Rodriguez[ad] and P. Pistor[ae]

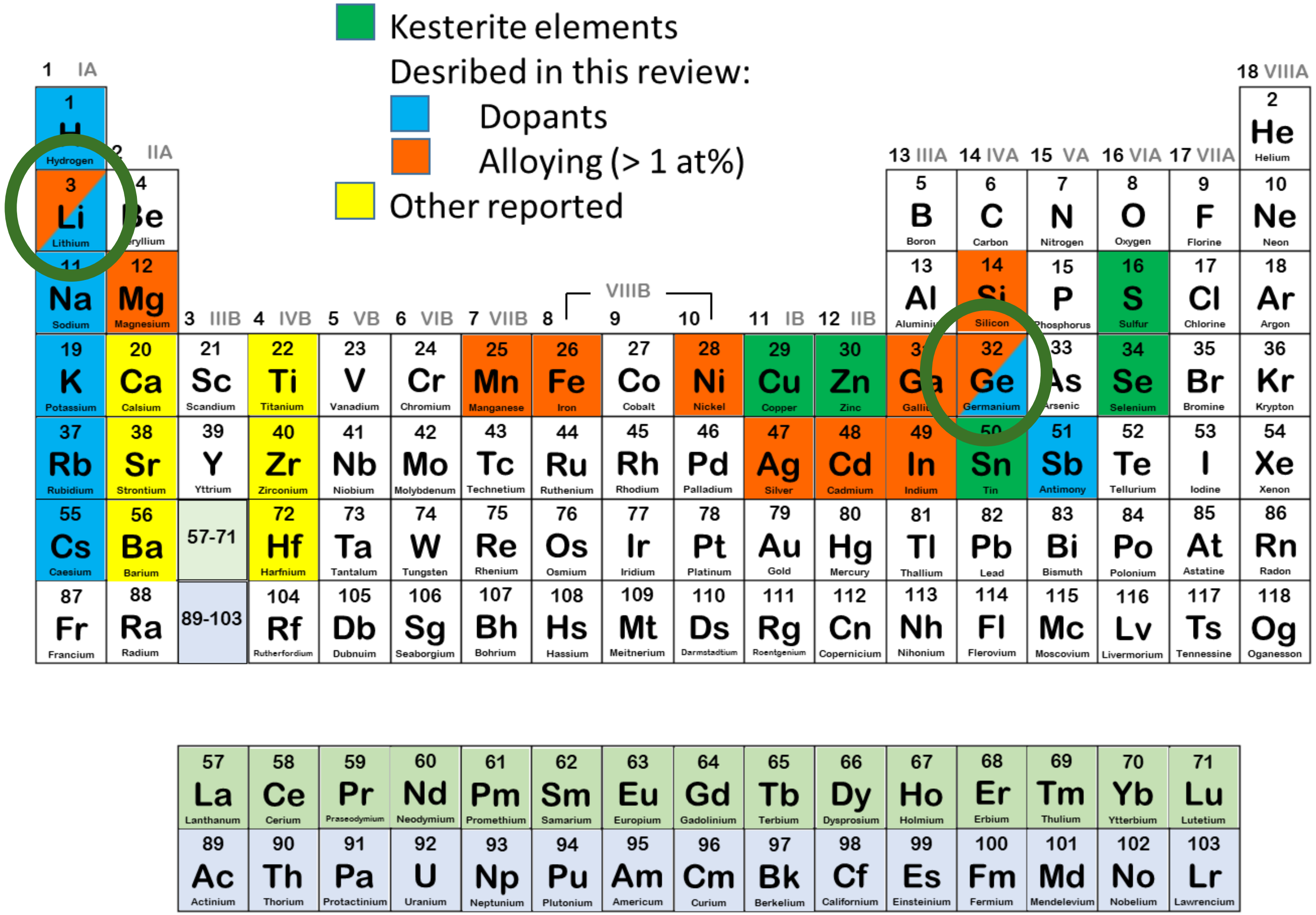


S. Giraldo et al., Energy Env. Scie. 11, 2018, 582.



- ✓ Ge has been demonstrated as a relevant doping and alloying element to improve kesterite efficiency
- ✓ Ge^{+4} substitutes Sn^{+4} in the kesterite structure

Extrinsic Doping


🟩 Kesterite elements

Desribed in this review:

🟦 Dopants

🟧 Alloying (> 1 at%)

🟨 Other reported

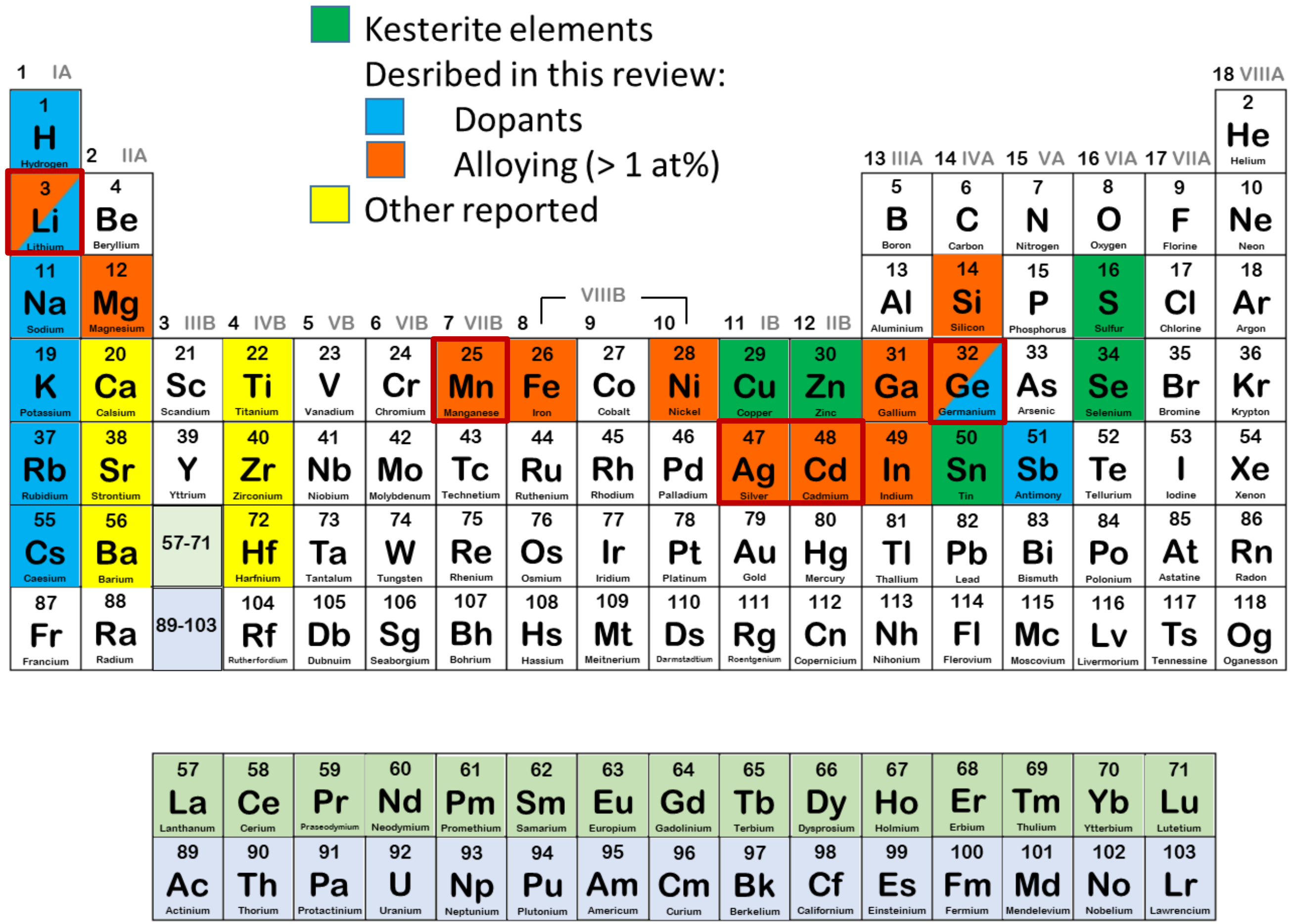
- ✓ Ge and Li are the only elements proved as efficient doping/alloying solutions
- ✓ Both of them demonstrates a strong interaction with Sn

✓ Something wrong happens with Sn.

✓ To understand and solve it can be one of the breakthrough for increasing the conversion efficiency

"Doping and alloying of kesterites", Yaroslav Romanyuk et al., Physics Energy 2019 (DOI: 10.1088/2515-7655)

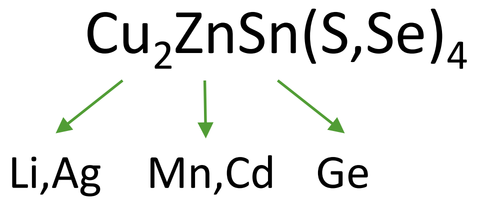
Alloying



“Doping and alloying of kesterites”, Yaroslav Romanyuk, Stefan Haass, Sergio Giraldo, Marcel Placidi, Devendra Tiwari, David Fermin, Xiaojing Hao, Hao Xin, Thomas Schnabel, Marit Kauk-Kuusik, Paul Pistor, Stener Lie and Lydia Helena Wong, J. Physics Energy 2019 (DOI: 10.1088/2515-7655)

Most relevant

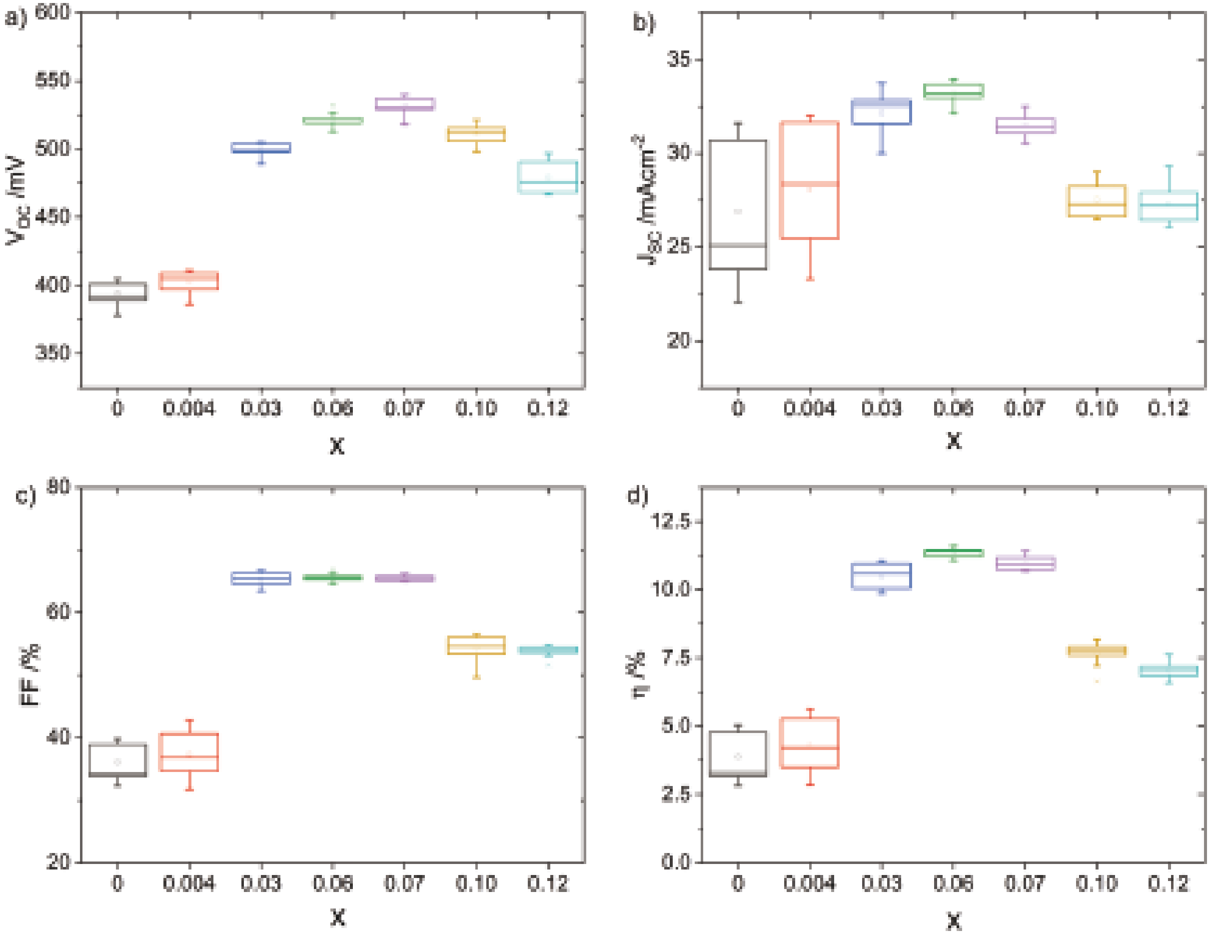
Alloying: Li, Mn, Ag, Cd and Ge



$Cu_2ZnSn(S,Se)_4$

Li,Ag Mn,Cd Ge

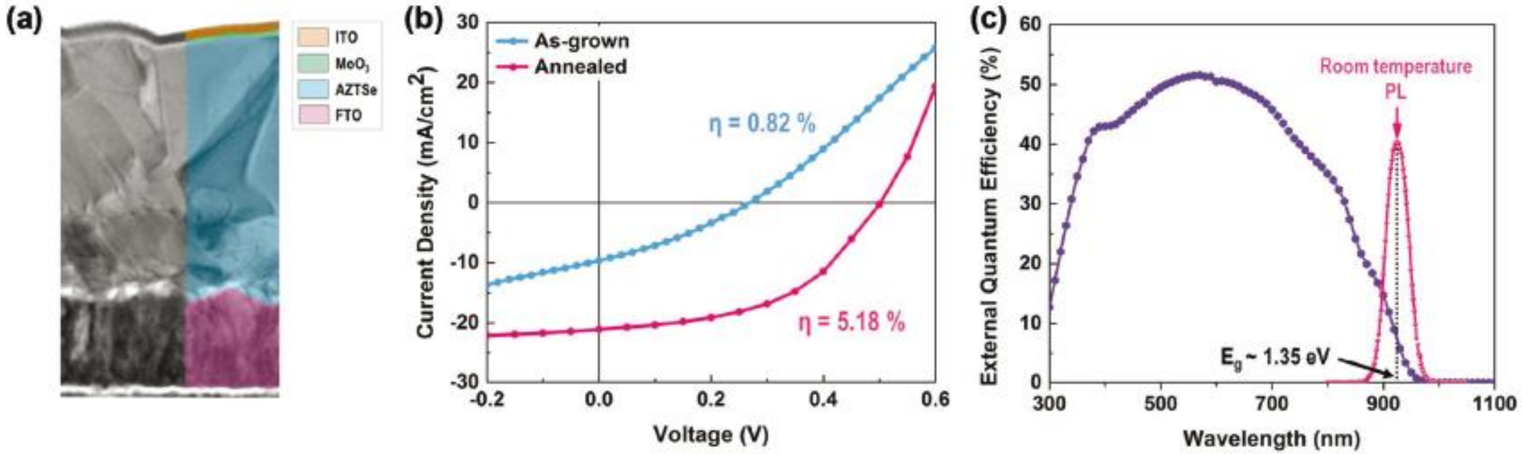
Lithium*: substitutes Cu



- Up to 12% Li alloying
- Large efficiency improvement with 3-7% Li (mainly Voc and FF improved)
- **Increase in the apparent carrier concentration** with Li
- **Increase of the quantum yield**
- No improvement in the minority carrier life-time
- Efficiency up to 12.2% is obtained

*Cabas-Vidani A, Haass S G, Andres C, Caballero R, Figi R, Schreiner C, Márquez J A, Hages C, Unold T, Bleiner D, Tiwari A N and Romanyuk Y E 2018 High-Efficiency $(Li_xCu_{1-x})_2ZnSn(S,Se)_4$ Kesterite Solar Cells with Lithium Alloying *Adv. Energy Mater.* **8** 1801191

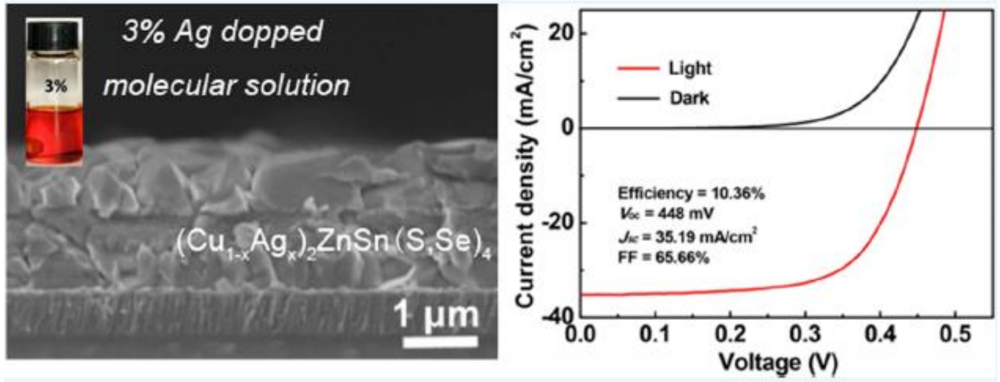
Silver*: substitutes Cu

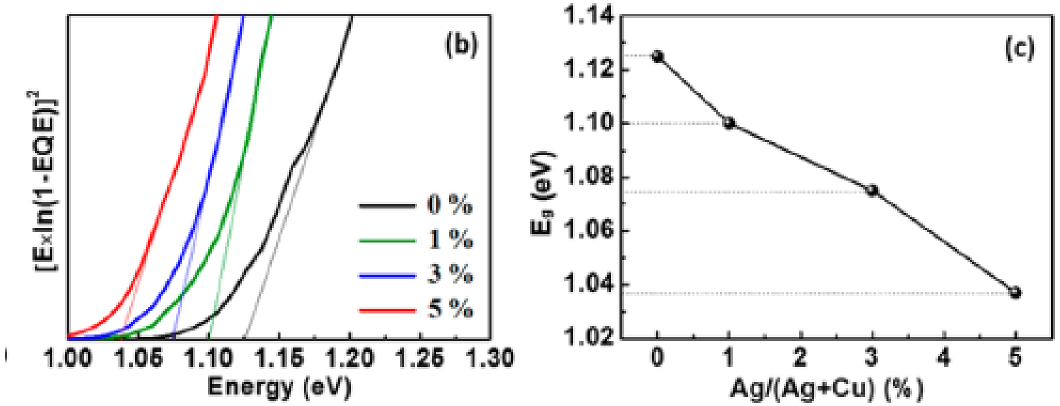


- Decent efficiencies have been reported using Ag in substitution of Cu[1]
- Band-gap suitable for graded E_g concepts
- Has shown to probably solve one of the main issues of kesterites: **Cu-Zn disorder**, most probably related to a change of the structure from kesterite to stannite
- Problems:
    - change of conductivity for high Ag concentrations
    - Ag is expensive

*T. Gershon et al., Adv. Energy Mater. 6, 2016, 1601182.

Silver*: substitutes Cu





- Possibility to **tune the band-gap** has been demonstrated*
- Ag seems to help **to improve the efficiency** of the devices
- Nevertheless, possibility of band-gap grading is not demonstrated
- The feasibility is in doubt, cause the high mobility of Cu ions, and the large quantity of Cu vacancies in kesterite

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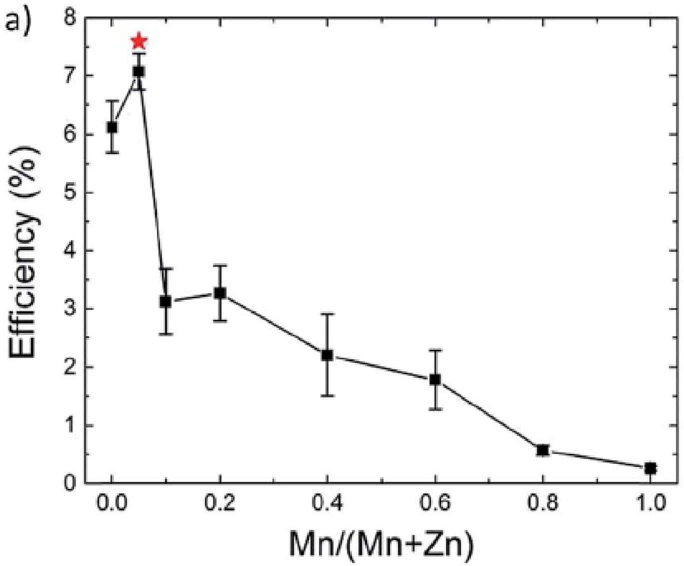
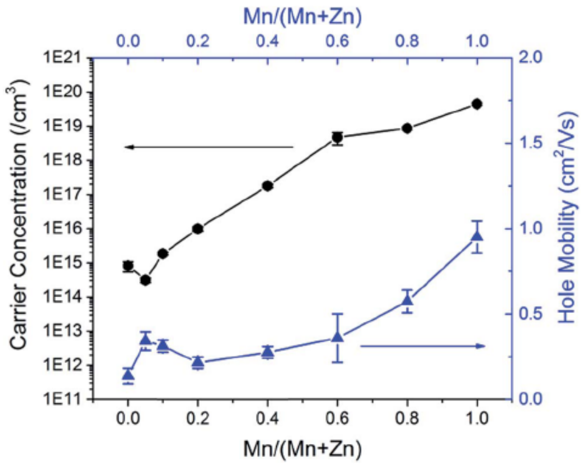
* Y. Qi et al., ACS Appl. Mater. Interfaces 2017, 9, 21243–21250.

Manganese*: substitutes Zn





- Substitution of Zn with Mn in CZTSSe thin films is shown to induce **structural transformation at x = 0.2** which is largely attributed to the difference in the atomic radius
- The variation of the Mn content is also found to **change the charge density, mobility and carrier lifetime** in CMZTSSe
- Improvement in the conversion efficiency of solar cell devices is observed for low Mn contents
- The improved open circuit voltage (Voc) and fill factor (FF) are attributed to the **improved shunt resistance and carrier transport** due to lower defect density especially at the CdS/CMZTSSe interface
- If **Mn** content is more than 5% (**x > 0.05**), the efficiency was reduced due to the significant **increase of carrier density**

*Lie S, Rui Tan J M, Li W, Leow S W, Tay Y F, Bishop D M, Gunawan O and Wong L H, “Reducing the interfacial defect density of CZTSSe solar cells by Mn substitution”, J. Mater. Chem. A 6 1540–50, 2018.

Cadmium*: substitutes Zn

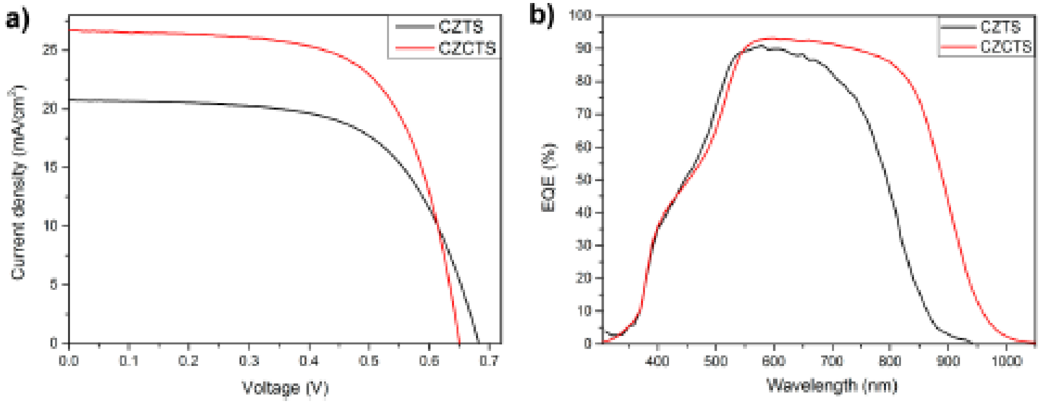
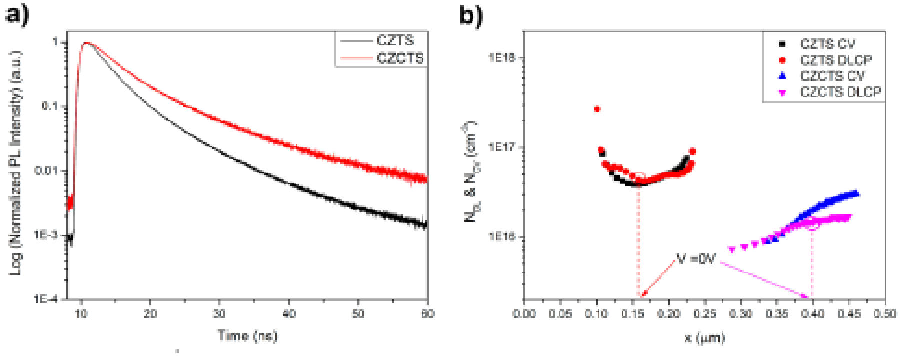


Figure 5. (a) *J–V* curves and (b) EQE curves of CZTS and champion CZCTS devices.

Table 2. Device Characteristics of the CZTS and CZCTS Solar Cells

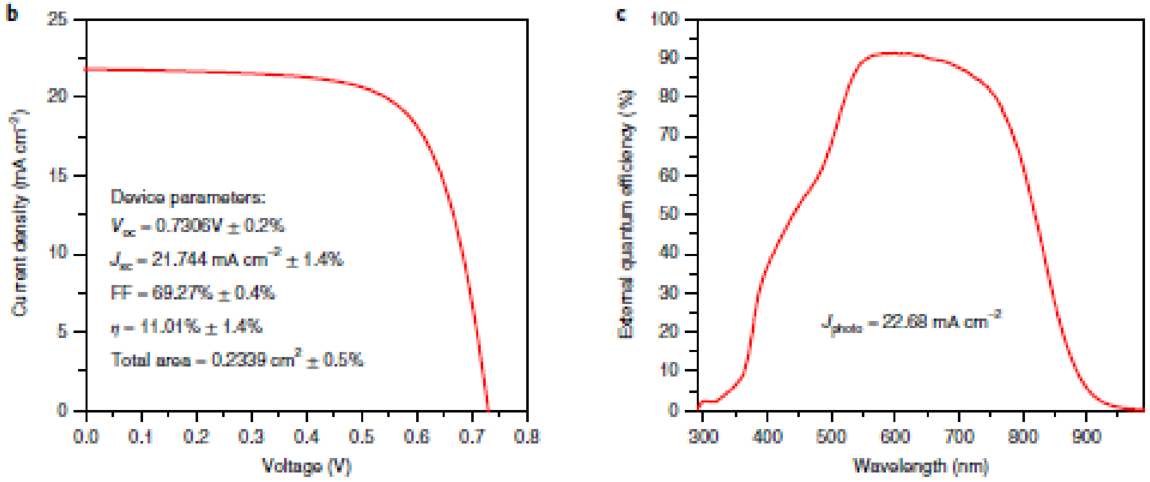
absorber	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	Eff (%)	$E_g/q\text{-}V_{oc}$ (mV)	$R_{s,L}$ (Ω cm²)	$G_{s,L}$ (mS cm⁻²)	*A*	J_0 (A/cm²)
CZTS	683	20.7	62.5	8.8	847	0.96	0.67	3.3	8.1×10^{-6}
CZCTS	650	26.7	66.1	11.5	730	0.45	1.0	2.5	1.2×10^{-6}

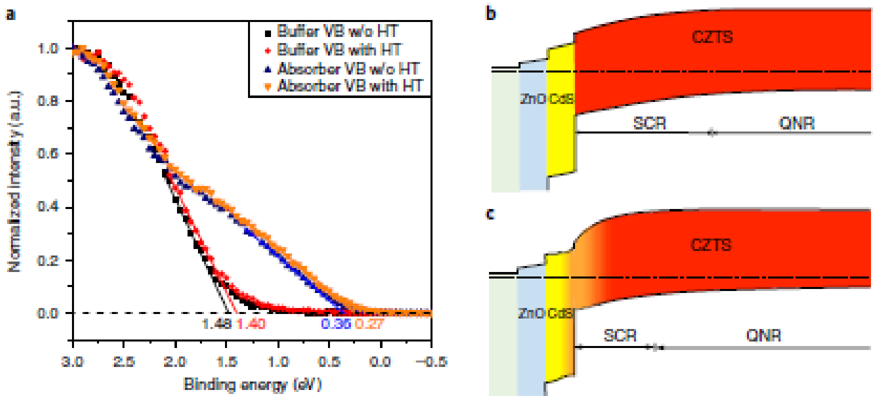


- ❖ Suitable for the S or S/Se compound
- ❖ Cd alloying into CZTS can **improve the microstructure** by facilitating the growth of larger grains and change the nature of the secondary phases of the absorber
- ❖ Alloying of Cd in CZTS can reduce the Voc deficit and recombination by **reducing the band tailing problem**
- ❖ Alloying of Cd can **increase minority carrier lifetime** and lowers the doping density (free carrier)
- ❖ Cd incorporation elevates the VBM position of CZTS rather than lower the CBM position of CZTS, suggesting an undesirable cliff-like heterojunction interface
- ❖ Efficiencies over 11% are achieved

*Yan C, Sun K, Huang J, Johnston S, Liu F, Veettil B P, Sun K, Pu A, Zhou F, Stride J A, Green M A and Hao X, "Beyond 11% Efficient Sulfide Kesterite $Cu_2Zn_xCd_{1-x}SnS_4$ Solar Cell: Effects of Cadmium Alloying", *ACS Energy Lett.* **2** 930–6, 2017.

Cadmium*: substitutes Zn

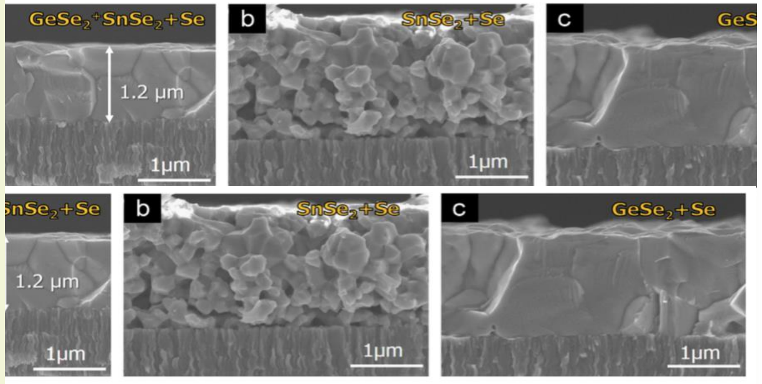




- ❖ Recent reported **10% certified efficiency** solar cell in large area (>1cm^2) (11% in standard size)
- ❖ **Inter-diffusion of CZTS/CdS** (selective surface alloying/doping)
- ❖ Elemental inter-diffusion: Zn into CdS and Cd into CZTS
- ❖ Na accumulation and local Cu depletion at the heterojunction
- ❖ **New phases formation**: $Cu_2Cd_xZn_{1-x}SnS_4$, $Zn_xCd_{1-x}S$, and $Cu_{2-x}Na_xZnSnS_4$.
- ❖ **More favorable band-alignment** is demonstrated and **recombination** at the hetero-junction is **reduced**

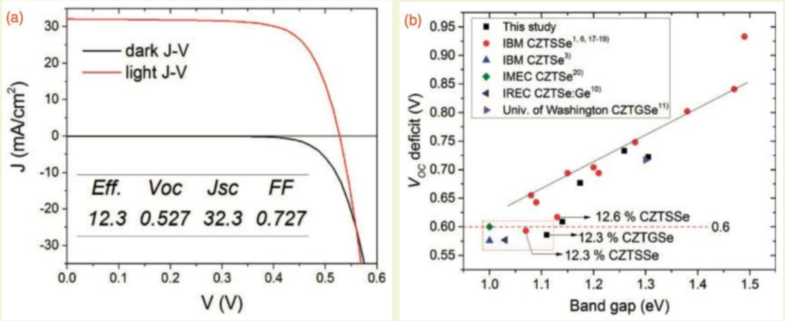
*Yan, Chang; Huang, Jialiang: Sun, Kaiwen; Johnston, Steve; Zhang, Yuanfang; Sun, Heng; Pu, Aobo; He, Mingrui; Liu, Fangyang; Eder, Katja; Yang, Limei; Cairney, Julie M.; Ekins-Daukes, N. J.; Hameiri, Ziv; Stride, John A.; Chen, Shiyou; Green, Martin A.; Hao, Xiaojing, "Cu2ZnSnS4 solar cells with over 10% power conversion efficiency enabled by heterojunction heat treatment", Nature Energy 3 (9) 764-772, 2018.

Germanium: substitutes Sn



First group reporting Ge alloyed CZTSe with Eff > 10%: [1]

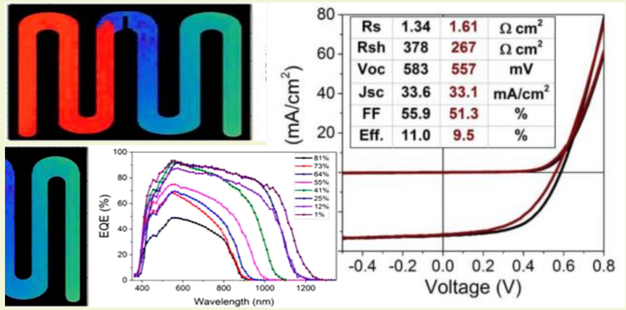
- **Improved morphological properties**: flat surfaces, dense morphologies, and large grains.
- Highest **efficiency** of **10.03%**, with an **open-circuit voltage (V_{OC})** of **0.54 V**, as well as an **improved V_{OC} deficit** of 0.647 V



Eff.	Voc	Jsc	FF
12.3	0.527	32.3	0.727

Best efficiency reported for Ge alloyed CZTSe: [2]

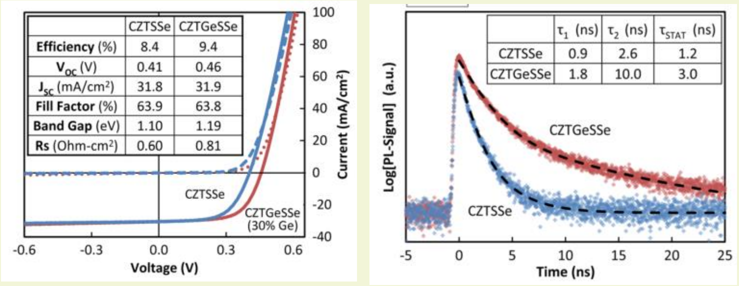
- **Conversion efficiency** of **12.3%**
- **Improved V_{OC} deficit** of **0.583 V** and **FF** of **72.7%**
- Reduced band tailing and carrier recombination.



Rs	1.34	1.61	Ω cm^2
Rsh	378	267	Ω cm^2
Voc	583	557	mV
Jsc	33.6	33.1	mA/cm^2
FF	55.9	51.3	%
Eff.	11.0	9.5	%

Study of CZTGeSSe devices as function of Ge/(Ge+Sn) rel. content using spray coated absorbers with molecular inks: [3]

- **Highest efficiency: 11.0% with 25%Ge relative content** (band gap of about **1.2 eV**) with reduction of V_{OC} deficit



	CZTSSe	CZTGeSSe
Efficiency (%)	8.4	9.4
V_{OC} (V)	0.41	0.46
J_{SC} (mA/cm^2)	31.8	31.9
Fill Factor (%)	63.9	63.8
Band Gap (eV)	1.10	1.19
Rs (Ohm-cm^2)	0.60	0.81

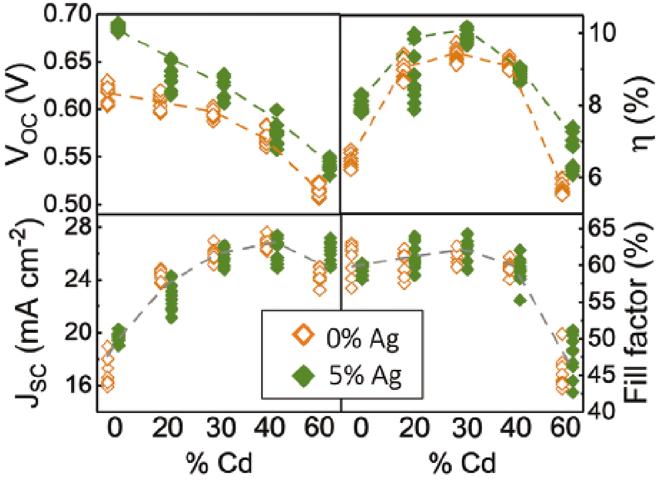
	τ_1 (ns)	τ_2 (ns)	τ_{STAT} (ns)
CZTSSe	0.9	2.6	1.2
CZTGeSSe	1.8	10.0	3.0

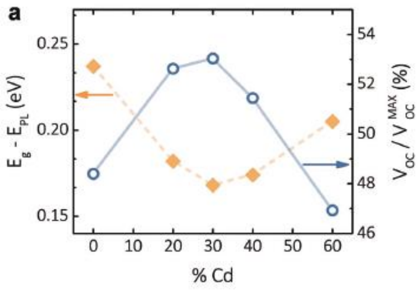
Nanocrystal-based CZTGeSSe absorbers with tunable band gap: [4]

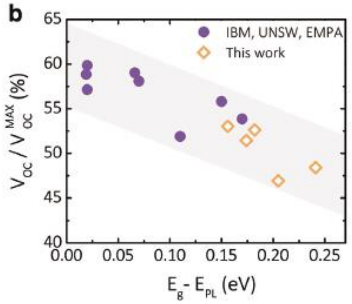
- Maximum conversion **efficiencies** of **up to 9.4%** are achieved with a Ge content of 30 at.%
- Enhanced performance due to **increased minority charge carrier lifetimes** as well as **reduced voltage-dependent charge carrier collection**.

[1] S. Kim et al, Sol. Energy Mater. Sol. Cells. 2016, 144, 488-492
[2] S. Kim et al. Appl. Phys. Express 2016, 9, 102301
[3] A.D. Collord, H.W. Hillhouse. Chem. Mater. 2016, 7, 2067–2073
[4] C.J. Hages et al, Prog. Photovoltaics Res. Appl. 2015, 23, 376–384

Bonus!: double cation substitution (Cd, Ag)







- Double cation substitution can be used to **improve** upon the device **performance** achievable via single cation substitution, if the **two cations affect different limiting factors** of CZTS.
- **Cd alters the position of acceptor defects near the valence band**, and the maximum device performance is obtained at the Cd content corresponding to the shallowest acceptor defects.
- **Ag decreases the charge carrier density**, **improves the photoluminescence decay time and efficiency**, as well as the open-circuit voltage, indicating a **reduction** of the **nonradiative recombination** via defects.
- Double cation substitution can be used as a tool to fine-tune the properties of the absorber material.
- Efficiencies over 10% are reported (5% Ag and 25% of Cd)

*Shreyash H. Hadke, Sergiu Levcenko, Stener Lie, Charles J. Hages, José A. Márquez, Thomas Unold, and Lydia H. Wong, “Synergistic Effects of Double Cation Substitution in Solution-Processed CZTS Solar Cells with over 10% Efficiency”, Adv. Energy Mater. 2018, 8, 1802540.

Summary*

Material	Doping element	Eg (eV)	Voc (mV)	Eff (%, total area)	Ref
CZTSSe	nominally undoped*	1.13	513	12.6	[3]
CZTSSe	Li	1.04	449	11.5	[26]
CZTSe	Na*	1.0	423	11.6	[39]
CZTSe	K	1.02	432	9.7	[45]
CZTSSe	Rb	0.96	419	8.8	[26]
CZTSSe	Cs	0.97	439	9.1	[26]
CZTSe	In	1.02	423	7.8	[82]
CZTSe	Ge	1.04	463	11.8	[106]

Material	Alloying element	Eg (eV)	V_{OC} (mV)	Eff. (%, total area)	Ref.
ACZTSSe	Ag/(Ag+Cu)=3%	1.07	448	10.4	[57]
CMZTSSe	Mg/(Mg+Zn)=4%	1.01	419	7.2	[72]
CZCTS	Cd/(Cd+Zn)=40%	1.38	650	11.5	[75]
CZTGSe	Ge/(Ge+Sn)=22%	1.11	527	12.3	[113]
CMZTS	Mn/(Mn+Zn)=5%	1.055	418	8.9	[142]
ACZCTSSe	Ag: 5%, Cd:25%	1.4	650	11.1	

- ❖ Most promising doping elements: Li, Na and Ge
- ❖ Most promising alloying elements: Cd and Ge, maybe double cation substitution?

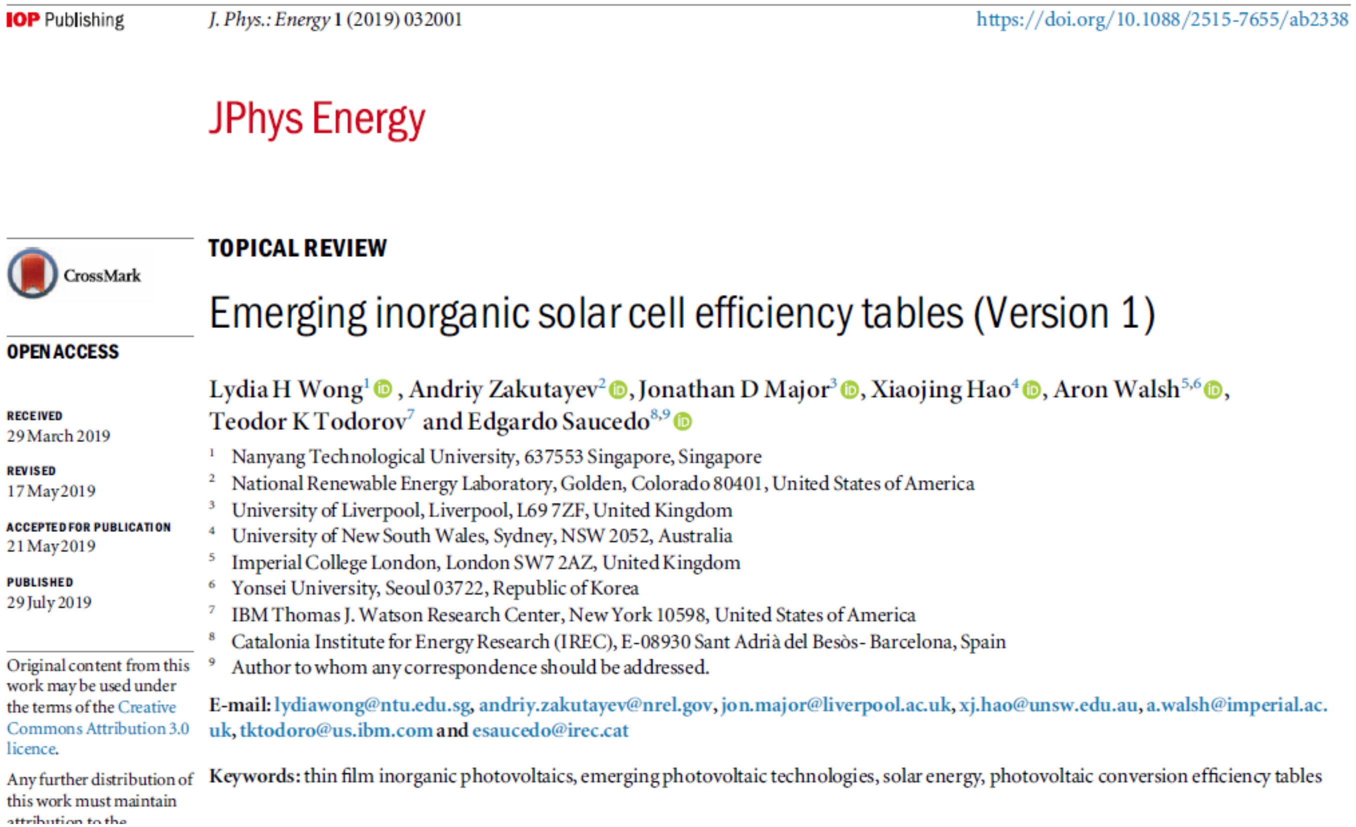
*"Doping and alloying of kesterites", Yaroslav Romanyuk, Stefan Haass, Sergio Giraldo, Marcel Placidi, Devendra Tiwari, David Fermin, Xiaojing Hao, Hao Xin, Thomas Schnabel, Marit Kauk-Kuusik, Paul Pistor, Stener Lie and Lydia Helena Wong, J. Physics Energy 2019 (DOI: 10.1088/2515-7655)

OUTLINE

Presentation of CUSTOM-ART project

1. Introduction
2. Characteristics and challenges of kesterite
3. Doping and alloying strategies
4. **Beyond kesterites**
5. Conclusions and perspectives

You are very lucky!!!..



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TOPICAL REVIEW

Emerging inorganic solar cell efficiency tables (Version 1)

Lydia H Wong[1], Andriy Zakutayev[2], Jonathan D Major[3], Xiaojing Hao[4], Aron Walsh[5,6], Teodor K Todorov[7] and Edgardo Saucedo[8,9]

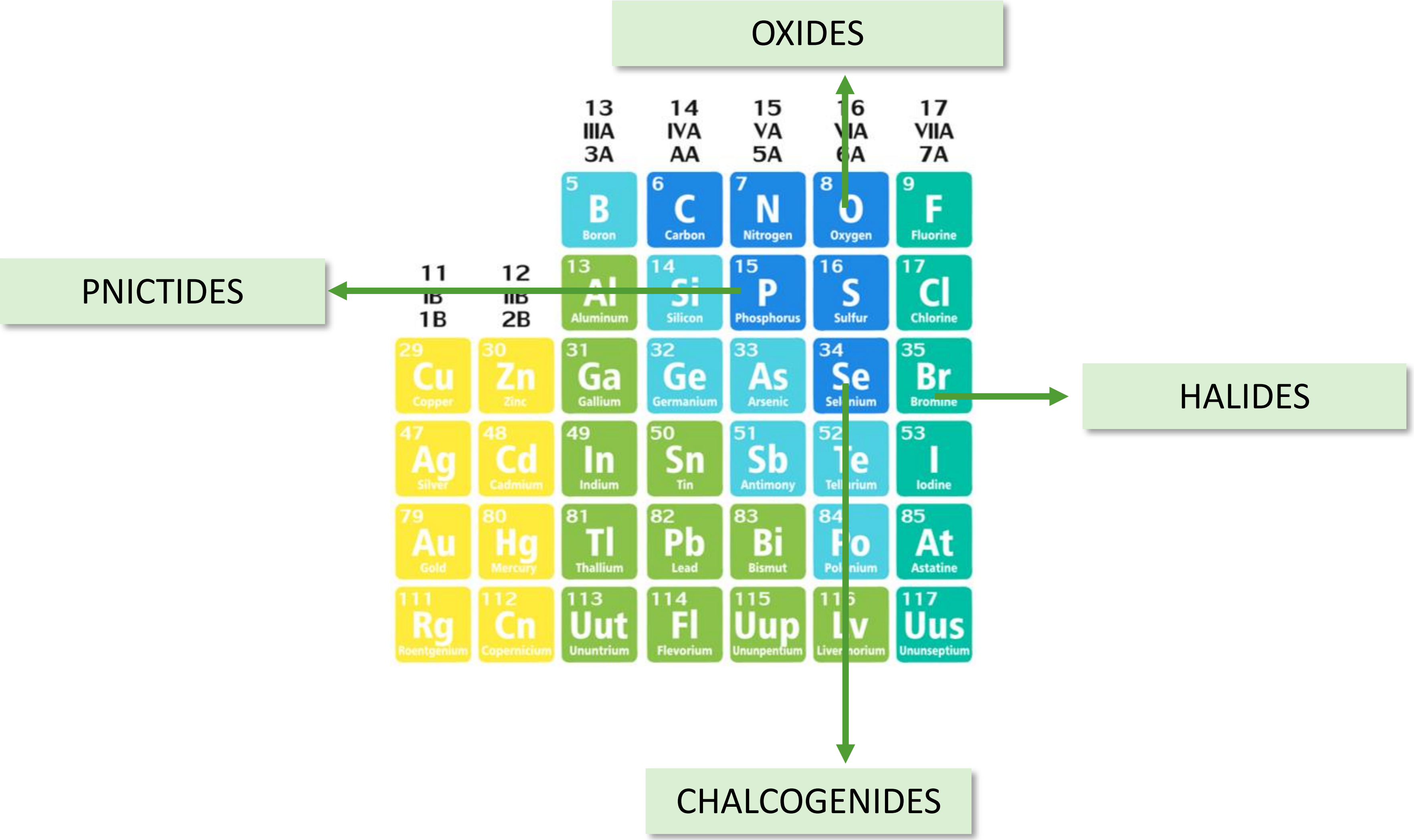
[1] Nanyang Technological University, 637553 Singapore, Singapore
[2] National Renewable Energy Laboratory, Golden, Colorado 80401, United States of America
[3] University of Liverpool, Liverpool, L69 7ZF, United Kingdom
[4] University of New South Wales, Sydney, NSW 2052, Australia
[5] Imperial College London, London SW7 2AZ, United Kingdom
[6] Yonsei University, Seoul 03722, Republic of Korea
[7] IBM Thomas J. Watson Research Center, New York 10598, United States of America
[8] Catalonia Institute for Energy Research (IREC), E-08930 Sant Adrià del Besòs- Barcelona, Spain
[9] Author to whom any correspondence should be addressed.

E-mail: lydiawong@ntu.edu.sg, andriy.zakutayev@nrel.gov, jon.major@liverpool.ac.uk, xj.hao@unsw.edu.au, a.walsh@imperial.ac.uk, tktodoro@us.ibm.com and esaucedo@irec.cat

Keywords: thin film inorganic photovoltaics, emerging photovoltaic technologies, solar energy, photovoltaic conversion efficiency tables

- Since last year a group of international scientists we are compiling the Efficiency Tables of Emerging PV Inorganic Materials in collaboration with Institute of Physics of UK (IOP)

What options do we have?



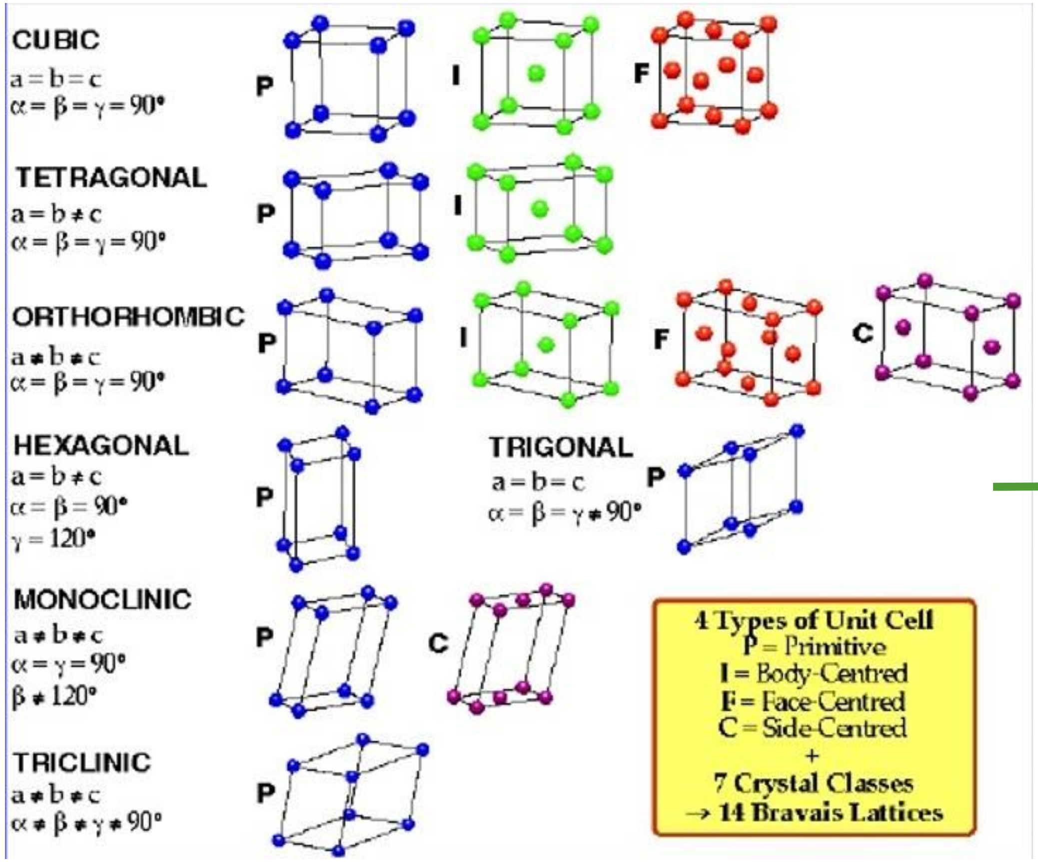
OXIDES

PNICTIDES

HALIDES

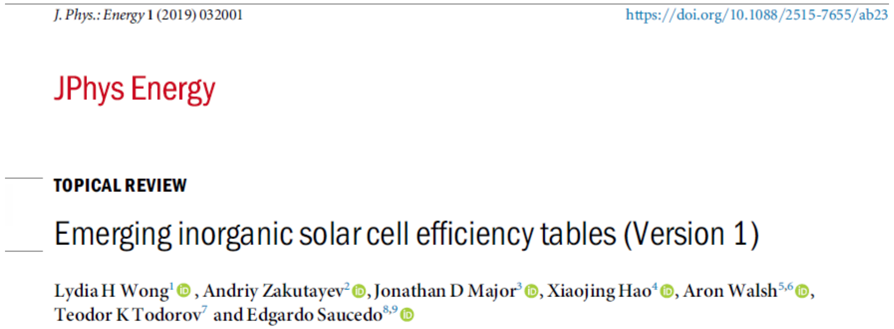
CHALCOGENIDES

Example: selection through the structure



Most of the good performing PV materials belong from Cubic or Tetragonal crystal system with tetrahedrally bonded elements

Recently, more disordered systems (orthohrombic, hexagonal, monoclinic), with non-tetrahedrally bonded elements: anisotropic materials, low dimensional materials…



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CHALCOGENIDES

- Se
- GeSe
- PbS
- Sb2Se3
- Sb2S3
- Bi2S3
- SnS
- AgBiS2
- Cu2SnS3
- CuSbS2
- CuSbSe2

- Cu2FeSnS4
- Cu2ZnGeSe4
- Ag2ZnSnSe4
- (Li,Cu)2ZnSn(S,Se)4
- Cu2(Zn,Mn)Sn(S,Se)4
- Cu2BaSnSe4
- Cu2BaSnS4
- Cu2ZnSnSe4
- Cu2ZnSnS4
- Cu2CdSnS4

OXIDES

- Cu2O
- Bi2FeCrO6

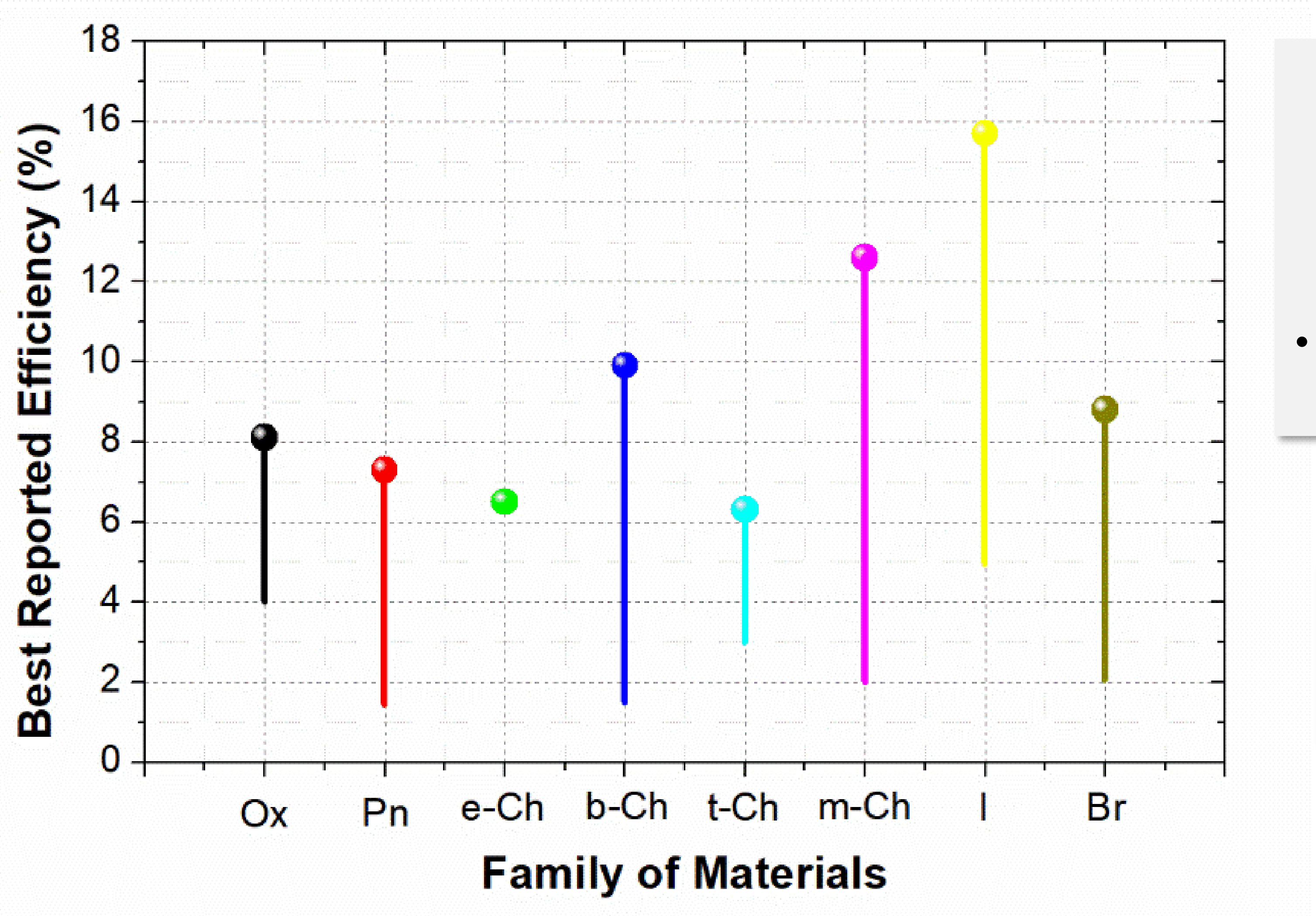
PNICTIDES

- InP
- (In,Ga)N
- (Zn,Sn)N2

HALIDES

- BiI3
- CsPbBr3
- CsPbI3
- CsSnBr3
- CsSnI3
- Cs(Sn,Ge)I3

- Few oxides and pnictides
- Some halides but increasing interest
- Several chalcogenides, from simple to multinary compounds



MOST PROMISING:

- Multinary chalcogenides not only with kesterite structure
- Perovskites mainly iodides or mixed iodides/bromides
- Binary chalcogenides, mainly anisotropic materials

NON CUBIC OR TETRAGONAL INORGANIC MATERIALS BECOMES FOR THE FIRST TIME VERY RELEVANT

SENSATE

LOW DIMENSIONAL SEMICONDUCTORS FOR OPTICALLY TUNEABLE SOLAR HARVERSTERS

H2020-ERC-CoG-2019-866018

Project Coordinator: Prof. Dr. Edgardo Saucedo (Polytechnic University of Catalonia)

Starting date: 1st June 2020 (5 years)

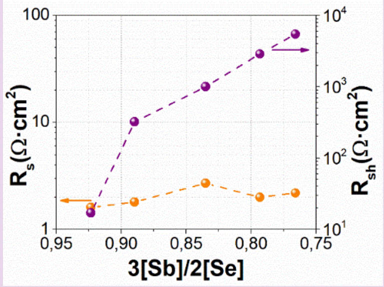
THE SENSATE INNOVATIONS

Q-1D PV Absorbers

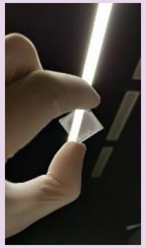
High throughput screening of (Ge,Sn,Sb,Bi):

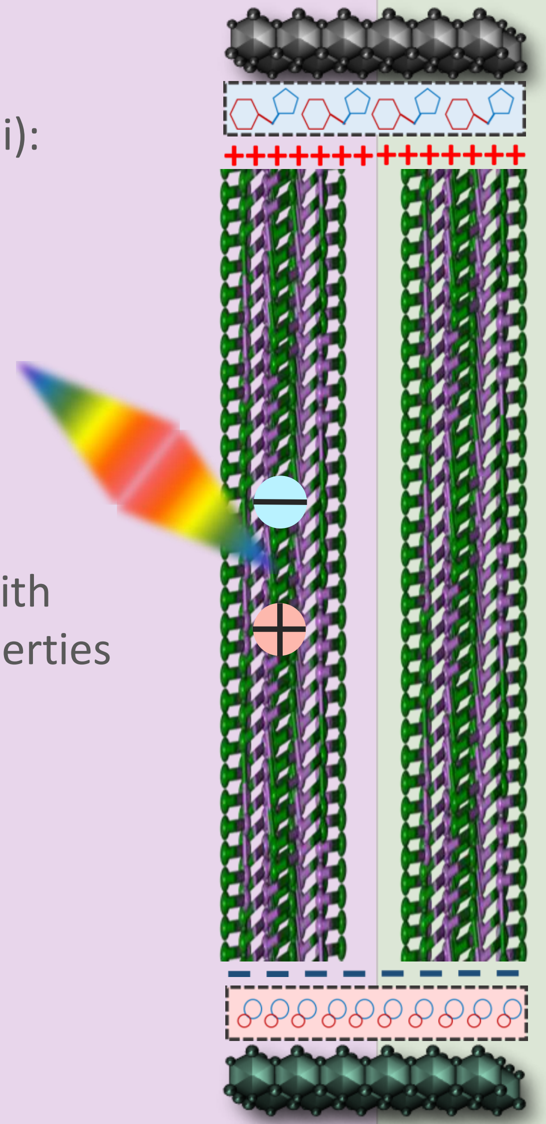
- Chalcogenides
- Halides
- Mixed chalco-halides

Best suited anisotropic **Q-1D** materials with
“A la carte” **tuneable optical/electrical** properties



Eff. = 5.9%





Selective contacts with dipoles

Bi-layer nano-scale asymmetric contact structure:

- p- and n-type transition metal oxides already developed at IREC
- Dipolar organic and inorganic molecules

Very efficient charges extraction creating **highly asymmetric polarized interfaces**

OUTLINE

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5. **Conclusions and perspectives**

CONCLUSIONS AND PERSPECTIVES

KESTERITE

- Unambiguously demonstrated **alkaline doping as a key issue** for kesterite technology. Other dopants like **Ge** becomes very relevant.
- **Ge, Li and Cd** are identified as the most **versatile** alloying elements.
- Something happens with Sn! Maybe there one of the solutions to increase the efficiency is waiting for us.

BEYOND KESTERITE

- **Oxides, Pnictides, Chalcogenides, Halides**…examples in the literature abound
- Among them, **perovskite halides** and **anisotropic chalcogenides** are at the forefront for the moment in terms of efficiency
- **We are facing the revolution of the non-cubic/non-tetragonal materials!!!???**

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UNIVERSITAT DE BARCELONA

CUSTOM-ART
DISRUPTIVE KESTERITE-BASED THIN-FILM TECHNOLOGIES

H2020-LC-SC3-2020-RES-IA-CSA-952982

SENSATE

H2020-ERC-CoG-2019-866018

To the organizing Committee:
Alex Redinger, Amit Munshi, Jiro Nishinaga,
Negar Naghavi, Romain Carron,
Rutger Schlatmann, and Sophie Spangenberger

Virtual Chalcogenide PV Conference 2020
1st vCPVC – 25th - 28th May 2020

Virtual Chalcogenide PV Conference 2020.

Thanks for your attention!