CVD Diamond Surface Characterization and Contact Interface Properties

C.E. Nebel

Diamond Research Center,

National Institute of Advanced Industrial Science and Technology,

Tsukuba, Japan

Acknowledgement

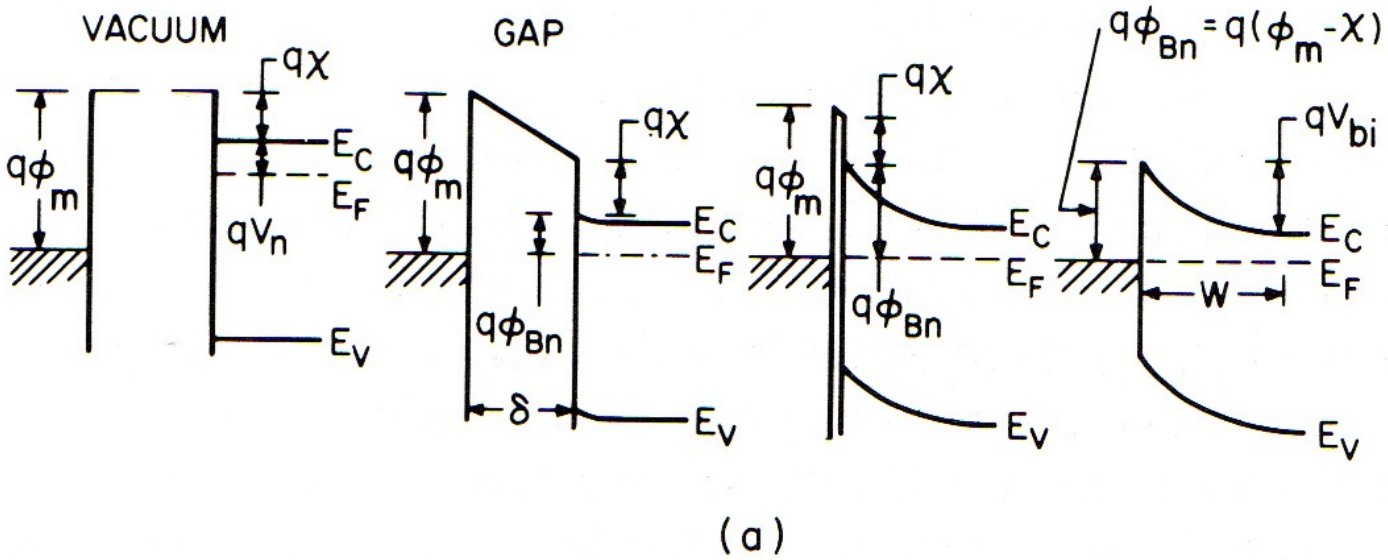
Team members:

Dr. D. Takeuchi (Photoelectronspectroscopy)
Dr. B. Rezek (AFM, Kelvin Force)
Dr. D. Shin (Electrochemistry, Biofunctionalization)
Ms. T. Yamamoto (Photoconductivity, Device Fabrication)
Dr. S. Ri (XPS)
Dr. H. Watanabe (Growth of CVD Diamond)
Dr. T. Nakamura (Chemist)

Outline

1) Introduction: The Ideal Schottky Contact Theory
2) Atomic Arrangement of Diamond Surface ((111) and (100))
3) Electron Affinities of Diamond
4) Surface Geometrical Properties
5) Surface Defects of clean, O and H terminated diamond
6) Fermi-level determination by Kelvin Force Experiments
7) Surface electronic properties
8) The electronic Density of State Distribution at the surface
9) Contact Properties to Diamond

1. Introduction: Schottky Contact Theory



Schottky Barrier Hight: $q\Phi_{Bn} = q(\Phi_m - \chi)$

Two Parameter: Metal Workfunction Φ_m
Electron Affinity of Semiconductor χ

Metal Work-Functions (Sze) Φ_m

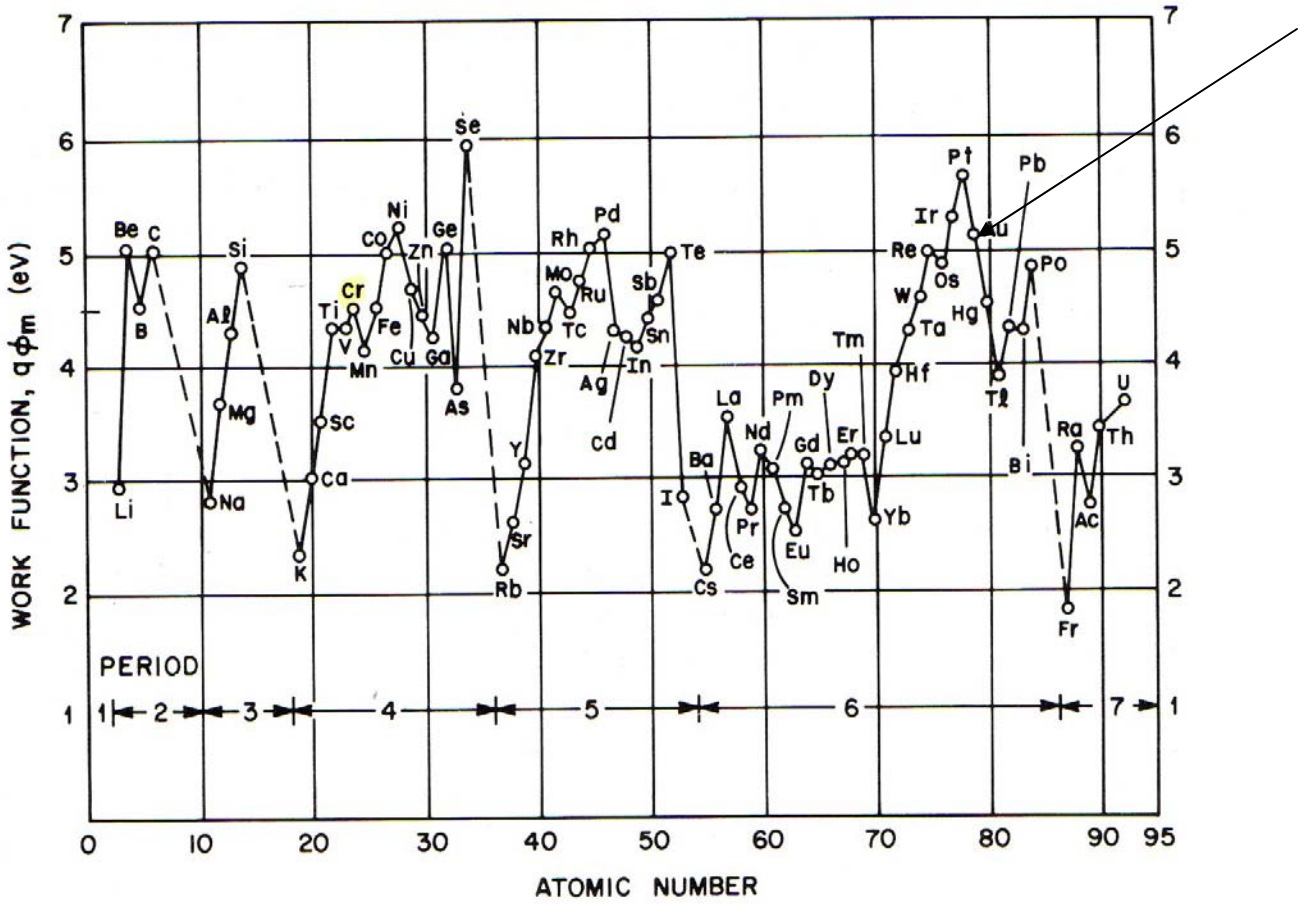


Fig. 4 Metal work function for a clean metal surface in a vacuum versus atomic number. Note the periodic nature of the increase and decrease of the work functions within each group. (After Michaelson, Ref. 9.)

Work-Functions of Metals?

Example Au, which is used as a calibration standard in Photo-Yield experiments:

Au Textbook data: 5.2 eV

Experimentally detected: 4.3

What to take in reality?

2. Geometry of Diamond Surface: (111) Diamond

Clean (111)-(2x1) reconstructed
Formation of π-bonded dimers

Defect free !!!

H-term. (111)-(1x1):H

Trihydrid structure

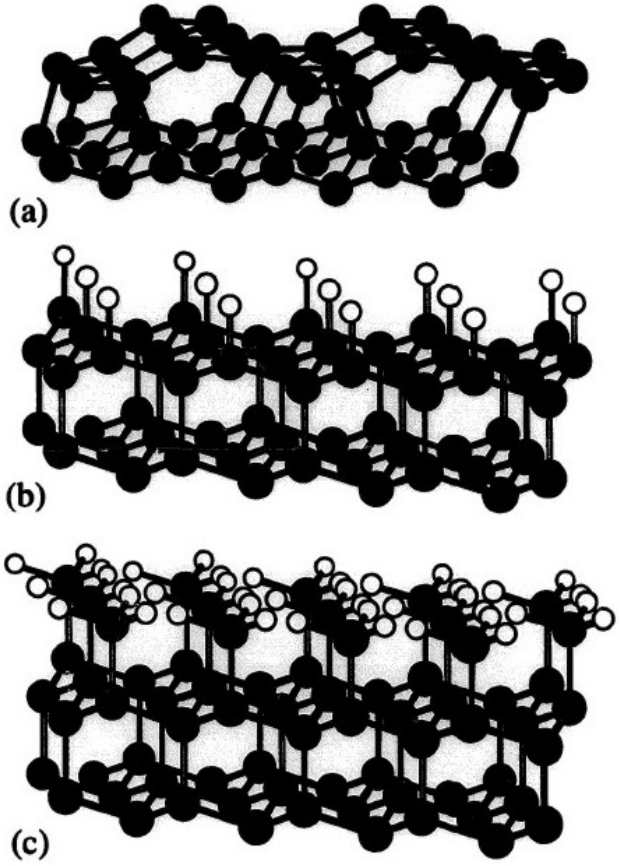


Fig. 19. Schematic representation of building blocks forming diamond (0 0 1) surfaces. (a) Clean (1 1 1)-2 × 1 structure where dangling bonds are involved to form π-bonded dimers. (b) (1 1 1)-1 × 1:H structure composed of monohydride dimers where each dangling bond per carbon atom is terminated by hydrogen. (c) (1 1 1) Trihydride structure where each dangling bond per carbon atom is terminated by trihydride carbon.

(001) Diamond Surface

Clean (001)-(2x1) reconstructed
Formation of π-bonded dimers

Defect free !!!

H-term. (001)-(2x1):H
Monohydrid dimers

Two dangling bonds
per carbon are H-terminated

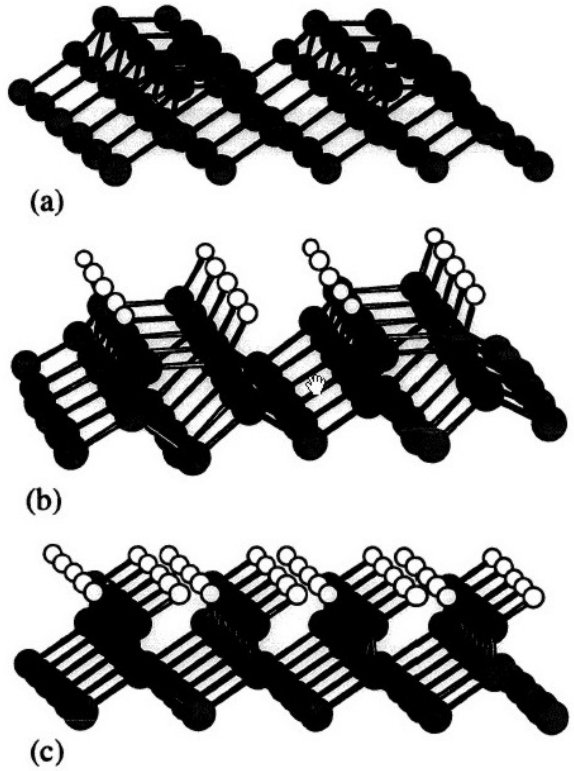


Fig. 12. Schematic representation of building blocks forming diamond (0 0 1) surfaces. (a) Clean (0 0 1)-2 × 1 structure where dangling bonds are involved to form π-bonded dimers. (b) (0 0 1)-2 × 1:H structure composed of monohydride dimers where each dangling bond per carbon atom is terminated by hydrogen. (c) (0 0 1)-2 × 1:2H structure where two dangling bonds per carbon atom are terminated by hydrogen.

Natural single crystal (100) diamond after annealing at 1.100 °C

STM Result

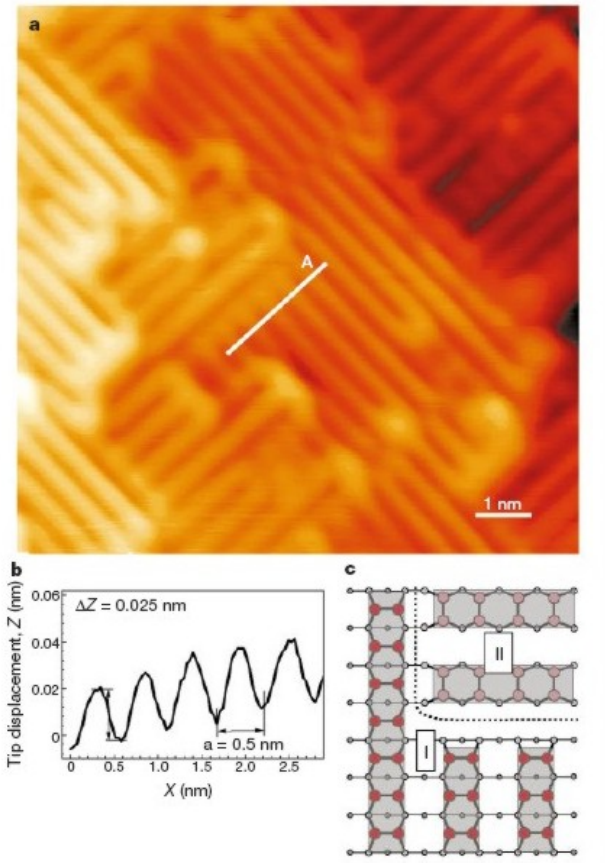
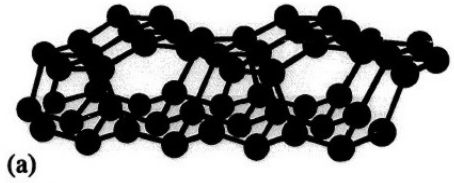


Figure 2 Clean diamond C(100)–(2×1) surface. **a**, The STM topography (10 nm × 10 nm) of the clean diamond surface recorded in the near-field emission regime (U_{bias} = 5.9 V, I = 1.1 nA). **b**, Height variation of the STM tip along the line A. **c**, Top-view of a monoatomic step on the two-domain (2×1) reconstructed surface. The coloured circles represent the carbon atoms belonging to the top four surface layers; the biggest circles represent the carbon–carbon dimers. The domains labelled as I and II represent the upper and lower terrace, respectively. The dimer rows are highlighted by shading, whereas the troughs between them are unfilled. The dashed line shows schematically the boundary between the domains.

H-free surface,
clean diamond

(2x1) reconstruction with
π-bondet dimers



K. Bobrov, G. Dujardin, et al., Nature 413, 616 (2001)

National Institute of
Advanced Industrial Science and Technology

STM topography of hydrogenated C(100)-(2x1):H

CH-dimer rows without (a) and with one defect (b)

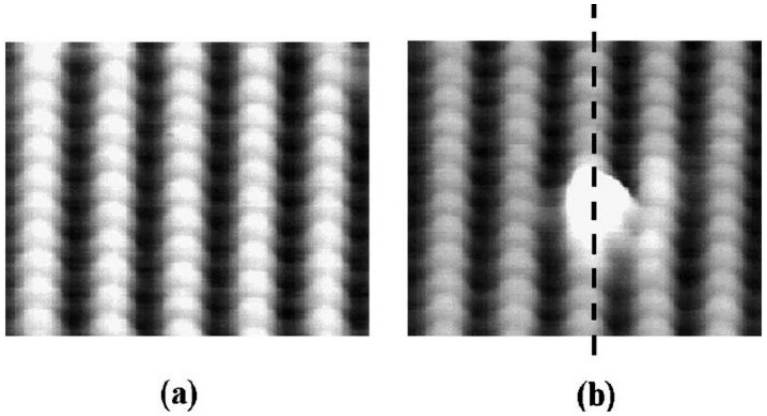


Fig. 2. Desorption of individual hydrogen atoms from the hydrogenated diamond C(1 0 0)-(2 × 1):H surface. The corresponding STM topographies (2.1 × 2.6 nm), before (a) and after (b) the desorption procedure, were recorded at $U_{bias} = -1.5$ V, $I_t = 1.0$ nA. The bright feature visible in (b) represents the dangling bonds after desorption of individual hydrogen atoms.

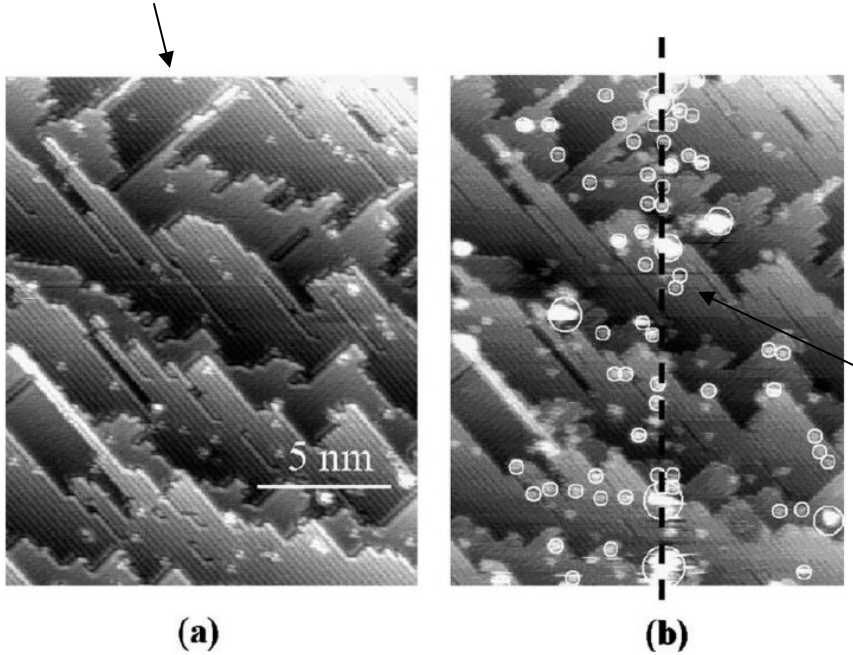
Hydrogen desorption by pulsed voltage to the STM Tip (b)

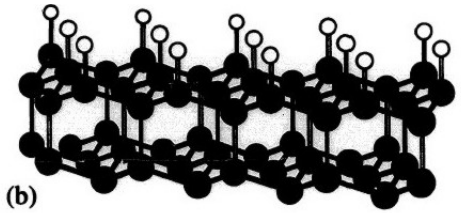
K. Bobrov , G. Dujardin, et al. Surface Science 528, p. 138 (2003)

STM topography oh hydrogenated natural C(100)-(2x1):H

H-termination has been done ex-situ at 800 ^{o}C, for 1h

a): Atomically flat surface with mono-atomic steps





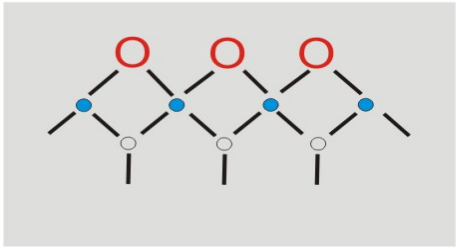
b) After desorption
of individual H by STM tip.
Circles are defects

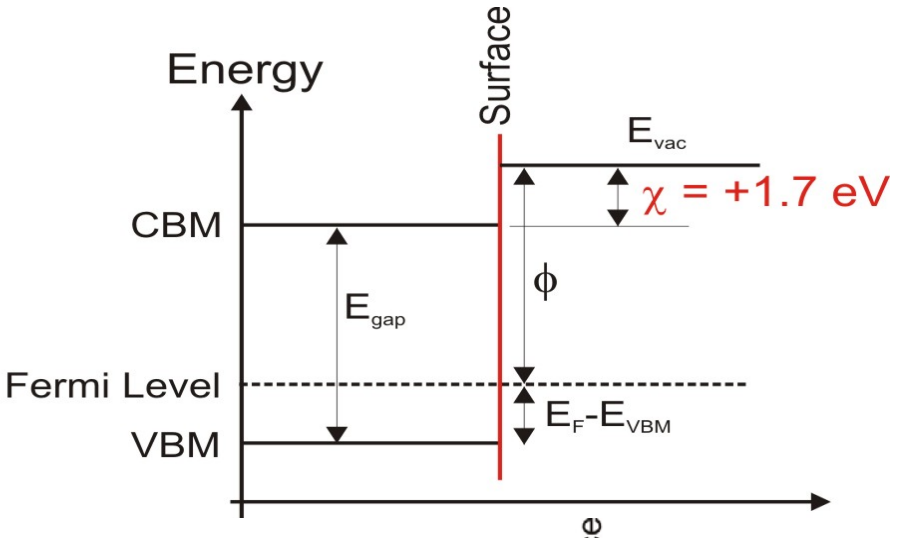
Fig. 1. Desorption of hydrogen from the hydrogenated diamond C(1 0 0)-(2 × 1):H surface. The corresponding STM topographies (15 × 19 nm) before (a) and after (b) the desorption procedure were recorded at $U_{bias} = -1.5$ V, $I_t = 1.0$ nA. The dashed line in (b) indicates the manipulation line. The bright features in (b), scattered around the dashed line and highlighted by enclosing into white circles, represent the dangling bonds after desorption of individual hydrogen atoms.

K. Bobrov, G. Dujardin, et al. Surface Science 528, p. 138 (2003)

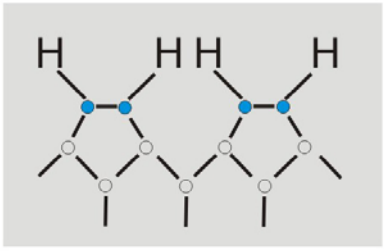
3. Electron Affinities of Diamond

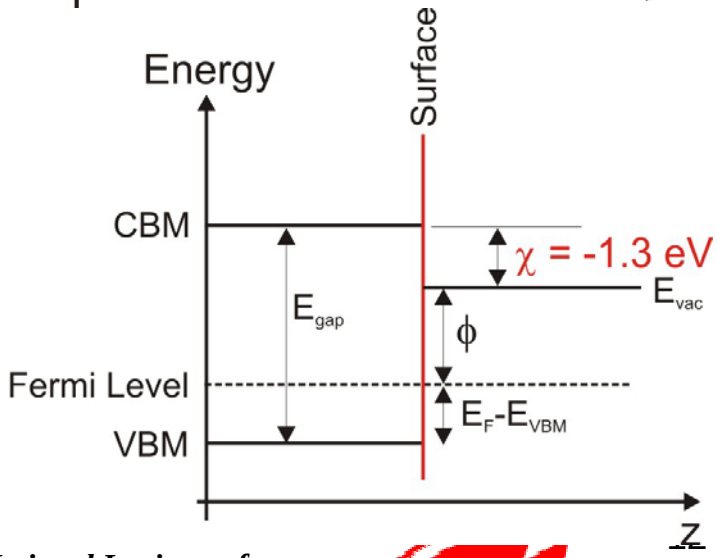
Fully Oxidized
C(100)-(1x1):O





Hydrogen Terminated
C(100)-(2x1):H





Data from:
Maier et al., Phys. Rev. B, 64, 165411 (2001)

Electron Affinities of Diamond: Mixed Surface Properties

Vacuum level variations from -1.1 to +1.7 eV (ΔE = 2.8 eV)

For partially H-terminated diamond, where is the vacuum level?

C(100)-(2x1):H

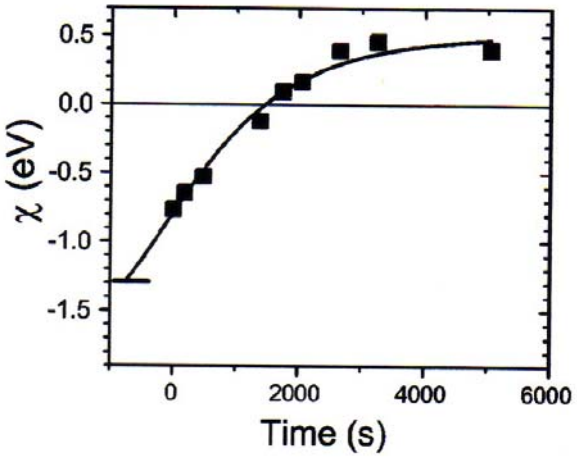


FIG. 5. Electron affinity χ versus annealing time at 1050 °C during hydrogen desorption; the solid line is a fit to the data points with a dipole moment $p_z = 0.08$ e Å and a polarizability $\alpha = 1.0 \times 10^{-30}$ Asm^2/V (see text).

C(100)-(1x1):O

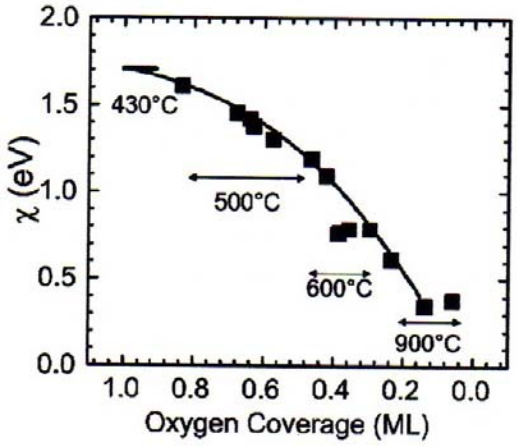


FIG. 6. Electron affinity χ versus oxygen coverage; the solid line is a fit to the data with a dipole moment $p_z = -0.10$ e Å and a polarizability $\alpha = 2.0 \times 10^{-30}$ Asm^2/V (see text).

F. Maier et al. Phys. Rev. B 64, 165411 (2001)

Electron Affinities of Diamond Surface

TABLE I. Summary of electron affinities of clean, hydrogen and oxygen covered diamond surfaces. (sc: natural single crystal type IIb; homo: homoepitaxial boron doped CVD-film; HF-H *in situ* hydrogenation via hot filament; P-H/P-O: *ex situ* plasma hydrogenation/oxidation; UHV-A: Annealing in UHV).

Diamond	Sample Preparation	χ in eV	Reference
(111)-(2×1)	sc UHV-A	≈0.5	11
	sc UHV-A	0.5	14
	sc UHV-A(1000 K)	0.38	16
	sc UHV-A	1.5	15
(111)-(1×1):H	sc HF-H	≤−0.7	11
	sc chem. oxidized, P-H	<0	14
	sc P-H	≤−0.9	15
	sc P-H	−1.27	16
(111) graphitized	sc UHV-A(1400 K)	0.80	17
(111)-(2×1)	theory	0.35	18
(111)-(1×1):H	theory	−2.03	18
(100)-(2×1)	sc UHV-A	0.75	14
	sc UHV-A	1.3	15
	sc UHV-A	0.5	this work
(100)-(2×1):H	sc P-H	≈−0.8	12
	sc HF-H	≈−0.4	13
	sc P-H	≤−1.0	15
	homo P-H	0.19	7
	sc P-H	−1.3	this work
(100)-(1×1):O	sc chem. oxidized	≈1.0−1.5	14
	homo P-O	≈0.64	7
	sc chem. oxidized	1.7	this work
(100)-(2×1)	theory	0.51	18
(100)-(2×1):H	theory	−2.05	18
(100)-(1×1): O_{ether}	theory	2.61	18
(100)-(1×1): O_{ketone}	theory	3.64	18

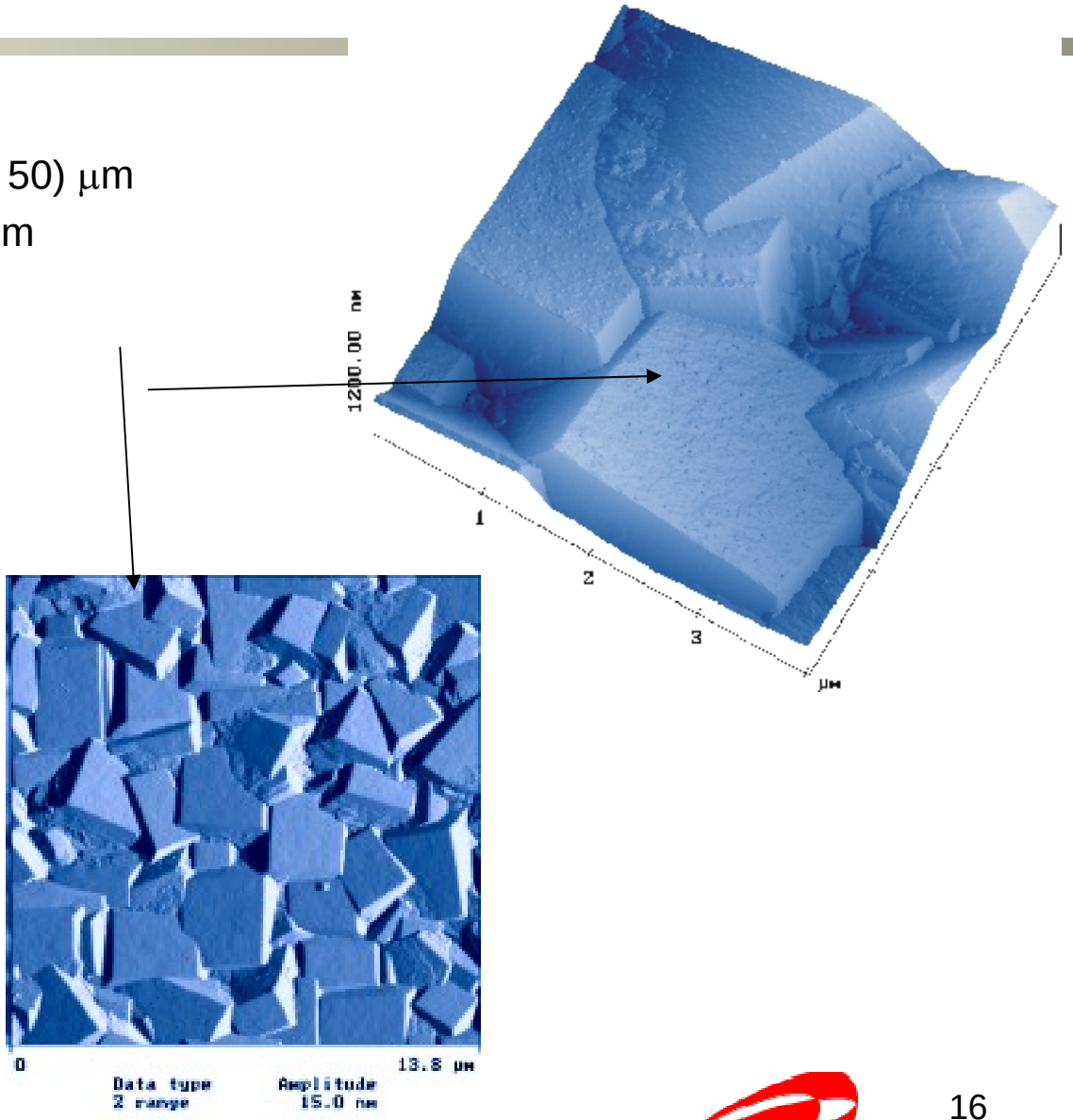
F. Maier et al., Phys. Rev. B 64, 165411 (2001)

4. Surface Geometrical Properties

Diamond Surface: Poly CVD Diamond

Crystallite roughness about: (20 – 50) μm

Roughness on planes: (10 – 20) nm

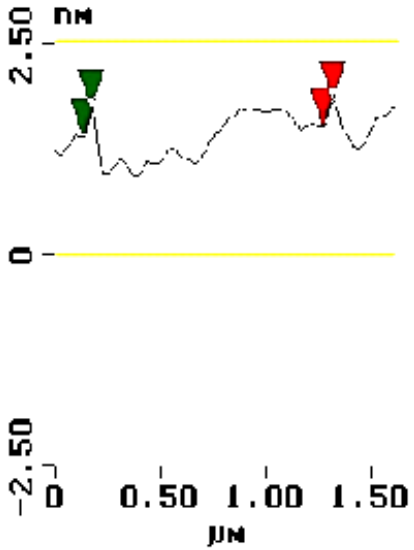


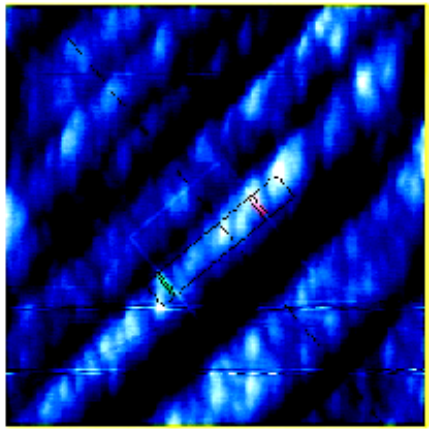
Diamond after polishing

Polishing Roughness: 8 - 15 nm

Electronic Properties are bad,
due to defects, generated by polishing !

No electronic grade interface !





Homo-epitaxial Growth of CVD Diamond (AIST)

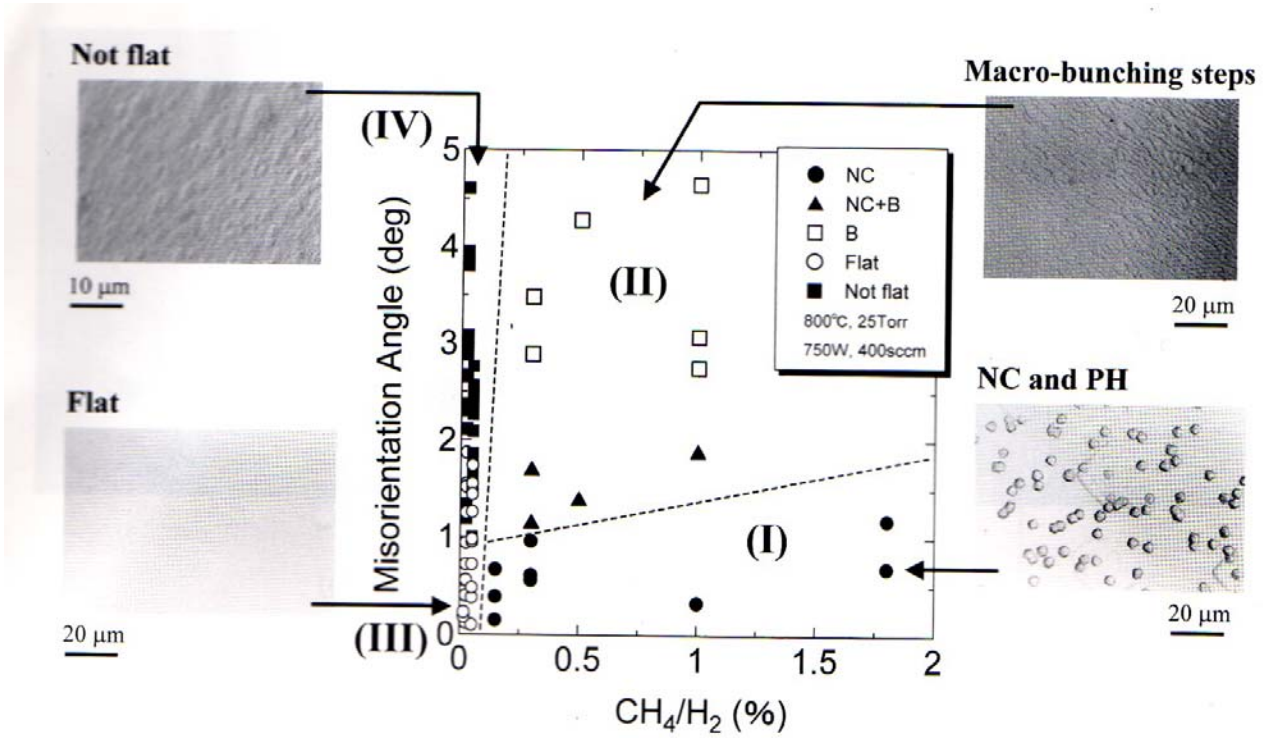


Fig. 1. Map of the surface morphology as a function of both the misorientation angle and the CH_4/H_2 ratio.[1] The dotted lines in the figure serve as a guide to the eye and are used to divide the area into four regions I–IV. A detailed explanation is given in the text.

H. Watanabe et al., New Diamond and Frontier Carbon Technology, 12, 369 (2002)

Homo-epitaxial Growth of CVD Diamond (AIST)

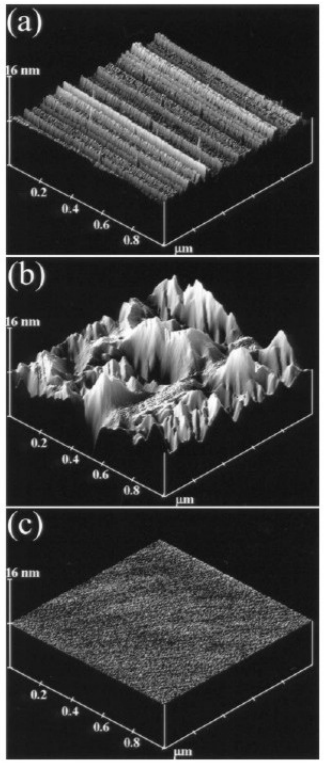


Fig. 3. AFM top view images of (a) surface of as-received Ib (001) substrate, (b) surface treated by the H-plasma (i.e. 0% CH_4 concentration) for 6 h, and (c) growth surface at 0.025% CH_4 concentration for 42 h.

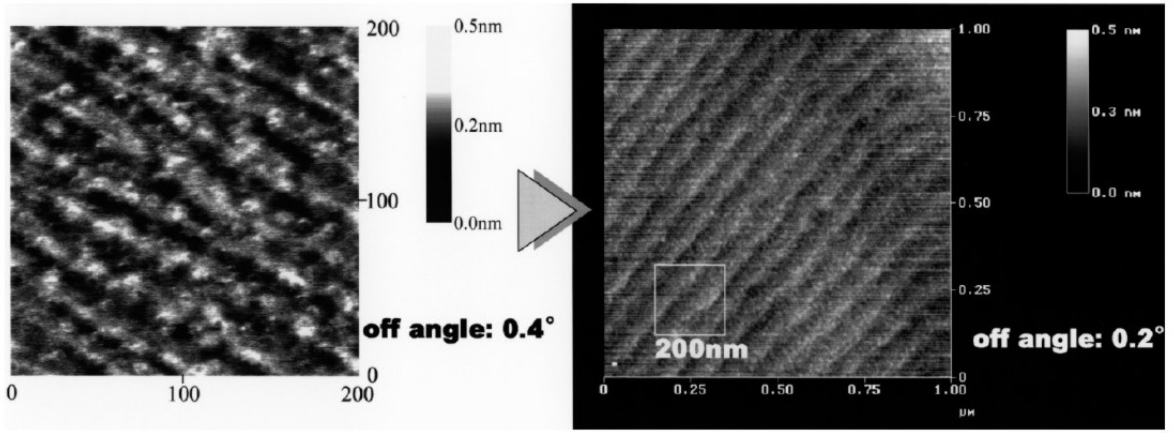


Fig. 2. Typical surface morphologies of the homoepitaxial diamond film in region III in Fig. 1. (a) a top-view AFM image (200 nm × 200 nm × 0.5 nm) the surface morphology for the misorientation angle of 0.4° at 0.025% CH_4/H_2 ratio for 42 h deposition, and (b) a top-view AFM image (1 μm × 1 μm × 0.5 nm) for the misorientation angle of 0.2° at 0.025% CH_4/H_2 ratio for 6 h deposition.

Atomically flat surface with step-etch growth.
Terraces run parallel to the (110) direction

H.Okushi, Diam. Rel. Mat. 10, 281 (2001)

Bulk Properties of Homo-epitaxial CVD Diamond

Near band-edge cathodo-luminescence at 300 K.

Free exciton emission lines at:
235 nm (5.27 eV)
and
242 nm (5.12 eV)

High bulk electronic property indication!

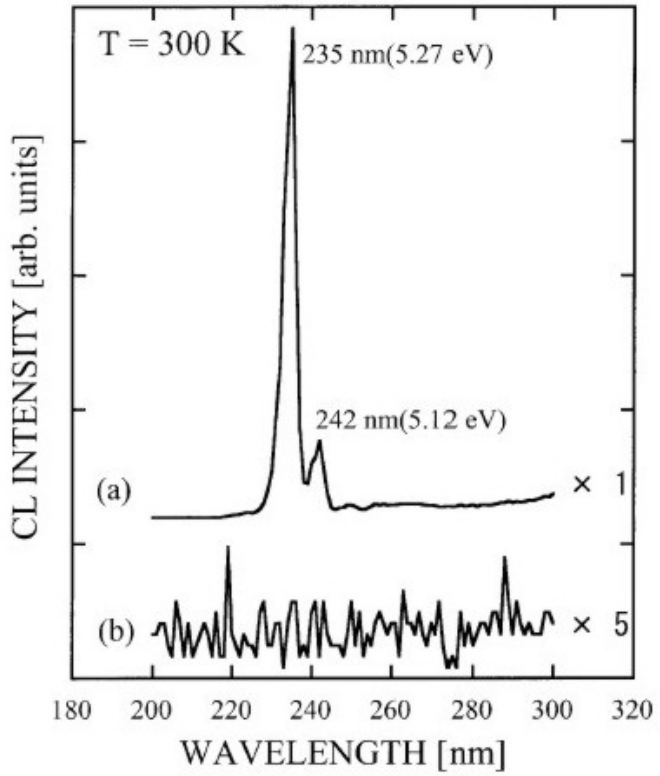


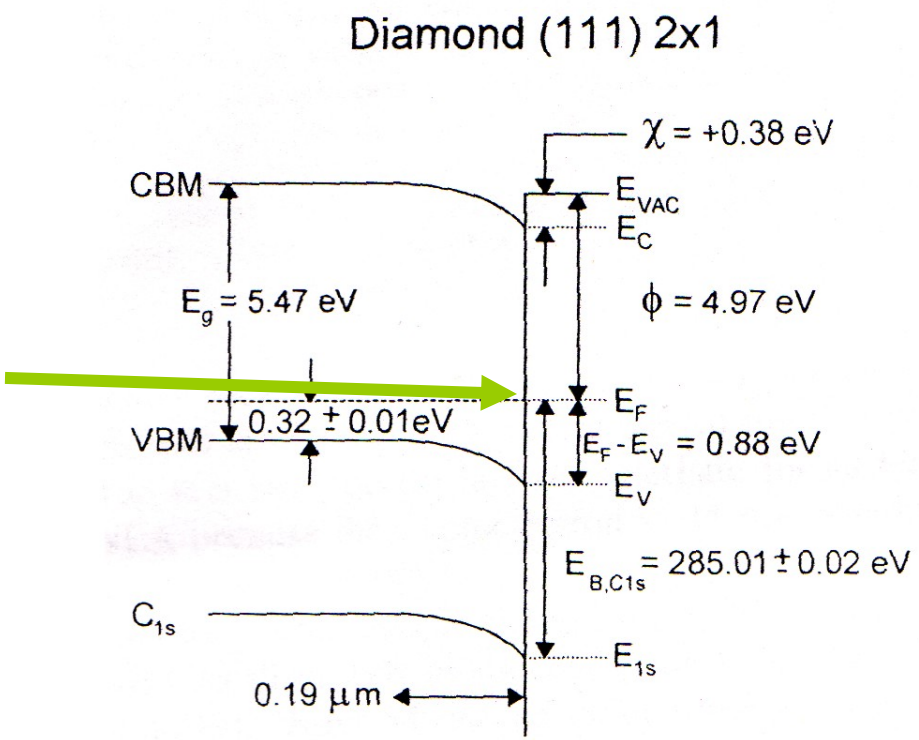
Fig. 3. Near-band-edge CL spectra at room temperature, where (a): the spectrum for the diamond film and (b): the Ib diamond substrate [8].

5. Surface Defects of clean, O and H terminated diamond

Surface Fermi Level on (111)-(2x1) reconstructed Diamond

Photoelectron yield and core level photoemission spectroscopy

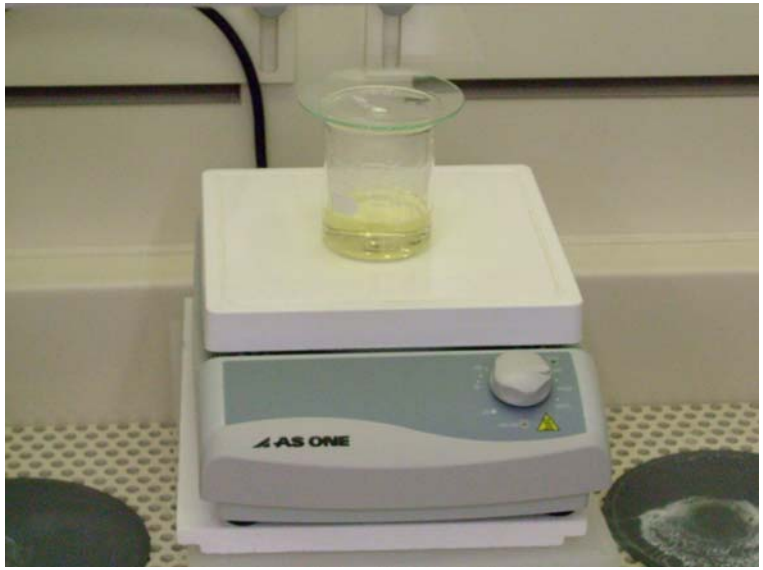
Surface defects



J.B. Cui et al. Phys. Rev. Lett. 81, 429 (1998)

Oxidation

Wet-Chemical Oxidation



Oxygen Coverage (111) by XPS:
ca 50 %

Boiling in:
HNO_3:H_2SO_4 = 1:3
at 230 ^oC
for 1 h

Properties:

- insulating surface
- hydrophilic
- removement of graphitic layers (at grain boundaries)
- Fermi-level pinning at the surface due to defects?

Surface defect density of O-terminated diamond surface

Before SiO_2-deposition

1) plasma-ashed in 2% O_2 in He
2) cleaned at 200 ^oC in solution of $(NH_4)_2S_2O_8$ and H_2SO_4

SiO_2 Deposition:

atmospheric pressure CVD using SiH_4, Ar, N_2 and O_2
T= 625 ^oC on (100) diamond

Surprisingly good interface !

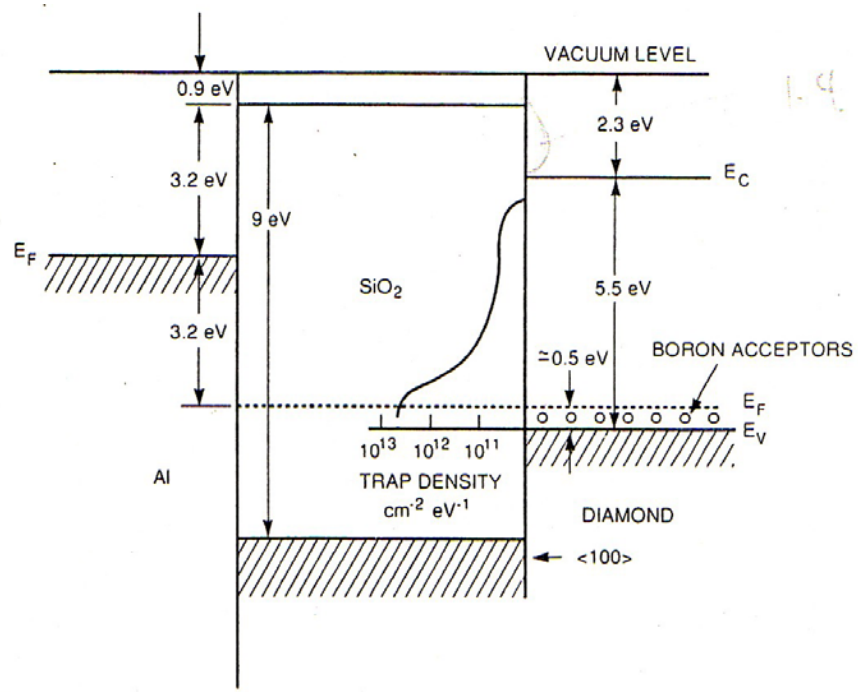


Fig. 8. Energy diagram of metal–SiO_2–diamond structure for (100)-oriented substrate. E_C is the minimum energy of electrons in the conduction band, E_v is the maximum energy of electrons in the valence band, and E_F is the Fermi energy level. A lower estimate of the positive interface trap level density is plotted versus energy (the energy axis coincides with the SiO_2–diamond interface).

M.W. Geis et al. IEEE Trans. Electron Dev. 38, 619 (1991)

SiO_2 – Silicon Interface Quality

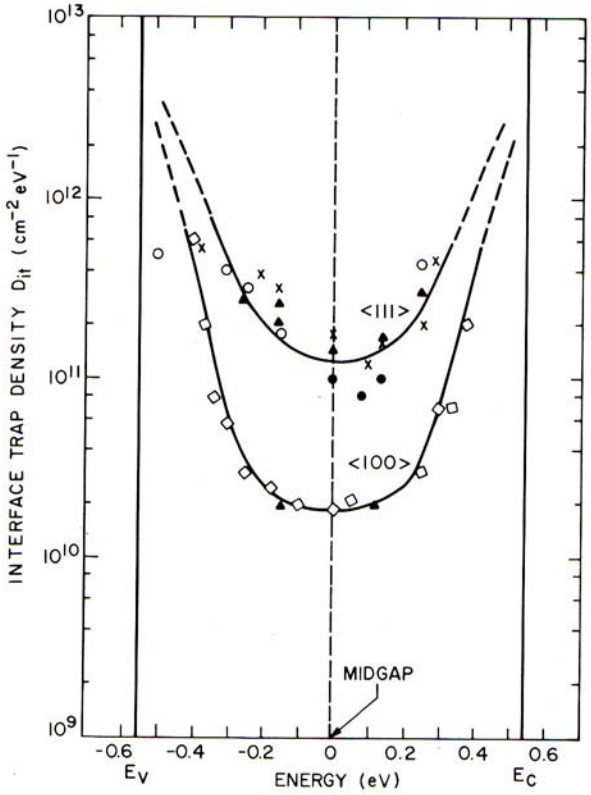
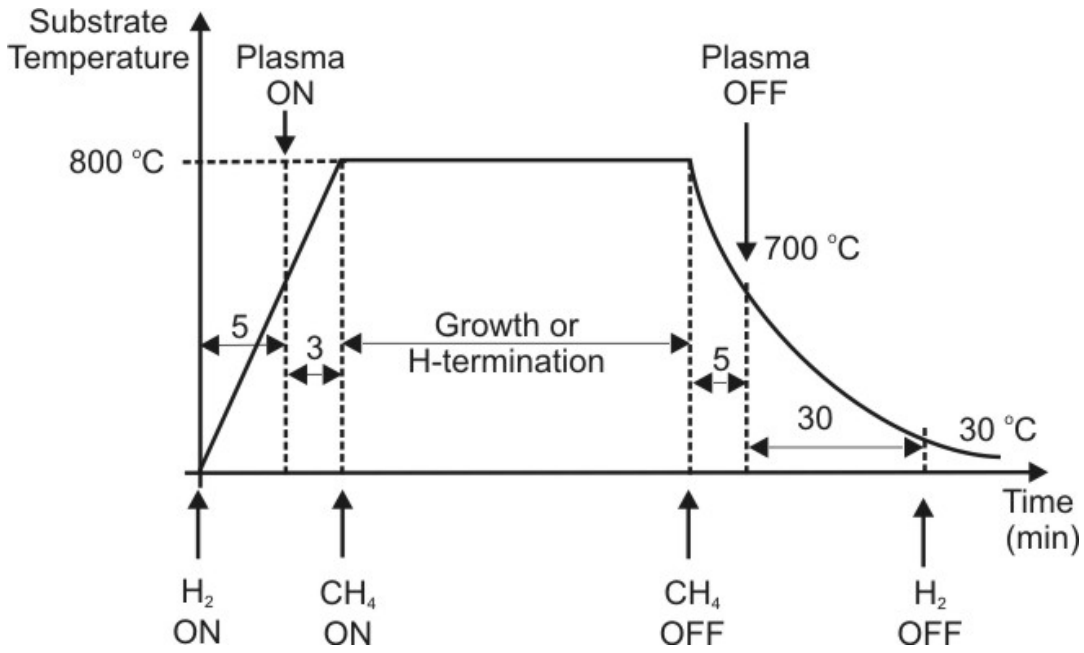


Fig. 19 Interface-trap density in thermally oxidized silicon. (After White and Cricchi, Ref. 27.)

Sze, in “Physics of Semiconductor Devices”

Hydrogen Termination

H-termination



H-termination parameter

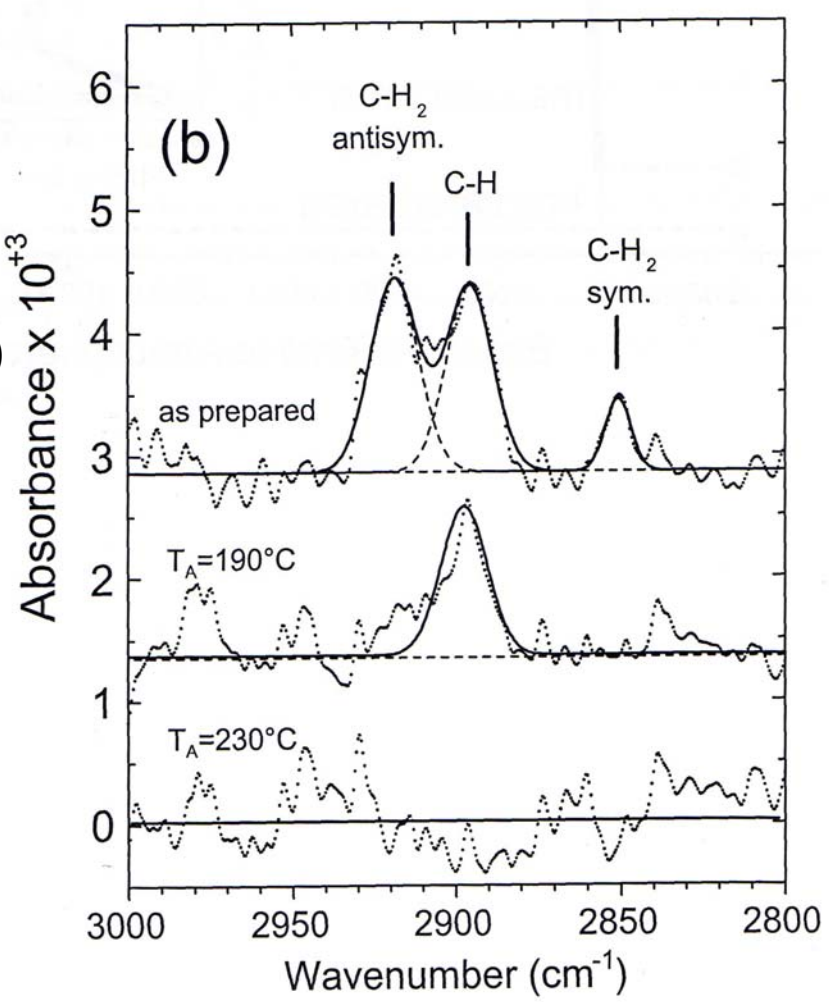
sample		d01
date		*8.6.04*
stage temperature	[°C]	800
microwave power	[W]	750
total gas pressure	[Torr]	25
total H2 flow	[sccm]	400
total CH4 flow	[sccm]	0
exposure time	[min]	5
plasma off at	[°C]	700

IR-Properties (characterized in air)

Annealing in air:

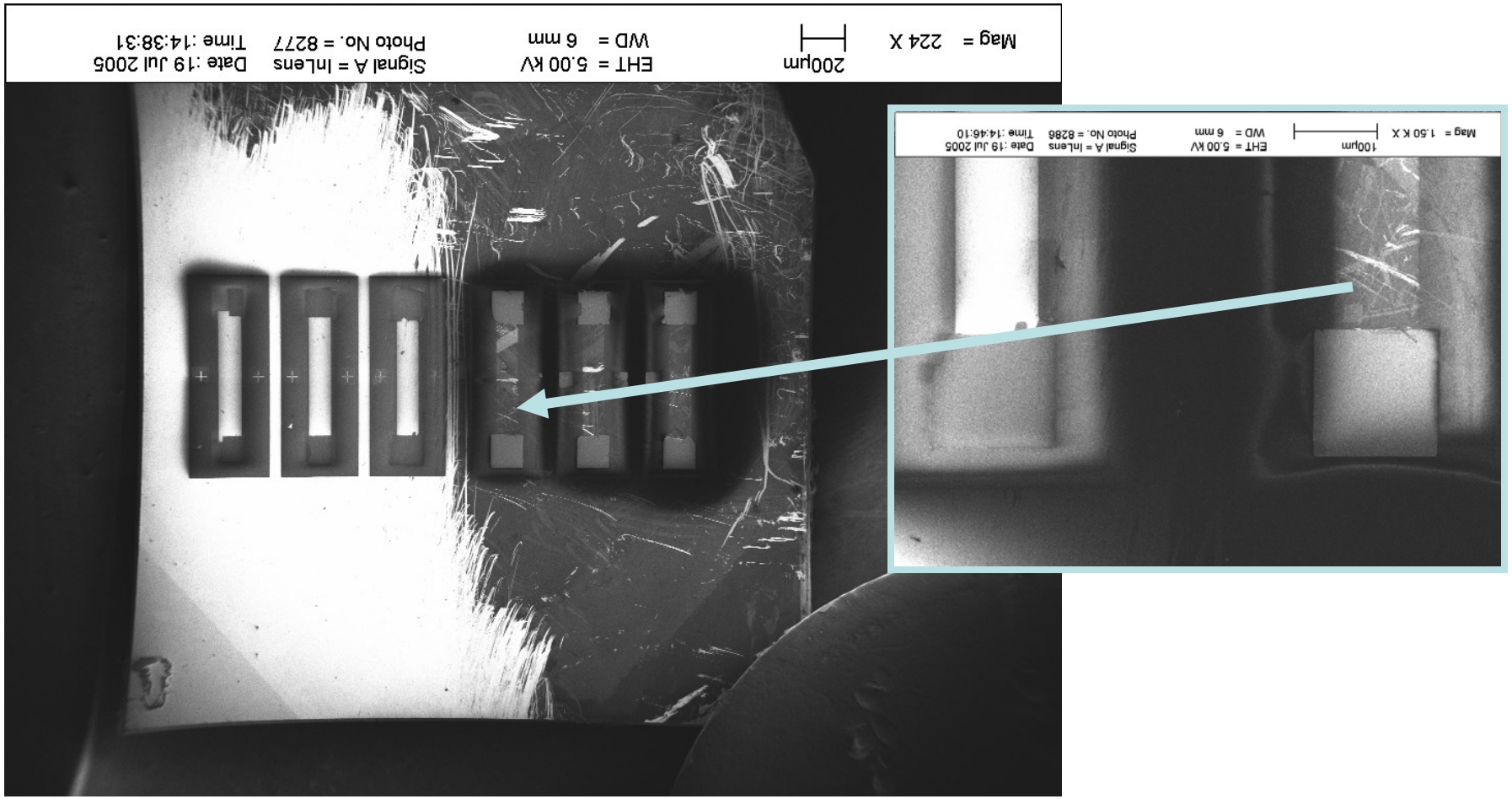
CH peak at 2896 cm^{-1} (stretching mode) of (100)-(2x1):H surface

Symmetric (2851 cm^{-1}) and antisymmetric (2920 cm^{-1}) stretching modes of CH_2 groups of physisorbed n-alkanes.



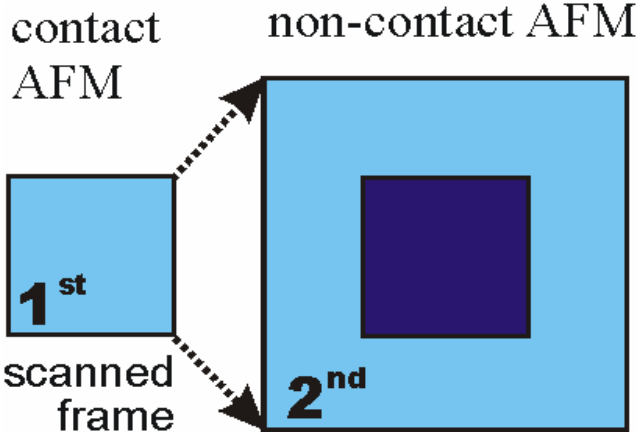
F. Maier et al. Phys. Rev. Let. 85, 3472 (2000)

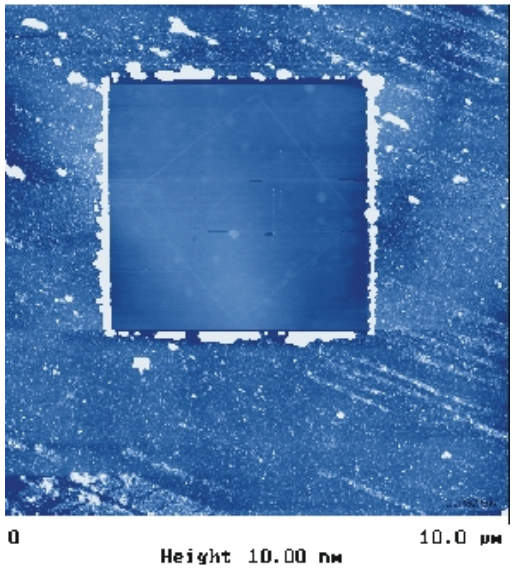
SEM image of Bar-Contact structures



partially wiped
in ethanol

Cleaning by contact mode AFM





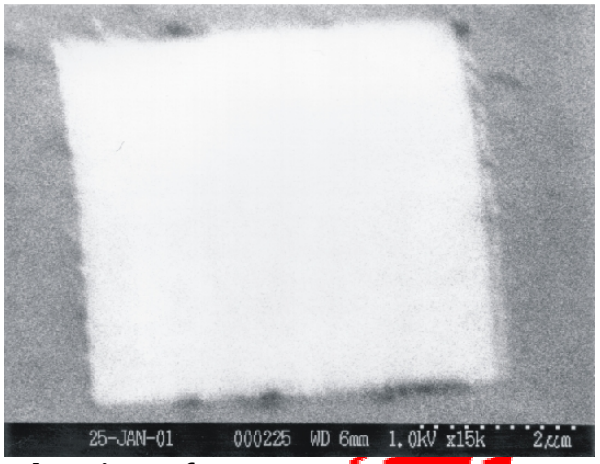
Surface is covered with a thin

(1 -10) nm thick adhesive layer.

Removal Force: 1mN/100 nm^2

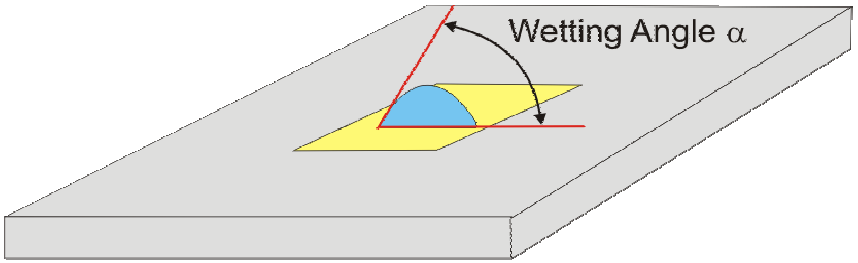
Non-conductive layer !

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



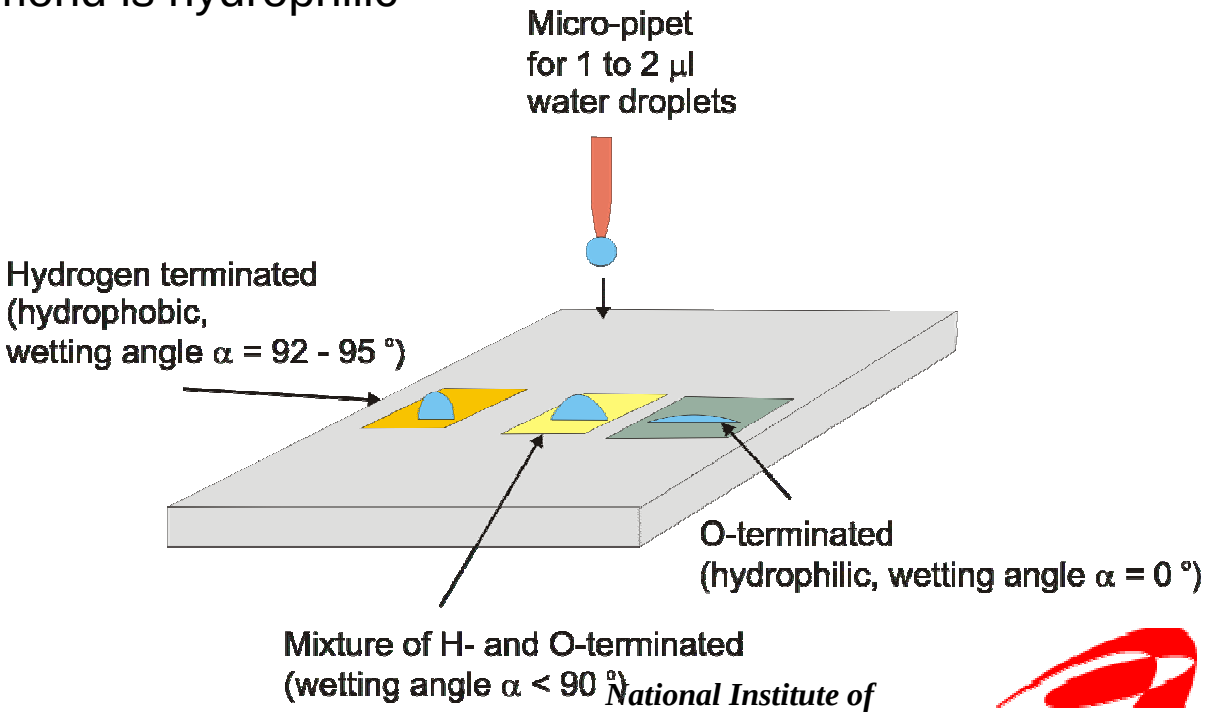
National Institute of
Advanced Industrial Science and Technology

Wetting Angle Experiments on H-terminated diamond



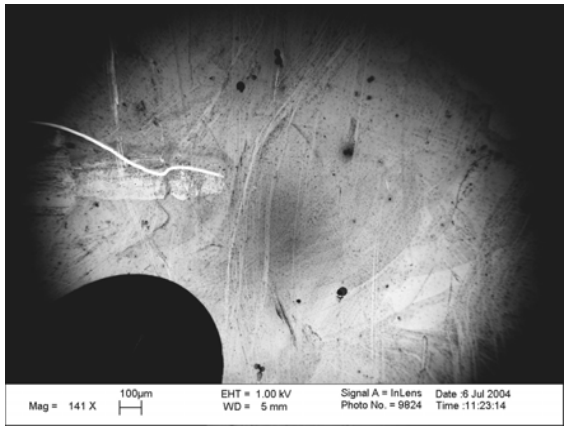
H-terminated diamond is hydrophobic

Oxidized diamond is hydrophilic

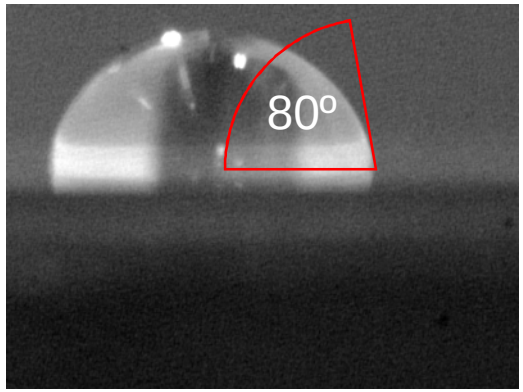


H-term. CVD diamond

After hydrogen plasma treatment:



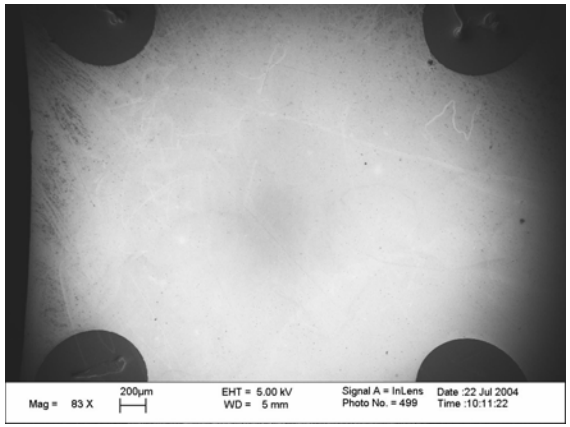
SEM

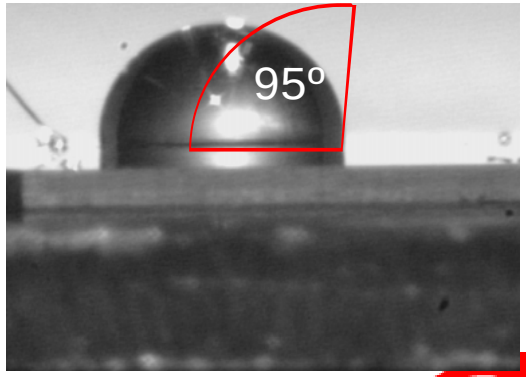


wetting angle (1ul droplet)

80°

After mechanical cleaning in Ethanol:



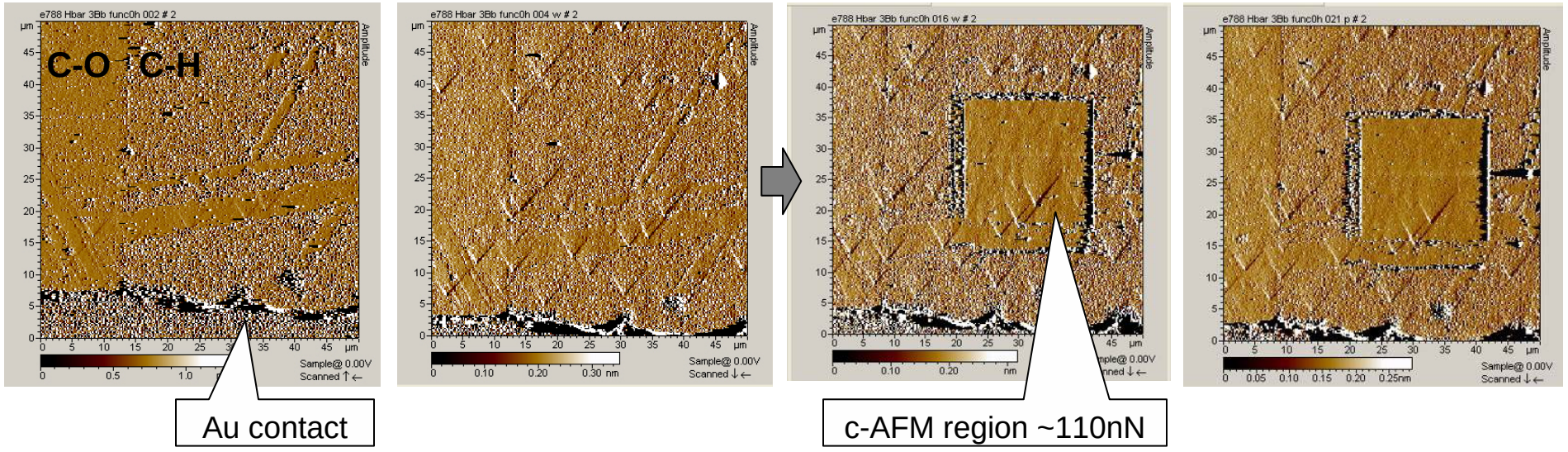


95°

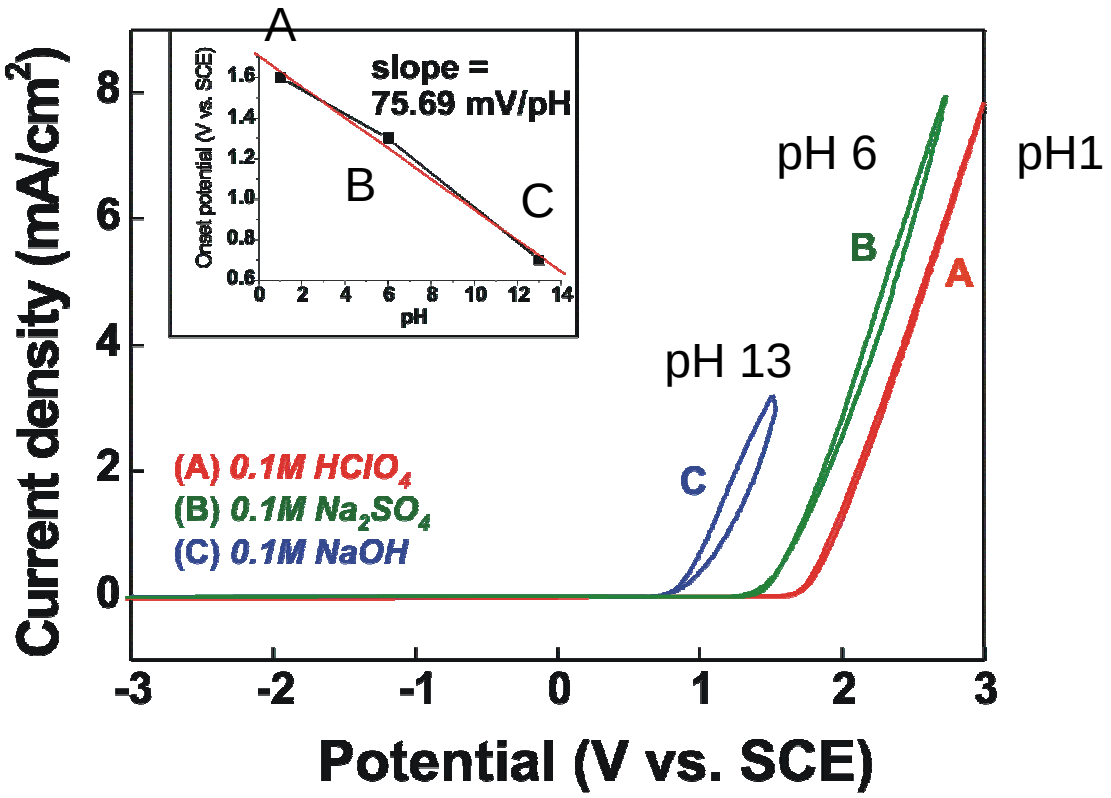
National Institute of
Advanced Industrial Science and Technology

AFM – carbon deposit in air and liquids (e788)

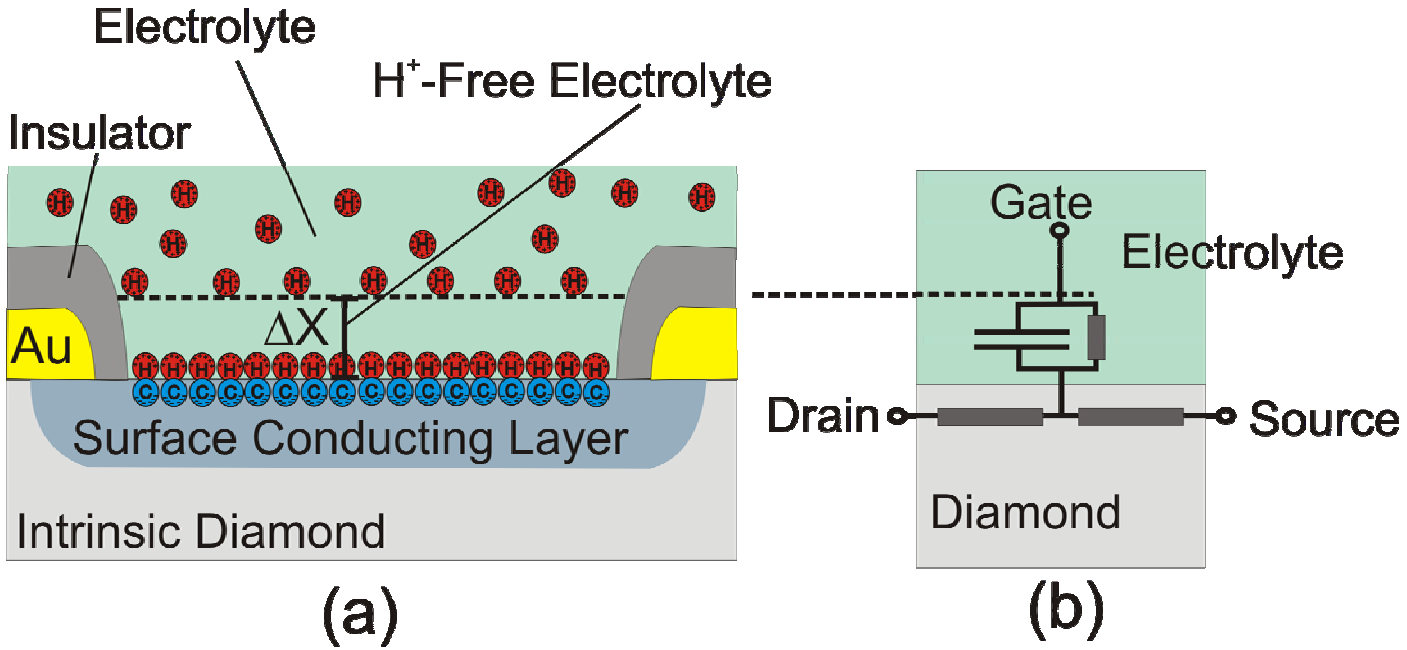
in air | in water | in water | in isopropanol



pH sensitivity of Intrinsic Diamond: Oxygen Evolution



pH Sensitivity of Intrinsic Diamond: Virtual Gate-Insulator



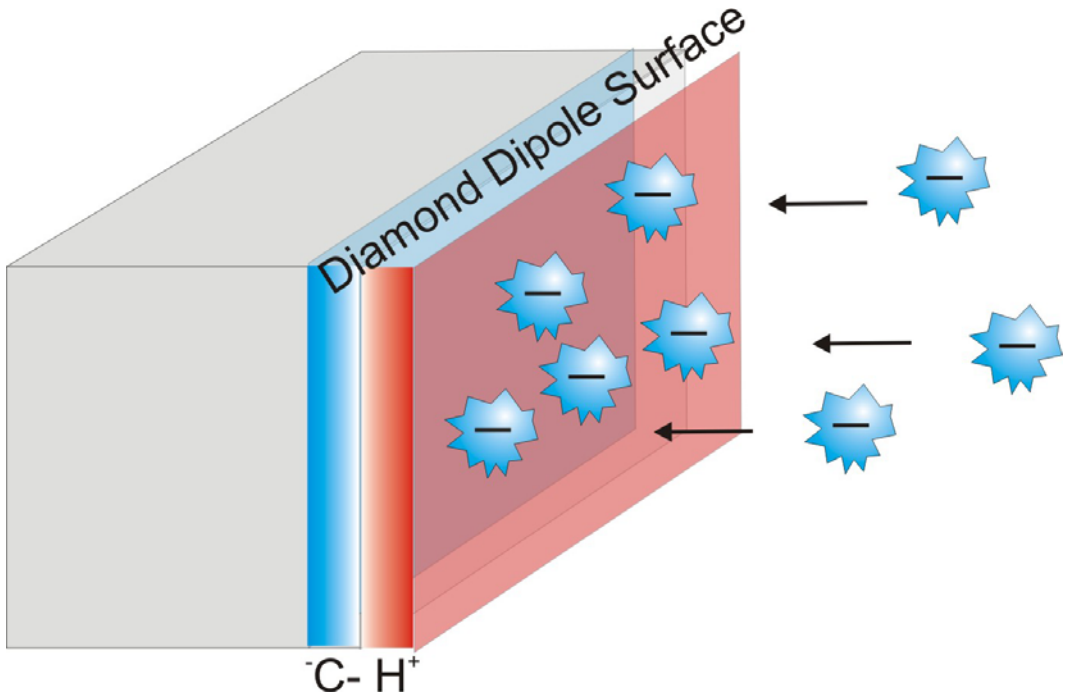
Electrostatic Attraction of Ionized Nano-Particles

Accumulation of charged particles on the surface, in the water adsorbate?

Due to electrostatic force,
only small particles will be attached

•CH Dipole

•CO Dipole



6. Fermi-level determination by Kelvin Force Experiments

Current detection

$$I = \frac{dQ}{dt} = \frac{1}{dt}\left\{C\left[-(\phi_1 - \phi_2) + U_{comp}\right]\right\}$$

For I = 0

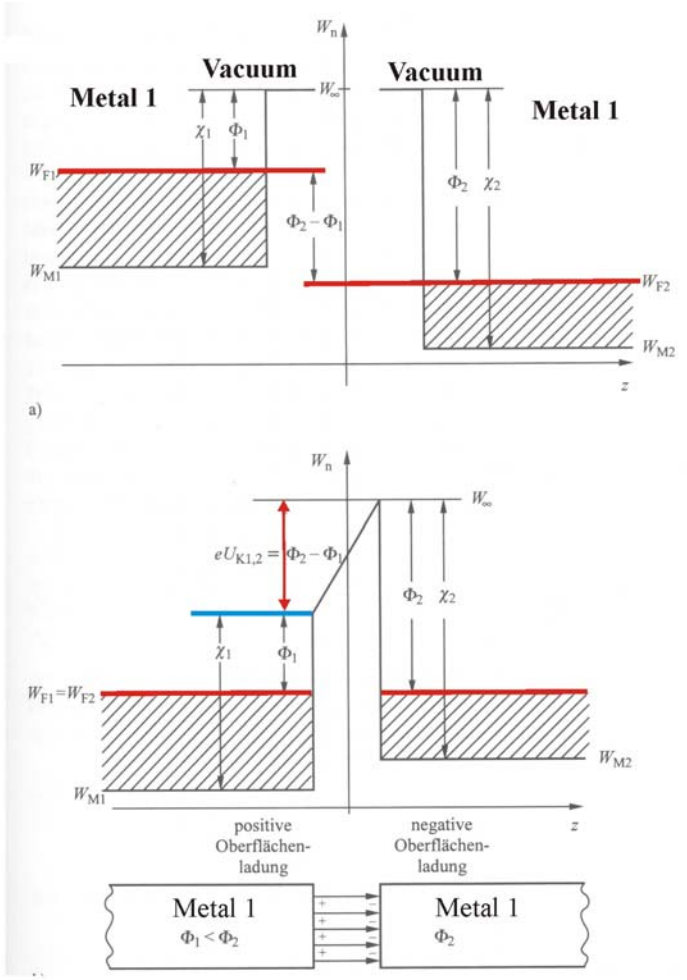
$$\phi_1 - \phi_2 = U_{comp}$$

Kelvin Force Microscopy:

$$F_z = \frac{1}{2}\frac{dC}{dz}U^2$$

$$F_\omega = \frac{dC}{dz}\left[-(\phi_1 - \phi_2) + U_{comp}\right] = 0$$

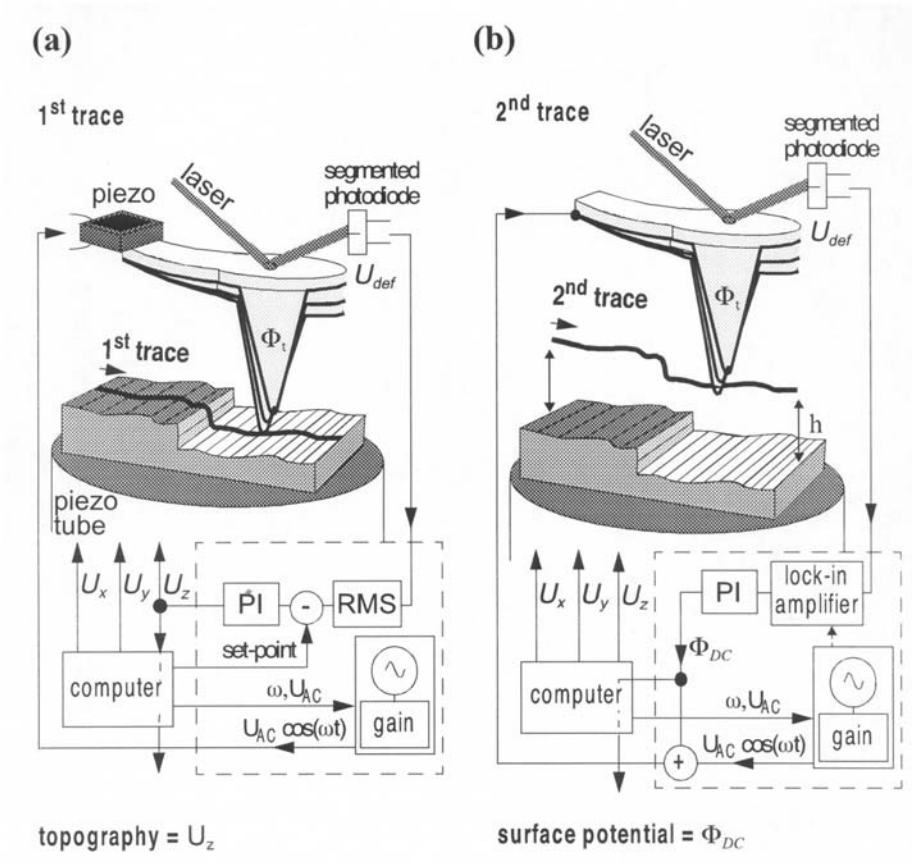
$$\phi_1 - \phi_2 = U_{comp}$$



Kelvin-Force Microscopy:

Kelvin Probe Microscopy **Cantilever: PtIr5/Cr**
Si (n-type)

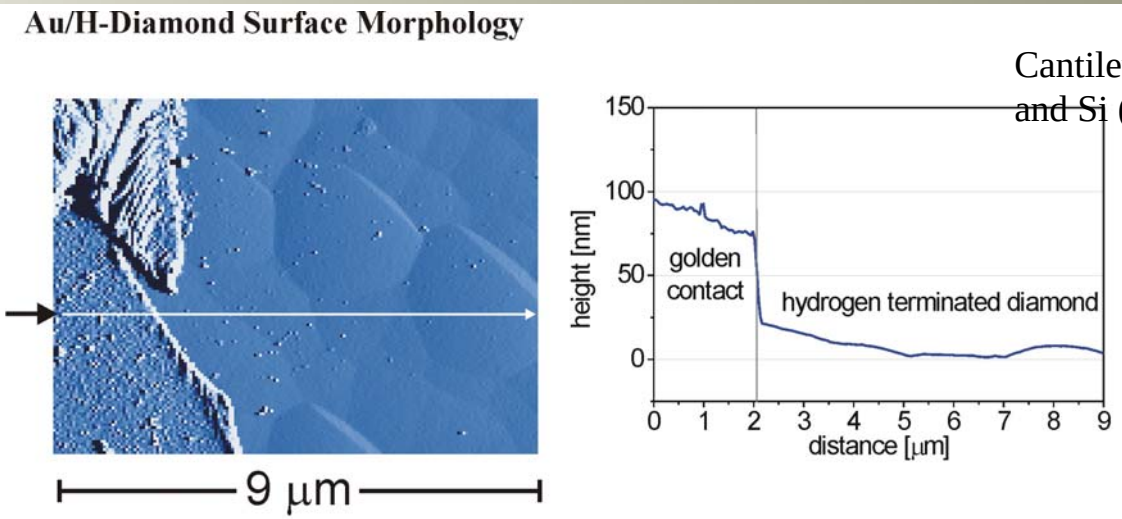
A) Topography **B) Surface Potential**



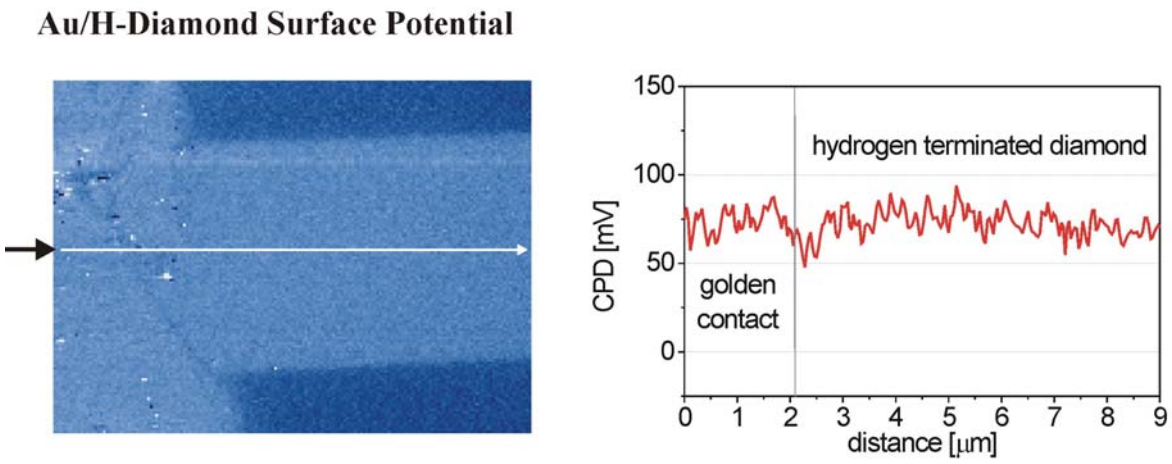
Kelvin Force Microscopy on Hydrogen Terminated Diamond

Cantilever: PtIr5/Cr and Si (n-type)

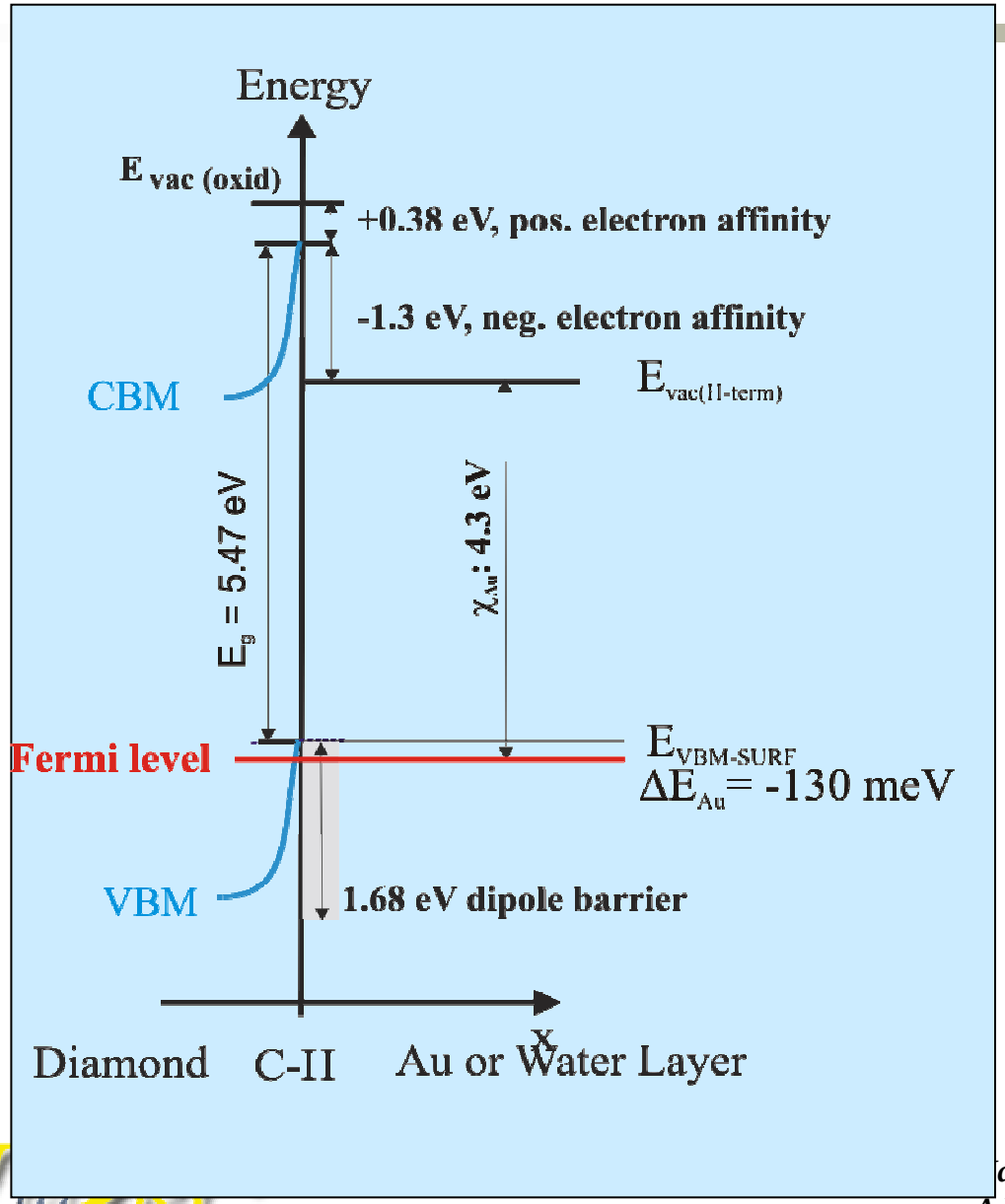
Topography



Surface Potential



Surface Energy Diagram of H-Terminated Diamond



Work-function of Au:

a) Photoyield Experiments

(new from D. Takeuchi):

4.3 (+/-0.1 eV)

b) Textbook data:

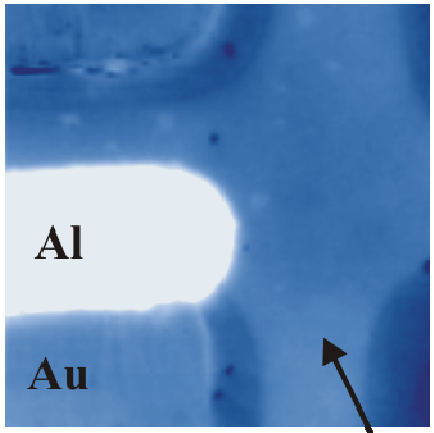
4.9 - 5.14 eV

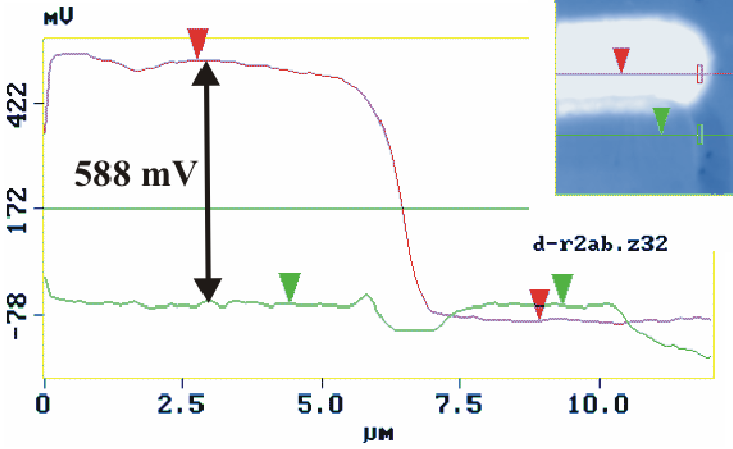
Fermi Level:

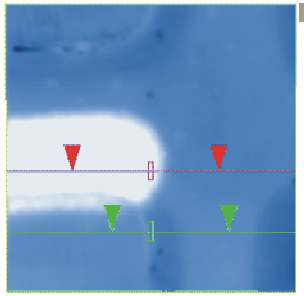
0.13 eV

in the Valence Band !!!!!!

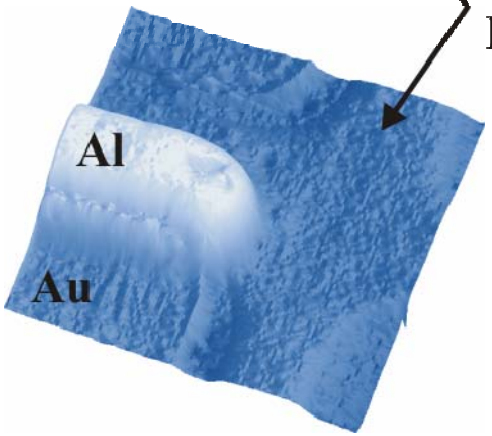
KFM on Al / Au / H-Terminated Diamond







H-Terminated Diamond



Electron Affinities:

Al: $\Phi_{Al} = 4.3$ eV

Au: $\Phi_{au} = 5.1$ eV

$\Delta\Phi = 0.8$ eV

(Sze, in Physics of Semiconductor Devices, Wiley)

Work-function difference: Al / Au or Al / H-Term-Diamond: 590 meV

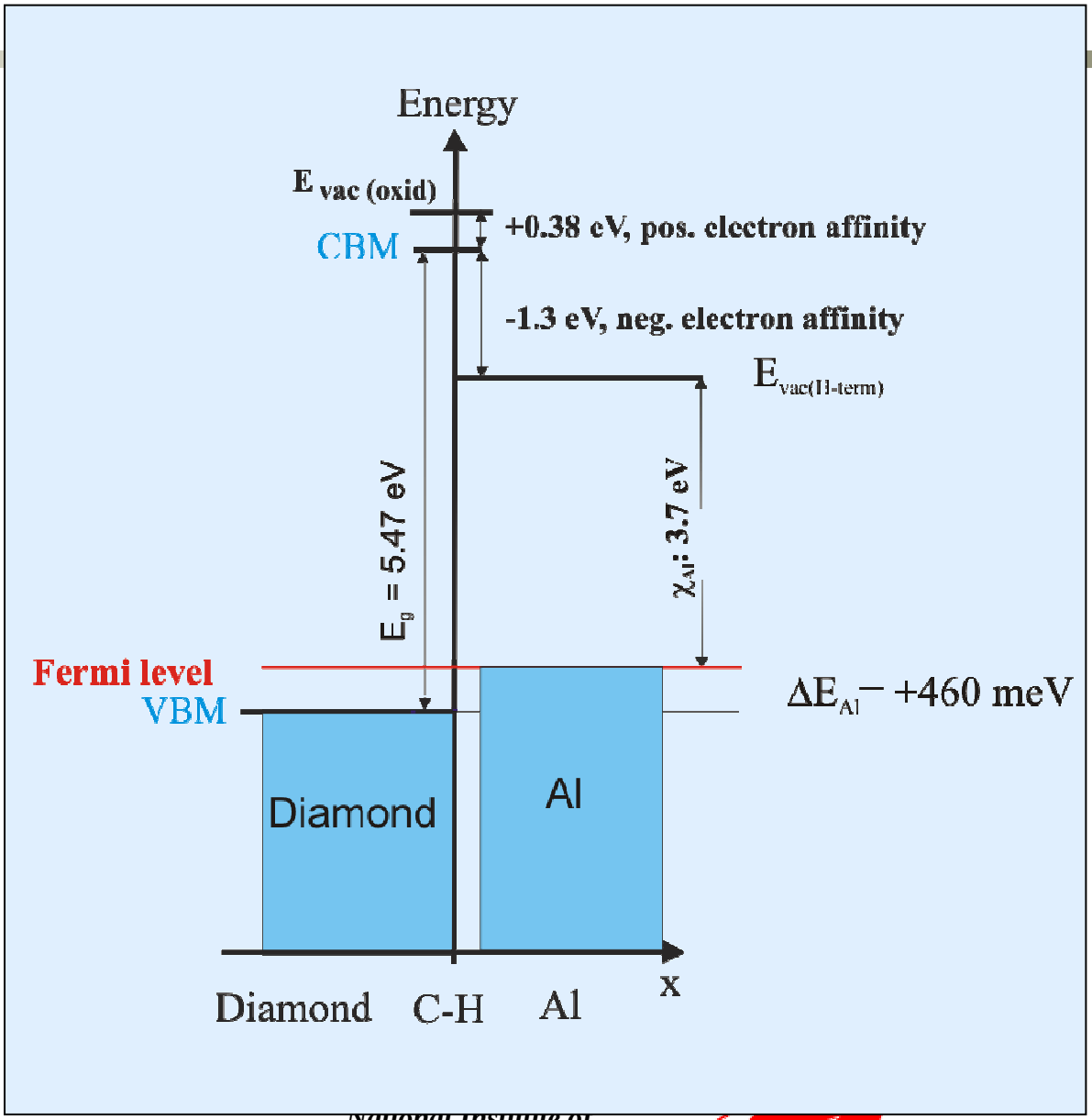
Al on H-Terminated Diamond

For Al the Fermi–Level is:

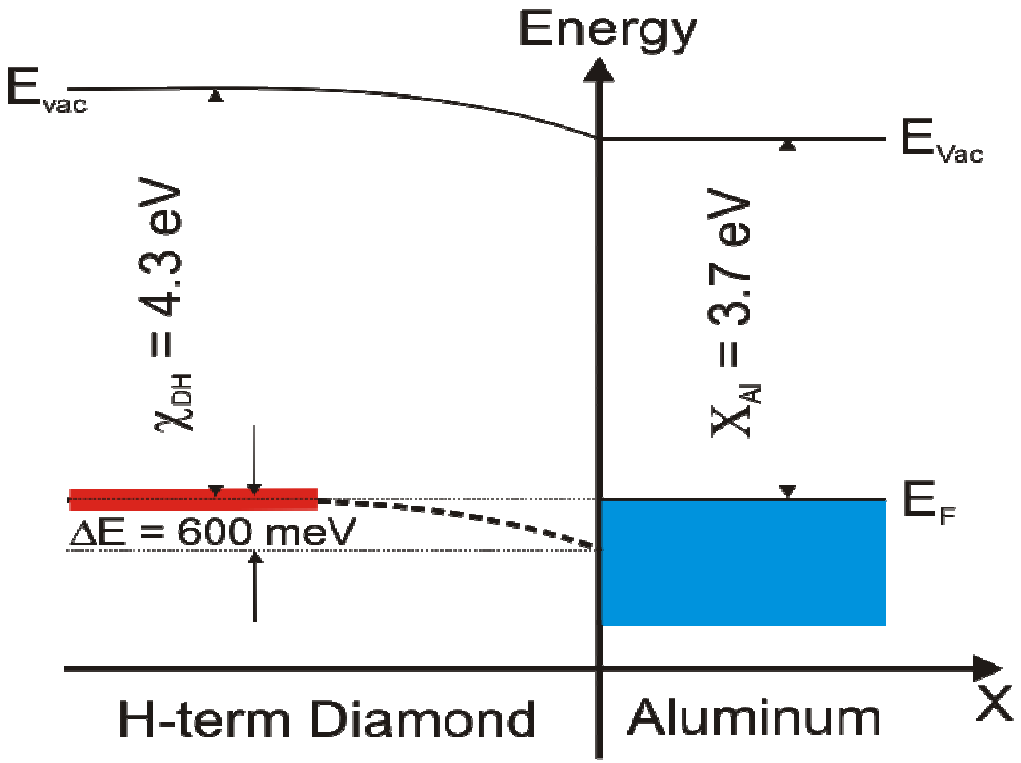
0.47 eV

above the Valence Band Maximum

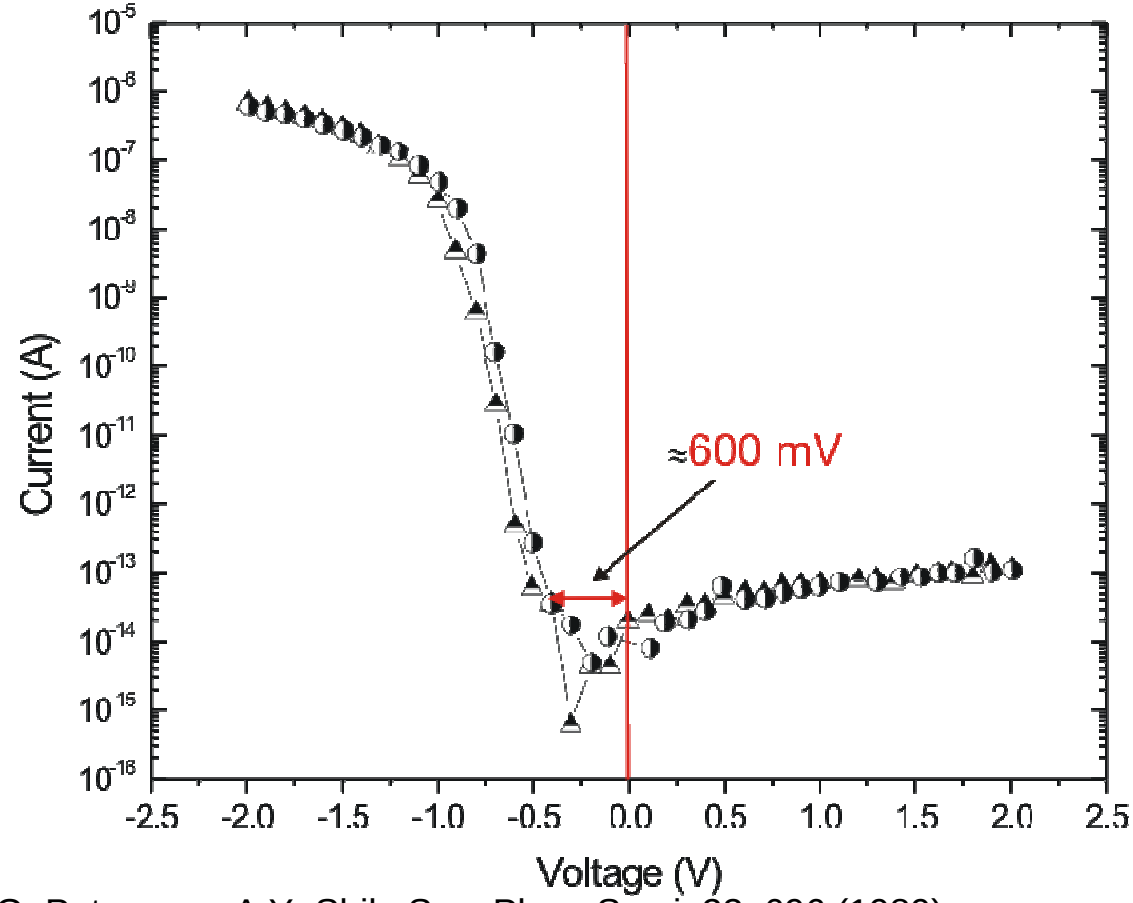
No Hole Accumulation Layer



2D Aluminum-Schottky Junction to H-terminated diamond



IU on Al-Schottky Junctions on H-term Diamond



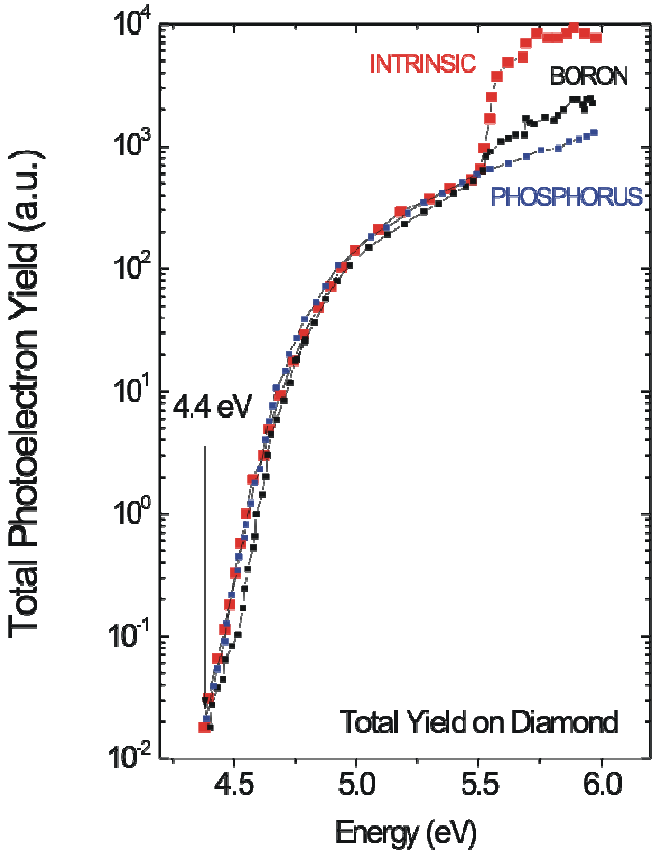
2D-contact properties:

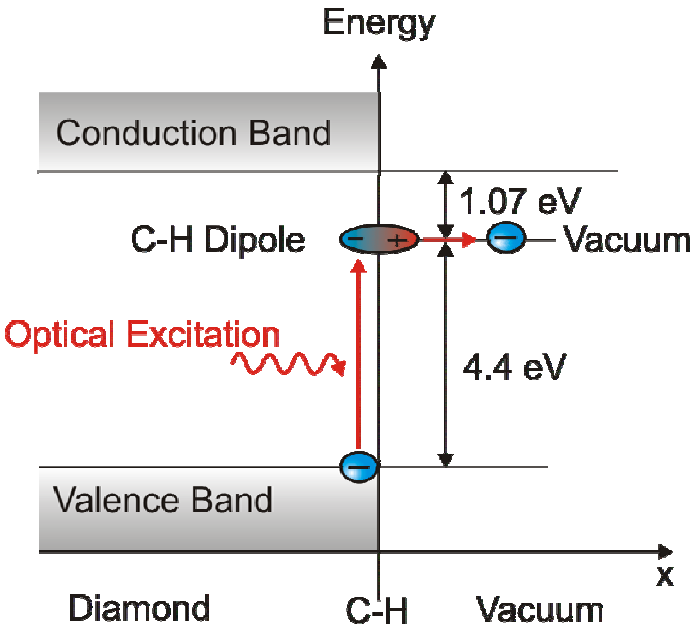
$$j \approx j_{rev}\left[\exp\left(\frac{eU}{kT}\right)-1\right]$$

S.G. Petrosyan, A.Y. Shik, Sov. Phys. Semi. 23, 696 (1989)

7. Surface electronic properties

Secondary Photoelectron Emission Spectra on intrinsic (100), n- (111) and p- (111) type diamond

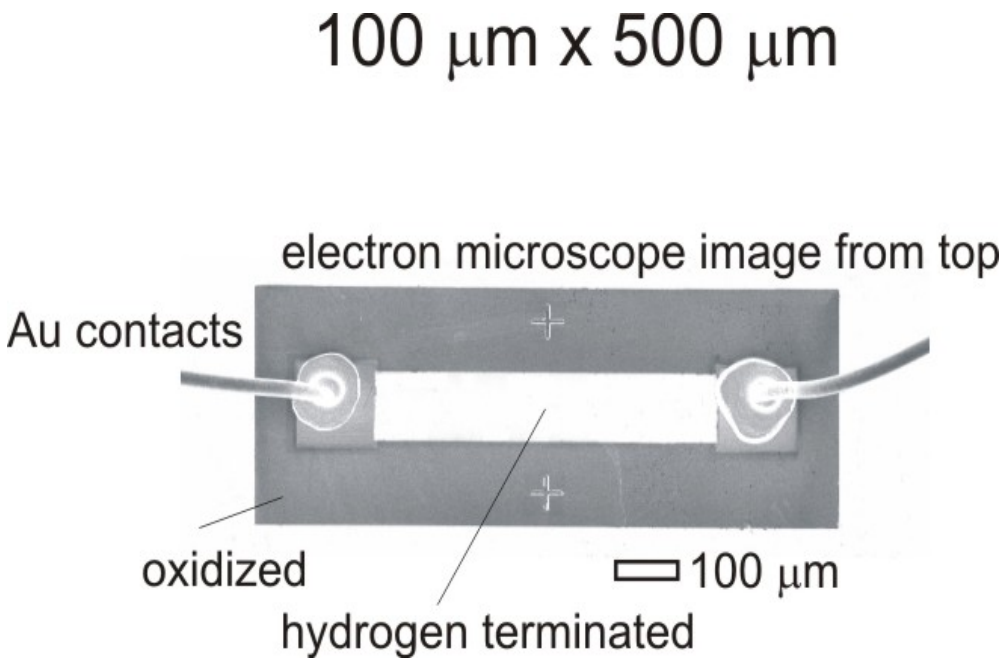




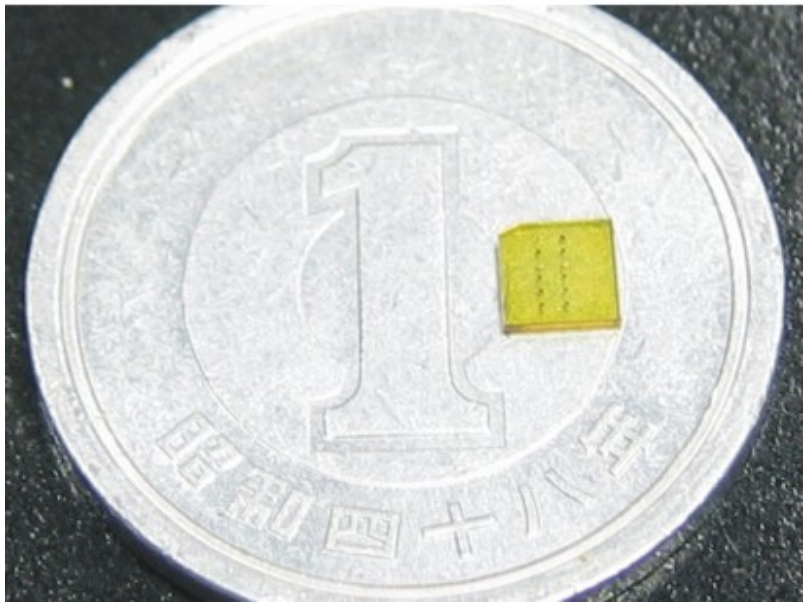
Negative electron affinity: $\chi = E_g - E_{th} = 5.47\ eV - 4.4\ eV = -1.07\ eV$

Spectrally Resolved Photoconductivity (SPC)

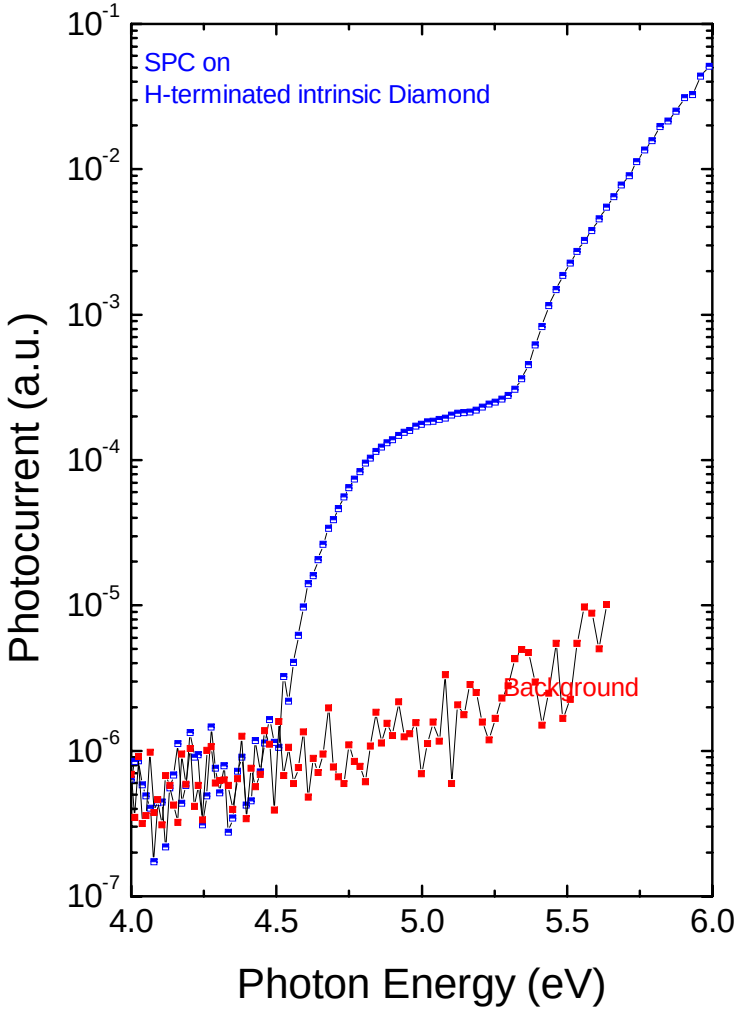
Contact Arrangement



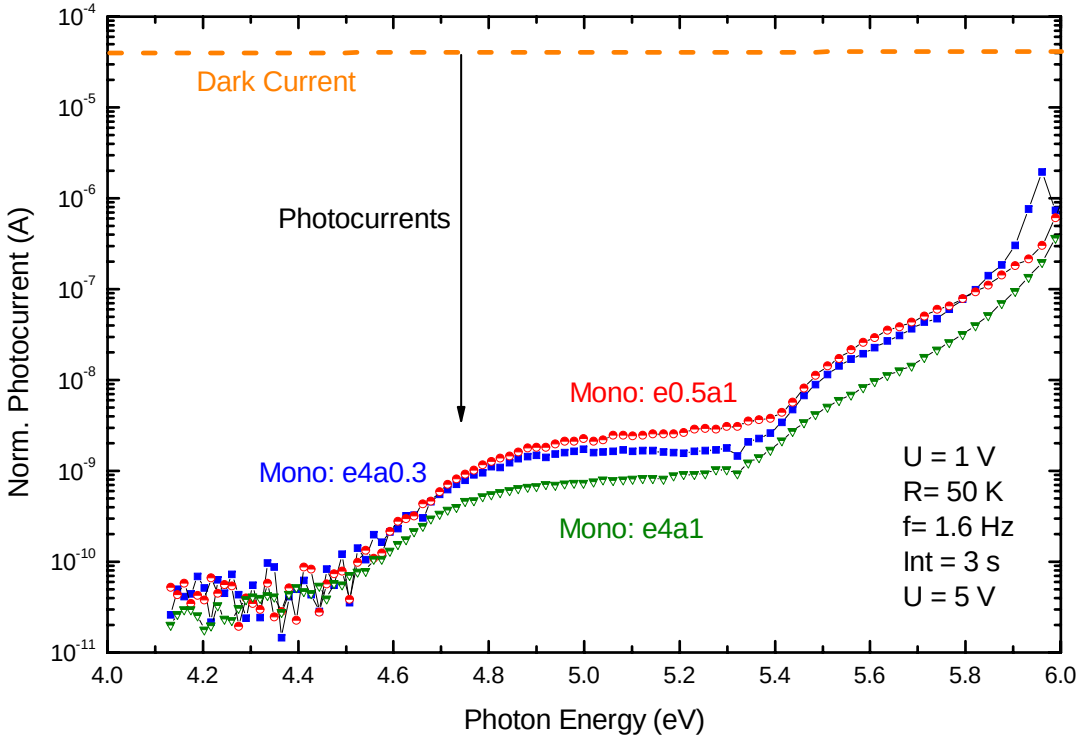
Contact Size for SPC:



Typical SPC on H-terminated Diamond

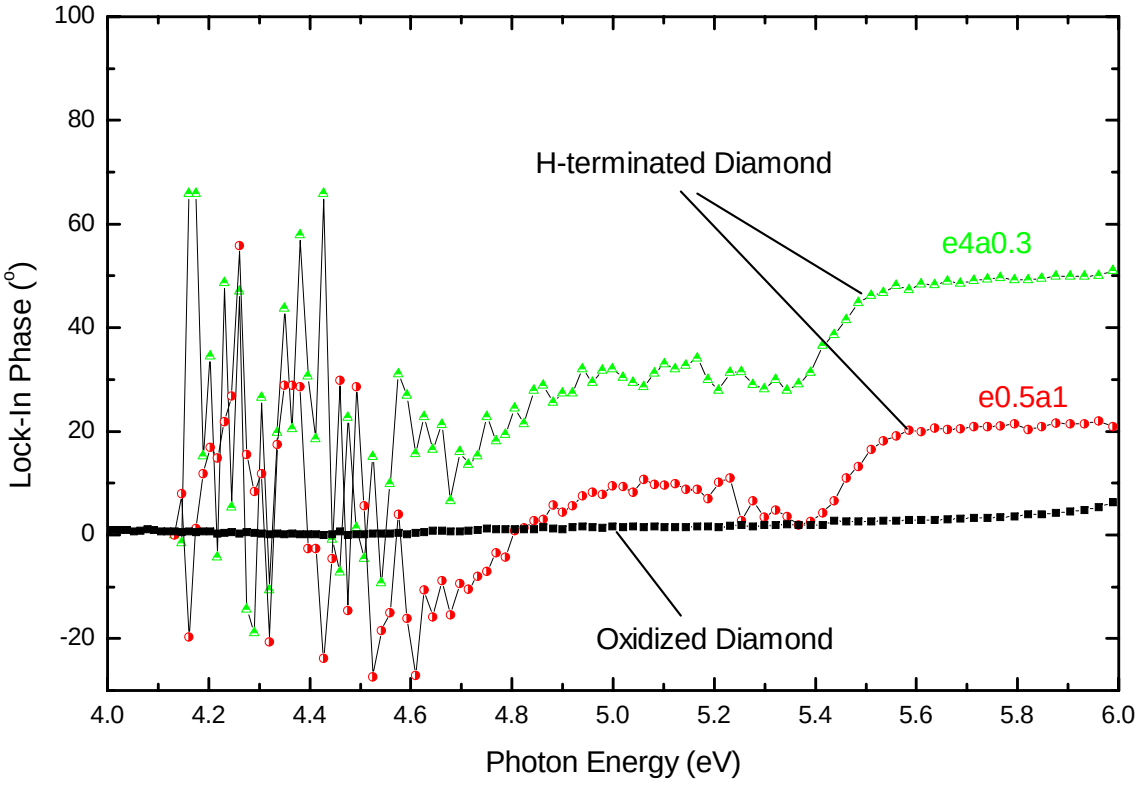


Other sample, H-terminated



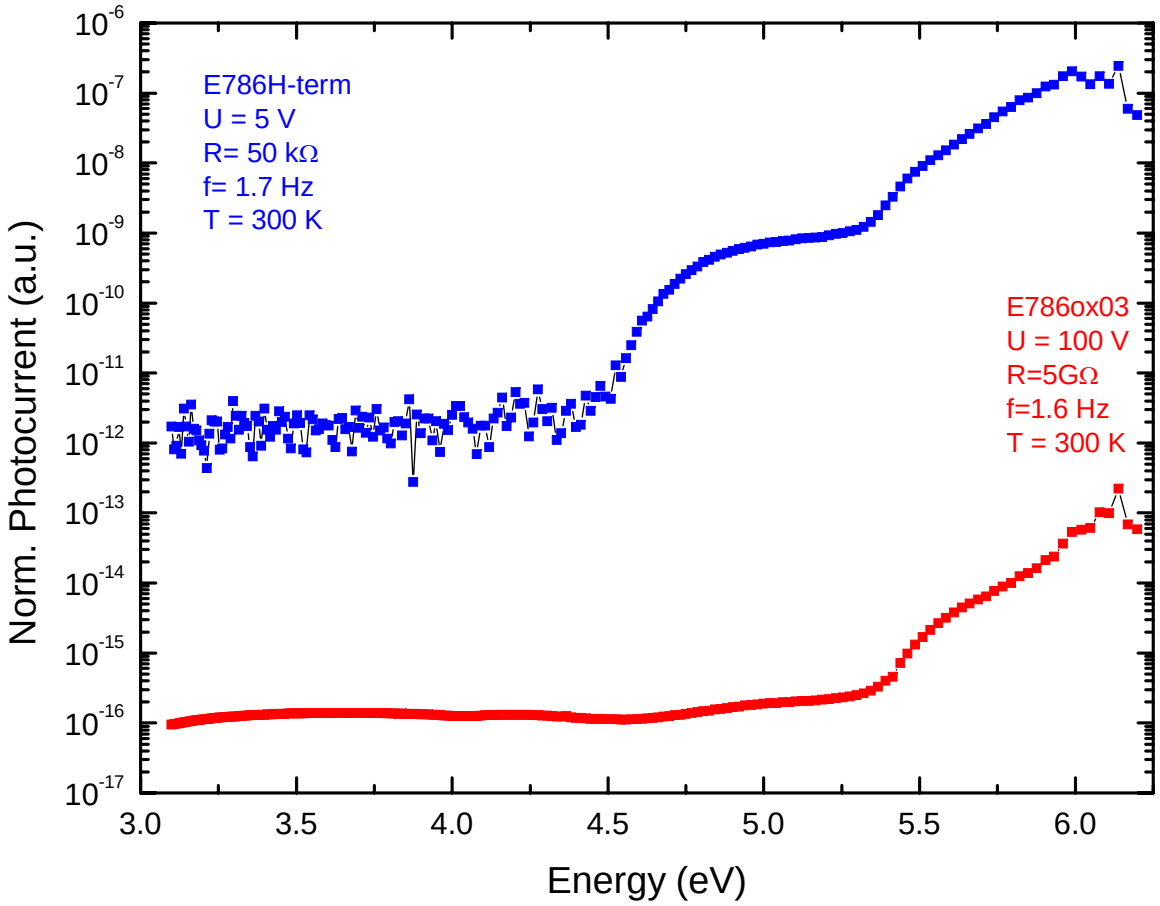
File: Bohus sample
Folder: Ergebnisse/Surface functionalization/H-termination/Bohus Sample

Lock-In Phase Detection

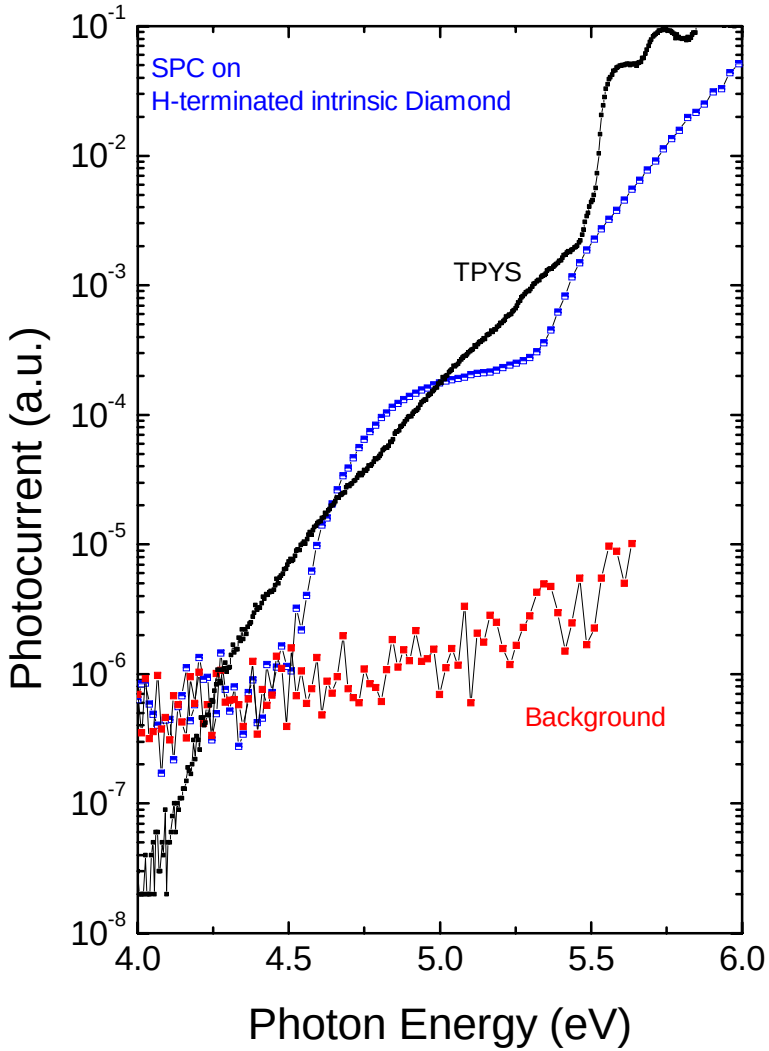


File: Bohus sample
Folder: Ergebnisse/Surface functionalization/H-termination/Bohus Sample

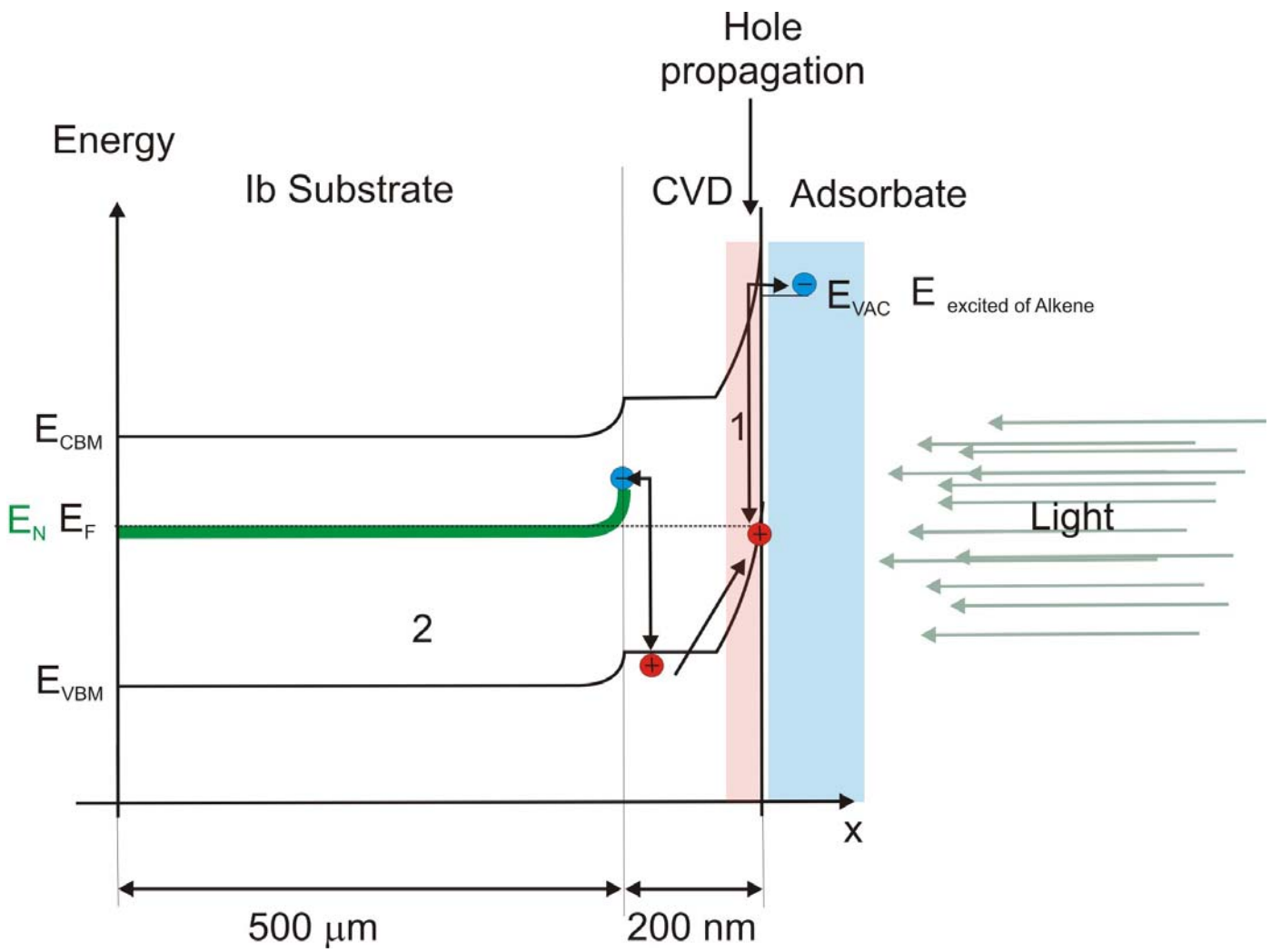
Comparision: H-term to Oxidized



Comparison with TPYS



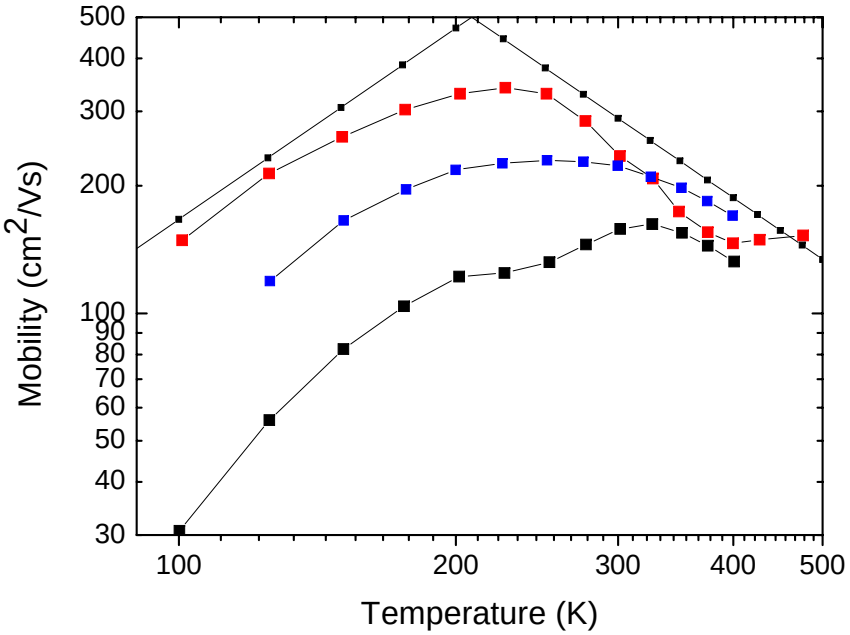
Hole Generation



8) The electronic Density of State Distribution at the surface

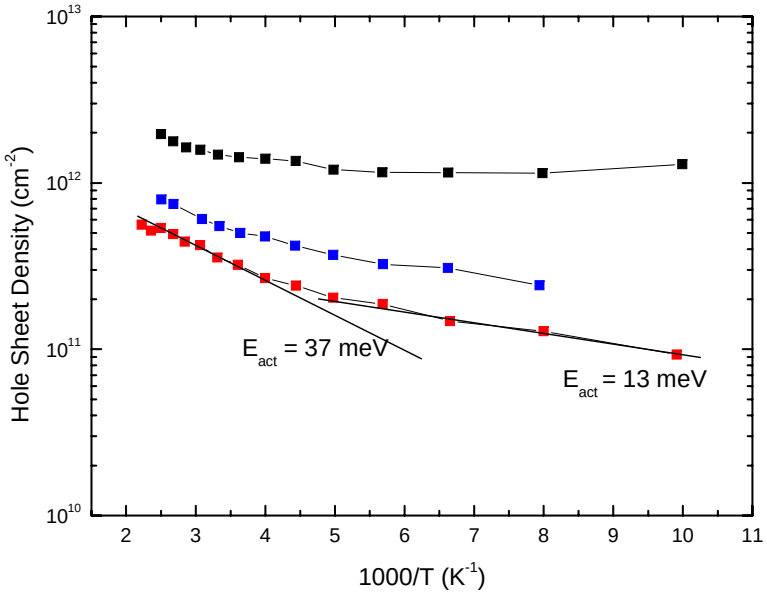
Electronic properties of H-term. diamond surface

Hall Mobilities



Mobilities up to 350 cm^2/Vs

Sheet Hole Densities



Typically: 10^{11} to $2x10^{12}$ cm^{-2}

National Institute of Advanced Industrial Science and Technology

One dimensional numerical solution of Schrödinger and Poisson Equations:

Effective confinement potential:

$$V(x) = -e\phi(x) + V_{xc}(x)$$

Electrostatic potential

Hetero-junction Discontinuity

Schrödinger Eq. (BenDaniel-Duke form):

$$-\frac{\hbar^2}{2}\frac{d}{dx}\frac{1}{m(x)}\frac{d\varphi_i(x)}{dx} + V(x)\varphi_i(x) = E_i\varphi_i(x)$$

Poisson´s Eq.

$$\frac{d}{dx}\varepsilon_o\varepsilon_r(x)\frac{d\phi(x)}{dx} = e\sum_i N_i\varphi_i(x) - \rho_I(x)$$

Number of holes per unit area in sub-band i:

$$N_i = \frac{mkT}{\pi\hbar^2}\ln\left[1+\exp\left(\frac{E_F - E_i}{kT}\right)\right]$$

Valence Band Structure of Diamond

Parameters used:

Luttinger parameters for diamond
(M. Willatzen, M. Cardona, N.E. Christensen, Phzs. Rev. B 50, p.18054, 1994

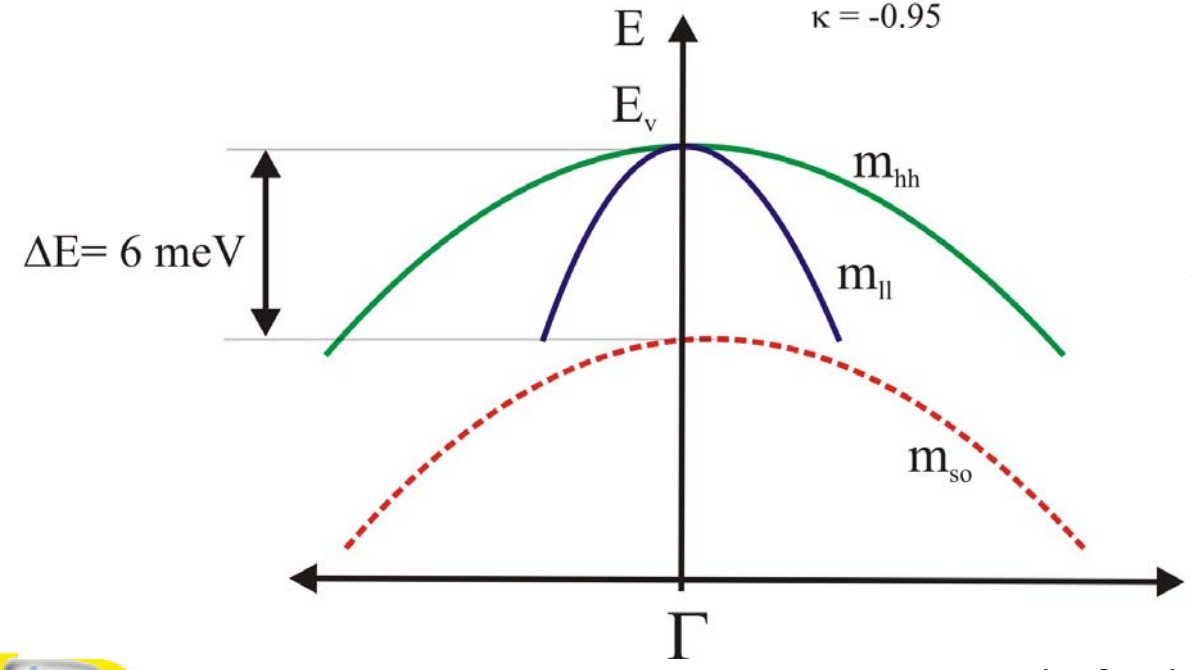
$\gamma 1 = 2.54$
$\gamma 2 = -0.1$
$\gamma 3 = 0.63$
$\kappa = -0.95$

100-direction:

$m_{hh} = 0.427\ m_o$
$m_{ll} = 0.366\ m_o$
$m_{so} = 0.394\ m_o$

$\varepsilon = 5.7$

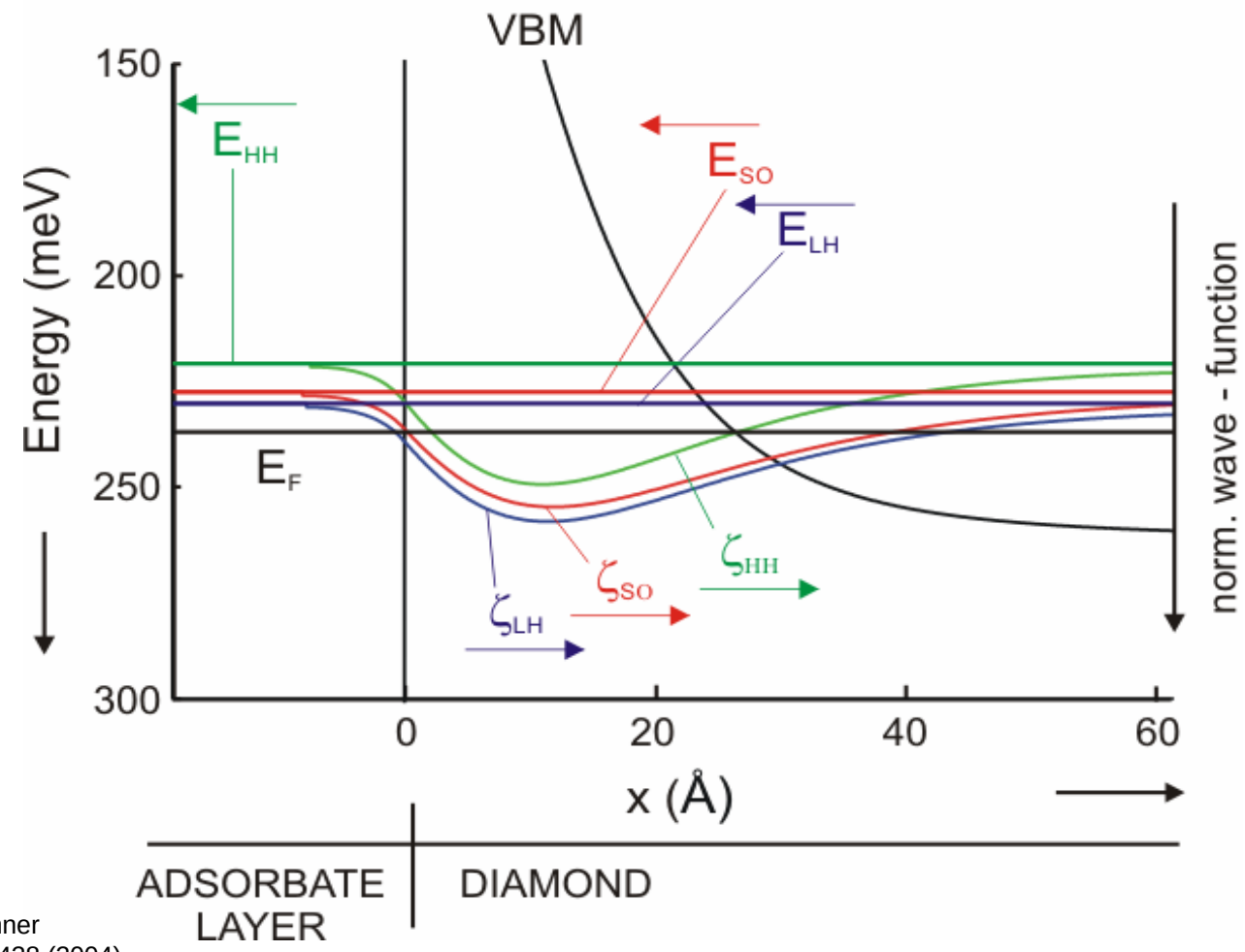
Diamond valence bands



Sheet hole densities:

$10^{10} – 10^{14}$ cm^{-2}

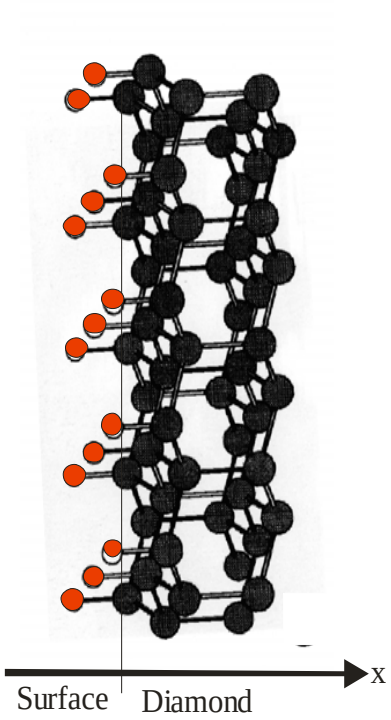
Result for $5x10^{12}$ cm^{-2} sheet hole density:



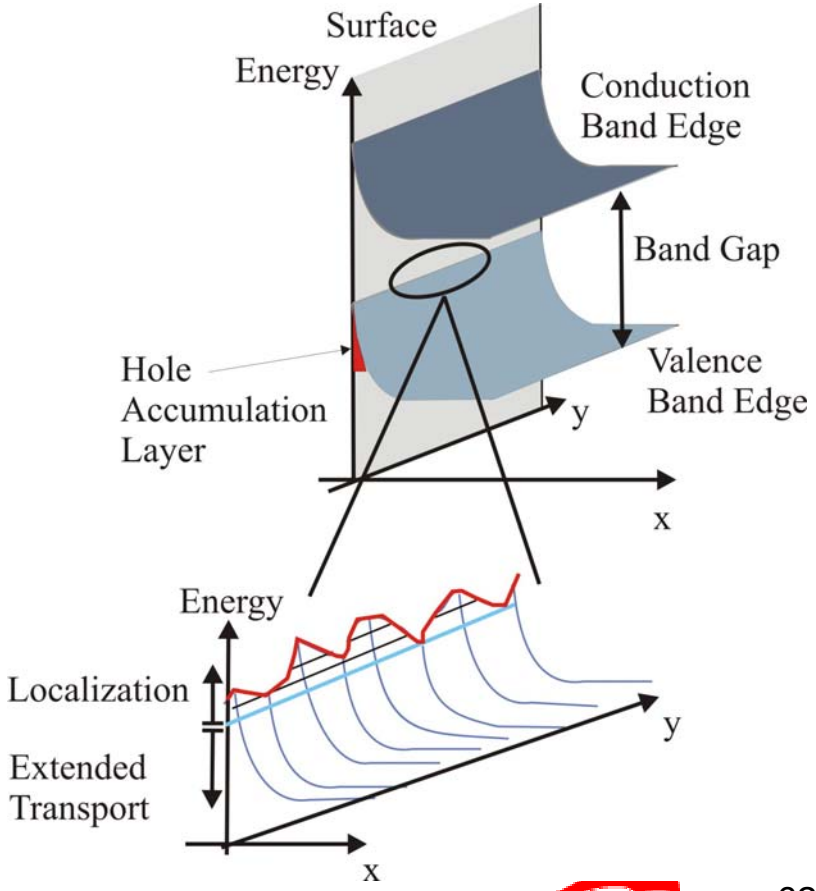
C.E. Nebel, B. Rezek, A. Zrenner
phys. Stat. sol. (a) 11, 2432-2438 (2004)

C.E. Nebel, B. Rezek, A. Zrenner
Diam. and Rel. Mat. Vol 13/11-12, 2031-2036 (2004).

Disorder Induced Localization of States:

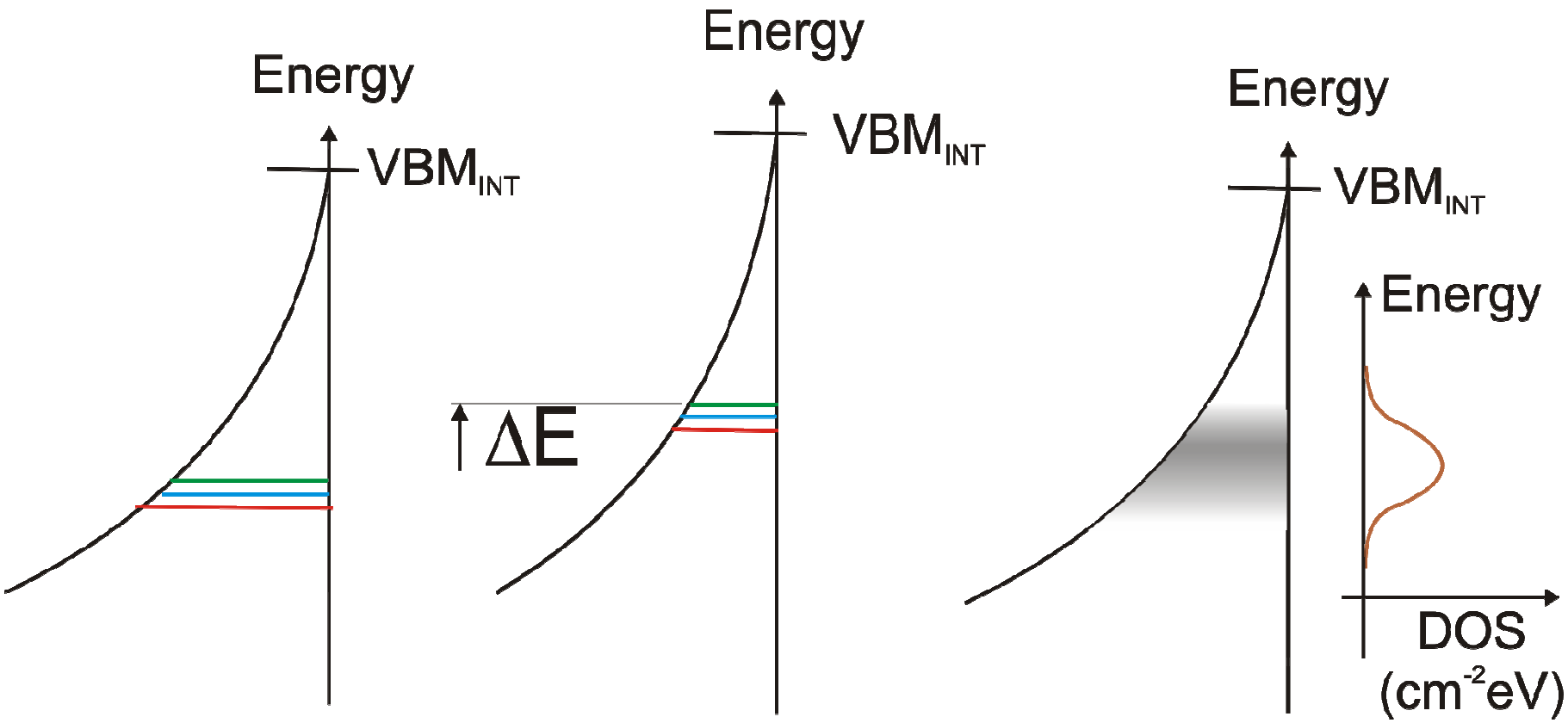


1) Hydrogen Termination not Perfect
2) Ionic Effects of Adsorbate Layer
3) Surface Roughness



H-term. Diamond Surface

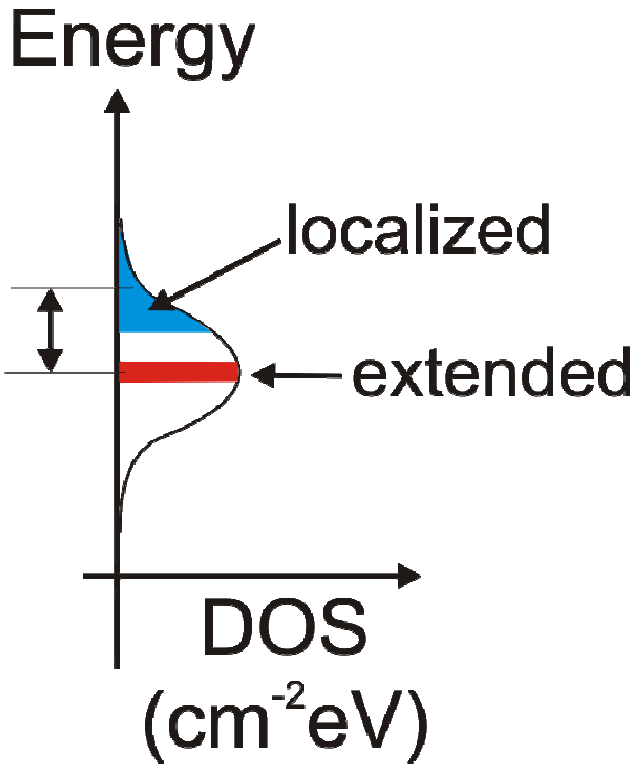
Disorder-Effects



Activation Energy in the Miniband

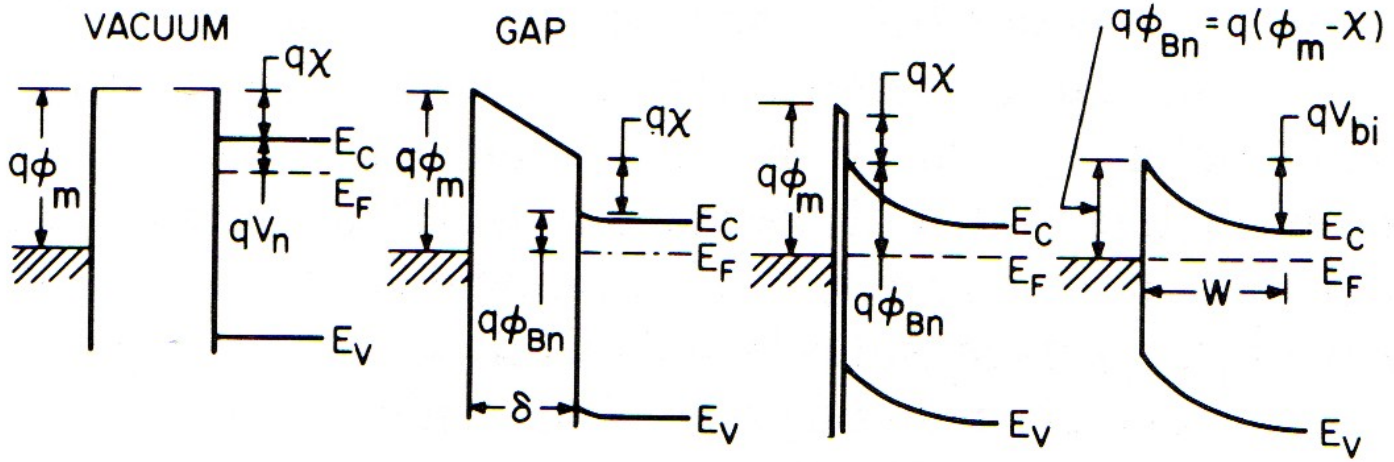
Energy Gap:

E_{act}= (0.2 -23) meV



9. Contact Properties to Diamond

Ideal Schottky Contact



Capacitance-Voltage Measurements on Metal-SiO_2-Diamond (100)

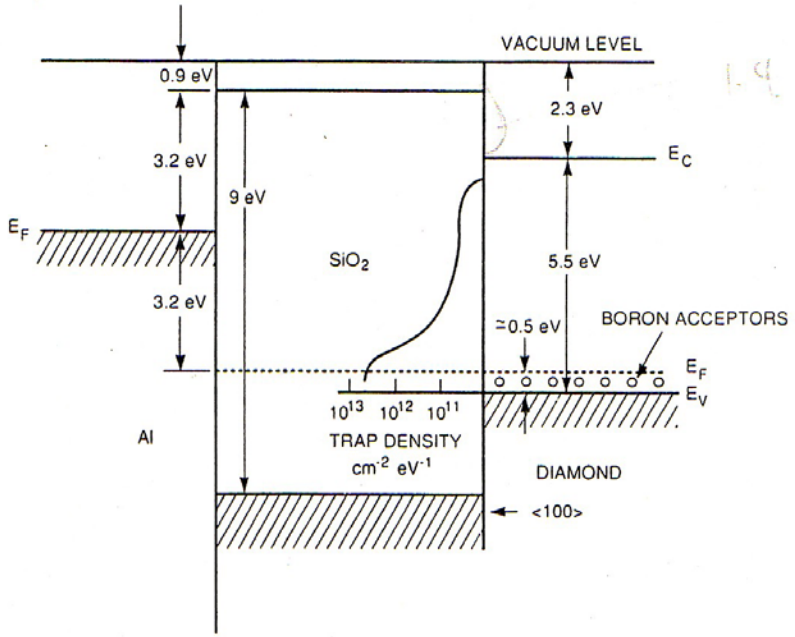


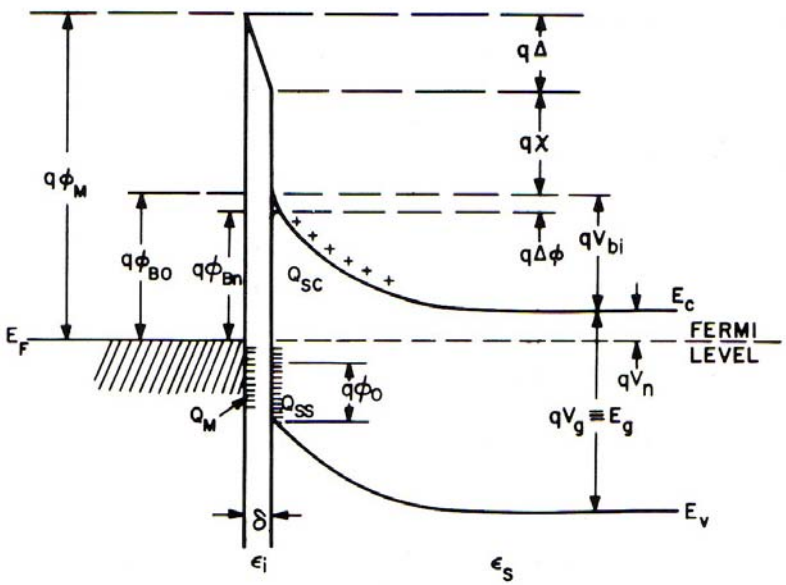
Fig. 8. Energy diagram of metal–SiO_2–diamond structure for (100)-oriented substrate. E_C is the minimum energy of electrons in the conduction band, E_v is the maximum energy of electrons in the valence band, and E_F is the Fermi energy level. A lower estimate of the positive interface trap level density is plotted versus energy (the energy axis coincides with the SiO_2–diamond interface).

M.W. Geis et al, IEEE Transactions on Electron Devices 38, 619 (1991

Real Schottky Contact

Surface Fermi-level pinning by surface defects

Schottky barrier is not dependent on metal.

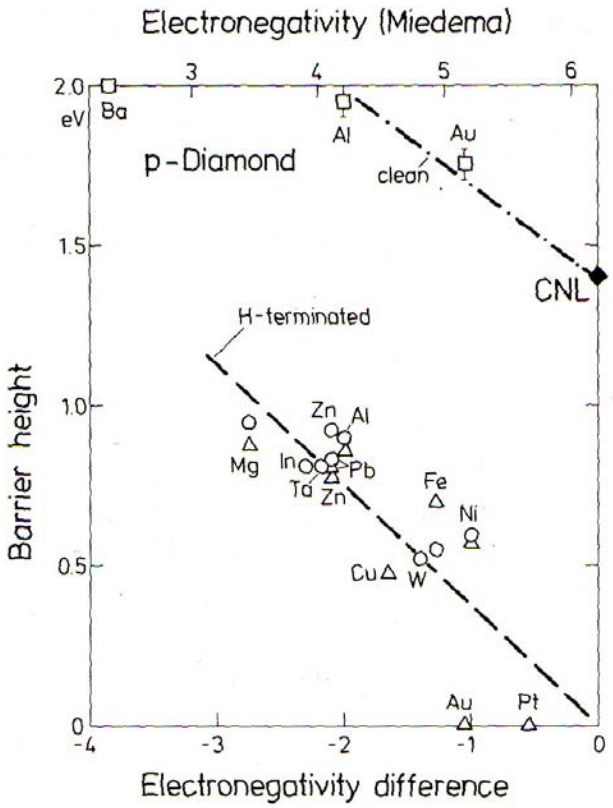


ϕ_M = WORK FUNCTION OF METAL
ϕ_{Bn} = BARRIER HEIGHT OF METAL-SEMICONDUCTOR BARRIER
ϕ_{BO} = ASYMPTOTIC VALUE OF ϕ_{Bn} AT ZERO ELECTRIC FIELD
ϕ_O = ENERGY LEVEL AT SURFACE
$\Delta\phi$ = IMAGE FORCE BARRIER LOWERING
Δ = POTENTIAL ACROSS INTERFACIAL LAYER
χ = ELECTRON AFFINITY OF SEMICONDUCTOR
V_{bi} = 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

National Institute of Advanced Industrial Science and Technology

Schottky Barrier Hight

(W. Moench, in Semiconductor Surface and Interfaces, Springer1995, p. 368



CNL = Charge Neutrality Level

Fig. 19.14 Barrier heights of metal/*p*-diamond contacts against electronegativity difference: o data from *Kawarada* et al. [1994]; □ data from *Glover* [1973], *Mead* and *McGill* [1976]; dielectric mid-gap energy from *Cardona* and *Chrsistensen* [1987]. From *Mönch* [1994b]

National Institute of
Advanced Industrial Science and Technology

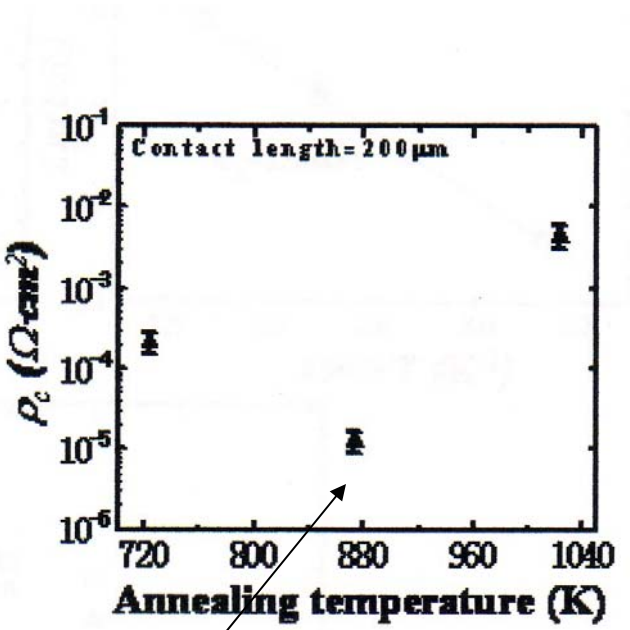
Thermal annealing of Ti on Boron-Doped Diamond

Boron doped CVD diamond: (3-6)x10^{17} cm^{-3} B-concentration

Ti/Pt/Au contacts

annealed in Ar

for 30 minutes



Minimized contact resistance: $\rho_C = 10^{-5}\ \Omega cm^2$

Specific Contact Resistance of: Ti, Mo, Cr, Pd, Co

Annealing

Ti	(400 °C 5 min)
Mo	(600 °C, 60 min)
Cr	(600 °C, 10 min)
Pd	(600 °C, 10 min)
Co	(600 °C, 10 min)

in vacuum

optimized annealing conditions.

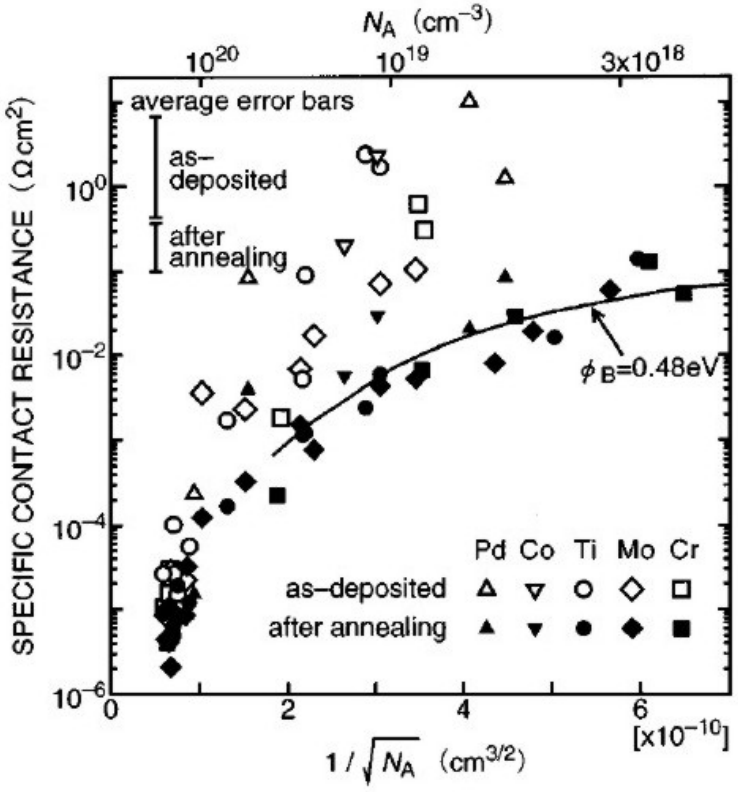


FIG. 5. Specific contact resistances of the Ti, Mo, Cr, Pd, and Co contact before and after annealing vs $N_A^{-1/2}$ at room temperature.

M. Yokoba et al., JAP 81, 6815 (1997)

Formation of thermally stable graphite layer during annealing

Formation of
1) Cr_3C_2
2) Graphite

At the interface

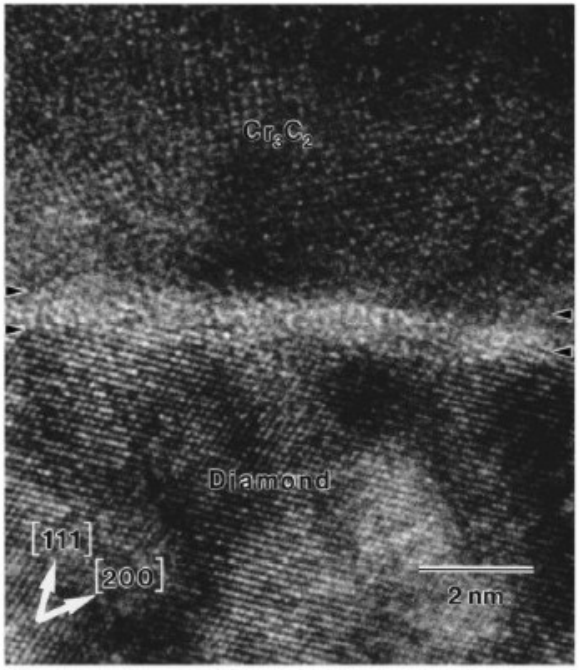


FIG. 4. A high-resolution lattice image of the diamond/Cr interface after annealing at 600 °C for 10 min.

M. Yokoba et al., JAP 81, 6815 (1997)

Summary

God invented “BULK PROPERTIES”

The Devil: THE SURFACE !