Radiation Hardness of Insulating Materials and Semiconductors

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31. 08. 2005

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The Problem:

What determine the Sensitivity of Solids to Radiation?

a) The electronic configuration of the atoms

b) The crystal structure

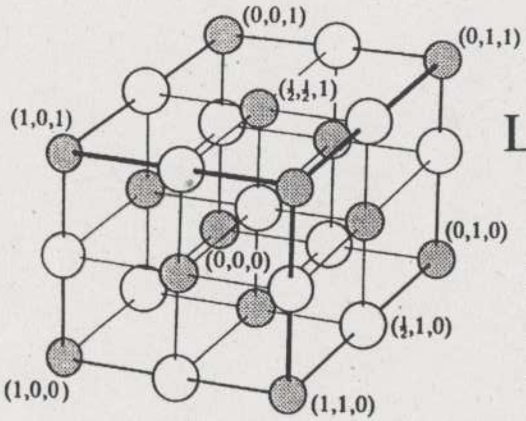
I. Damage creation in Dielectrics Two classes of insulating materials

II. Semiconductors Si; SiC

III. Peculiarities of Damage creation under heavy ion irradiation

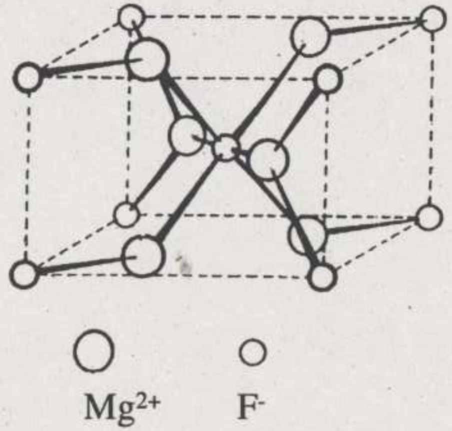
I. Damage Creation in Dielectrics by the Decay of Electronic Excitations [1, 3, 5, 6, 12]

Crystal structure



LiF (cubic)

a = 4.028 Å
ρ = 2.635 g/cm³
F^- r = 1.33 Å
Li^+ r = 0.74 Å
E_g =14.6 eV

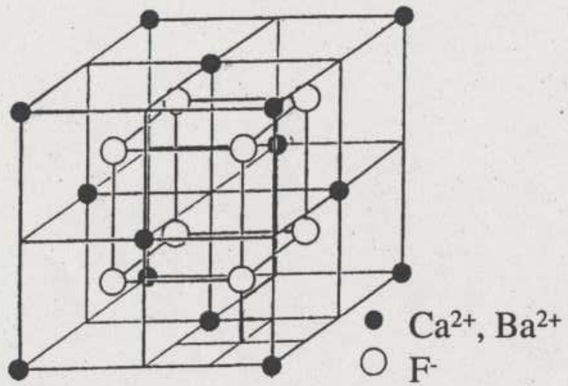


MgF_2 (tetragonal)

a = 4.623 Å c = 7.354 Å
ρ = 3.18 g/cm³
F^- r = 1.33 Å
Mg^{2+} r = 0.72 Å
E_g = 11 eV

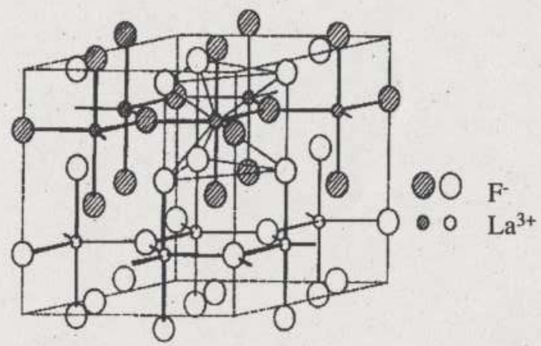
CaF_2 (cubic)

a = 5.463 Å
ρ = 3.18 g/cm³
F^- r = 1.33 Å
Ca^{2+} r = 0.99 Å
E_g =11.2 eV



BaF_2 (cubic)

a = 6.200 Å
ρ = 4.89 g/cm³
F^- r = 1.33 Å
Ba^{2+} r = 1.34 Å
E_g =8.3eV



LaF_3 (hexagonal)

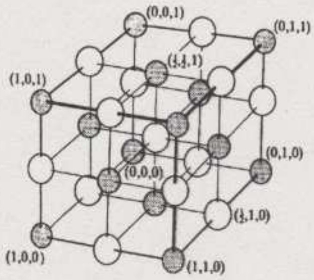
a = 4.148 Å c = 7.354 Å
ρ = 5.9 g/cm³
F^- r = 1.33 Å
La^{3+} r = 1.1 Å
E_g =10.5eV

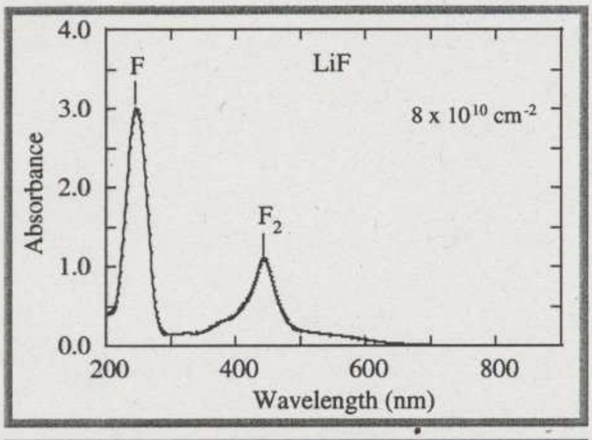
other fluoride crystals

U (5.9 MeV/u)

LiF (cubic)

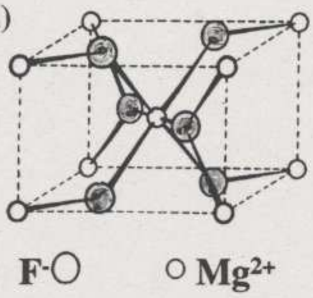
a = 4.028 Å
ρ = 2.635 g/cm³
F^- r = 1.33 Å
Li^+ r = 0.74 Å
E_g = 14.6 eV

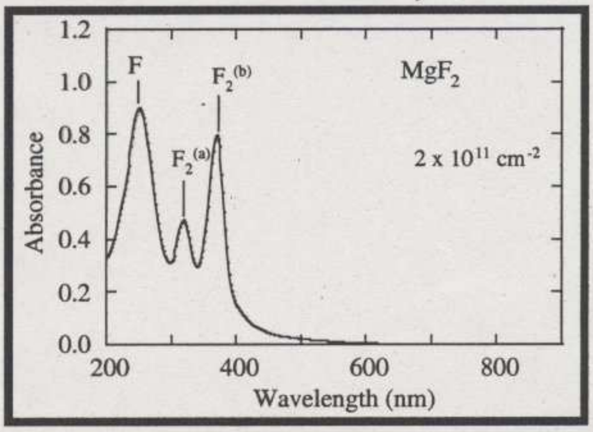




MgF_2 (tetragonal)

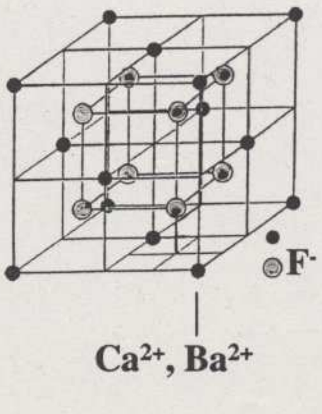
a = 4.623 Å
c = 7.354 Å
ρ = 3.18 g/cm³
F^- r = 1.33 Å
Mg^{2+} r = 0.72 Å
E_g = 11 eV

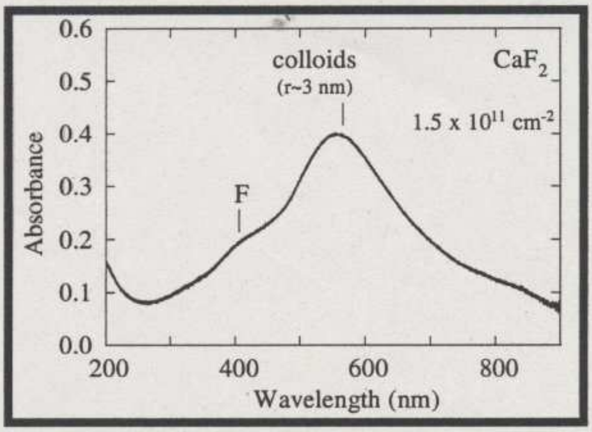




CaF_2 (cubic)

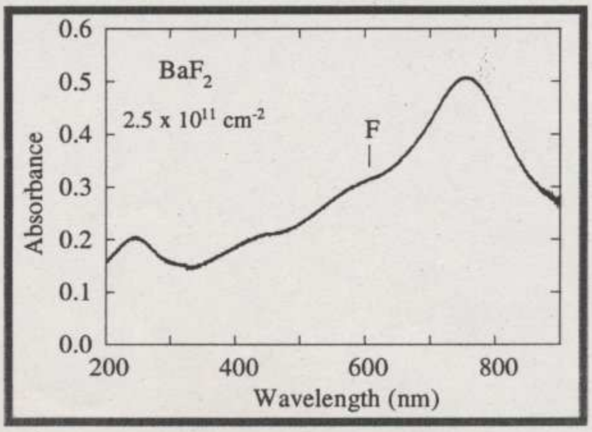
a = 5.463 Å
ρ = 3.18 g/cm³
F^- r = 1.33 Å
Ca^{2+} r = 0.99 Å
E_g = 11.2 eV





BaF_2 (cubic)

a = 6.200 Å
ρ = 4.89 g/cm³
F^- r = 1.33 Å
Ba^{2+} r = 1.34 Å
E_g = 9.1 eV



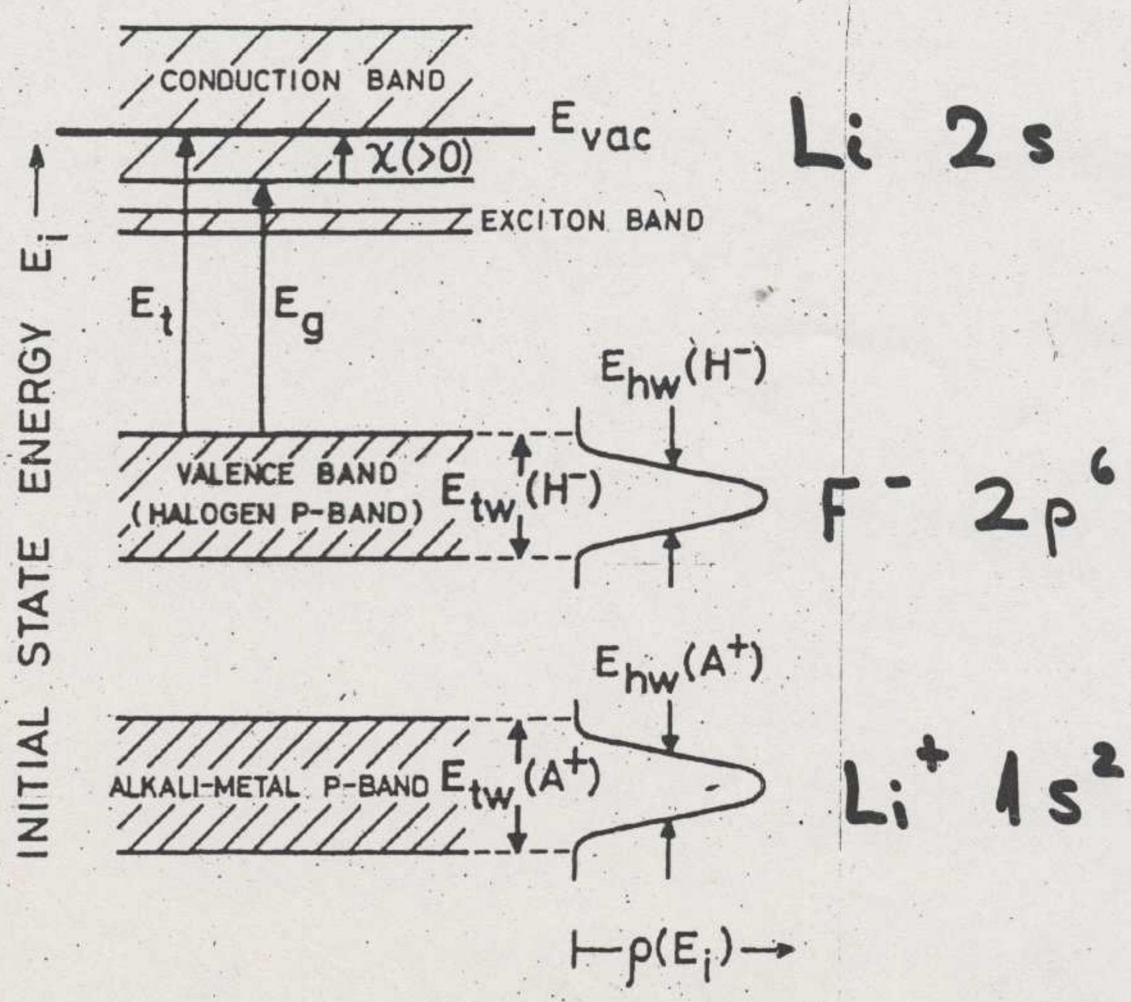
A. El-Said (GSI)

Electronic Band Structure of LiF

R. T. Poole et al. Phys. Rev. B 11 (1975) 5179

CB Li 2s VB Li^{+} $1s^2$[He]

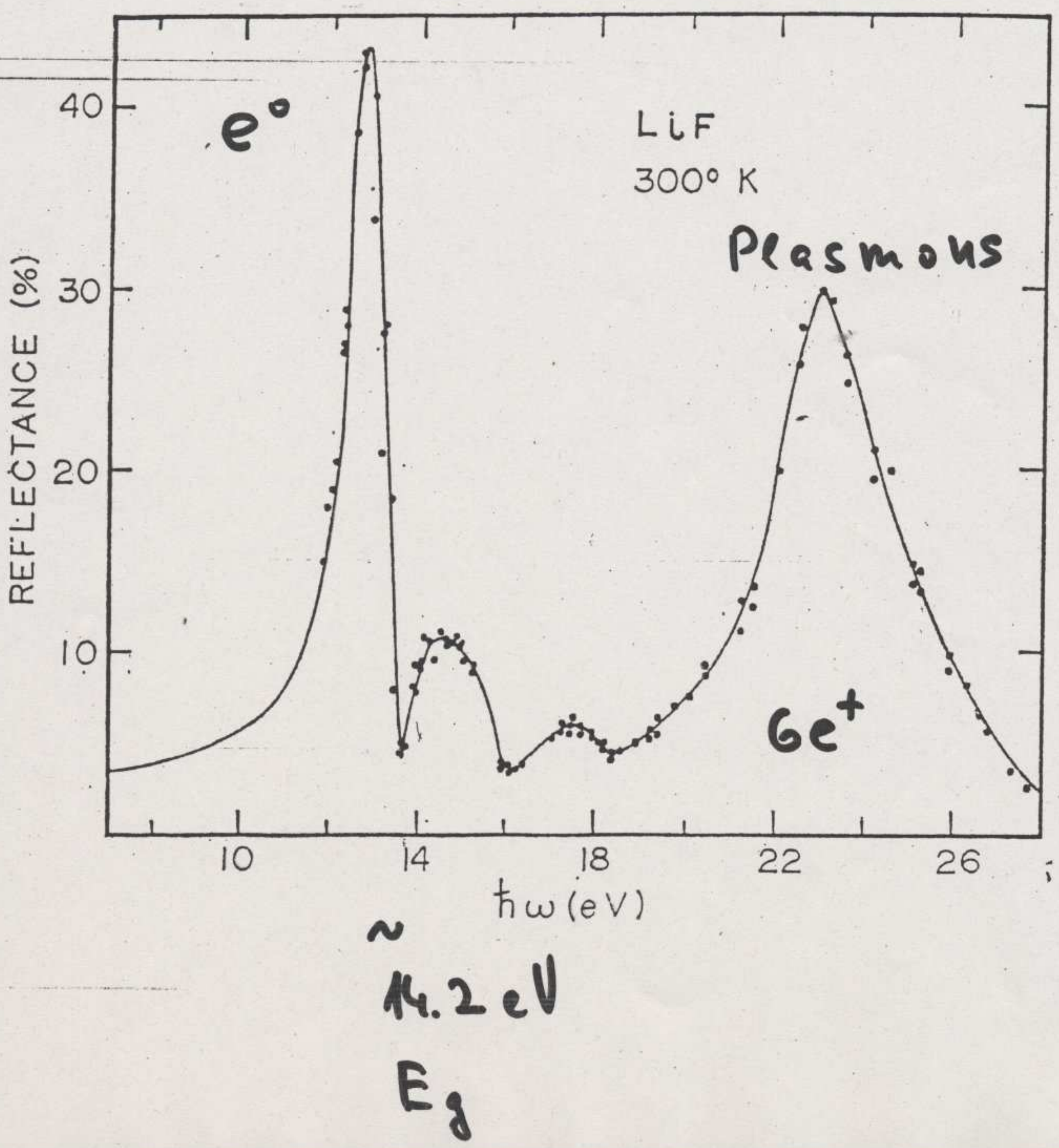
VB F^{-} $2p^6$ [Ne]



Electronic structure:

Anion Exciton 13.6 eV
Gap E_g = 14.2 eV
Plasmons 25 eV
Cation Exciton 63 eV

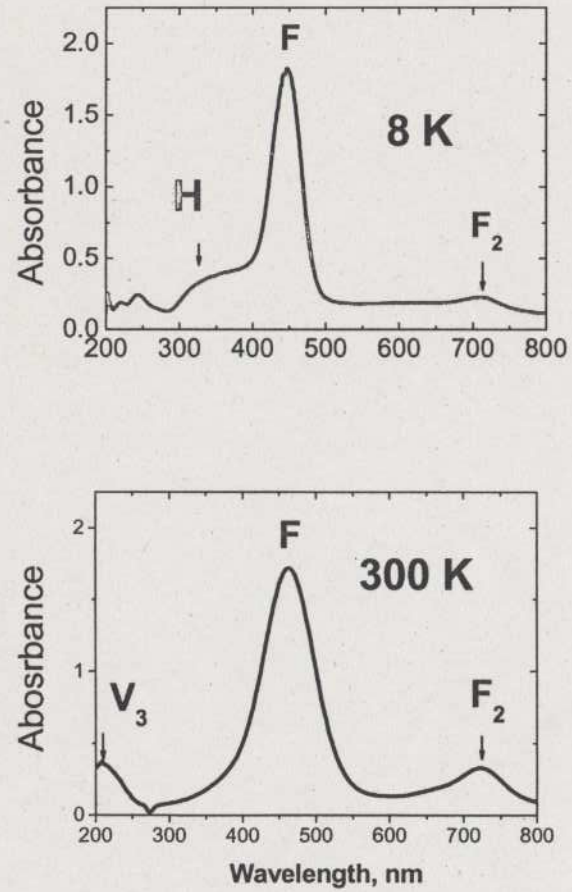
D. M. Roessler, W. C. Walker,
J. Phys. Chem. Solids28 (1967) 1507

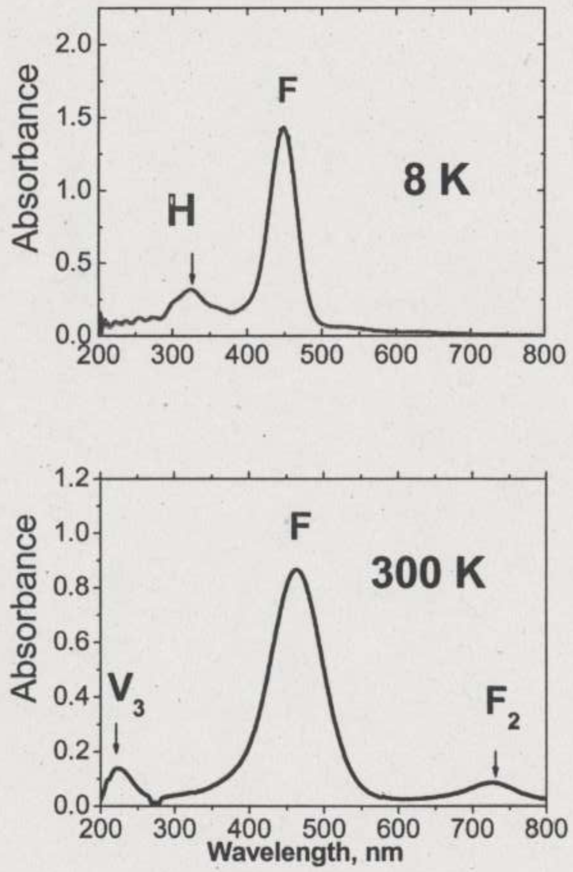


Appearance of H centers at 8 K Irradiation

^{238}U | ^{12}C

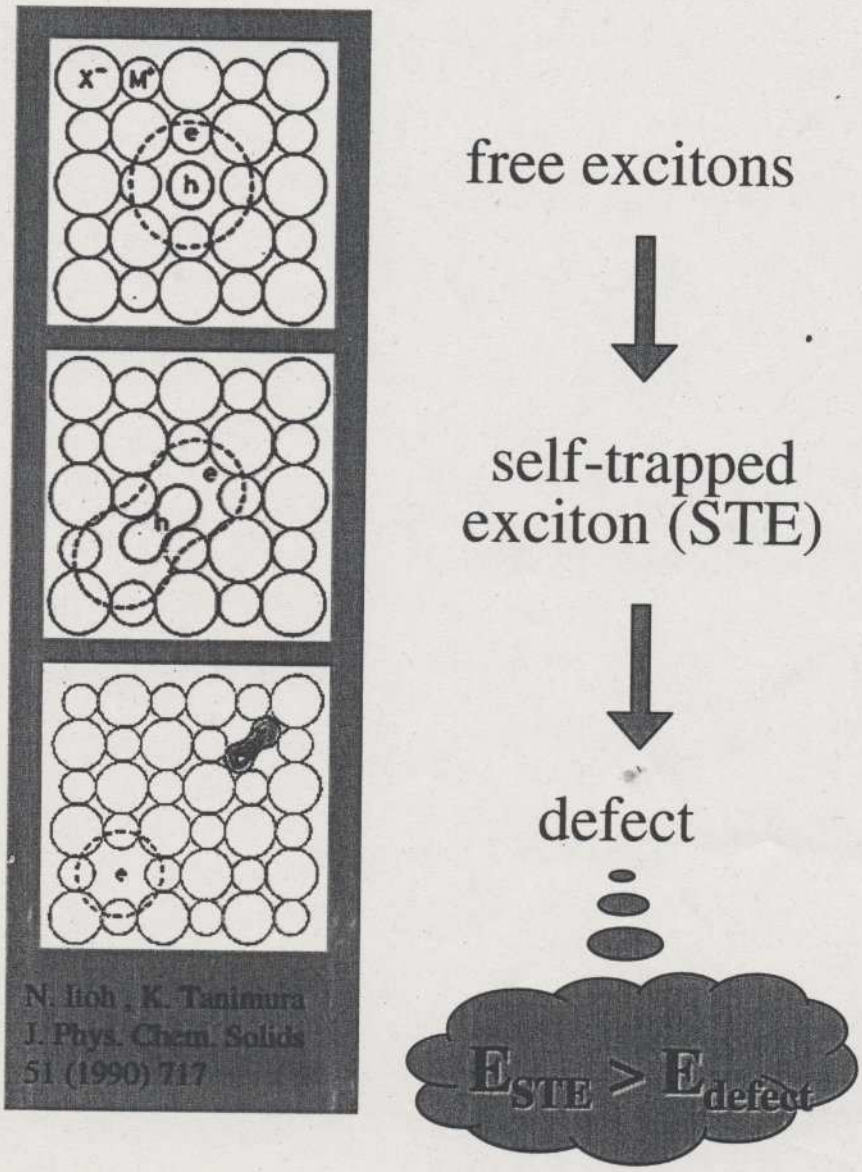
NaCl





H centers are not stable at T > 70 K

Exciton mechanism



The discovering of exciton mechanism in 60ths

Ch.B. Lushchik et al., Sov. Phys. Solid State 6 (1965) 1789

H.N. Hersh, Phys. Rev. 148 (1966) 928

D. Pooley, Proc. Phys. Soc. 87 (1966) 245

Ch.B. Lushchik et al., Sov. Phys. Uspekhi 20 (1977) 489 (review)

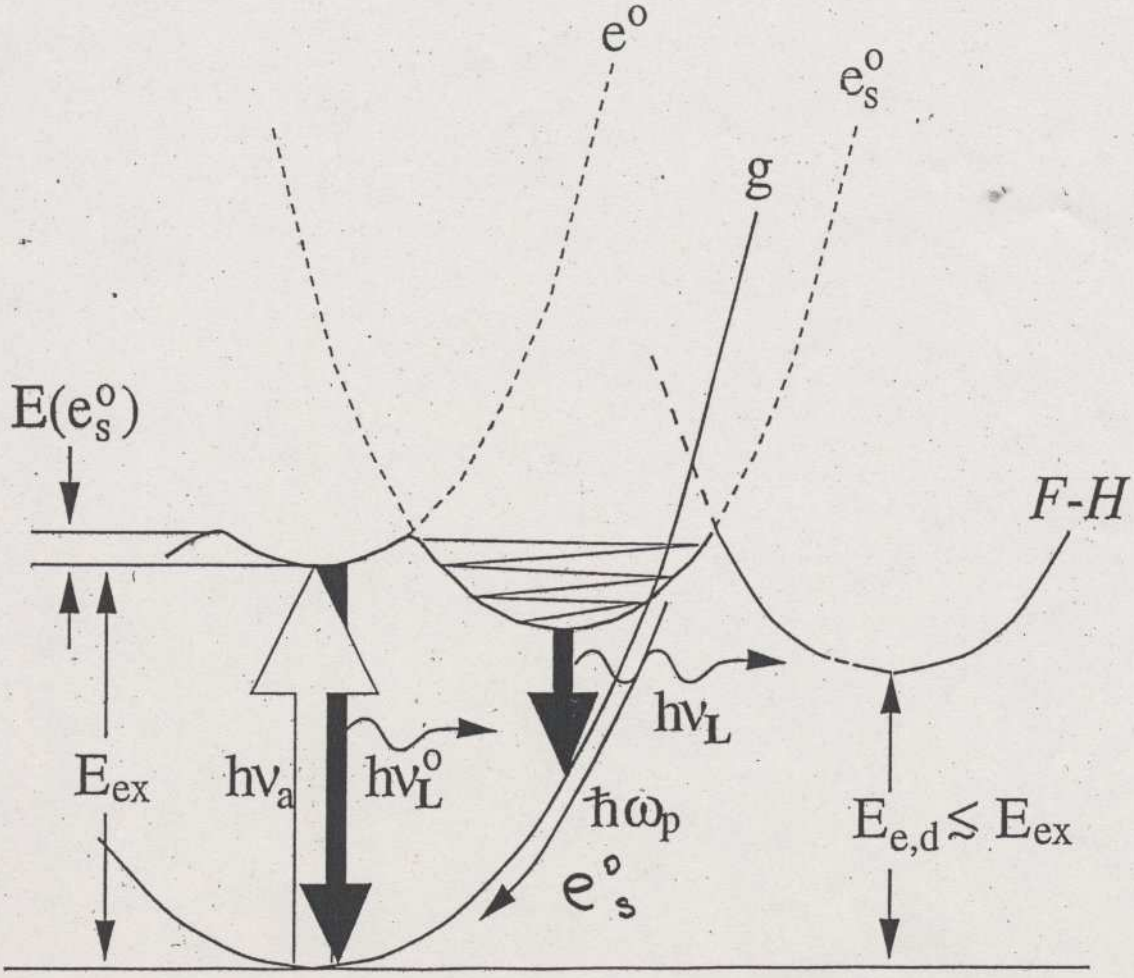
Exciton Processes in Dielectrics

$E(e^0)$ free Exciton Energy

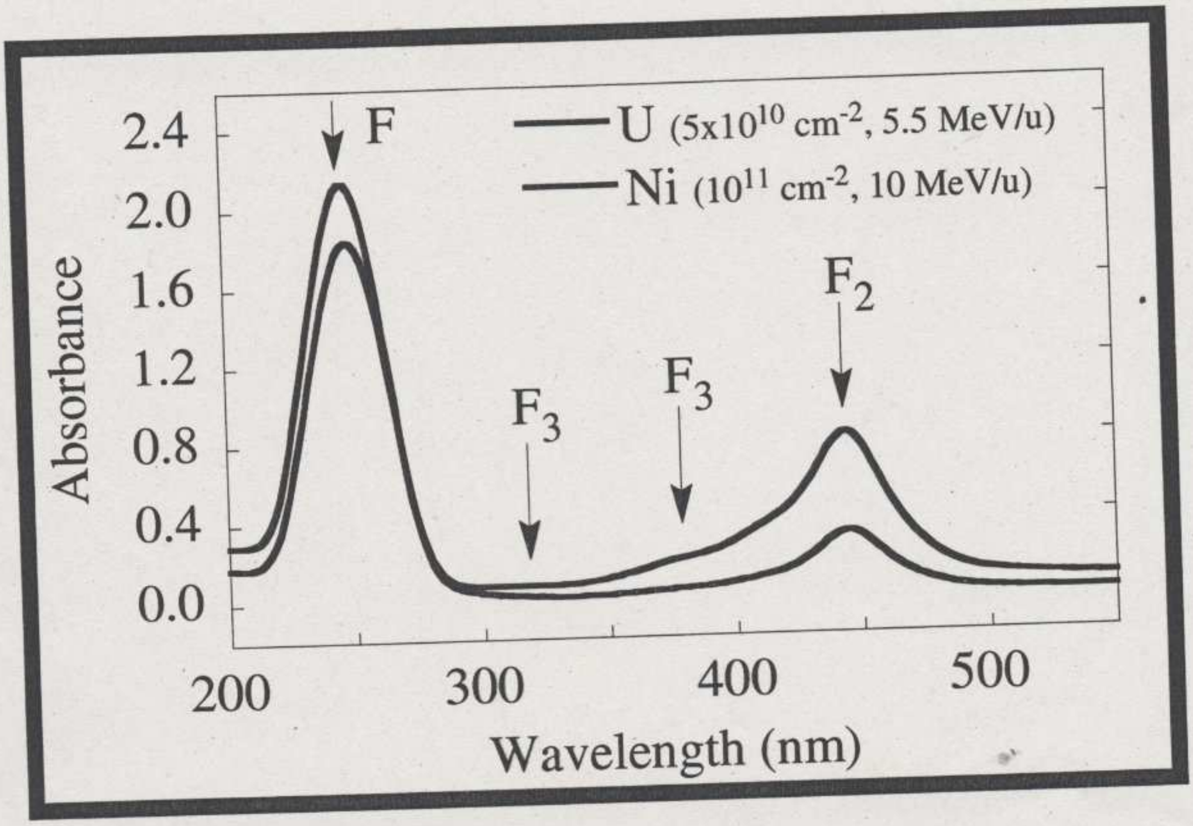
$E(e^0_s)$ elf trapped Exciton Energy

Frenkel Pair F - H

Luminescence $h\nu_L$



Efficiency of F-center creation in LiF



	photons	gammas	light ions (C, S, Ni)	heavy ions (Au, Pb, U)
energy / F-center	42 eV $\sim 3E_g$	400 eV	500-600 eV	900-1200 eV
F-centers / track			10^5	10^6

Electron-Hole Pair Creation Energies

R. C. Alig and S. Bloom, Phys. Rev. Let. 55 (1975) 1522

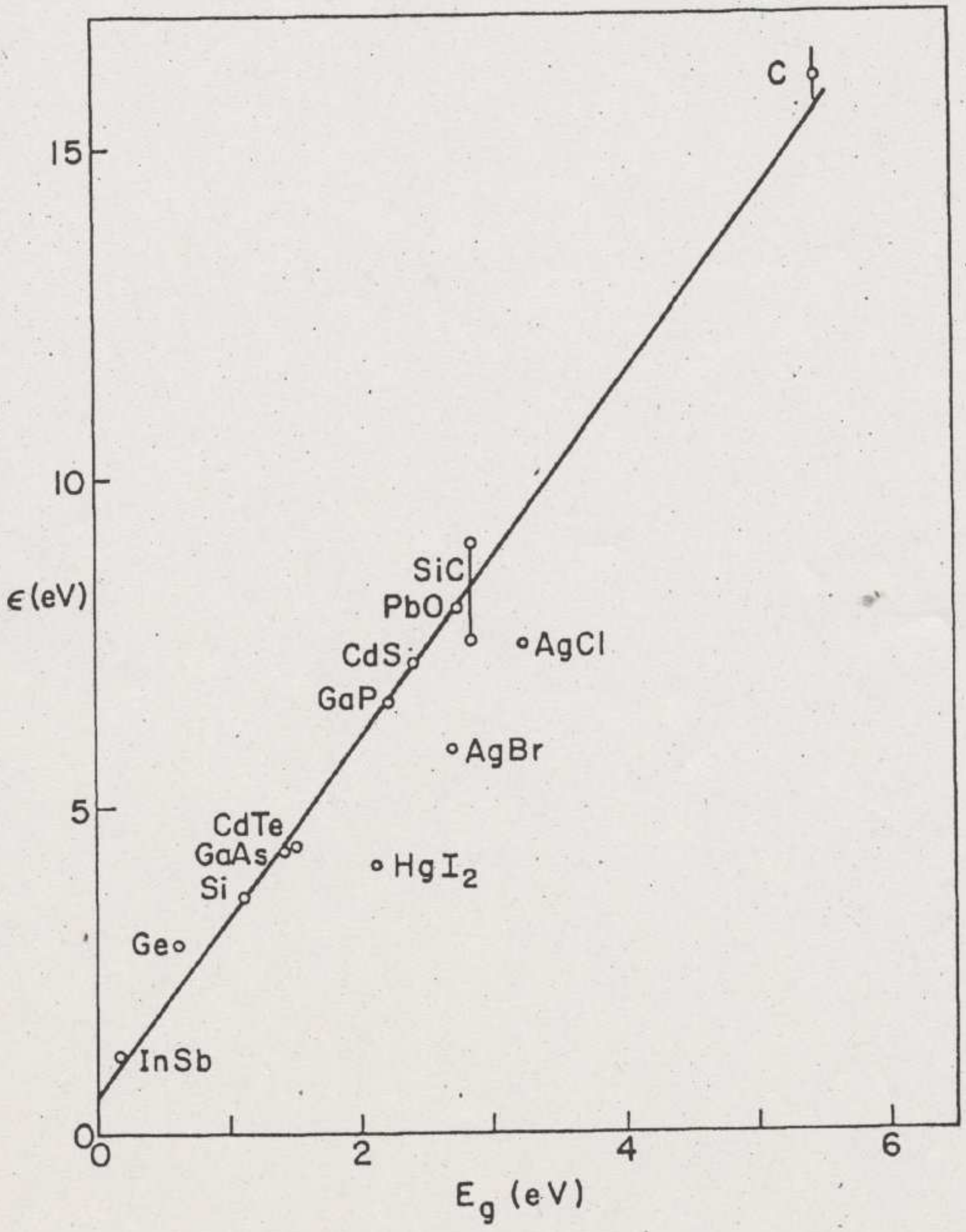


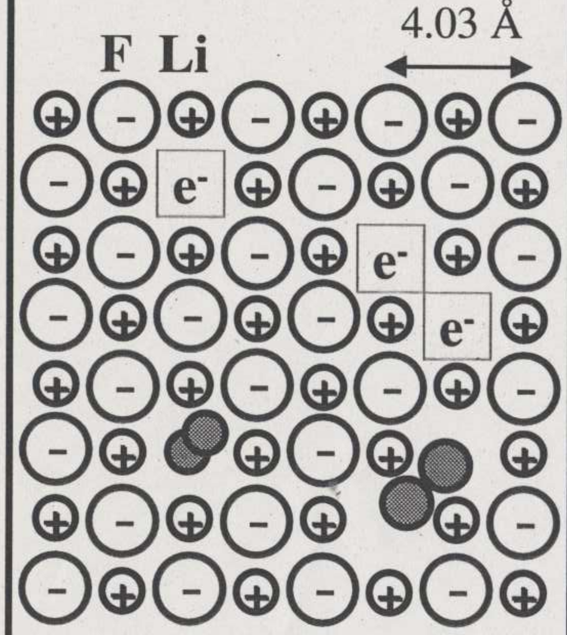
FIG. 1. The measured pair-creation energies ϵ of several semiconductors, versus the fundamental semiconductor band gap E_g. A straight line has been fitted to selected points on this plot.

Defect creation in ionic crystals

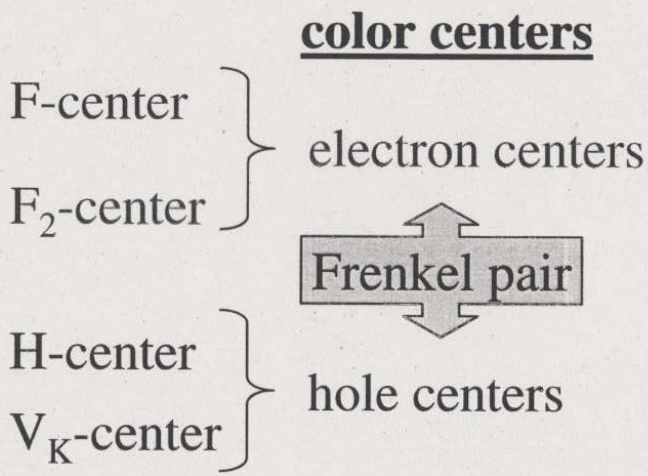
LiF, NaCl, KCl, MgF_2, CaF_2, BaF_2

non-amorphisable !!

lithium fluoride



fcc lattice, E_g=14.6 eV
cleaving along (100) plane



II. Damage Creation in Dielectrics by Elastic Collisions [1, 2, 4, 7, 8, 10, 11]

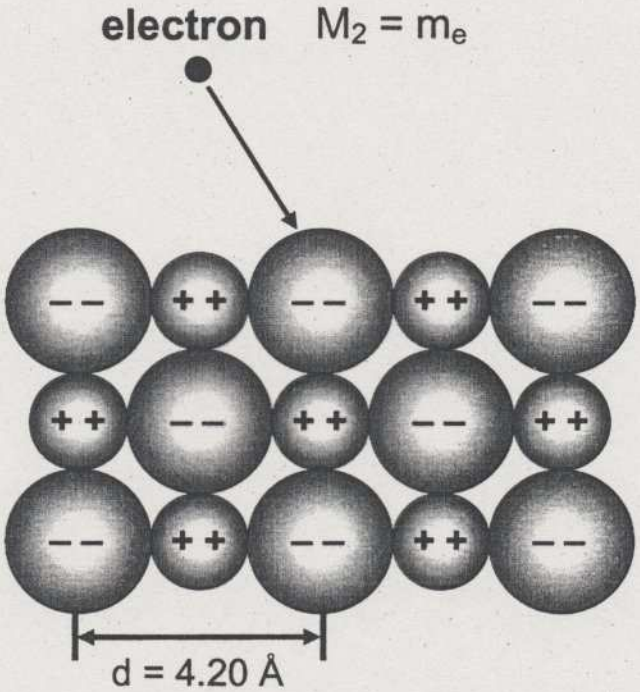
Radiation Hardness and Self Trapping

N. Itoh, NIM B 122 (1997) 405 - 409

Table 1
Presence and absence of self-trapping of carriers in major materials

Material	Electrons	Holes	Excitons
Diamond, silicon, germanium	no	no	no
III–V compounds	no	no	no
II–VI compounds	no	no	no
Se			yes
As_2S, As_2Se			yes
Cupper halides	no	no	no
Thallous halides	no	no	no
Alkali halides with NaCl structure	no	yes	yes
Alkali halides with CsCl structure	no	yes	yes
Alkaline earth fluorides	no	yes	yes
$PbCl_2$	yes	yes	
PbI_2	no	no	no
MgO	no	no	no
ZnO	no	no	no
SiO_2	no	no	yes

Defect production in MgO



$r_{O^{--}} = 1.40$ Å $\quad E_d\,(O^{--}) = 59$ eV

$r_{Mg^{++}} = 0.74$ Å $\quad E_d\,(Mg^{++}) = 64$ eV

$M_1 = A_1$ or A_2

$O^{--} \quad A = M_1 = 16$

$$\Delta E_{tr} = \frac{4 \cdot M_1 \cdot M_2}{(M_1+M_2)^2} \cdot E_0$$

$\Delta E_{tr} = E_d\,(O^{--}) = 59$ eV

$M_2 = 1/1840$

$$E_0^{min} = \frac{\Delta E_{tr} \cdot (M_1+M_2)^2}{4 \cdot M_1 \cdot M_2} \sim 430 \text{ keV}$$

Damage Creation in MgO

W. A. Sibley, NIM B 1 (1984) 419 - 426

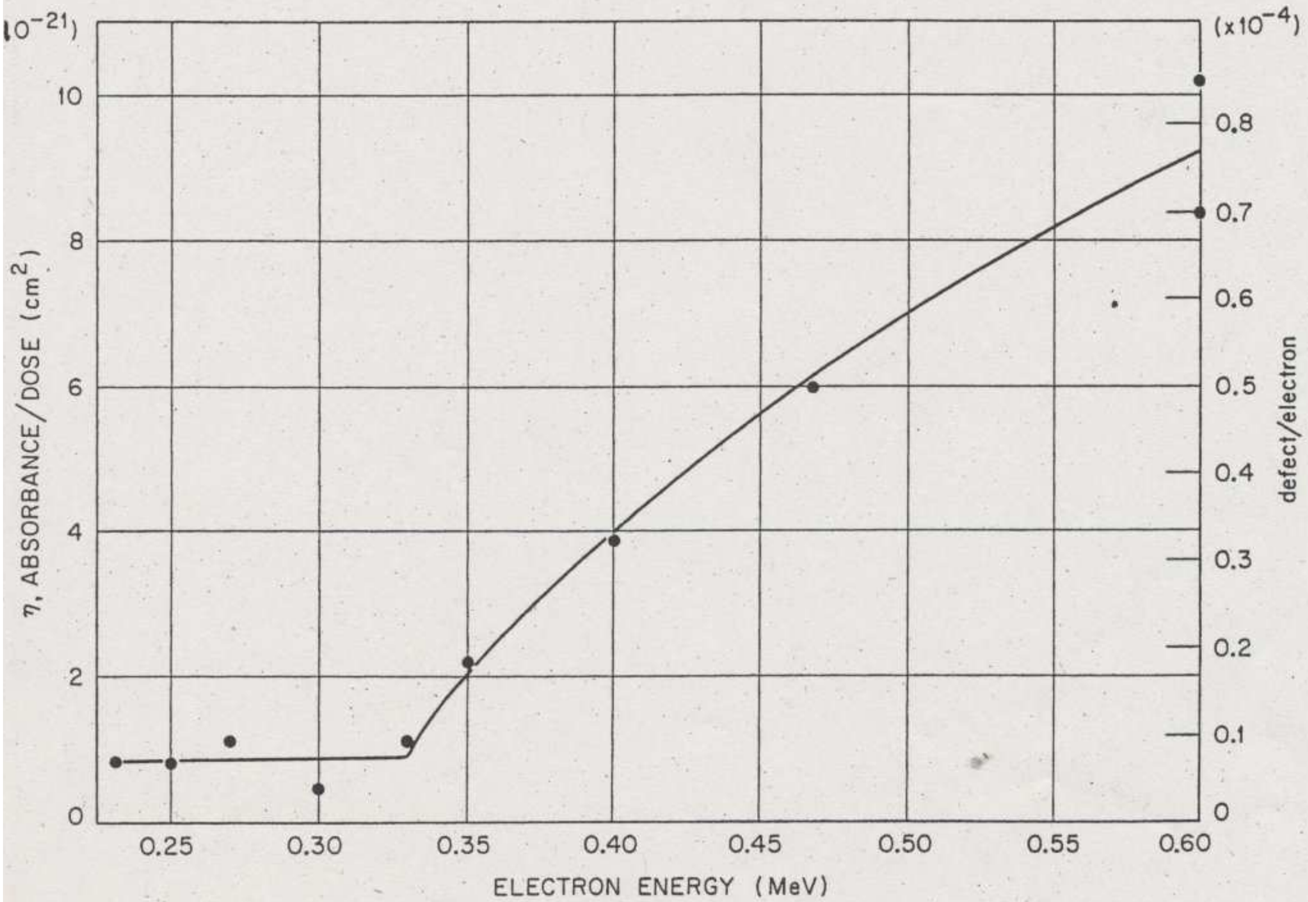


Fig. 4. Defect production rate as a function of irradiation energy for MgO crystals (after ref. 10).

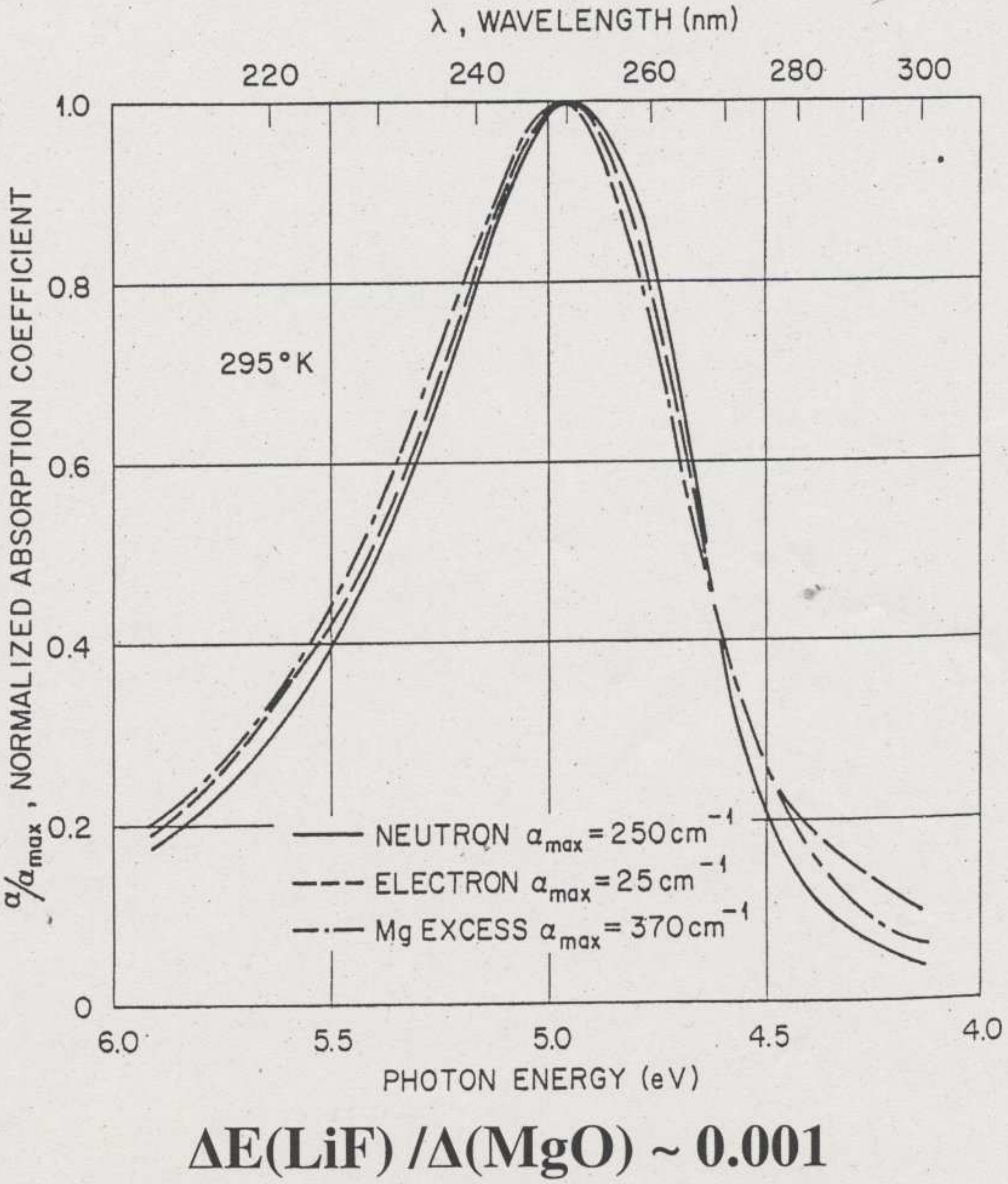
Threshold Effect

ΔE(LiF) /Δ(MgO) ~ 0.001

Damage Creation in MgO

W. A. Sibley, NIM B 1 (1984) 419 - 426

F center absorption



ΔE(LiF) /Δ(MgO) ~ 0.001

Table 2
Displacement energies for some non-metals near room temperature

Material	T^d (eV)	Material	T^d (eV)
C (graphite)	28–31	SiC	45–90
C (diamond)	80	MgO	64(Mg) 60(O)
Si	11–22	Al_2O_3	18(Al) 76(O)
Ge	12–30	$MgAl_2O_4$	56(O)
GaAs	9(Ga) 9(As)	ZnO	40(Zn) 57(O)
ZnS	10(Zn) 15(S)	UO_2	40(U) 20(O)
CdS	7(Cd) 9(S)	BeO	76(O)

Radiation Damage and Stress Effects in Superconductors: Materials for High-Field Applications

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Upton, NY 11973
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ELSEVIER

Nuclear Instruments and Methods in Physics Research B 116 (1996) 305–321

NIM B
Beam Interactions with Materials & Atoms

Silicon carbide: synthesis and processing

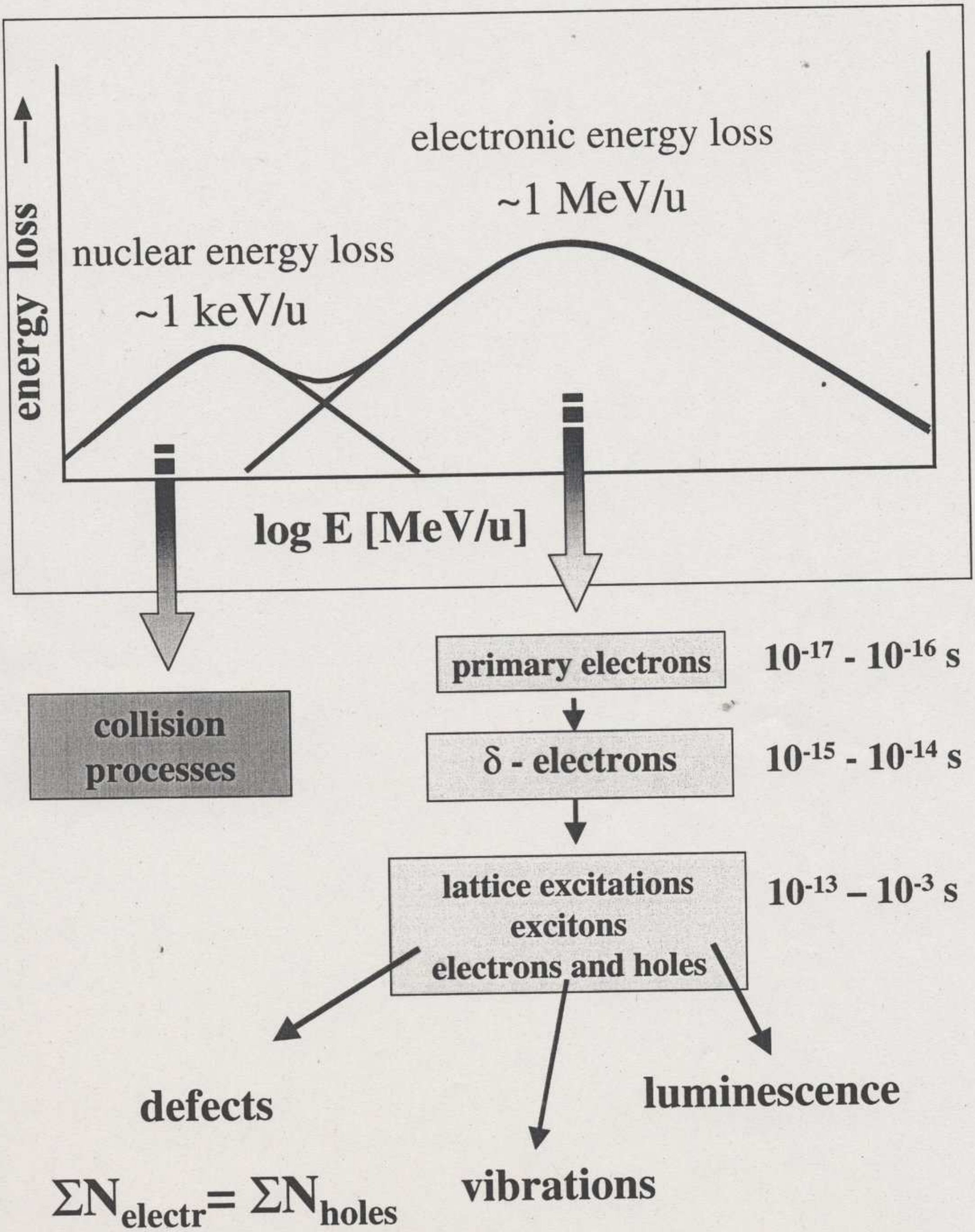
W. Wesch

Friedrich-Schiller-Universität Jena, Institut für Festkörperphysik, Max-Wien-Platz 1, D-07743 Jena, Germany

Table 2
Comparison of selected semiconductor properties

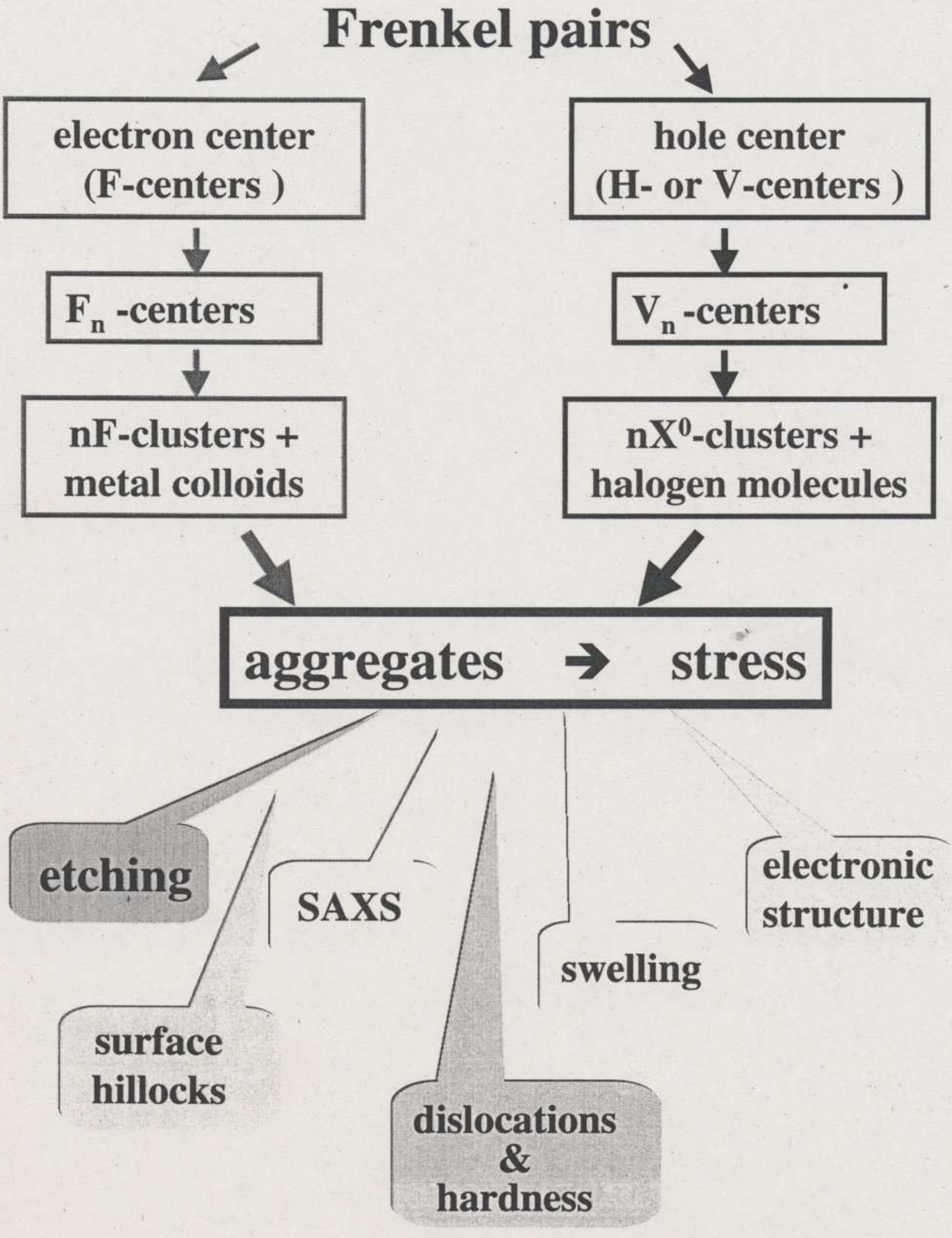
	Si	GaAs	6H-SiC	4H-SiC	3C-SiC	Diamond
Bandgap [eV]*	1.1	1.42	3.0	3.3	2.3	5.5
Melting point [°C]	1420	1238	sublimes > 1800			phase change
Thermal conductivity [W cm^{-1} K^{-1}]	1.5	0.5	4.9	4.9	5.0	20
Electron mobility at 10^{16} cm^{-3} [cm^2 V^{-1} s^{-1}]	1100	6000	370	800	750	(2200)
Hole mobility at 10^{16} cm^{-3} [cm^2 V^{-1} s^{-1}]	420	320	90	115	40	(1600)
Breakdown field at 10^{17} cm^{-3} [MV cm^{-1}]	0.6	0.6	3.2	3	4	(10)

III. Peculiarities of Damage Creation in Dielectric Materials under Heavy Ion Irradiation [1, 5, 6]



energy loss
nuclear energy loss
~1 keV/u
electronic energy loss
~1 MeV/u
log E [MeV/u]
collision processes
primary electrons
10^{-17} - 10^{-16} s
δ - electrons
10^{-15} - 10^{-14} s
lattice excitations
excitons
electrons and holes
10^{-13} – 10^{-3} s
defects
vibrations
luminescence
$\Sigma N_{electr} = \Sigma N_{holes}$

Aggregation of single defects



N. Itoh and A. M. Stonham
"Materials Modification by Electronic Excitation",Cambridge University Press, Cambridge,2001, p. 439

Self Trapping and Threshold Stopping Power for Track Registration

System	Threshold stopping power (keV/nm)	Self-trapped exciton?	Reference (stopping power)
Continuous tracks	1–10	Yes	
SiO_2	2	Yes	Meftah *et al.* (1993)
$Y_3Fe_5O_{12}$	4	Probably yes	Toulemonde *et al.* (1994)
Mica	5	Possibly yes	Toulemonde *et al.* (1994)
$LiNbO_3$	7	Probably yes	Meftah *et al.* (1993)
LiF	$\gtrsim$10	Yes	Schwartz *et al.* (1998)
Fragmentary tracks	>20		
MgO	20		Canut *et al.* (1995)
Al_2O_3	21		Canut *et al.* (1995)
Bi	31		Wang *et al.* (1996)
Si	>28		Dunlop *et al.* (1998)

Lithium Fluoride

* complex damage structure
* since amorphisation is not possible, swelling is probably linked to the formation of defect aggregates
* SAXS radii in LiF are much smaller than any radii measured in amorphisable crystals

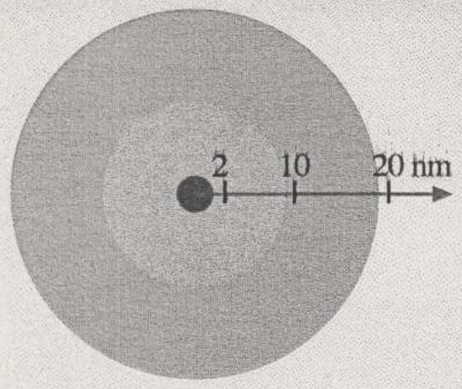
Oxides

* swelling can be explained by a transition from the crystall to the amorphous phase
* the swelling radii and the threshold is about the same observed by other techniques (TEM and RBS/C)

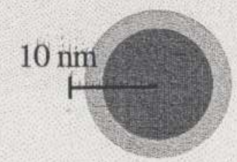
swelling

occurs at a lower threshold than track etching

	LiF	SiO_2 quartz
swelling	4 keV/nm	2 keV/nm
etching	10 keV/nm	7 keV/nm



F-centers
swelling
SAXS



RBS/C and TEM
swelling

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