Characterization of Conductivity: Basic Properties and Challenges

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Conductivity

$$\sigma = en\mu_n + ep\mu_p$$

e :	elementary charge
n:	electron density
p:	hole density
μ_n:	electron mobility
μ_p:	hole mobility

Outline

1) Introduction
2) Defects in Diamond
3) Deep Trapping Lifetime, Schubweg and Mobility
4) $\mu\tau$–Products as a Function of Nitrogen Content
5) Properties of Poly-Crystalline CVD Diamond
6) Spectrally Resolved Photoconductivity
7) Contact Properties
8) Summary

1. Introduction: Comparison Sheet

Physical characteristics of Si and major WBG semiconductors

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, E_g (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric Constant, ε_r	11.9	13.1	9.66	10.1	9	5.5
Electric breakdown field , E_C (MV/cm)	0.3	0.4	2.4	2	0.2	5.6
Electron mobility, μ_n (cm^2/Vs)	1,500	8,500	370	720	1,250	4,500
Hole mobility, μ_p (cm^2/Vs)	600	400	101	115	850	3,800
Thermal conductivity, λ (W/cmK)	1.5	0.46	4.9	4.9	1.3	22
Saturation electron drift velocity, v_{sat} ($x10^7$ cm/s)	1	2	2	2	2.2	2.7

Diamond

Available:

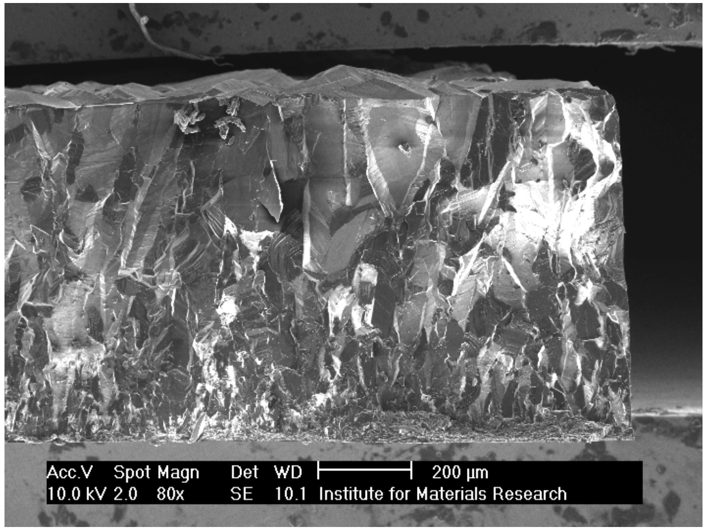
- natural
- High pressure high temperature (HTHP)
- CVD diamond

Morphology:

- ❑ single-crystalline
- ❑ poly-crystalline
- ❑ nano-crystalline
- ❑ ultra-nano-crystalline

Single Crystalline Diamond
4 mm x 4 mm

Poly-Crystalline CVD Diamond



Electron Mobilities

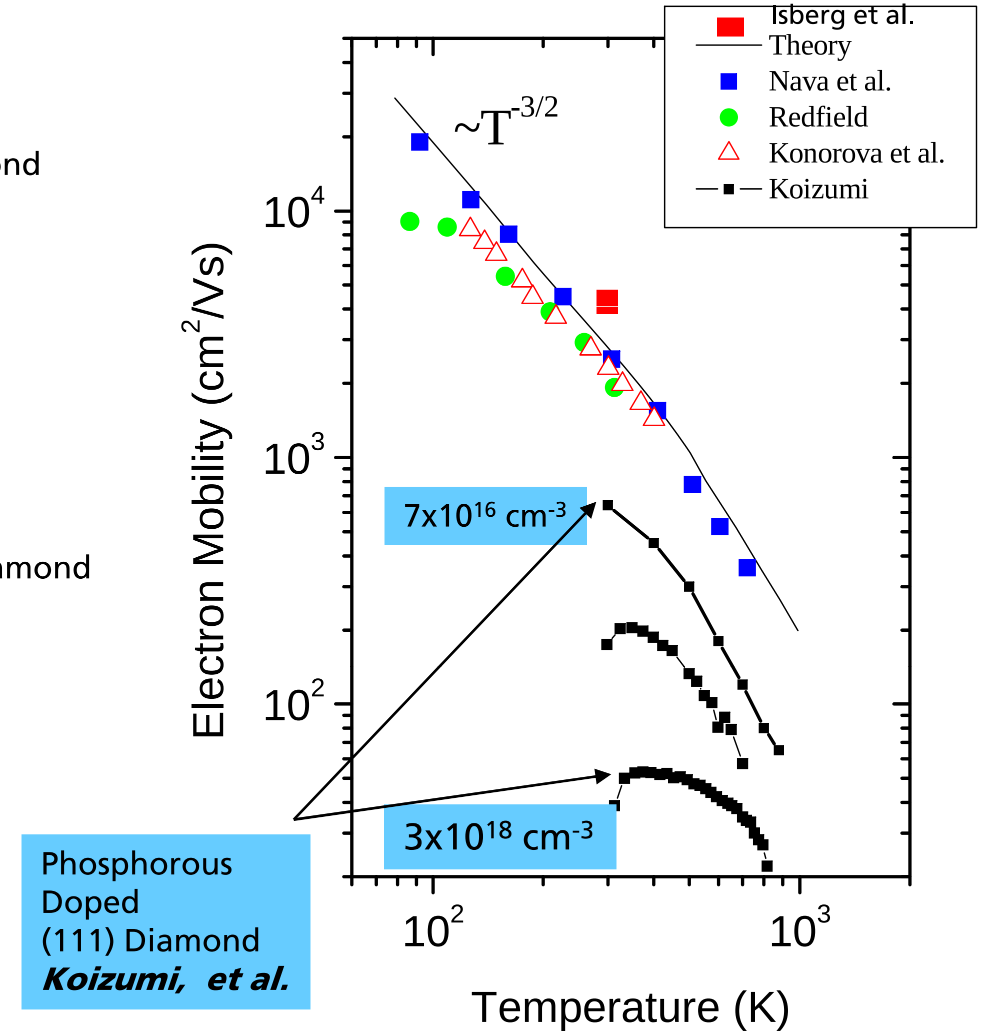
$T^{-3/2}$: acoustic phonon scattering

Isberg et al.,: Time-of-flight in undoped CVD diamond
(Science 297, p. 1670 (2002): **4500** cm²/Vs)

Nava: Time-of-flight on natural undoped diamond
Konorova: Hall effect
Redfield: Hall effect

Koizumi et al.: Hall effect on Phosphorus doped diamond

RT-mobility: 725 to 4500 cm²/Vs



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Hole Mobilities

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

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

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

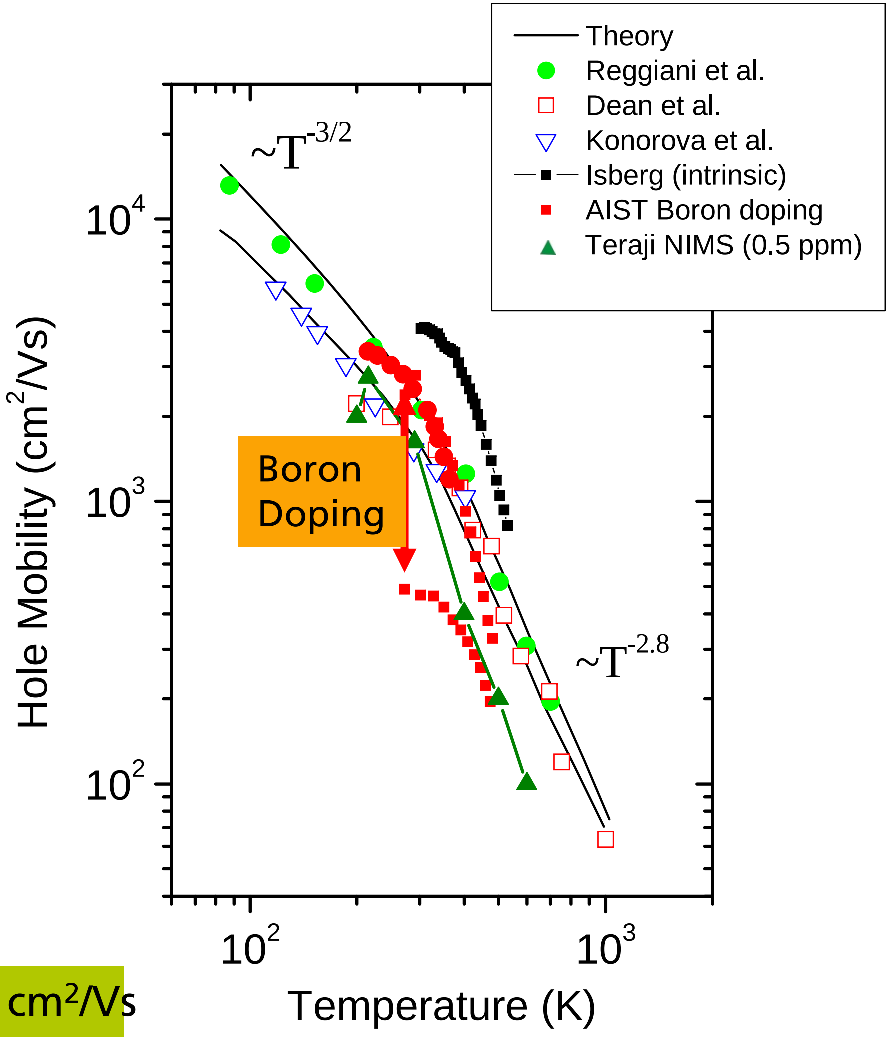
(Science 297, p. 1670 (2002): **3800 cm²/Vs**)

Reggiani: Time-of-flight on undoped natural diamond

Dean and Konorova: Hall Mobilities

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

Teraji, Hall effect on (001) 0.5 ppm: 1620 cm²/Vs at 290 K



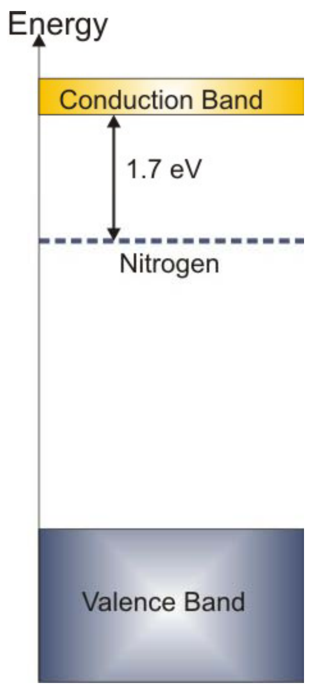
Room temperature mobility: 500 to 3800 cm²/Vs

Doping of Diamond for Electronic Applications

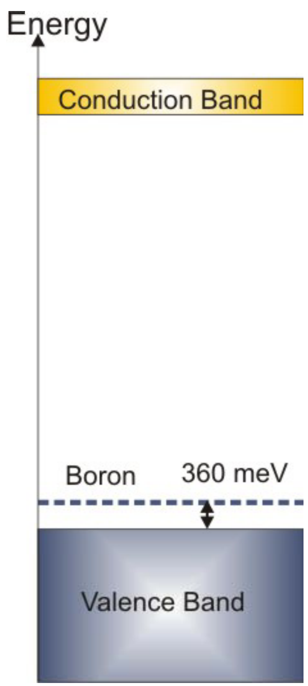
n-type Diamond

S. Koizumi, H. Ozaki, M. Kamo,
Y. Sato and T. Inuzuka,
Appl. Phys. Lett., 71, 1064-1067 (**1997**)

undoped Diamond



p-type Diamond



S.D. Smith, W. Taylor,
Proc. Phys. Soc. 79, 1142 (**1962**).
A.T. Collins, P.J. Dean,
E.C. Lightowlers, W.F. Sherman,
Phys. Rev. 140, A1272 (**1965**).

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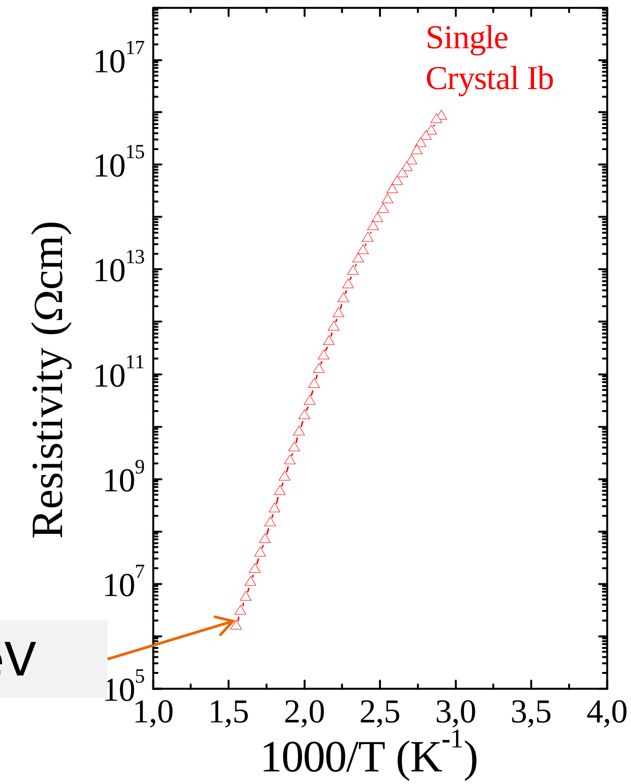
Thermal Activated Resistivity of Undoped Diamond

$$\sigma = e\,\mu(T)\,n_o\,e^{-E_{act}/kT}$$

Ib-Diamond



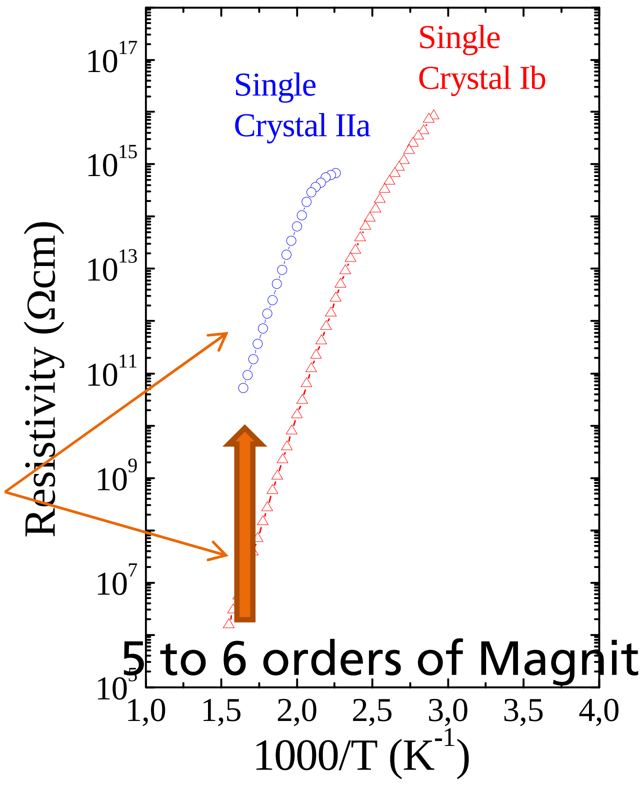
E_{act} ca. 1.7 eV

Thermal Activated Resistivity of Undoped Diamond

$$\sigma = e\,\mu(T)\,n_0\,e^{-E_{act}/kT}$$

E_{act} ca. 1.7 eV

IIa and Ib Diamond



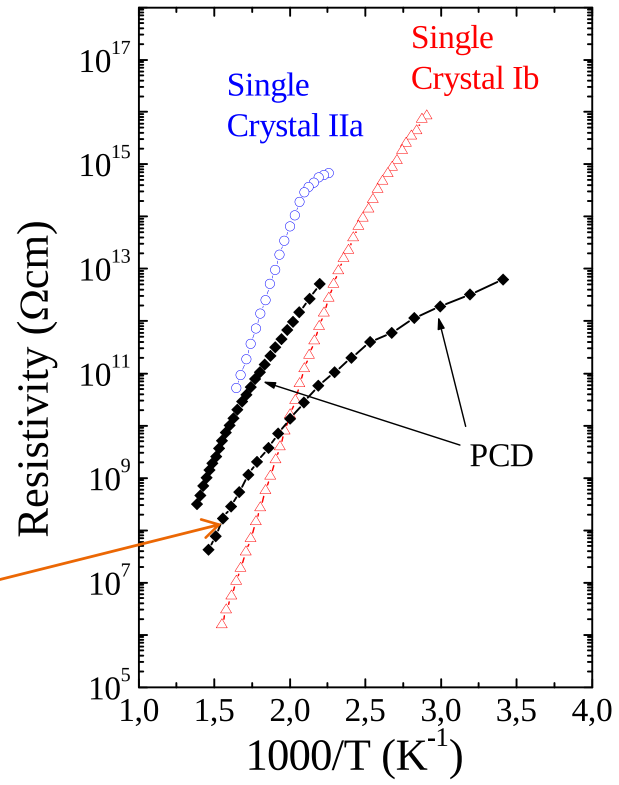
5 to 6 orders of Magnitude

Thermal Activated Resistivity of Undoped Diamond

$$\sigma = e\,\mu(T)\,n_o\,e^{-E_{act}/kT}$$

Polycrystalline CVD Diamond

E_{act} ca. 1 eV

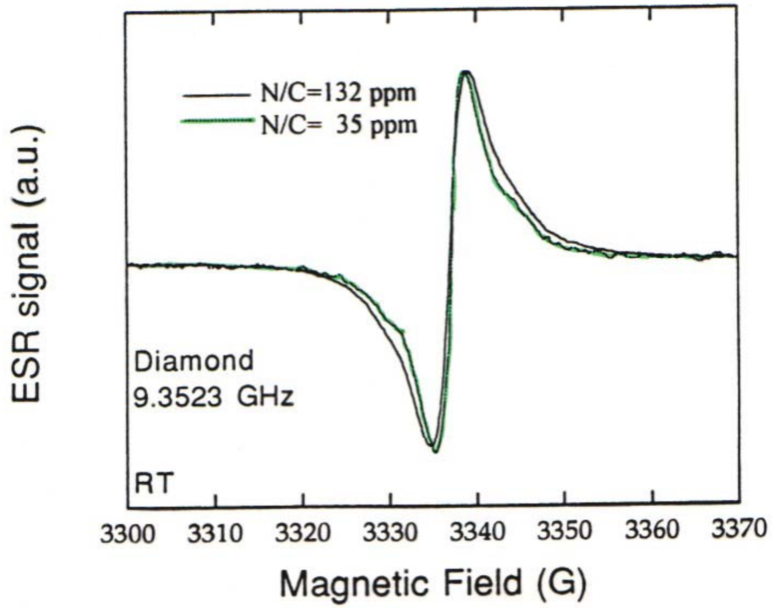


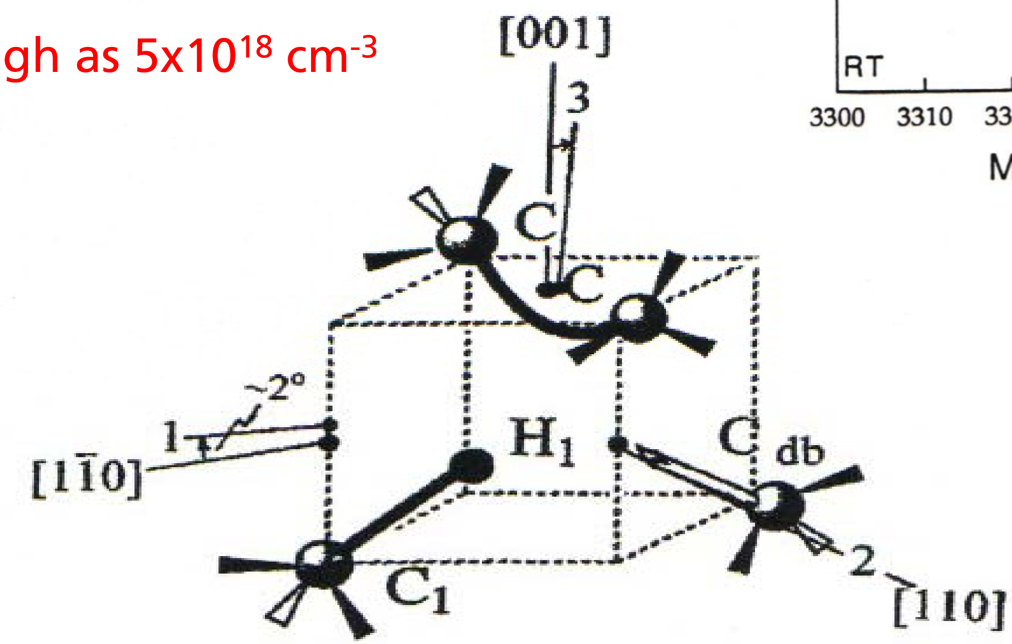
2. Defects in Diamond: H1 Center

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

Homoepitaxial single crystalline diamond:

Density as high as $5x10^{18}$ cm^{-3}





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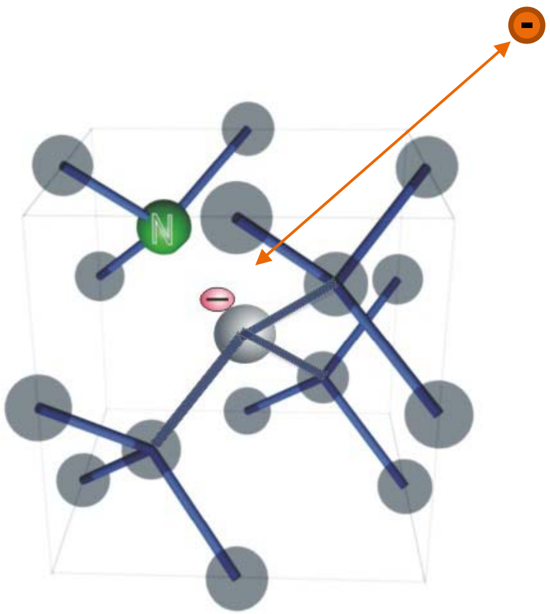
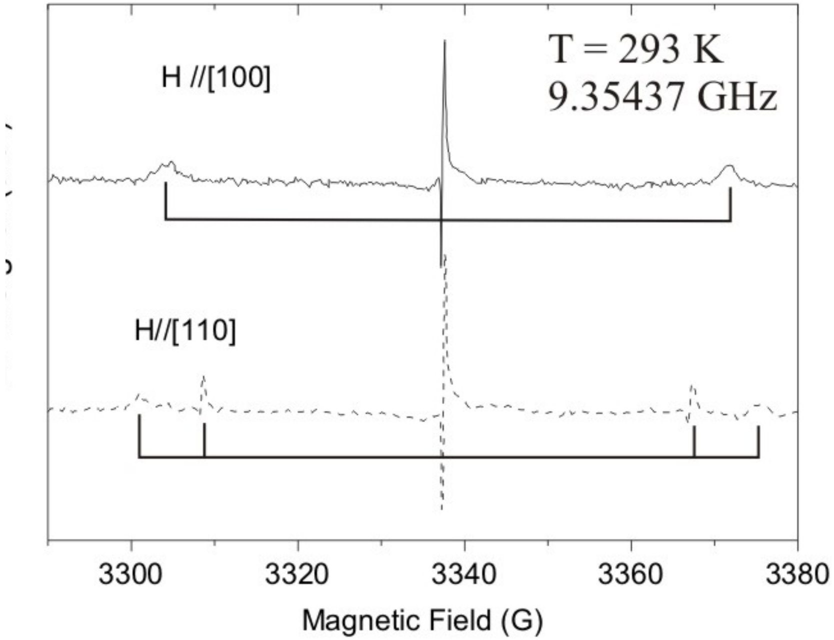
P1 Center (N-Dopant, g = 2.0024)



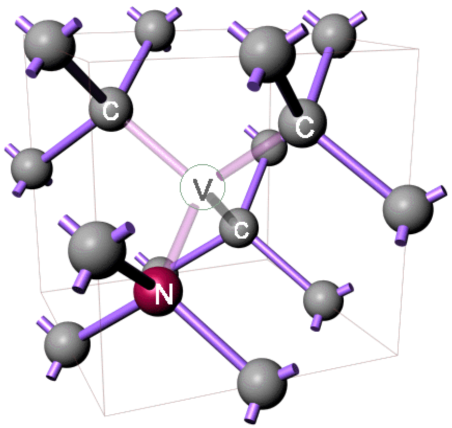


Capture Cross Section: 10^{-14} cm^{-2}

EPR of substitutional nitrogen (g=2.0024).
Satellite positiondepends on magnetic field with respect to (111)-orientation

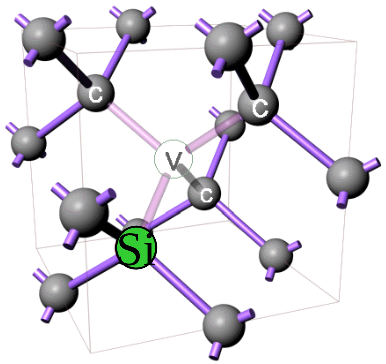
Color Centers in Diamond

NV



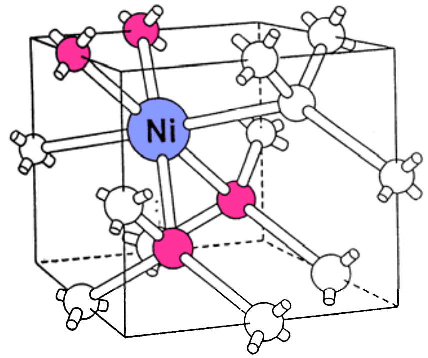
NV: 637 nm

SiV



SiV: 740 nm

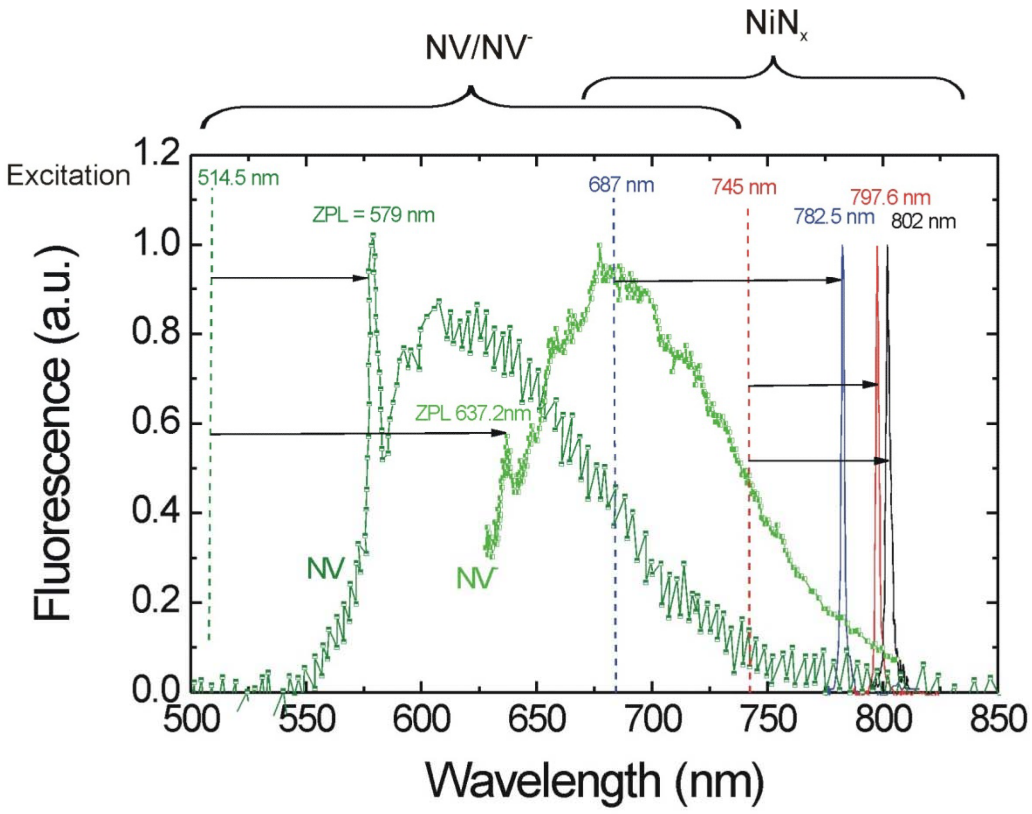
NE8



NiN_x

around 800 nm

Optical Excitation and Emission of NV and NiN_x



The **NV centers** show two broad emission bands excited by 514.5 nm:

ZPL(1): 579 (neutral NV)
ZPL(2): 637.2 nm (neg. charged NV^-)

The **NiN_x centers** show three very narrow (FWHM of 1.7 nm) emission lines excited by 687 nm and 745 nm:

782.5nm
797.6 nm
802.0 nm

This shift is caused by slightly different arrangements of this Center (need to be characterized).

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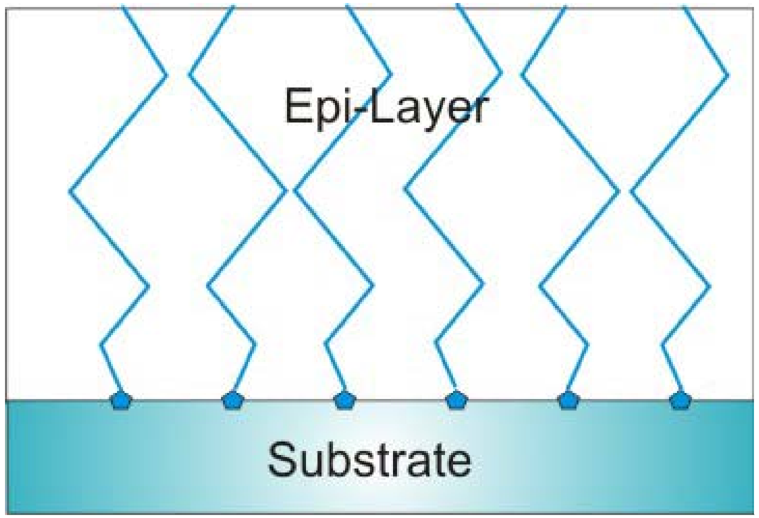
Dislocations



- Lattice distortion
- Grow from substrate into epi-layer
- Killer of high voltage devices

- Minimization:

soft etching of substrate befor growth , to remove distortions

3. Deep Trapping Lifetime, Schubweg and Mobility

$$\tau = \frac{1}{N_D v_{th} \sigma_{cross}}$$

$v_{th} = 10^7$ cm/s
$\sigma_{cross} = 10^{-14}$ cm^2
$N_D = 10^{18}$ cm^{-3}, 10^{17} cm^{-3}, 10^{16} cm^{-3}

Deep Trappping Livetime
$\tau_1 = 10^{-11}$ s
$\tau_2 = 10^{-10}$ s
$\tau_3 = 10^{-9}$ s

Schubweg:

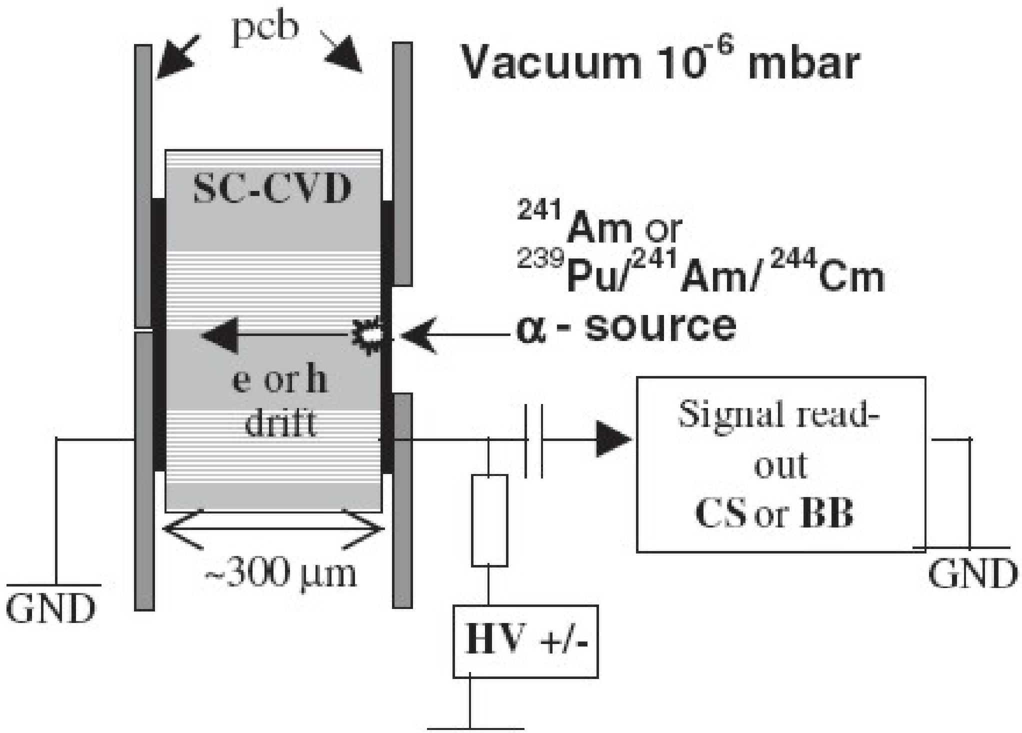
$$s = F\mu\tau$$

For F = 10^4V/cm and $\mu = 10^3$ cm^2/Vs : s = 10^{-4} cm, 10^{-3} cm, 10^{-2} cm

$\mu\tau$ Products: 10^{-8} cm^2/V, 10^{-7} cm^2/V and 10^{-6} cm^2/V

Time of flight set-up for α-particle detection

Source for α-particle ^{90}Sr or ^{241} Am



5.5 MeV α–particles
12 µm Absorption Depth

M. Pomorski et al., phys. stat. sol.(a) 202, 2199-2205 (2005)

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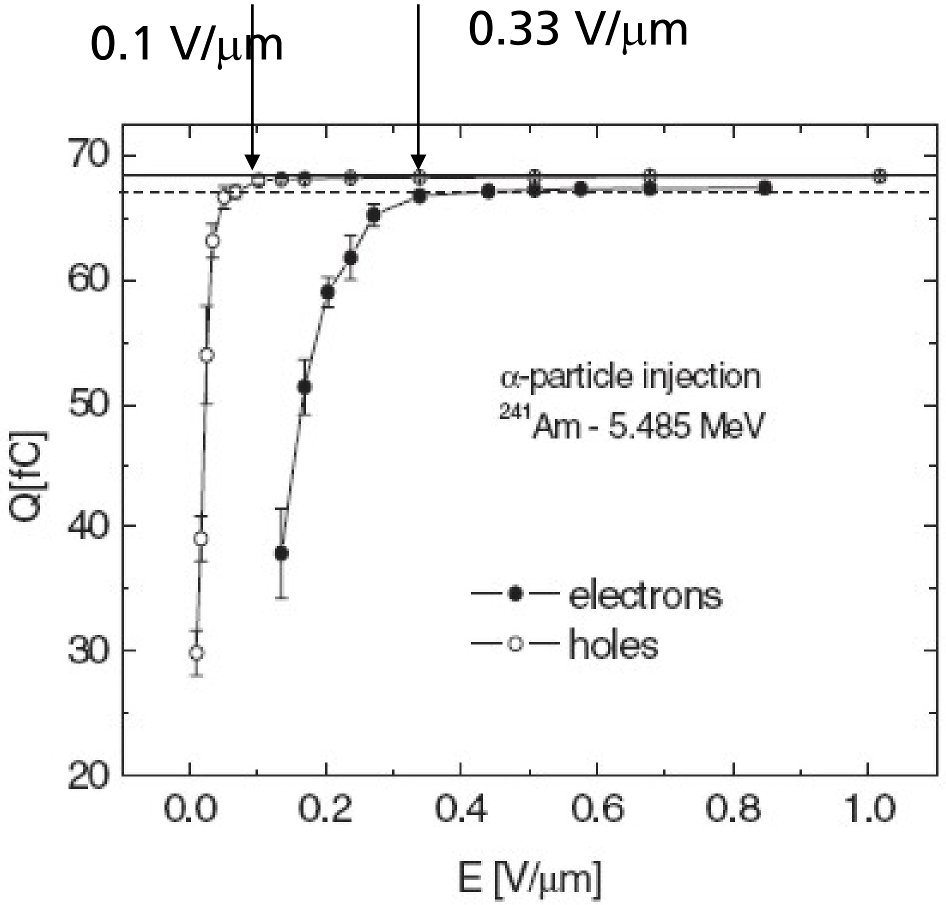
300 μm SC Diamond (e6)

Collection efficiency of holes better than of electrons: but good!



Schubweg: > thickness of diamond

M. Pomorski et al., phys. stat. sol.(a) 202, 2199-2205 (2005)

Time of Flight Signals

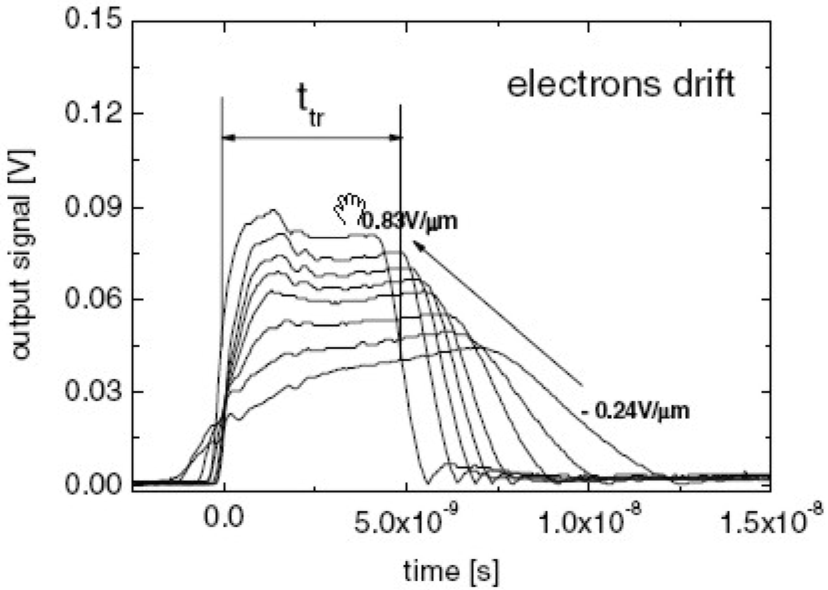


Fig. 7 Electron-drift signals at different electric fields: 0.24, –0.27, –0.34, –0.44, –0.51, –0.58, 0.68, –0.83 V/µm.

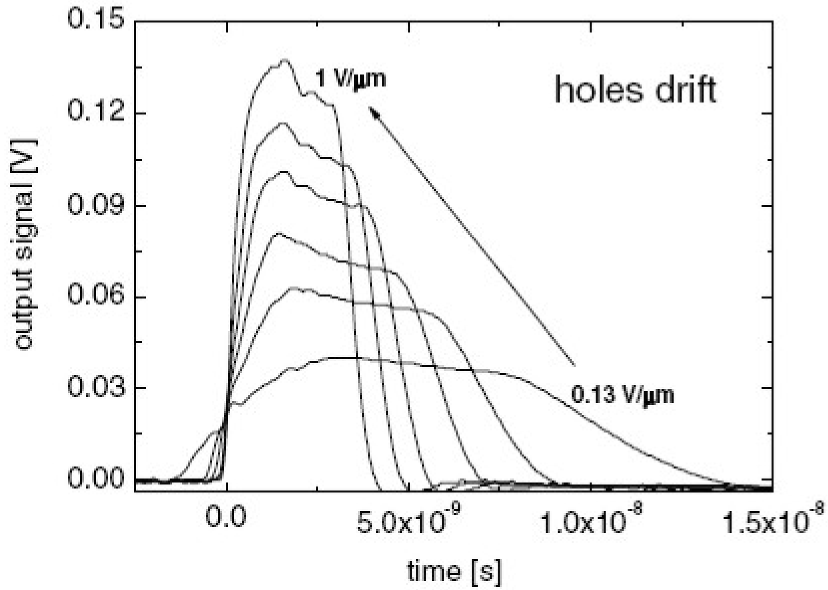
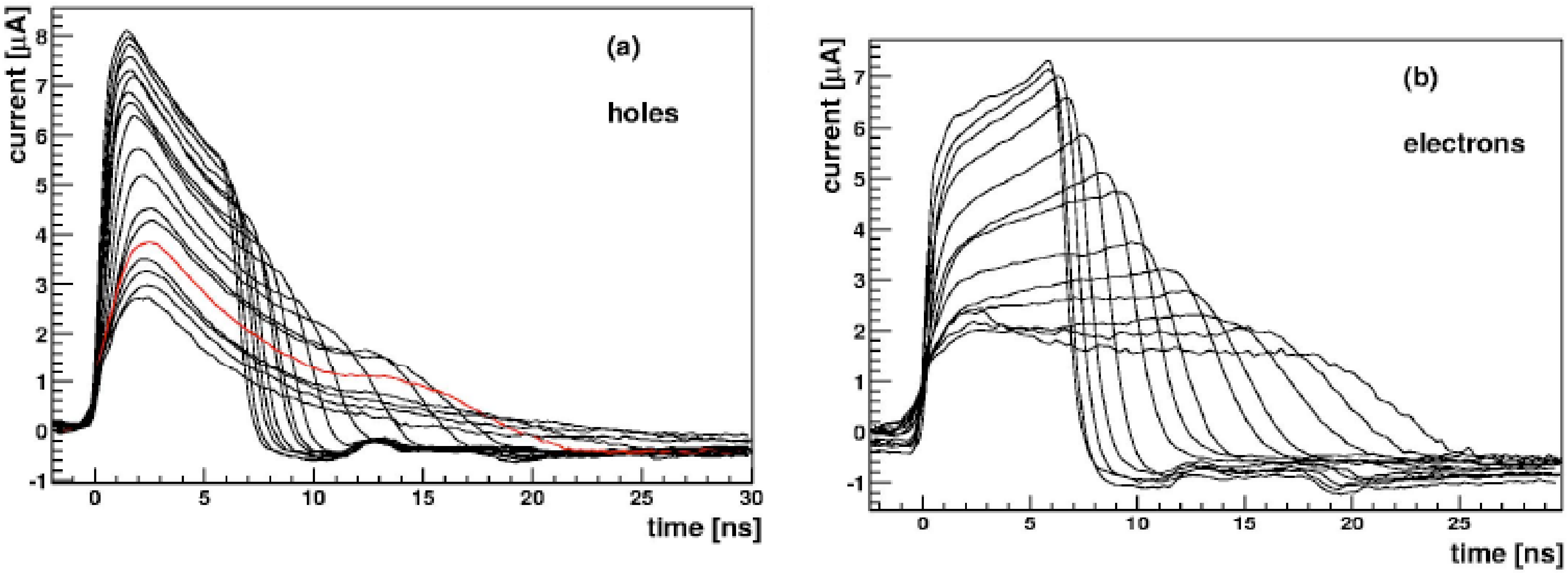


Fig. 8 Hole-drift signals at different electric fields: E = 0.18, 0.24, 0.34, 0.51, 0.68, 1 V/µm.

M. Pomorski et al., phys. stat. sol.(a) 202, 2199-2205 (2005)

TOF by Pernegger et al.



H. Pernegger, CERN, RD42 coll. Meeting May 2004

Result Summary

M. Pomorski et al., phys. stat. sol.(a) 202, 2199-2205 (2005)

	μ_0 – low field mobility [cm²/Vs]	v_s – saturation velocity [cm/s]	τ – life time [ns]
electrons	2071 ± 212	$0.85 \pm 0.08 \times 10^7$	174 ± 15
holes	2630 ± 123	$1.34 \pm 0.05 \times 10^7$	968 ± 230

Excellent Properties, but not 4500 and 3800 cm^2/Vs
Saturation velocity of electrons < $1.5x10^7$ cm/s
Electon properties are not as good as holes!

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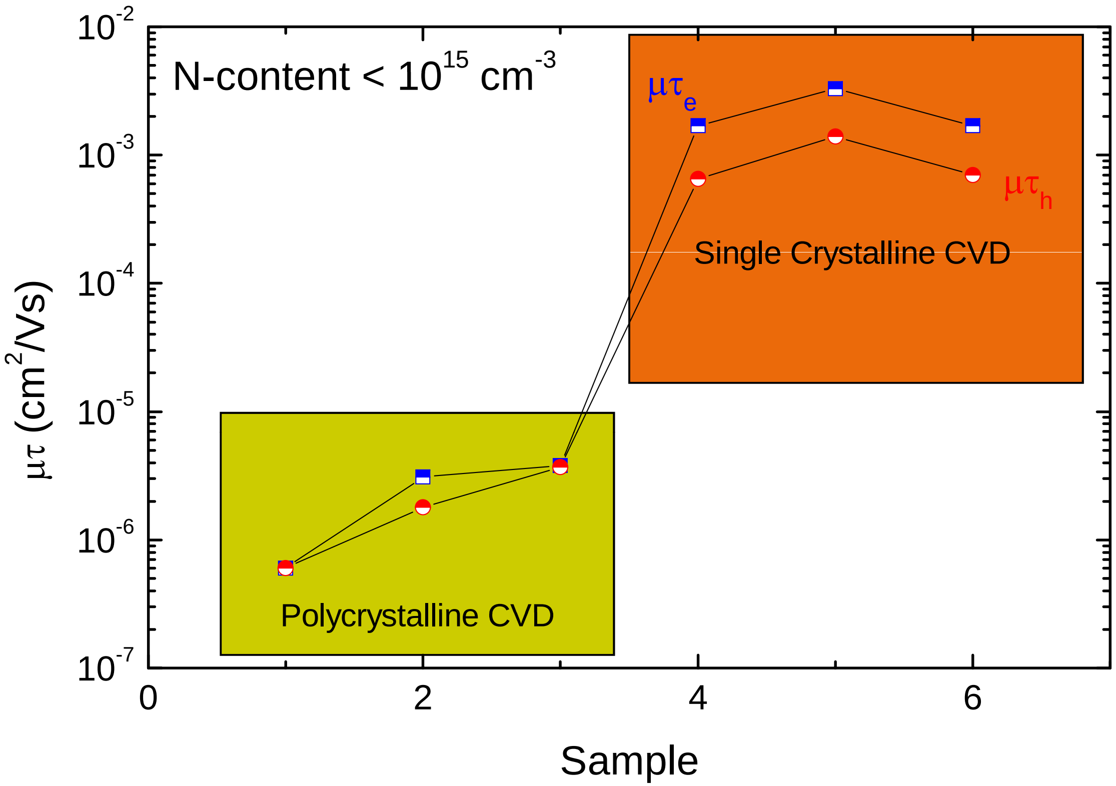
4. $\mu\tau$ –Product as Function of Morphology and Nitrogen

$\mu\tau$ = 10^{-5} cm²/V → 10^{15} cm^{-3} Nitrogen
$\mu\tau$ = 10^{-4} cm²/V → 10^{14} cm^{-3} Nitrogen
$\mu\tau$ = 10^{-3} cm²/V → 10^{13} cm^{-3} Nitrogen



Single Crystalline Diamond

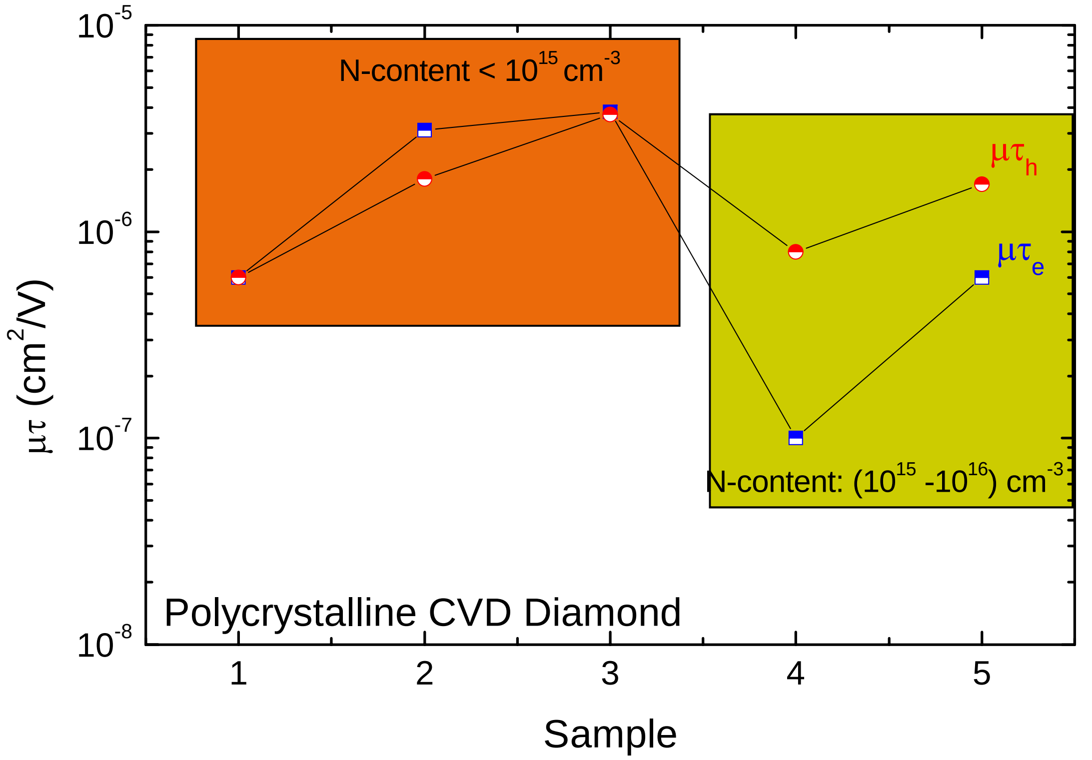
Factor 1000 better

Polycrystalline Diamond

J. Isberg et al., Diam. Rel. Mat. 13 (2004) 872.

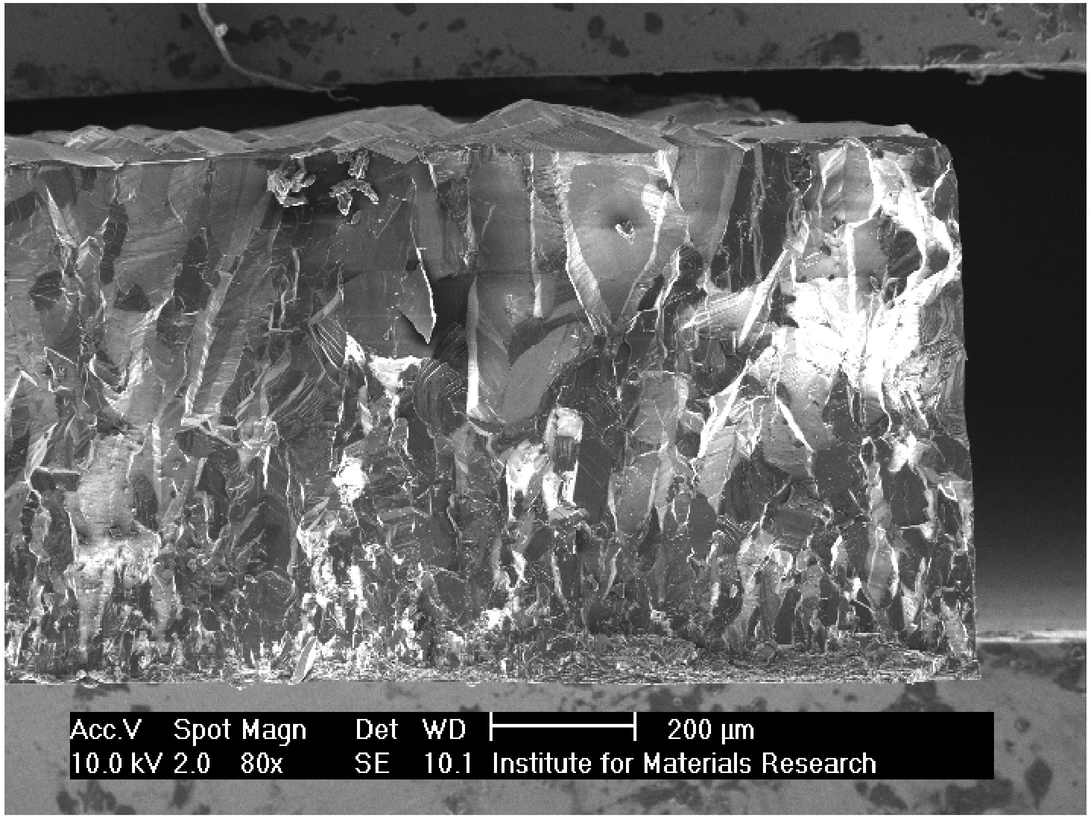
$\mu\tau$-Product as Function of Nitrogen Content

Nitrogen not important (Isberg!!!!

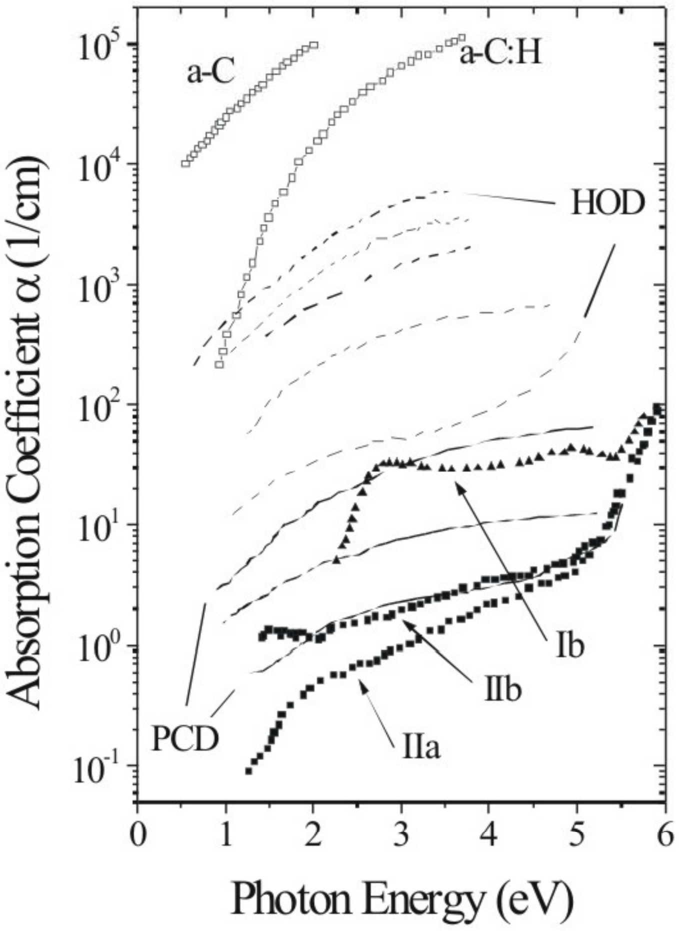


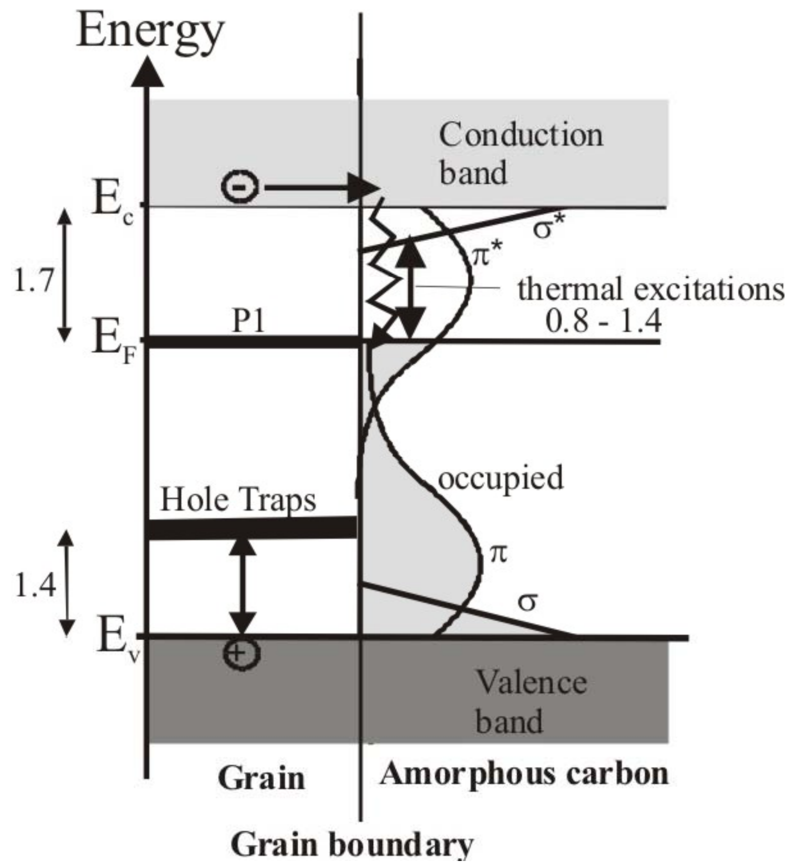
J. Isberg et al., Diam. Rel. Mat. 13 (2004) 872.

5. Properties of Poly-Crystalline CVD Diamond

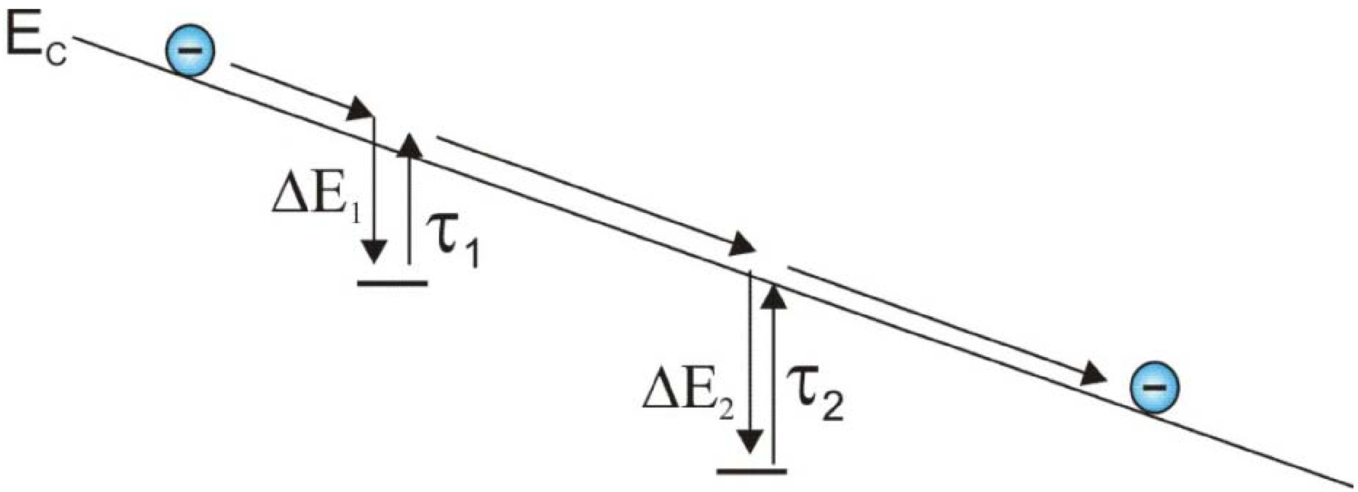


Density-of-State Distribution





Charrier Propagation: Trapping and Emission Dominated

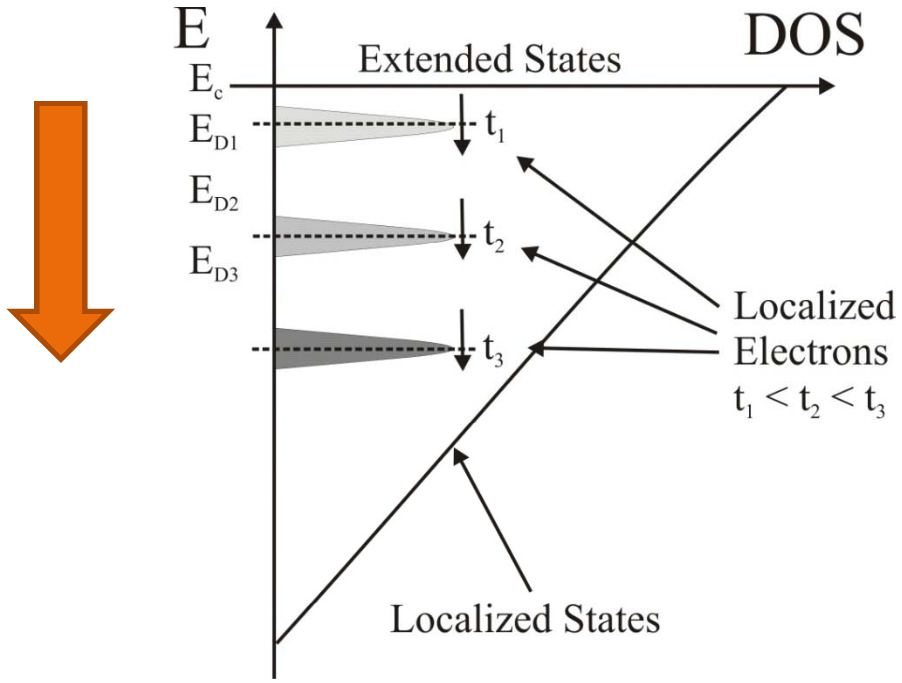


Trapping Time constant: $$\tau = \frac{1}{v_{th} N_D \sigma}$$

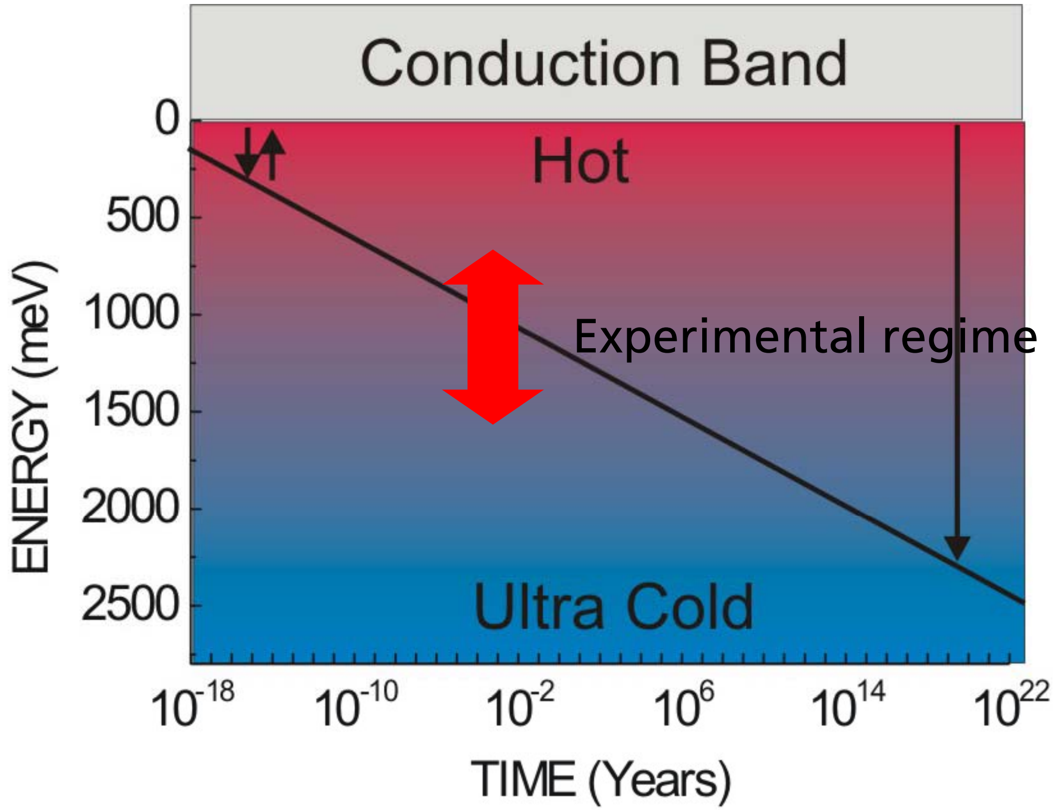
Re-Emission Time Constant τ: $$\nu(E)\,\tau \geq 1 \;\Longrightarrow\; \tau(E) = \frac{1}{\nu_o} e^{\frac{\Delta E}{kT}}$$

Where: $\nu_o = 10^{12}$ to ^{13} 1/s (Raman Frequence)

Thermalization of Carriers into the DOS

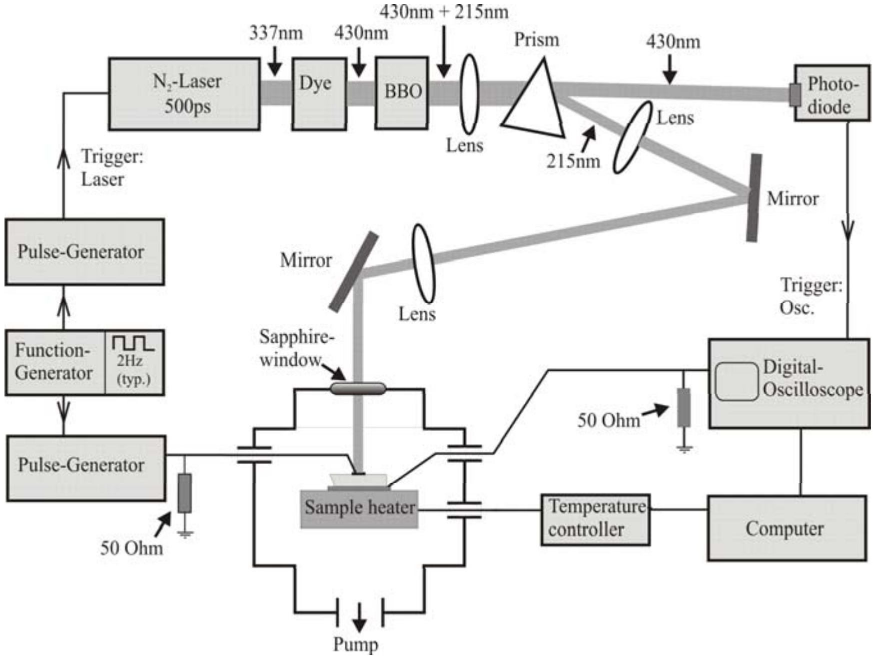


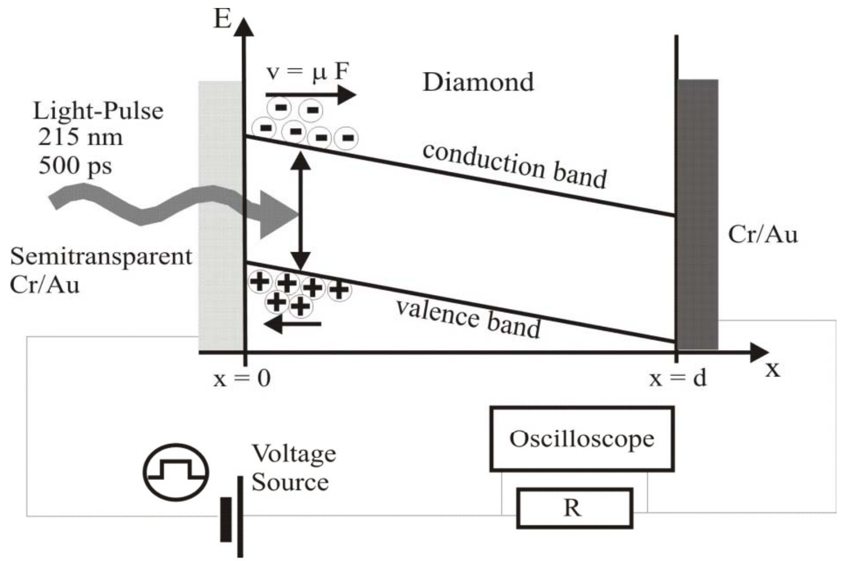
Diamond is: ULTRA COLD



Assumptions: T = 300 K, ν_o = 10^{13} 1/s

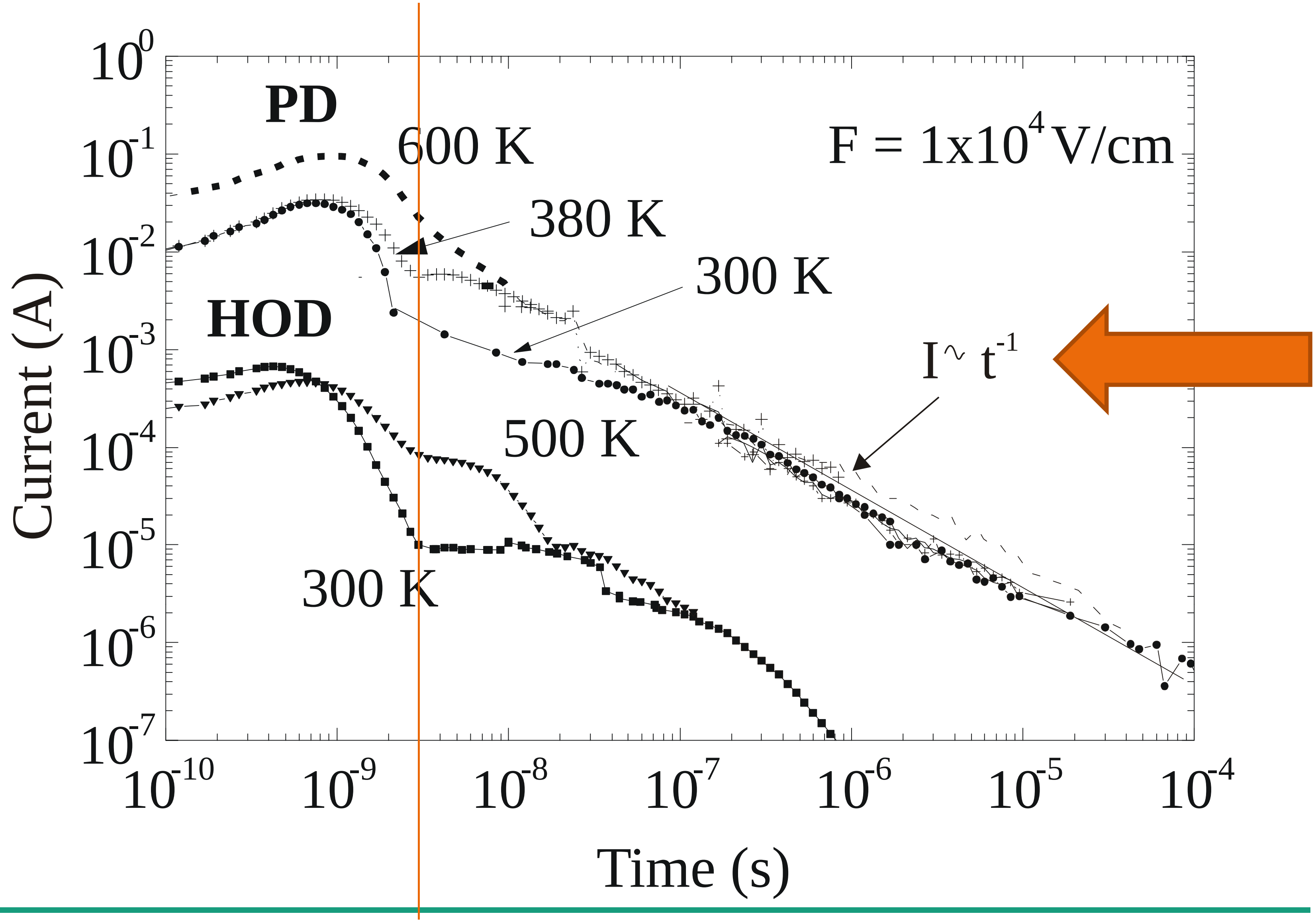
TOF Set-Up





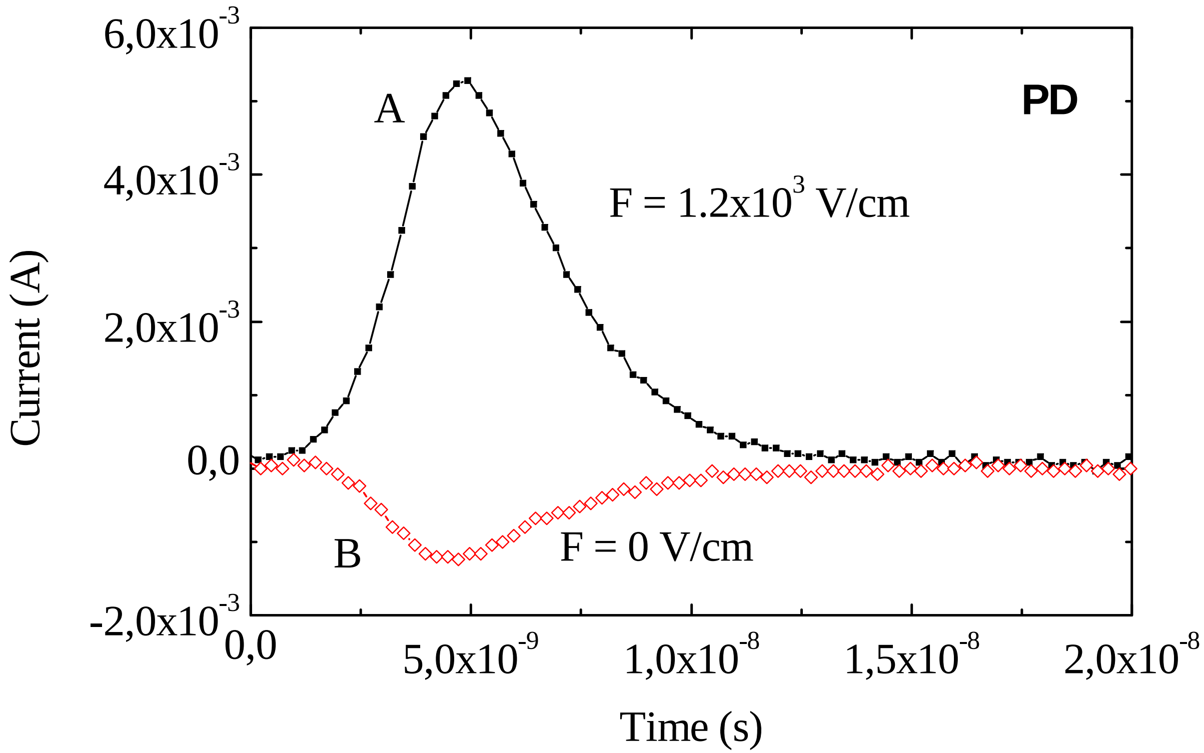
tof1.cdr

TOF on PCD

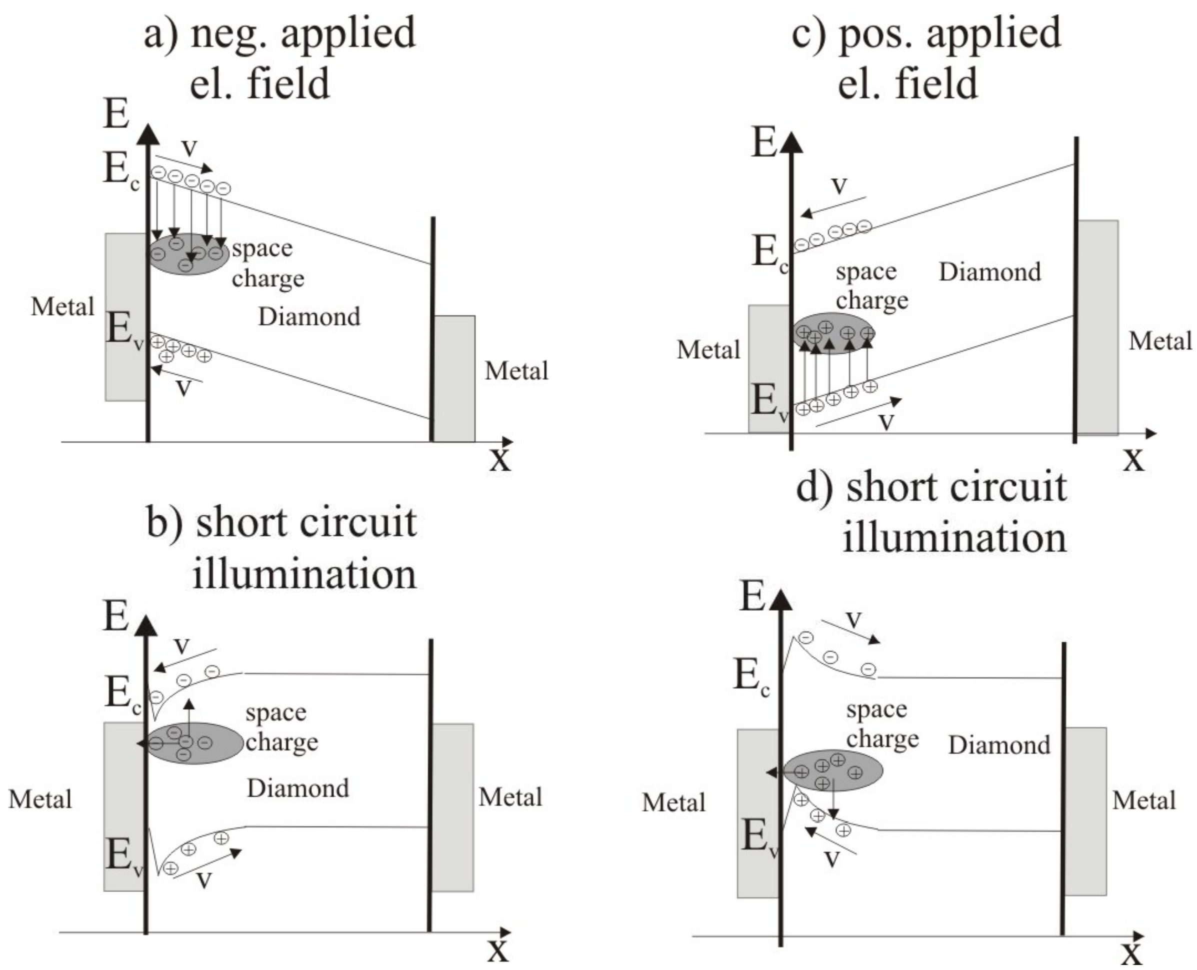


PD
600 K
380 K
300 K
HOD
500 K
300 K
F = 1x10^4 V/cm
I~ t^-1
Current (A)
Time (s)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4

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



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



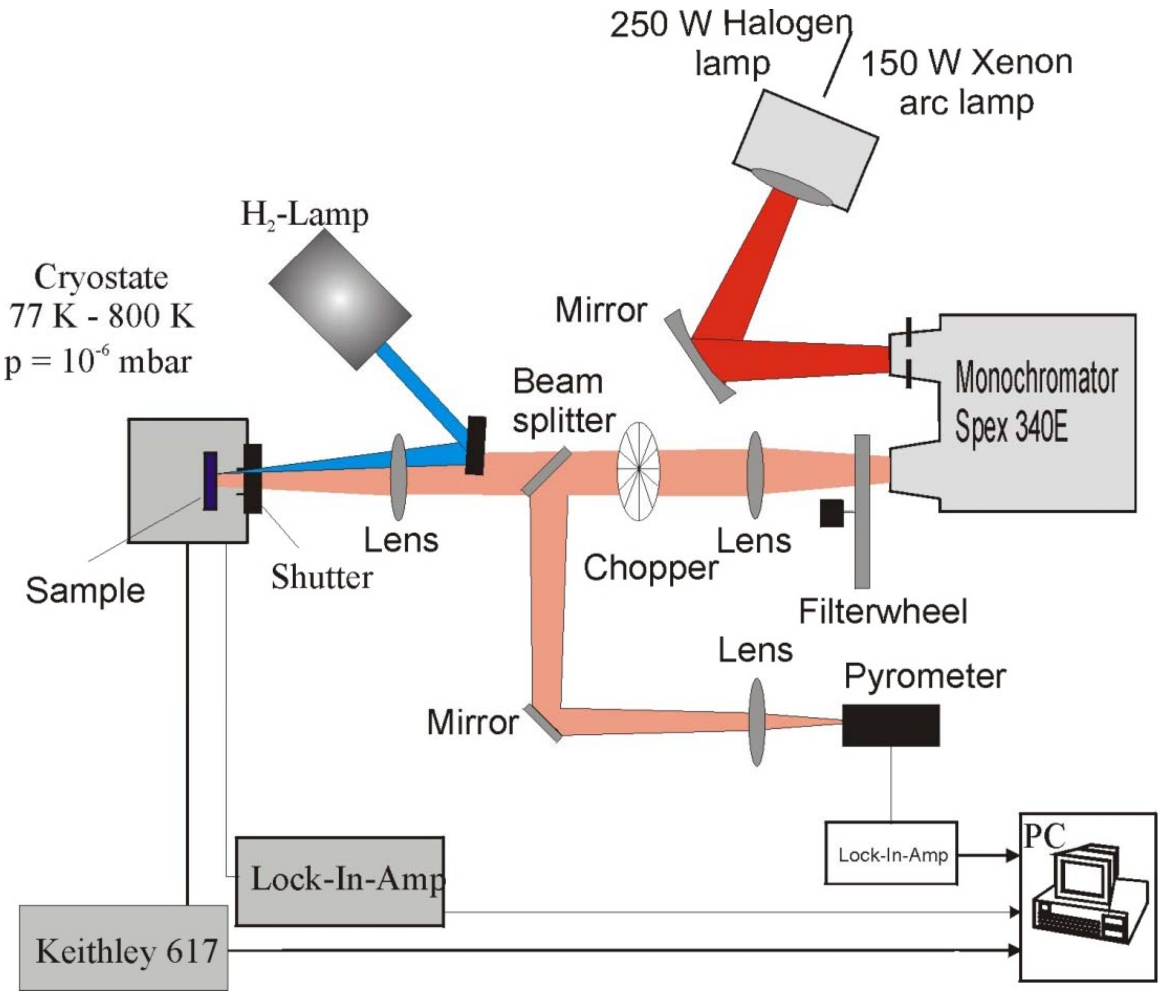
6. Spectrally Resolved Photoconductivity

$$\frac{j_{ph}(h\nu)}{\Phi_o(h\nu)} \approx \tau_n \alpha(h\nu)$$

where:

j_{ph} : photo-current
Φ_o : photon flux
τ_n = lifetime
$\alpha(h\nu)$= absorption coefficient

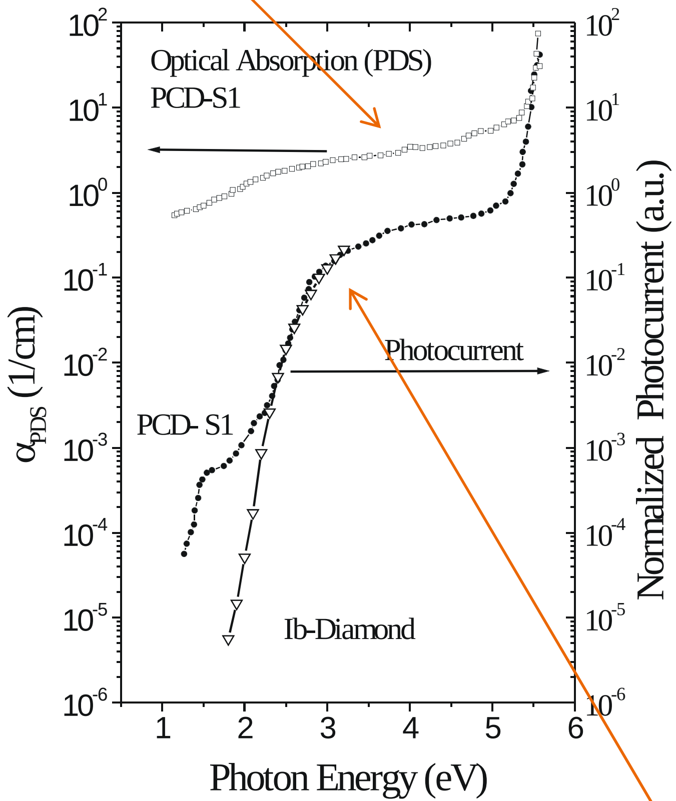
Set-Up

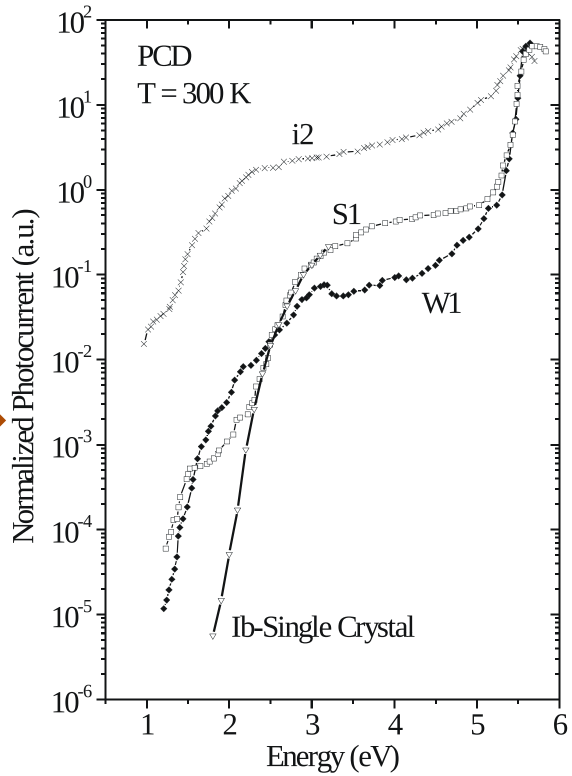


250 W Halogen lamp
150 W Xenon arc lamp
H_2-Lamp
Cryostate
77 K - 800 K
p = 10^{-6} mbar
Mirror
Beam splitter
Monochromator Spex 340E
Sample
Shutter
Lens
Chopper
Lens
Filterwheel
Lens
Pyrometer
Mirror
Lock-In-Amp
PC
Lock-In-Amp
Keithley 617

Spectrally Resolved PC and PTD Spectroscopy

all carriers





mobile carriers

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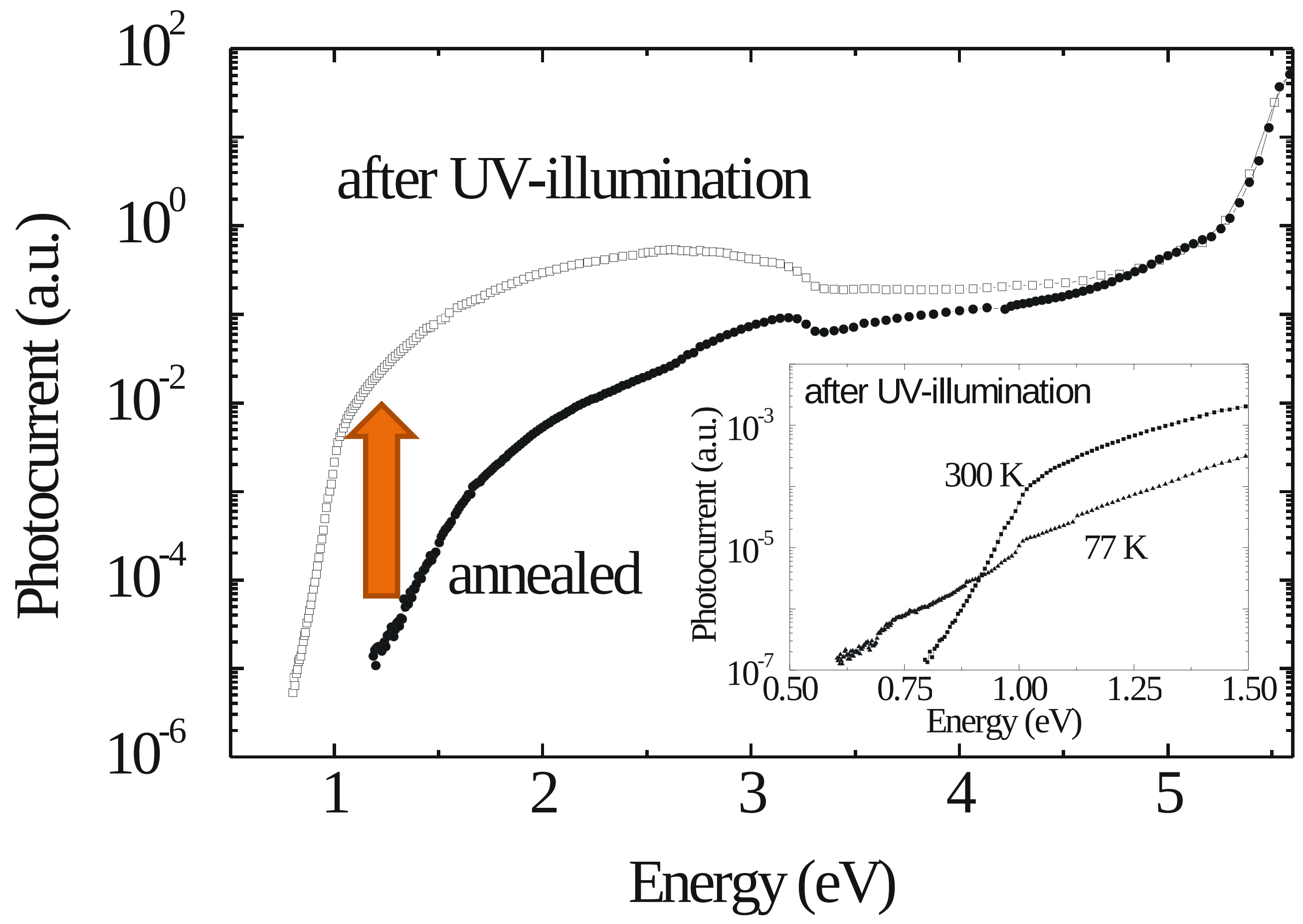
Spectrally Resolved PC:



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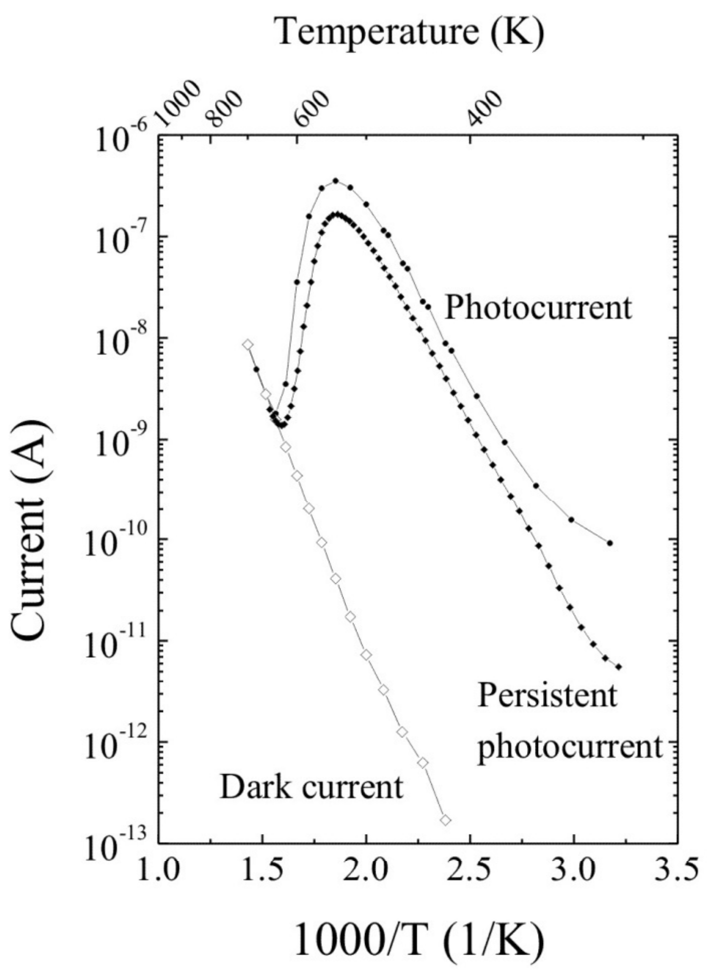
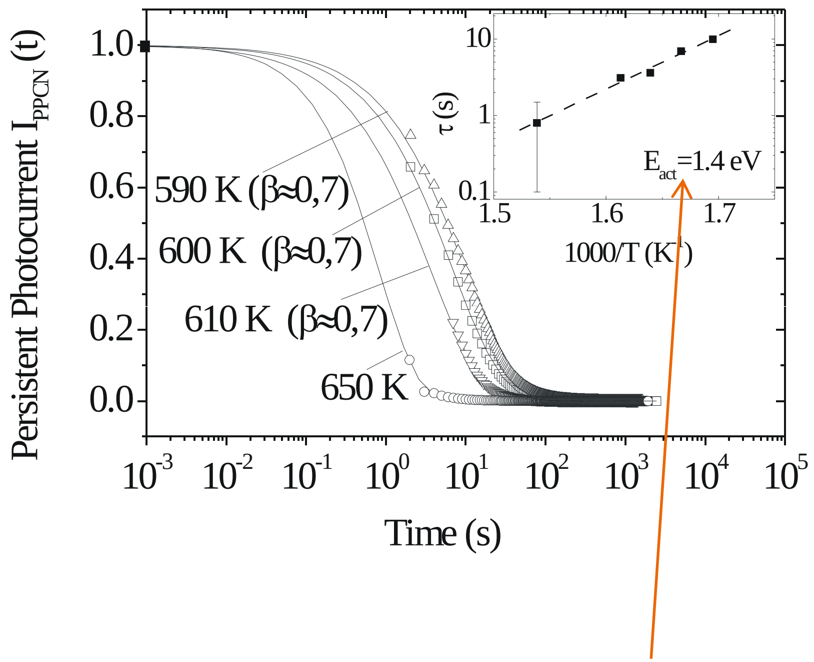
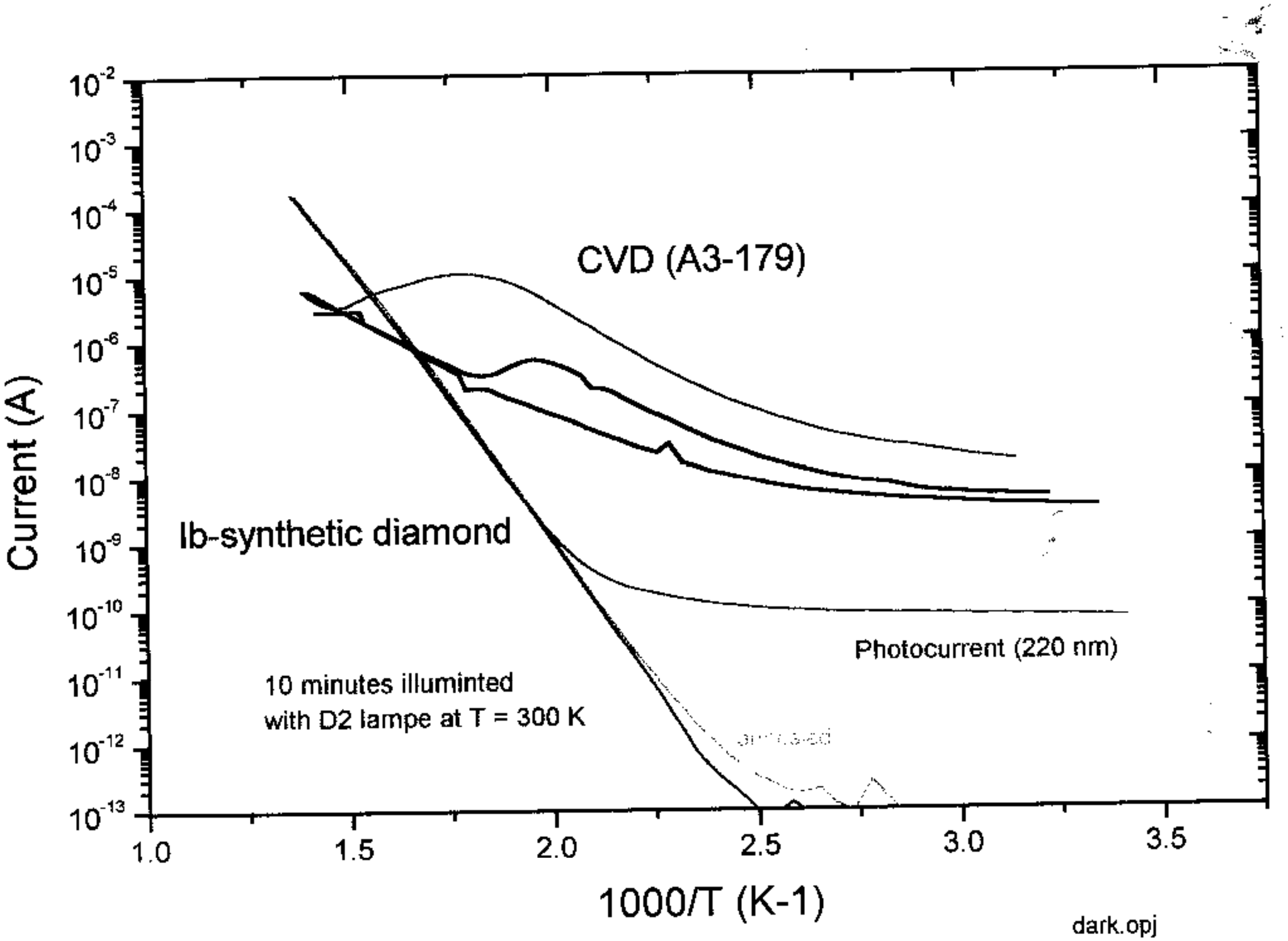
Thermally Stimulated Currents



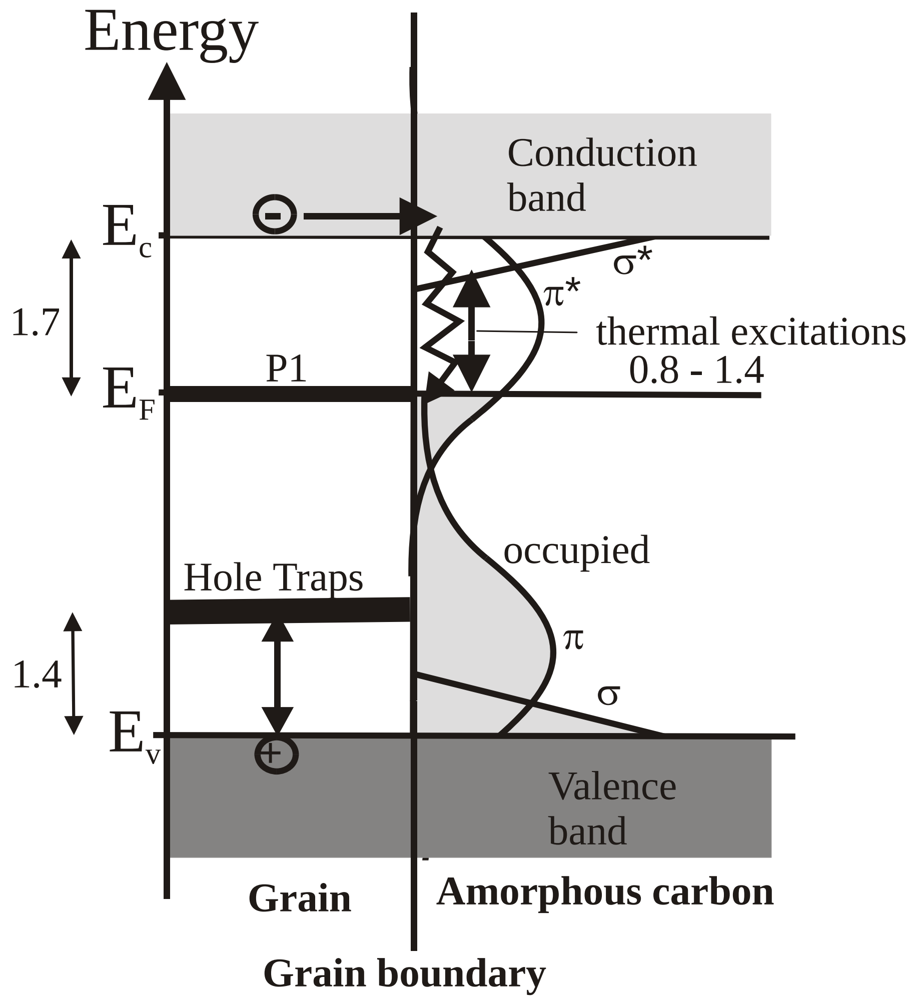


Annealing Out Energy: 1.4 eV

Thermally Stimulated Currents in PCD and Single CD

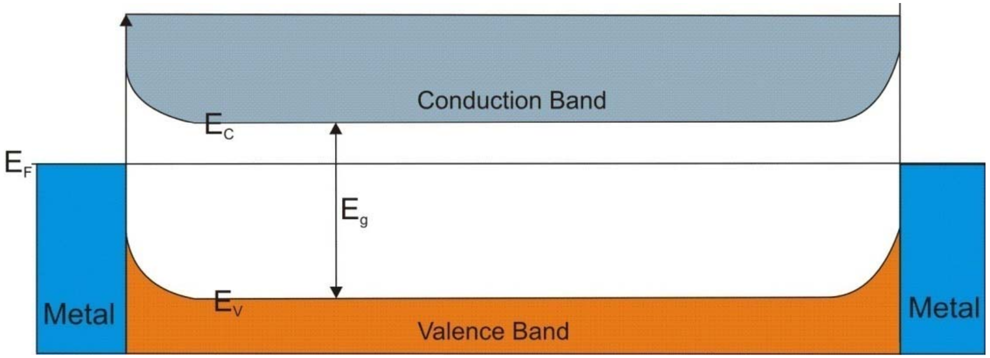


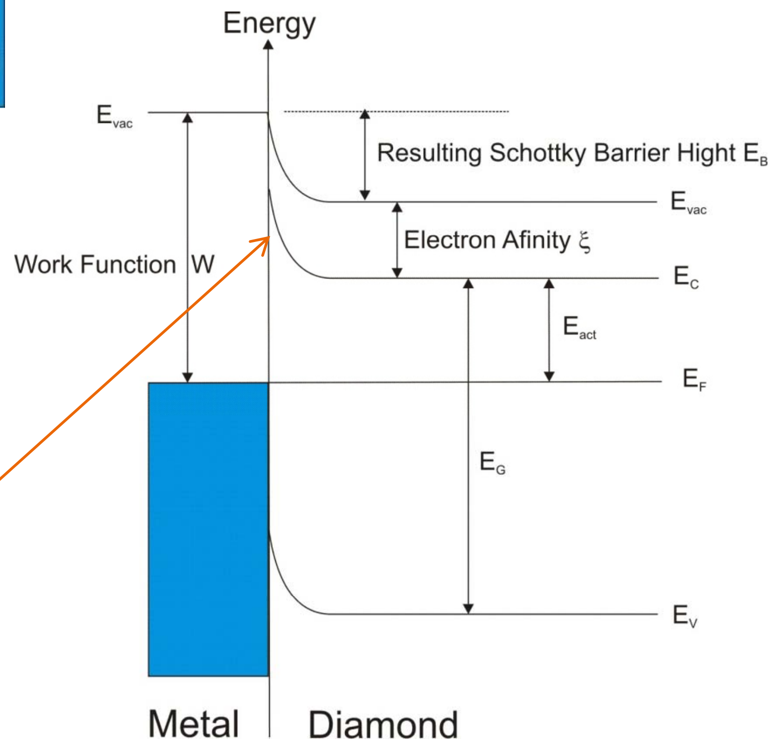
Model:



Energy
Conduction band
E_c
1.7
σ^*
π^*
thermal excitations 0.8 - 1.4
P1
E_F
occupied
Hole Traps
π
1.4
σ
E_v
Valence band
Grain
Amorphous carbon
Grain boundary

7. Contact Properties





$$E_B = W - (E_{act} + \xi)$$

Metal Workfunction (Sze) Φ_m

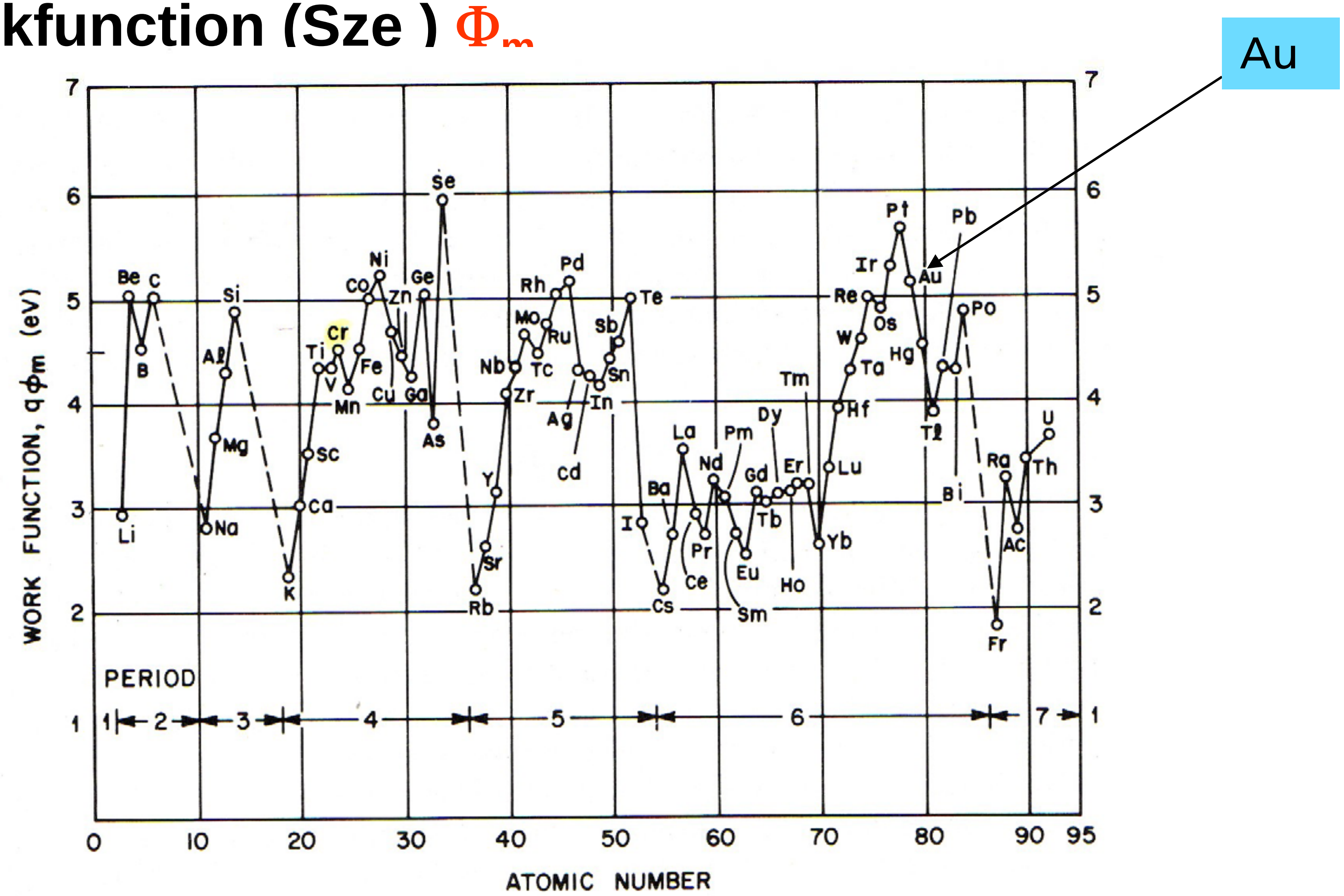
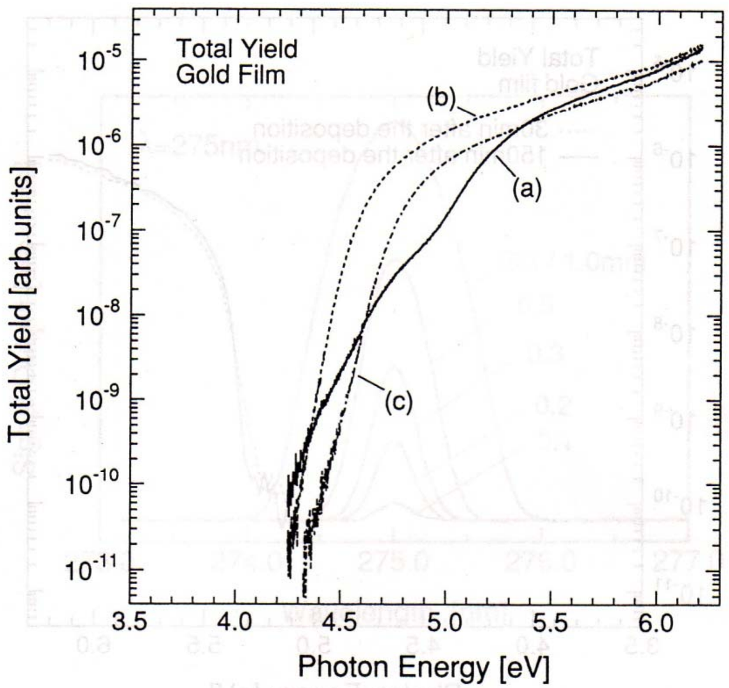
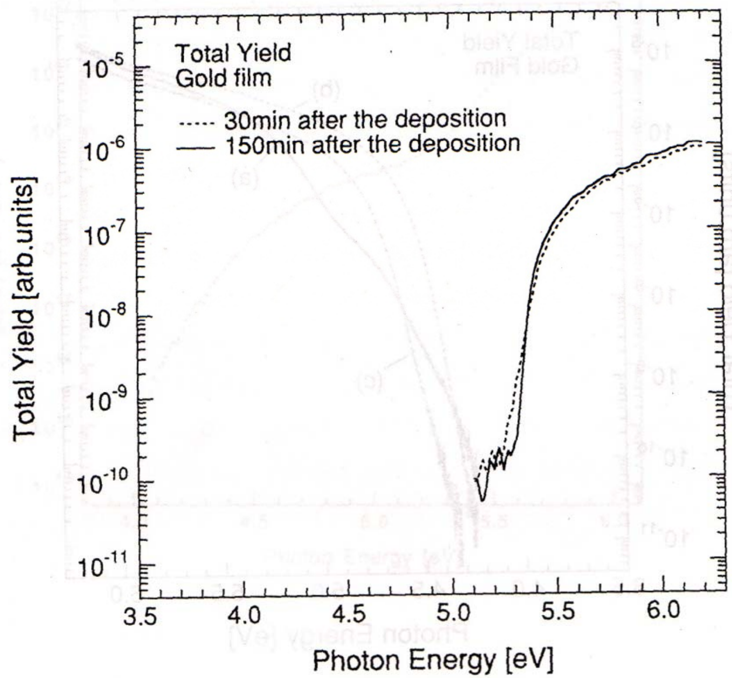


Fig. 4 Metal work function for a clean metal surface in a vacuum versus atomic number. Note the periodic nature of the increase and decrease of the work functions within each group. (After Michaelson, Ref. 9.)

Au Workfunction (S. Gonda, PhD Tokyo Institut of Technology 1995)





Wokfunction: 4.5 eV

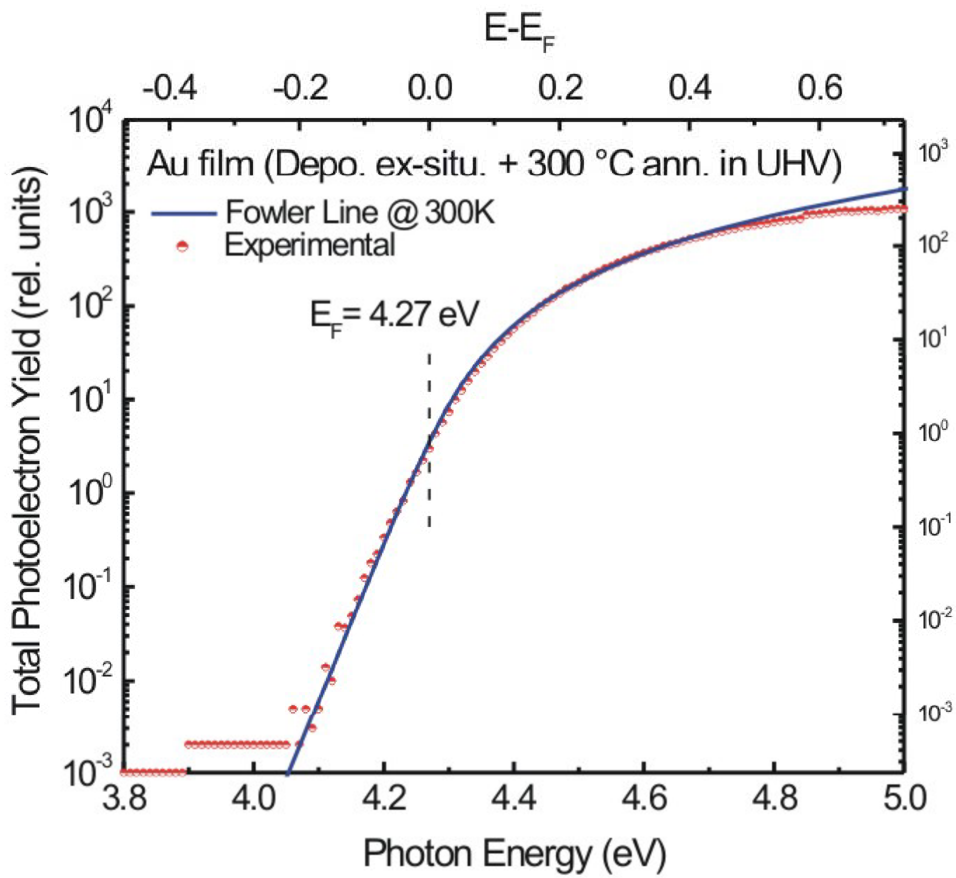
Workfunction: 5.2 eV

Au TPYS of AU: a) measured after 30 min,
b) after 150 min in-situ evaporation in a vacuum of $4x10^{-8}$ Torr
c) ex-situ evaporation

Au TPYS spectrum measured a) after 30 min
and b) after 150 min. in-situ evaporation at $5x10^{-10}$ Torr

Fraunhofer IAF

TPYS on Au at DRC/AIST:

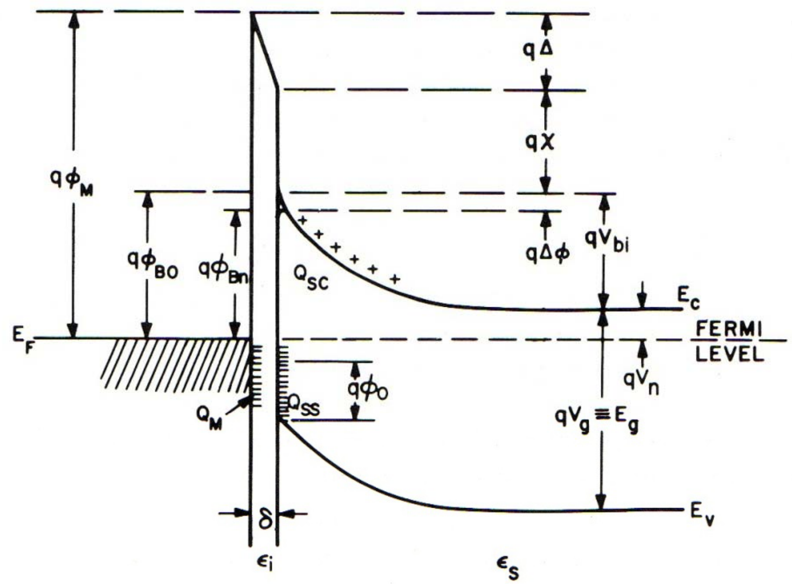


Workfunction 4.27 eV

Real Schottky Contact

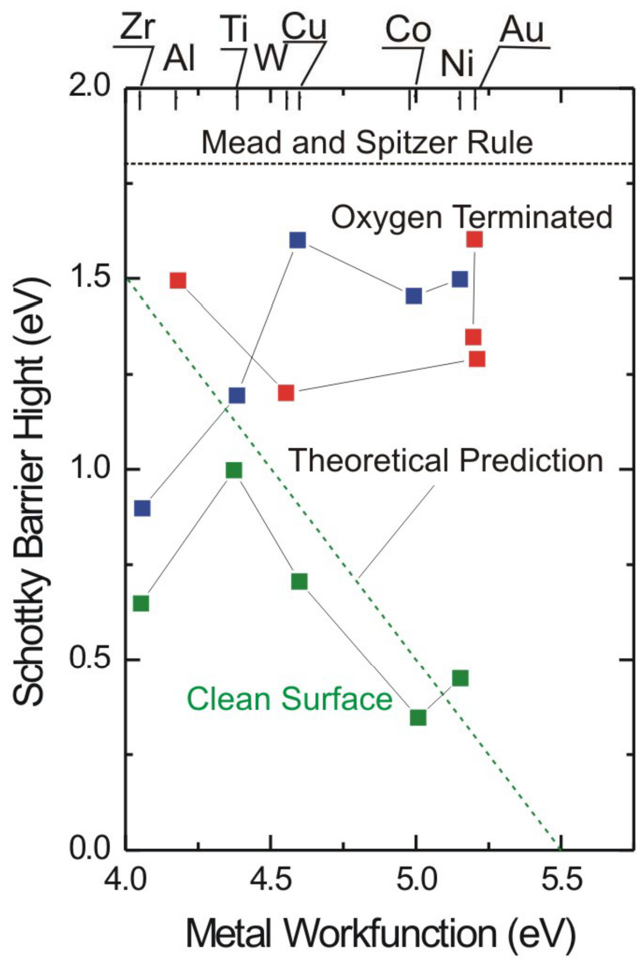
Surface Fermi-level
pinning by
surface defects

Schottky barrier is
not dependent
on metal.



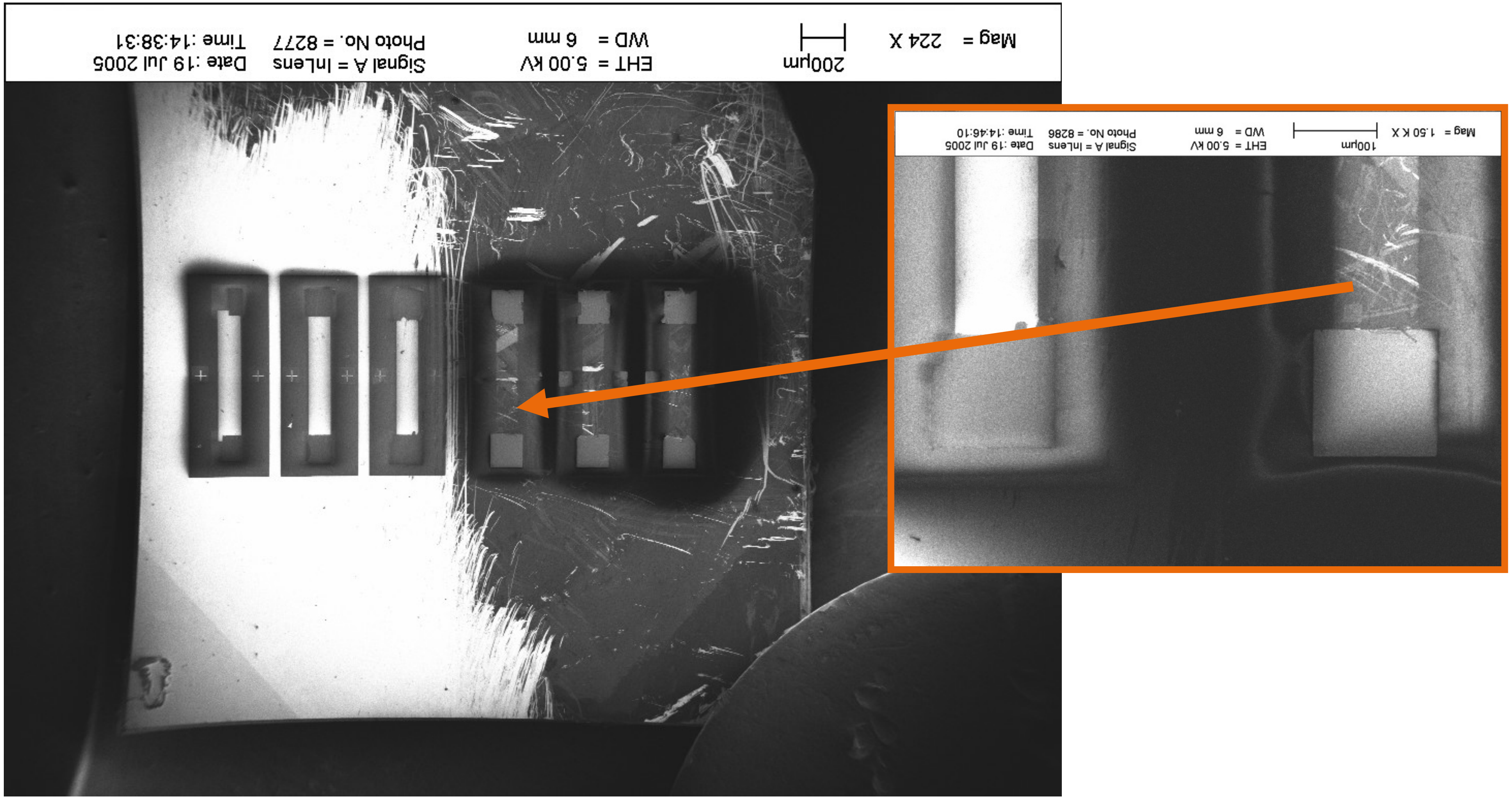
ϕ_M = WORK FUNCTION OF METAL
ϕ_{Bn} = BARRIER HEIGHT OF METAL-SEMICONDUCTOR BARRIER
ϕ_{BO} = ASYMPTOTIC VALUE OF ϕ_{Bn} AT ZERO ELECTRIC FIELD
ϕ_0 = ENERGY LEVEL AT SURFACE
$\Delta\phi$ = IMAGE FORCE BARRIER LOWERING
Δ = POTENTIAL ACROSS INTERFACIAL LAYER
χ = ELECTRON AFFINITY OF SEMICONDUCTOR
V_{bi} = BUILT-IN POTENTIAL
ϵ_s = PERMITTIVITY OF SEMICONDUCTOR
ϵ_i = PERMITTIVITY OF INTERFACIAL LAYER
δ = THICKNESS OF INTERFACIAL LAYER
Q_{SC} = SPACE-CHARGE DENSITY IN SEMICONDUCTOR
Q_{SS} = SURFACE-STATE DENSITY ON SEMICONDUCTOR
Q_M = SURFACE-CHARGE DENSITY ON METAL

Schottky Properties: Clean and Oxygen Terminated Diamond



from:
M. Werner, Semicond. Sci. Technol. 18 (2003) S41

Cleanness: SEM image of Bar-Contact structures



partially wiped
in ethanol

Fraunhofer IAF

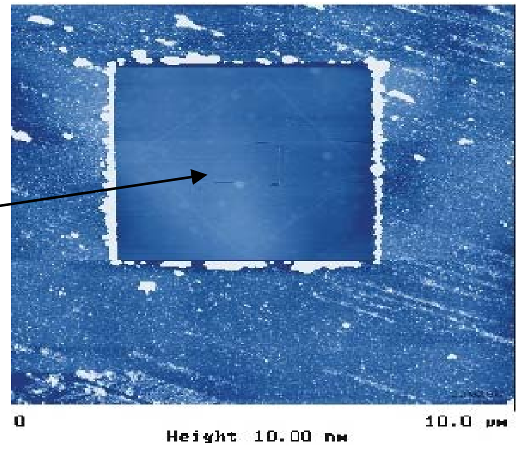
Cleaning by contact mode AFM

Tapping Mode AFM
Surface Morphology

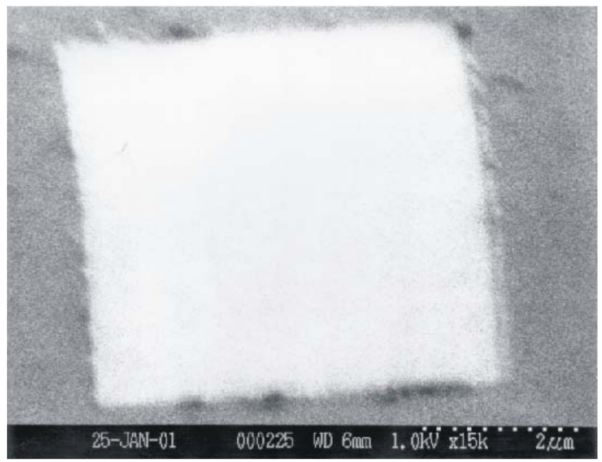
Contact Mode AFM
Cleanning

Surface is covered with a thin
(1 -10) nm thick adhesive layer.

AFM Image



SEM Image



B. Rezek, C.E. Nebel, M. Stutzmann
Diam. and Rel. Mat. 13, 740-745 (2004)

8. Summary:

Alles ist einfacher,
als man denken kann,

zugleich verschränkter,
als zu begreifen ist.

Johann Wolfgang von Goethe