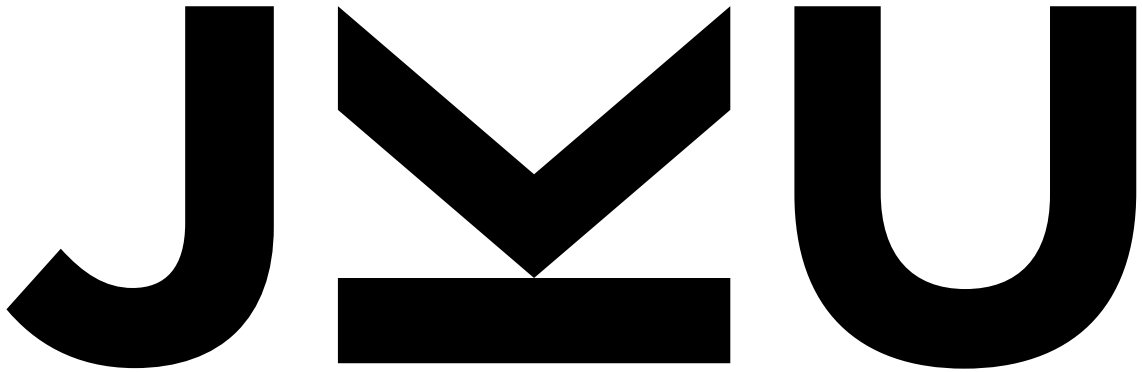

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Magnetic co-doping in $Al_xGa_{1-x}N$: An emission Mössbauer spectroscopy study

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HFP | Institut für Halbleiter- und Festkörperphysik

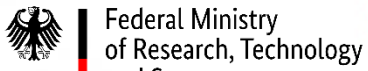
Collaboration at ISOLDE/CERN · Mößbauer

ISOLDE

CERN

JOHANNES KEPLER UNIVERSITY LINZ

Collaborations and funding



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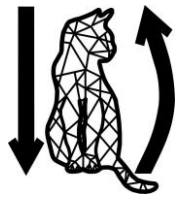
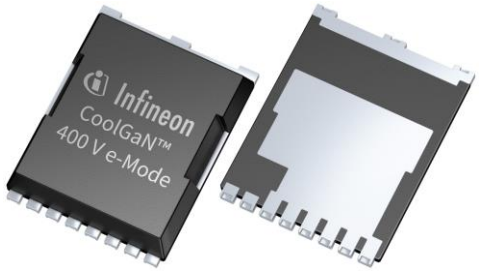
Elettra Sincrotrone Trieste



$Al_{1-x}Ga_xN$ – A key player in solid state electronics

- **Optoelectronics**
  - Light emitting diodes

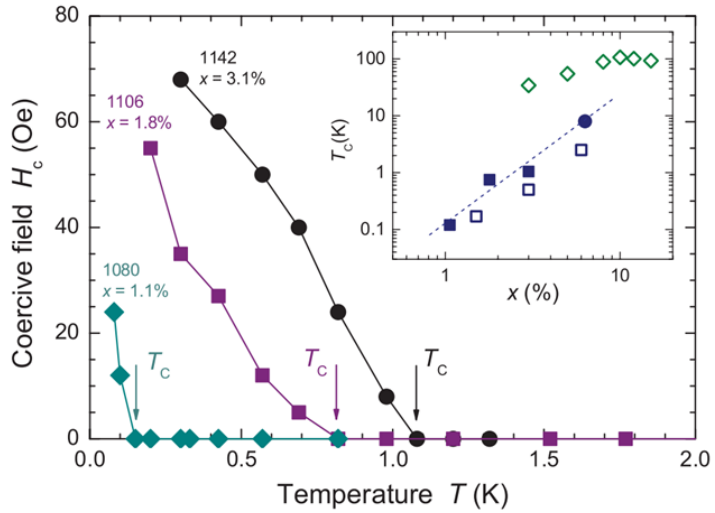
- **High-power electronics**
  - High electron mobility transistors

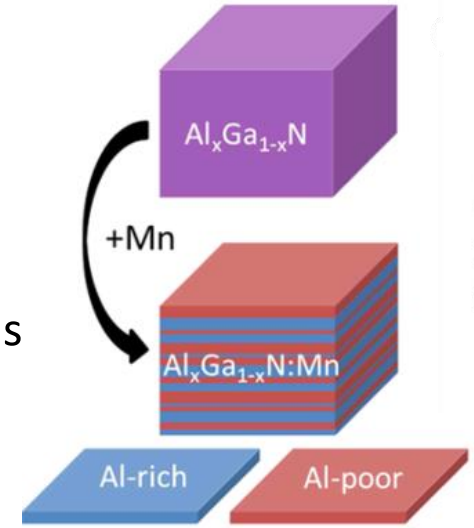


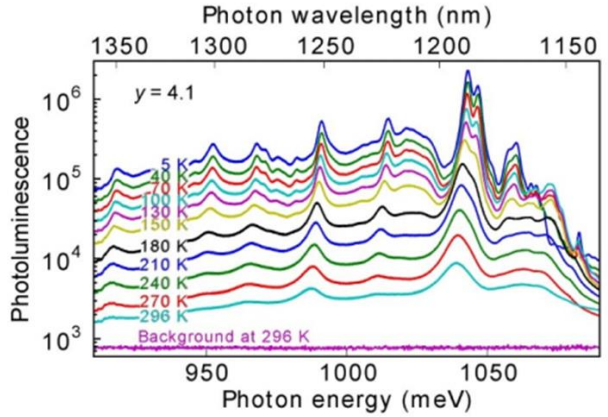
- **And more**
  - space: III-nitride based devices for satellites
  - medicine: implantable systems, prosthetics
  - environment: water purification
  - security: THz detector and emitters

Mn doping of III-nitrides

- Superexchange mediated ferromagnetism in GaN:Mn
- Piezoelectromagnetic effect
- Surfactant role of Mn for self-assembling AlGaN heterostructures
- Mn-Mg complexes: IR emission in GaN: (Mn,Mg)
- Distributed Bragg reflectors AlGaN:Mn/GaN for IR applications







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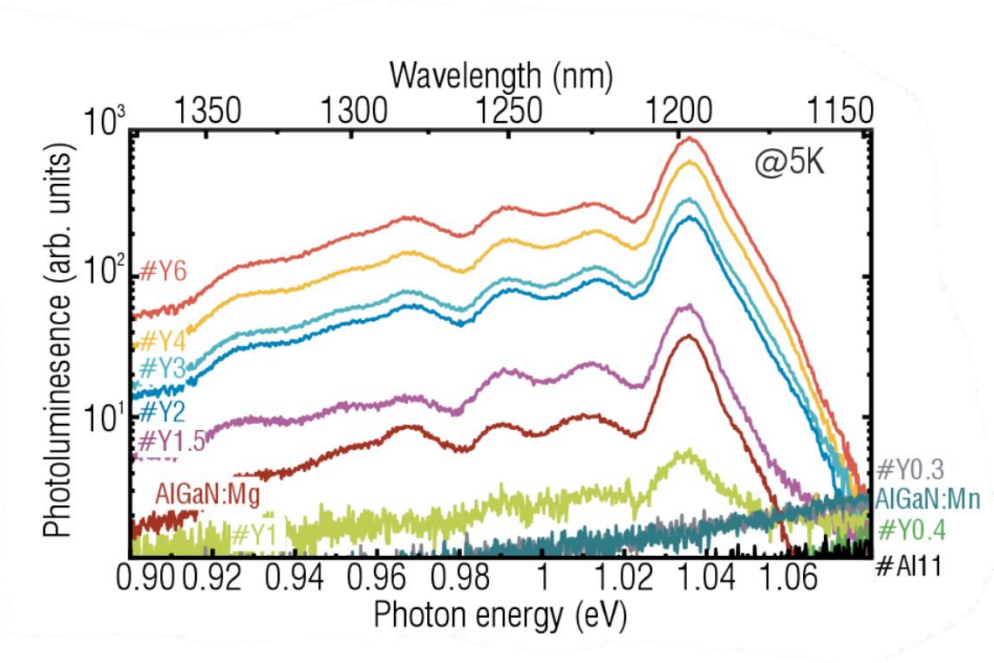
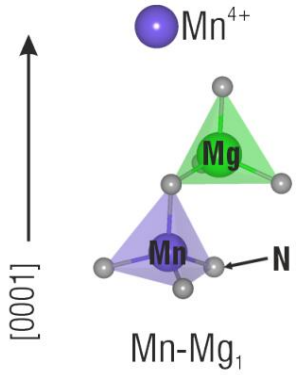
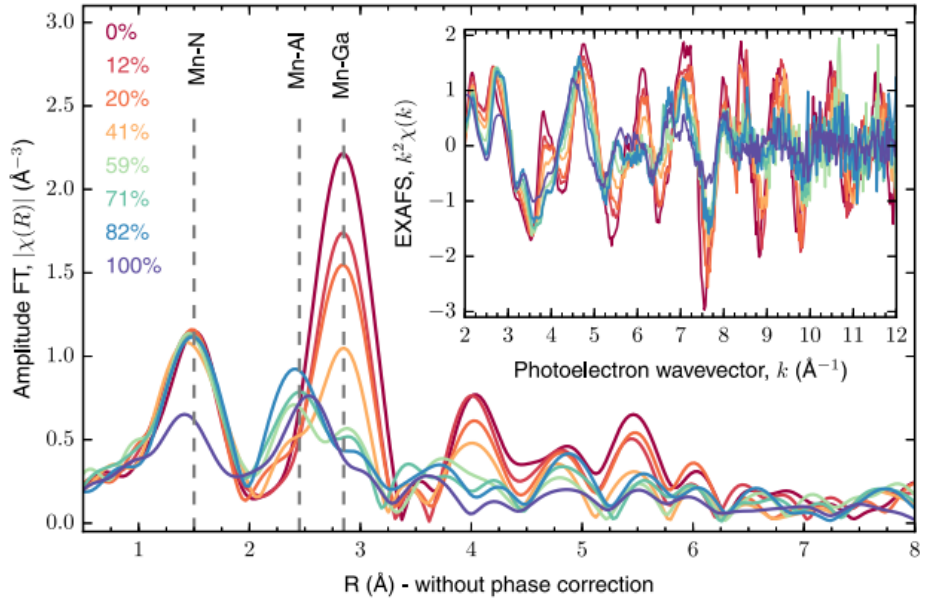
D. Sztenkiel, RA *et al*. Nat. Commun. **7**, 13232 (2016)
M. Sawicki *et al*. Phys. Rev. B **85**, 205204 (2012)

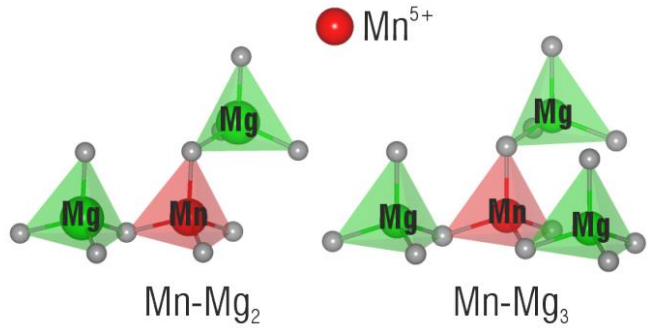
$Al_{1-x}Ga_xN$:Mn and non-magnetic co-doping

- $Al_{1-x}Ga_xN$:Mn – antiferromagnetic Mn-Mn interactions
- Mn ~ 1%
- $Al_{1-x}Ga_xN$:Mn – Mn substitutes Ga; No Mn interstitials
- Mg co-doped AlGaN:Mn – IR emission fron Mn-Mg_k complexes









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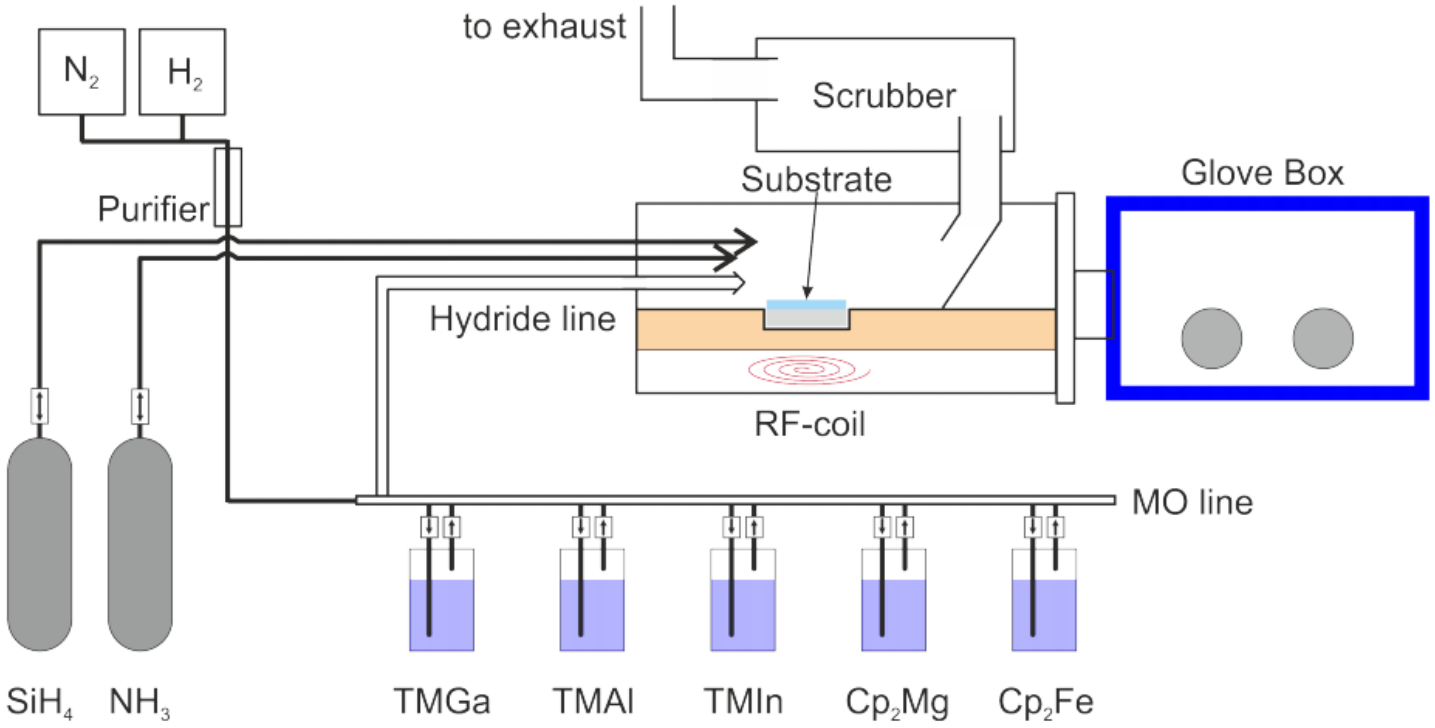
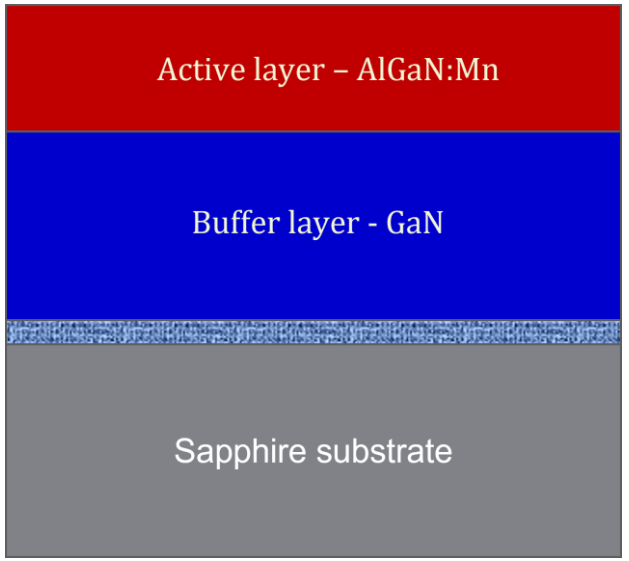
A. T. Spindlberger, PhD Thesis (2022)
Unpublished data

Samples: Growth

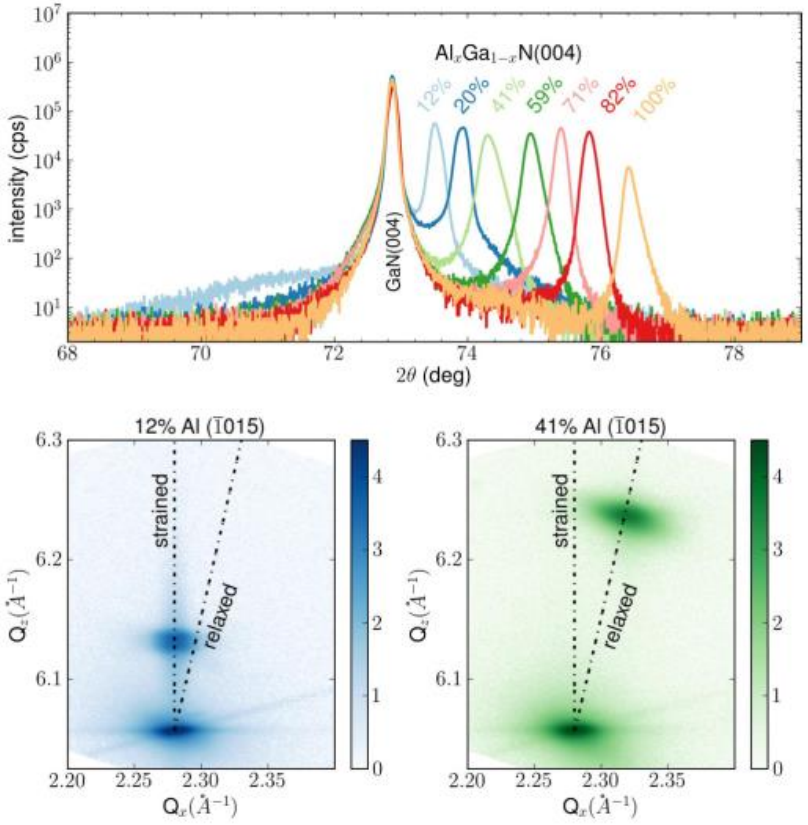


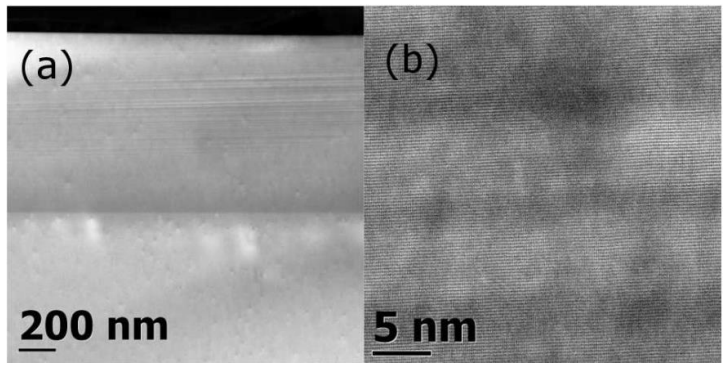
Metal organic vapor phase epitaxy (MOVPE)

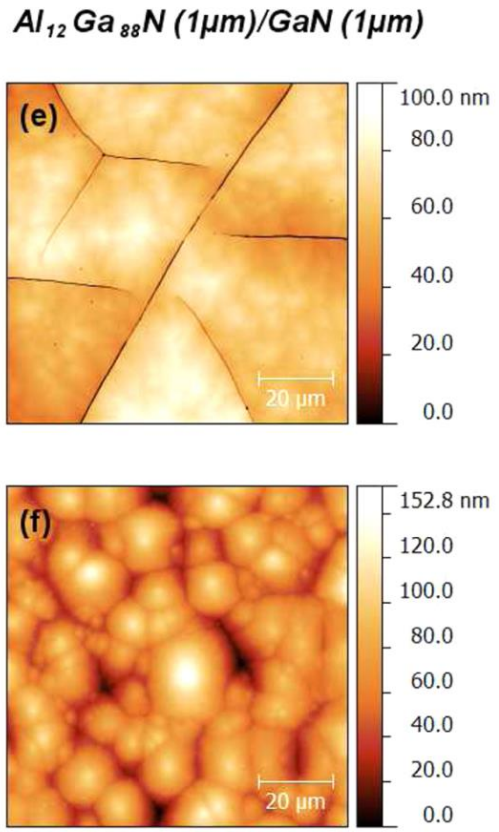


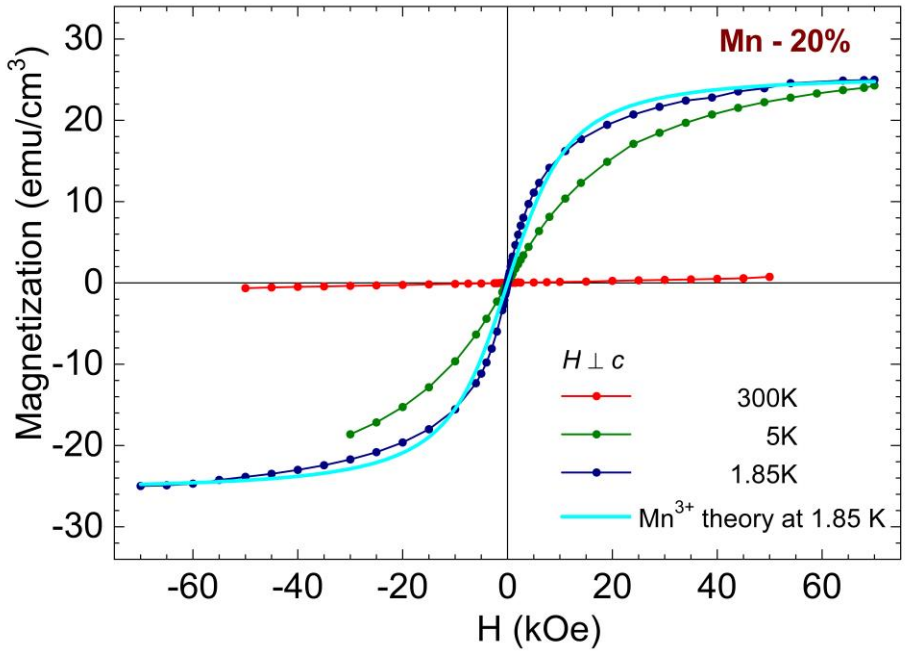
$Al_{1-x}Ga_xN$:Mn schematic

Samples: Characterization









- Primarily superexchange Mn-Mn interactions
- Mn^{3+} state
- Can magnetic co-doping promote double exchange?

Captain, there‘s a question and it is logical !!

Motivation

Can magnetic co-doping in $Al_{1-x}Ga_xN$:Mn enhance its functionality ??

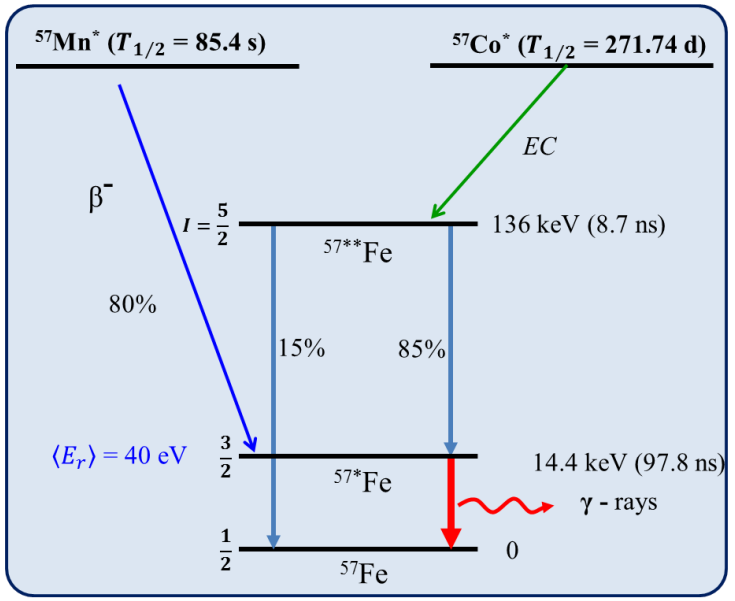
What exactly do you have in mind, Spock?

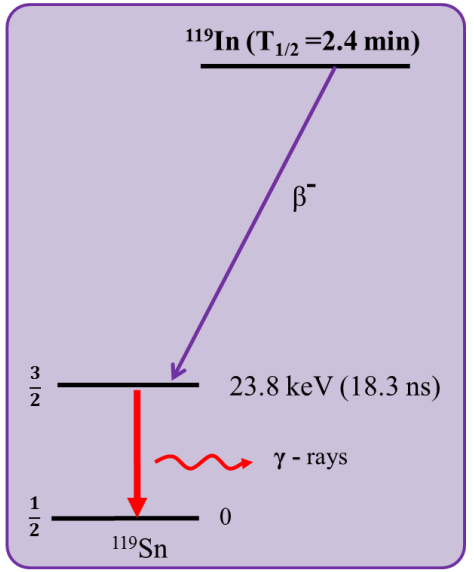
Captain, Rudolf Mössbauer!!

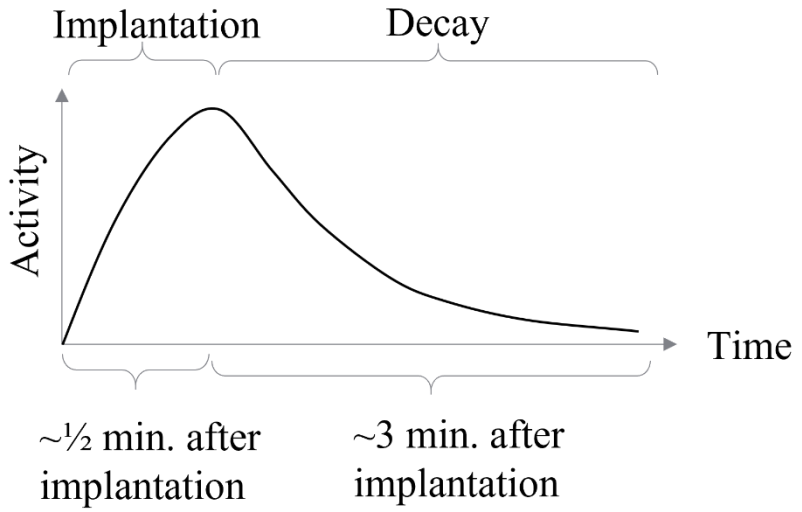
- ✓ Very dilute Fe in $Al_{1-x}Ga_xN$:Mn
- ✓ Study its local magnetic structure
- ✓ Charge, spin states, interaction

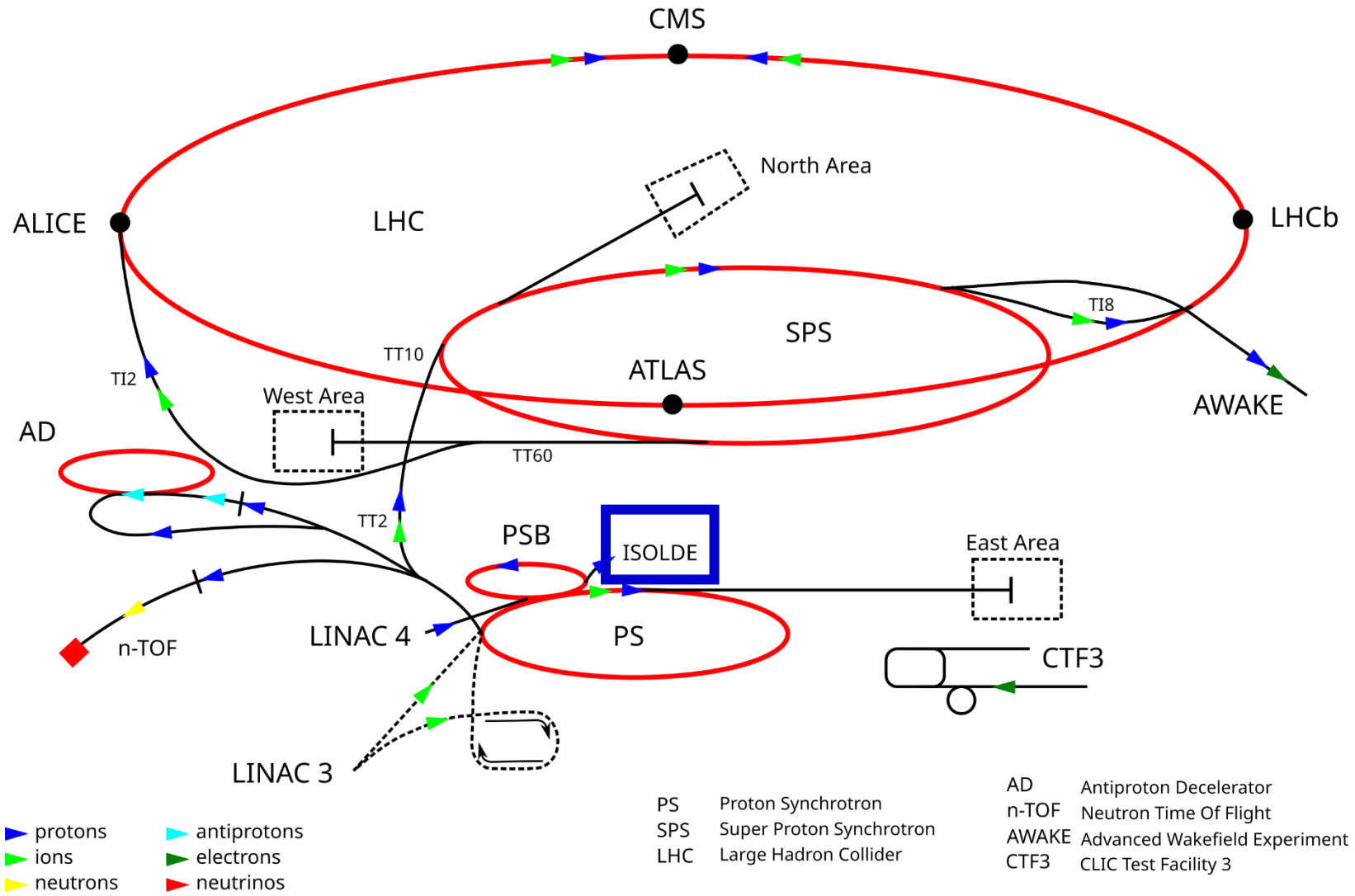
Why Mössbauer spectroscopy?

- Probes local environment
- Valence state
- Site symmetry
- Charge states
- Spin states
- Local magnetic interactions
- local concentrations ~10^{-4} at.%
- Always two elements that play role
  - ^{57}Fe
    - Parent (^{57}Mn, 1.5 min) → daughter (^{57*}Fe, 100 ns)
    - Parent (^{57}Co, 272 d) → daughter (^{57*}Fe, 100 ns)
  - ^{119}Sn
    - Parent (^{119}In, 2.1 min) → daughter (^{119*}Sn, 18 ns)
- At ISOLDE, CERN we can measure spectrum in few minutes,

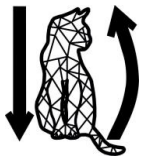








ISOLDE: **I**sotope **S**eparator **O**n **L**ine **DE**vice



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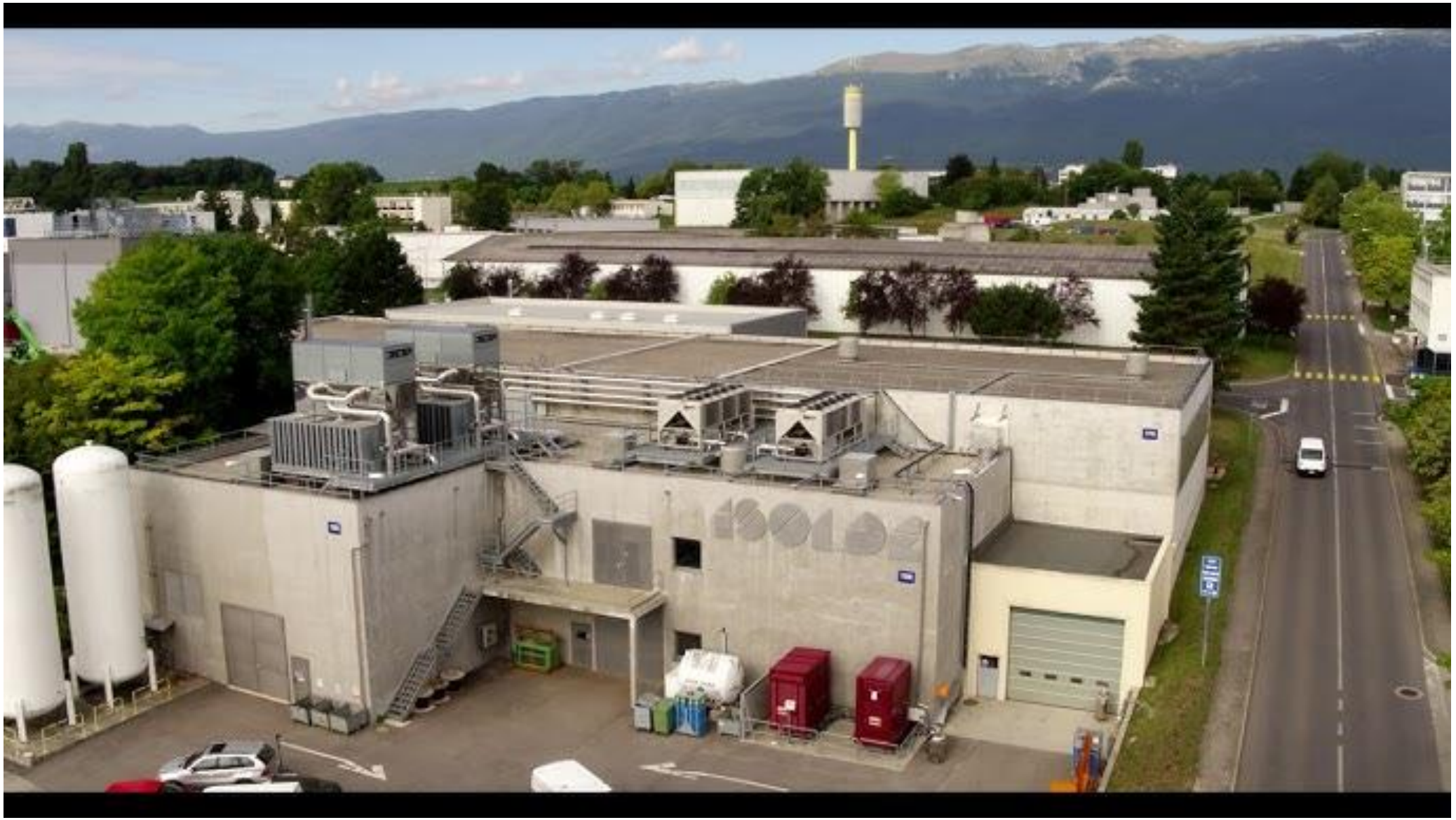
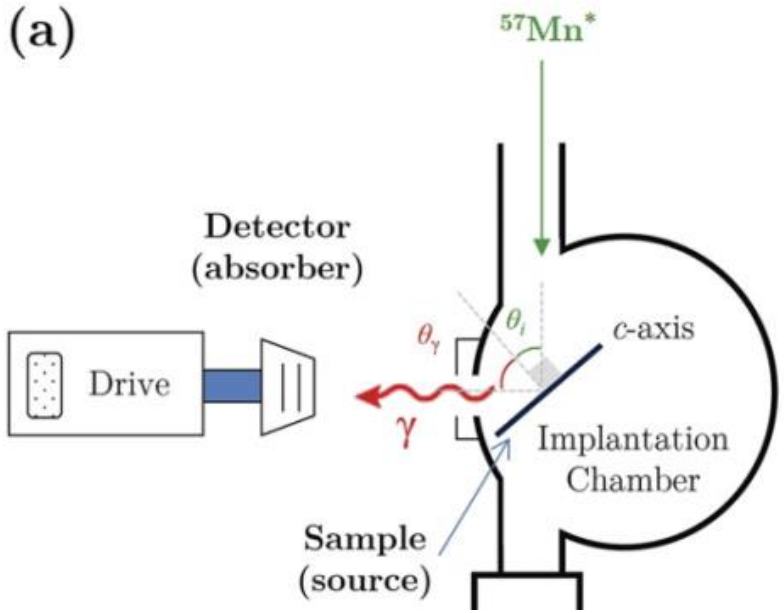
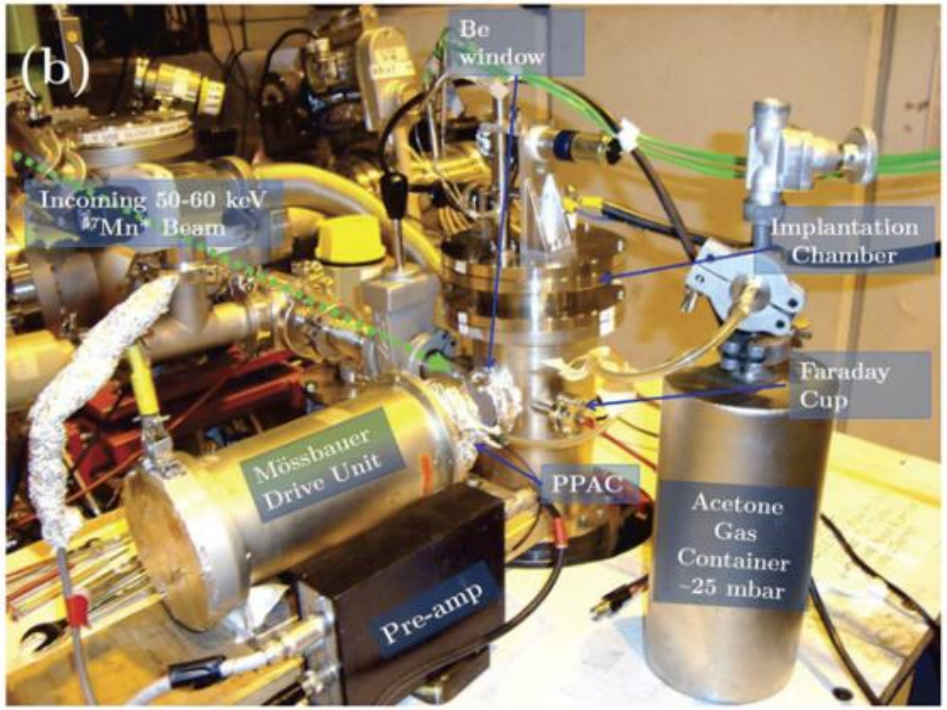
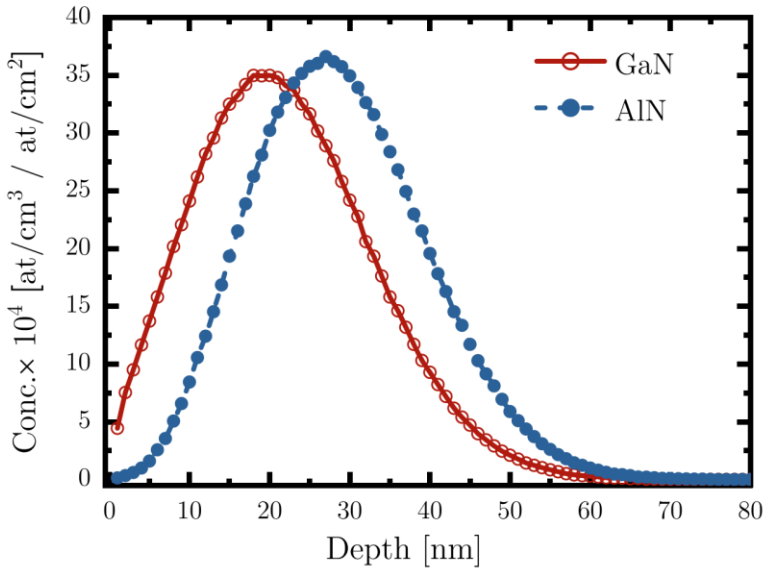


Emission Mössbauer spectroscopy

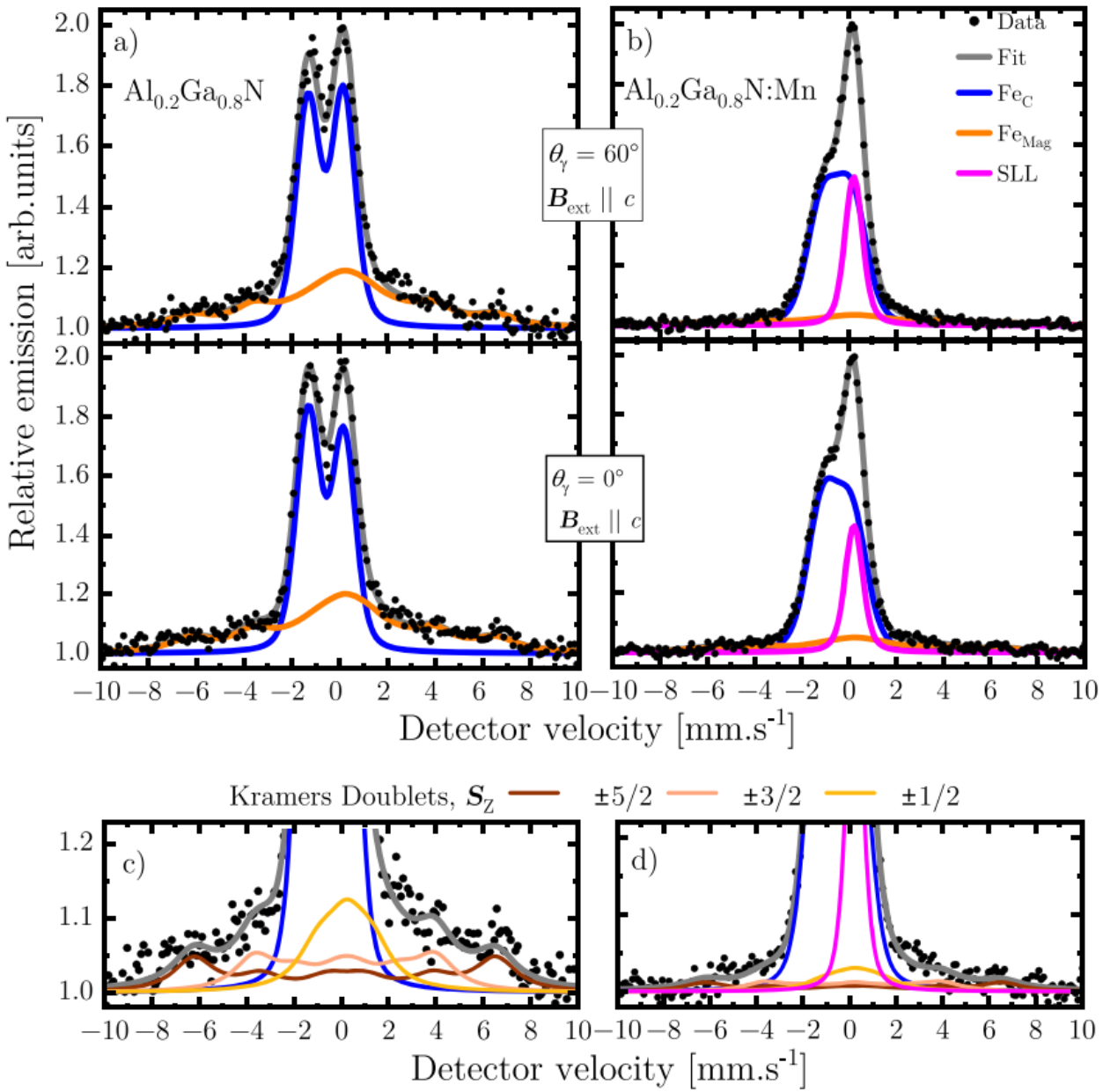






H. Masenda, RA *et al*. New. J. Phys. **24**, 103007 (2022)

eMS results on AlGaN and AlGaN:Mn



AlGaN

- Strong central component
- Slow relaxing paramagnetic Fe^{3+}
- Fe^{2+}-V_N

AlGaN:Mn

- Additional SLL component
- Attributed to Fe^{4+}
- Slow relaxing paramagnetic Fe^{3+}
- Fe^{2+}-V_N

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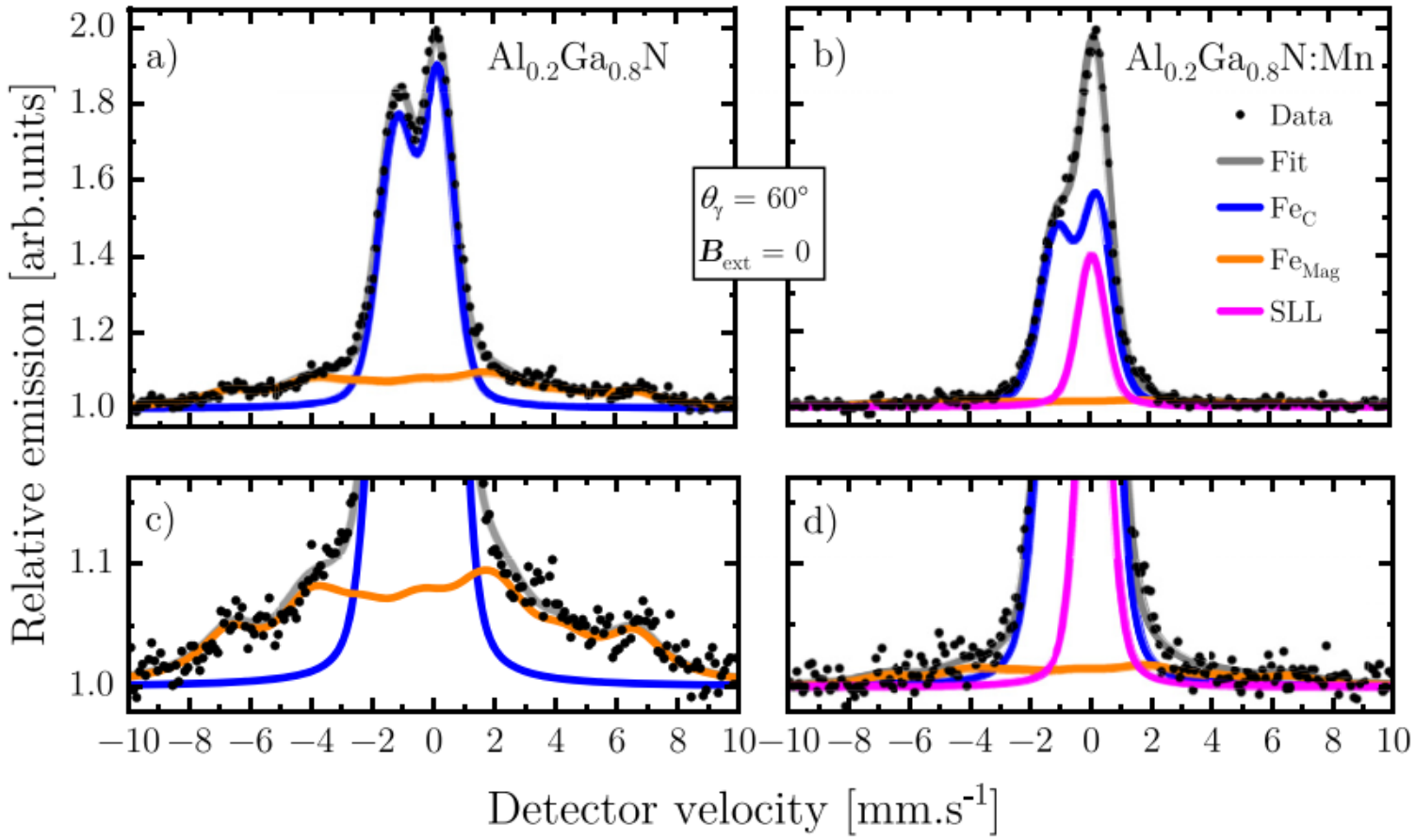

AlGaN:Mn

- SLL due to interstitial Fe or Fe in V_N?
- Energetically unfavorable
- Attributed to Fe^{4+}
- 3d hybridization with Ga valence bands

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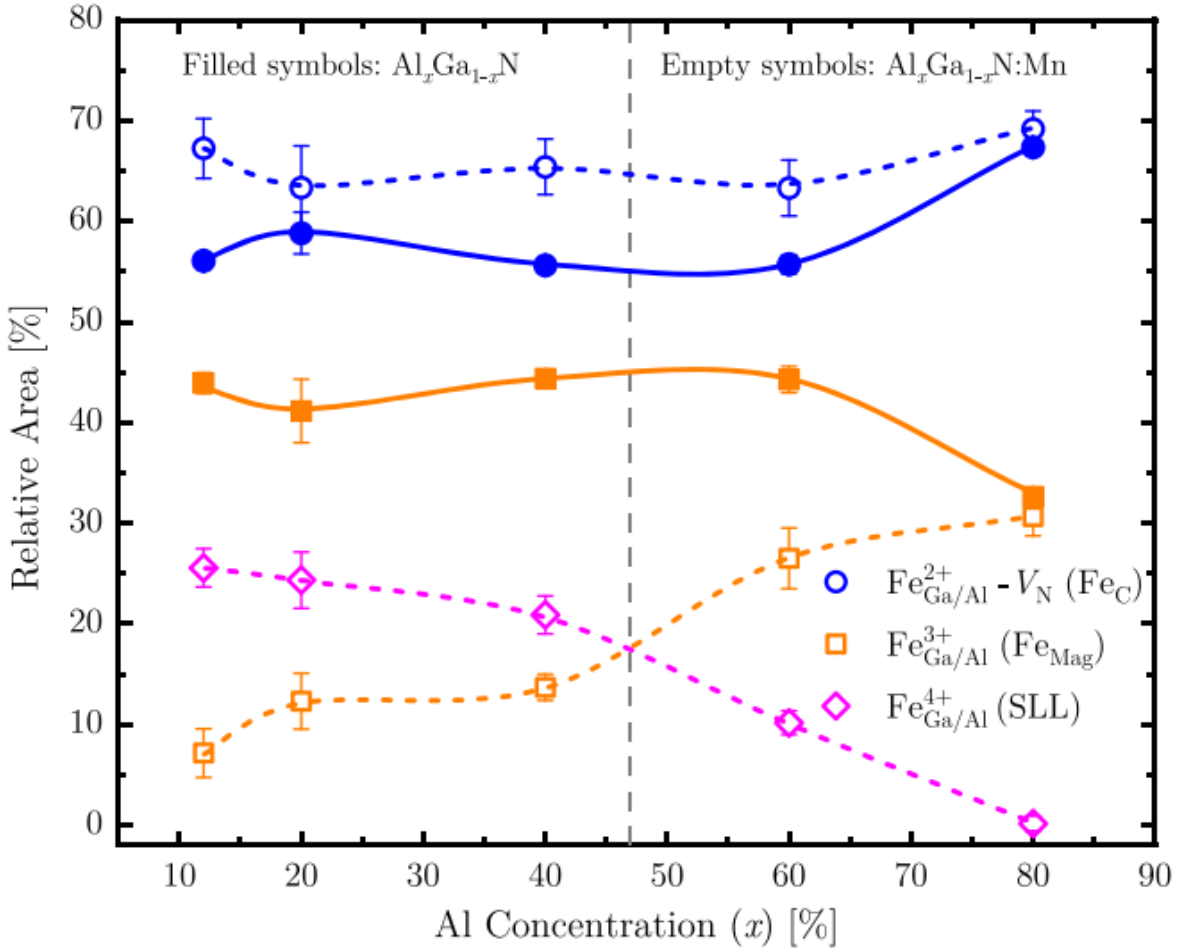

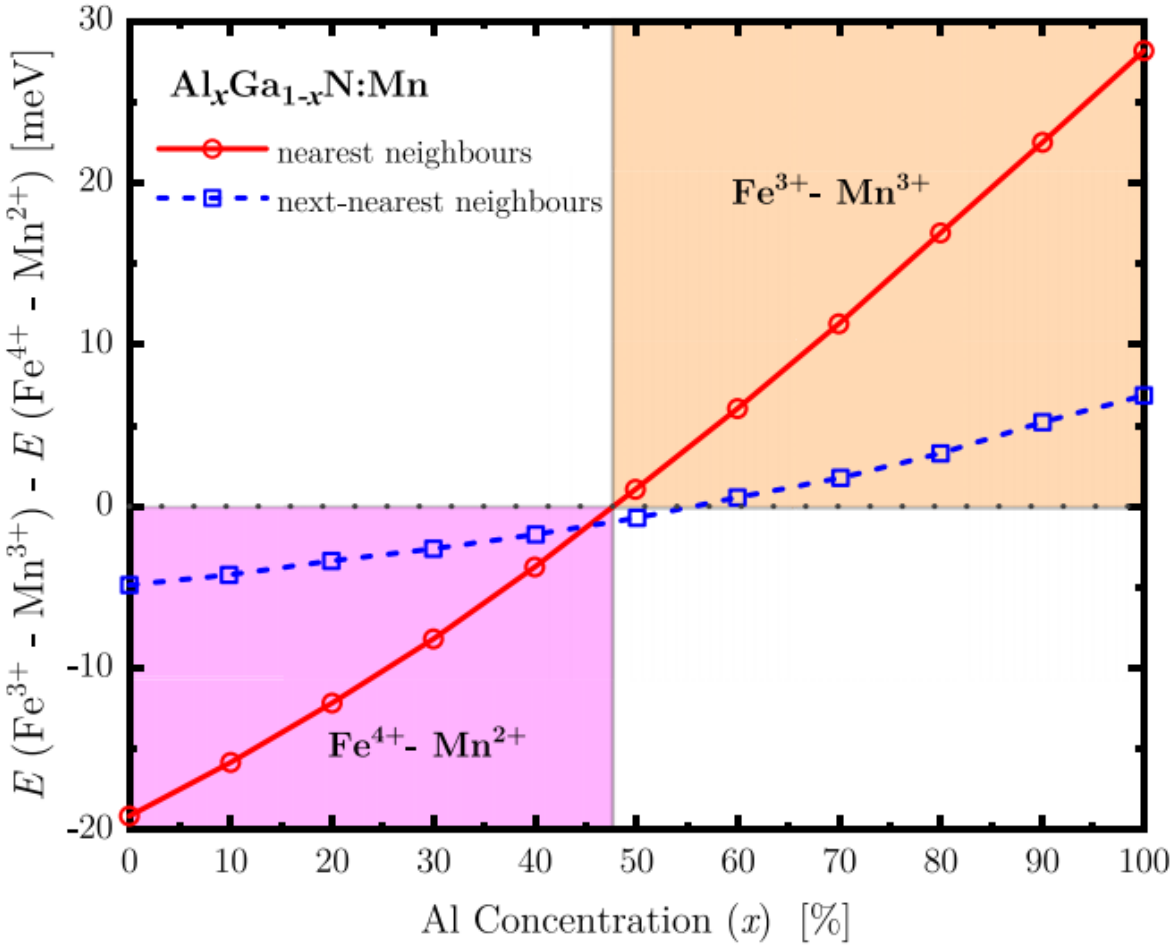

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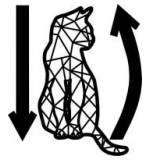
Result: co-doping promotes unusual charge states Fe^{4+}-Mn^{2+} which is pronounced in low AlGaN:Mn with low Al (<50%)

Summary

- Magnetic co-doping promotes unusual charge states Fe^{4+}-Mn^{2+}
- Pronounced in low AlGaN:Mn with low Al (<50%)
- Fe^{4+} diminishes for > 50% Al in AlGaN:Mn
- Provides a new option to enhance magnetic functionality

Outlook

- Ongoing studies: co-doped GaN and AlGaN
- Growth of samples with higher Fe doping
- Full characterization protocol to elucidate the yet unexplored properties




THANK YOU!