Photoluminescence and infrared spectroscopy for impurities identification in silicon for photovoltaic applications

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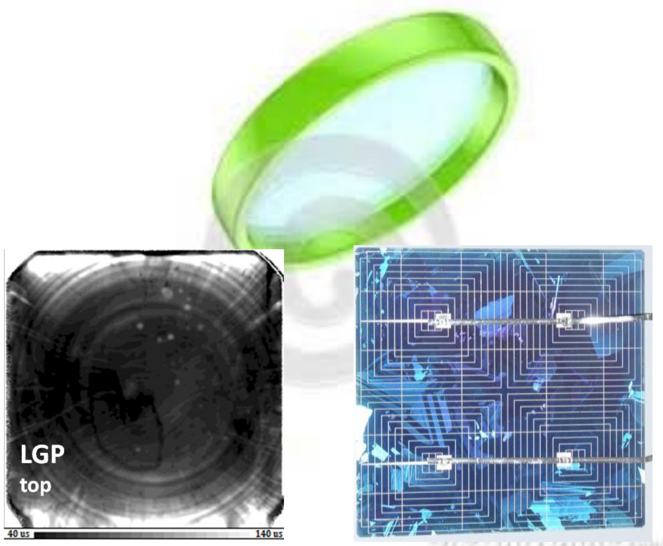
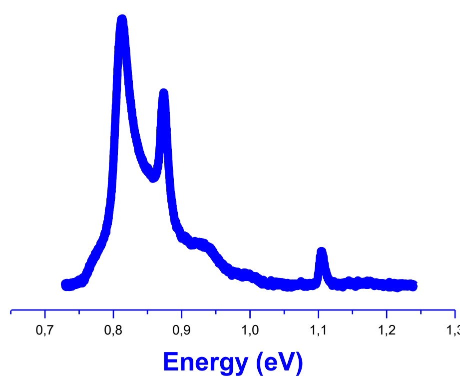
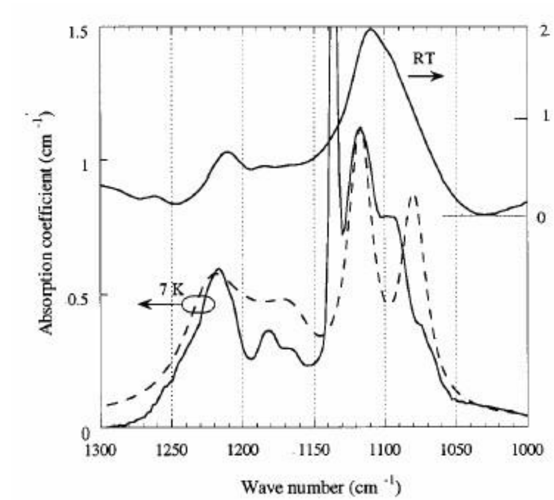




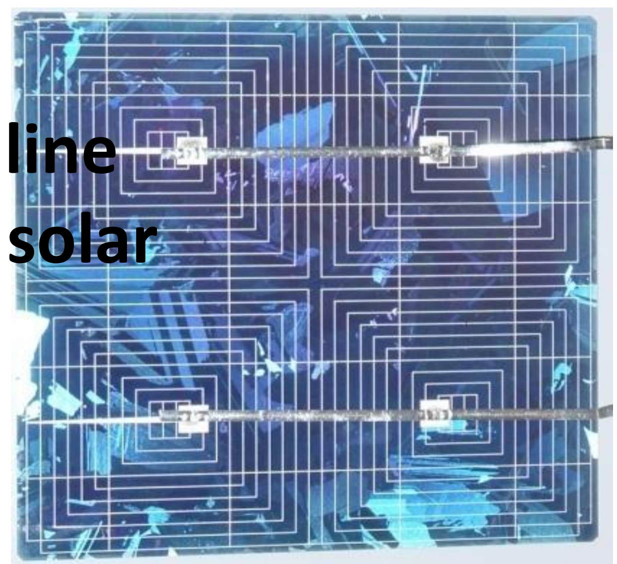


PV Facts

- The cumulative installed PV capacity exceeded 550 GW
- All major future energy scenarios forecasts a Key role of PV
- 4 600 GW of installed PV capacity by 2050 would avoid the emission of up to 4 gigatonnes (Gt) of CO_2 annually

Which technology is responsible of that ?

Crystalline silicon solar cell

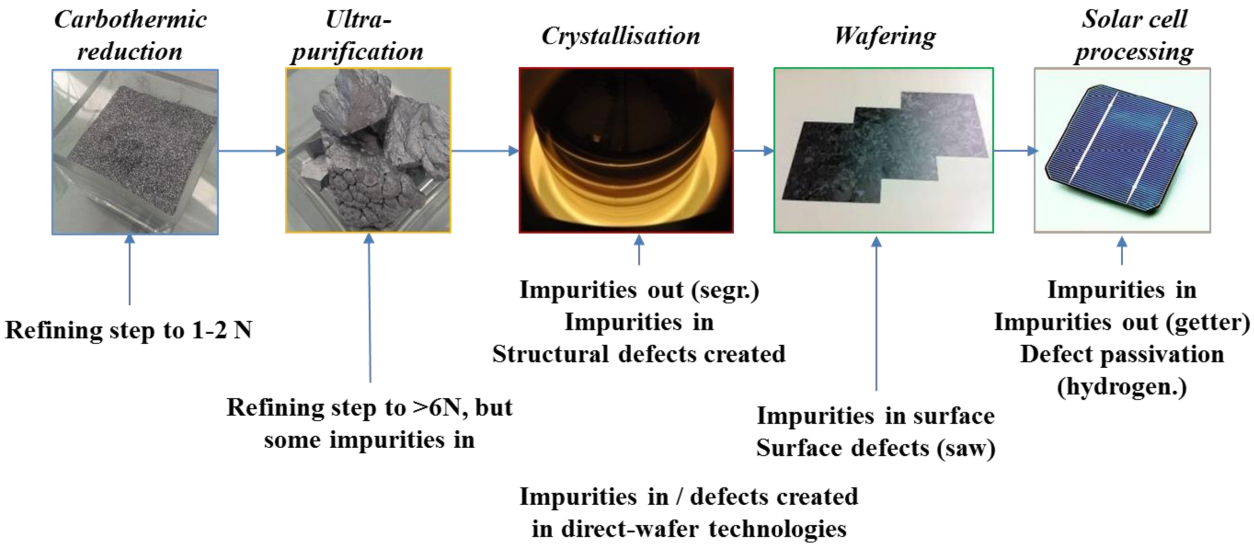


Silicon's advantages

- ✓Availability
- ✓No toxicity
- ✓Low cost
- ✓High module efficiency
- ✓Long lifetime
- ✓ Sustainability
- ✓Recycling process

Up to now Silicon has no competitors !

Silicon solar cells



Producing the right wafer is not the end of the story : *

The process involves a number of high temp steps, with the potential incorporation of contaminants, but with the opportunity to rearrange the impurities

*C.Del Canizo, S. Binetti, T. Buonassisi in *"Purity Requirements for silicon in PV application"* Chapter 1 in Solar Silicon Processes: Technologies, Challenges, and Opportunities CRC press ***(2016)***

What are we aiming for?

Efficiency is the key driver

For efficiencies >25%, the monocrystalline silicon lifetime must be high

For efficiency >20 % in multicrystalline silicon the main focus is on how to reduce the impact of impurities and defects on quality and yield

To make tandem solar cells with Si, controlling any contamination is important

The knowledge of the role of the defects must be high !

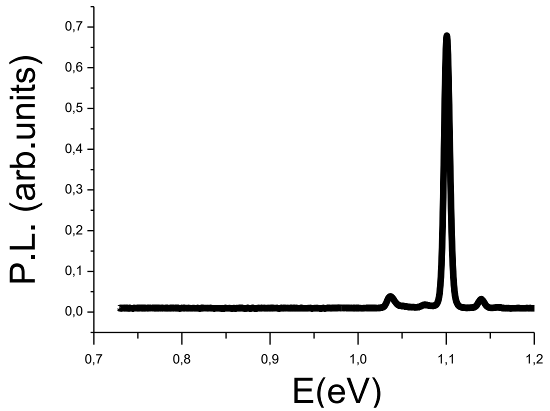
Present

✓ Controlling defects, their role and the defect engineering in PV process is still a priority !

↓

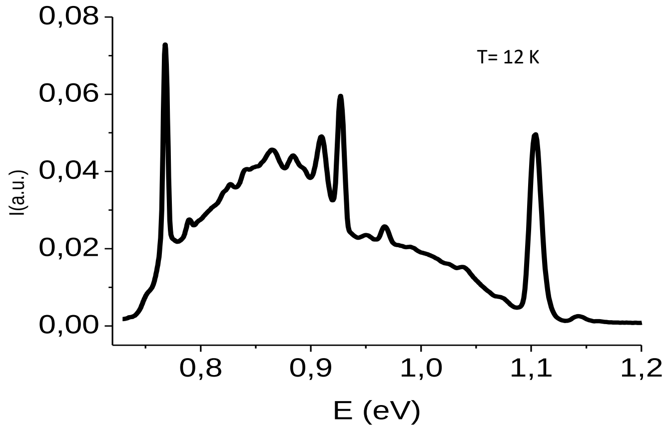
Dealing with defects and impurities in solar silicon requires:

- A deep optimization and knowledge of processes to produce silicon and cells as well
- A development of analytical procedures able to detect and quantify impurities at the level below part per billion of atoms or less
- Correlated processes to defects and the subsequent defects interaction.



Monocrystaline Si

Spectroscopical techniques

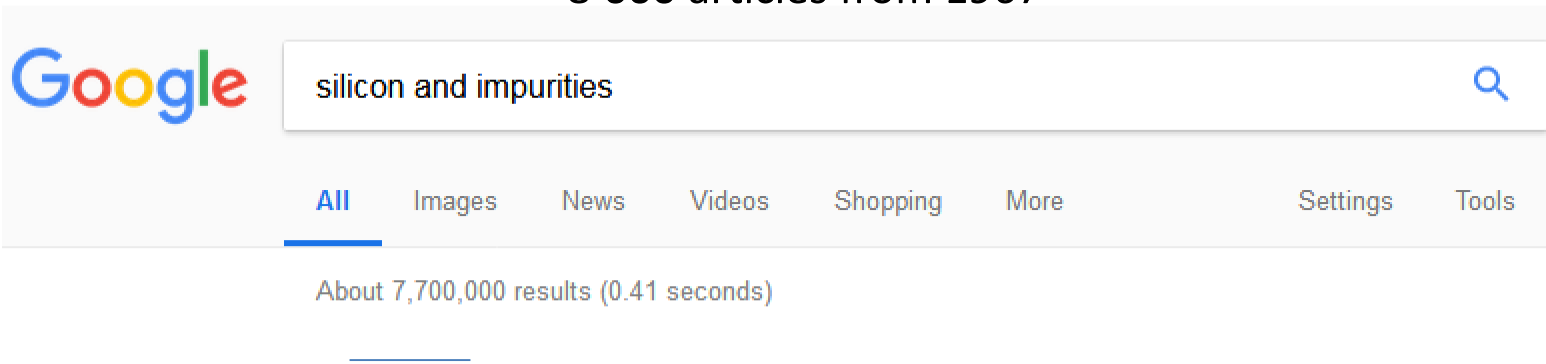


Solar grade mc Si

..an old story

silicon and impurities and photoluminescence and, infrared spectroscopy

8'**000** articles from 1967



- Most of these works are very old and concerned with fundamental physics

PHYSICAL REVIEW VOLUME 161, NUMBER 3 15 SEPTEMBER 1967

New Radiative Recombination Processes Involving Neutral Donors and Acceptors in Silicon and Germanium

P. J. Dean,* J. R. Haynes,† and W. F. Flood
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 10 April 1967)

(Received 10 April 1967)

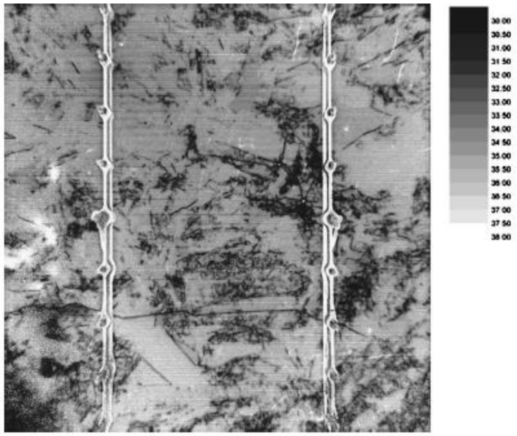
- More than 150 reported luminescence systems refer to irradiated, heat treated or contaminated silicon or concern silicon for microelectronics

Outline

- Brief description of PL and IR techniques as analytical tools
- Luminescence lines and IR peaks of the most important defects in solar silicon :
  - dopants
  - oxygen and carbon
  - dislocations

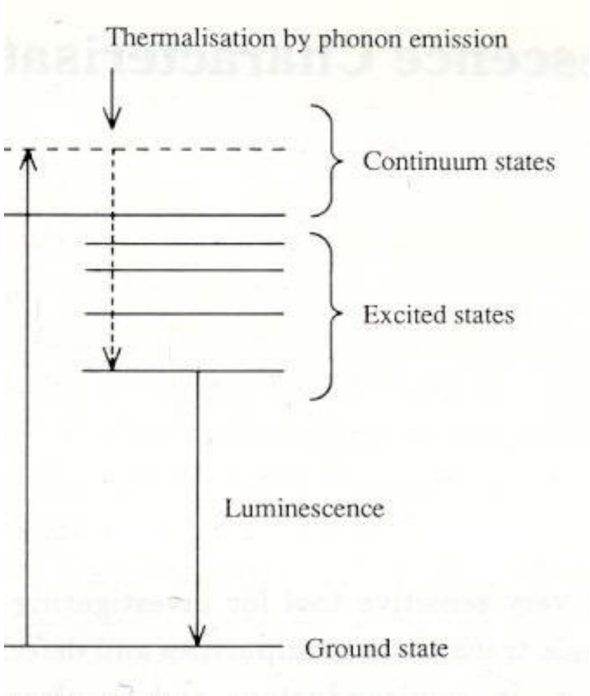
- Some examples of using PL and IR
- New approach of studying impurities and defects

Photoluminescence spectroscopy



✓ Imaging of band edge photoluminescence at room temperature is one of the most useful technique for evaluating the quality of wafers for solar cells *

✓ PL is a contactless, nondestructive method of probing electronic properties of materials



PL can be used for :

- Material quality
- Imaging or mapping
- Band gap determination
- **Impurity levels and defect detection**

* T. Trupke, R.A. Bardos, M. C. Schubert, W. Warta, Appl. Phys. Lett., 044107, (2006)
M. Bernhard, G., Johannes W. Warta, Wilhelm; IEEE JOURNAL OF PHOTOVOLTAICS, 2, 348 (2012)
Giesecke, J. A.; Niewelt, T.; Ruediger, M.; et al and Warta W. SOLMAT 102, 220-224 (2012)
Giesecke, J. A. M. Kasemann and W. Warta JAP 106. 014907 (2009)

Laser excitation hν> Eg

↓

Electron –hole pairs

↓

Free excitons (FE)

FE luminescence
Phonon assisted

12 K < T< 77 K

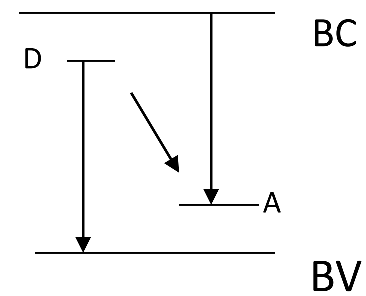
Capture by shallow donors and acceptors

Impurity specific
BE luminescence
No phonon or phonon assisted

4.2 K<T< 12 K

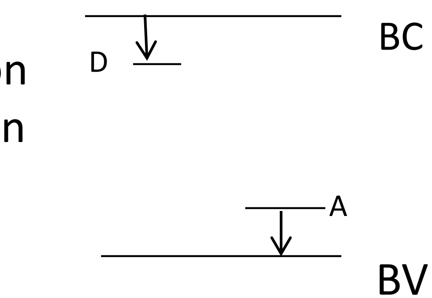
Radiative transition
Between a band an impurity states:
Deep transitions

T range 4.2 K –300 K



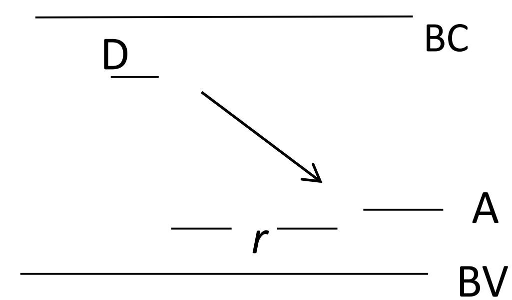
Radiative transition
Between a band an impurity states:
Shallow transition

T< 12 K



Donor – Acceptor Transitions

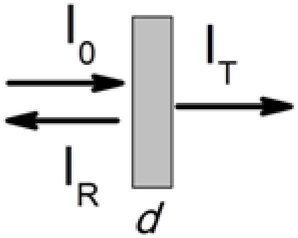
T range 4.2 K –77 K



Infrared spectroscopy

✓IR spectroscopy is among the most widely used optical techniques for the study of impurities, thanks to its characteristics :

- good sensitivity
- quantitative results about the species detected
- easy to use
- non destructive

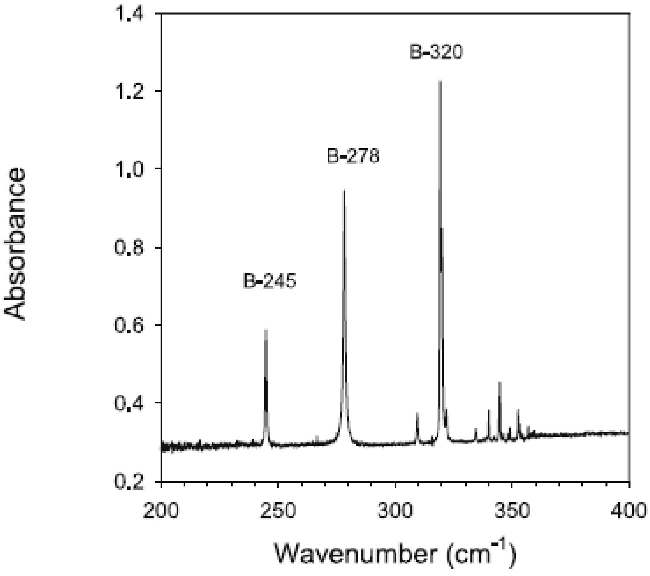


$$\nu = \frac{1}{2\pi}\sqrt{\frac{k}{\mu}}$$

- The intensity is related to the number of bonds (or atoms) of the specific type absorbing the IR light and, as such, can be used to quantify those impurities

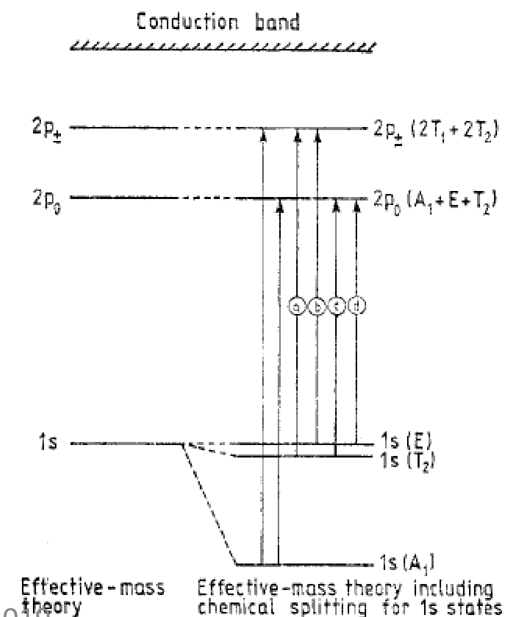
Dopant by FTIR

- At low temperatures (T<15K) the doped silicon IR spectrum exhibits a series of intense absorption bands due to **electron** (or hole) transitions from the ground state of neutral impurities to a series of hydrogenic-like levels lying close to their respective band edge.



Boron

Line (cm-1)	Transition
245.2	$1S_{(3/2)}$ $2P_{3/2}$
278.5	$1S_{(3/2)}$ $2P_{5/2}$
309.3	$1S_{(3/2)}$ $3P_{3/2}$
320.4	$1S_{(3/2)}$ $3P_{5/2}$



- *J.J. White, Can J. Phys. 45 2797 (1967)*
- *A. Baldereschi, N.O.Lipari Physical Review B 9, (1974) 1525,*
- *A. K. Ramdas, S. Rodriguez Rep. Prog. Phys. (1981) 44, 1297*

Strongest Absorption band and calibration factor for shallow impurities

Impurity	**Band (cm^{-1})**	**Calibration factor (f)**
Aluminium	473.2	32.7
Antimony	293.6	10.4
Arsenic	382.0	8.5
Boron	319.6	9
Gallium	548.0	42.4
Indium	1175.9	244.4
Phosphorus	316.0	4.99

ASTM F1630-95

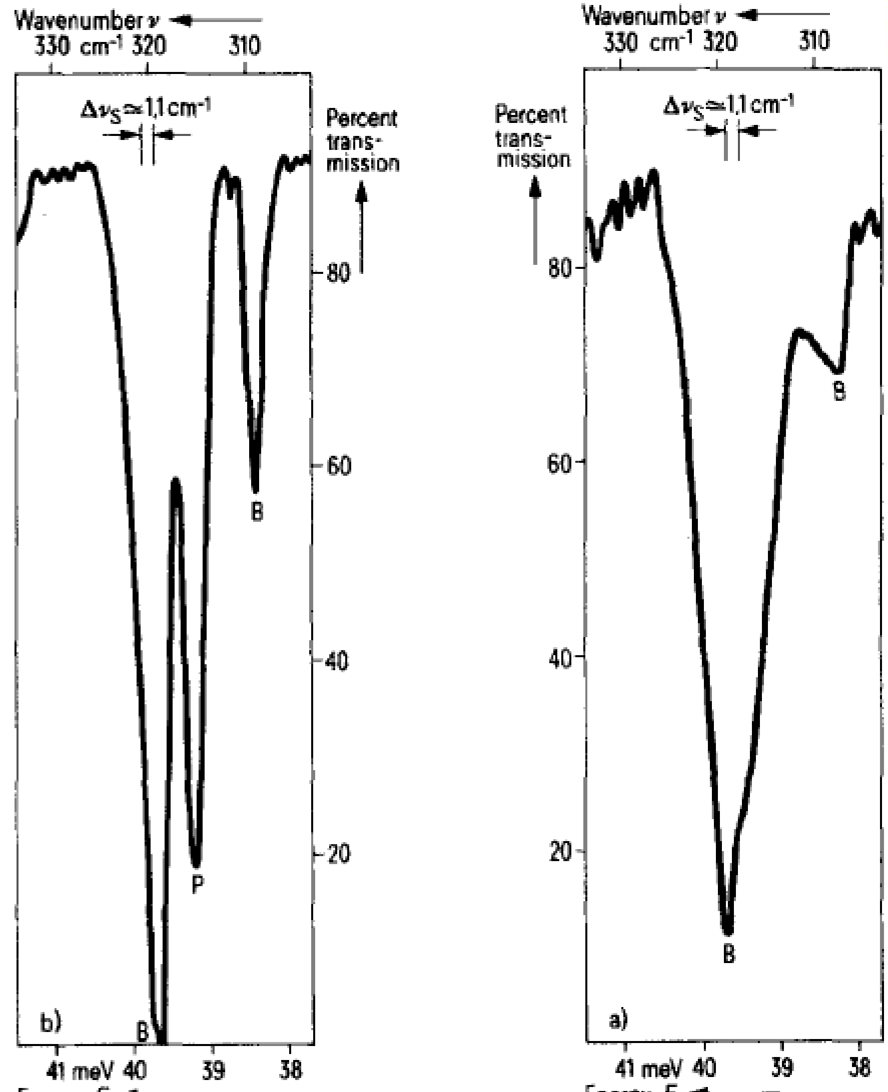
$$[impurity] = \frac{A}{x} 5.10^{13} f$$

The determination limits for B and P for 10 mm thick samples are:
$5x10^{11}$ atoms/cm^3 (0,01 ppba) - 10^{16} at/cm^3 (5.0 ppba)

Dopant determination in compensated mc -Si

For compensated samples:
illuminating the sample
with white light to allow neutralization

- Effect of strain (low thickness)
- Effect of concentration
- Effect of simultaneous presences of dopants



Broadening of the peak

Broadening increases with compensation ratio

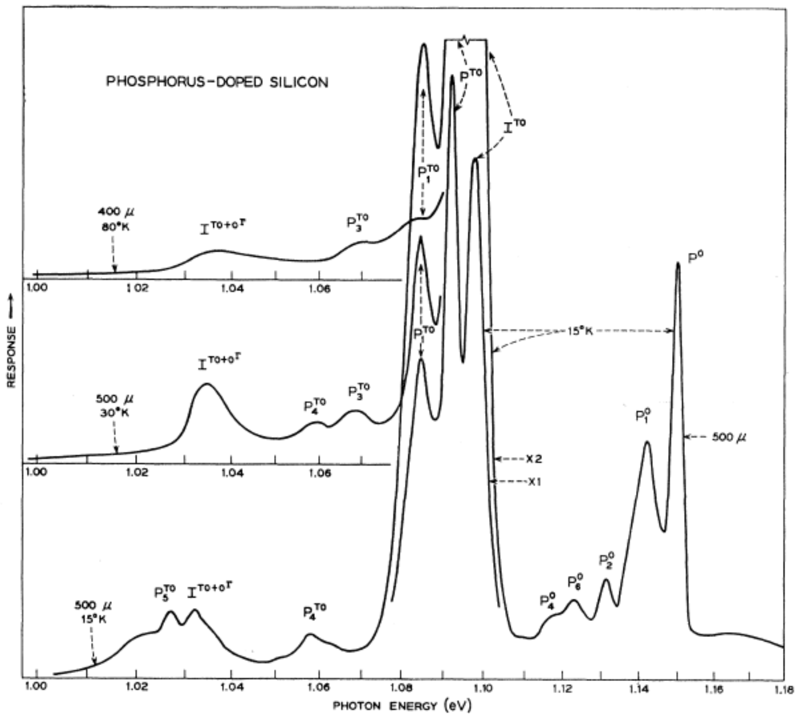
B. Pajot J. Phys chem solids (1964), 25 613

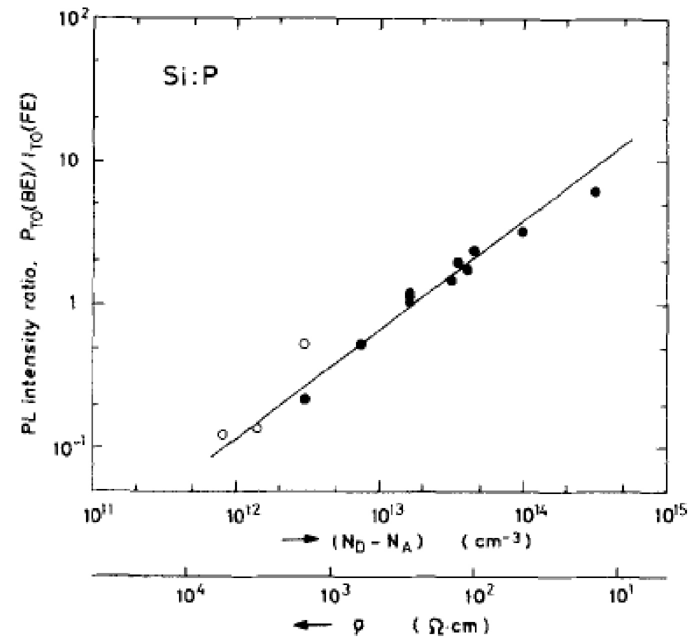
It can not be directly applied to standard mc-Si due to low thickness

Dopant determination by Low T PL

Bound excitons to dopants (As, P, Sb,Bi, Ga,In, Al)

P. J. Dean et Phys. Rev. **161,** 711–729 (1967)



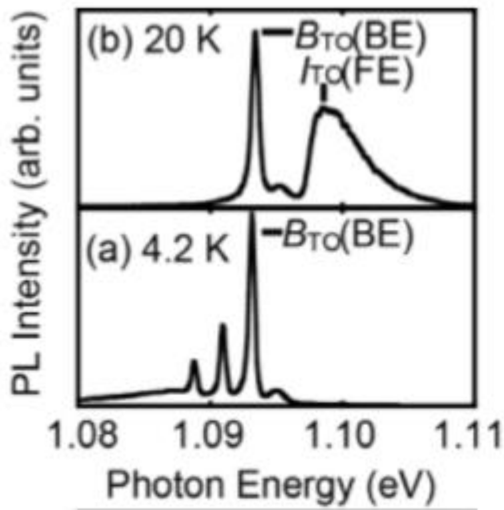


- *M. Tajima Appl. Phys. Lett., 32 719 (1978)*
- *SEMI MF 1389-0704 (2004).*

- A calibration for B, P, Al, As in silicon has been developed based on the ratio between Area of BE peak/ area of FE peak @T=4.2 K

Upper limit of 10^{15} at/cm^3

- Advantages:
  - Simultaneous determination of B and P
- Disadvantages :
  - not applicable to concentrations higher than 10^{15}at/cm^3 because the FE lines was almost undetectable.

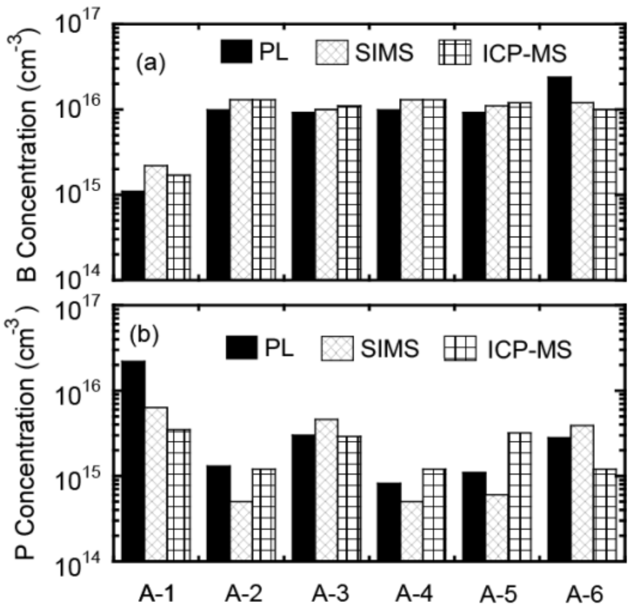


[B], [P]: 10^{14} and 1 x 10^{17} cm^{-3}
in (SOG-Si) by FE-line shape at 20 K

$$\left[B_{TO}(BE) / I_{TO}(FE)\right] = 9.42x10^{-17} \times n_B^{0.896} \times e^{\left(\frac{71.1}{T}\right)}$$

and

$$\left[P_{TO}(BE) / I_{TO}(FE)\right] = 1.48x10^{-16} \times n_P^{0.837} \times e^{\left(\frac{77.2}{T}\right)} .$$



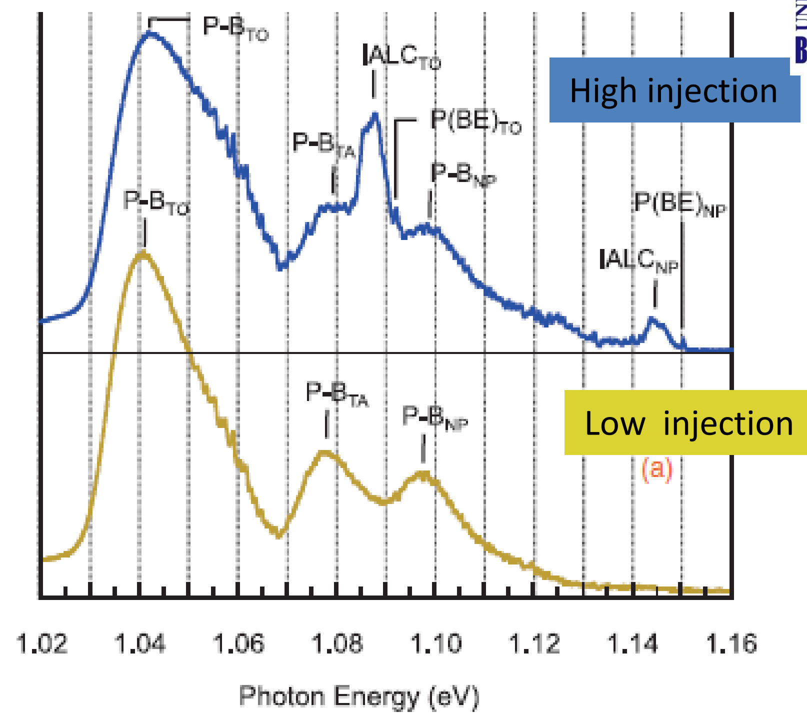
T. Iwai et al. Phys. Status Solidi C 8, No. 3, 792–795 (2011)

Donor – Acceptor transition (DAP) in Silicon

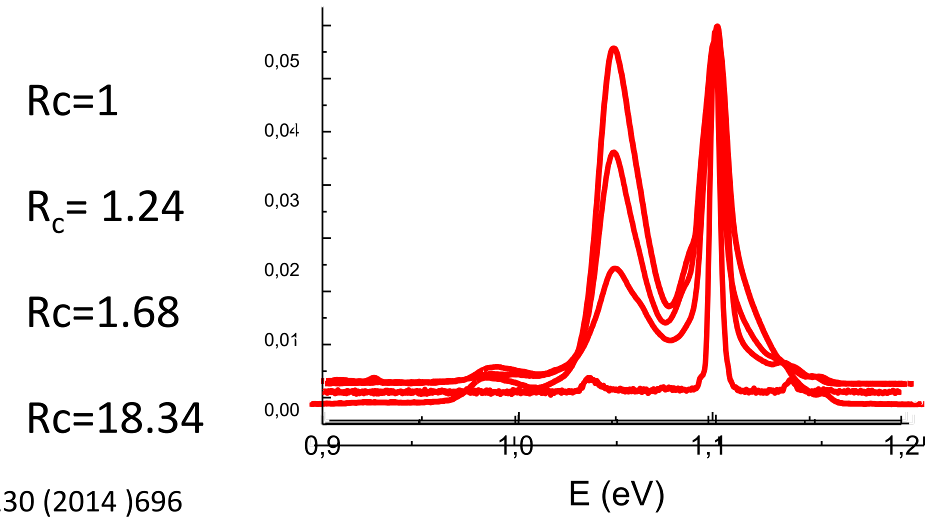
- In B-P compensated samples three bands appeared at 1.098, 1.079, and 1.041 eV

M. Tajima, , T. Iwai, H. Toyota, S. Binetti, and D. Macdonald J. Appl. Phys. 110, 043506 (2011) ;
M. Tajima, T. Iwai, H. Toyota, S. Binetti, and D. Macdonald, Appl. Phys. Express 3, 071301 (2010)

R.C. Enck, A. Honig The Physical Review 177 , 1182 (1969)



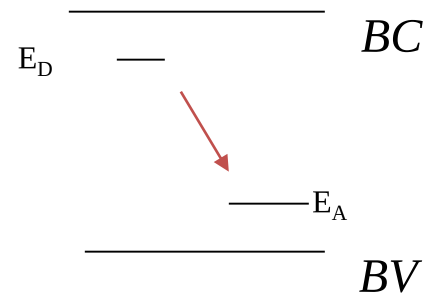
- In solar grade silicon DAP band increases with compensation @T= 12 K



S. Binetti et al. Solar Energy Materials & SolarCells, 130 (2014)696

Fine Structure of DAP in Silicon

$$h\nu = E_G - (E_D + E_A) + \frac{e^2}{4\pi\varepsilon_0\varepsilon_r r} - \frac{a}{r^6} \qquad \text{eq.1}$$



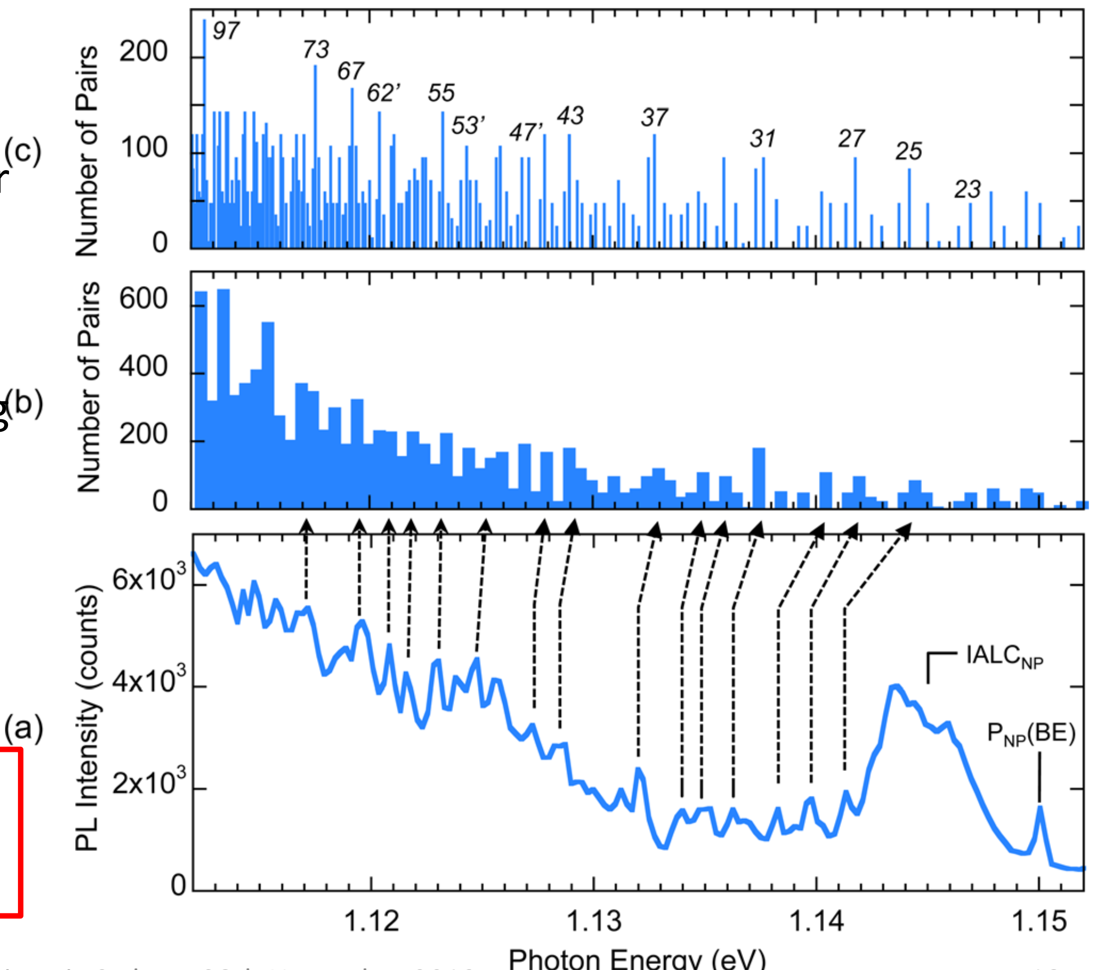
- E_D, E_A dopant ionization energy ,
- *r* is the DA pair separation.
- *a* is a constant for a given DA pair related to the Van der Waals interaction

E_D and E_A can be obtained by a comparison between the theoretical spectrum of donor-acceptor (DA) pair luminescence (eq.1) and the observed fine spectral structure

- In our work a close agreement using the generally accepted P and B ionization energies was obtained

↓

No formation of P- B complexes



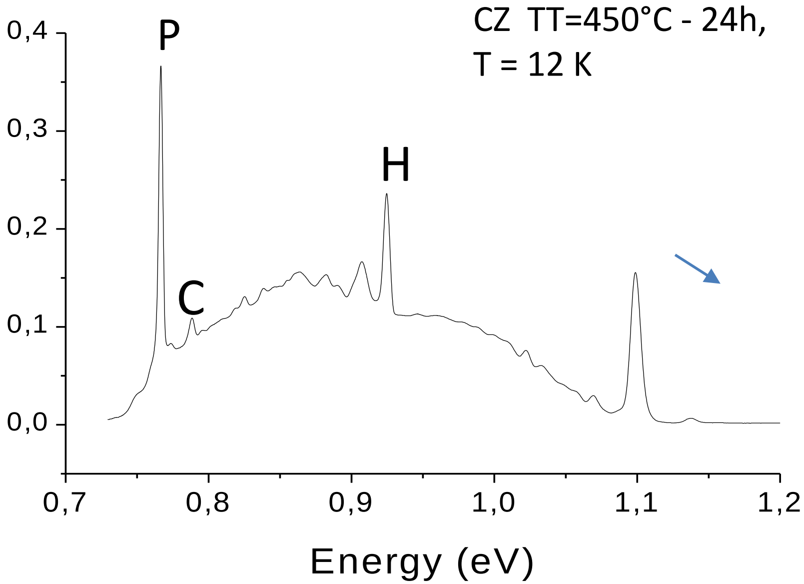
M.Tajima, T. Iwai, H.Toyota, S. Binetti, D. Macdonald J. Appl. Phys. 110, 043506 (2011)

•Carbon in Infrared spectrum: 605 cm^{-1}

ASTM F1391-93

•Carbon related complexes detected by PL

- G line 0.969 eV (C_i-C_s)
- C line* @ 0.789 eV (C_i-O_i) dominant in radiation damage Si associated to IR C(3) defect at 865 cm^{-1}
- H line @ 0.926 eV ;



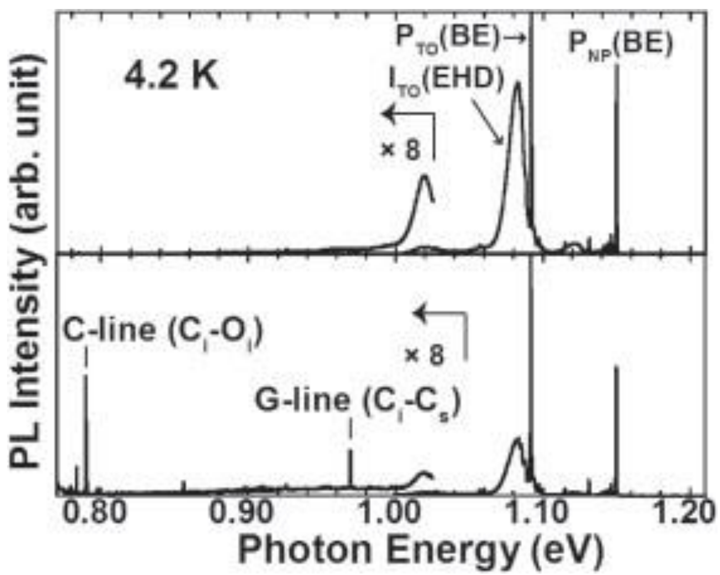
[O] = 24 ppma , [C]= 1 ppma .

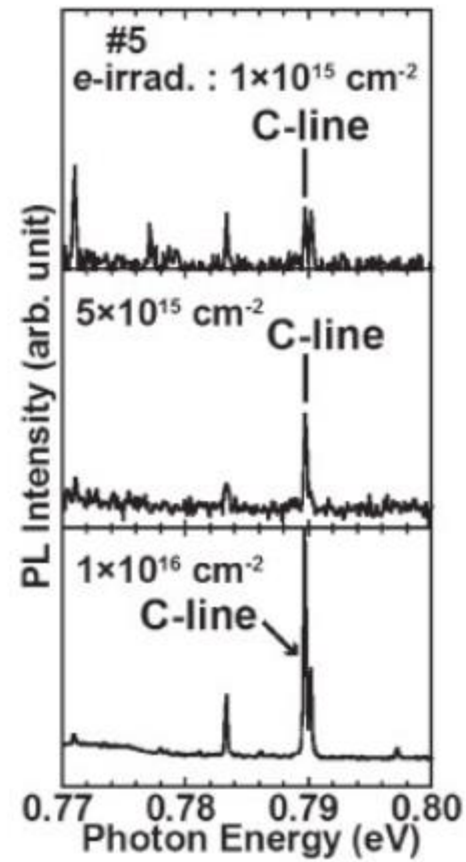
•formation of (C-O)n complex in any codoped C and O silicon samples submitted to heat treatment

•SiC (and SiOx) nanoprecitates: broad band is probably due to strain

Determination of Low Carbon Concentration in CZ-Si

By Luminescence activation method





A correlation was found between the relative intensity of the C-line and [Cs]

Detection limit ≈ $5 10^{12}$at/cm^3

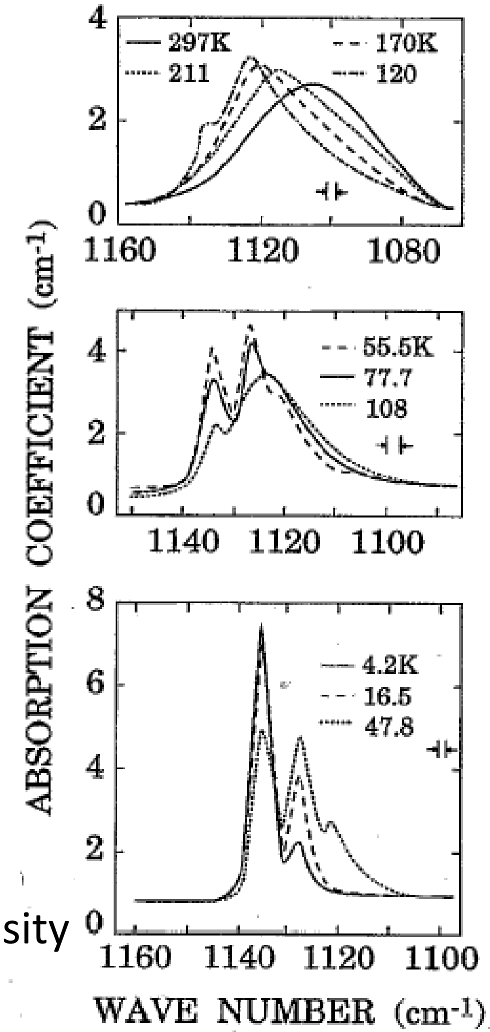
The samples were irradiated with 2 MeV electrons

H. Kiuchi et al. Japanese Journal of Applied Physics 56, 070305 (2017)
M. Tajima et al Appl.Phys Express 10, 046602 (2017)
M.Tajima et al. Appl.Phys Express 11, 041301 (2018)

Oxygen and Infrared spectra

Routine measurement for [Oi] IR @ 300 K (ASTM 1188-93a)

O_i IR band



Conversion factors for the determination of interstitial oxygen concentration from IR-absorption measurements at different T

Band position (cm^{-1})	χ (10^{17} atoms/cm^2)	T (K)
1107	3.14±0.09	300
1127.5	1.1±0.1	77
1136.4	$0.14\pm0.02\Delta\omega_{obs}$	8
1136	0.169[a]	4
515	1	300

T<77 K
O_i band strongly increases in intensity

Low T IR for quantitative analysis in low [Oi] and very thin samples (up to 3x 10^{14}at/cm^3)

•A. Borghesi, et al. B. Pivac, A. Sassella, A. Stella, J. Appl. Phys 77 (1995) 4169 and its more than 400 references

S. Binetti et al. Solar Energy Materials & SolarCells, 130 (2014)696

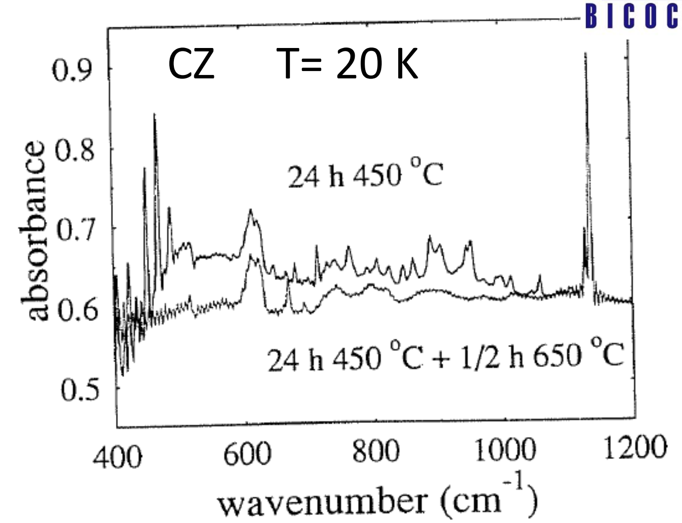
Early stage of Oxygen precipitation: Thermal donors

by IR

- Thermal donors : IR absorption lines associated to electronic transitions from the ground state into excited states from 300 to 900 cm^{-1}

W. Götz et al. Physical Review B 1992; 46: 4312–4315
H.J. Stein et al J. Appl. Phys 1986 , 59 3495

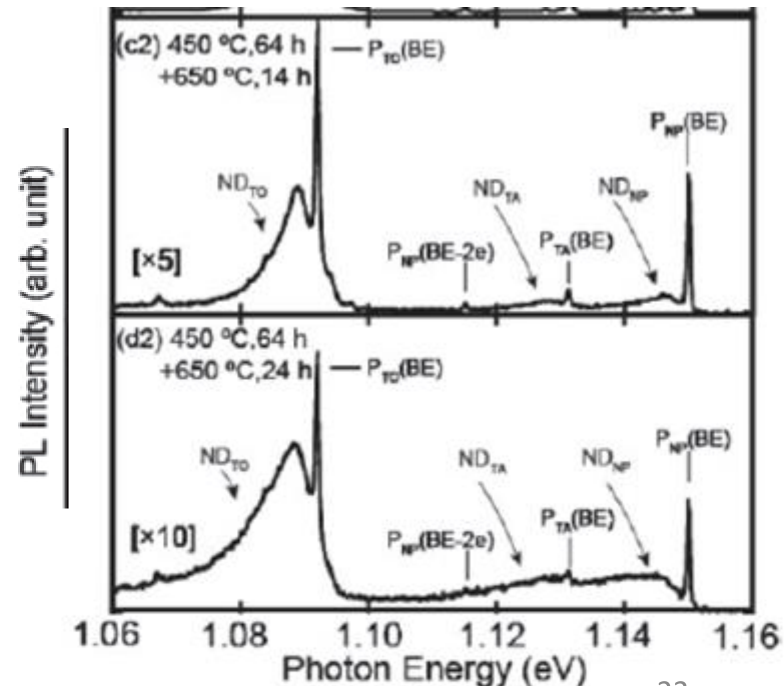
Oi> 5 ppma



S. Binetti et al Science and Technology 1995; 11: 665

by PL

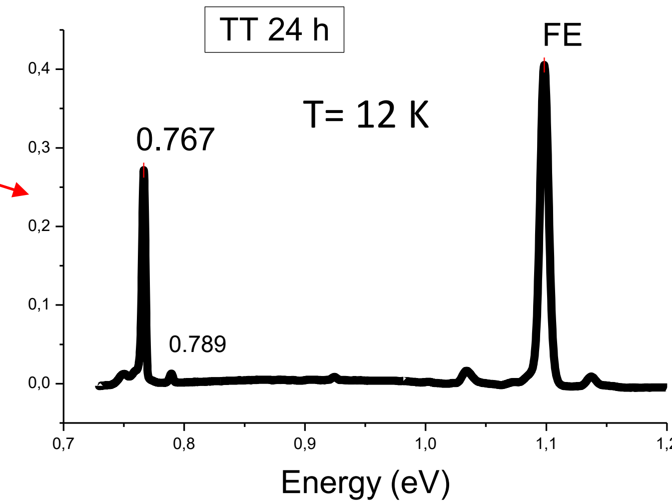
- No luminescence lines are associated to Oi
- TDs can be detected with BE excitons line



F. Higuchi et al. Jpn. J. Appl. Phys. 56, 070308 (2017)

Early stage of Oxygen precipitation by PL

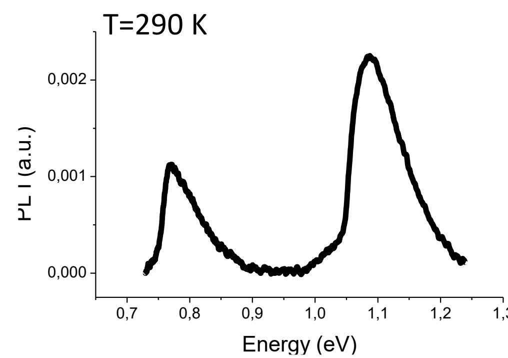
Silicon heated at 450 °C exhibits a strong line at 0,767 eV (P- line)



P line is due to a transition from a TD level (NL8) to a deep center (E_v+0.37 eV) identified by DLTS

S. Binetti et al Solar Energy Materials & SolarCells 130 (2014) 696–703

M. Acciarri , S. Pizzini, S. Binetti et al. J.Phys. Condensed Matter, 14 13223, (2002)



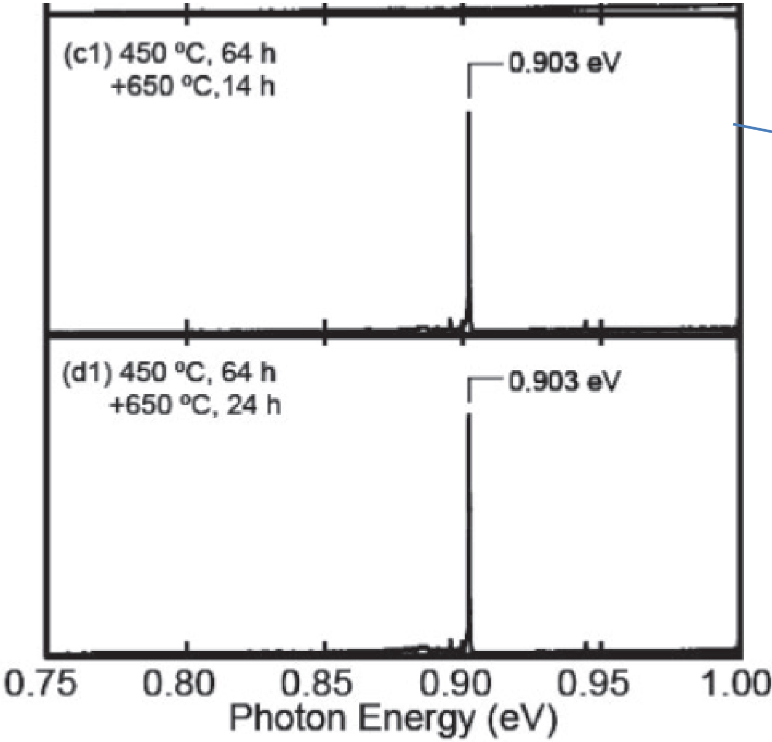
•visible at room temperature :
can be used a " diagnostic" line.

•Fingerprint of ingot thermal history:

Based on the PL intensity of P line at room temperature it was found that the effect of the thermal history of a crystal pulled at 0.8 mm/min was equivalent to an annealing at 500°C for 3 h *

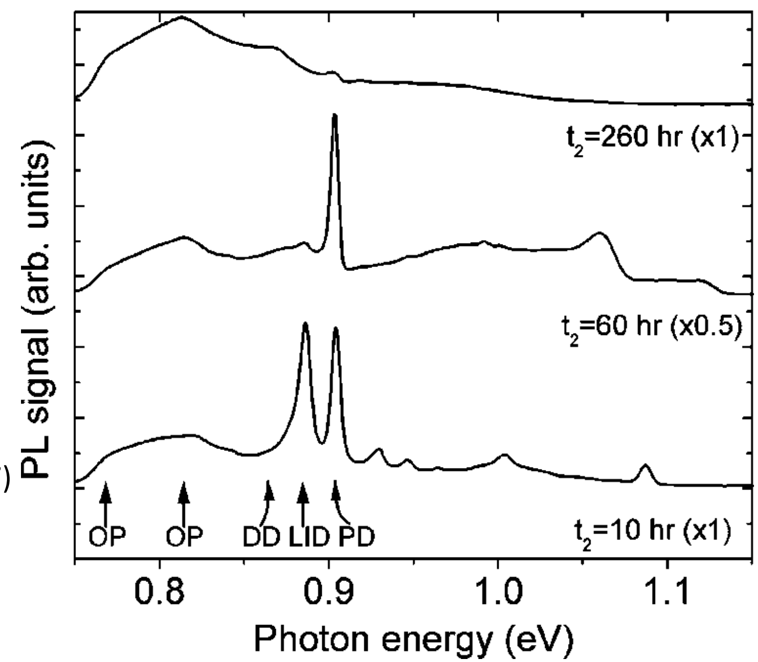
*M. Hamada et al. Jpn. J. Appl. Phys., 35 (1996), 182

Early stage of Oxygen precipitation by PL



F. Higuchi, M. Tajima, et al. Jpn Journal of Applied Physics 56, 070308 (2017)

The 0.903 eV line to be due to the {311} defects formed by the aggregation of Si self-interstitials emitted by oxygen precipitates.



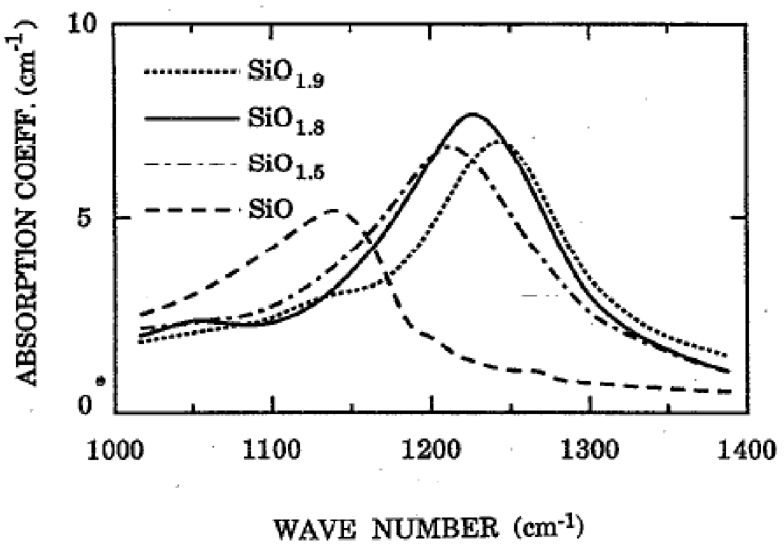
T. Mchedlidze , S. Binetti et al JOURNAL OF APPLIED PHYSICS **98,** 043507 (2005)

Oxygen precipitates

by IR

- Oxygen precipitates : absorption bands are detected from 1000 -1300 cm-1

ν_{exp} (cm^{-1})	ν_{sim} (cm^{-1})	m	f	% Total	Shape
1085, 1095, 1116	1079, 1117	3.5	10×10^{-6}	76	Sphere
1170, 1183 1217	1175 (broad), 1219	25	3.2×10^{-6}	24	Platelet

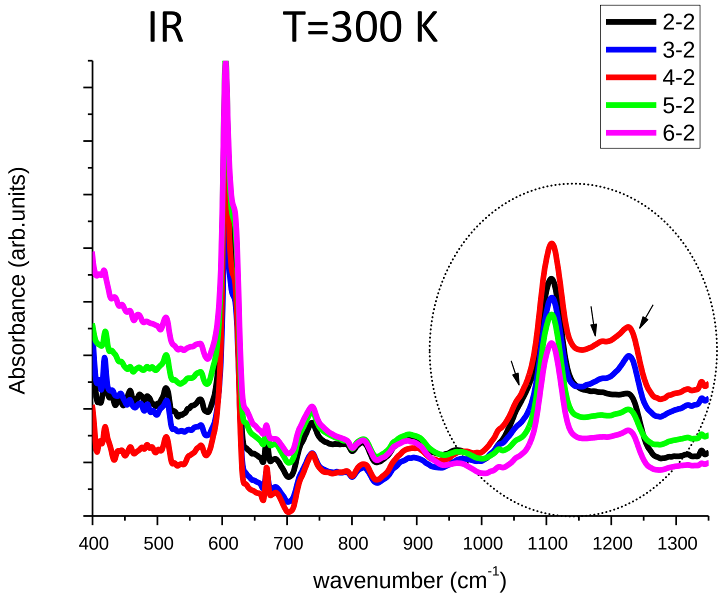


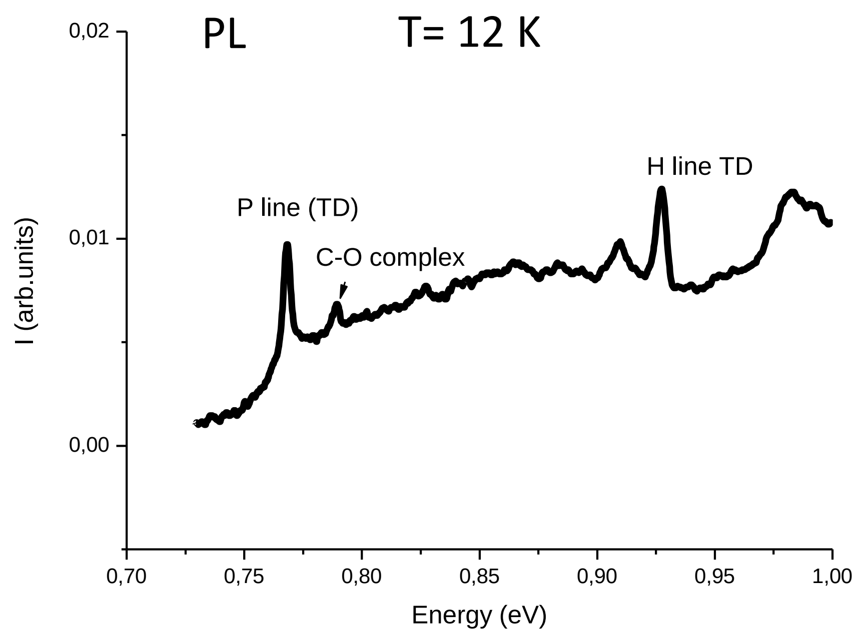
A correlation among the spectral position and line shape and the precipitate type has been obtained

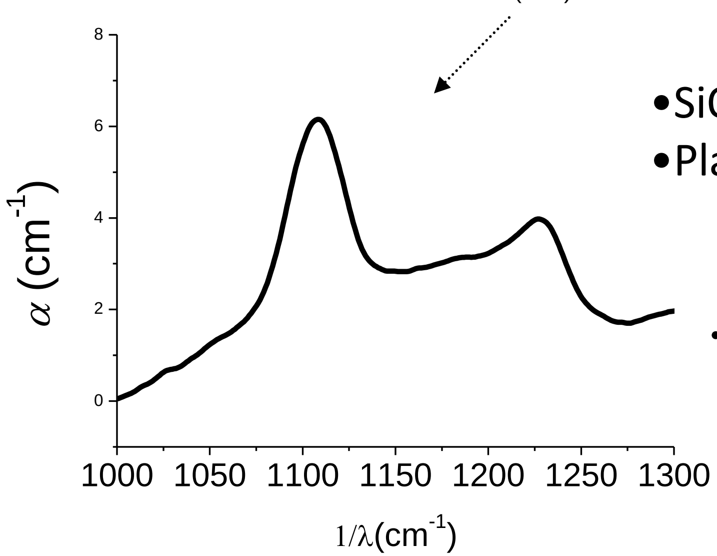
A. Borghesi et al and 450 references bythere
A. Sassella et al. App. Phys. Lett 75, 1131 (1999)

S. Binetti et al Solar Energy Materials & Solar Cells 130 (2014) 696–703

Example: INFRARED AND PHOTOLUMINESCE SPECTRA of solar grade silicon







- SiOx precipitates
- Platelet precipitates

Thermal donors
C-O complexes

- *S*. Binetti, et al. Materials Science and Engineering B **159–160** (2009) 274

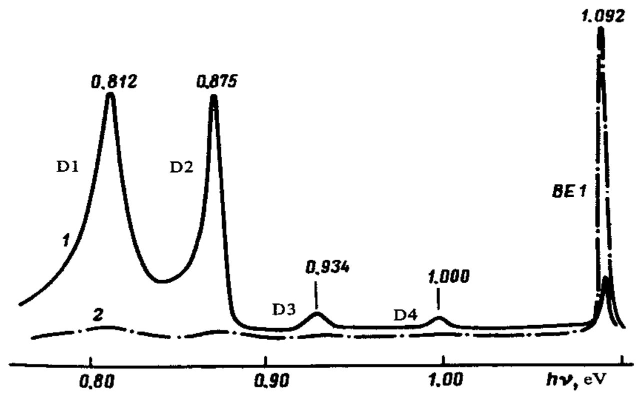
[O] = 23-27 ppma
[C]= 4-10 ppma

Oxygen precipitates by PL

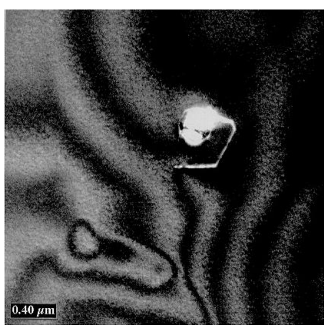
Problem:

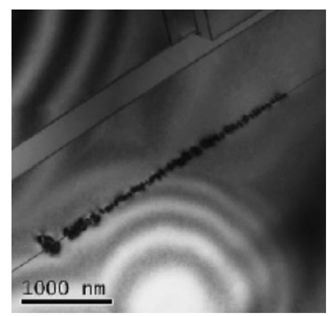
Precipitates → Self interstitials → Dislocations

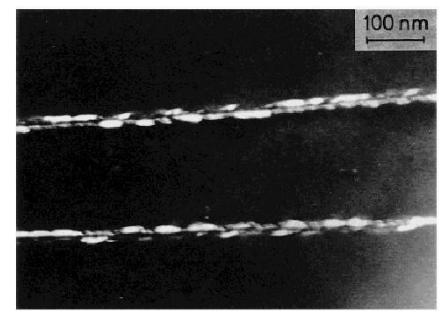
Dislocations → Precipitates



D-line







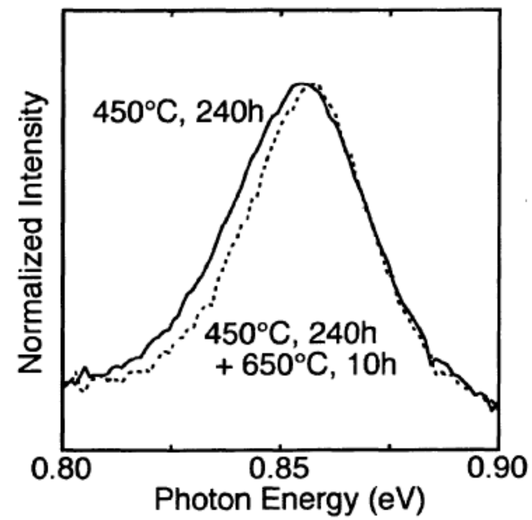
S. Pizzini , et al. J. Phys: Condens. Matter 12 (2000) 10131

S. Binetti et al. Materials Science & Engineering B **159,** (2009) 274

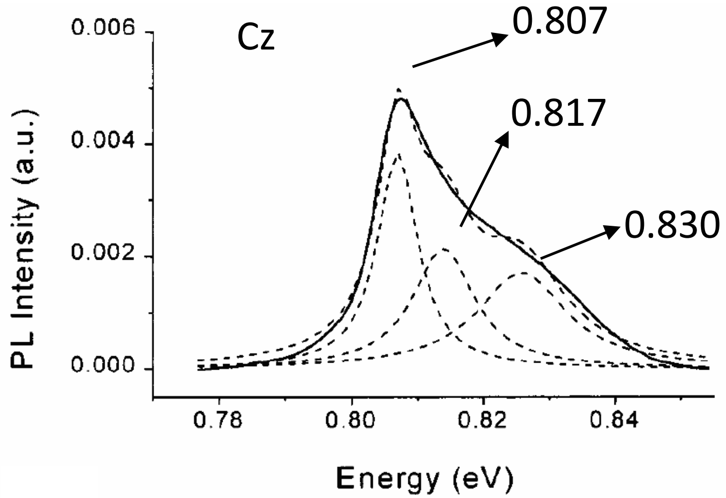
Sumino et al. Phys. Stat. Sol. (a) 171 , 111 (1999)

Oxygen precipitates by PL

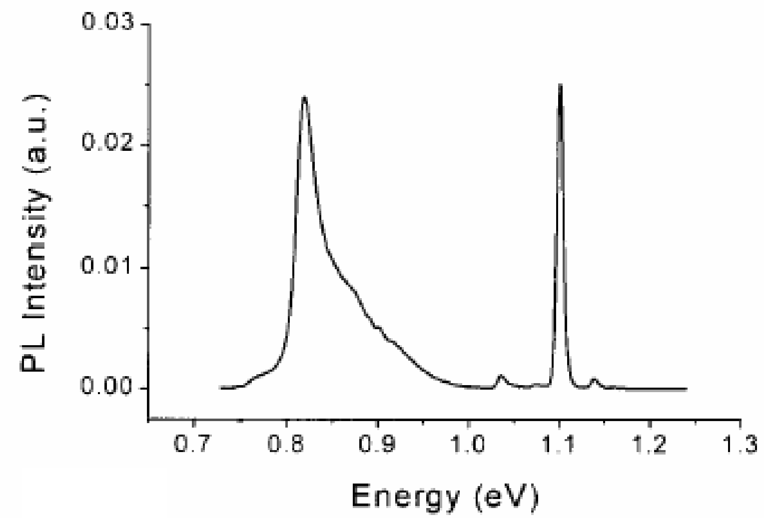
Tajama et al. was the first to assign a luminescence line to oxygen precipitates at around 0.820 eV from 77 K to 150 and at 0.768 eV at 300 K



M. Tajima, et al. Mater. Sci. Forum, Vol. 83-87, 1327 (1995)



- 0.807 eV Dislocation
- 0.817 eV SiOx precipitates
- 0.830 eV nuclei
- 0.920 eV nuclei



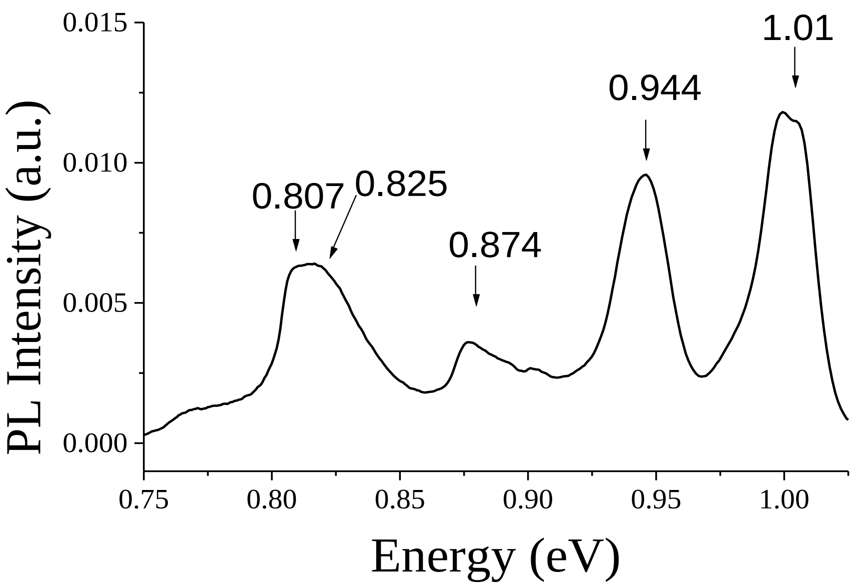
S. Binetti et al. J. Appl. Phys. 92, 2437 (2002)
E. Leoni, S. Binetti, et al, Eur. Phys. J.: Appl. Phys. 27, 123 (2004)
D. Cavalcoli, A. Cavallini, S.Pizzini, S.Binetti App. Phys. Lett. 86, 162109, (2005)

L.I. Fedina et al JAP , 124, 053106 (2018)

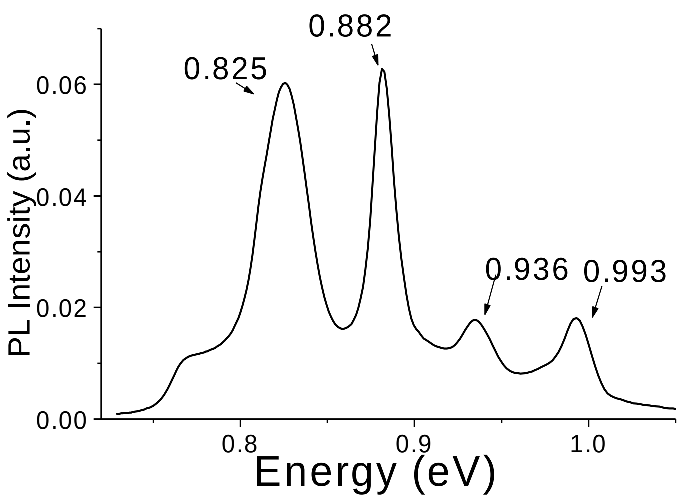
Dislocation: Effect of nitrogen doping and annealing

S.Binetti, et al. J.Phys.Condensed Matter, 14 13247 (2002)
S.Binetti, et al. Microelectronic Engineering 66(1-4) 297 (2003)

Nitrogen free

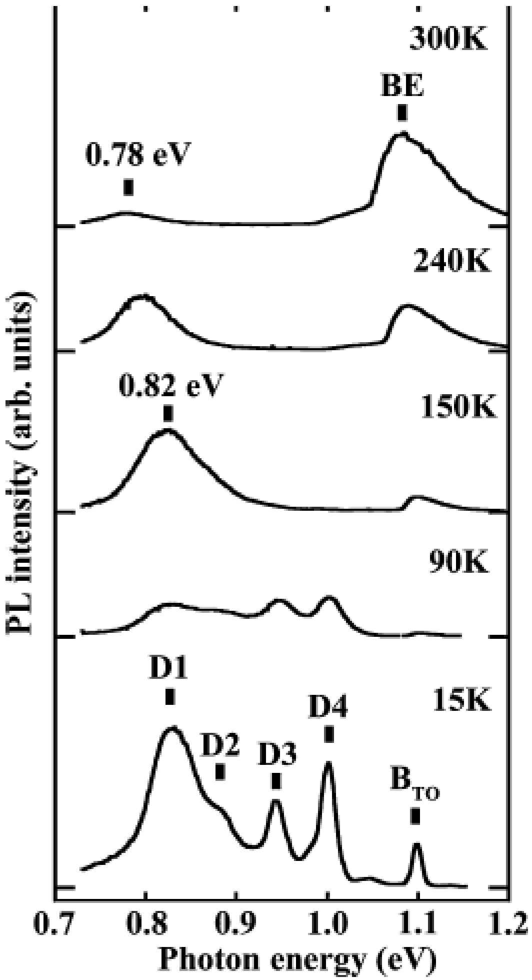


Nitrogen doped [N]= 10^{15} at/cm^3

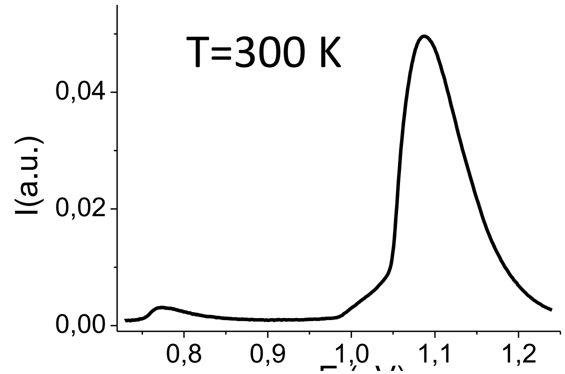


N favours the segregation O at dislocations and changes the D bands

D1 is still present at room temperature

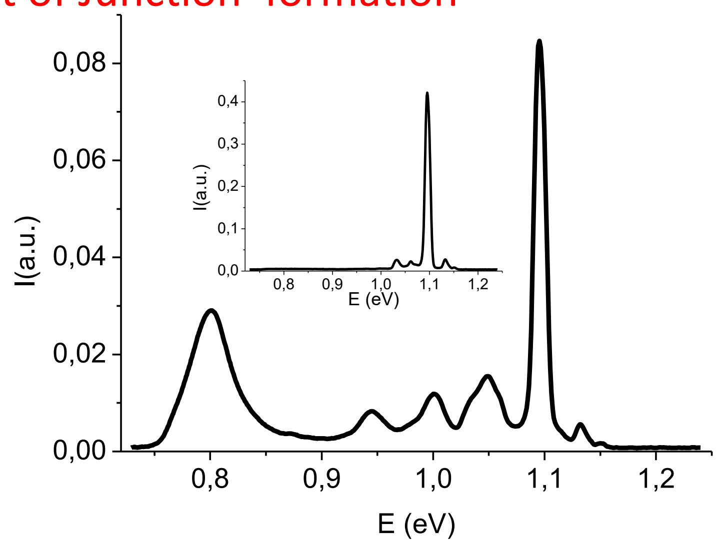


S. Binetti et al. SOLMAT 86, 11 (2005)



In mc- Si the D bands shapes and intensities depend considerably on samples, heat treatments, defects interaction , position along on the ingots …

- Effect of Junction formation



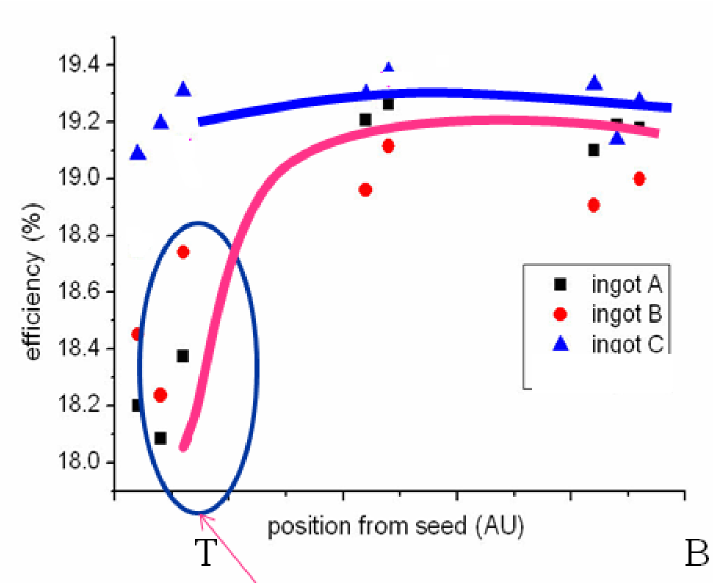
Defects in high efficiency industrial silicon solar cells

Ingot	Ingot Classification	Doping	Resistivity [Ωcm]	Oi [ppma]
A	Reference	n-type	1 – 5	<18 , 7.8 -8.6 at /cm^3
B	Low Grade Polysilicon	n-type	1 – 5	<18 8.1- 9.3 at /cm^3
C	Low Oxygen level	n-type	1 - 5	<16 7.2 -7.6 at /cm^3

+ standard n-type cell processing on wafers coming from different ingot positions

- Cells of ingot A,B show evidence of decrease of η % in the seed side.

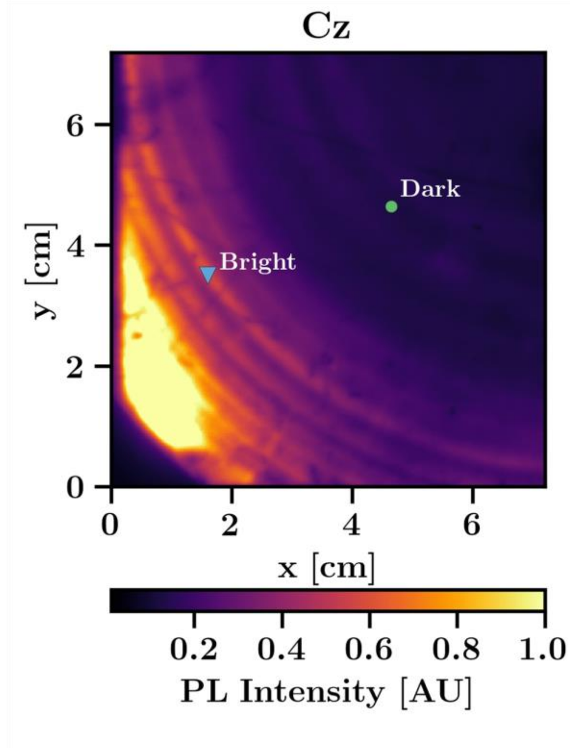
- What type of defect is responsible for the degradation?



G. Colletti et al. Solmat 130, 647 (2014)

Striations in n-Type Cz cells

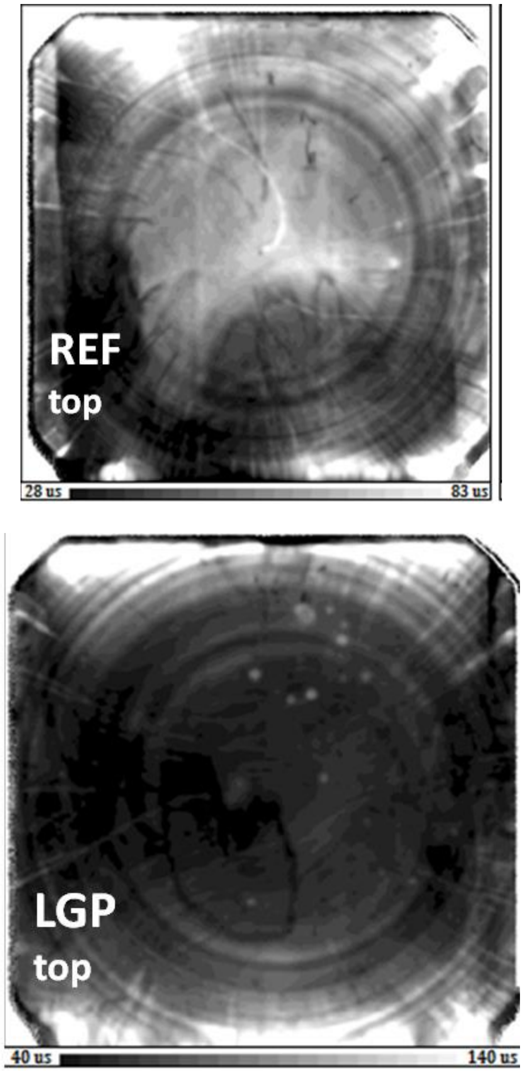
- Room Temperature PL images of the band-to-band (BB) emission shows the bright/dark rings (striations)
- Dark striations correspond to lower effective minority carrier lifetime than the bright striations.
- No direct correlation exists between the feedstock quality and the occurrence of striations (Absence of striations in the middle and bottom wafers of the REF/LGP ingots and in the whole LOO)



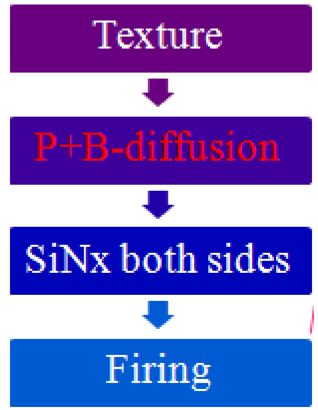
A. Le Donne, S. Binetti * & G. Coletti Applied Physics Letter 109, (2016), 033907

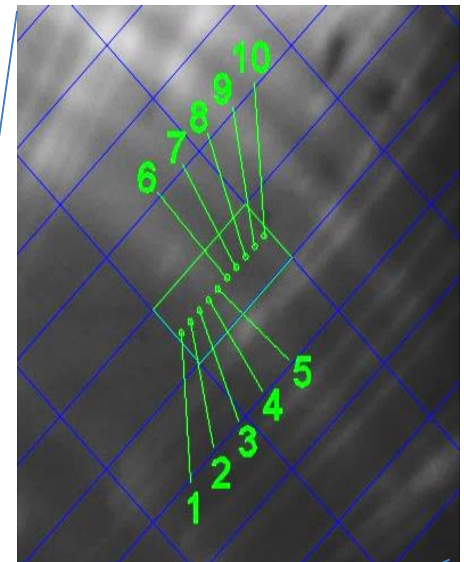
S

Characterization

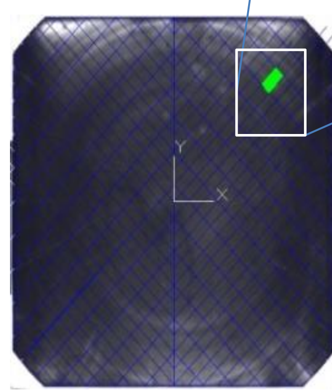


µPCD maps





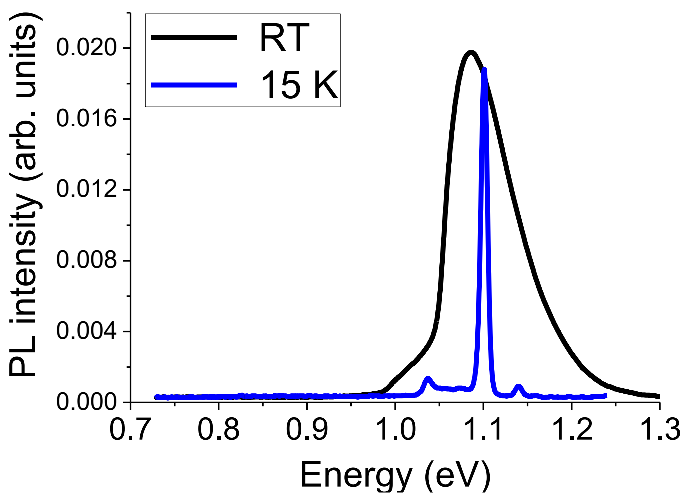
PL imaging

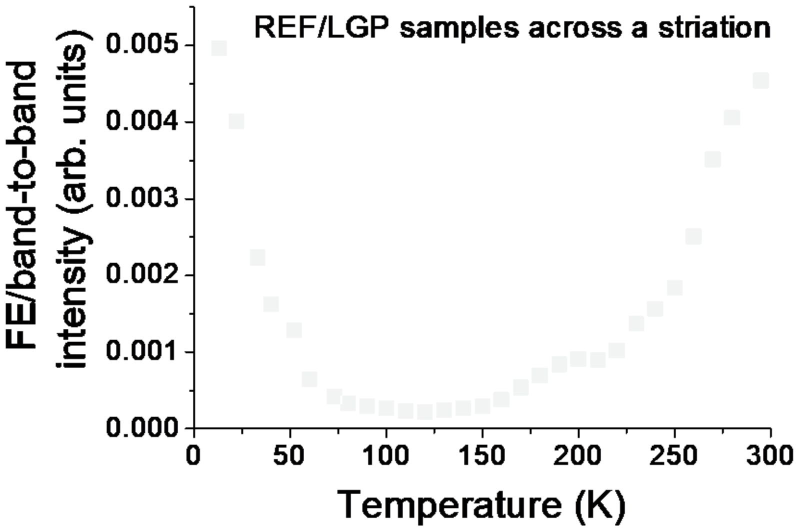


Local PL at different temperatures in regions with and without striations.

PL investigation @UNIMIB

On Striations :
- lower PL BB intensity
- same intensity of the BB at 300 K and 15 K

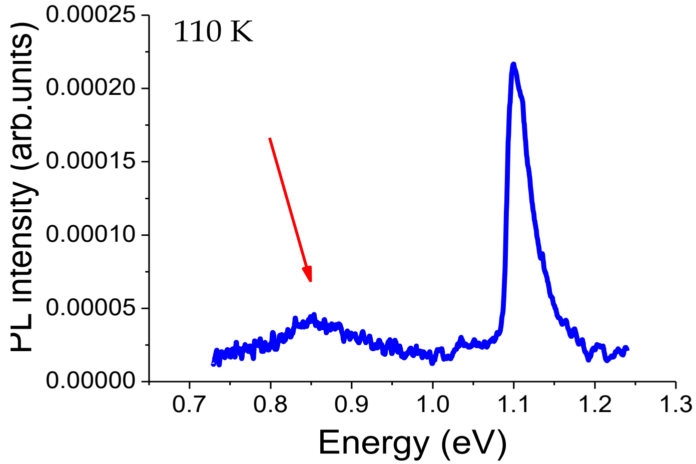


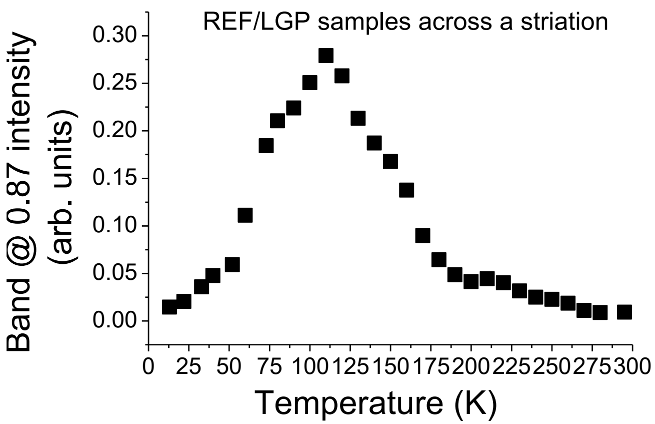


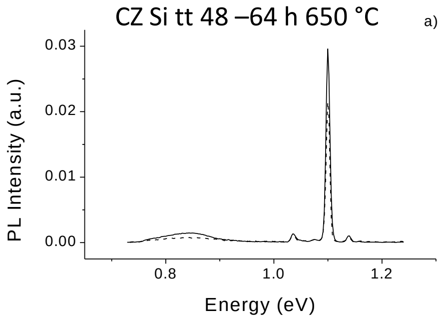
A.Le Donne, S. Binetti *, et al . Applied Physics Letter 109, (2016), 033907

PL results @UNIMIB

On striations







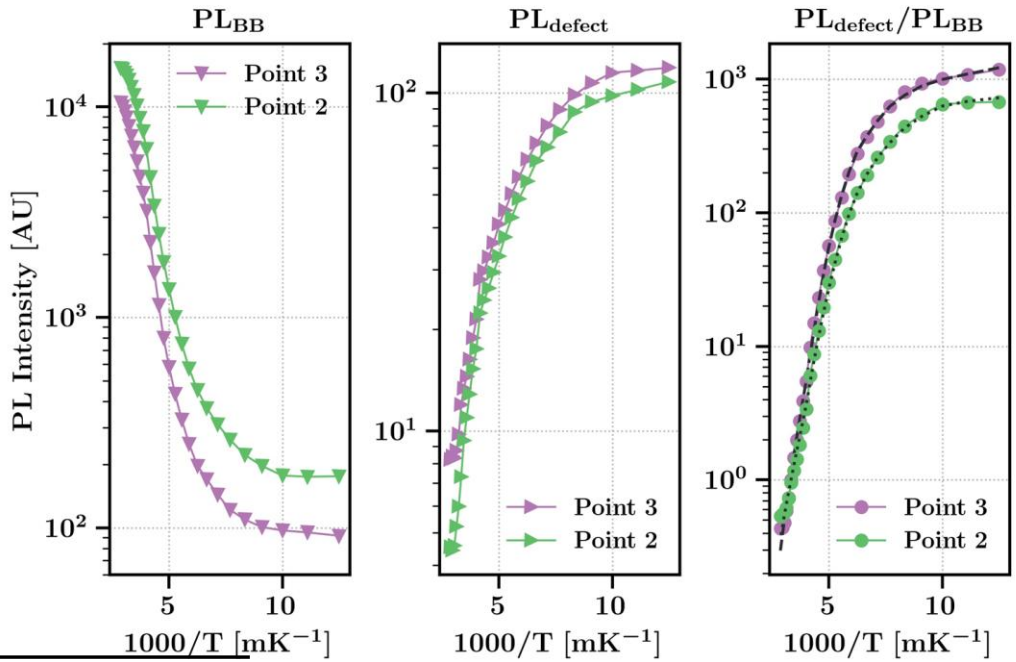
Position of the band (0.87eV) and temperature dependence
in agreement with Tajima's works and associated to oxide precipitates*

SiO_x nanoprecipitates (density about 10^{11} cm^{-3}):**
are responsible of the striations

**M. Tajima, IEEE Journal of Photovoltaics 4(6), 1452(2014) ; M. Tajima, et al. Mater.Sci.Forum 196, 1749 (1995)*
*** S. Binetti, et al. J.Appl. Phys. 92, 2437 (2002) ; E. Leoni , S. Binetti, et al. J Electrochemical Society 151, G866 (2004)*

Striations by Integrated Temperature Dependant PL @UNSW

- Determine the defect energy level by temperature dependence ($\sigma \propto T^{-r}$ for cascade capture)
- Not equal defect parameters in bright and dark regions ;
- $E_a = (E_{defect} - E_{bandedge})$~ 70 to 100 meV and *r* from 2.8 to 3.2



$$\frac{PL_{defect}}{PL_{BB}}(T) = \frac{PL_0}{\frac{B_{rad}(T)}{v_{th}(T)\sigma(T)}\left[N + n_i(T)exp\left(\frac{E_a}{kT}\right)\right]}$$

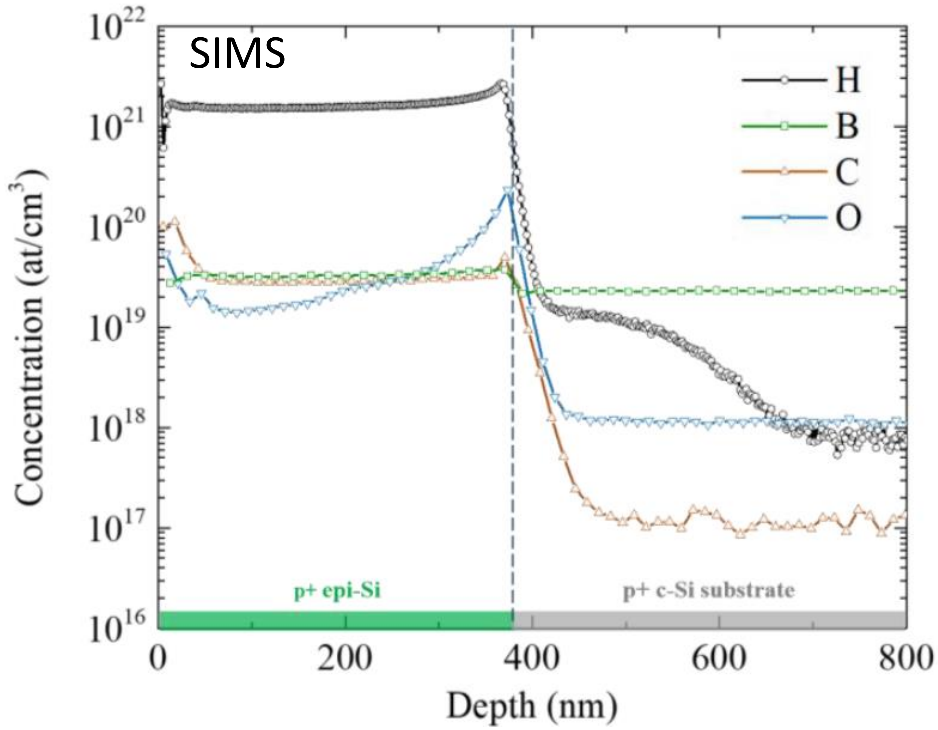
L. Chin , R.M.R Zhu, G. Coletti, S. Binetti , Z. Hameiri IEEE conference 8547892 pp-. 2524-2527 (2018)

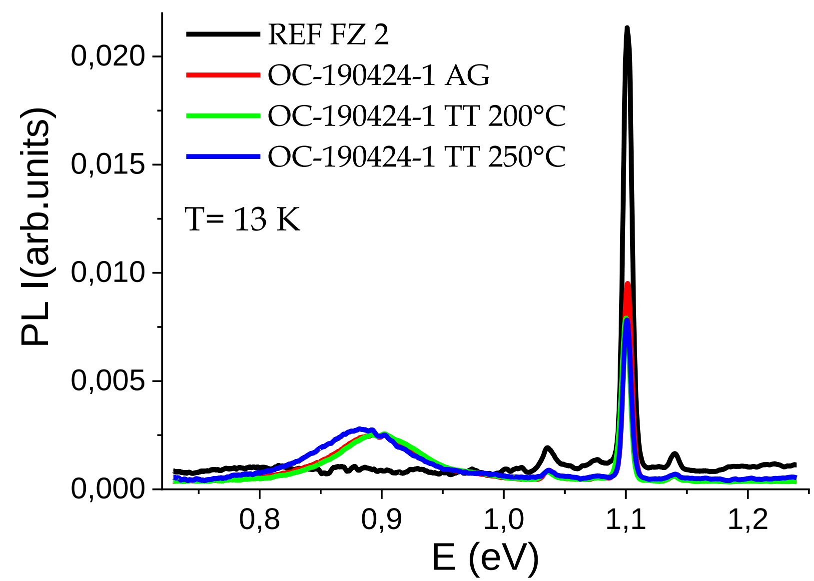
New very intersting results in Robert Lee Chin' PhD thesis

Boron emitter p+ epi –Si by low temperature PECVD

Advantages: lower thermal budget, control of doping profile

Several epi layers annealed from 175 -220 °C (B-H)





Platelets like exdended defects due to H*

HTREM measurement in progress

M. Chrostowski , J.Alvarez , A. Le Donne, S. Binetti, Pere Roca Cabarrocas , Materials 2019, 12(22), 3795
* H.Weman et al. Phys. Rev B 1990, 42, 3109

Defects and growth process: a different approach
Oxygen, carbon, dopant: unavoidable defects

How we can go further in their control ?

Melt Convections govern the formation and distribution of impurities in solid phase

Experiments under **microgravity** can contribute to a better understanding of the processes occuring during solidification as chemical segregation, interaction of particles can be studied under purely diffusive transport conditions

Parsiwal and Sissi project
ESA Project

- We have studied impurities and defects distribution during silicon solidification in ad hoc terrestrial experiments and in microgravity conditions*

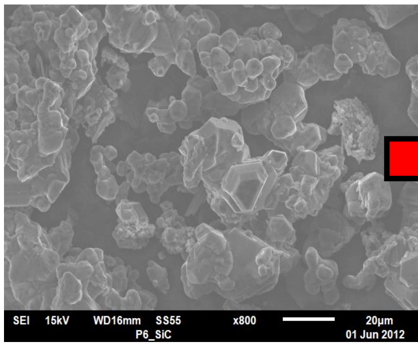
    – To understand the O, C impurities and SiC particles incorporation in the solid

*J. Friedrich, C. Reimann, et al J.Crys.Growth **447**, 18 (2016)
S. Binetti, M. Gonik, et al, Journal of Crystal Growth **417,** 9 **(** 2015)
A. Le Donne, et al. Proceedings of the 32nd EUPVSEC (2016) pp.1025 -1028, doi : 10.4229/EUPVSEC20162016

http://www.sscspace.com/texus-51

Experimental details

<100> Silicon rods of 8mm diameter and 40 mm long, were used to study the incorporation of SiC particles



SiC particles (7-60µm diameter, 4 mg)

A small hole is drilled into the rod and filled with 4 mg of particles @ 10 mm

Small piece of pure Si is placed on the top of the hole and then melting

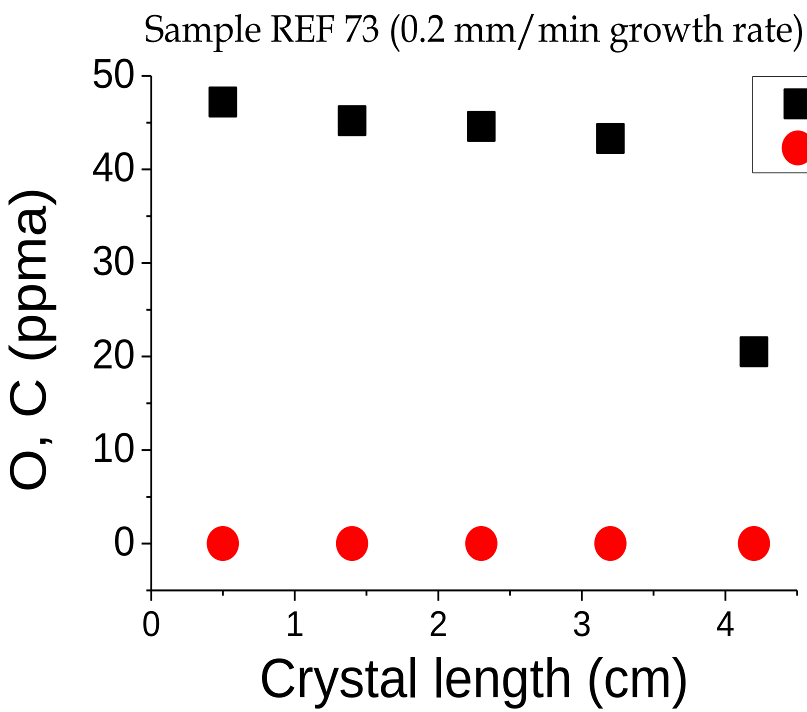
- **Silicon rod is covered by oxide skin**
- → Ampules with 1.5bar oxygen atmosphere

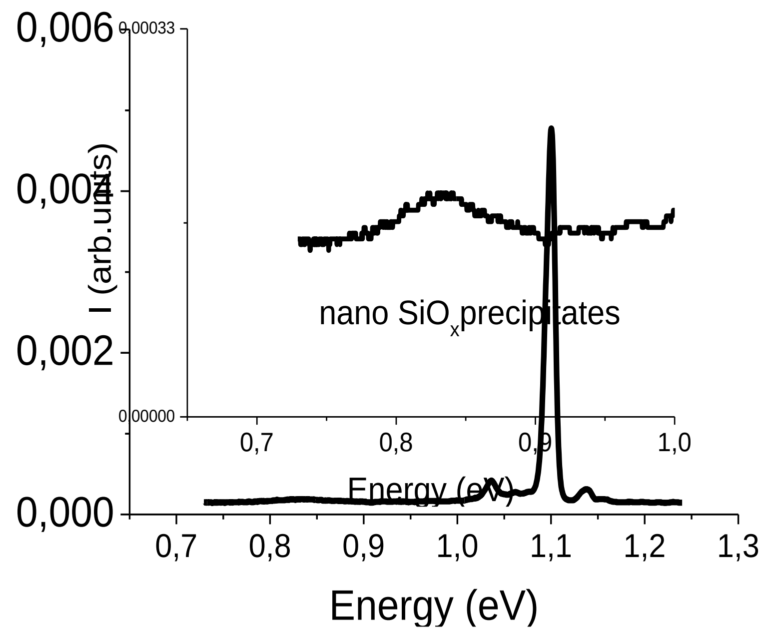
The abolition of free melt surface suppressed the Marangoni convection *

* A. Eyer et al J. Crystal Growth 71 (1985) 249

FZ growth in a mono ellipsoid mirror furnace

Effect of No Marangoni convection





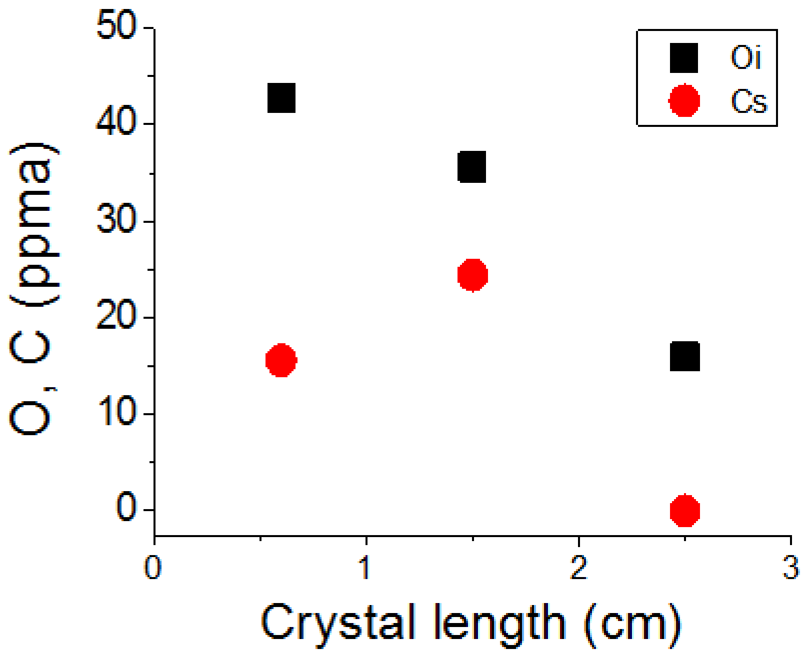
Oxygen concentration much higher than solubility

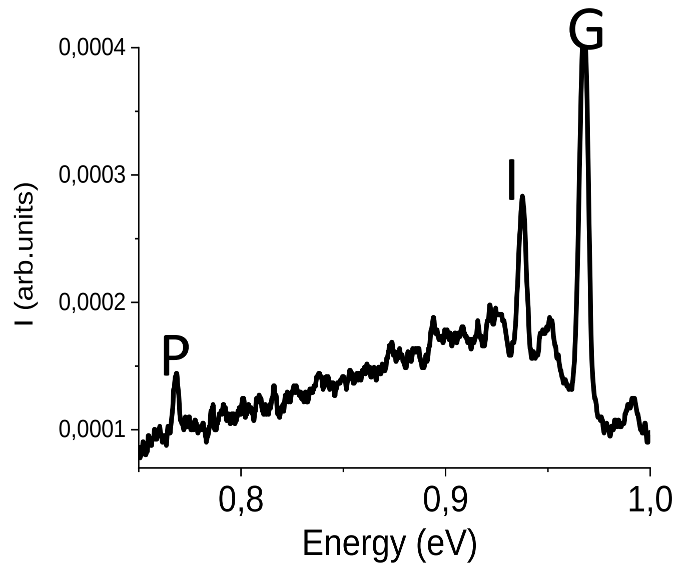
the Si:O solid solution is much stable

no SiO_X detected by FTIR @ 12 K and by PL except at the end of the growth

Effect of no Marangoni convection on SiC

with SiC particles





higher dissolution of SiC
lower SiC velocity

Presence of C_s, C_i :

- line G @ 0.979 eV C_s-C_i complexes
- Line I @ 0.935 eV involving C
- Line P @ 0.767 eV (Ci - TD8)

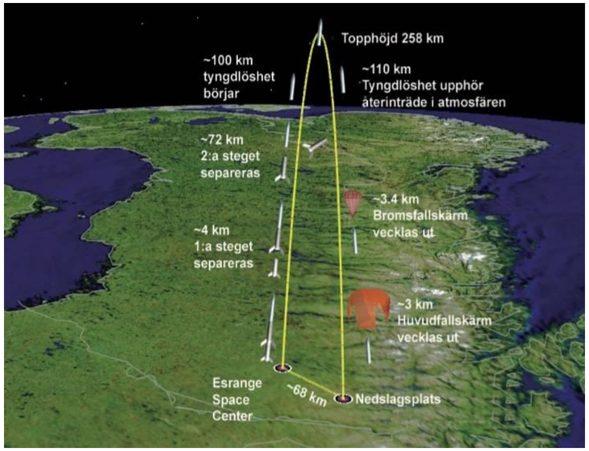
Microgravity TEXUS samples

Microgravity sample

	Particles	Crystal orientation	Dopant	Oxide skin	Growth rate	Crystal rotation rate	Furnace	Magnetic field
107 TEXUS 51 1g reference	7 and 60µm	100	P	5µm	2,5 und 10mm/min	12 U/min	ELLI EADS	7 mT RMF before crystal growth
109 TEXUS 51 µg	7 and 60µm	100	P	5µm	2,5 und 10mm/min	12 U/min	ELLI EADS	7 mT RMF before crystal growth

The rod was n type; ρ 0.002 Ohm cm

- Launched from European rocket launch site
- On its ballistic flight , the rocket reaches a peak altitute of 250 Km
- For 6 min conditions of microgravity prevails (~10^{-4} g)
- The payload of the rocket comes down on parachute (9.5 minutes)



For the microgravity experiment onboard TEXUS-51:

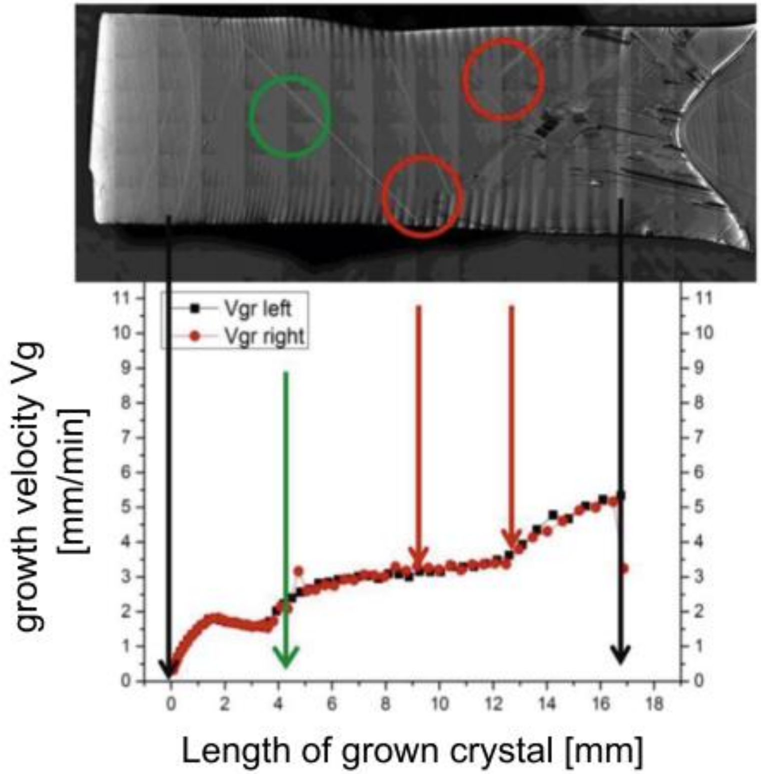
Before the launch, preheating of the sample ; the full lamp power was switched on 66 sec after launch of the rocket , the melting start around 80 s , after 110’ the molten zone was mixed by a B for 30’.

- after 160’ the pulling started ; (pulling rate V from 2 mm/min to 10 mm/min) . During the pulling a constant rotation rate of 12 rpm At 440 sec, just before the reentry of the payload, all switched off.

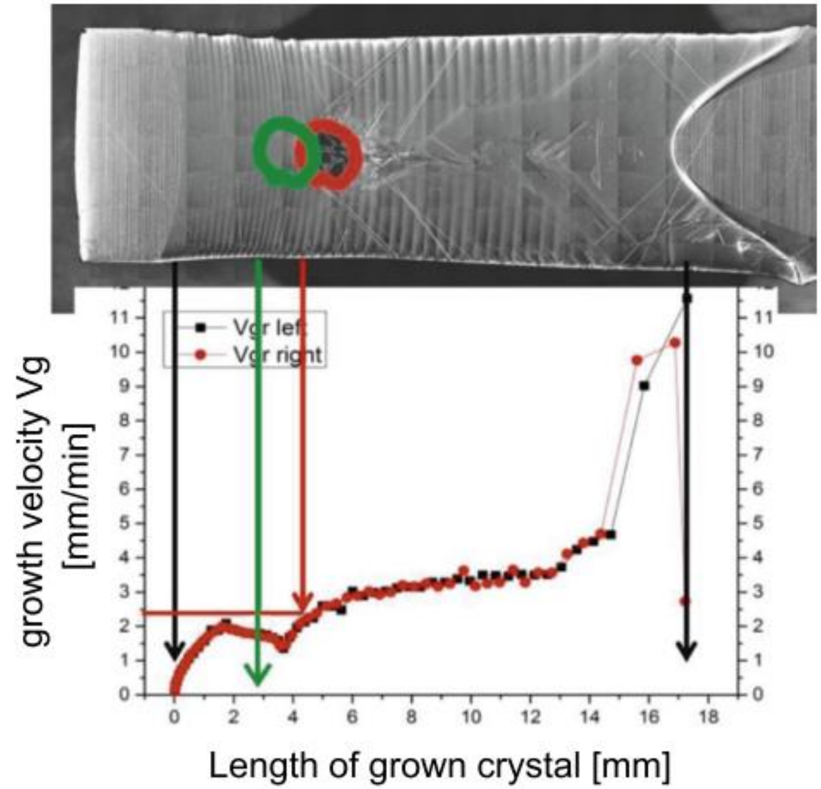
Microgravity on SiC particles movement

Fraunhofer IISB

KRISTALLOGRAPHIE FREIBURG



$1g: V_c = 3.4\text{-}3.8 mm/min$



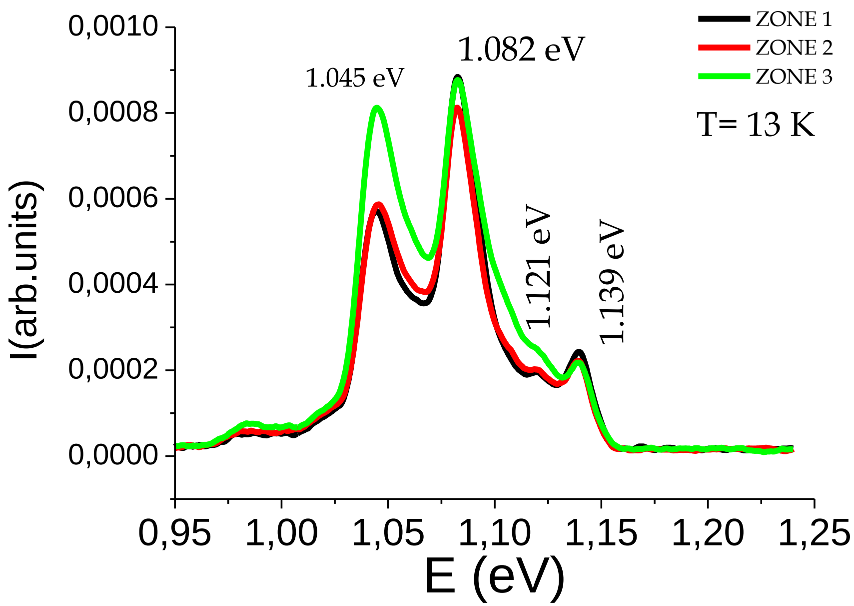
$\mu g: V_c = 2.4 mm/min$

Under microgravity, SiC particles are incorporated with a lower critical growth velocity of the moving solid-liquid interface, due to the absence of the lift-force (3-4 mm/min for 1 g and 2.2 mm/min for µg)

J. Friedrich, et al. J.Crys.Growth **447**, 18 (2016)

PL on microgravity samples

TEXUS 109 (μg)



By PL

- no SiO_x precipitates, no C related lines
- 30 ppma of Oxygen by FTIR

- The gravity influences the melt flow which determines the distribution of the particles in the melt volume:
- In microgravity conditions lower SiC velocity, uniform dopant distribution , less dissolution of oxide skin

Theoretical interpretation of the data work in progress

Conclusion

- PL and FTIR are useful techniques to monitor the impurity distribution , second phases and the effect of growth conditions or post thermal treatments

- Advantages
  - are non-destructive techniques
  - no particular sample preparation and handling are necessary
  - impurities and defects can be detected even at low concentration
  - are sensitive to the chemical species

- Critical points
  - quantitative information only for IR, difficult for PL
  - low temperature and small samples only

- The feasibility of PL mapping on PV silicon can be increased by a combination with low T PL spectra on selected area

- A lot of data and information are already in literature, but the application on PV silicon is not always straightforward → **still rooms for research activities**

Thank you for your attention !

MIB-SOLAR

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www.mibsolar.mater.unimib.it