

Muons in Semiconductors

(and many other non-metals)

What is a semiconductor?

Empty conduction band(s)

Full valence band(s)

Ideally, insulating

Add impurities:

Some ionised to release free electron

Some capture electron from valence band: leave a Hole

What is a muon?

Charged particle

Embedded in sample material

Acts as a dopant

Model for Hydrogen

Muon is its own probe
(often much easier than
NMR or ENDOR on H)

Effects noticed in the early days of muSR

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MUONIUM FORMATION IN SEMICONDUCTORS*

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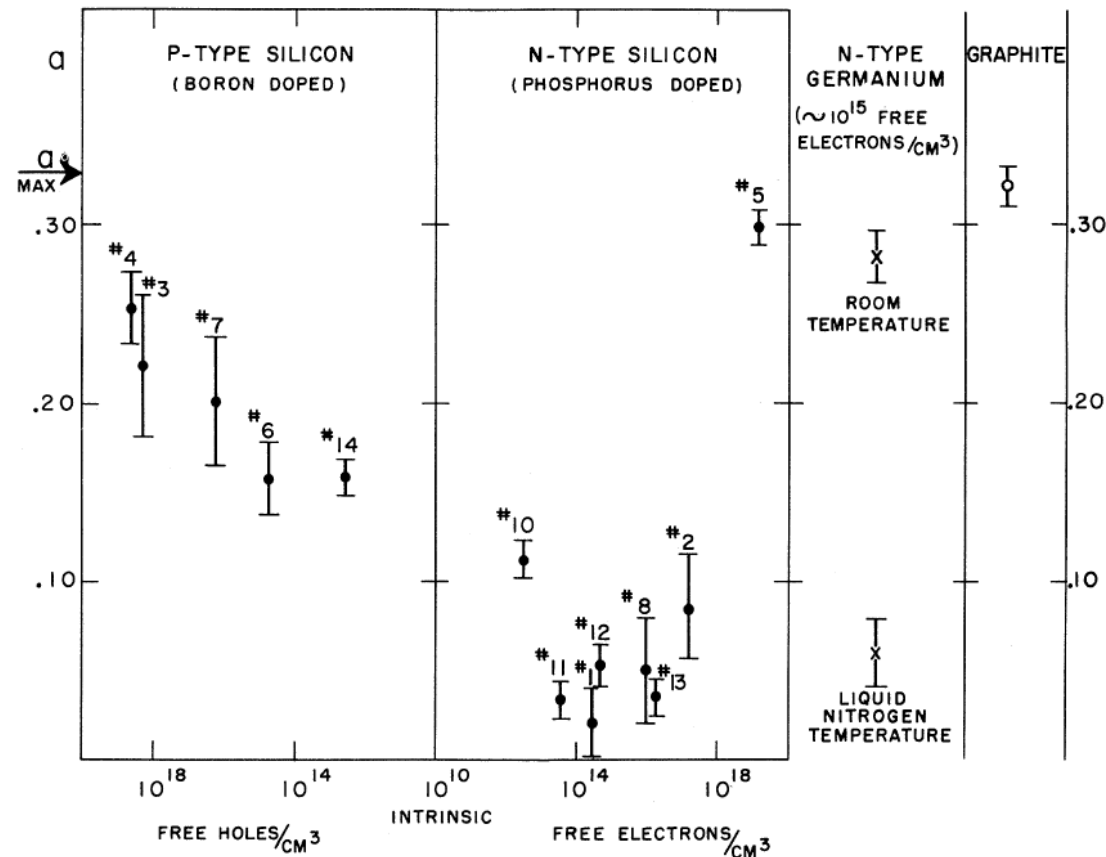
Bell Telephone Laboratories, Murray Hill, New Jersey and Columbia University, New York, New York

and

R. Prepost and A. M. Sachs

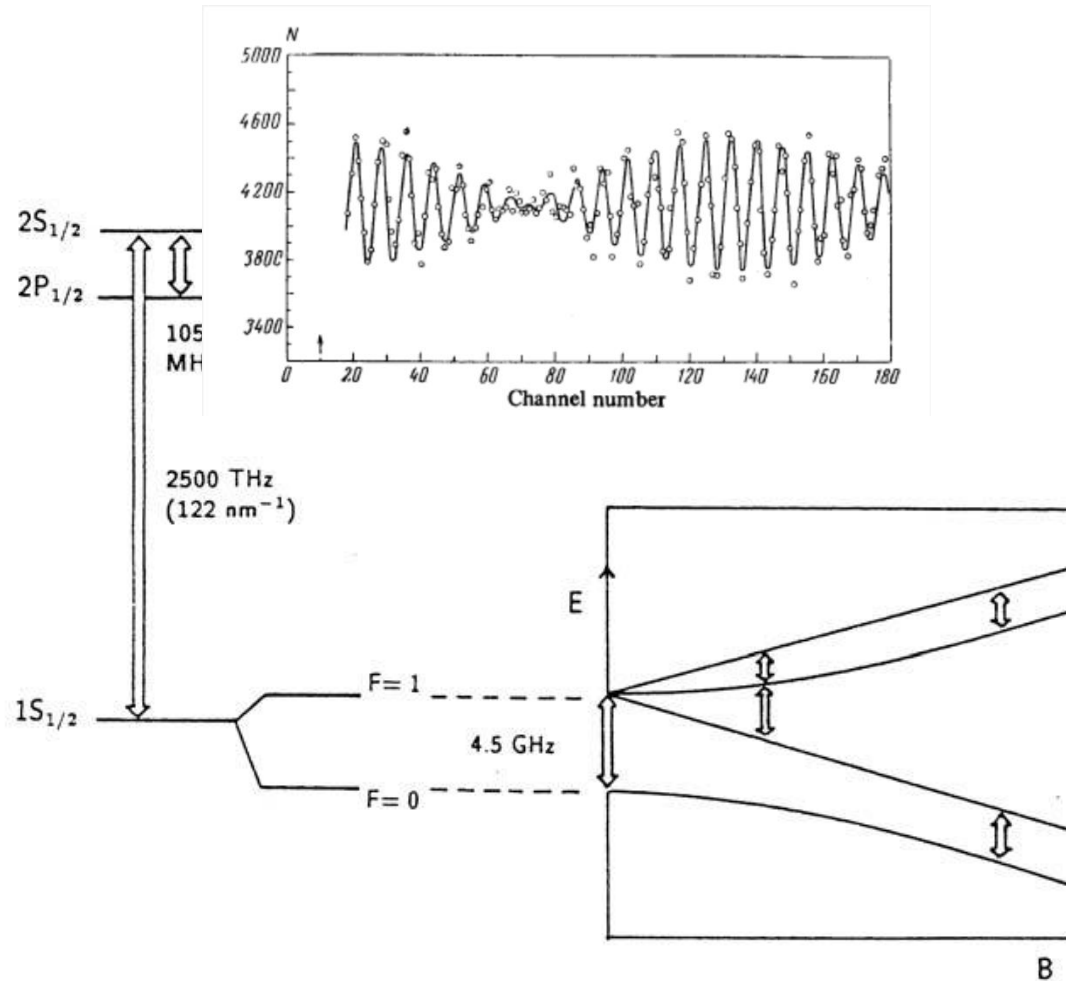
Columbia University, New York, New York

(Received November 4, 1960)

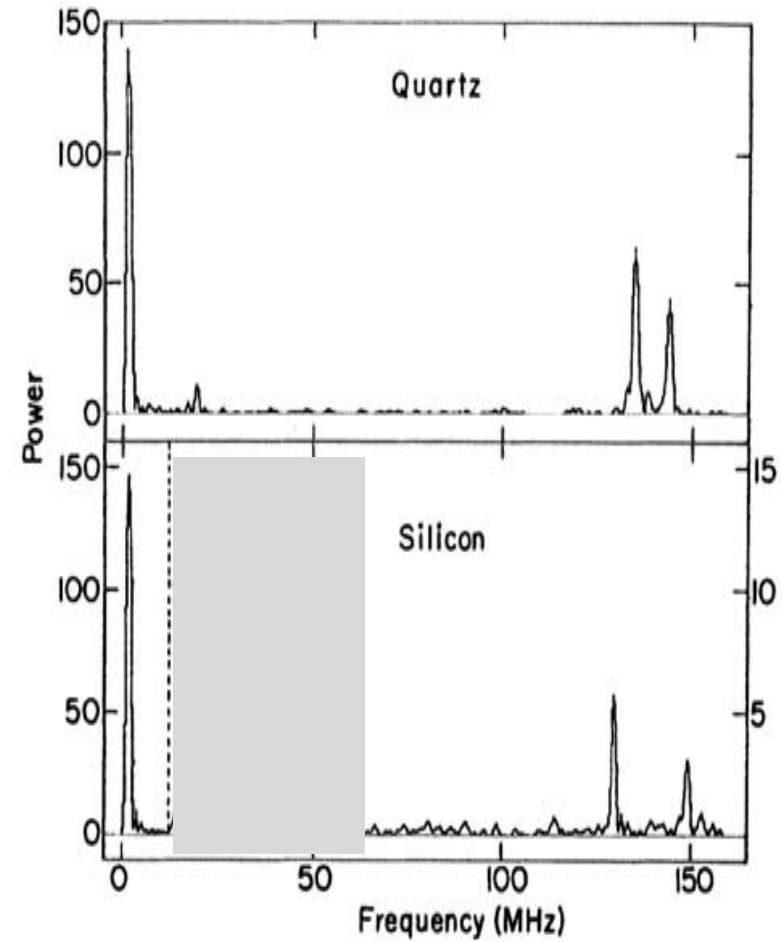


Apply small field to a non-magnetic sample.
Might expect all muons to precess at 135.5 MHz/T ?

Muonium spectroscopy

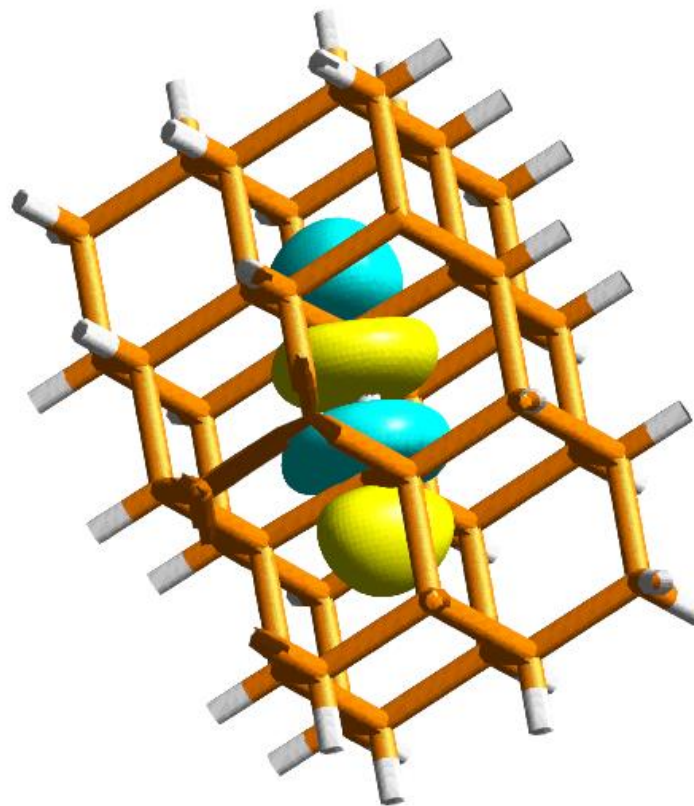
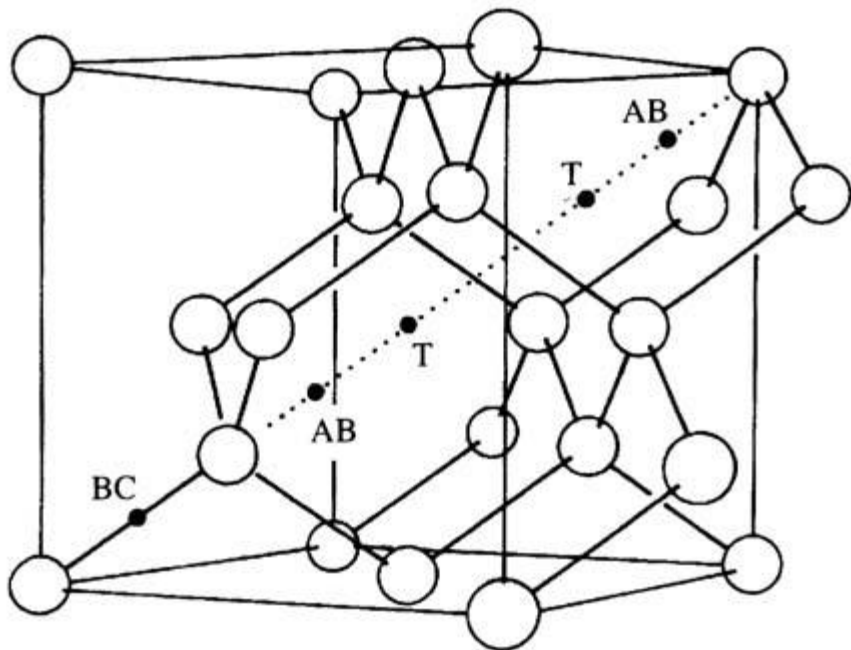


Energy levels for vacuum-state muonium.



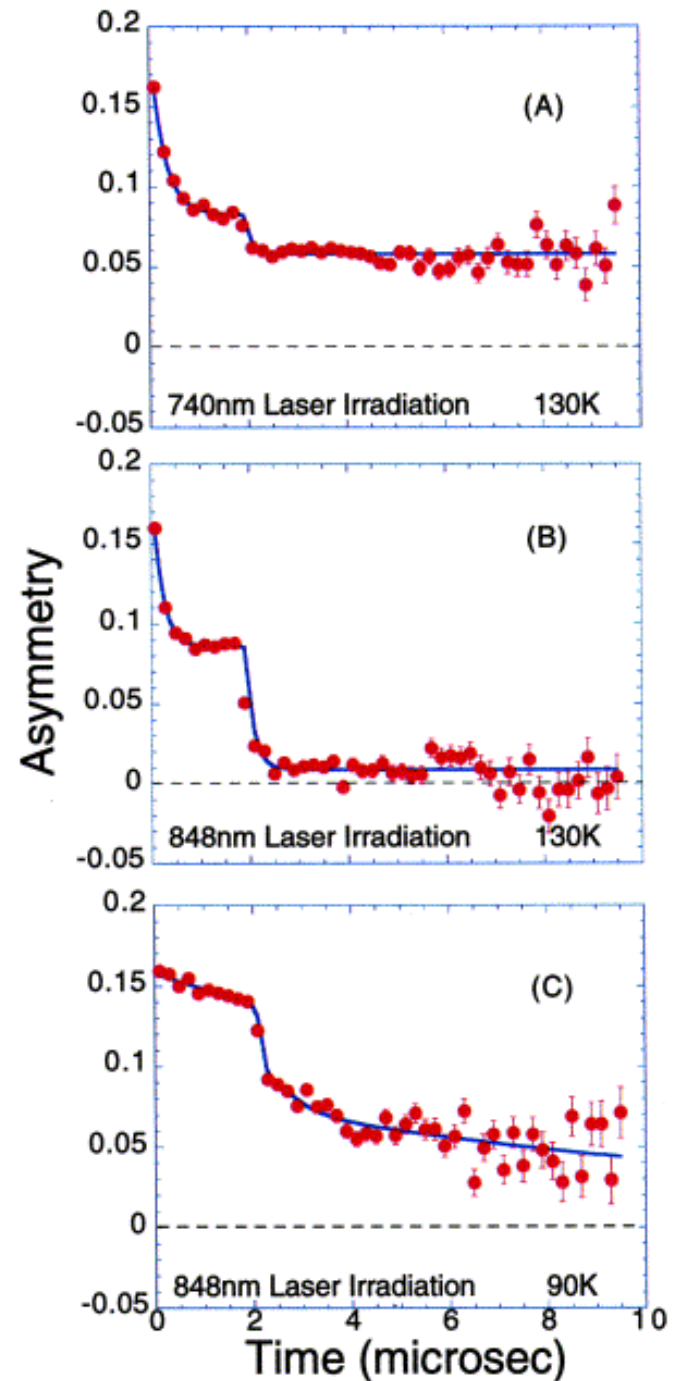
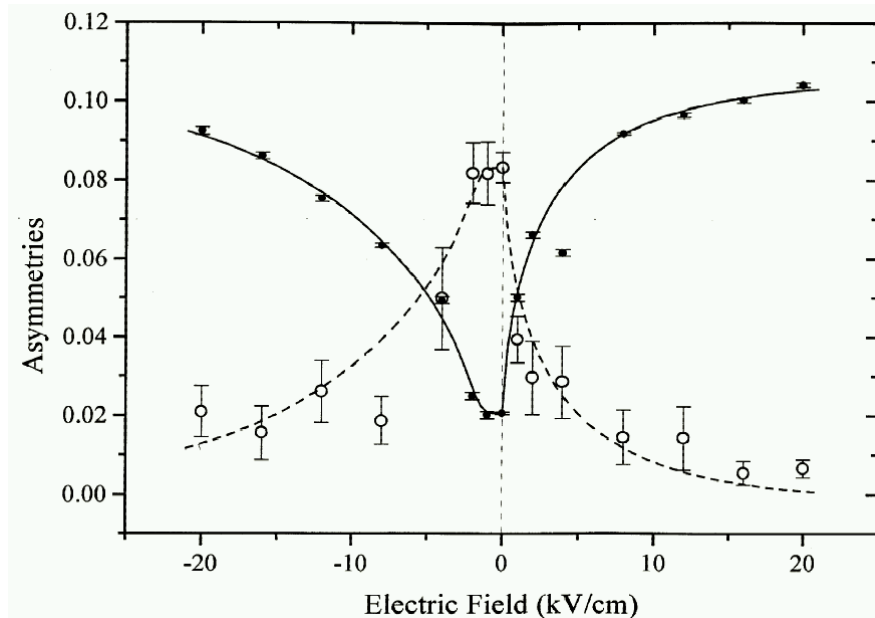
“Anomalous” or molecular radical states

- Anisotropic
- Much lower spin density on muon



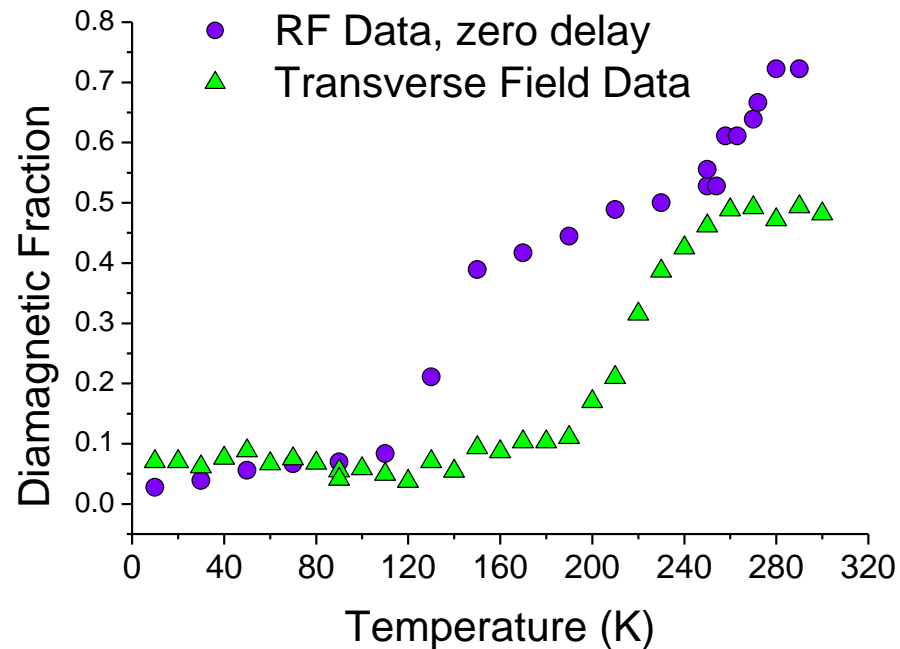
Low temperature

- Random choice of charge state?
- Capture of free electrons or holes
- Ionisation by incoming muon
- Add more with illumination
- Or sweep away by E field



Intermediate temperature

- State conversion – approach equilibrium



Silicon, conversion
from Mu^0 to Mu^+

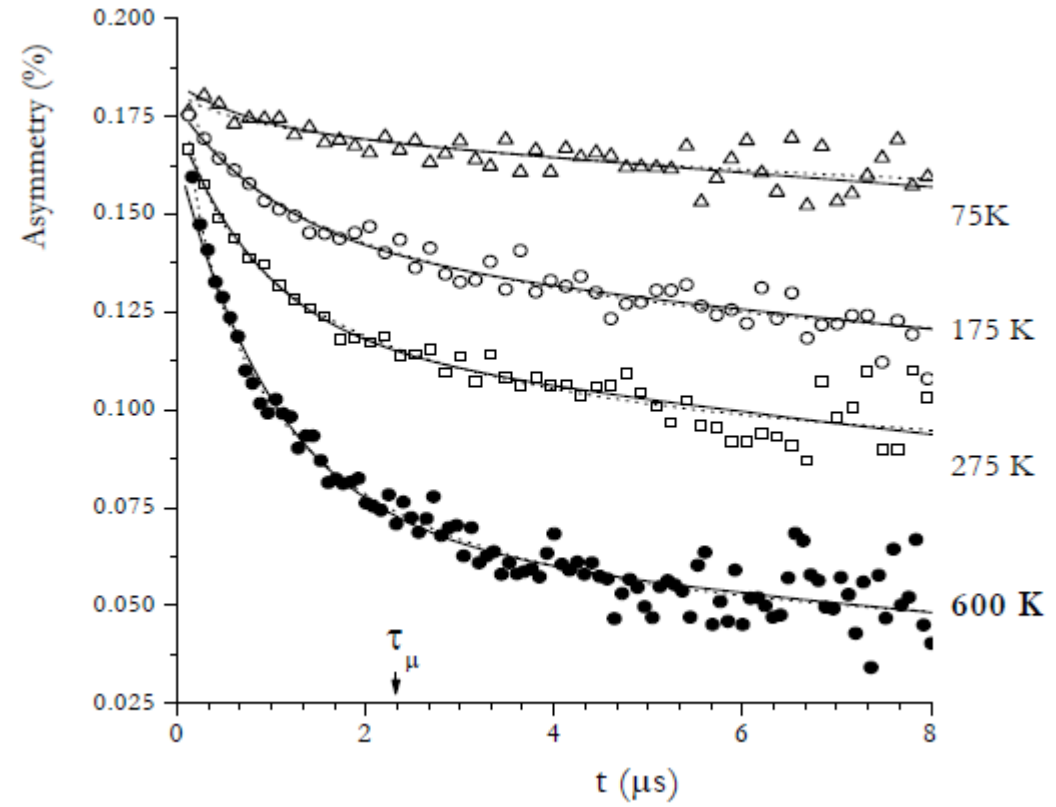
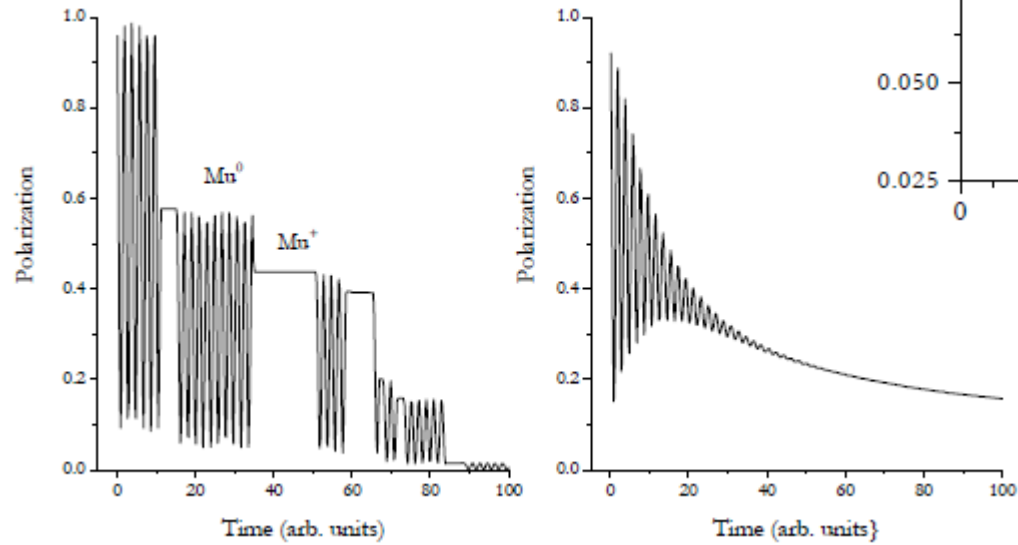
RF experiment sees
final state if conversion
on μs timescale

Transverse field needs
ns conversion

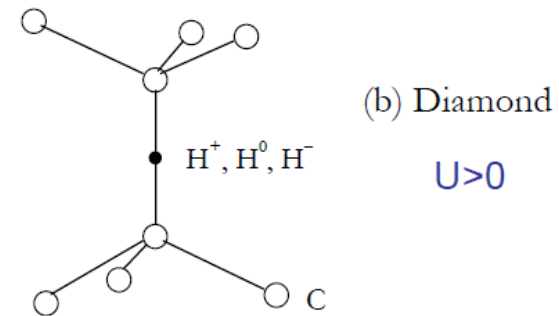
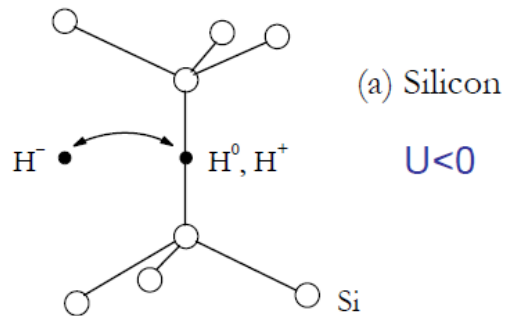
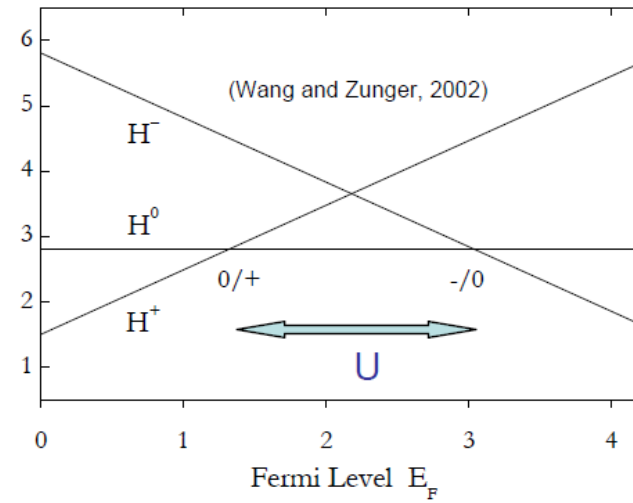
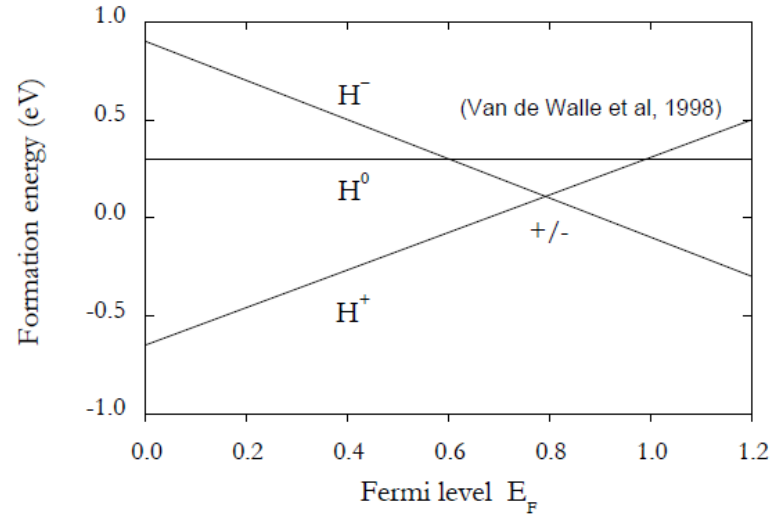
Extract energy barriers

High temperature

Charge cycling causing spin relaxation

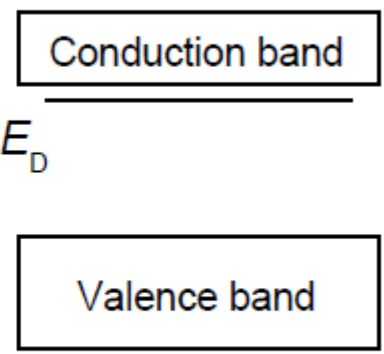
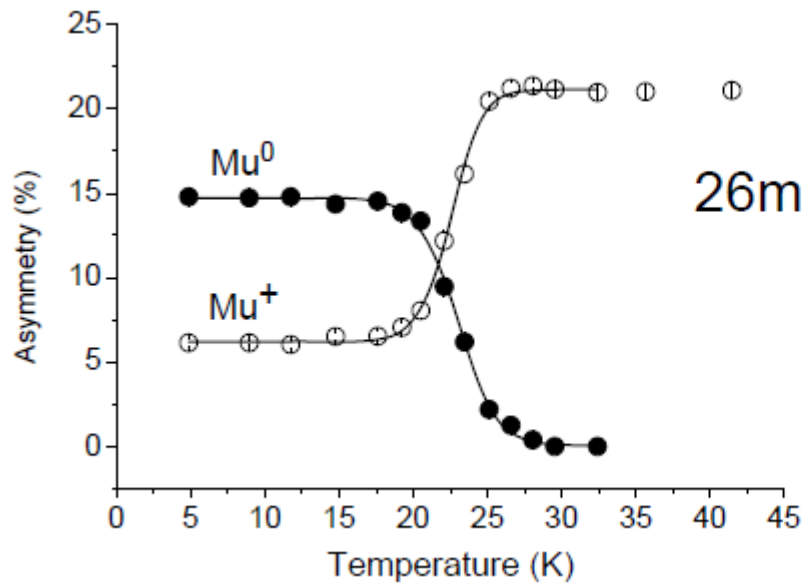
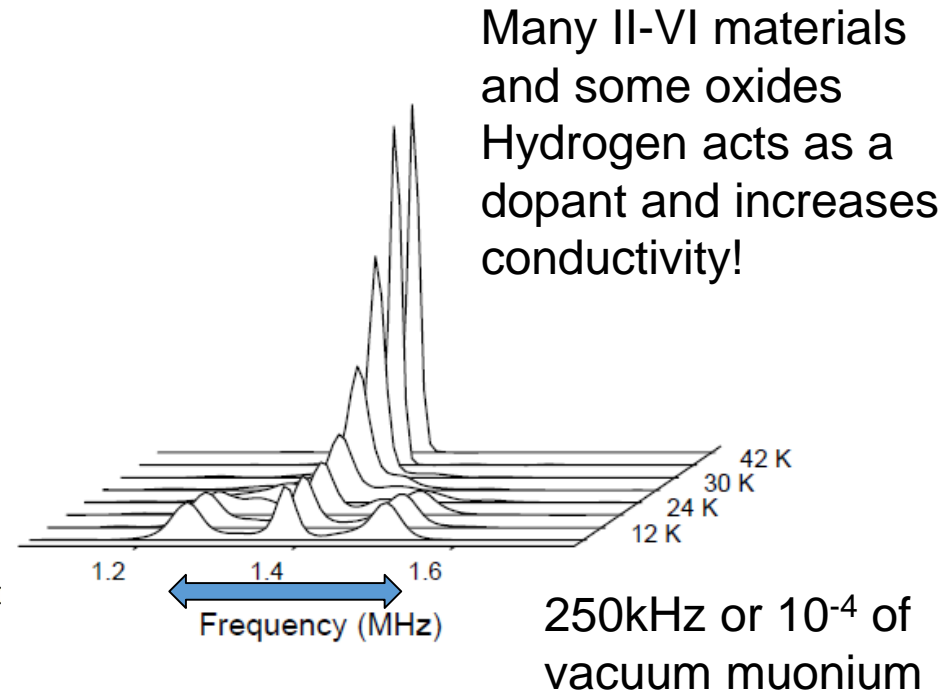
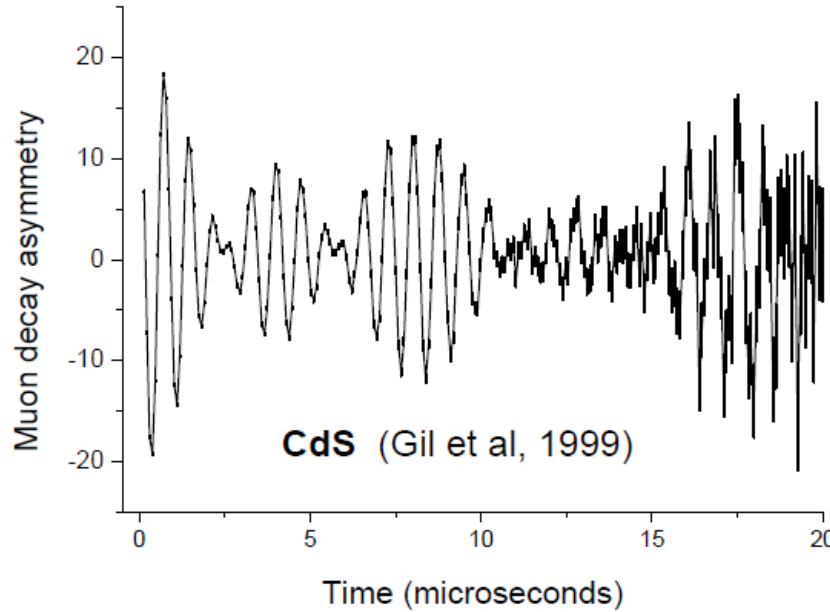


Energy levels



H is a compensating impurity in Si
 Fermi level pinned at 0.8eV
 if $n(H) > n(\text{Dopants})$
 Remains insulating

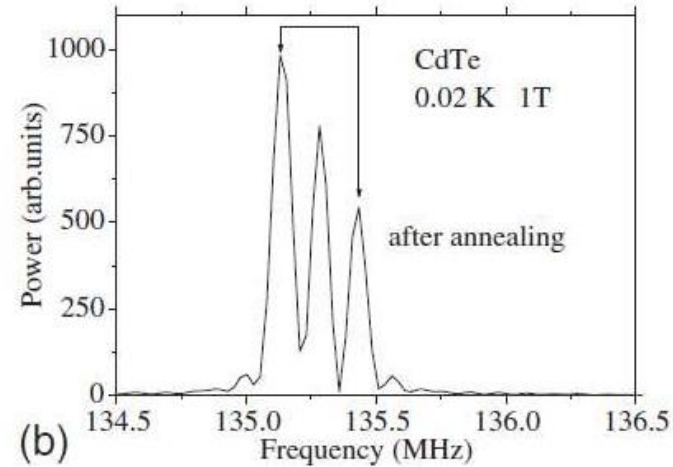
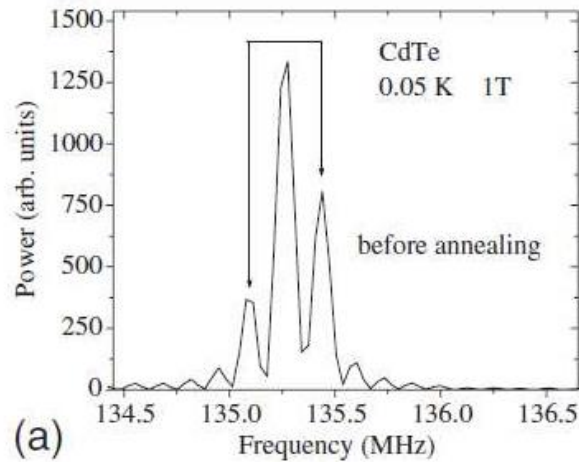
Shallow states



Hydrogenic state, depends on effective mass and bulk dielectric constant

Spin polarisation

- Low temperature and high field

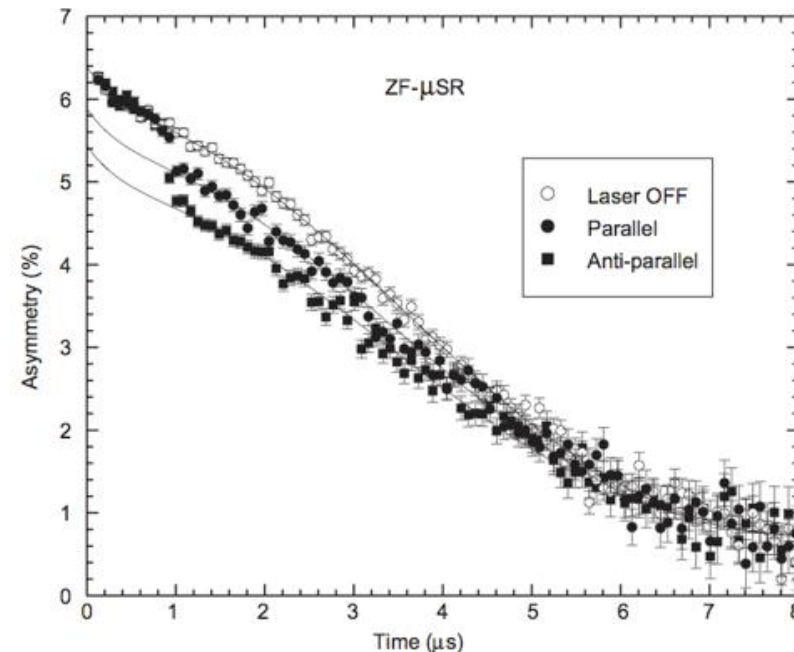


Are we polarising:
Electrons
Holes
Atomic muonium?

Depends on
formation route(s)

- Circularly polarised
light

Measure spin
diffusion lengths
and lifetime



Conclusion

- Muons can measure electrical activity in semiconductors
- The muon is a good model for hydrogen as an impurity in semiconductors and insulators