Doping of Ge via nonequilibrium processing

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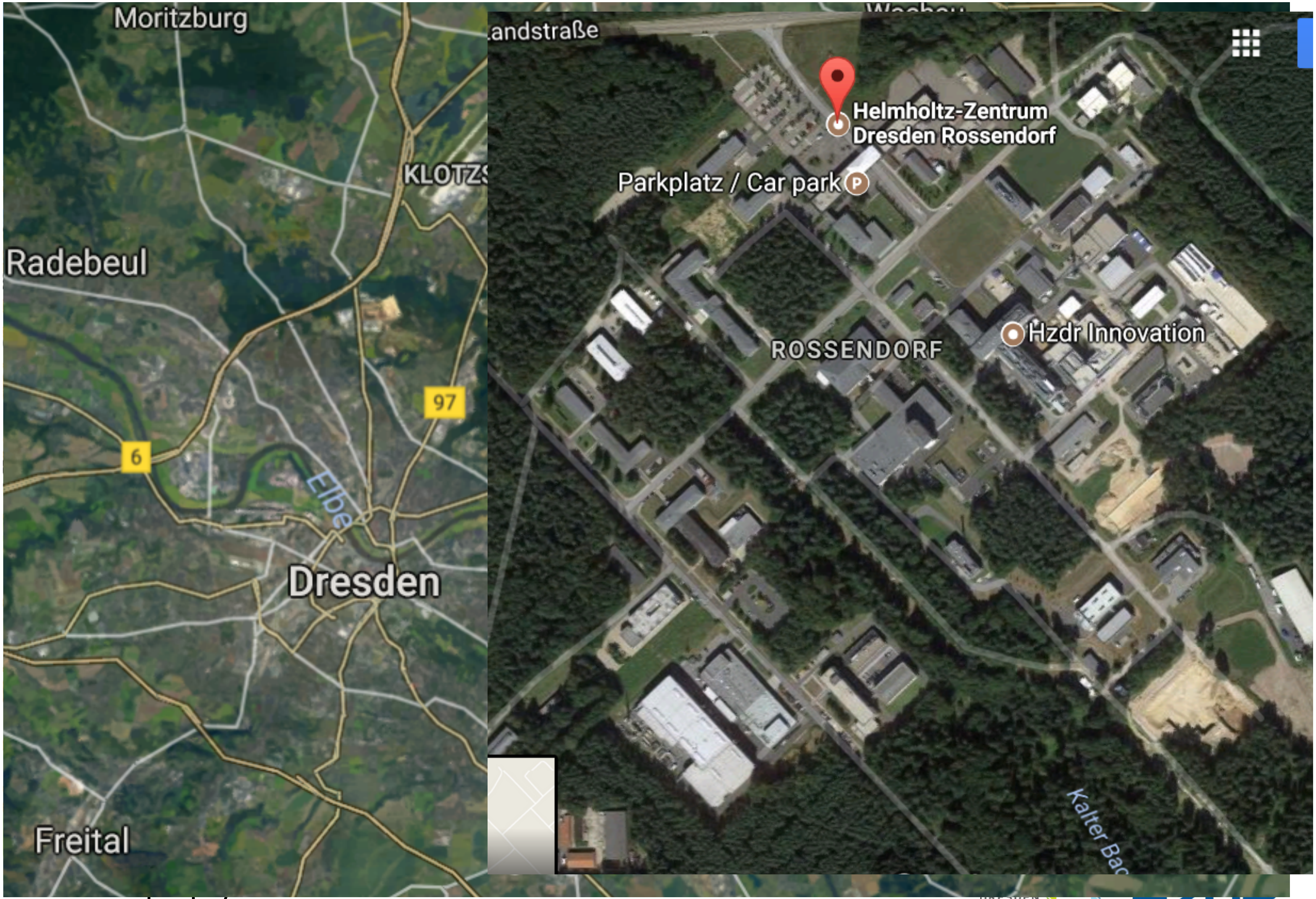
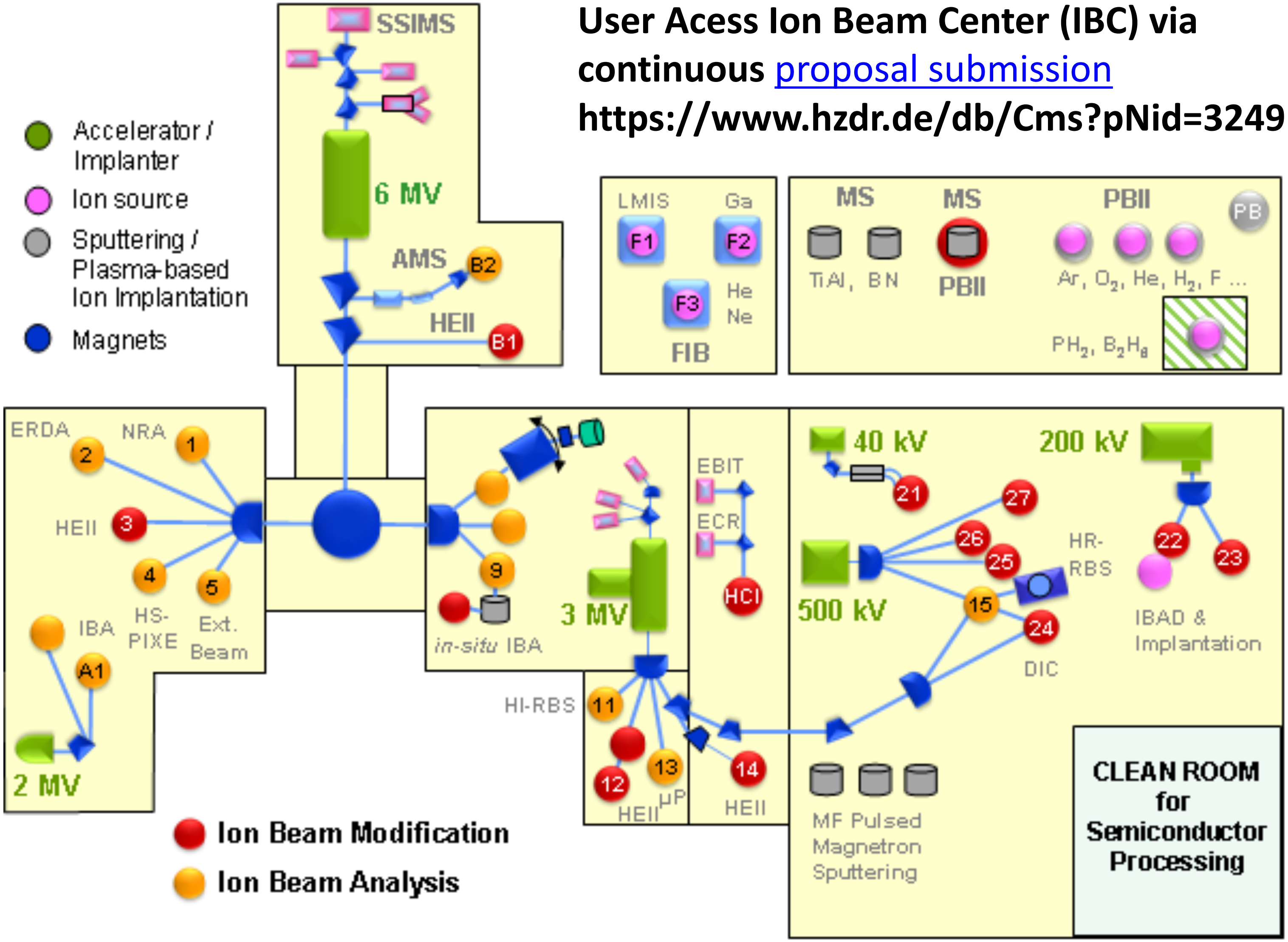


www.google.de/maps

Ion implantation at HZDR

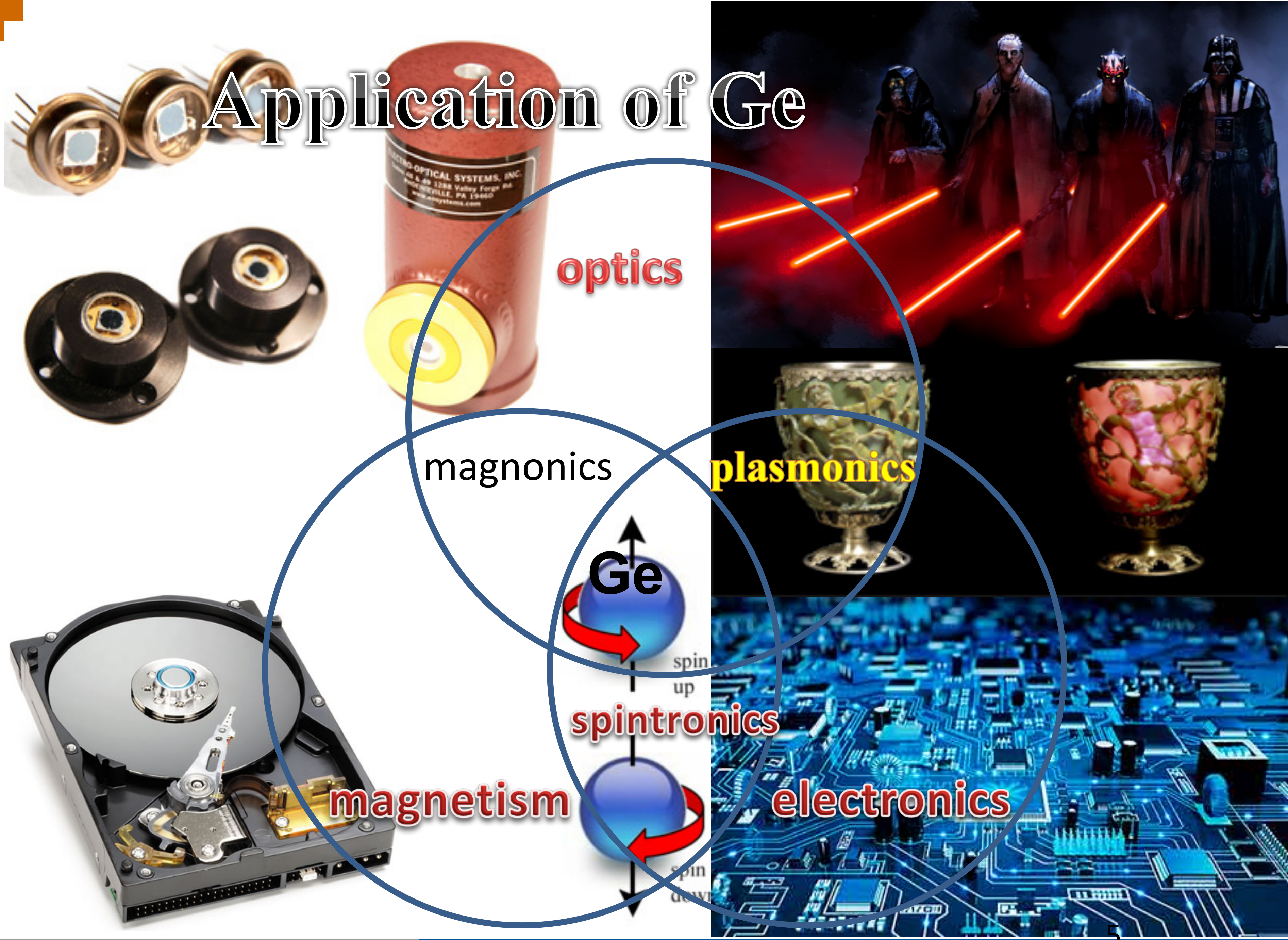
User Acess Ion Beam Center (IBC) via continuous proposal submission https://www.hzdr.de/db/Cms?pNid=3249



Outline

1. Doping of Ge
2. Ultra-doped Ge: superconductivity and plasmonics
3. Ultra-doped Ge: electronics
4. Ge for lasers
5. Conclusions

Application of Ge



optics

magnonics

plasmonics

Ge

spintronics

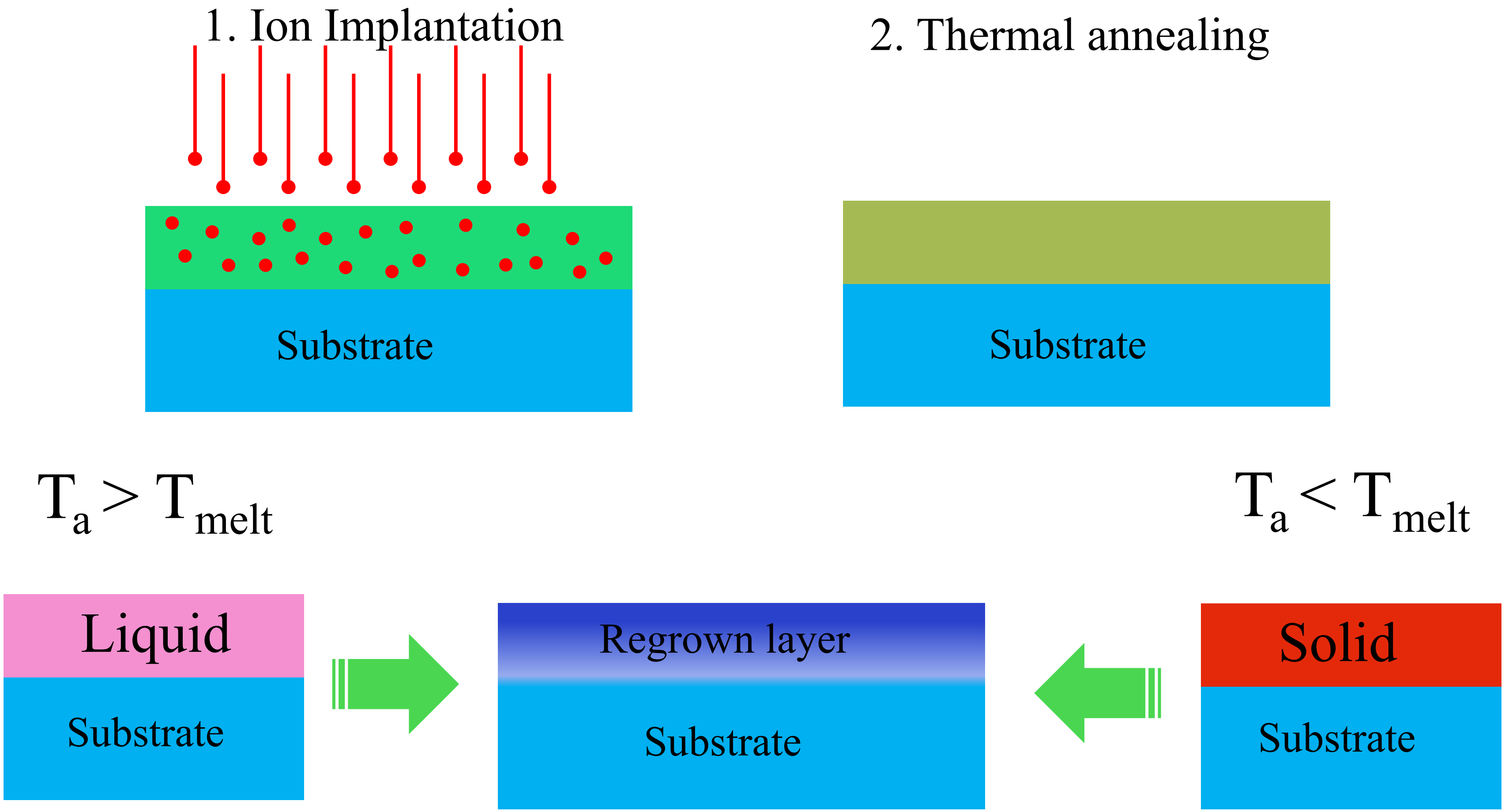
magnetism

electronics

Ultra-doped Ge and Ge-alloys

- MBE
- CVD
- Ion implantation + nonequilibrium annealing
  - Laser annealing (ns-range)
  - Plasma treatment (µs-range)
  - Flash lamp annealing (ms-range)
- ...

Ion implantation



1. Ion Implantation

2. Thermal annealing

Substrate

Substrate

$T_a > T_{melt}$

$T_a < T_{melt}$

Liquid

Substrate

Regrown layer

Substrate

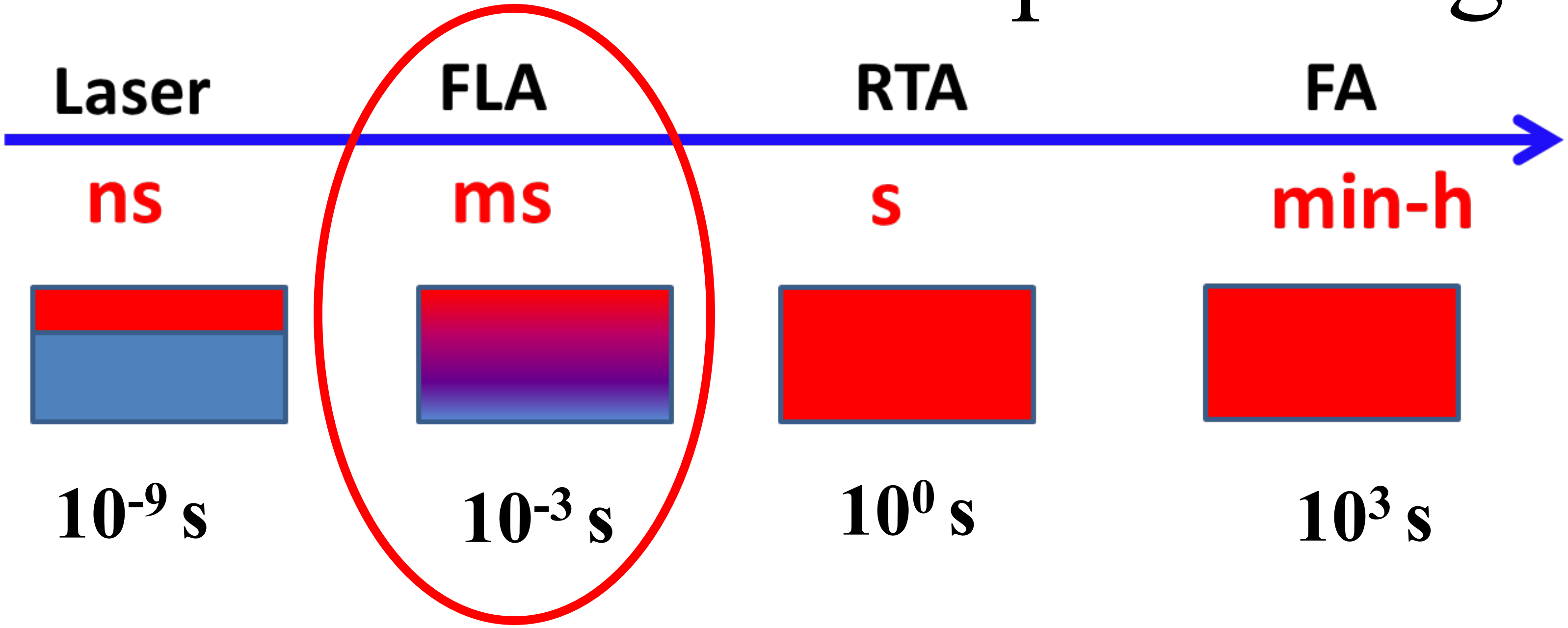
Solid

Substrate

Liquid Phase Epitaxy

Solid Phase Epitaxy

Advanced thermal processing



Laser | FLA | RTA | FA

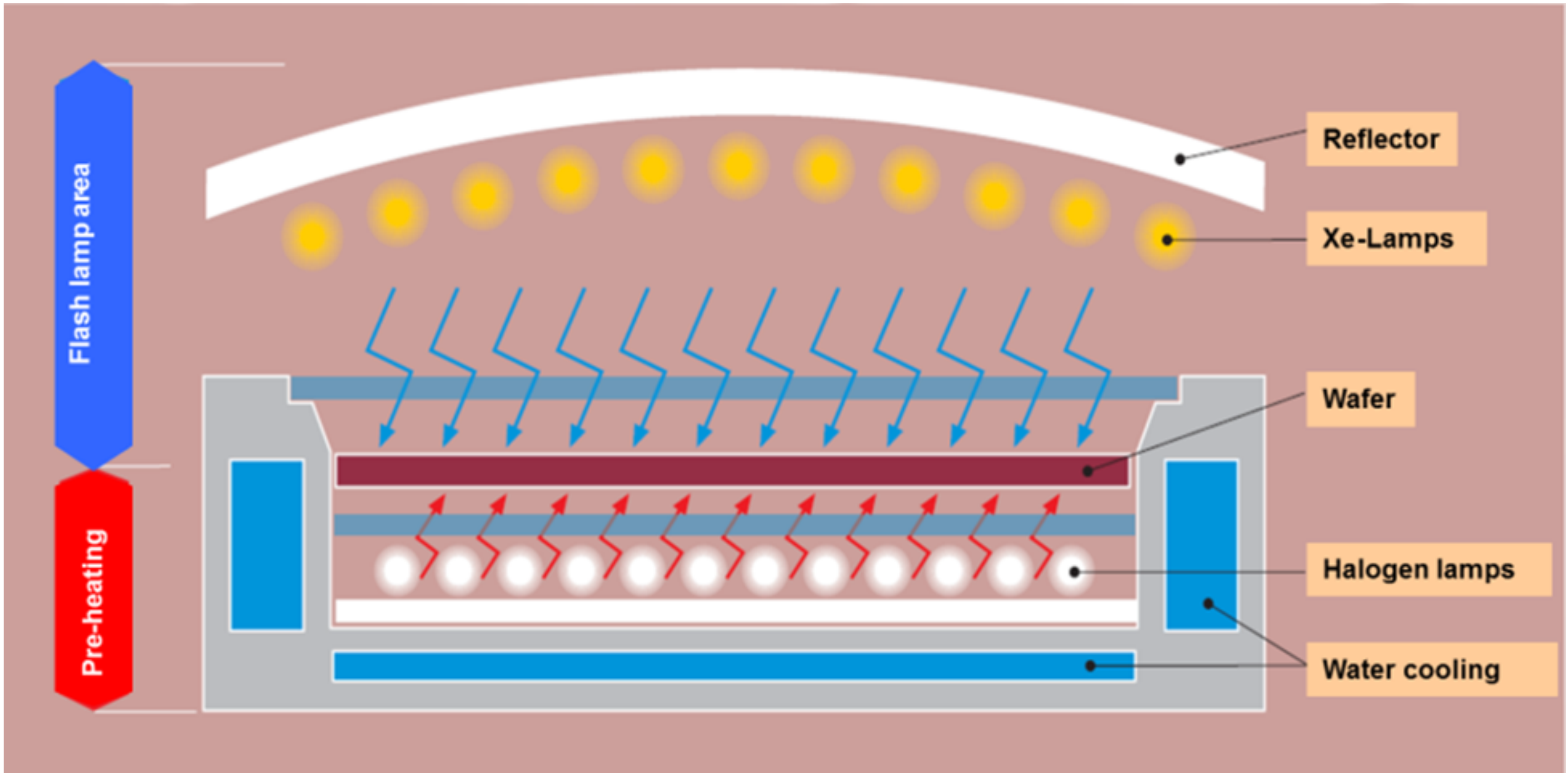
ns | ms | s | min-h

10^{-9} s | 10^{-3} s | 10^{0} s | 10^{3} s

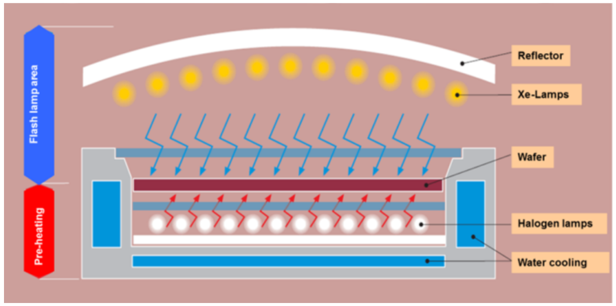
- **Ion implantation + <u>Sub-second annealing</u>:**

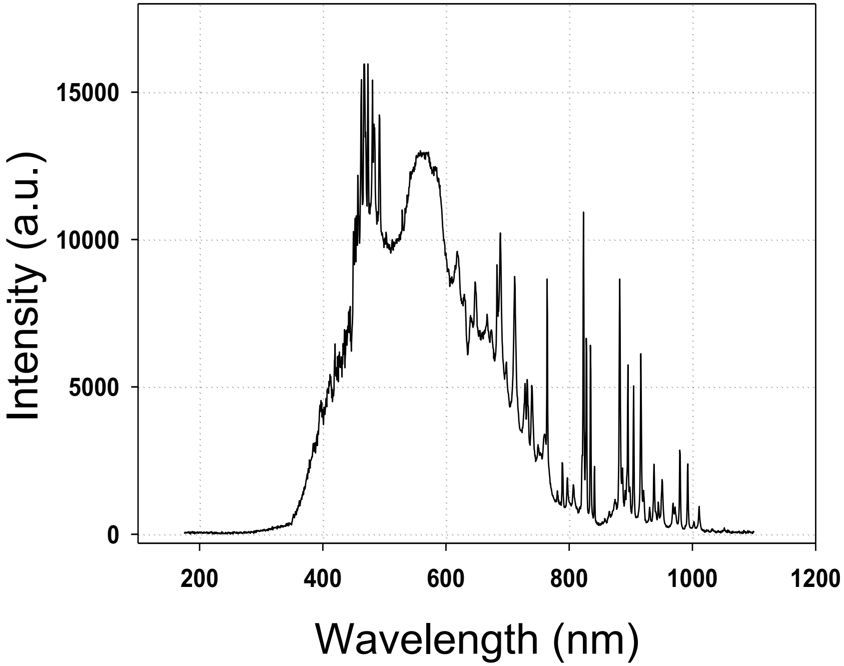
semiconductor processing far away from thermal equilibrium

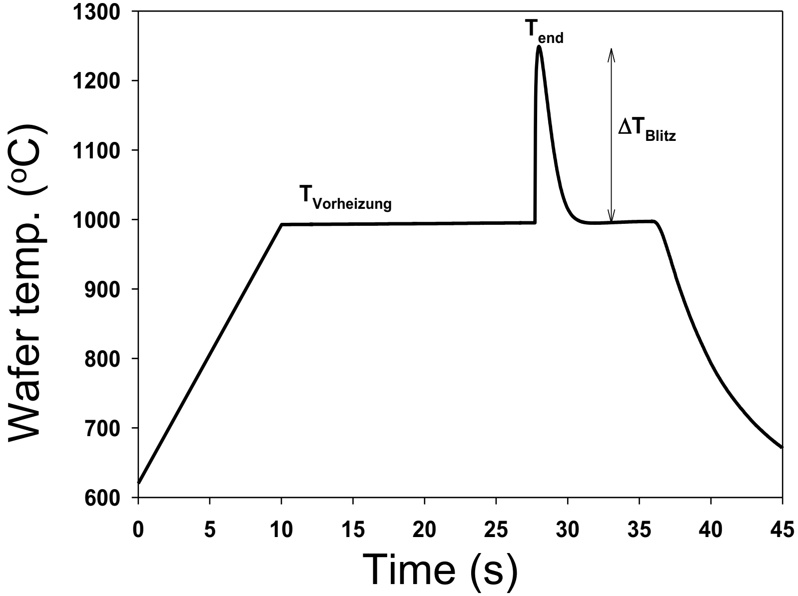
Flash lamp system at HZDR



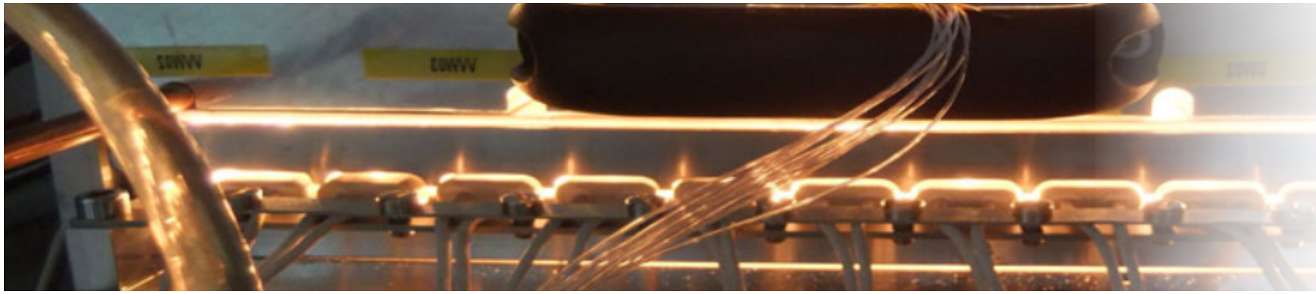
Flash lamp system at HZDR





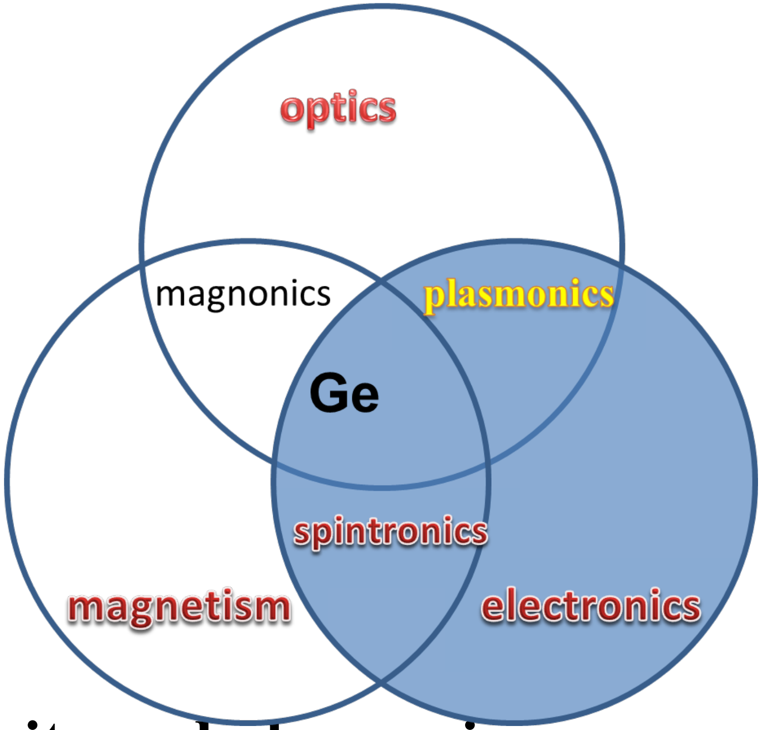


Flash lamp system



https://www.hzdr.de/db/Cms?pNid=3235

- FLA parameters
  - Lab scale up to 8 inch for single shot
  - Max temp. up to 2000 °C (achieved in SiC)
  - Annealing time 0.6 to 20 ms
  - Possible preheating up to 900 °C



Outline

1. Doping of Ge
2. **Ultra-doped Ge: superconductivity and plasmonics**
3. Ultra-doped Ge: electronics
4. Ge for lasers
5. Conclusions

Ultra-doped Ge

superconductivity

Requirements:
p-type Ge
Al, Ga, In
carrier concentration >5x10^{20}cm^{-3}
Single crystalline material

Challanges:
Dopant Segregation: metallic clusters
Low solubility limit (<5x10^{20}cm^{-3})
Diffusion

Dreams:
Quantum computers
Ultra-low power consumption devices

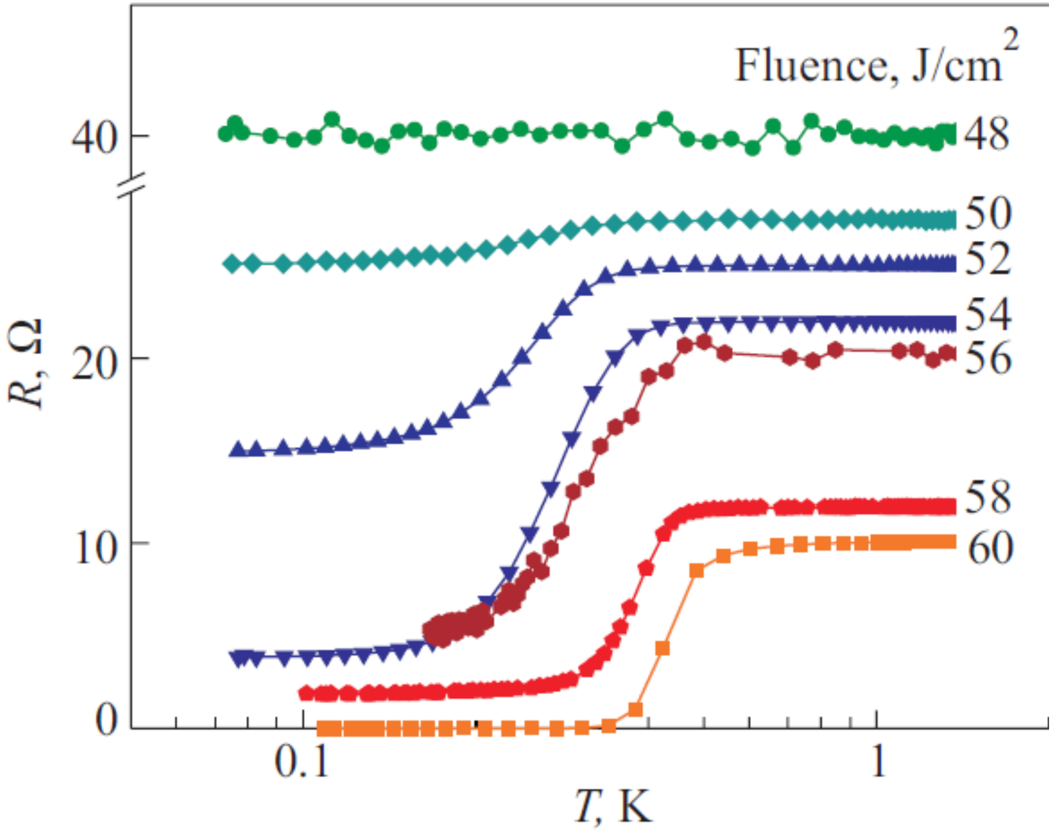
plasmonics

Requirements:
n-type Ge
P or As
carrier concentration >5x10^{19}cm^{-3}
Single crystalline material

Challanges:
Dopant Segregation
out-diffusion
Low solubility limit (<2x10^{20}cm^{-3})
p-type defects

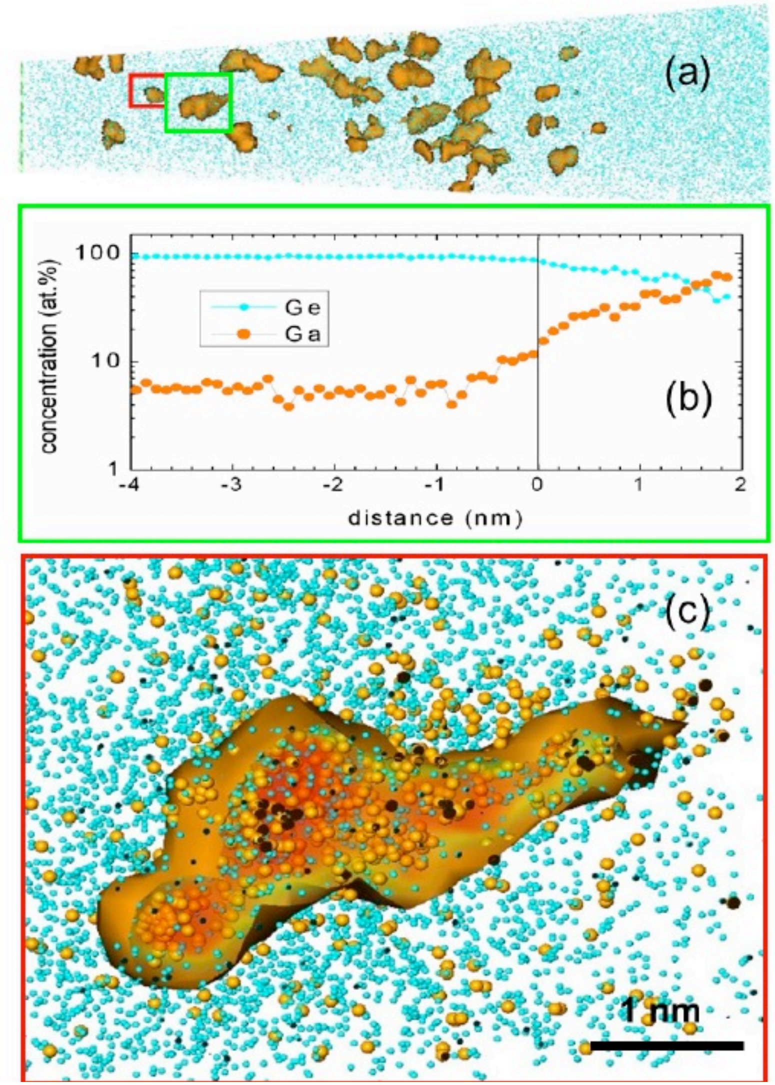
Dreams:
Detectors for bio-...
Lasers

Ultra-doped Ge: superconductivity



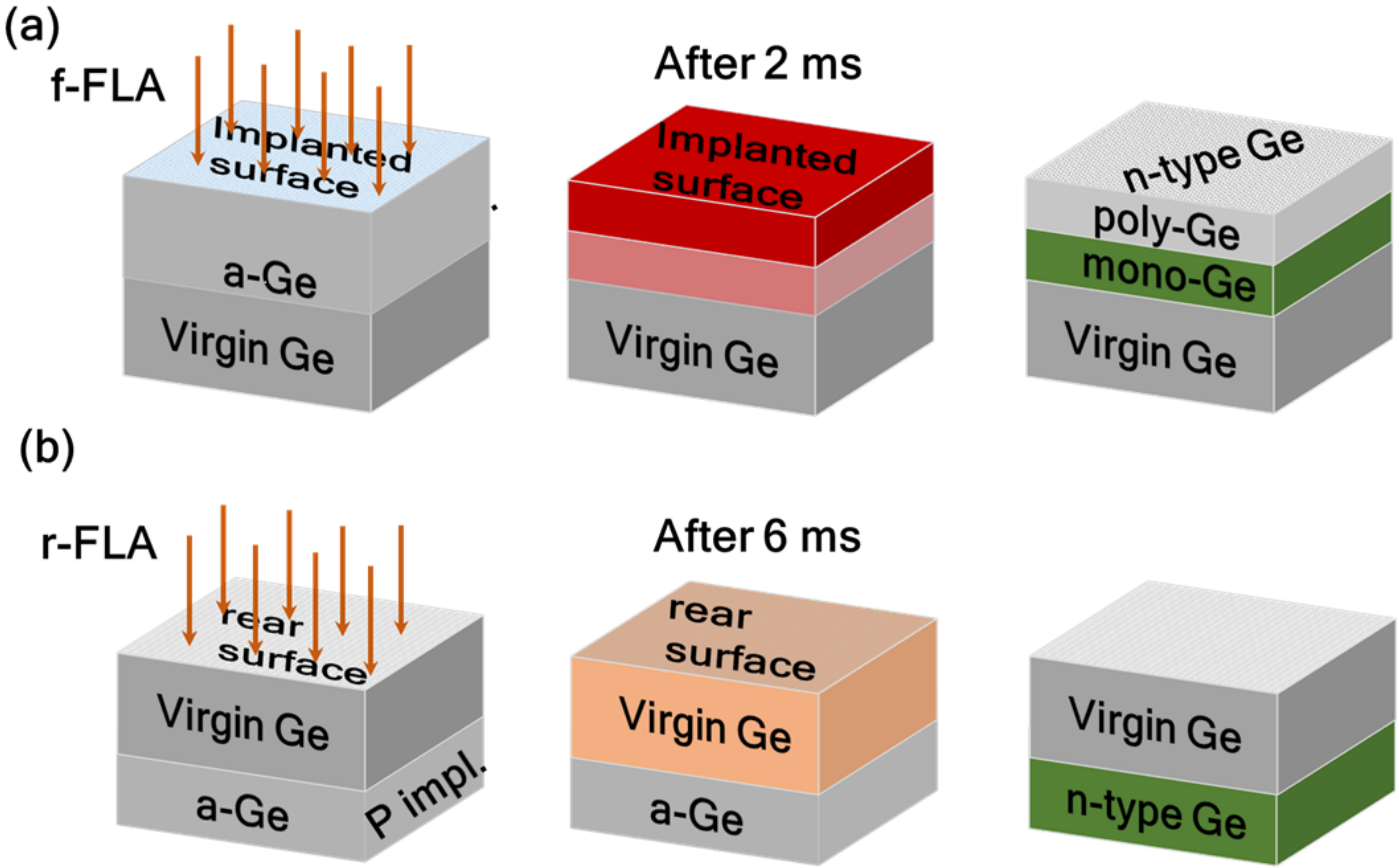
Ga concentration: $4\text{x}10^{21}$ cm^{-3}

After: V. Heera et al. Low Temperature, 37, 1098 (2011)



Supercond. Sci. Technol. **27** (2014) 055025

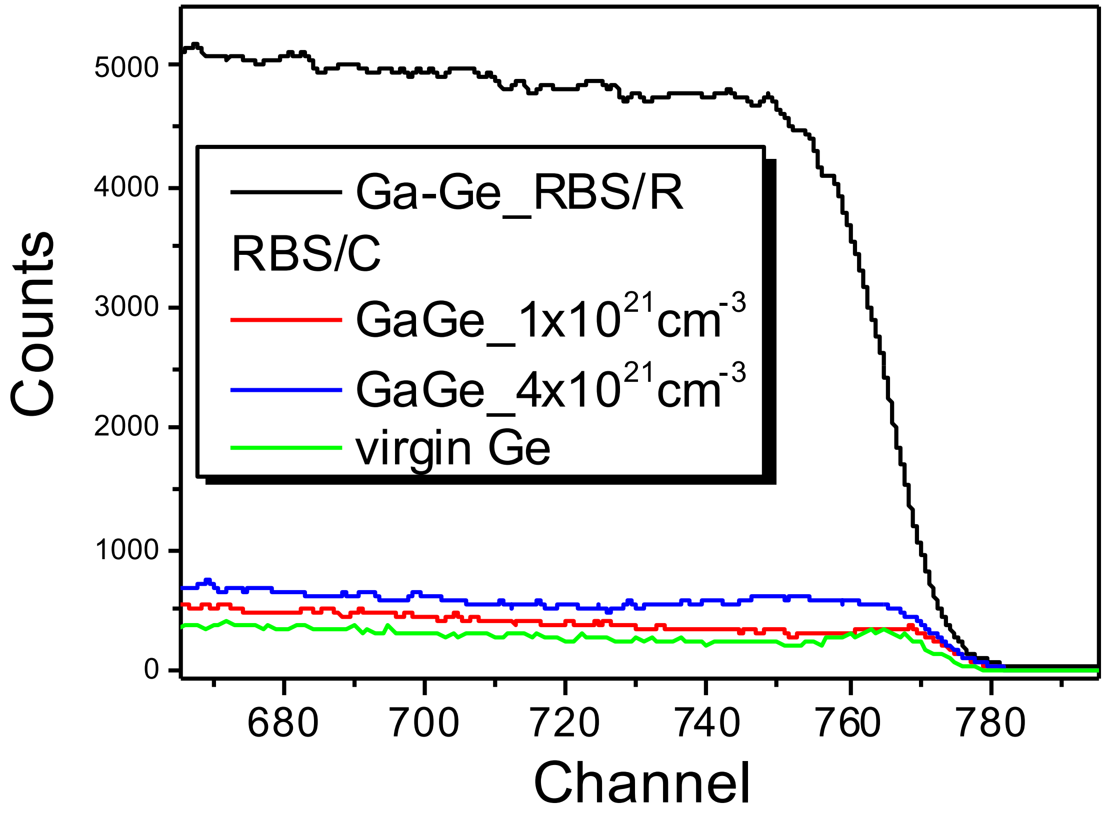
f-FLA vs r-FLA



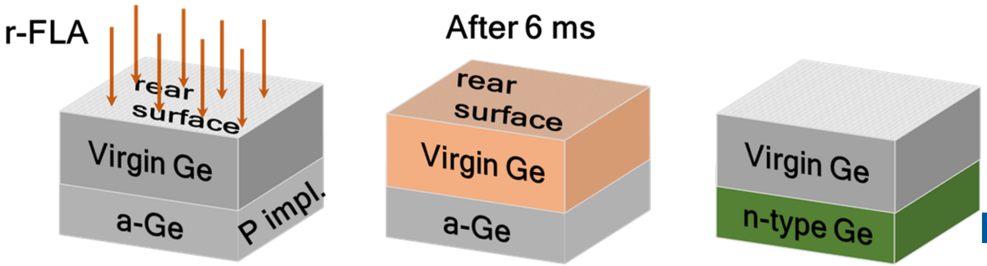
S. Prucnal, *et al.* Sci. Rep. **6**, 27643 (2016).

Ultra-doped Ge: superconductivity

New approach for the old samples: **r-FLA**

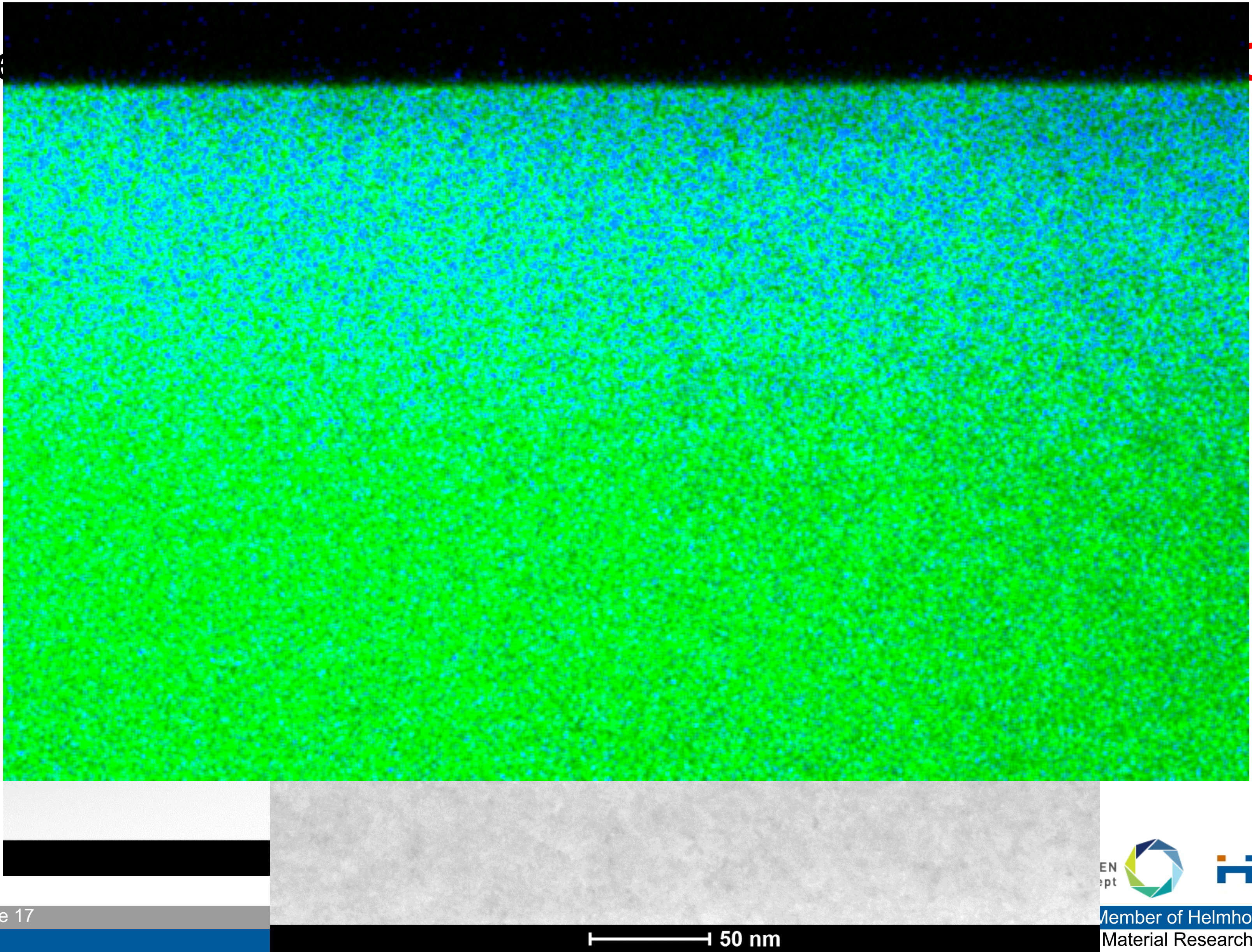


Annealing: r-FLA for 20 ms at 115 Jcm^{-2}



Ultra-doped Ge: superconductivity

Ne … 0^{21}cm^{-3})

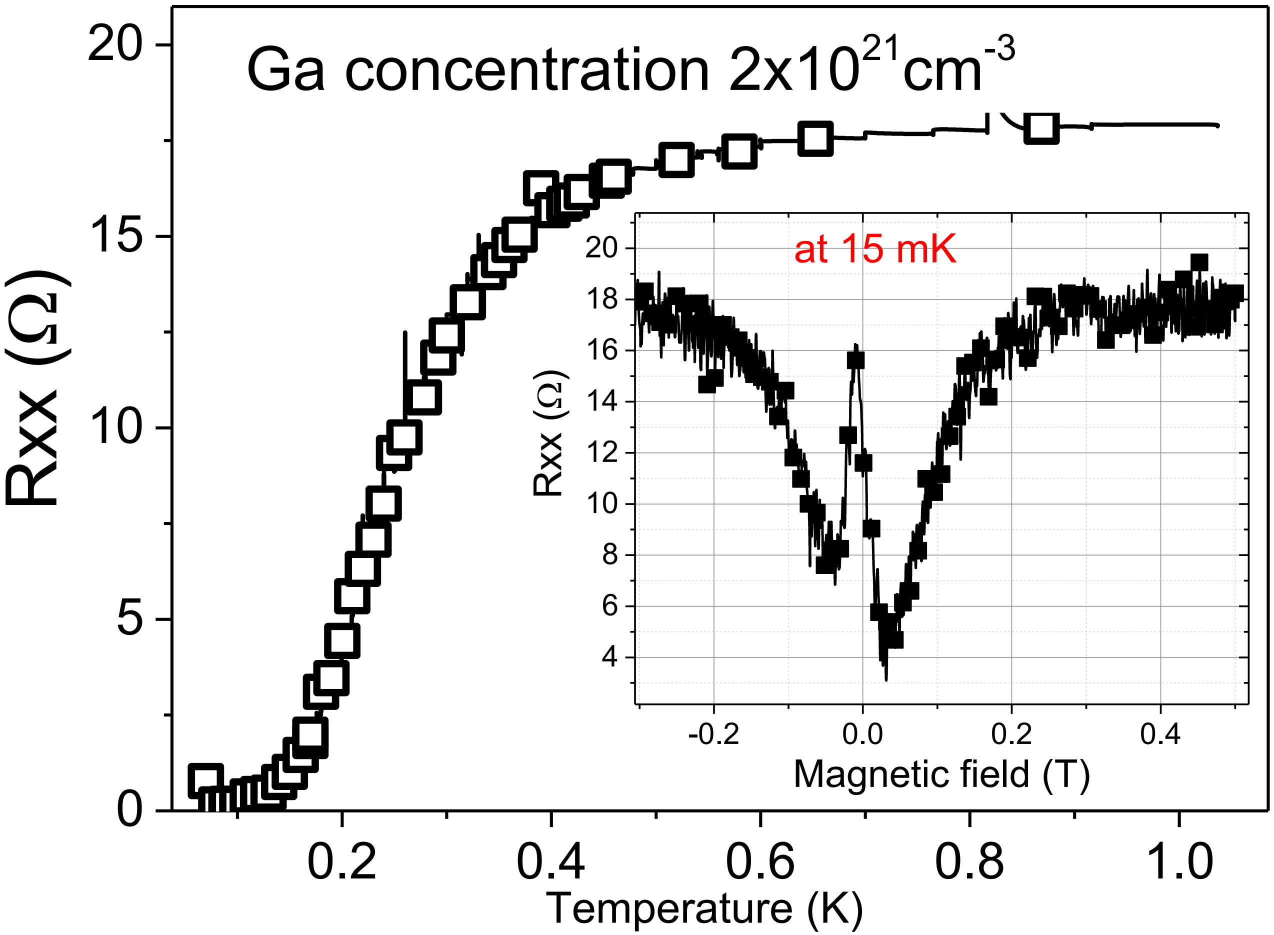


Ga

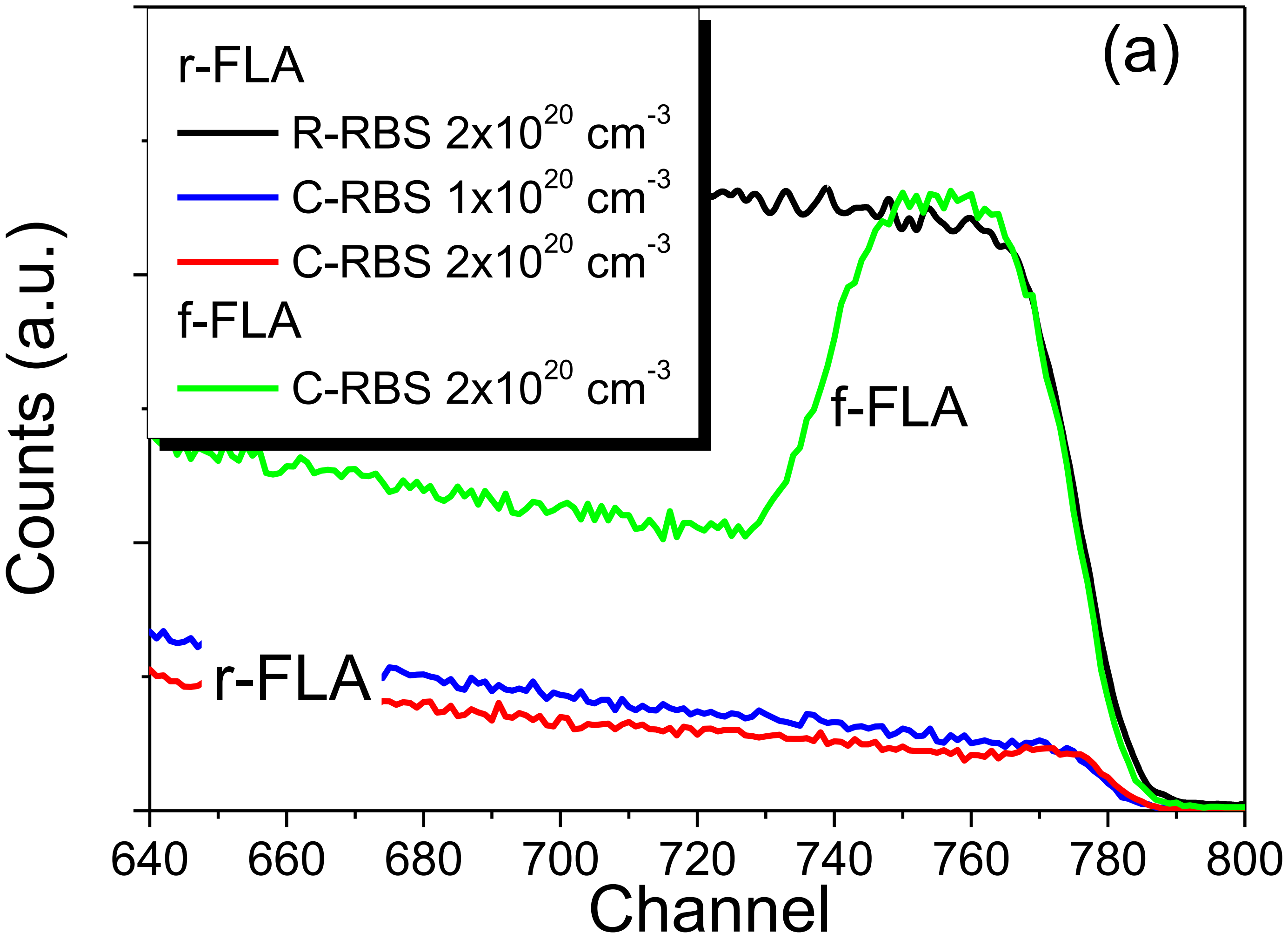
Ge

Si

Ultra-doped Ge: superconductivity



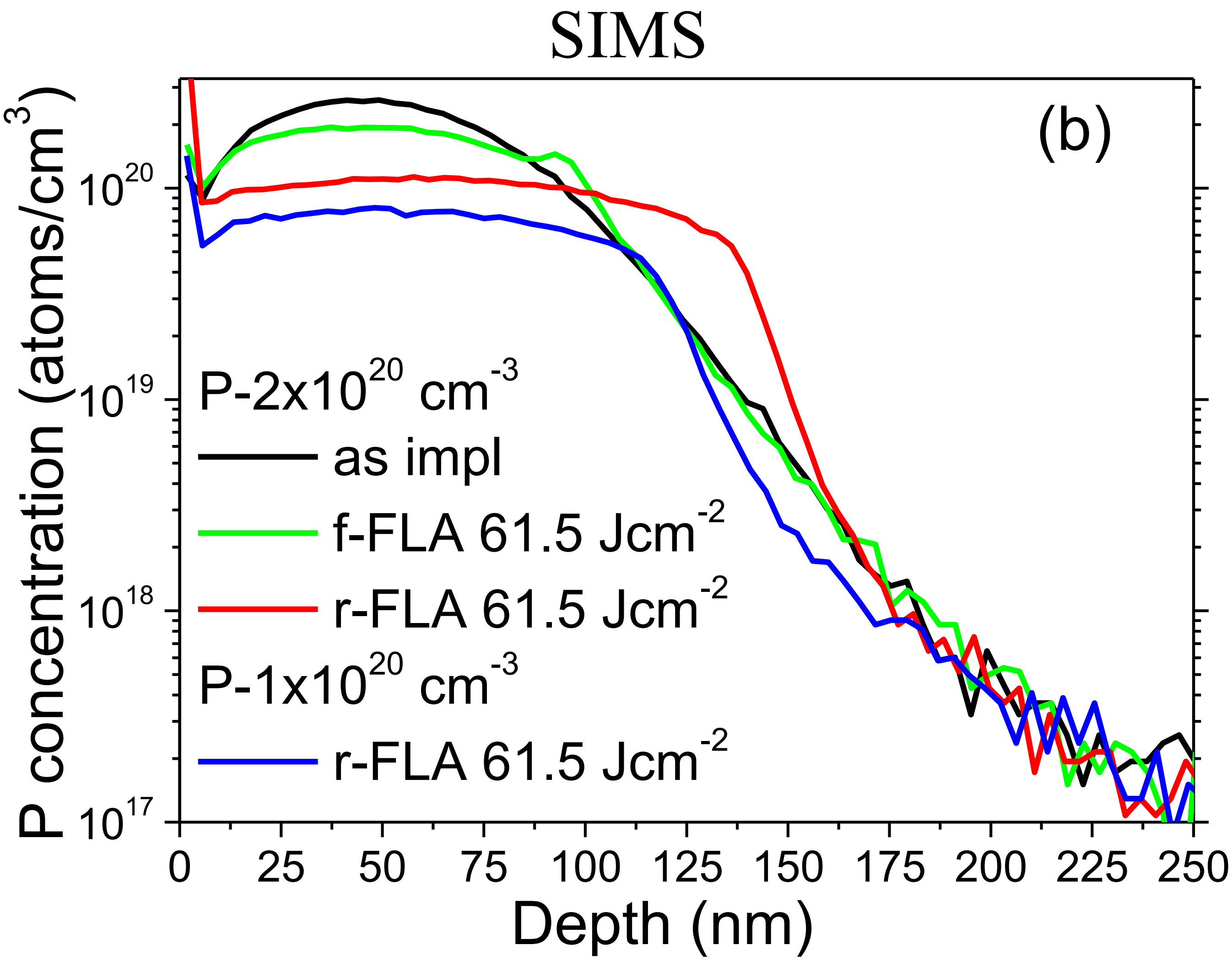
Ultra-doped Ge: **plasmonics**



RBS from P implanted Ge followed by r-FLA

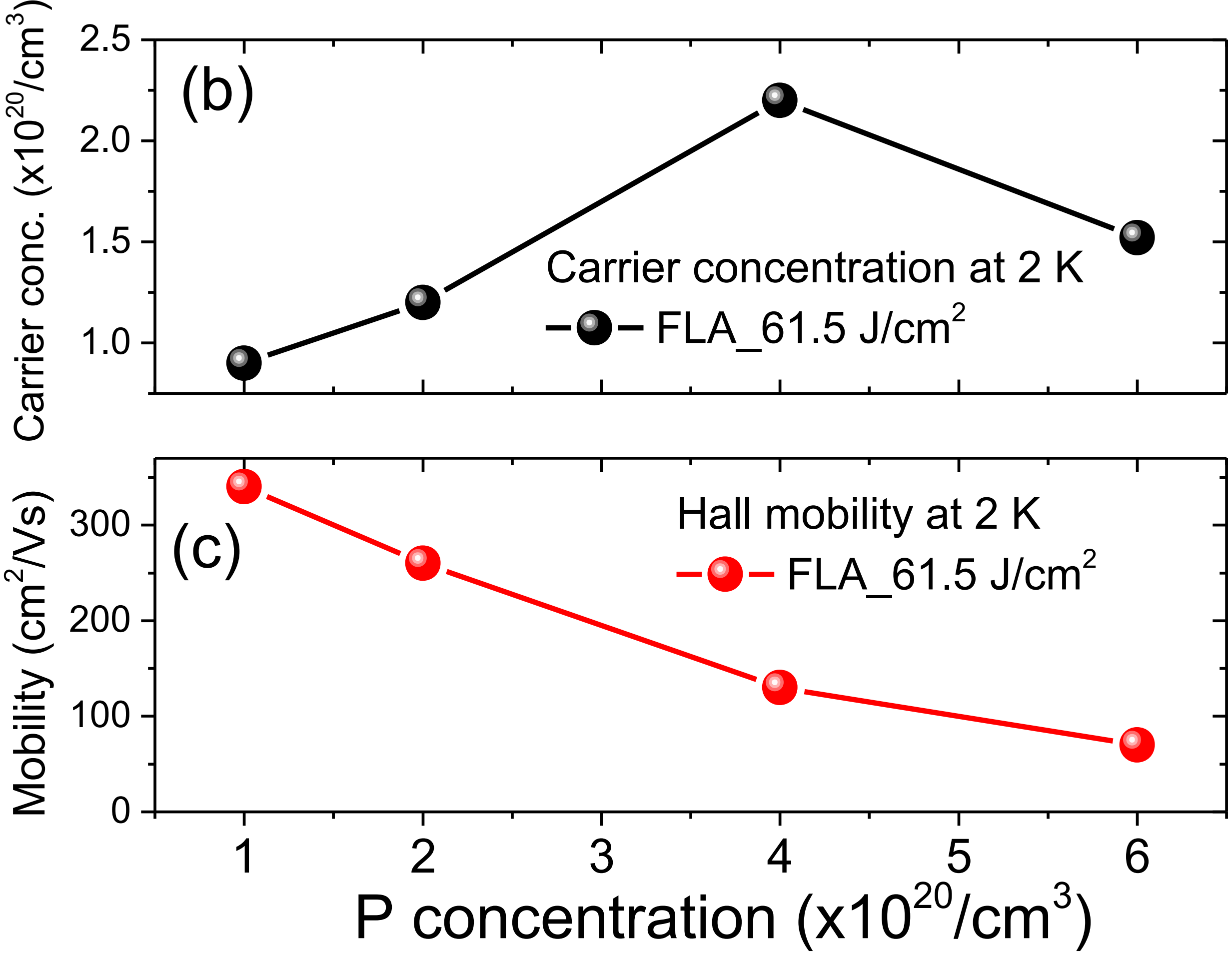
Sci.Rep. **6**, 27643, (2016)

Ultra-doped Ge: plasmonics



Sci.Rep. **6**, 27643, (2016)

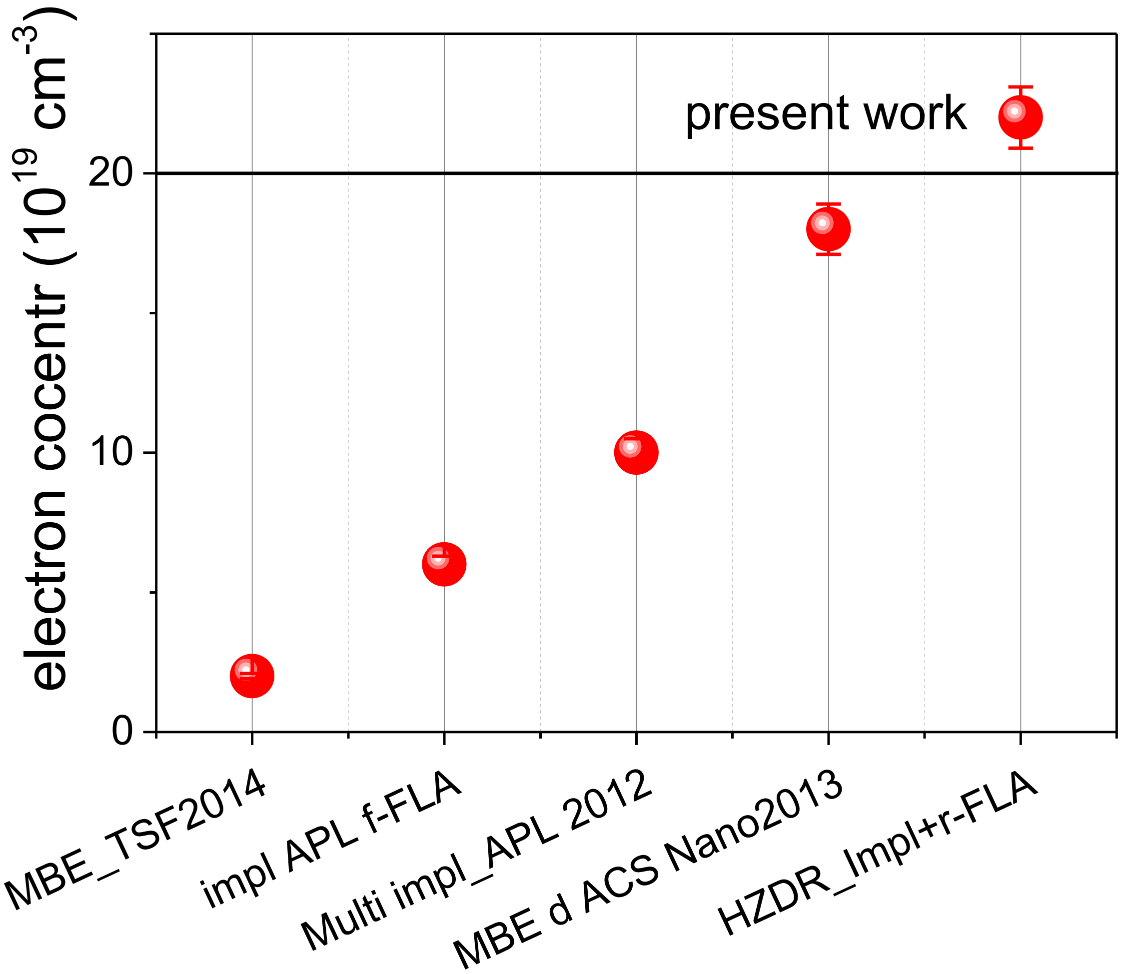
Ultra-doped Ge: plasmonics



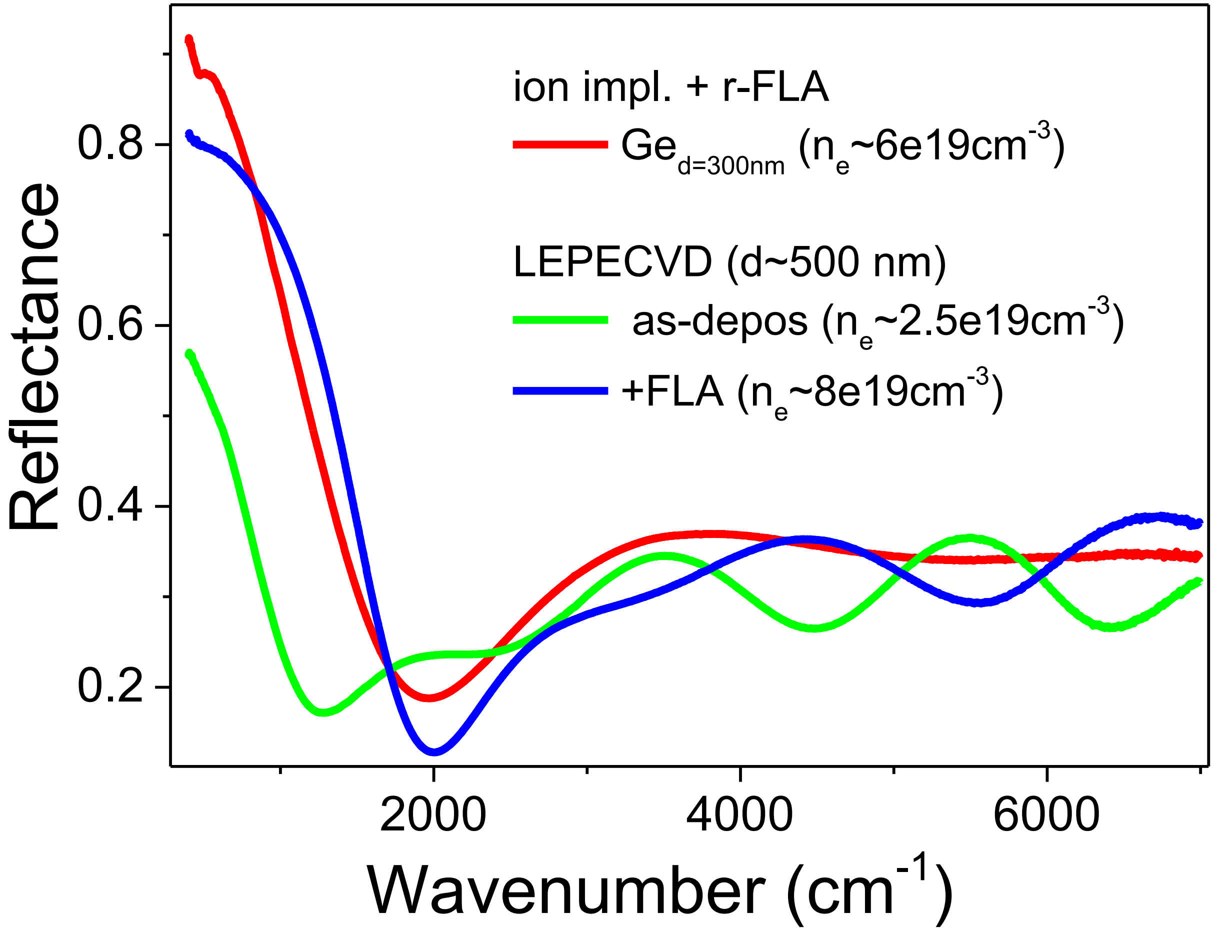
Hall effect

The highest activation efficiency (above 80 %) was obtained for P concentration of $2x10^{20}$ cm^{-3}. The doping above $4x10^{20}$cm^{-3} leads to electrically non-active P-P dimer formation.

Ultra-doped Ge: plasmonics

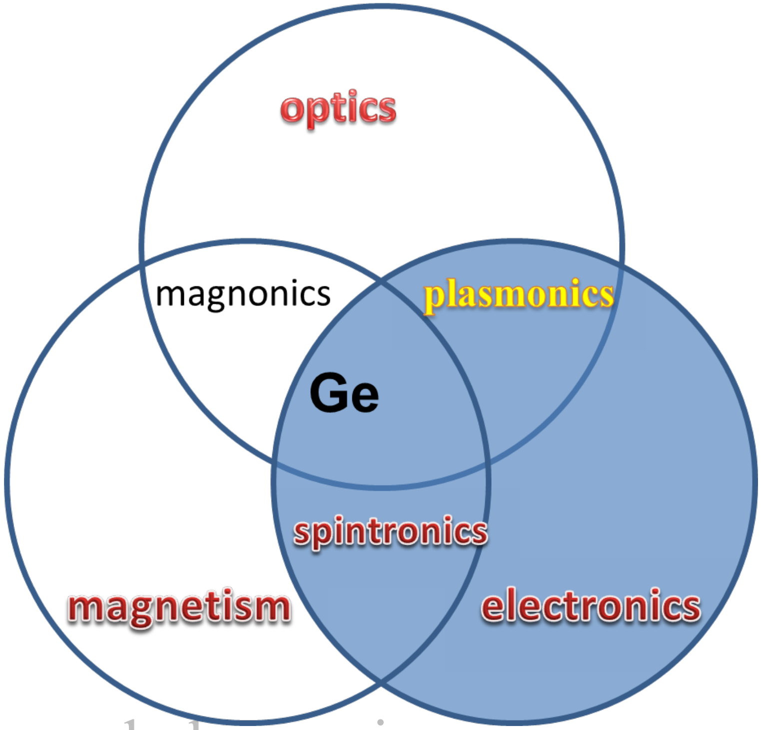


Ultra-doped Ge: plasmonics



LE PECVD samples are from G. Isella L-NESS, Milano

Outline



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Ultra-doped Ge: electronics

Yesterday

Si

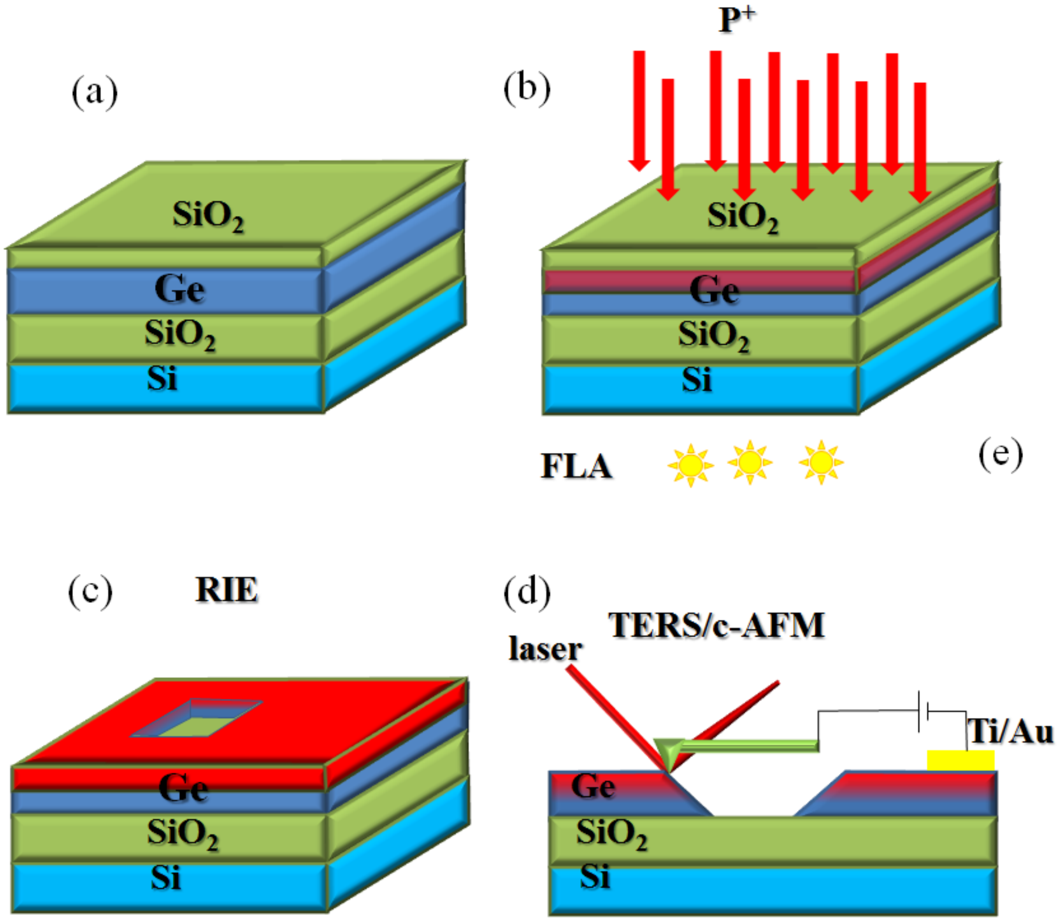
Today

http://images-2.drive.com.au/2010/08/20/1812428/VW-Beetle_420_m-420x0.jpg

Ge

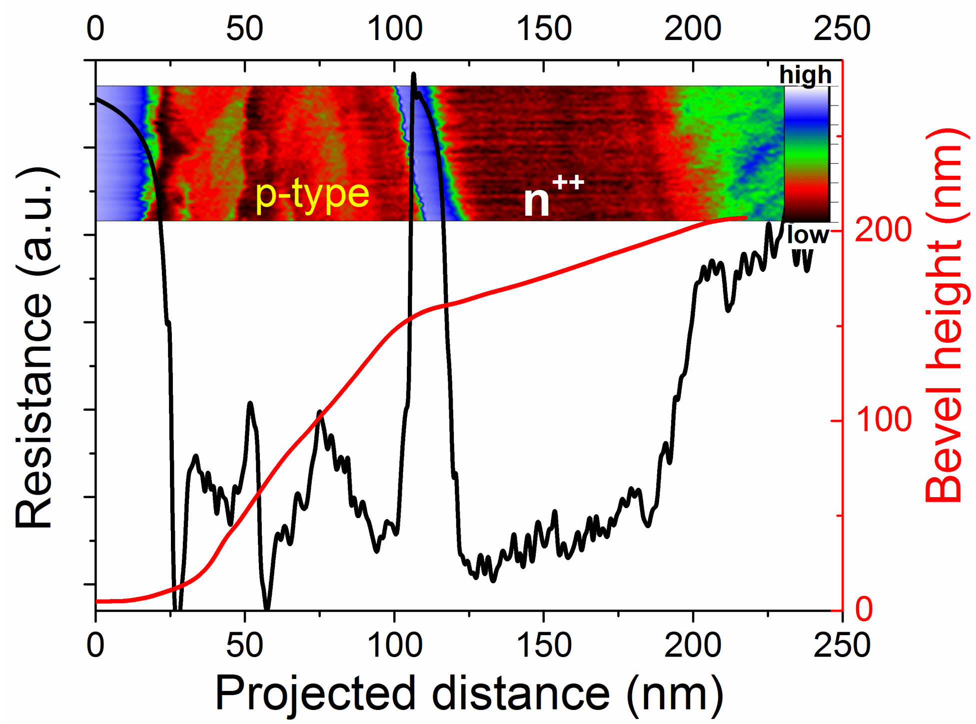
Tomorrow

Ultra-doped Ge: electronics

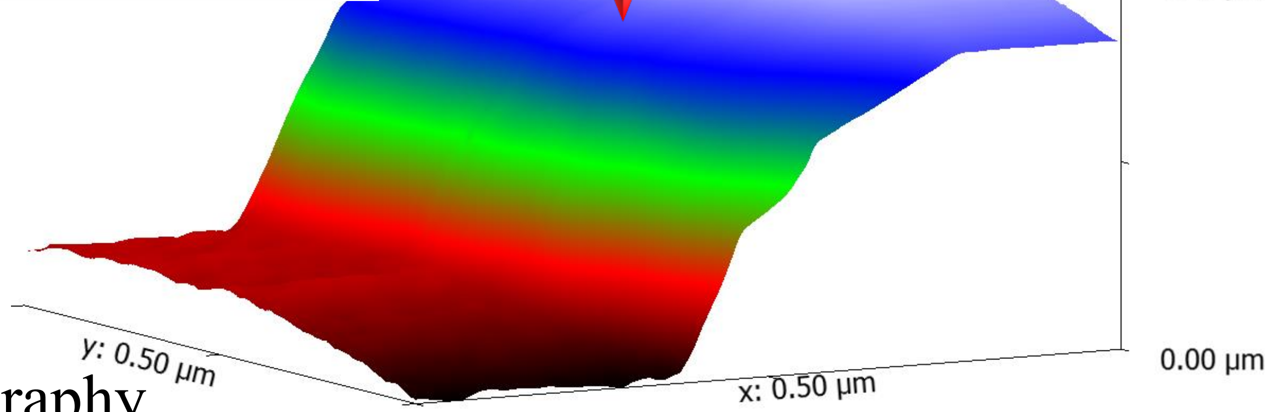


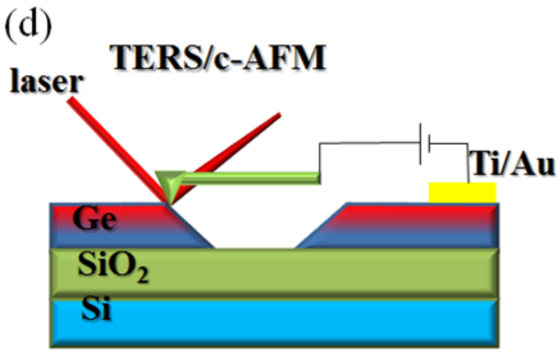
1. SiO_2 deposition
2. ion implantation ($5\times10^{15}cm^{-2}$)
3. rear side FLA for 20 ms
4. SiO_2 etching
5. e-beam lithography
6. reactive ion etching (SF_6+O_2)
7. ohmic contact formation to n-type Ge (Ti/Au)
8. characterization by TERS and c-AFM

Ultra-doped Ge: electronics



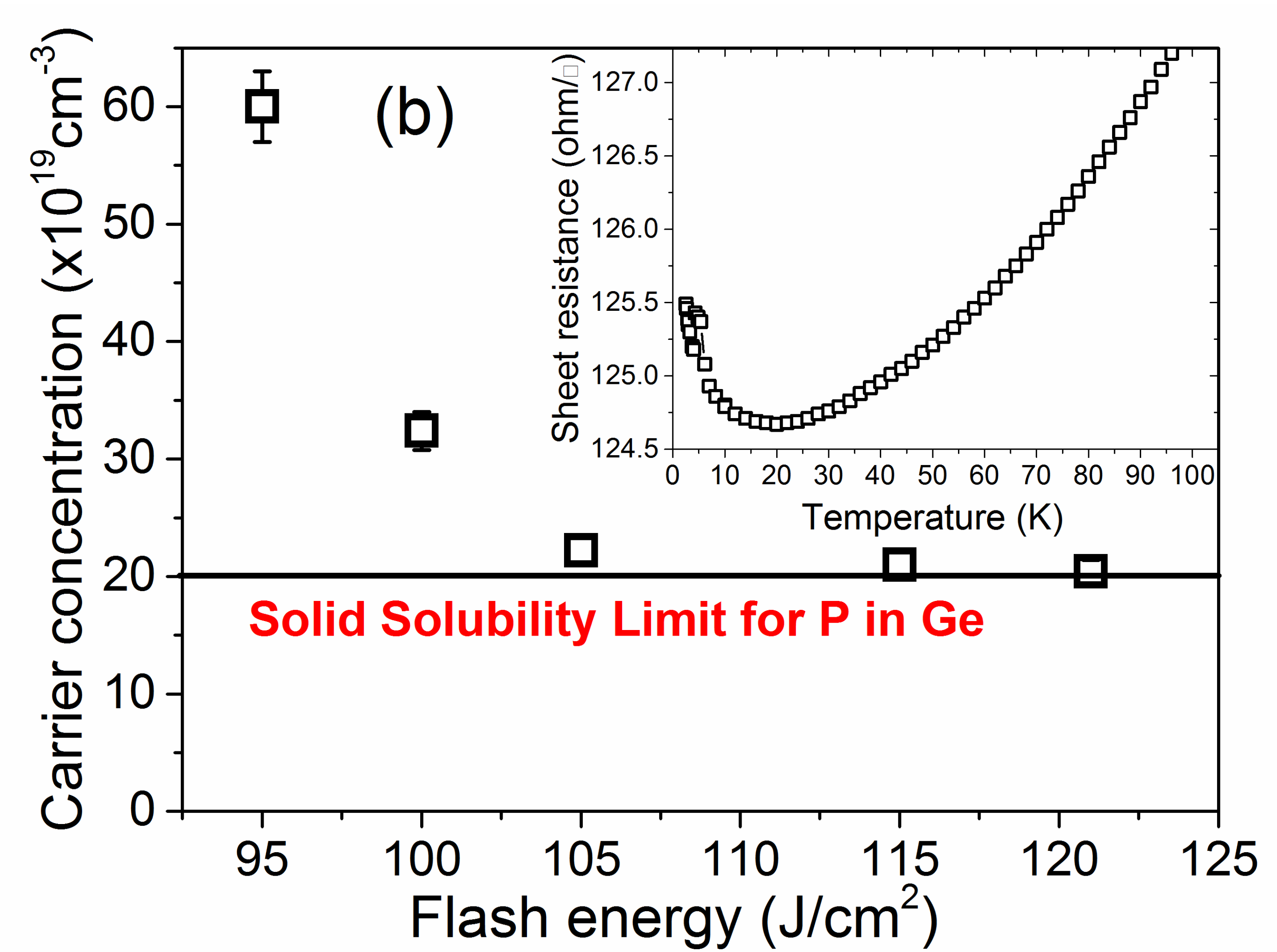
The resistance mapping over the n^{++}-p junction in GeOI made by c-AFM



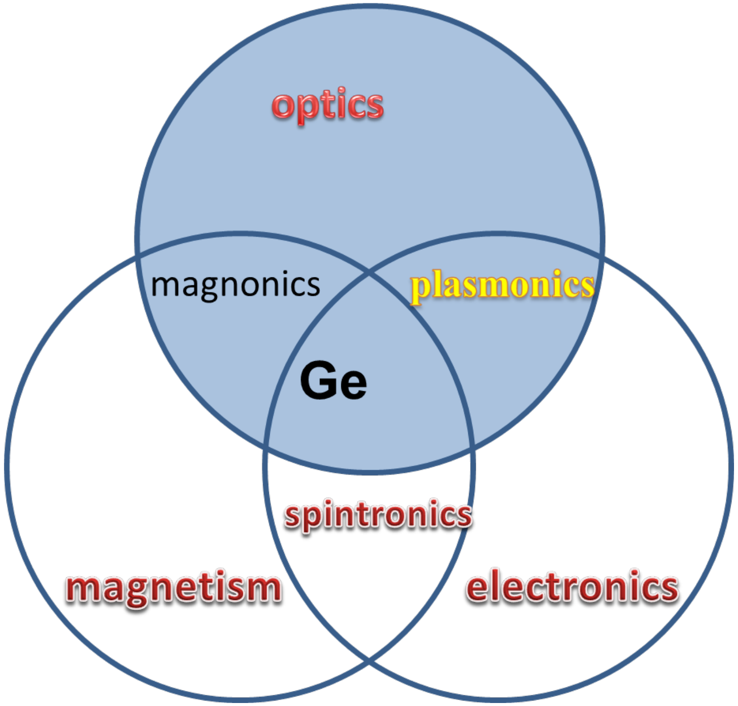


Topography

Ultra-doped Ge: electronics



Outline



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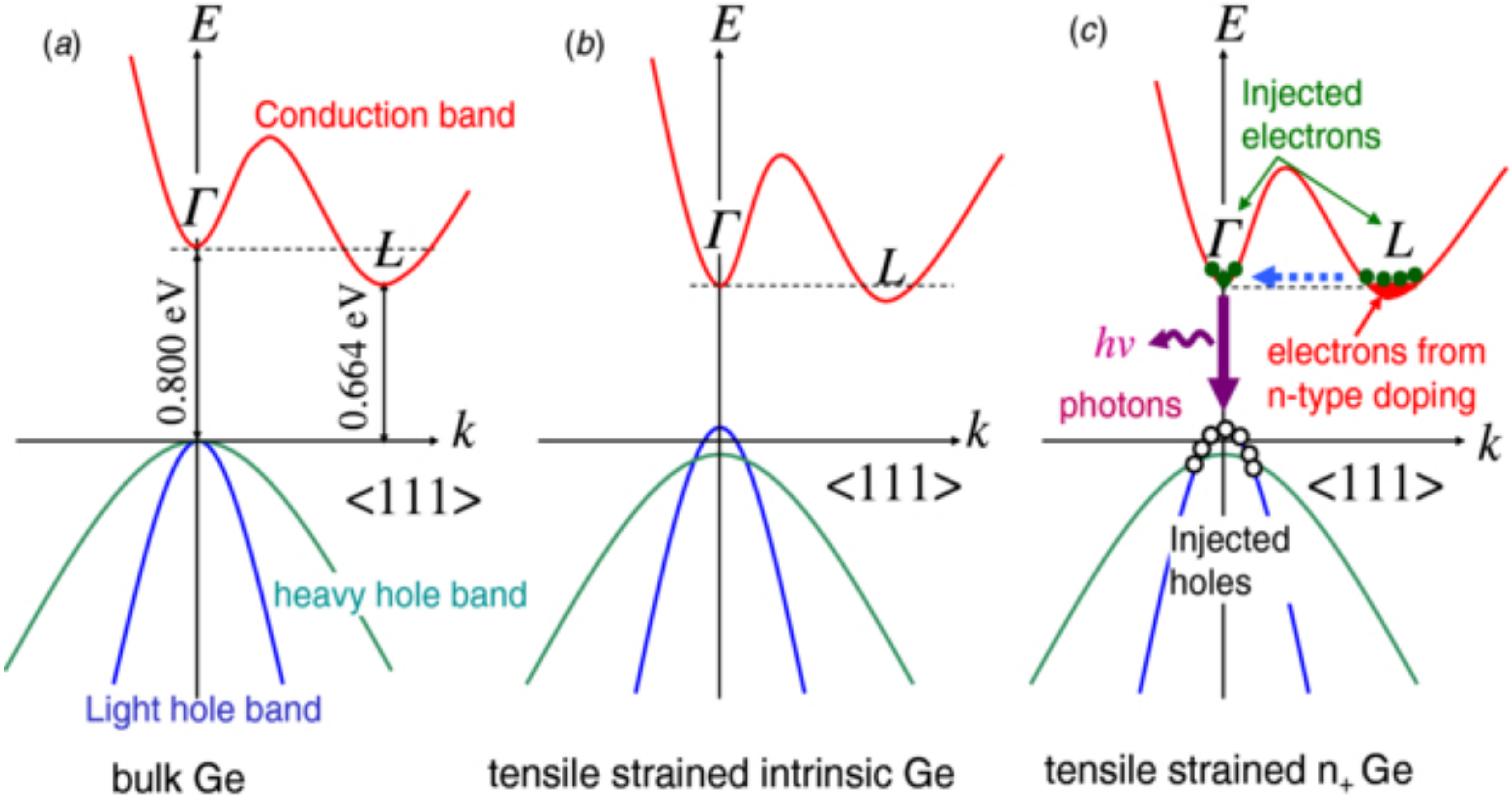
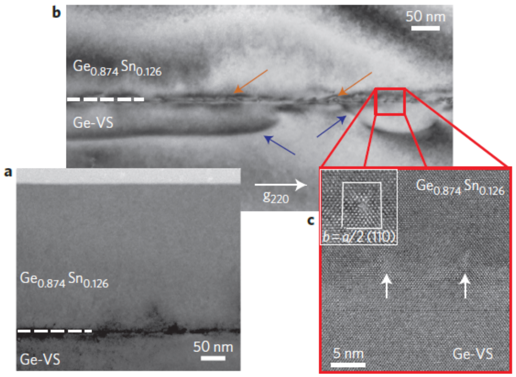
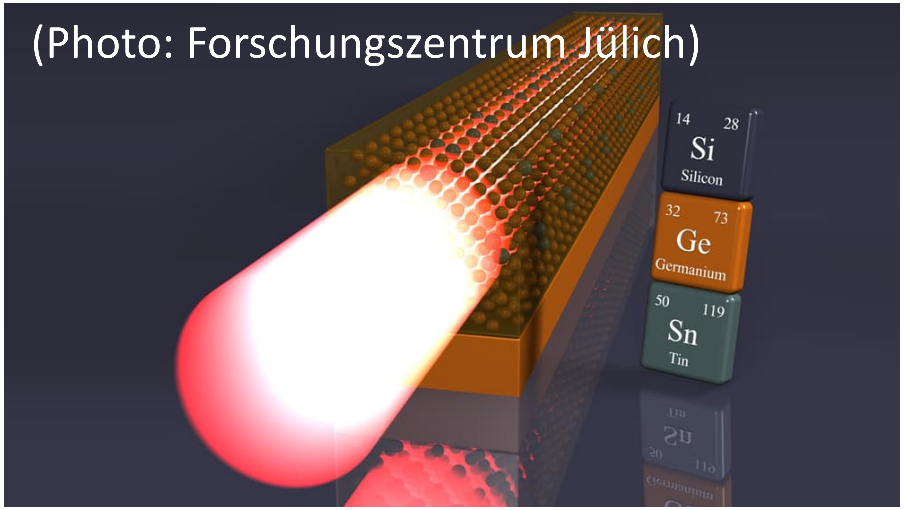
Band gap engineering in Ge

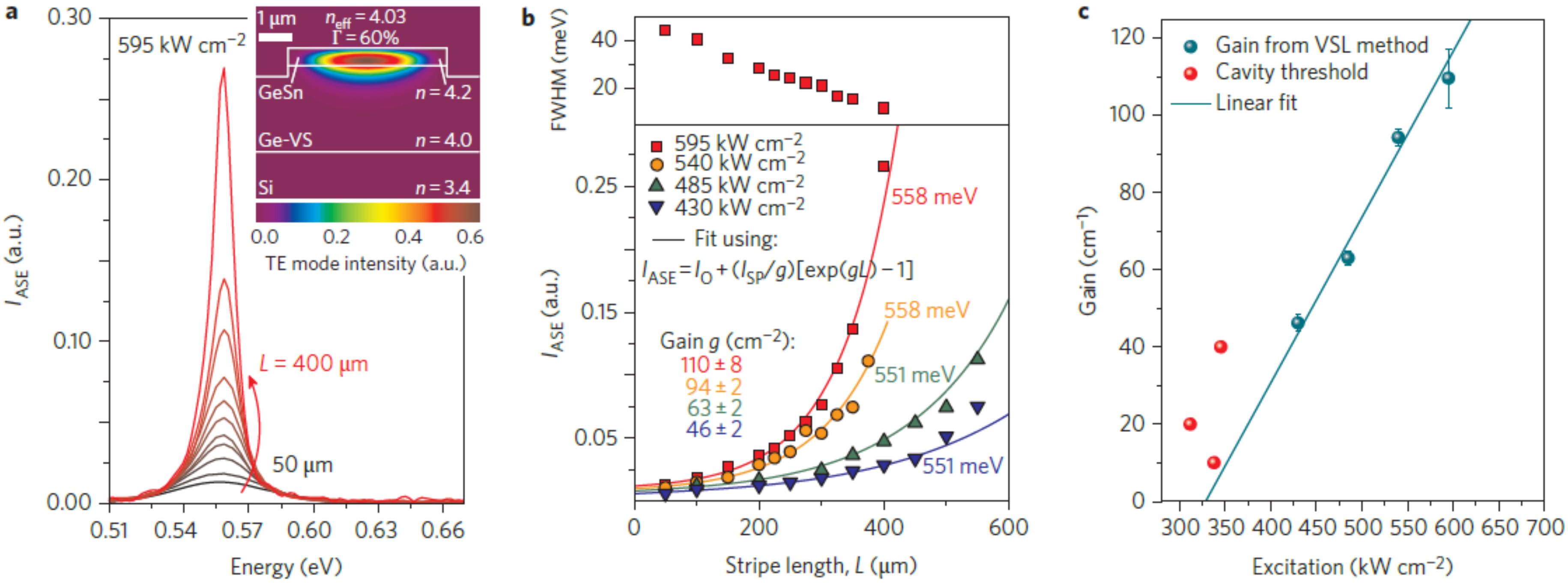


J. Liu, *et al. Photonics* **2014**, *1*(3), 162-197

Ge for lasers

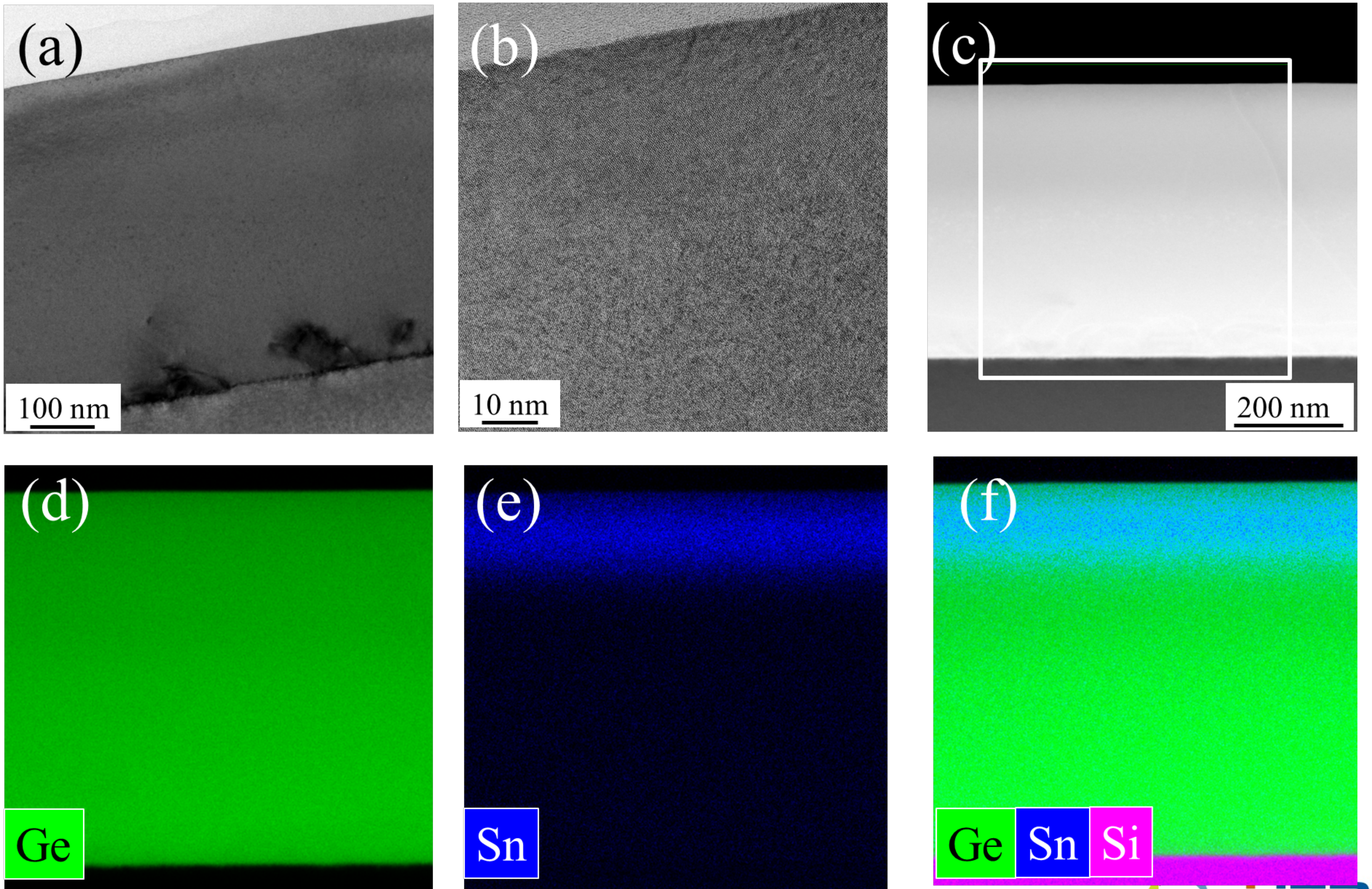



(Photo: Forschungszentrum Jülich)



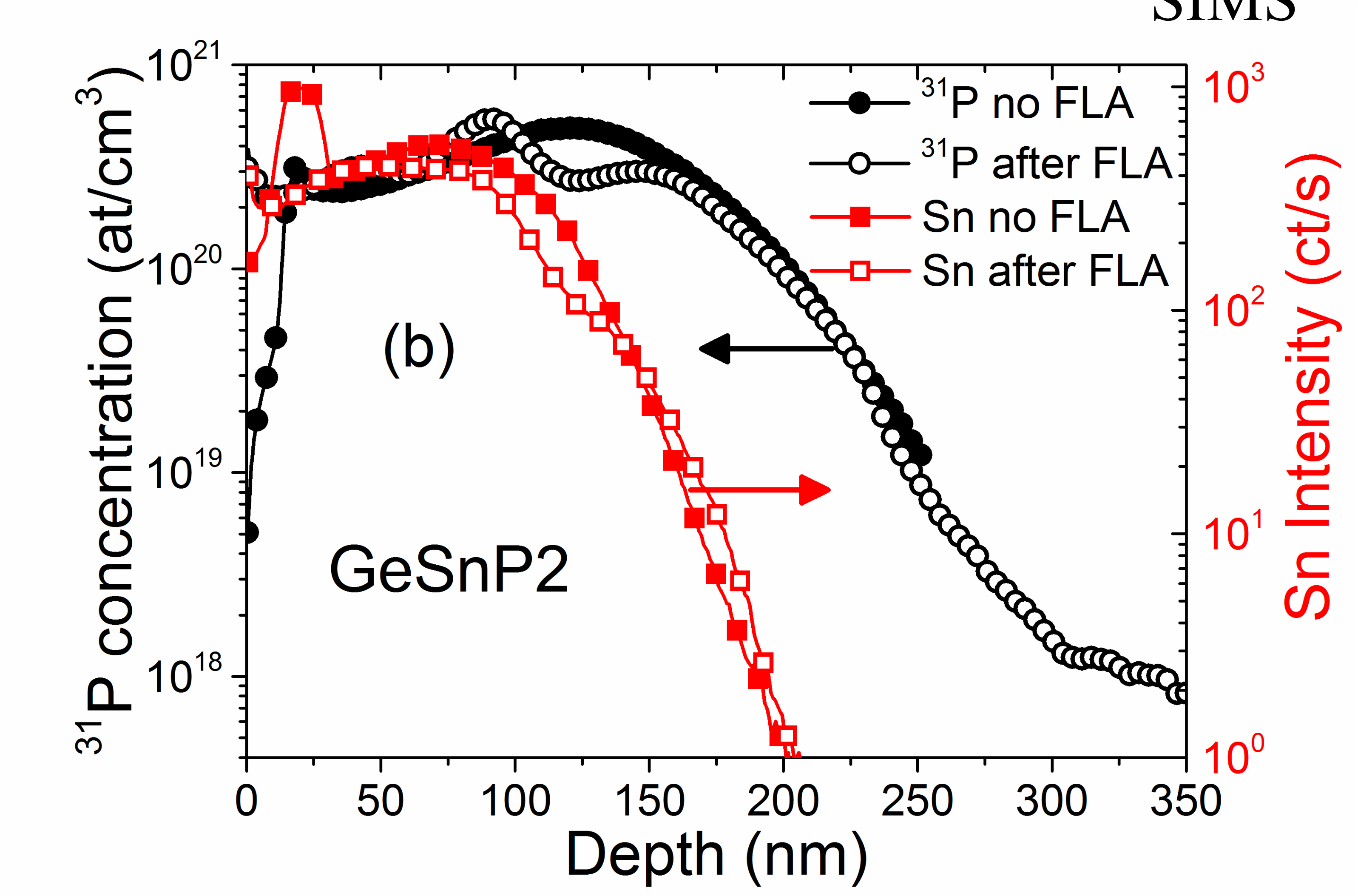
S. Wirths, et al. *Nature Photonics* **9**, 88–92 (2015).

Ge and GeSn for lasers

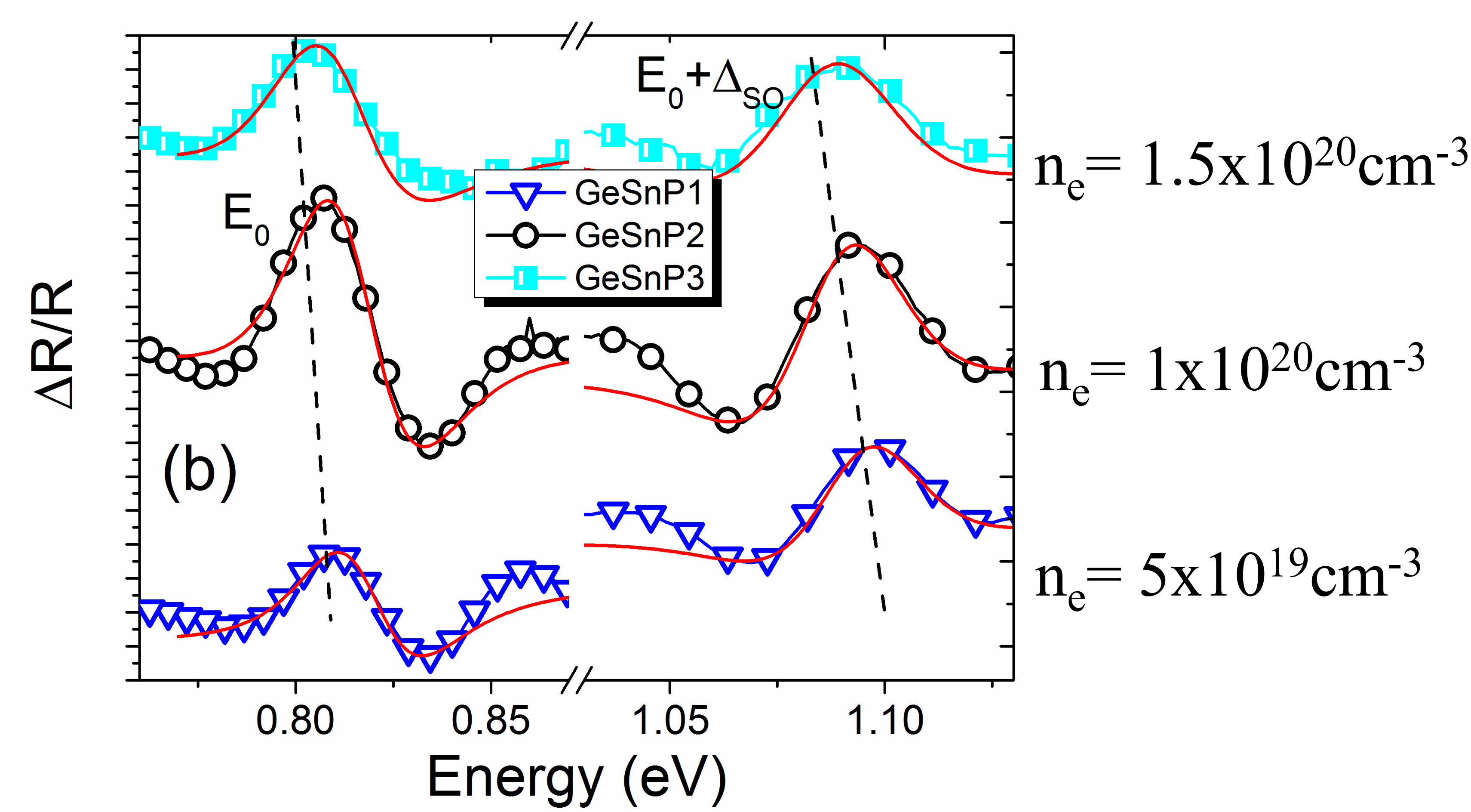


Ge and GeSn for lasers

SIMS



Ge and GeSn for lasers



Room-temperature photoreflectance (PR) spectra measured for $Ge_{0.97}Sn_{0.03}$ alloys with different concentrations of P after flash lamp annealing for 3 ms.

Conclusions

- Ge is fully compatible with Si technology
- Ge-based plasmonics and electronics are established.
- First attempt towards direct band gap Ge is demonstrated.

Acknowledgement

FWI HZDR

External:

M. Sawicki IF PAN Warsaw, Poland

G. Isella L-NESS, Politecnico di Milano, Italy

L. Vines Uni. Oslo, Norway

Thank you for your attention
and
you are welcome for
cooperation