Diamond Research Center

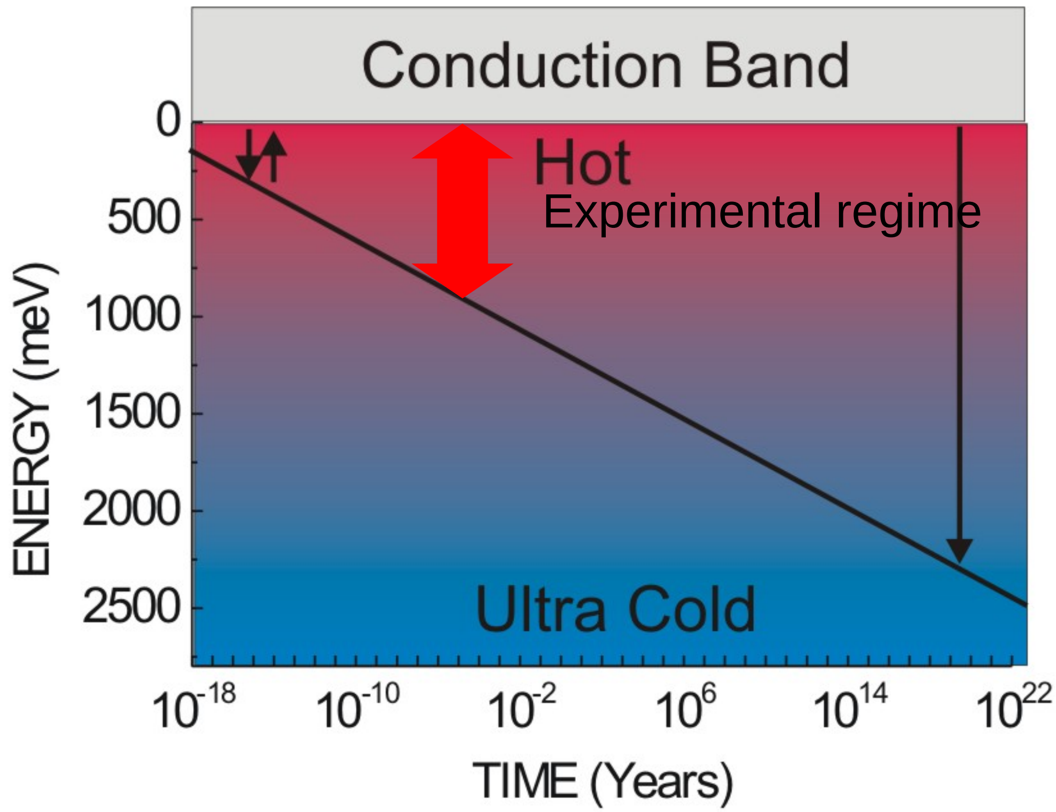
National Institute of
Advanced Industrial Science and Technology

Low Temperature Optical and Electronic Properties of CVD Diamond for Detector Applications

Christoph E. Nebel

Diamond Research Center, AIST, Tsukuba, Japan

Diamond is ULTRA COLD



Assumptions: T = 300 K, $\nu_o = 10^{13}$ 1/s

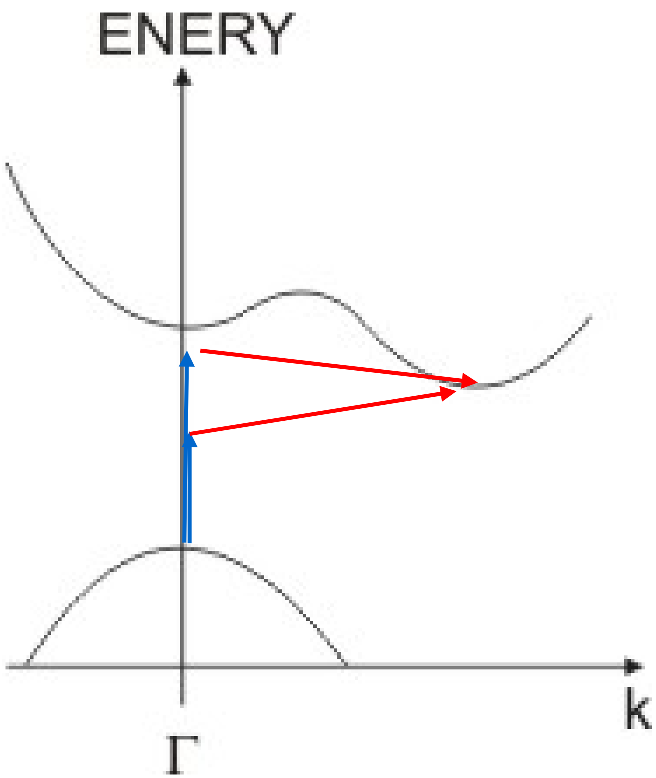
Outline:

I) Optical properties

II) Electronic Properties:

- Conductivity
- Mobility
- Drift Velocity in Diamond: Holes
- Defects (H1 center)
- Deep trapping of carriers

I. Optical Properties



Transition with phonon absorption ($h\nu > E_g - E_p$)

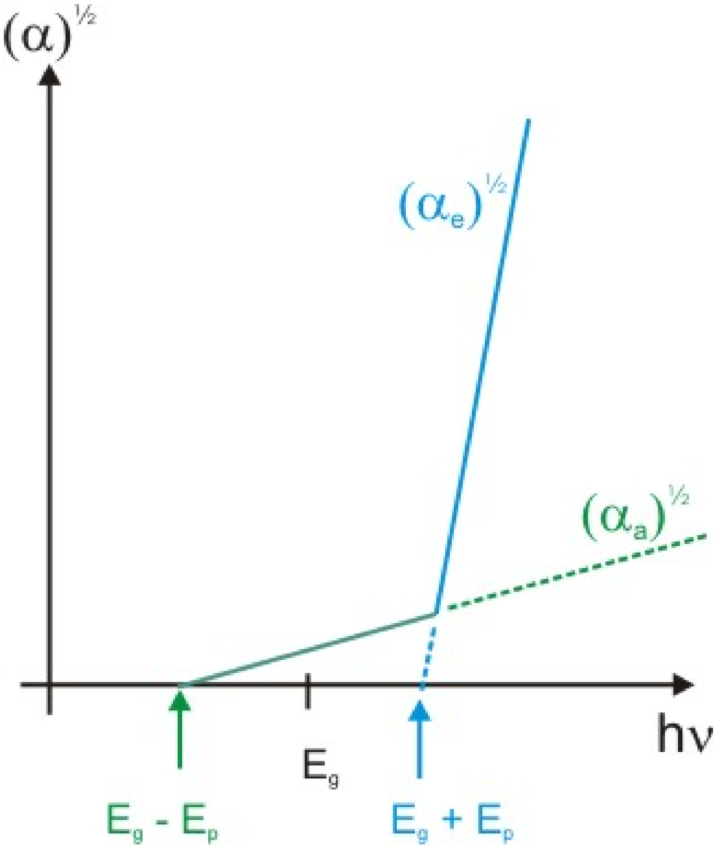
$$\alpha_a(h\nu) = \frac{A(h\nu - E_g + E_p)^2}{\exp\left(\frac{E_p}{kT}\right) - 1}$$

Transition with phonon emission ($h\nu > E_g + E_p$)

$$\alpha_e(h\nu) = \frac{A(h\nu - E_g - E_p)^2}{1 - \exp\left(-\frac{E_p}{kT}\right)}$$

For $h\nu > E_g + E_p$ both absorptions take place: $\alpha(h\nu) = \alpha_a(h\nu) + \alpha_e(h\nu)$

Schematic Absorption



Several types of phonons involver:

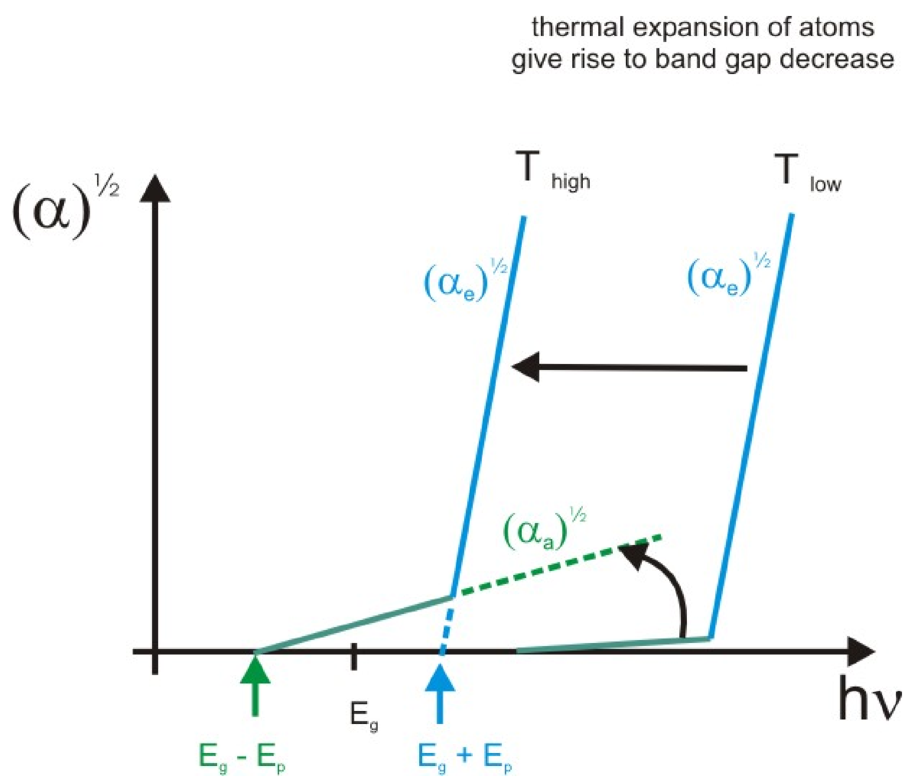
- one longitudinal acoustic phonon
- Two transversal acoustic phonons

Temperature dependent absorption

Diamond parameter

$$E_g(T) = E_g(T=0) - \frac{\alpha T^2}{T+\beta}$$

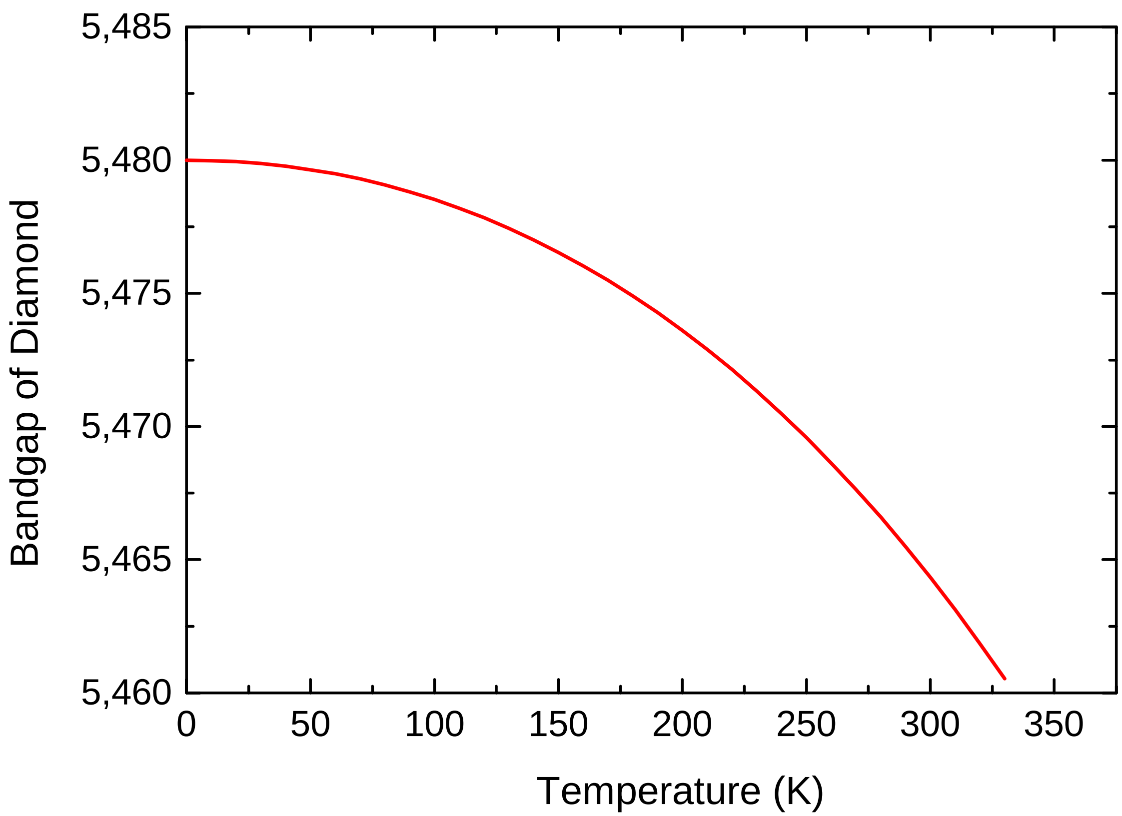
$E_g(T=0)=5.48$
α = -1.979
β = -1437



Temperature dependent variation of the band gap of Diamond

From 0 K to 300 K:

ΔE = 15 meV



Near band edge absorption

Phonon coupling with excitons:

LO = 163 meV

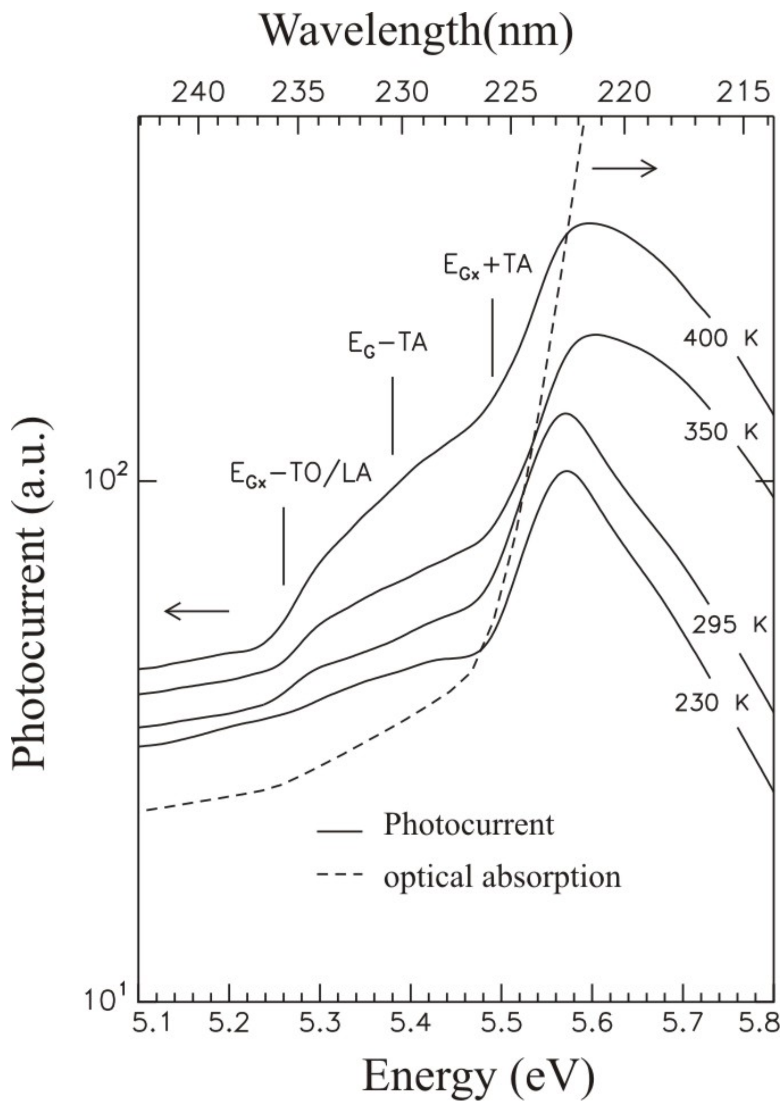
TA = 87 meV

TO = 141 meV

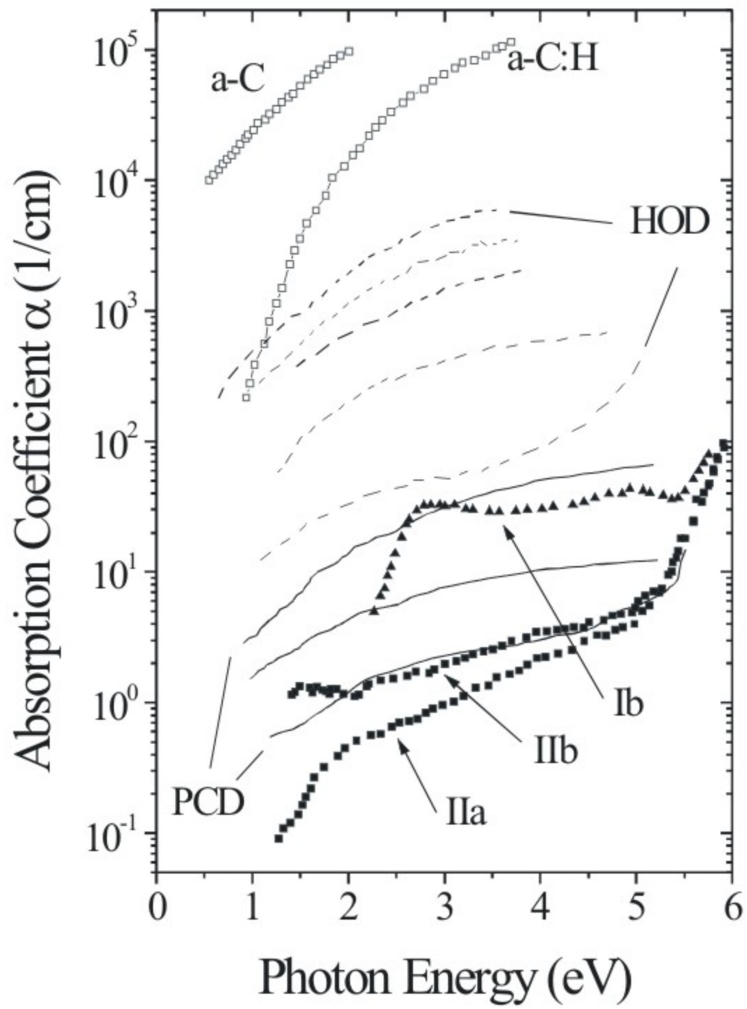
R. Sauer, in „Thin Film Diamond, Elsevier 2003

E_{Gx} = exciton threshold energies (5.406 eV)

E_g = 5.467 eV



Typical absorption spectra

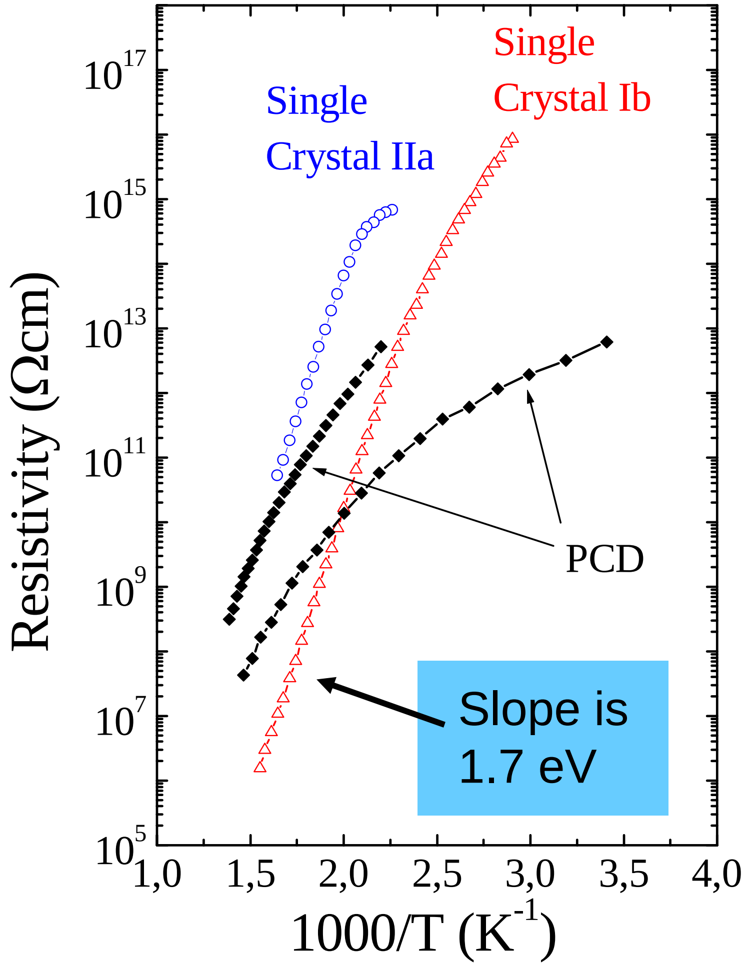


II. Electronic Properties: Conductivity

All undoped diamond layers (Ib, IIa and CVD) are n-type:

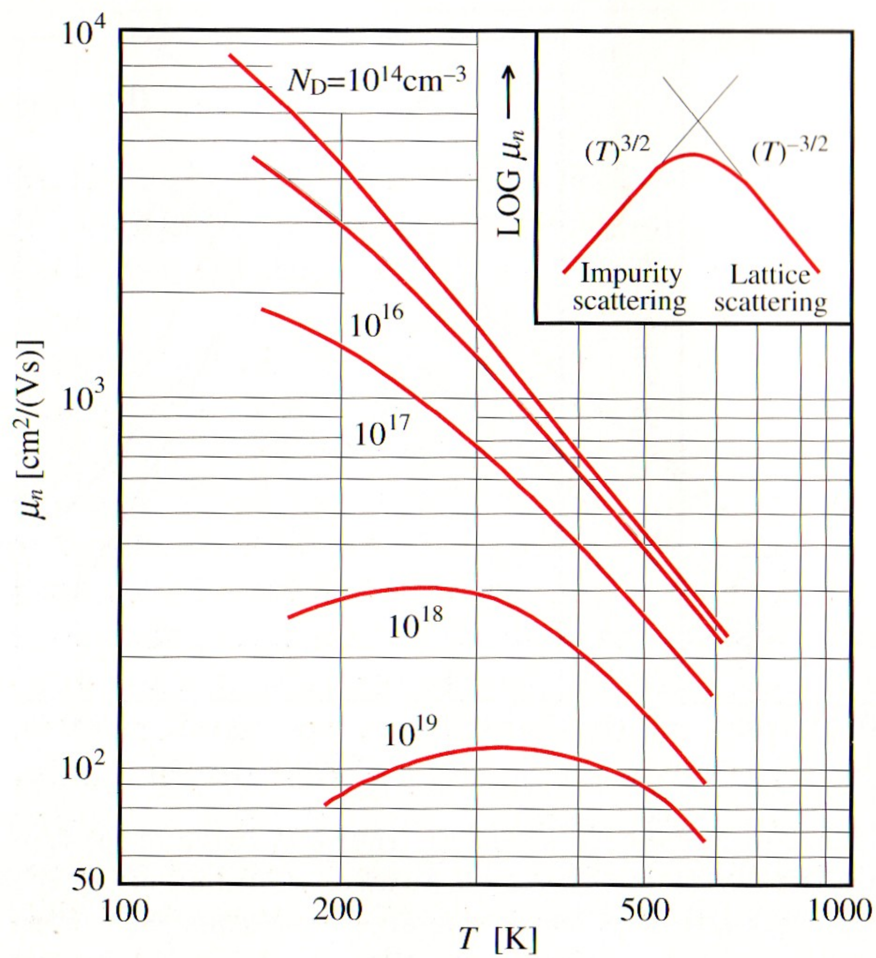
Conductivity of CVD diamond is governed by nitrogen doping (P1-center):

E_{act} = 1.7 eV



Mobility

Textbook example: Temperature dependent mobility in n-type Si (S.M. Sze:Semiconductor Devices)



The band structure and the phonon bands in diamond

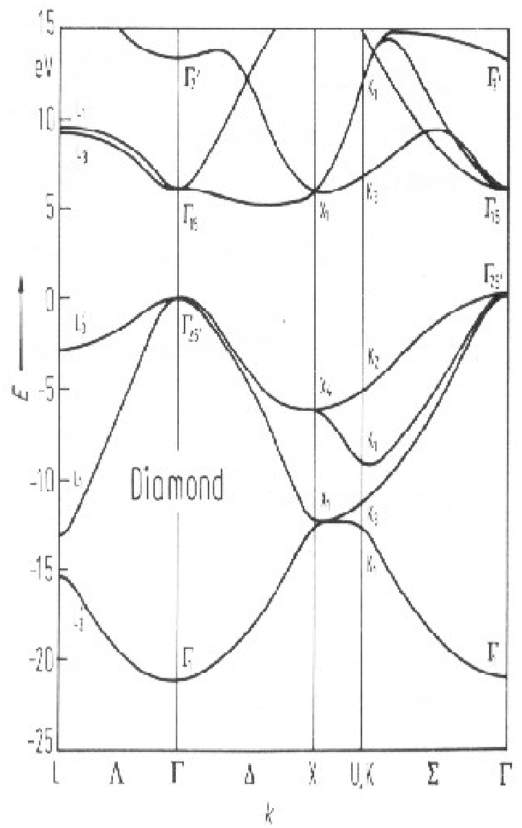
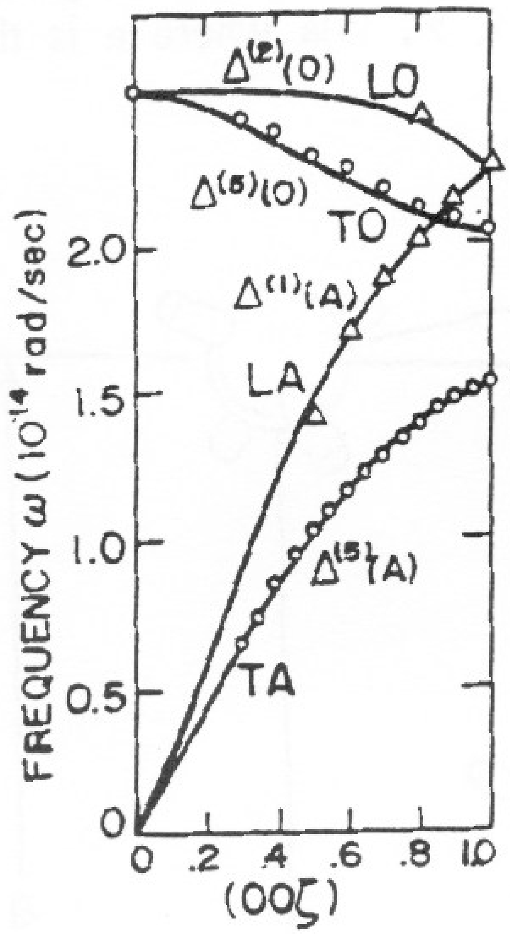


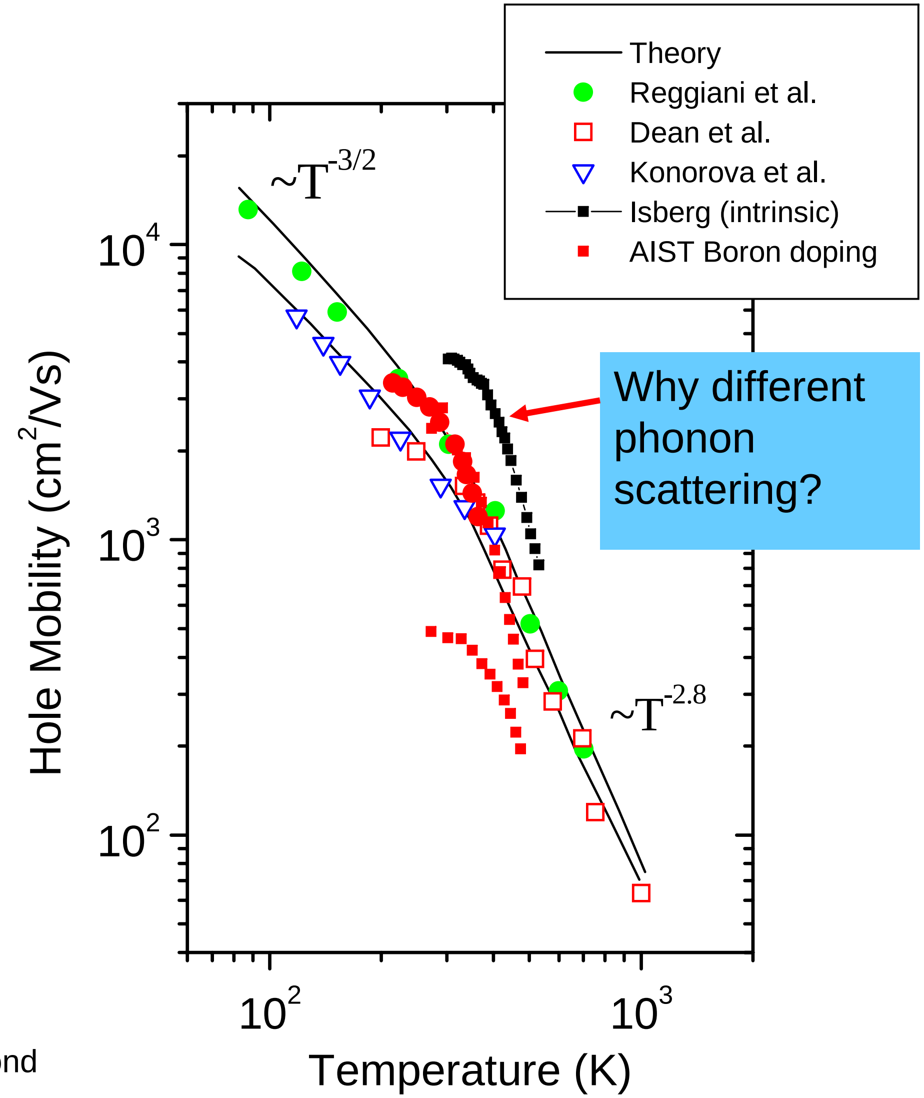
Fig. 1. Diamond. Band structure calculated by an ab intio LCAO method [84C].



Hole Mobilities

$T^{-3/2}$: acoustic phonon scattering

$T^{-2.8}$: optical phonon scattering



Isberg et al. : time-of-flight on undoped CVD diamond

(Science 297, p. 1670 (2002): 3800 cm^2/Vs)

Reggiani: Time-of-flight on undoped natural diamond

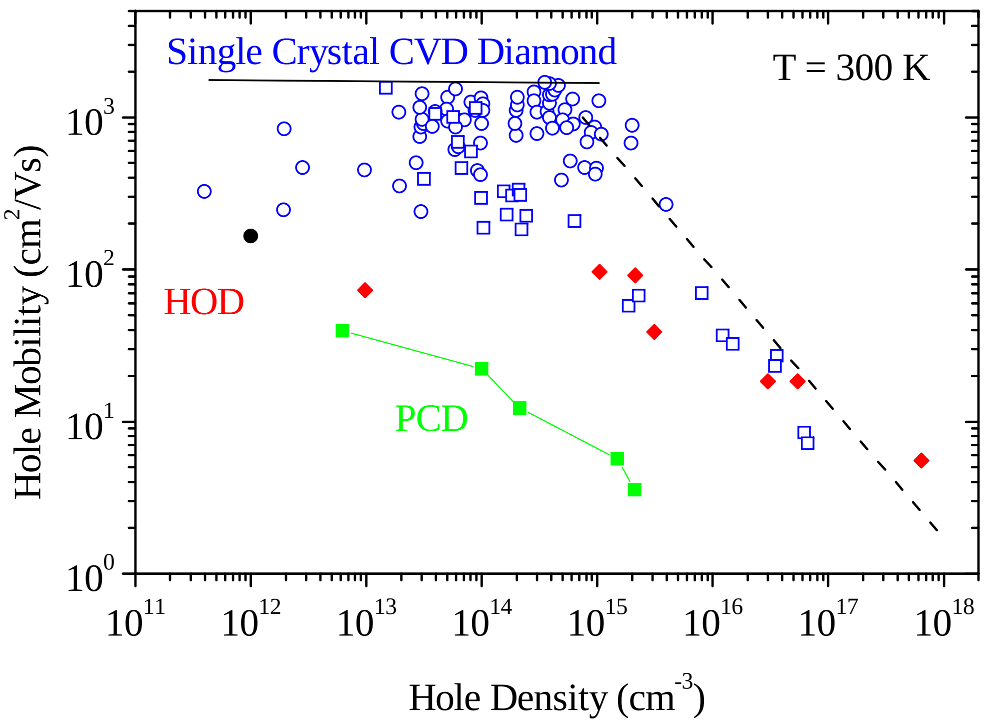
Dean and Konorova: Hall Mobilities

Dr. Okushi et al. AIST: Hall effect on boron doped CVD diamond

CVD Hole Mobility Limitations: Scattering due to residual impurities like Fe and Mo

Scattering at ionized impurities:

$$\mu \propto \left(m^*\right)^{1/2} \frac{T^{3/2}}{N_i}$$



Electron Mobilities in natural and P-doped Diamond:

$T^{-3/2}$: acoustic phonon scattering

Isberg et al.,: Time-of-flight in undoped CVD diamond

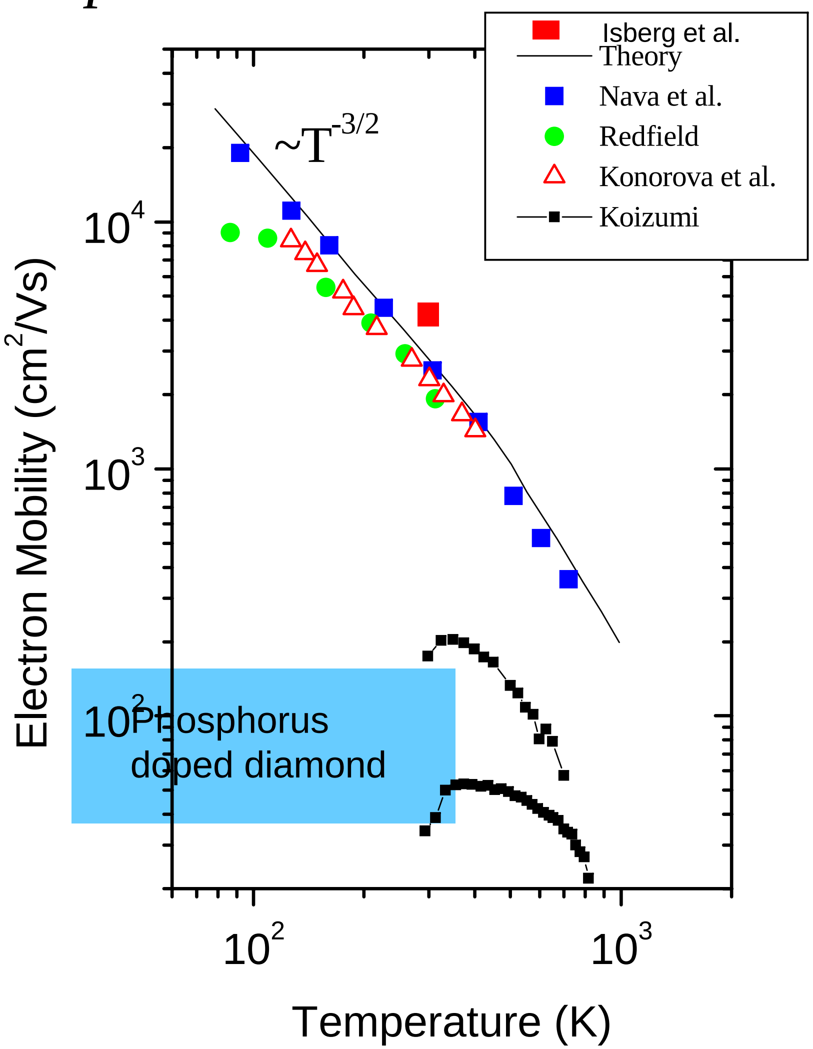
(Science 297, p. 1670 (2002): 4500 cm^2/Vs)

Nava: Time-of-flight on natural undoped diamond

Konorova: Hall effect

Redfield: Hall effect

Koizumi et al.: Hall effect on Phosphorus doped diamond



$\tau_e = \tau_m$

The saturation velocity limitation:

Energy relaxation $$\frac{d\Delta E}{dt} = eFv_s - \frac{E_{phonon}}{\tau_e}$$

Impuls relaxation $$\frac{d(mv_s)}{dt} = eF - \frac{mv_s}{\tau_m}$$

For steady state conditions: $$\frac{d\Delta E}{dt} = \frac{d(mv_s)}{dt} = 0$$

For only on scattering process (one phonon) $$\tau_e = \tau_m$$

Saturation velocity: $$v_s = \left(\frac{E_{phonon}}{m^*}\right)^{1/2}$$

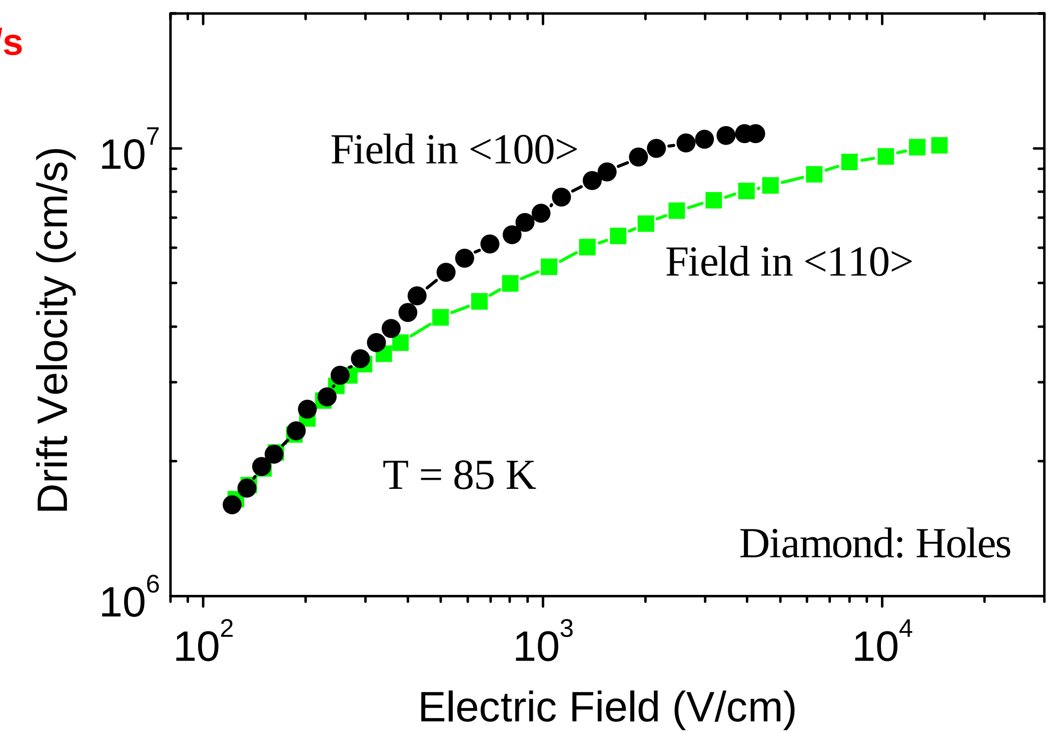
$v_s = 3.8 \times 10^7$ cm/s

for 165 meV and m = 0.2 m_o

Better: $$v_{sat} = \left[\frac{8E_{opticalphonon}}{3\pi m^*}\right]^{1/2}$$

Drift Velocity in Diamond: Holes

Saturation hole velocity: **1.1x10^7 cm/s**

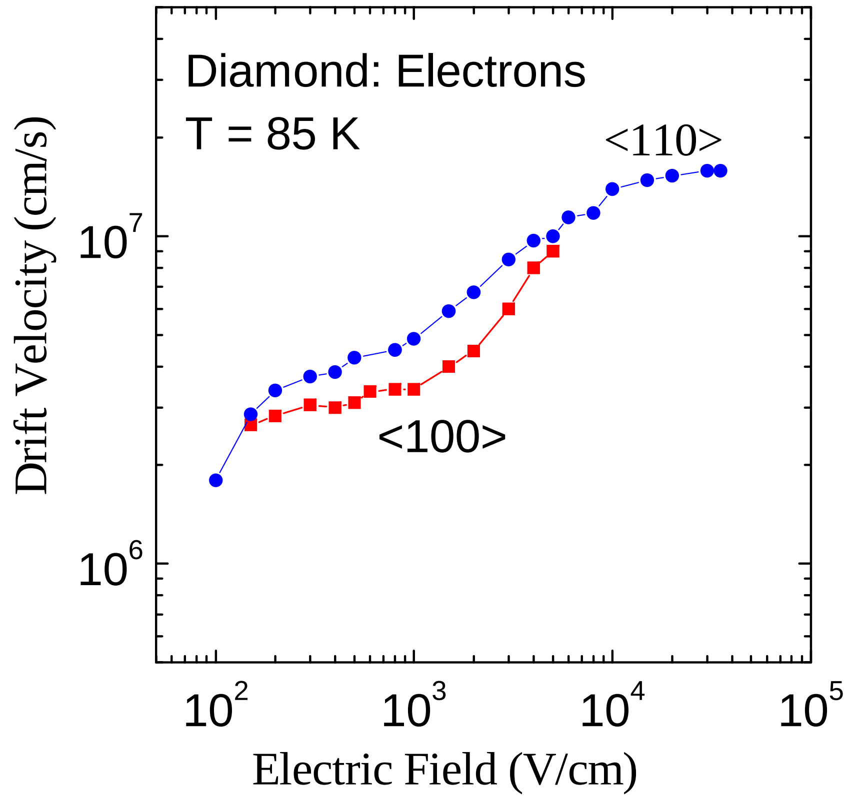


Reggiani et al, PRB 23 (1981) p. 3050

Drift Velocity in Diamond: Electrons

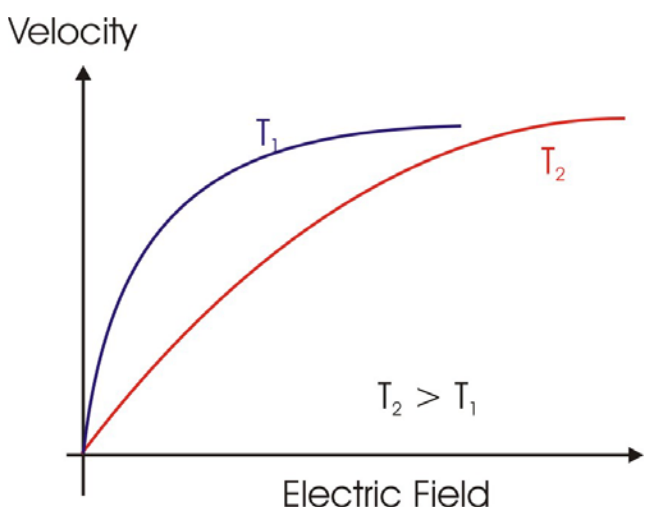
Saturated drift velocity: 1.5×10^7 cm/s

Anisotropy: multivalley band structure



F. Nava et al., Sol. Stat. Com. 33 (1980) p. 475

Drift velocity



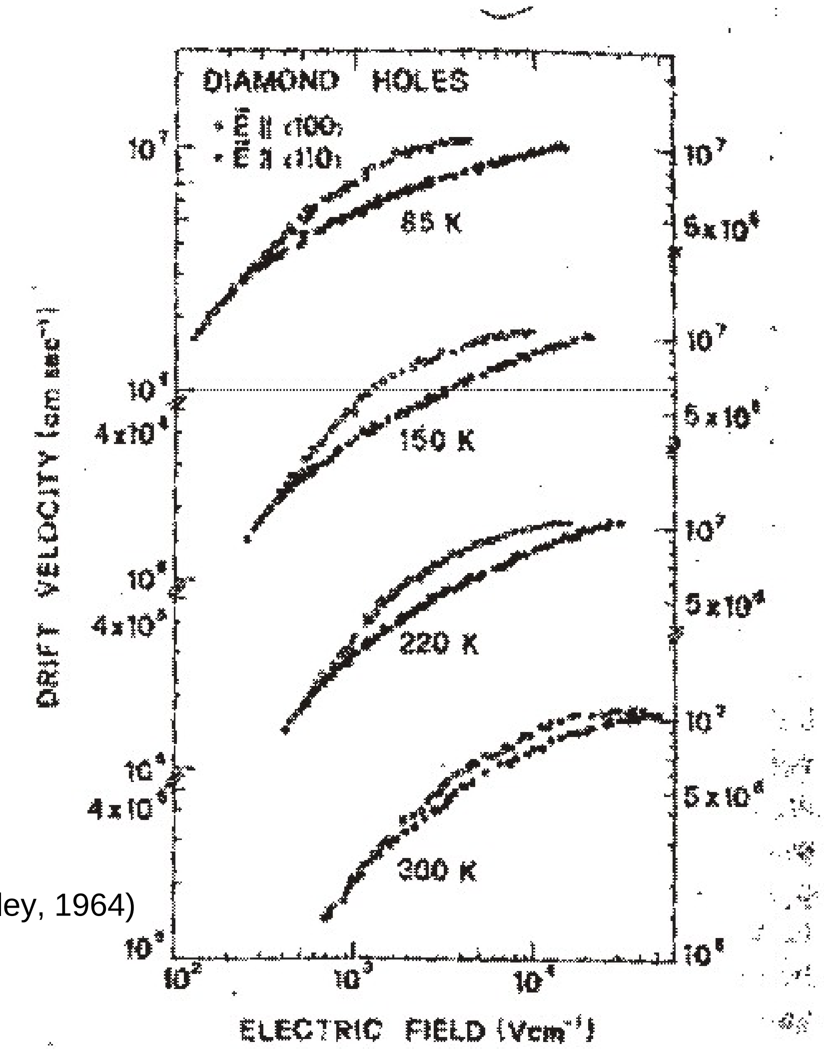
Drift velocity:

$$v_D = F\mu = F\frac{e}{m}\tau$$

Scattering time:

$$\tau = \tau_o\left(\frac{\varepsilon}{kT}\right)^r$$

J.L. Moll, Physics of Semiconductors (Wiley, 1964)



Reggiani et al, PRB 23 (1981) p. 3050

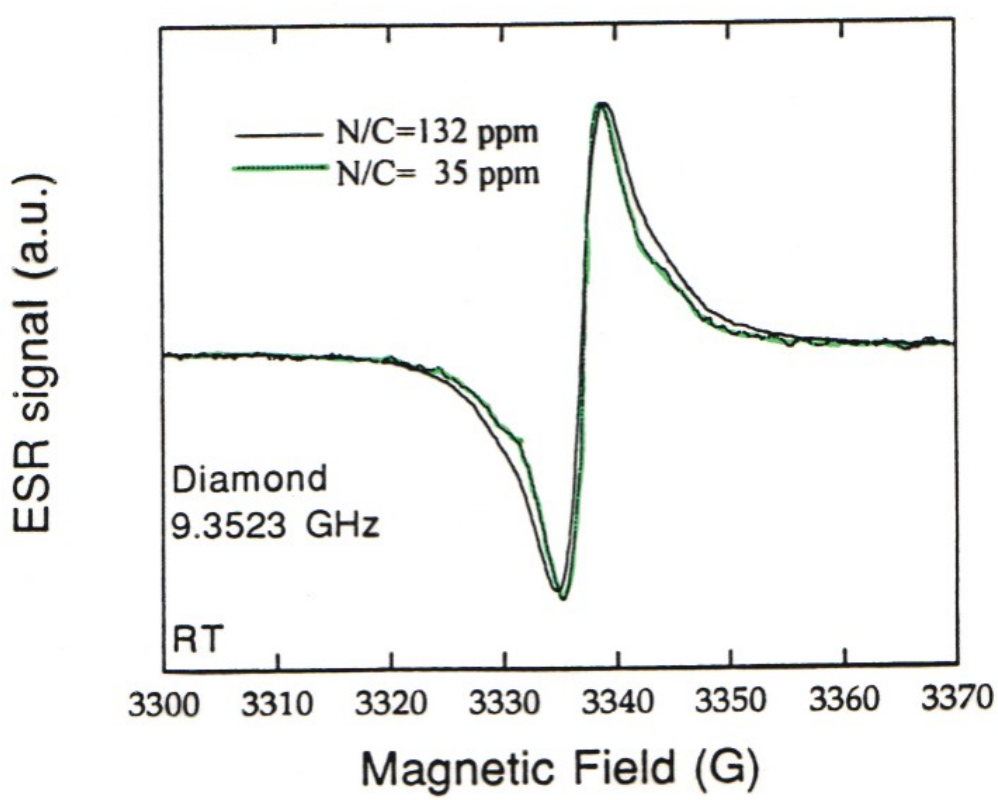
r = -0.5 acoustic deformation potential scattering

r = +3/2 ionized imurity scattering

Defects: H1 Center g = 2.0028

Homoepitaxial single crystalline diamond:

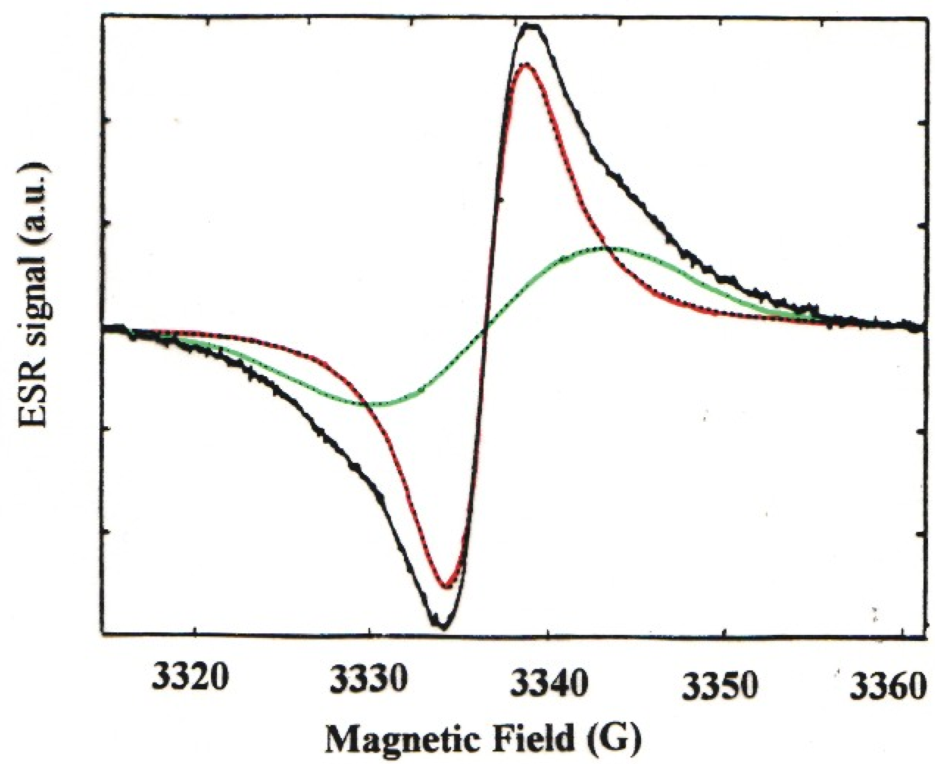
Typical Density: 5×10^{18} cm^{-3}



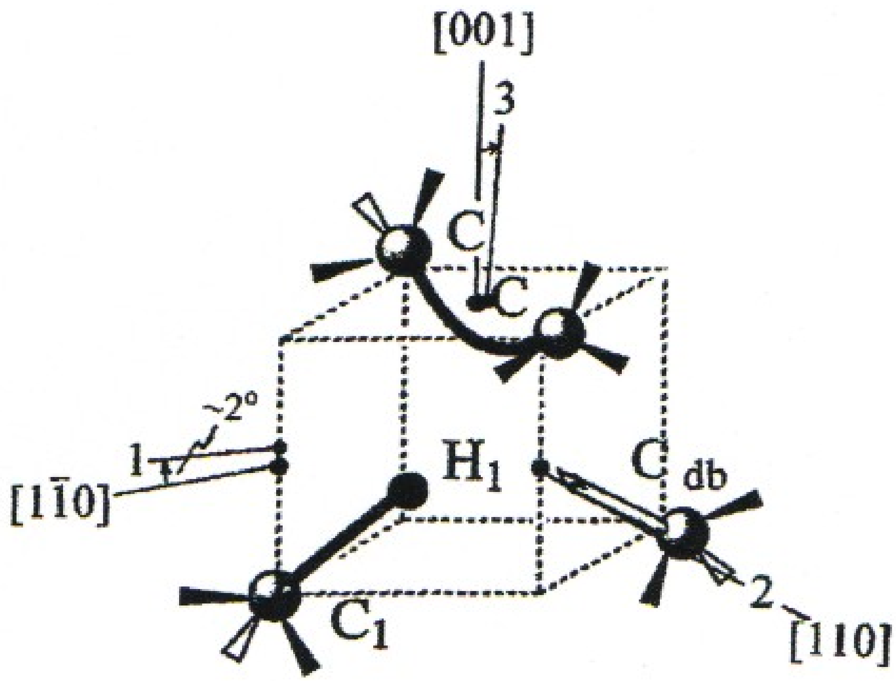
Zhou et al. PRB 54 (1996) p. 7881

N. Mizuochi et al. DRM in print.

Carbon hyperfine interaction with Hydrogen
Distance: 1.9 to 2.3 A



Defect Model: X. Zhou, G.D. Watkins et al. PRB 54 (1996) p. 7881



Deep trapping of carriers

Hecht equation: $$Q(t) = Q_o \frac{\mu\tau E}{L}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right]$$

Deep trapping lifetime $$\tau = \frac{1}{N_D v_{th} S_{cross}}$$

Capture cross section S_{cross}: 10^{-14} cm^2 – 10^{-15} cm^2

Ionized Impurities: $$E(r) = \frac{1}{4\pi\varepsilon_o\varepsilon_r}\frac{1}{r^2}$$

ε_r in diamond much smaller!

ε_r(Diamond) = 5.7

ε_r(Si) = 11.9

Temperature dependent capture cross sections for 7 deep levels in GaAs and two in GaP (D.V. Lang)

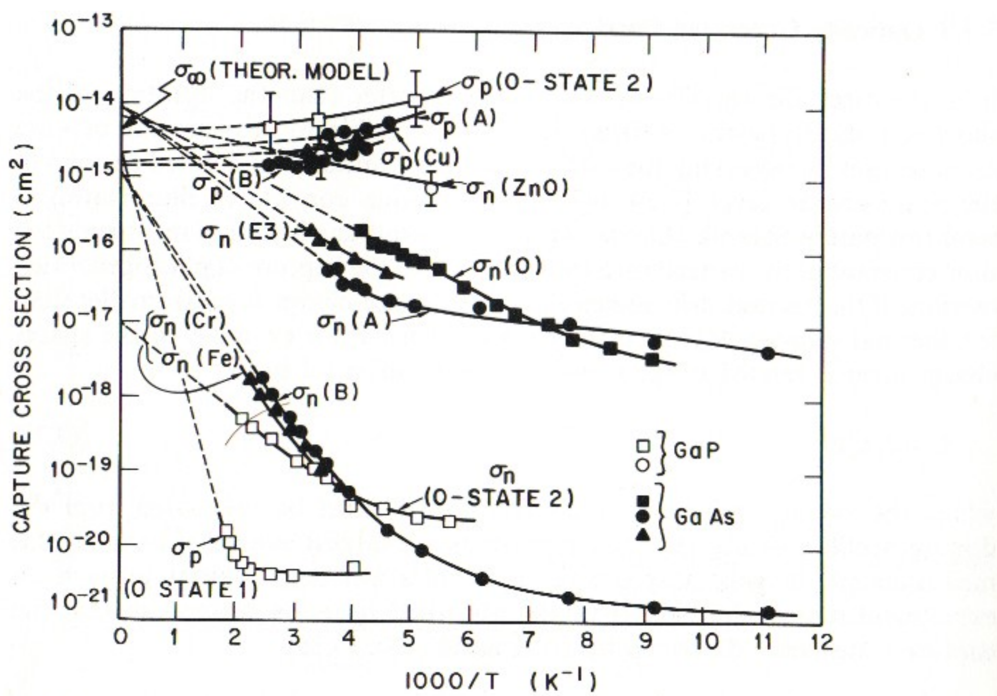
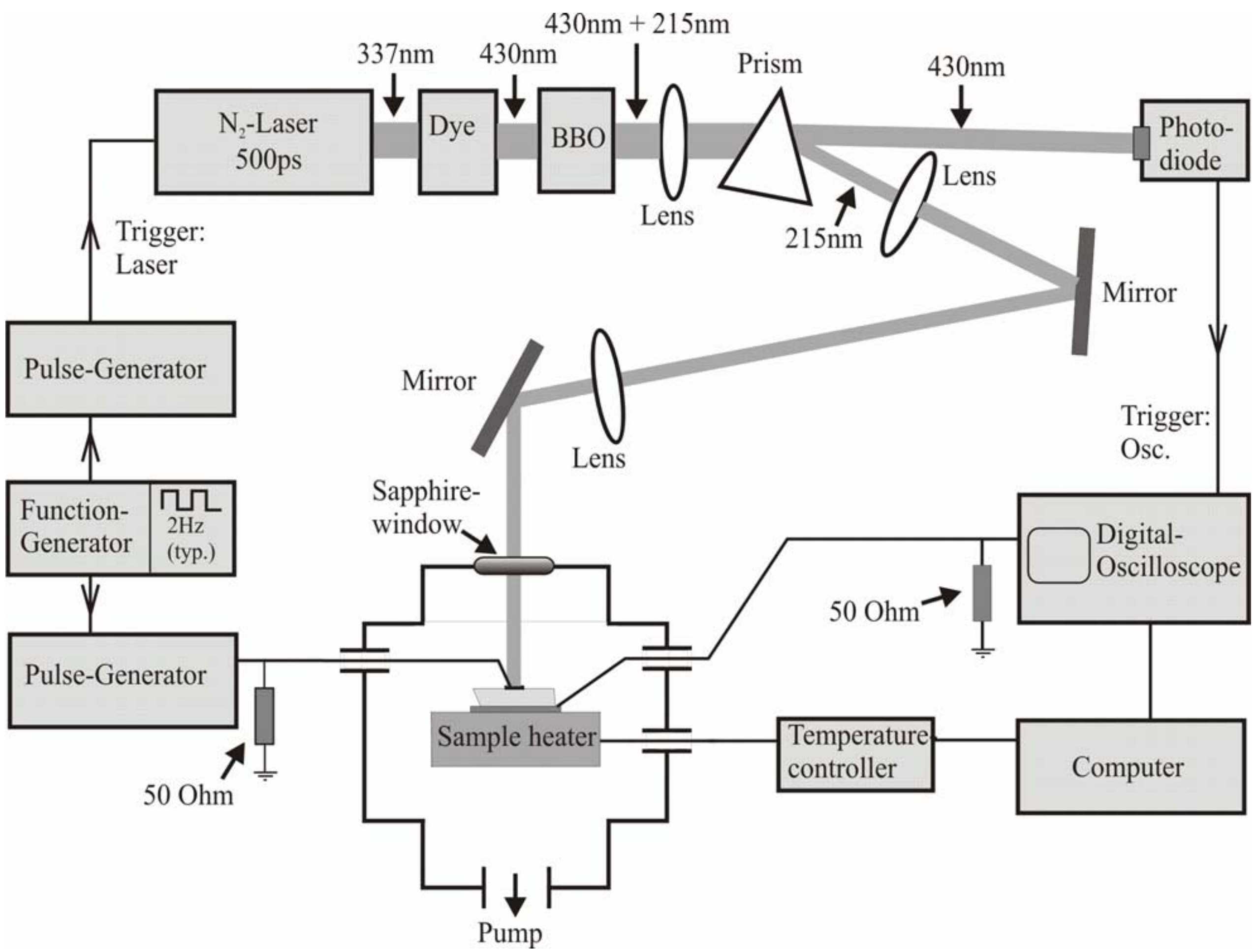
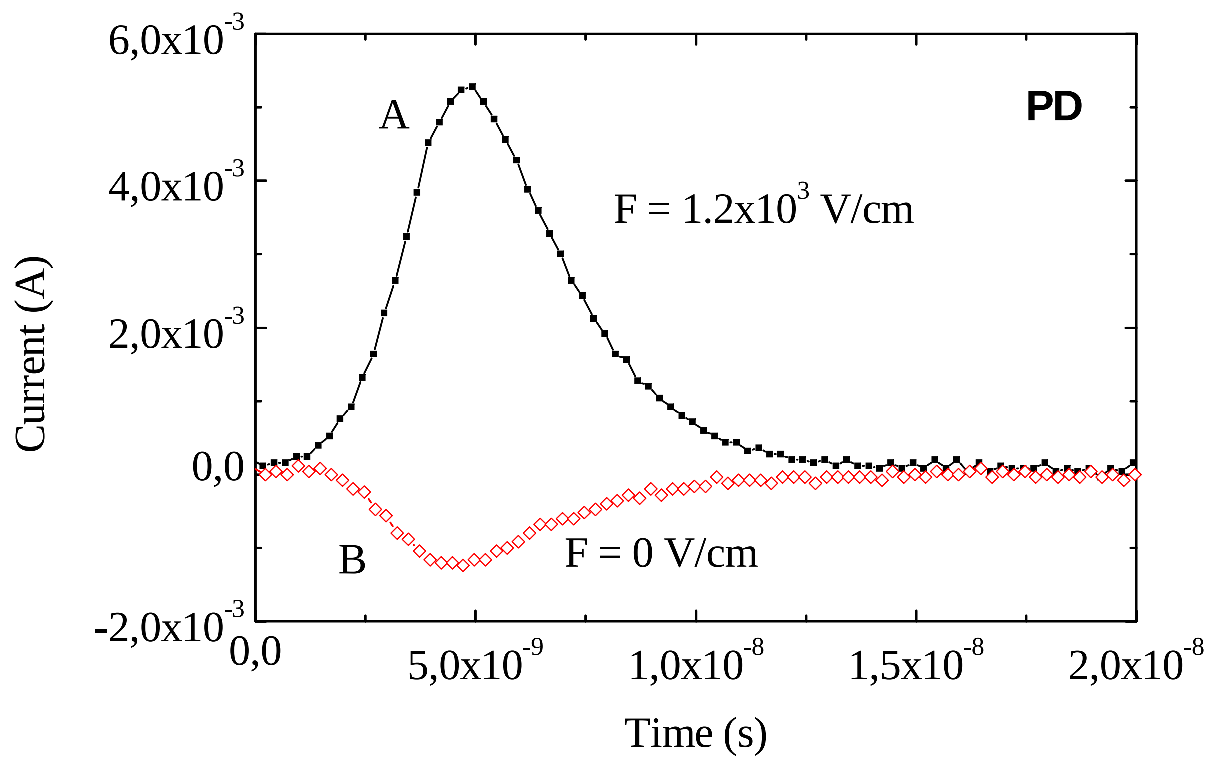


Fig. 3.21. Capture cross section (denoted here by σ) as a function of inverse temperature for seven deep levels in GaAs and two in GaP

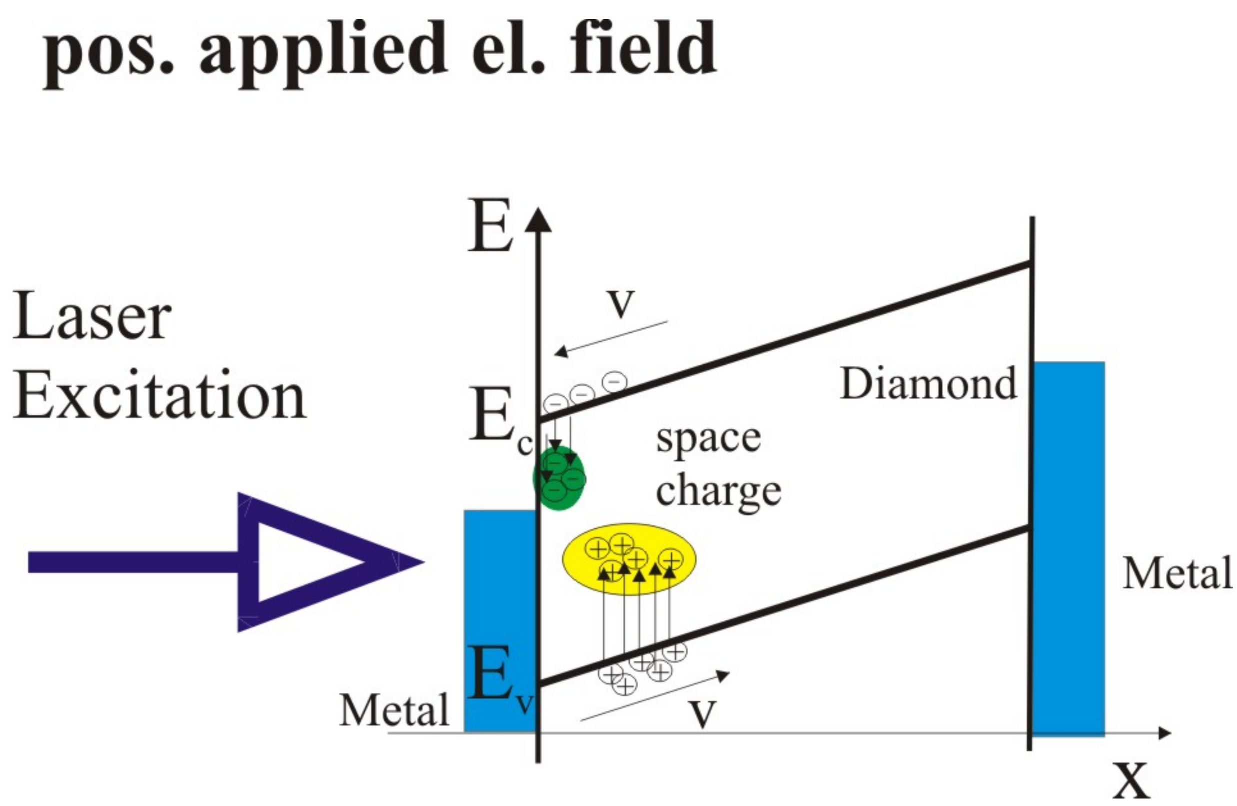
Time-of-flight setup



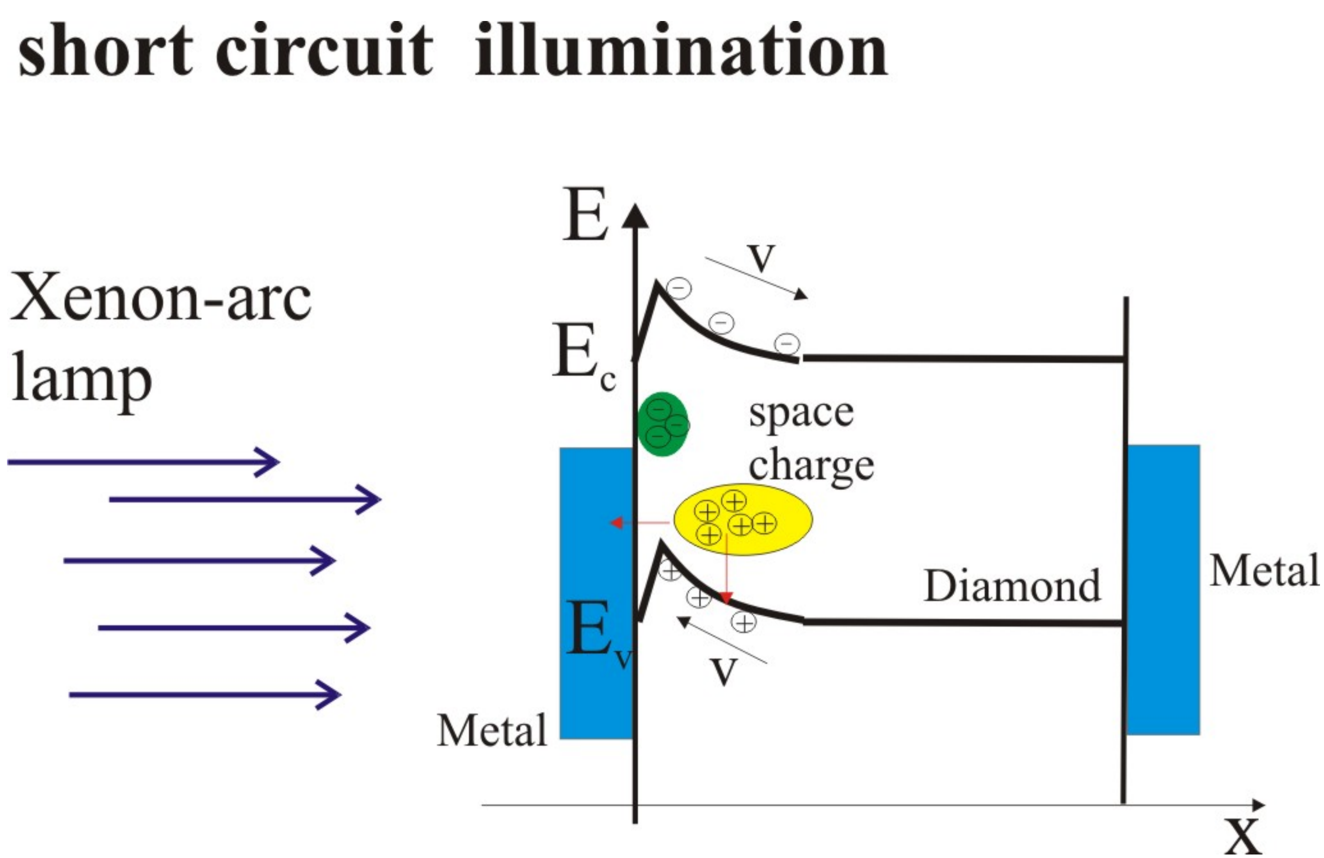
Deep trapping of carriers (electrons and holes) in undoped CVD diamond



Model:


pos. applied el. field
Laser
Excitation
E
v
E
c
Diamond
space
charge
Metal
E
v
Metal
v
x

After laser exposure the internal field is reversed, giving rise to a current in oposit direction



The same features for electrons and holes: Traps or defect, which can be occupied by electrons and holes!