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M. Lazar

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# Cathodoluminescence study of silicon vacancies color centers generated by ion implantation in 6H-SiC

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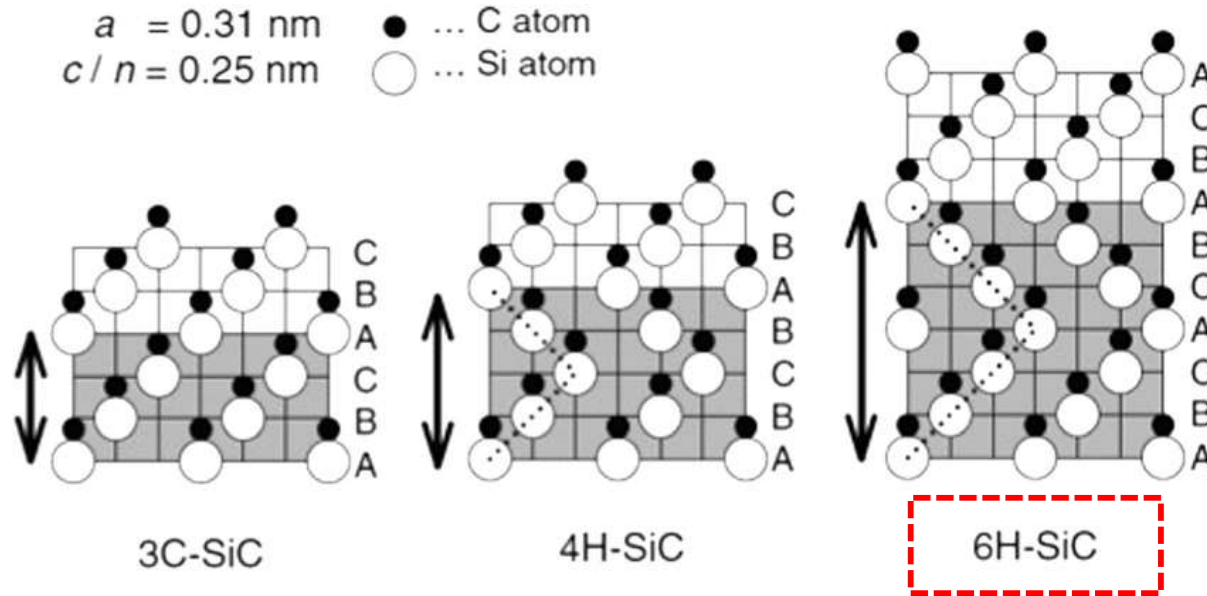
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<sup>\*\*\*</sup>Aix-Marseille Univ, Université de Toulon, CNRS, IM2NP, Marseille, France

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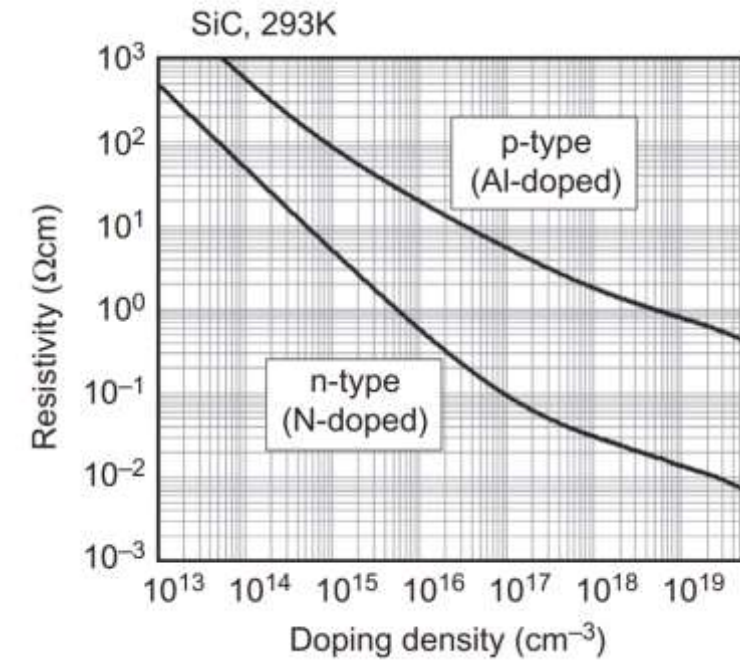
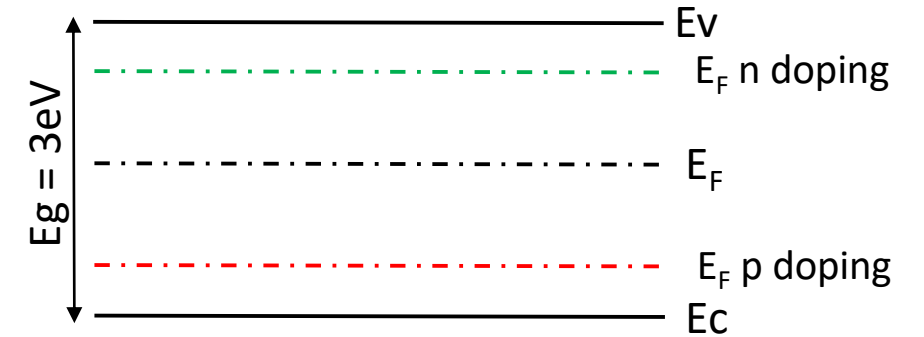
*Supervisor: Mihai Lazar*

## What is silicon carbide ?

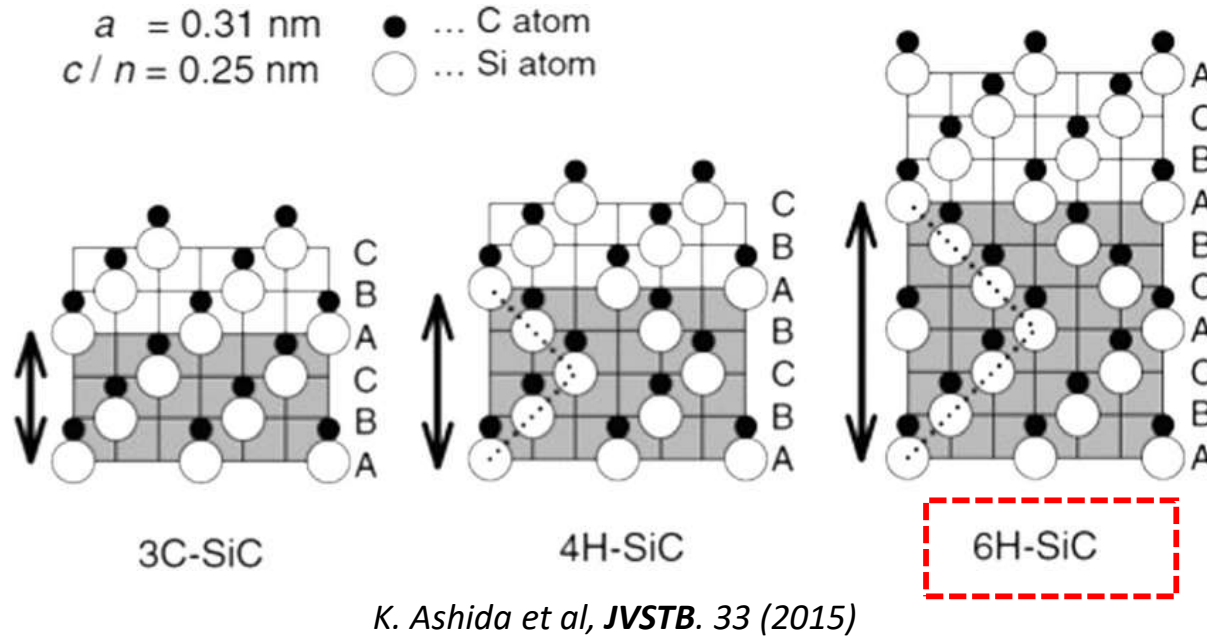


*K. Ashida et al, JVSTB. 33 (2015)*

- Wide bandgap semiconductor with multiple polytypes
- n and p-type doping possible

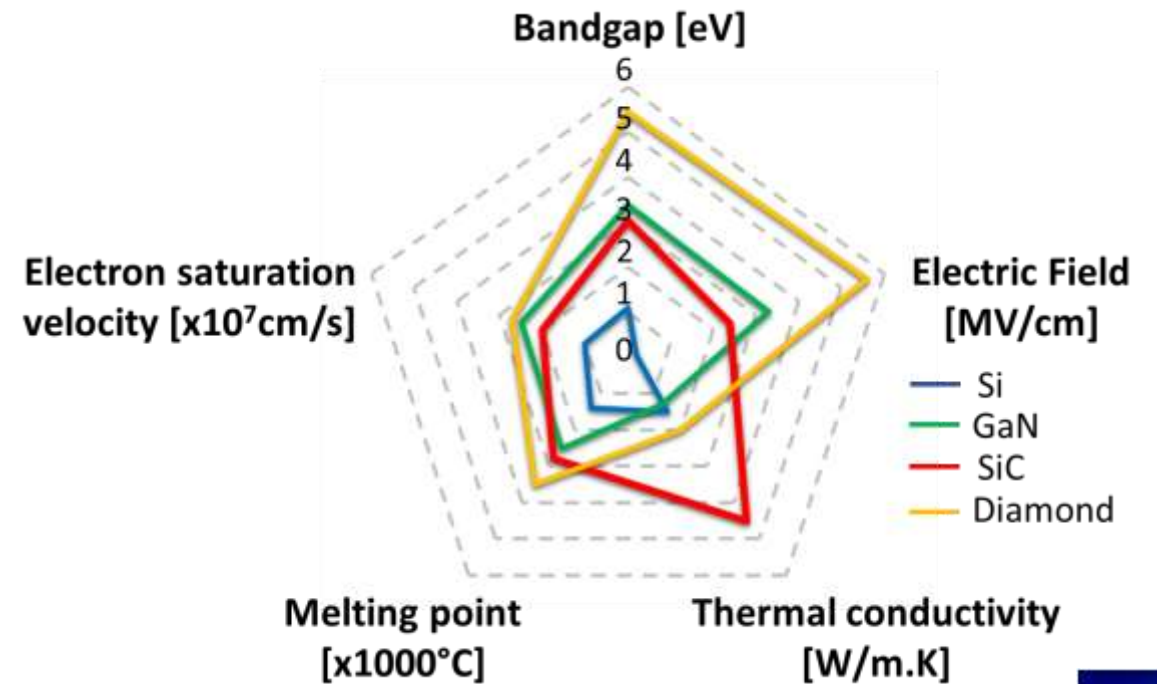
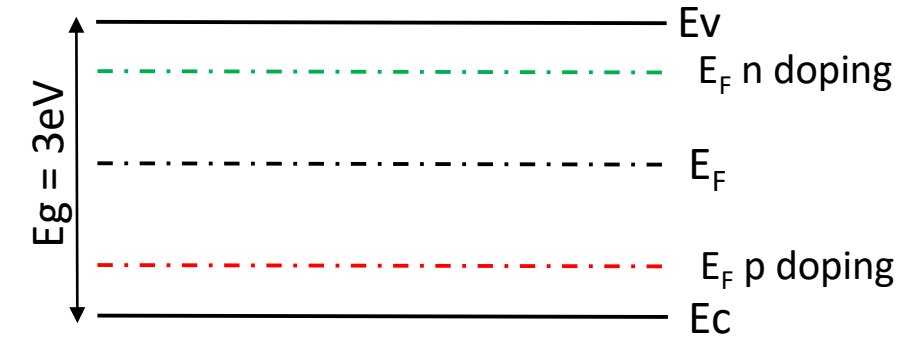


## What is silicon carbide ?

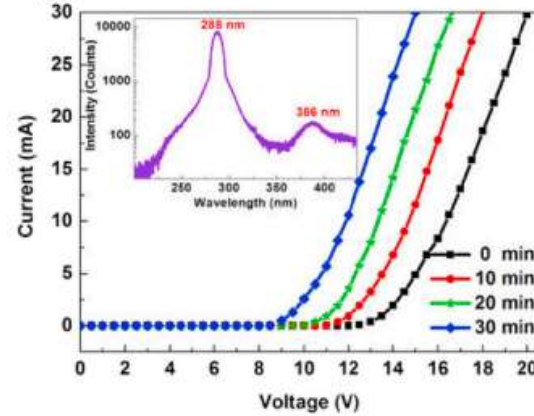
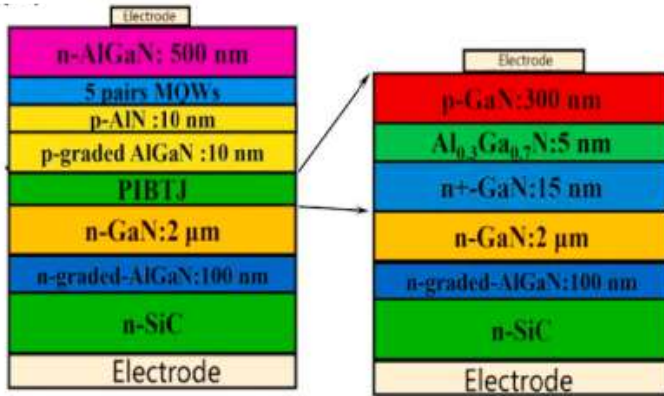


- Wide bandgap semiconductor with multiple polytypes
- n and p-type doping possible
- High thermal conductivity and temperature resistance
- High technological maturity

Applications in high-voltage, high-temperature power devices

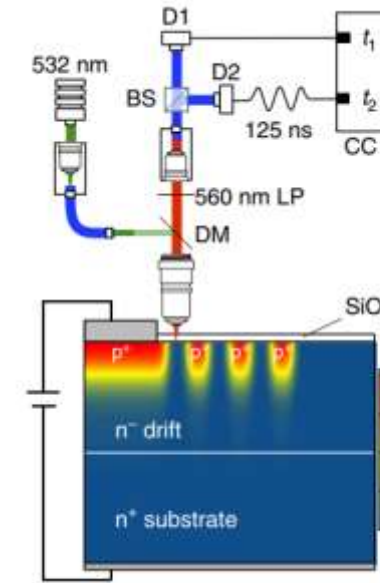


## SiC as a photonic device



Hongwei Liang *et al*, *Jpn. J. Appl. Phys.* 55 (2016)

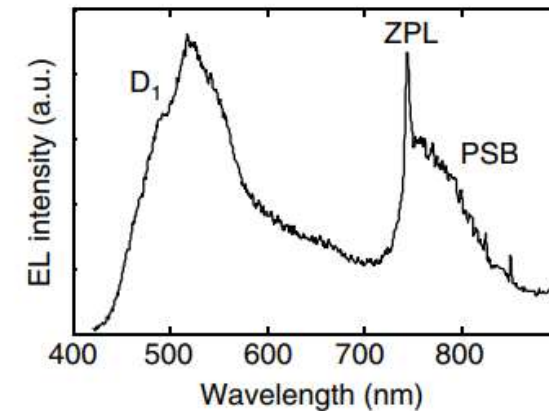
## Vertical UV LEDs on SiC



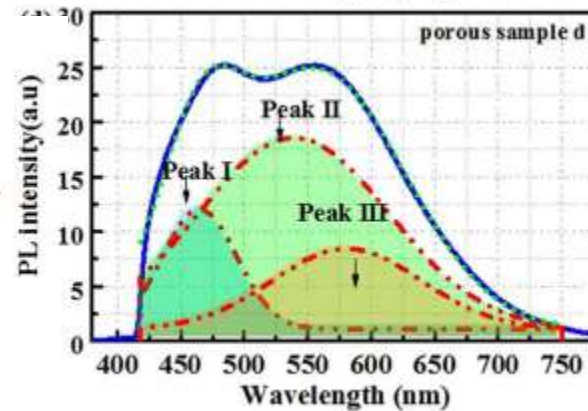
Single photon emitter  
p-n diode



Color centers

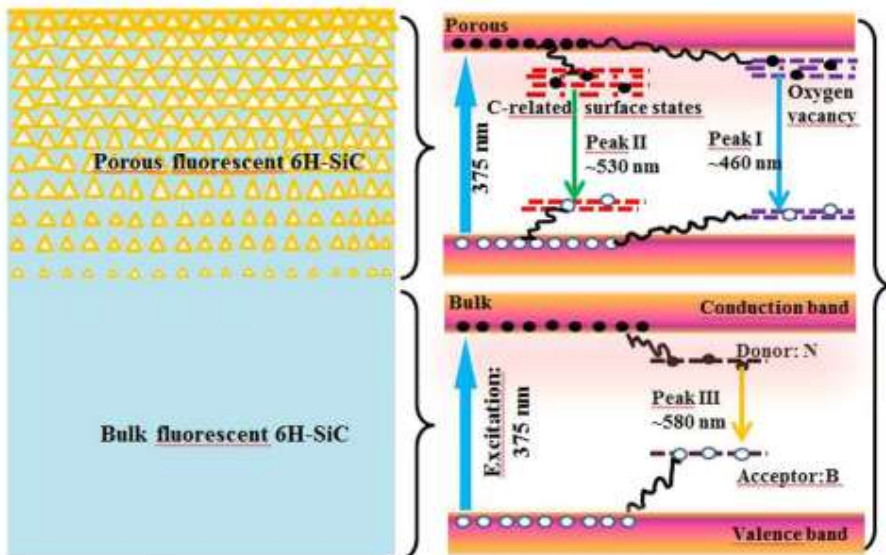


A. Lohrmann *et al*, *Nat. Commun.* (2015)

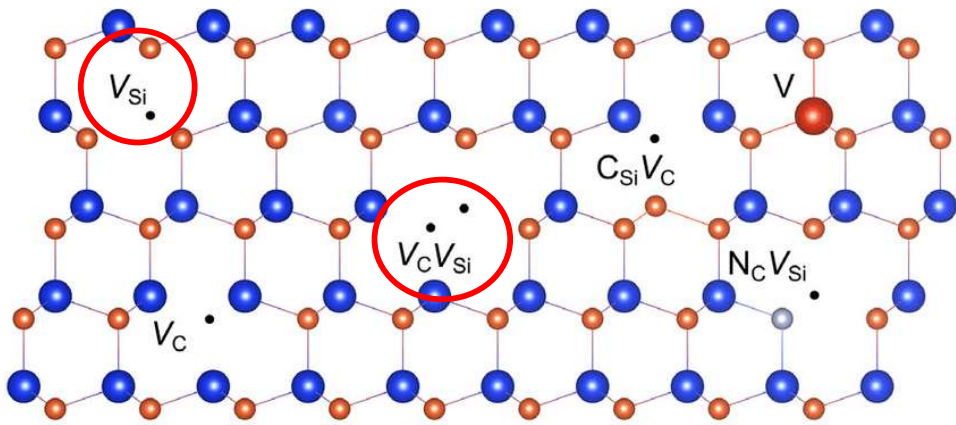


## Fluorescent SiC

Weifang Lu *et al*, *Scientific Report.* 7 (2017)



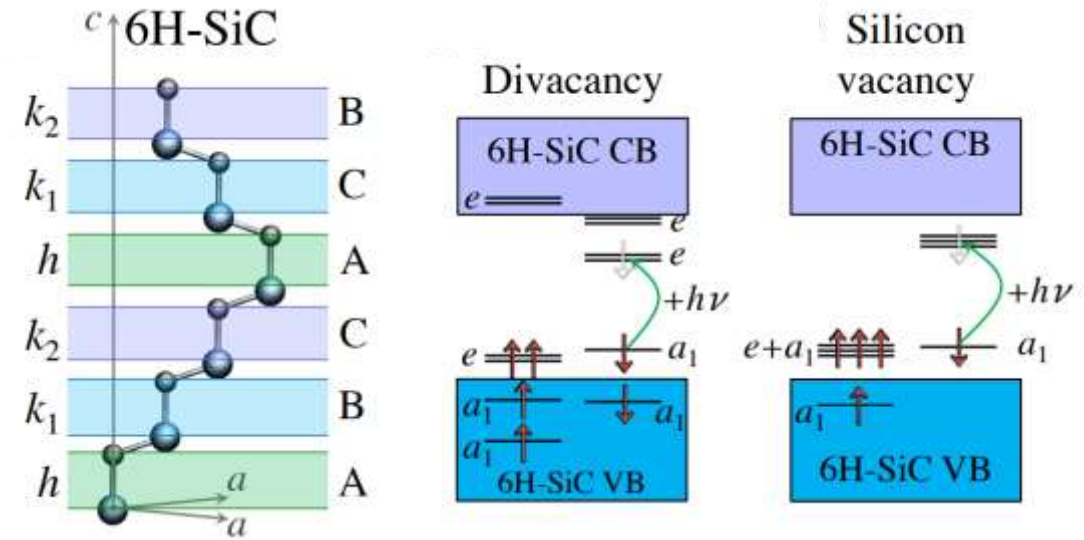
## Color centers in SiC



M.E. Bathen and L. Vines, *Advanced Quantum Tech.* (2021)

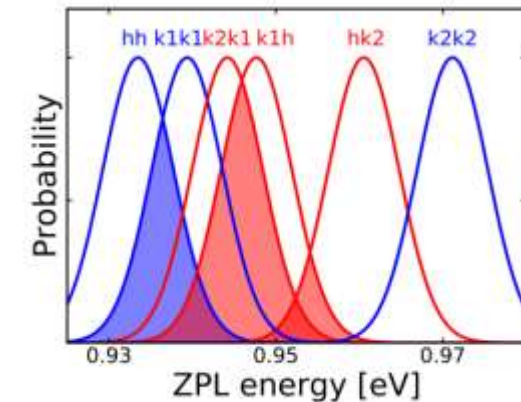
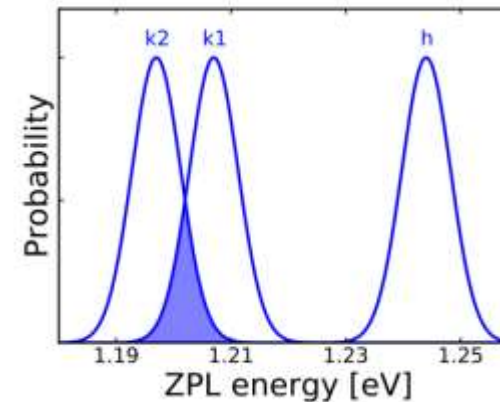
- Point defects within the lattice
- Single photon sources : qubits
- Emission of visible light in diamond
- Emission of **NIR light** in SiC

High technological maturity of SiC



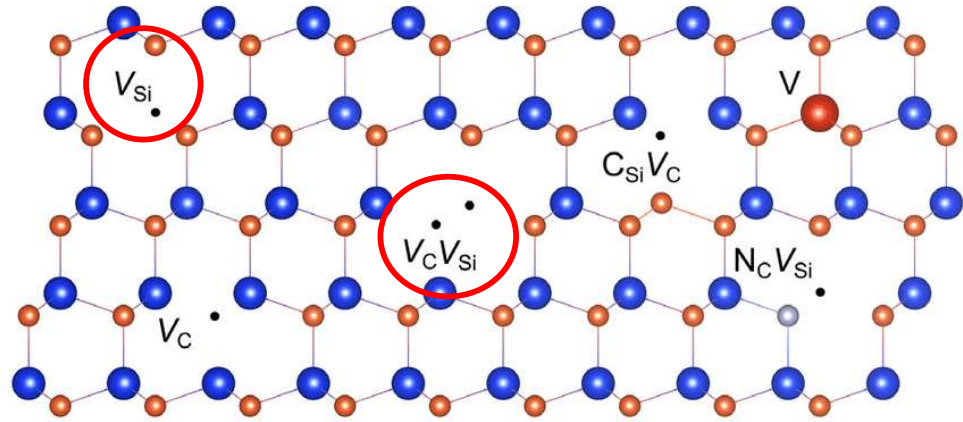
$V_{Si}(-)$

$V_{Si}-V_C$

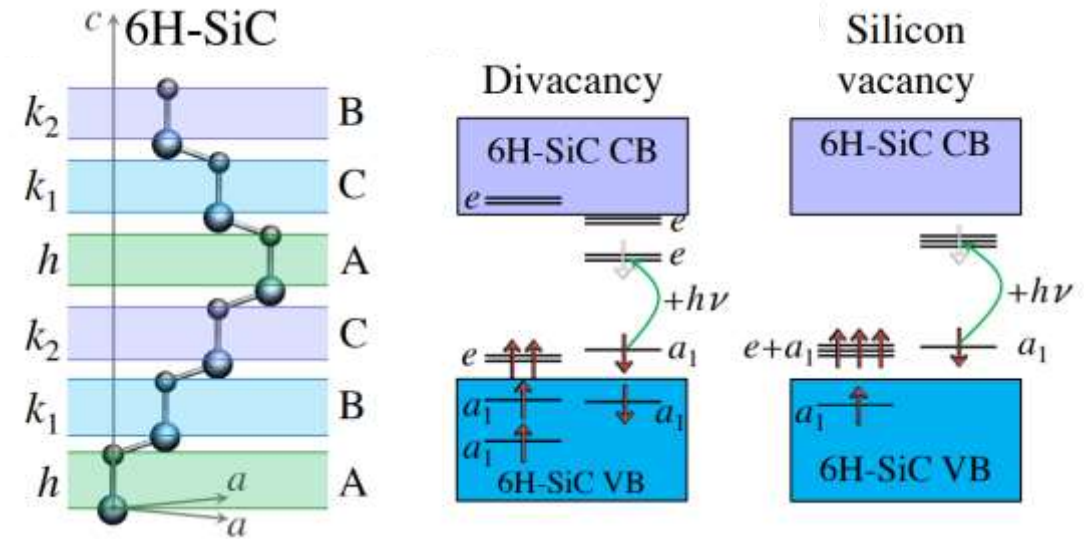


J. Davidsson et al, *Applied Physics Letters.* (2019)

## Color centers in SiC

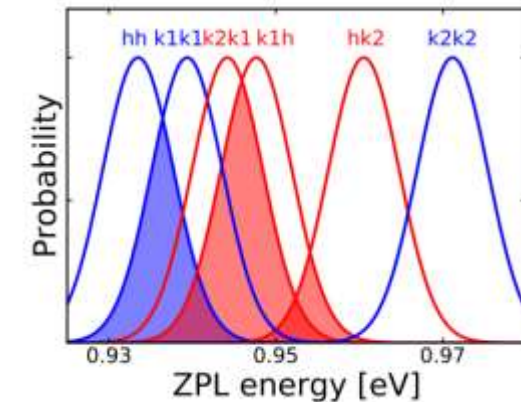
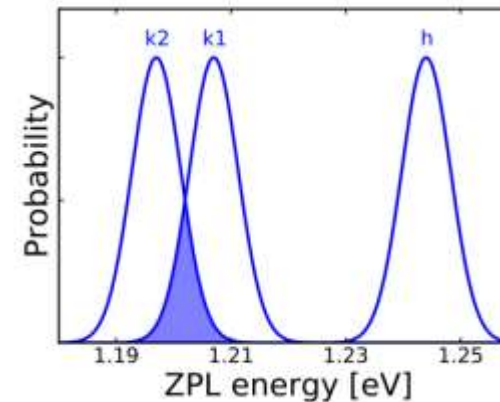


M.E. Bathan and L. Vines, *Advanced Quantum Tech.* (2021)



$V_{Si}(-)$

$V_{Si}-V_C$



**Objective:** To study the influence of ion implantation parameters on the generation of color centers in 6H-SiC samples

**Application :** To create a photonic device with these point defects → emission of NIR light

J. Davidsson et al, *Applied Physics Letters.* (2019)



Generation of the color centers



Crystallinity of the samples



Detection of the color centers





Generation of the color centers

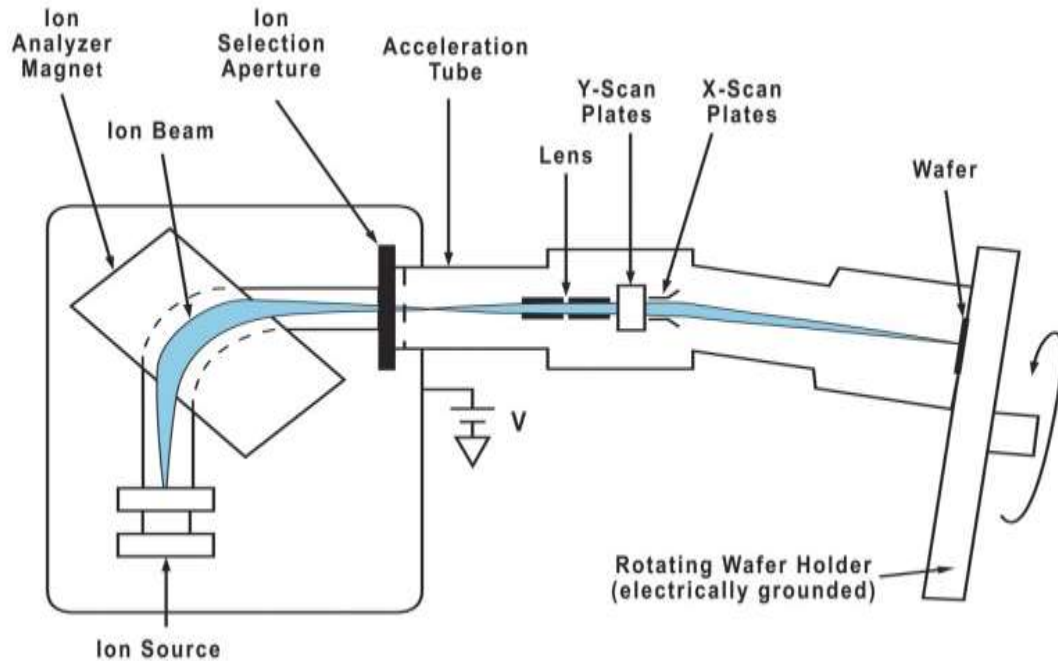


Crystallinity of the samples



Detection of the color centers

## Ion implantation



Ion implanter scheme

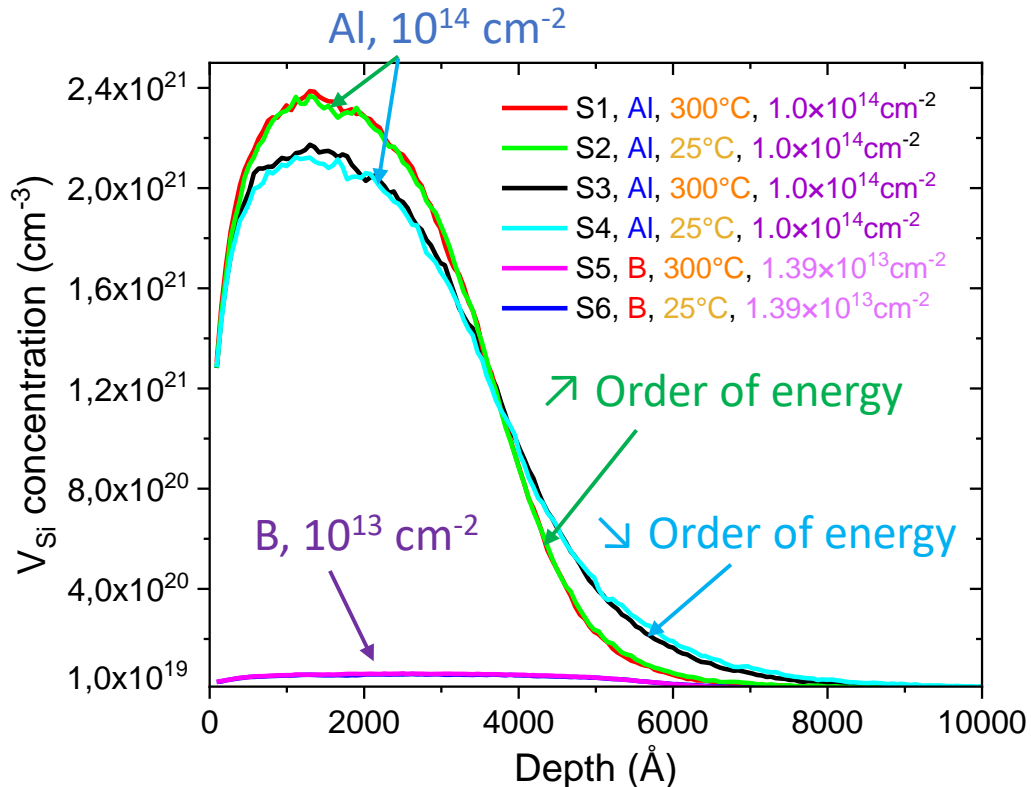
MKS, <https://www.mks.com/n/ion-implantation>

Samples	Dopant	T [°C]	E <sub>max</sub> [keV]	D <sub>T</sub> [cm <sup>-2</sup> ]
S1	Al	300	25 → 300	1.0×10 <sup>14</sup>
S2	Al	25	25 → 300	1.0×10 <sup>14</sup>
S3	Al	300	300 → 25	1.0×10 <sup>14</sup>
S4	Al	25	300 → 25	1.0×10 <sup>14</sup>
S5	B	300	340 → 20	1.39×10 <sup>13</sup>
S6	B	25	340 → 20	1.39×10 <sup>13</sup>
S7	NA	NA	NA	NA

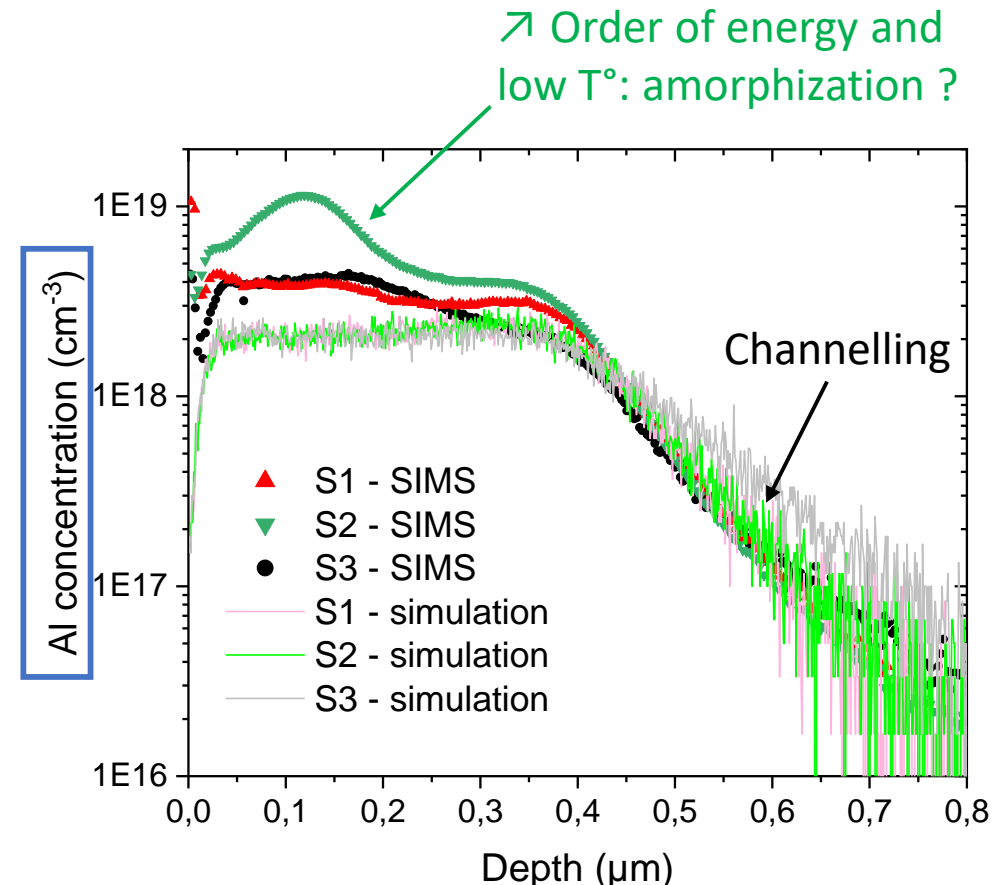
- Simulations close to the experimental results
- Generation of color centers in **localized and large areas**
- **Ion implantation of Al and B in 6H-SiC**
- Energy of implantation fixes the point defects depth
- Order of implantations can change the defects distribution
- Limited damage in the SiC lattice with well-controlled parameters : dose and temperature

## Silicon vacancy and dopant profiles

Monte Carlo simulations: I2SiC software



**Simulated silicon vacancy profiles**



**Simulated and experimental dopant profiles**

➤ The order of implantations and the dose impact the distribution of  $V_{Si}$

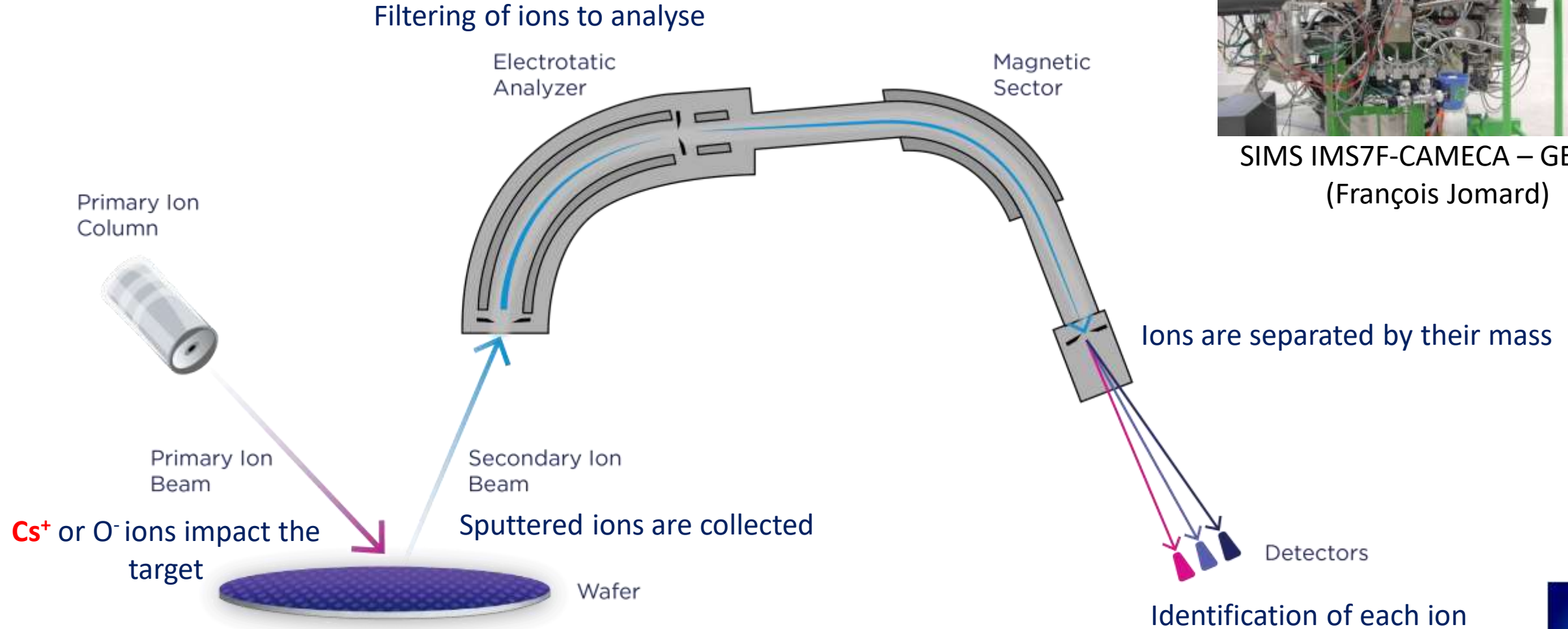
➤ **Difference** between simulations and experimental results (SIMS)

# GENERATION OF COLOR CENTERS IN 6H-SiC

## SIMS measurements



SIMS IMS7F-CAMECA – GEMAC  
(François Jomard)





Generation of the color centers



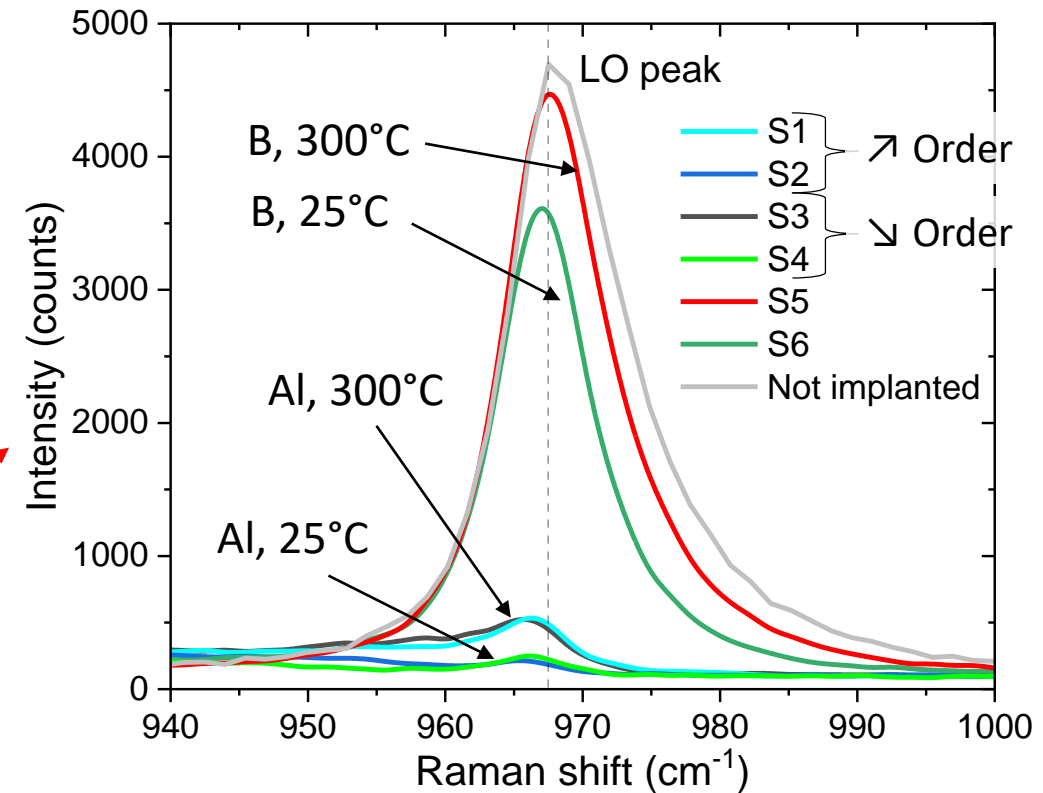
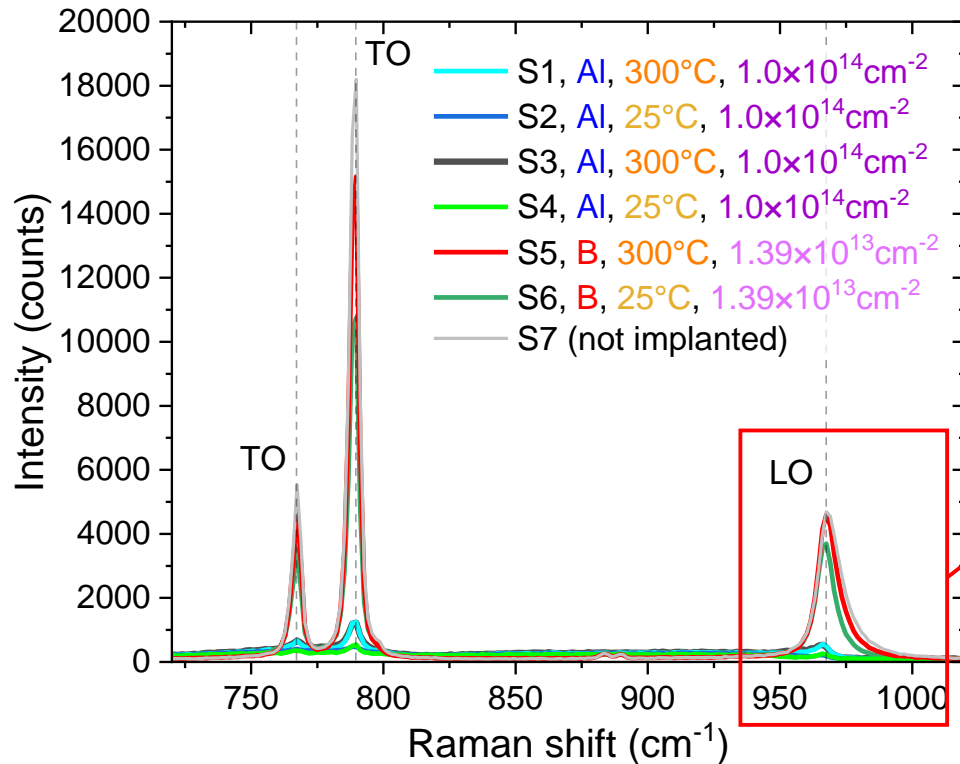
**Crystallinity of the samples**



Detection of the color centers

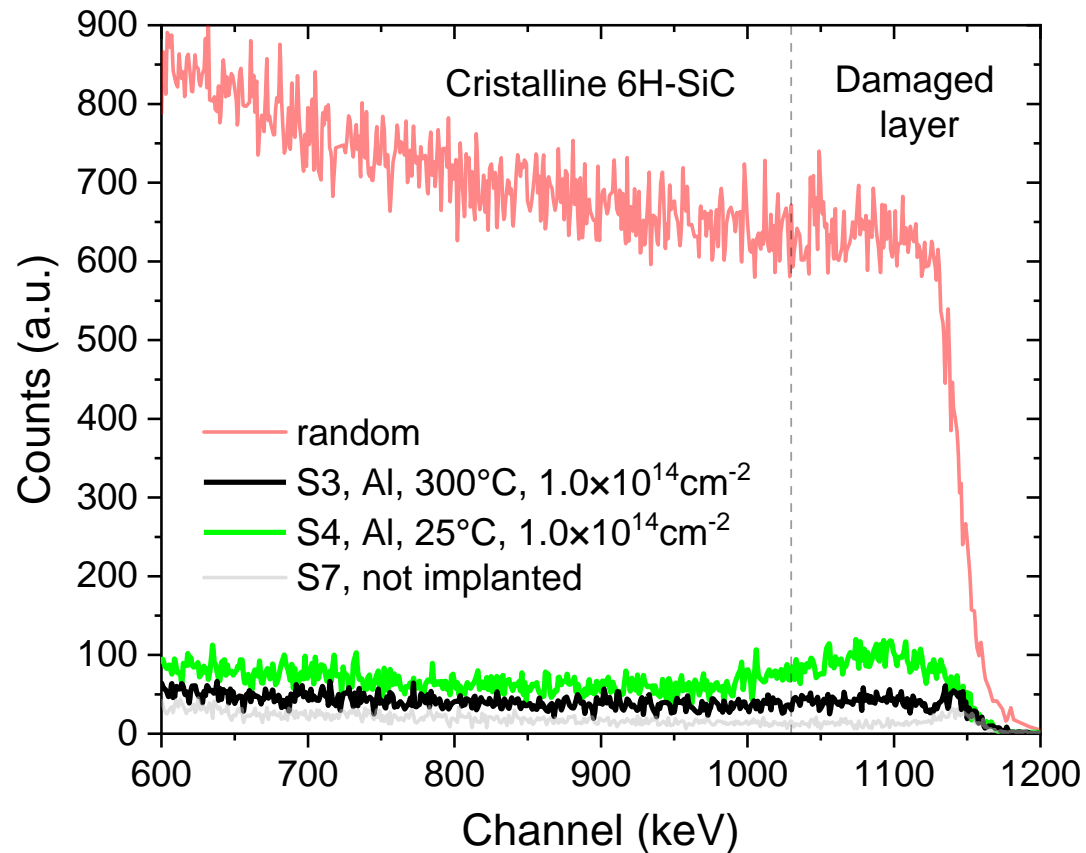
## Raman measurements

$\lambda_{exc} = 325\text{nm}$ , obj x40, 1800 gr/mm



↗ sample damage at the surface with implantations of high doses at low temperatures  
Contrary to simulations, temperature affects the lattice damage but not the order of implantations

## RBS/C measurements



- Slight samples' surface damage
- Far from the amorphization threshold
- Less sensible to damage compared to Raman
- Point defects can still be observed



Generation of the color centers



Crystallinity of the samples

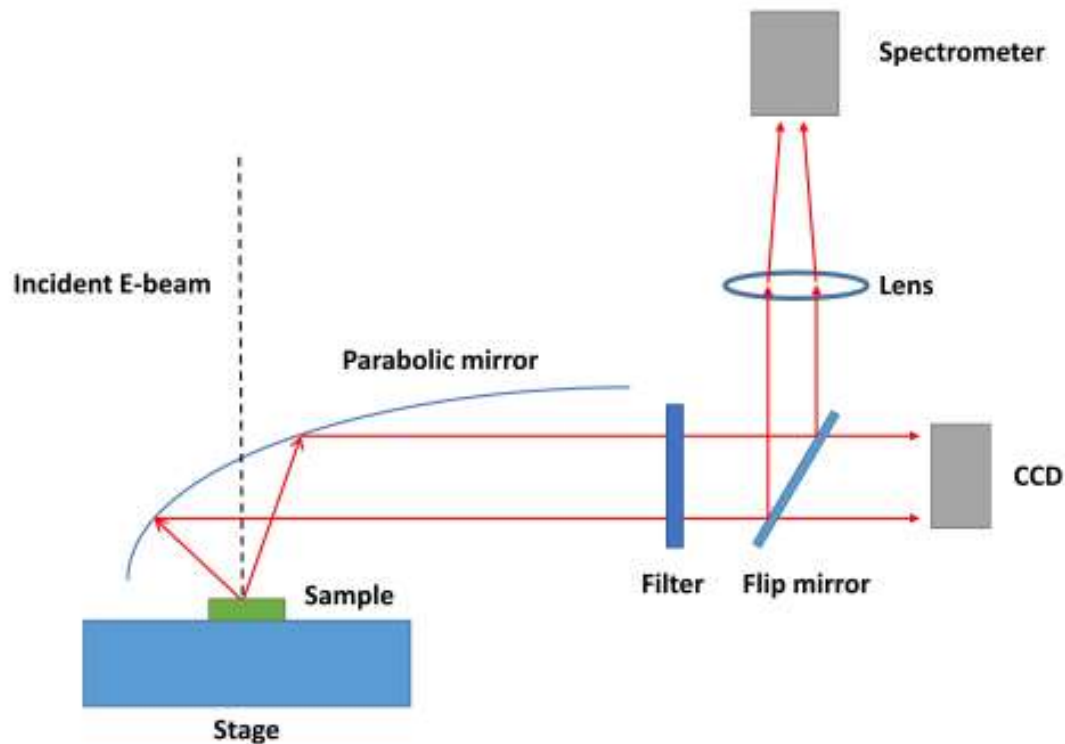


Detection of the color centers



## Cathodoluminescence

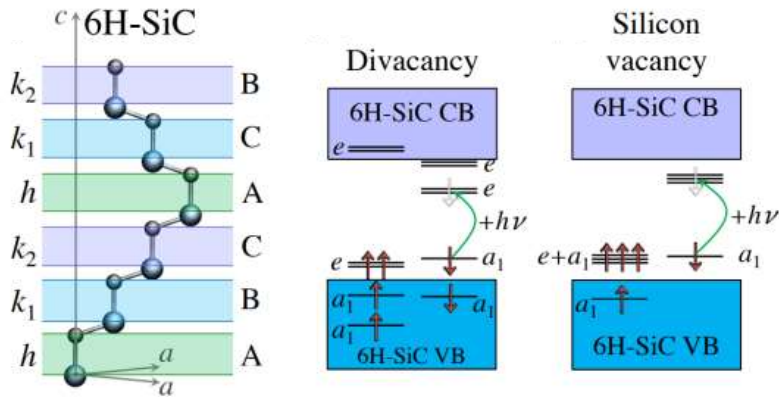
- Realized at **80K** (PL at RT)
- Measurements before and after annealing at **900°C for 15min**
- Good sensibility of the camera until **1000nm**



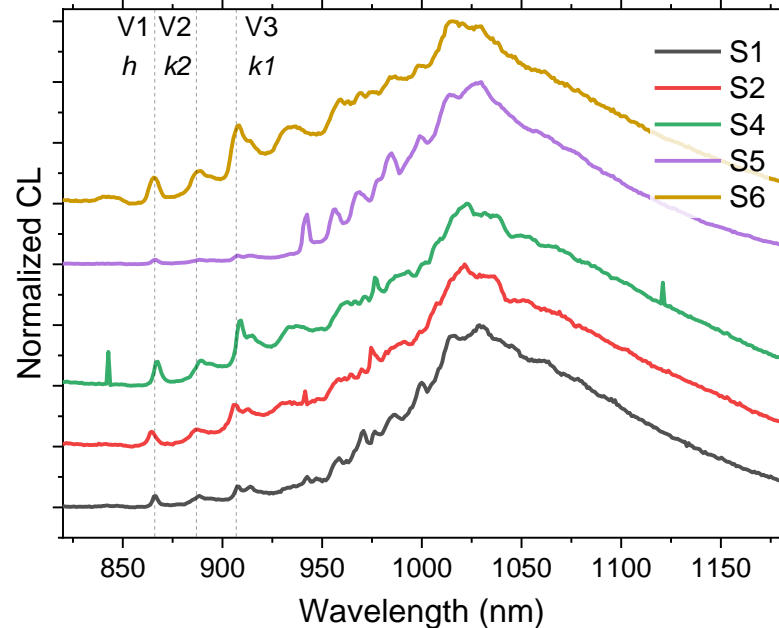
*Semicond. Spectro. Devices. <https://ssd.phys.strath.ac.uk/>*



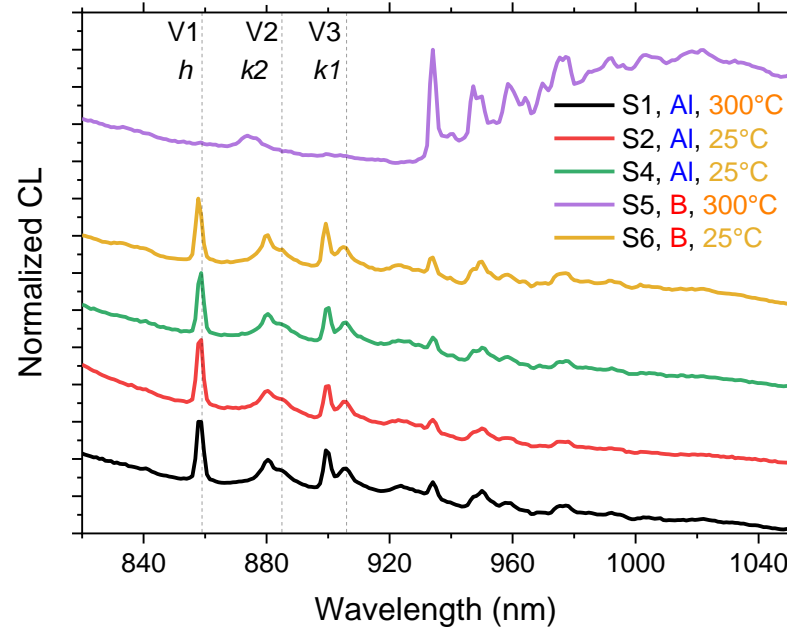
# DETECTION OF THE COLOR CENTERS



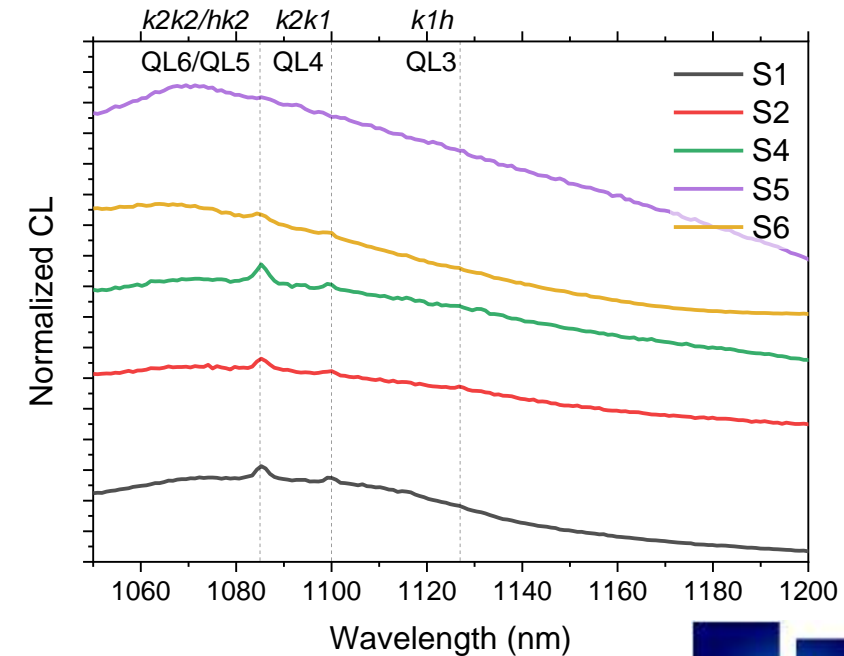
- **Silicon vacancy  $V_{Si}$** : present before and after annealing at 900°C,  $\searrow$  of phonon side-bands after annealing
- $V_{Si}$  changes of **preferential configuration** after annealing  $\rightarrow V3$  to  $V1$
- **Divacancy  $V_{Si}V_C$** : appears after annealing at 900°C for 15min  $\rightarrow$  we approach the **telecom wavelength**
- 9  $V_{Si}V_C$  configurations possible: ZPL not observed yet for three of them



**BEFORE ANNEALING**



**AFTER ANNEALING**



## Silicon vacancy evolution

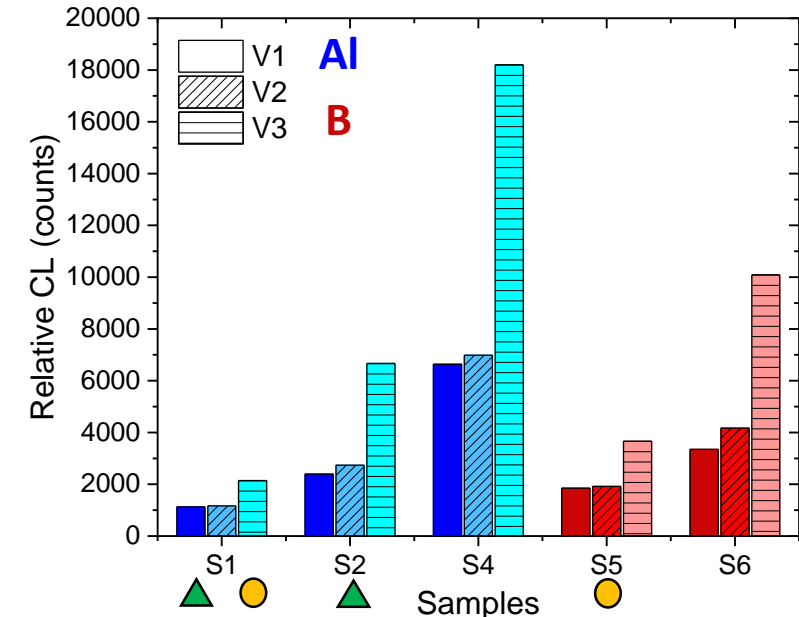
### Before annealing

- More defects for implantation of Al (higher dose) at low temperature with decreasing order of implantations
- V3 configuration favored (k1 site)

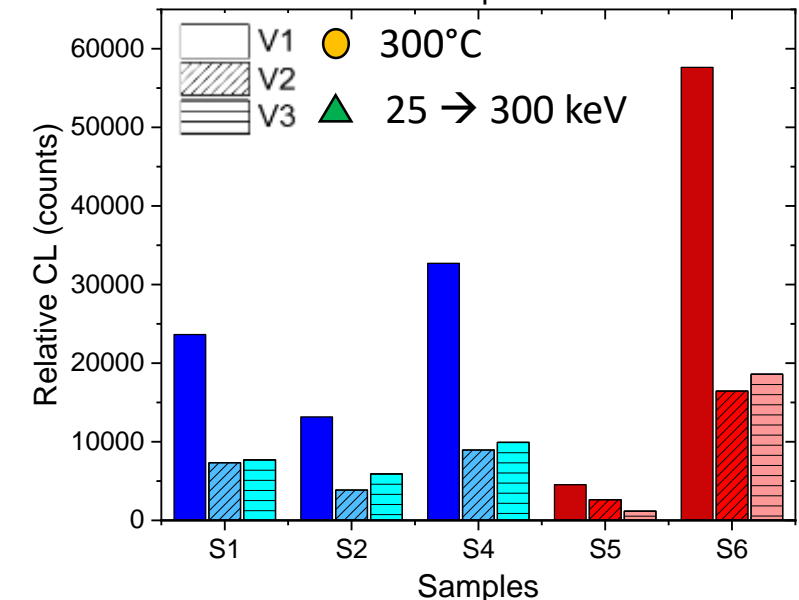
### After annealing

- **Silicon Vacancies**
  - V1 configuration favored (h site)
  - More defects for implantation of boron at low temperature → high diffusion of B in SiC through VSi
- **Divacancies  $V_{Si}V_C$** 
  - Weak signal of QL3 to QL5/QL6 defects and no signal of QL1 and QL2
  - No divacancies for S5 → not enough vacancies

BEFORE ANNEALING



AFTER ANNEALING



## Conclusion

- Color centers are generated by ion implantations of Al and B followed by annealing at 900°C
- Implantations of higher doses at low temperatures result in a loss of crystallinity at the sample surface → the amorphization threshold is not reached
- $V_{Si}$  appears directly after ion implantation: transition from V3 to V1 configuration after annealing.
- Annealing leads to the high diffusion of boron in SiC → more  $V_{Si}$
- $V_{Si}V_C$  appears after annealing at 900°C for 15min → closer to the telecom wavelength than  $V_{Si}$  + longer spin coherence time

## Perspectives

- CCD camera with good NIR sensibility + PL setup in NIR
- Integration of the point defects in a photonic device

Thank you !