EXPERIMENTAL OBSERVATION OF INTRINSIC LOCALIZED MODES IN GERMANIUM

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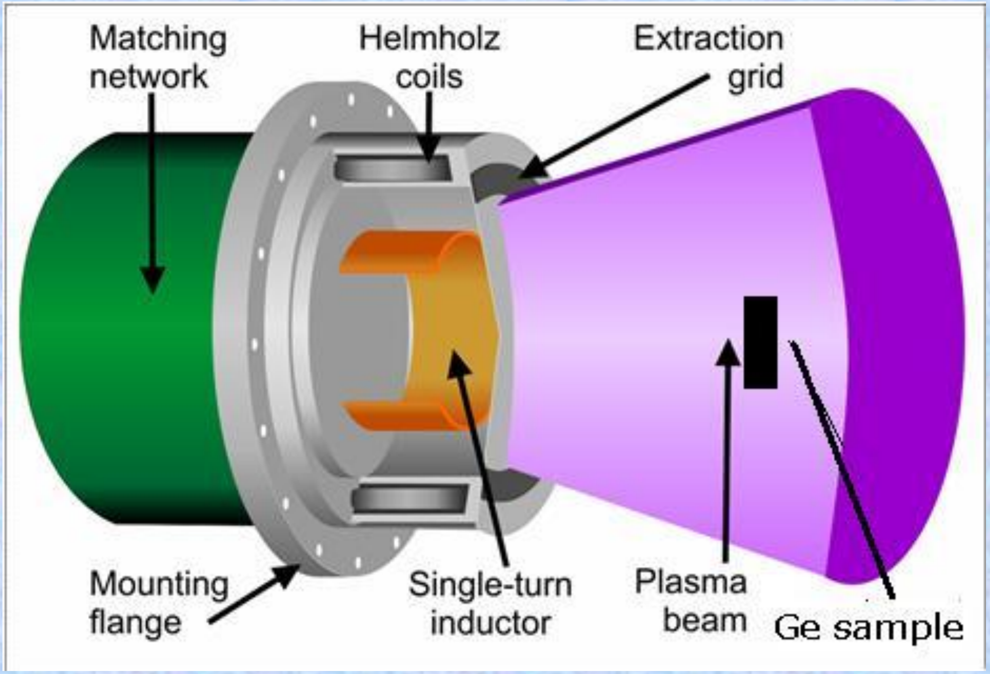
Our basic experiment: Plasma annealing of defects

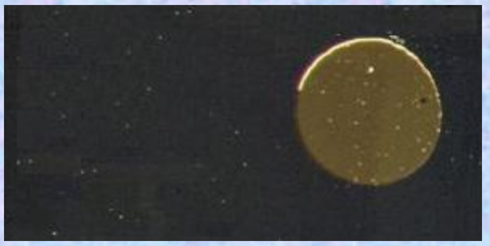
Copra ICP Ar plasma source



Sb-doped Ge

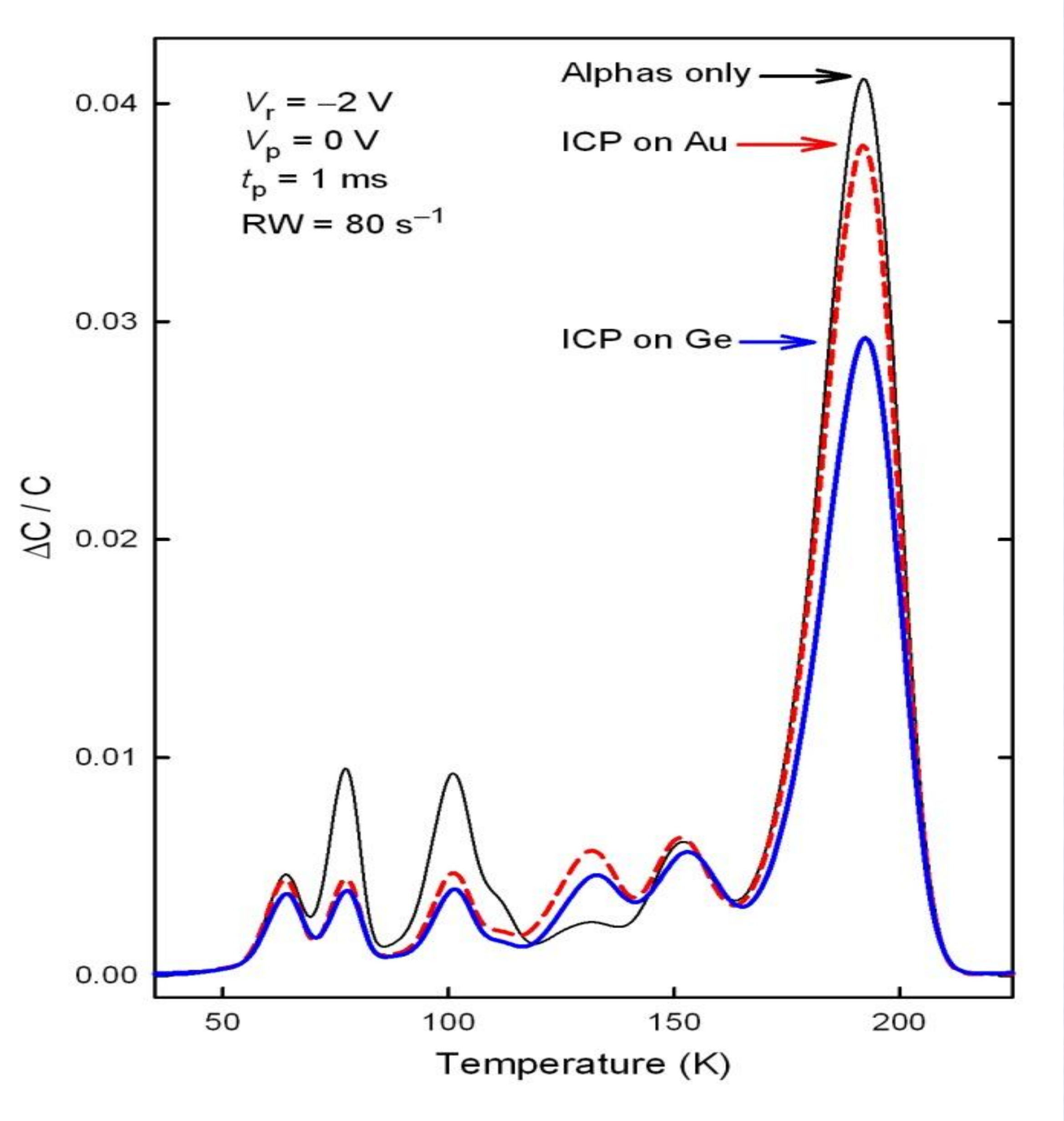
Defect detection by DLTS

N_{Ge}=4.42x10^{22} cm^{-3}
N_{Sb}=1.03x10^{15} cm^{-3}
N_{T}=1.07x10^{14} cm^{-3}



Ge sample with an Au diode

Our basic experiment: 30m, 4 eV ICP plasma annealing



Defects by alpha particles

Deep into Ge 2.6 microns

Reduction of defects in 30%

Similar rate of thermal annealing at 150 C needs 10^{16} more energy

Defect detection by DLTS

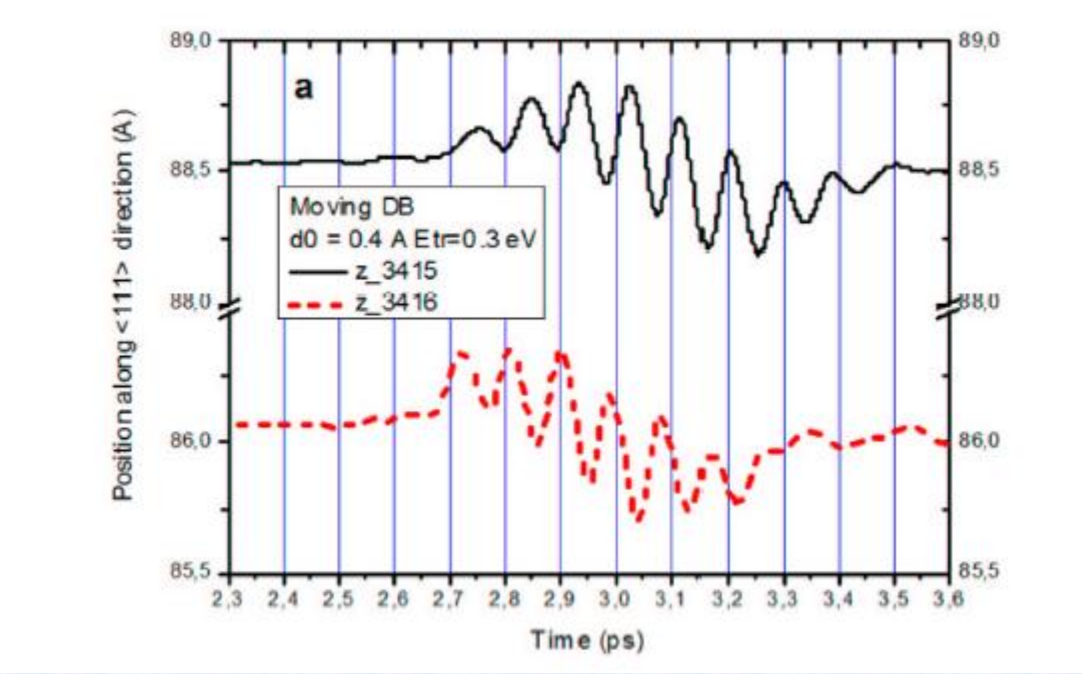
Reduction through Au diode (25nm) 7%

Very low flux

ILMs: Intrinsic (nonlinear) localized modes

- Moving ILMs
  - A perturbation of a medium that transport energy without mass transport
  - In a localized way
  - With little dispersion

  - It has a nonlinear vibrational component
  - It may have an electrical or other type component

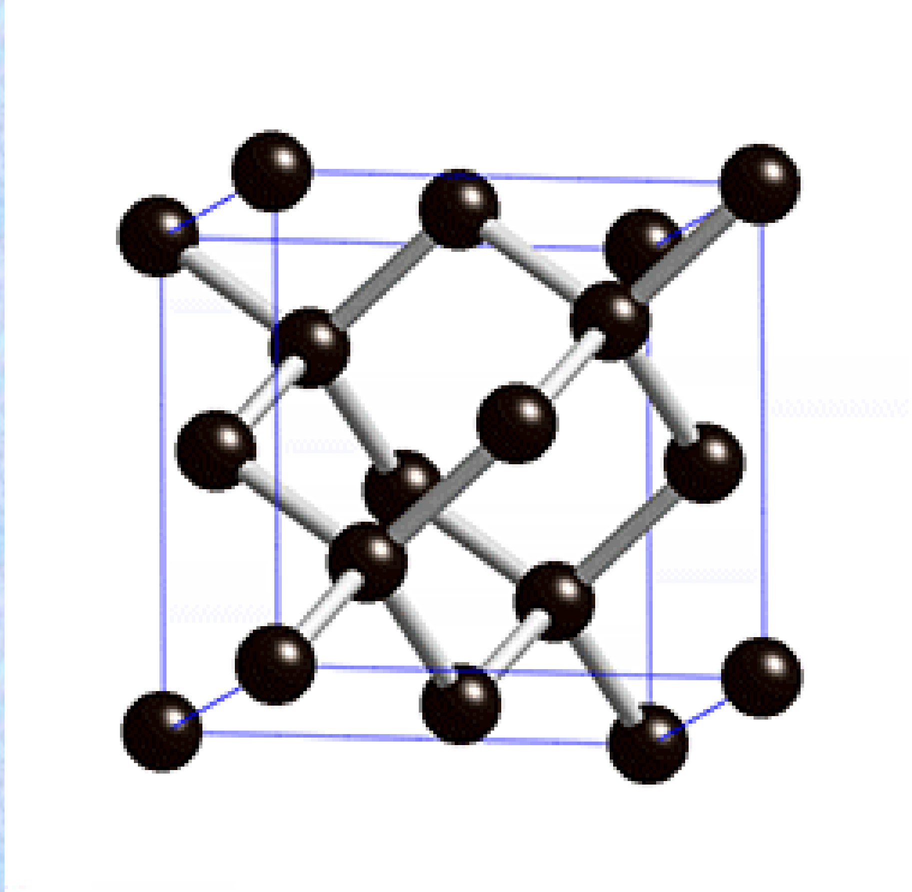


Terentyev, Dubinko, Dubinko, Dmitriev, Zhurkin, 2015

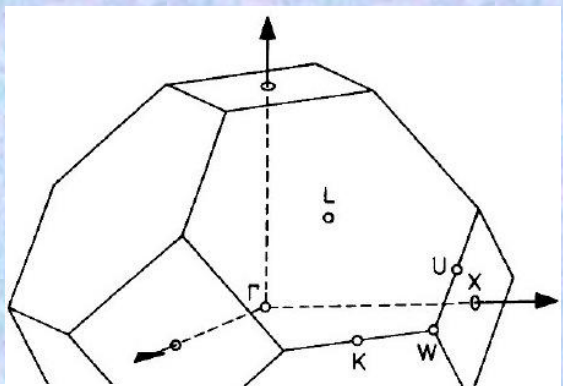
  - Standing ILM: localized energy that keeps localized, mainly vibrational

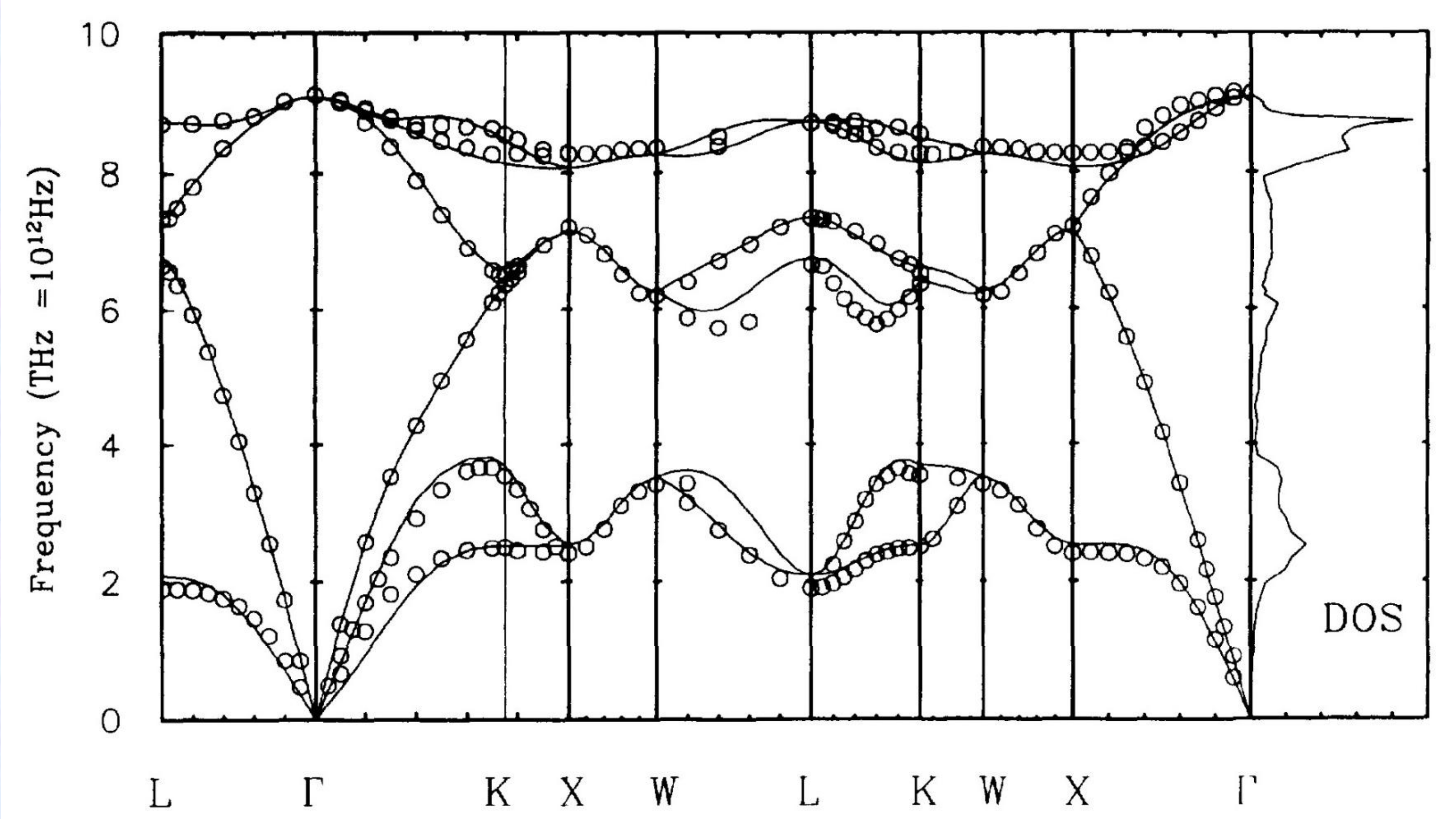
ILMs in Ge?

Stationary ones obtained by Voulgarakis et al (2004) and Hiznyakov et al (2014)



Where can be ILMs in Ge?





ILMs: how we can detect them?

- How many they are?

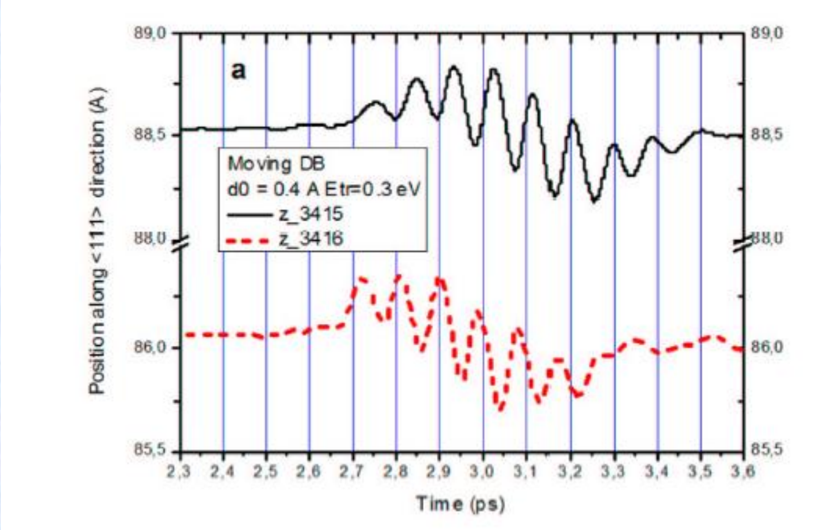
  They are vey few ~10^{-9} number of phonons

- What energy they have? ~1 eV

- How to detect them?

  What property they change?

Something $\frac{dN}{dt} \; \alpha \; \exp(-\frac{E_A}{k_B T})$



- How far they travel?

  100-1000 lattice units?

ILM detection: amplification effect of Arrhenius law

Suppose: E_A is changed in $\mathit{\Delta E}$ in Δt ; $-\mathit{\Delta E}$ in Δt

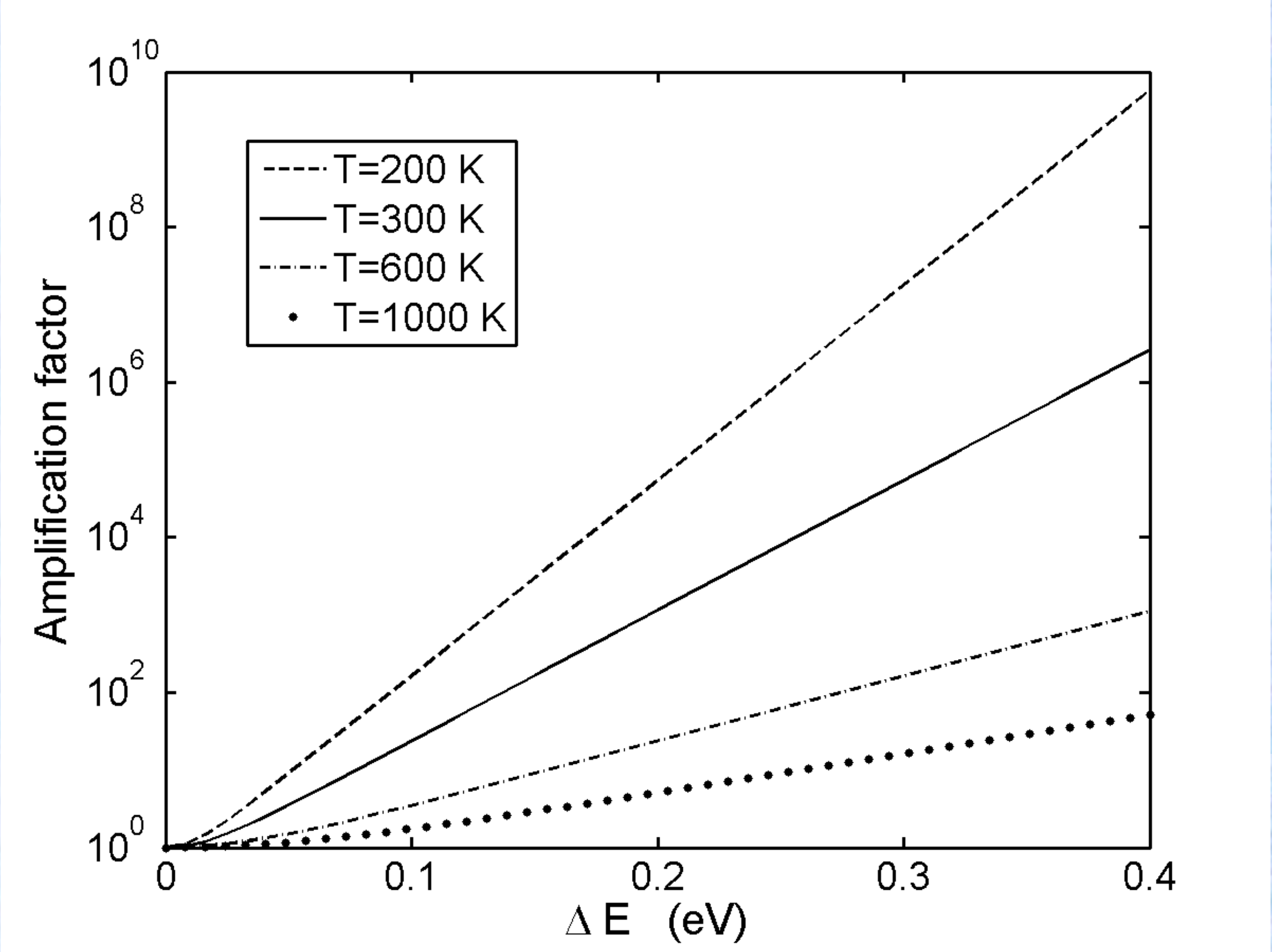
$$\left\langle \exp(-\frac{E}{k_B T}) \right\rangle = \frac{1}{2\Delta \mathrm{t}}[\exp(-\frac{E_A+\Delta E}{k_B T})\Delta t+\exp(-\frac{E_A-\Delta E}{k_B T})\Delta t]$$

$$= \exp(-\frac{E_A}{k_B T})\cosh(-\frac{\Delta E}{k_B T}) = \exp(-\frac{E_A}{k_B T}) I(-\frac{\Delta E}{k_B T})$$

Amplification factor

$$\boxed{I = \cosh(-\frac{\Delta E}{k_B T}) \approx \frac{1}{2}\exp(-\frac{\Delta E}{k_B T})}$$

ILMs: amplification effect on Arrhenius law



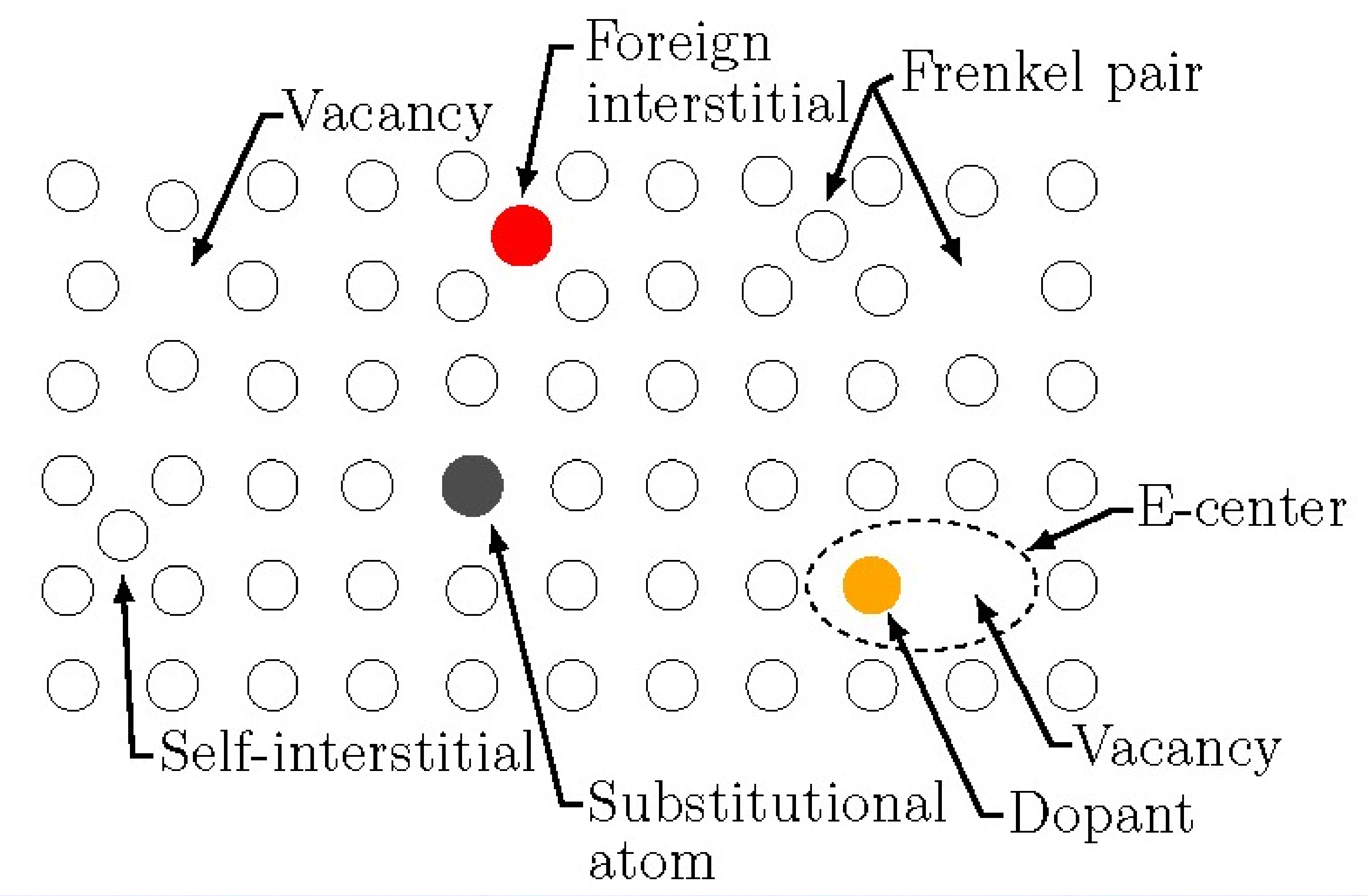
$$I = \cosh\left(-\frac{\Delta E}{k_B T}\right) \approx$$

$$\approx \frac{1}{2}\exp\left(-\frac{\Delta E}{k_B T}\right)$$

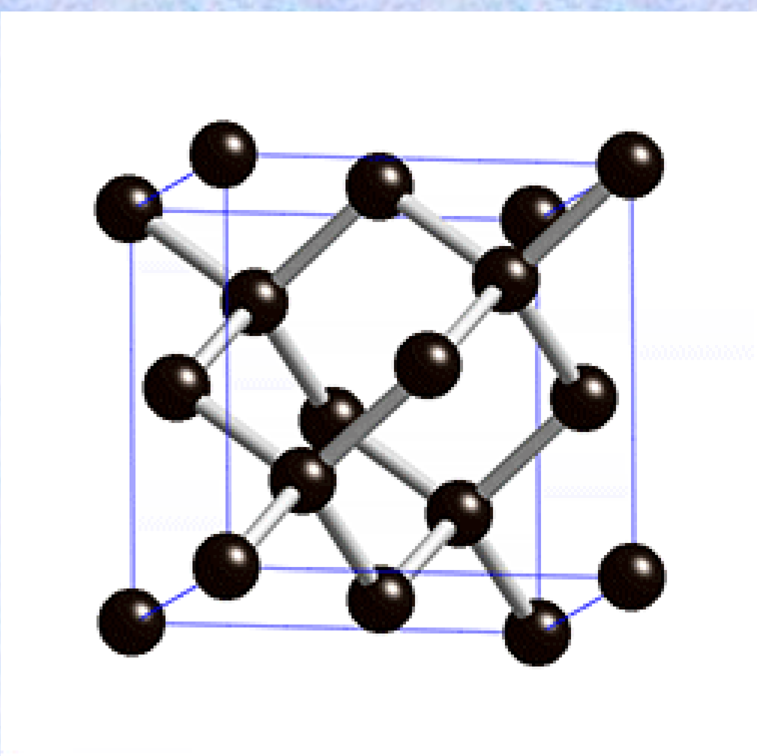
Dubinko, Selyshchev, Archilla,:
Reaction-rate theory with account of the crystal anharmonicity.
Phys. Rev. E **83, 041,124 (2011)**

Defects in germanium

- Can be produced by irradiation
- Of technological interest



Some complex defects in germanium



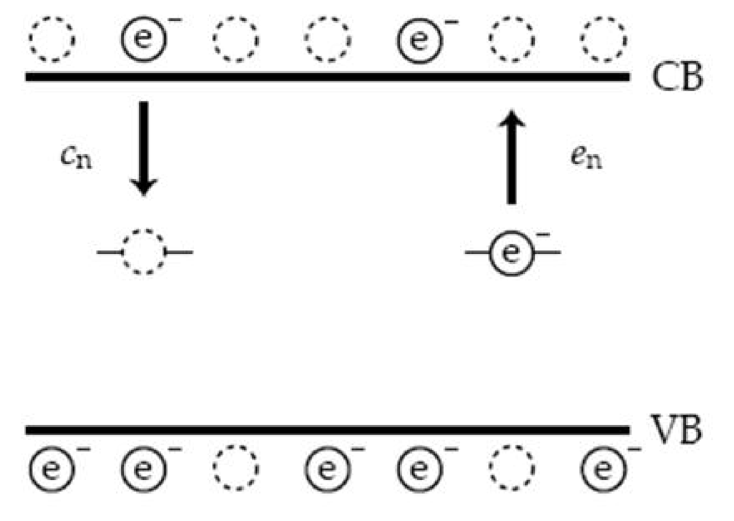
- Di-vacancy V-V
- Tri-vacancy V_3, Tetra-vacancy V_4
- Vacancy-Hydrogen VH_n
- I_2, I_3, …
- A center:

  Foreign interstitial 0-Vacancy
- E center

  Substitucional atom-Vacancy

  Sb doped Ge: Sb-V

Defects as electron traps



Deep level electron trap:

$$E_T = E_t - E_c \geq 0.1\,\text{eV}$$

$$E_{0.37}: \qquad E_T = 0.37\text{eV}$$

$$c_n = \sigma_n \langle v_n \rangle n$$

$$\boxed{e_n = \sigma_n \langle v_n \rangle N_c \exp\left(-\frac{E_T}{kT}\right)}$$

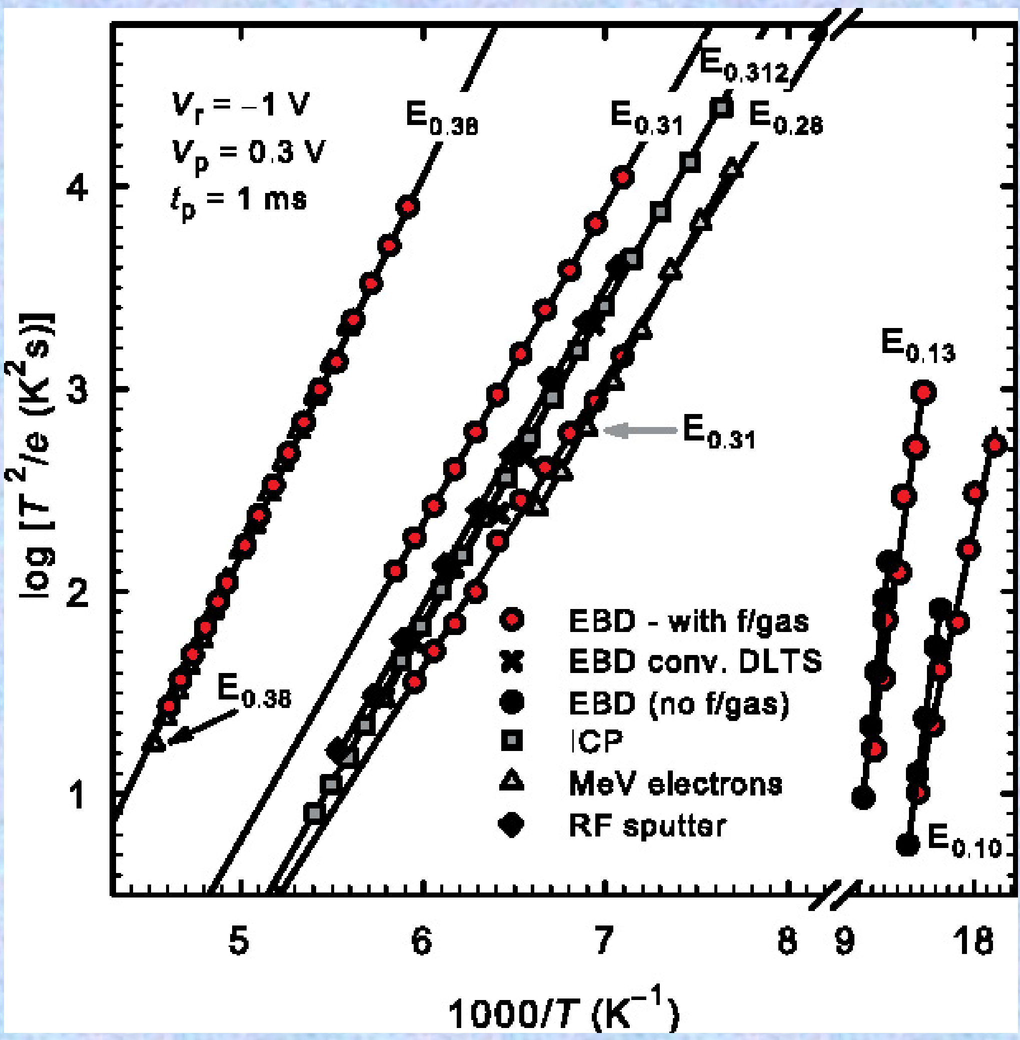
Empty level. defect can
-Capture an electron
from the CB

Defect populated by an electron can :
-Emit an electron
to the CB

Capture rate c_n

Emision rate e_n

Signature of the trap



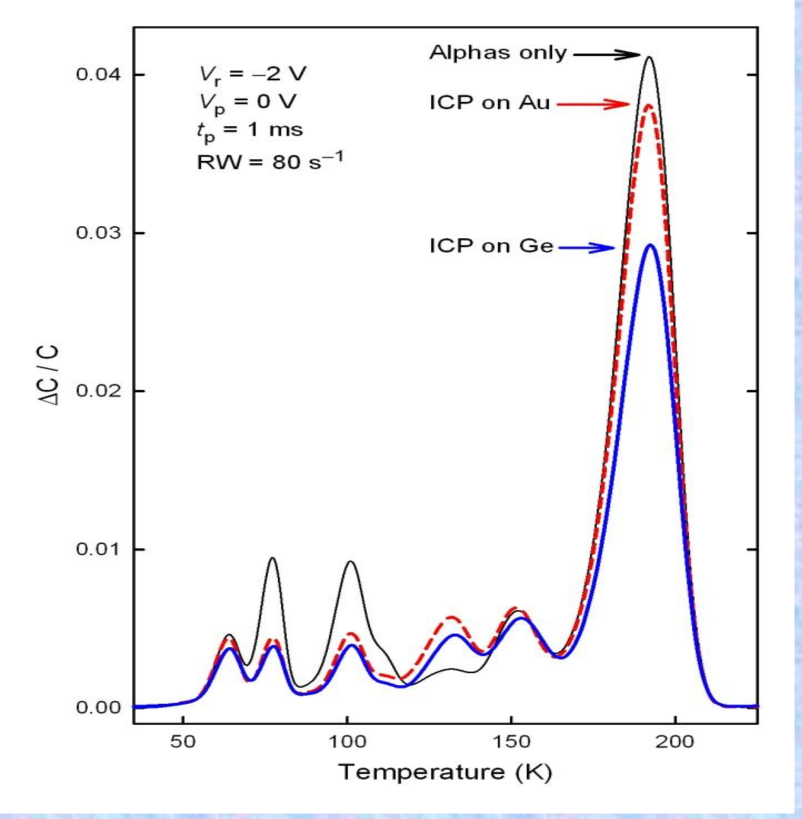
Energy of the trap

E_T

Capture cross section of the trap

σ_n

Plasma induced annealing and thermal annealing



Ion-induced $$-\frac{dN_T}{dt} = K_i N_T$$

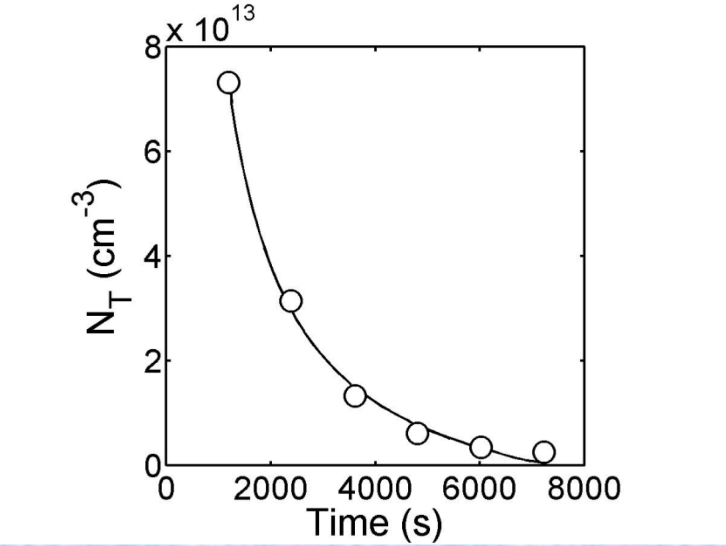
Thermal $$-\frac{dN_T}{dt} = K_{th}(T) N_T$$

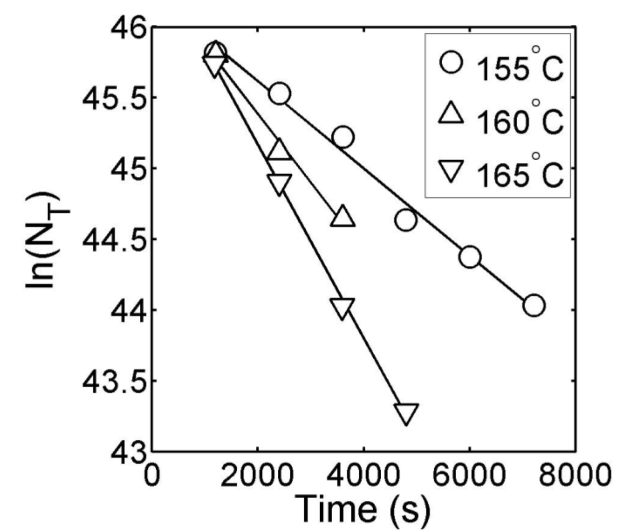
$$K_i = 2.0 \times 10^{-4}\ \mathrm{s}^{-1} \quad \text{(plasma)}$$

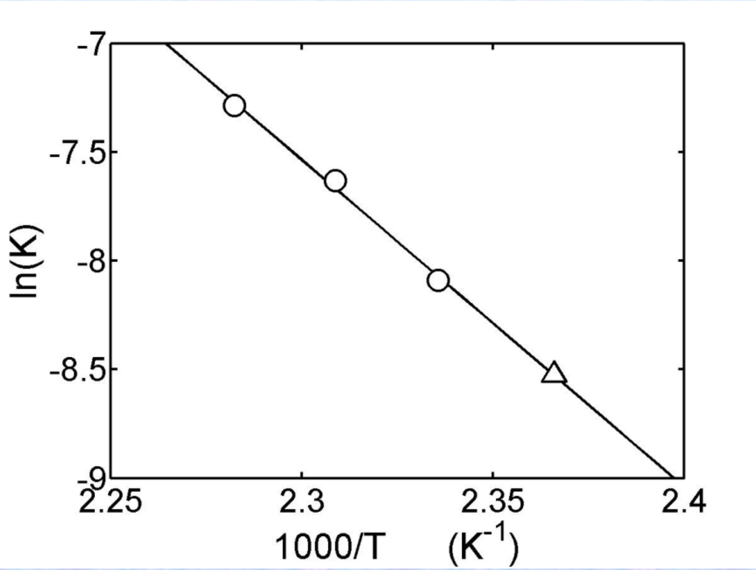
Room temperature: $$K_{th} = 9.6 \times 10^{-11}\ \mathrm{s}^{-1} \quad \text{(thermal)}$$

Equivalent temparature T_A =423 K (150 C) $$K_{th} = K_i$$

Thermal annealing





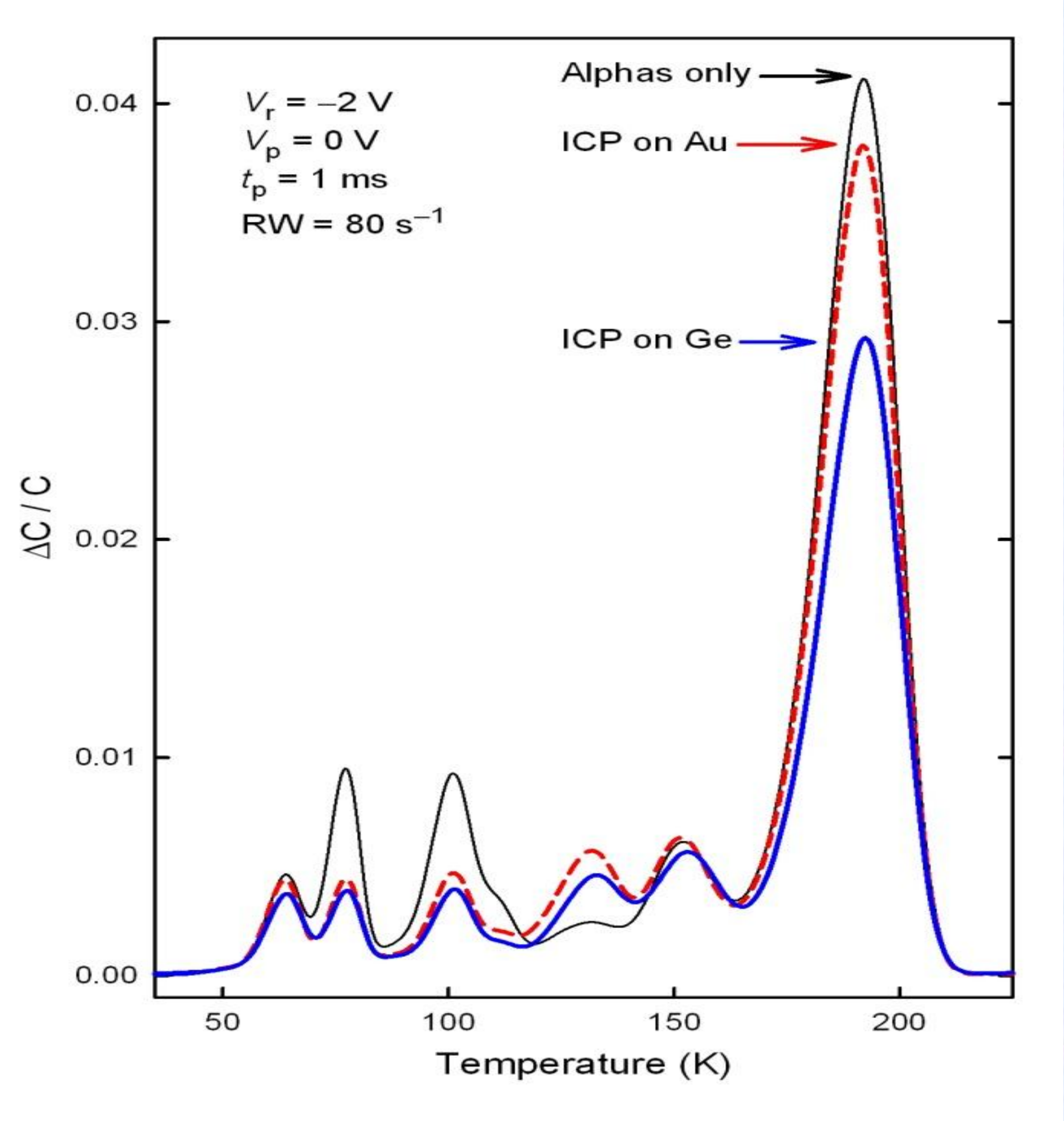


$$N_T = N_T(0)\mathrm{e}^{-K_{th}t} \qquad K_{th} = A\mathrm{e}^{-\frac{E_A}{k_B T}}$$

$$\boxed{A = 0.55\times 10^{12}\,\mathrm{s}^{-1}; \quad E_A = 1.3\,\mathrm{eV}}$$

$$T_A = 423\,\mathrm{K} \qquad (150\ ^{\circ}\mathrm{C})$$

Experimental details: 4 eV ICP plasma annealing



1.-Sb doped Ge is damage with 5 MeV alpha particles

2.- Rest 24 hours

3.-Au diode is evaporated in half the sample (half A)

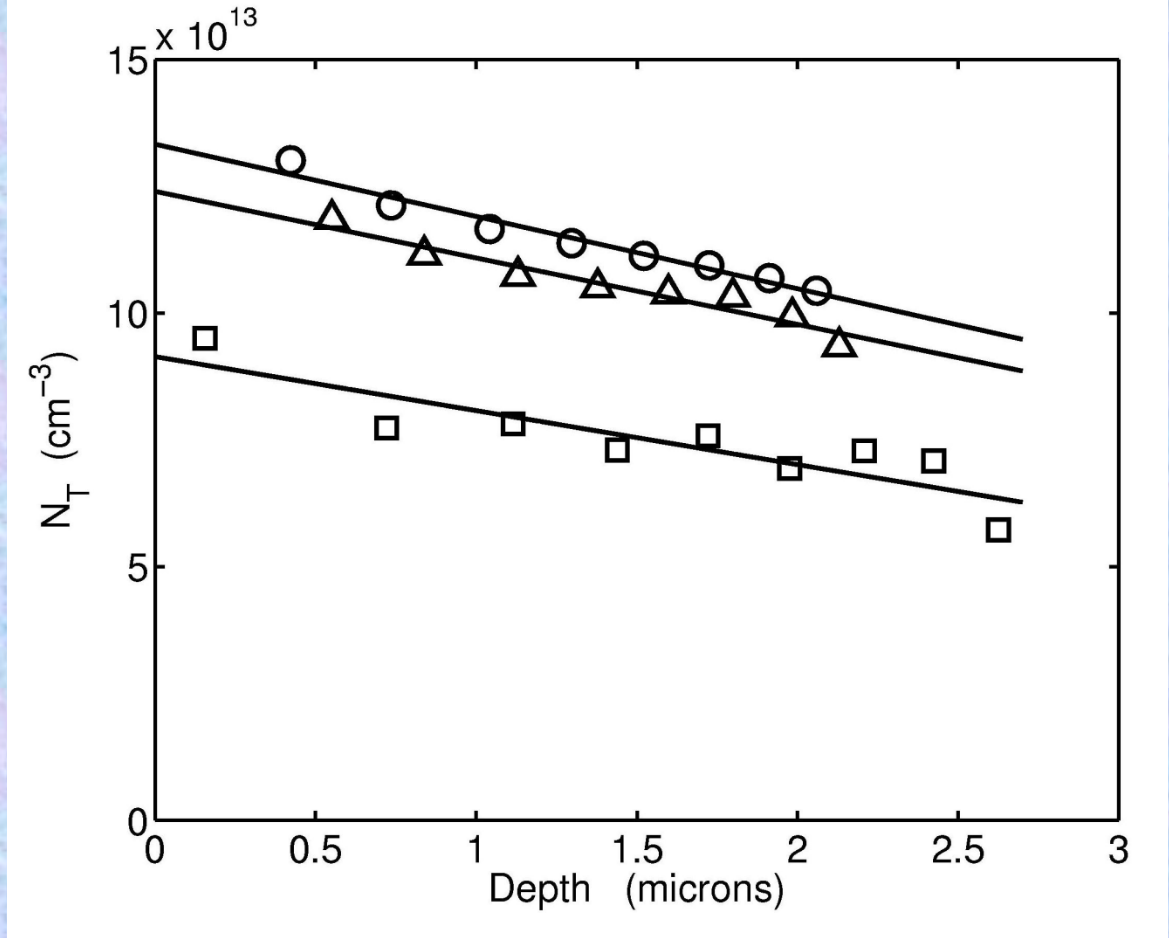
4.- DLST in A
(black, alphas only)
5.-ICP in A and B

6.- Au diode in B

7.- DLTS in A
(red, ICP on Au)

8.- DLTS in B
(blue, ICP on Ge)

Depth profile



Rate of annealing decreases very slowly

Our hypothesis: Ar ions impacting on Ge produce ILMs, which travel through Ge and anneal the defects.

Why?

1.-ILMs with MD in metals by Hyzhnyakov group have 0.5-5 eV

2.-The maximum energy transfer from Ar to Ge is 3.6 eV

3.- The activation energy for annealing an E center is 1.3 eV

4.- The energy to anneal a defect has to remain localized up to 10^4 lattice units

5.- Increasing the energy of the plasma does not enhance the effect, this is because ILMs typically have a definite range or energies.

6.- At least stationary ILMs have been obtained for Si and Ge with MD.

More is less: Some numbers on cross sections for ions

Ion current can be measured, then
ion cross section can be calculated

$$-\frac{dN_T}{dt} \approx \sigma_i \Phi_i N_T$$

For 4 eV Ar ions:

$$\Phi_i = 5.5 \times 10^{10} \text{cm}^{-2}\text{s}^{-1} \qquad \sigma_i = 4.4\sigma_0$$

for $\sigma_0 = (n_{Ge})^{-2/3} \approx 8\text{A}^2$

For 8 eV Ar ions:

$$\Phi_i(8\,\text{eV}) = 1.3 \times 10^{13} \text{cm}^{-2}\text{s}^{-1} \qquad \sigma_i(8\text{eV}) = 0.033\sigma_0$$

$$\boxed{\sigma_i(8\text{eV}) \approx \frac{1}{140}\sigma_i(4\text{eV})}$$

Some numbers on energy of phonons and ILMs

1.-Ion current can be measured $-\frac{dN_T}{dt} \approx \sigma_i \Phi_i N_T \quad ; \quad -\frac{dN_T}{dt} \approx \sigma_{ILM} \Phi_{ILM} N_T$

$$\boxed{\sigma_i \Phi_i = \sigma_{ILM} \Phi_{ILM}}$$

$$\Phi_{ILM} < \Phi_i \qquad ; \qquad \sigma_{ILM} > \sigma_i$$

$$n_{ILM} = \frac{\Phi_{ILM}}{c_s} \approx 10^{-18} \mathrm{n}_{Ge} \qquad E_{ILM} < E_{Ge,Max} \approx 3.6\,\mathrm{eV}$$

Energy in phonons and energy in ILMs for same annealing

$$u_{ph} = \frac{1}{n_{Ge}} \int_{T_R}^{T_A} g(E) \langle n(E) \rangle E dE \approx 30.1\,\mathrm{meV/atom}$$

$$u_{ILM} = \frac{1}{n_{Ge}} n_{ILM} E_{ILM} \approx 10^{-15}\,\mathrm{meV/atom}$$

$$\boxed{\frac{u_{ILM}}{u_{ph}} \approx 10^{-16}}$$

Conclusions:

0.- Plasma of 4eV produces annealing of defects very deep in Ge

Likely conclusions:

1.- 4 eV Ar hits produce ILM in Ge with very high efficiency

2.-ILMs of energy ~3eV travel distances of the order of at least 10^4 lattice units

3.- The annealing efficiency of DB with respect to phonons is extremely large

4.- The energy delivered by a DB to a defect is ~ 0.3 eV

References

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Chapters:
4 in mica; Russell, Eilbeck, Archilla, Russell
4 in MD of breathers (2D): Malomed, Cisneros, Johansson, Wattis
3 in MD of breathers (3D): Dmitriev, Hizhnyakov, Kosevich
3 in electrons and lattices: Brizhik, Chetverikov, Ebeling, Cruzeiro, Velarde
3 in semiconductors: Coelho, Dubinko, Archilla
3 in rogue waves, proteins, BC condensates

-Archilla, J.F.R., Coelho, S.M.M., Auret, F.D., Dubinko, V.I., Hizhnyakov, V., Nyamhere, C.: **Experimental observation of intrinsic localized modes in germanium.-**
-Coelho, S.M.M., Archilla, J.F.R., Auret, F.D., Nel, J.M.: **The origin of defects induced in ultrapure germanium by electron beam deposition.**
-Dubinko, V.I., Archilla, J.F.R., Dmitriev, S.V., Hizhnyakov, V.: **Rate theory of acceleration of the defect annealing driven by discrete breathers.**
-Hizhnyakov, V., Haas, M., Shelkan, A., Klopov, M.: **Standing and moving discrete breathers with frequencies above the phonon spectrum.**

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