Herstellung von Diamantschichten und deren Einsatz in der Festkörperphysik

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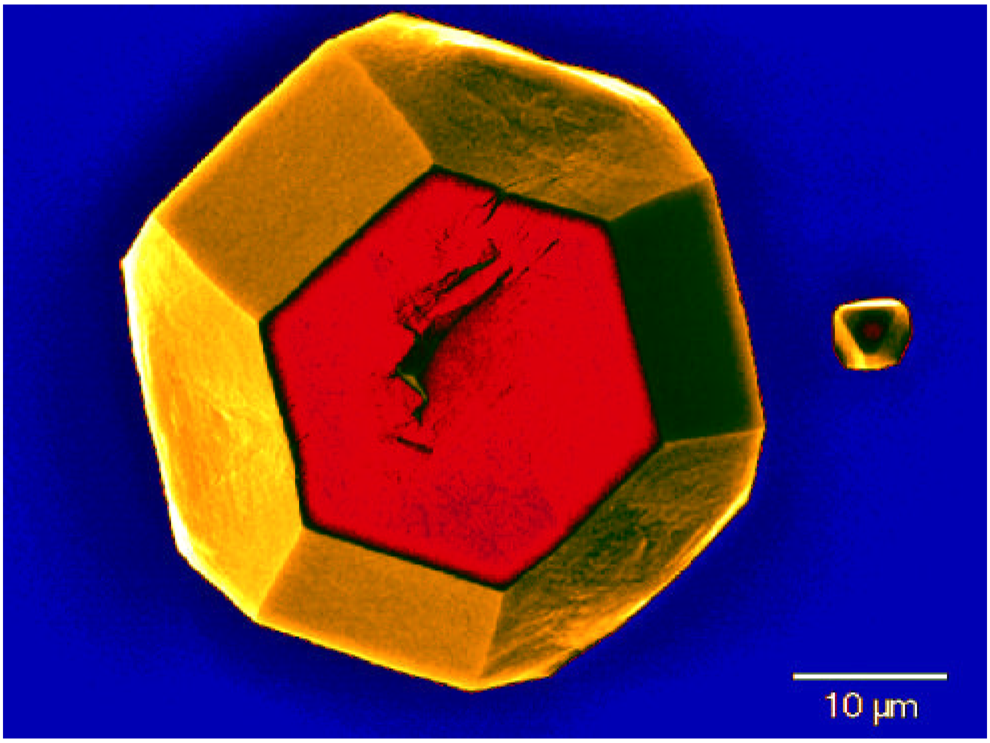


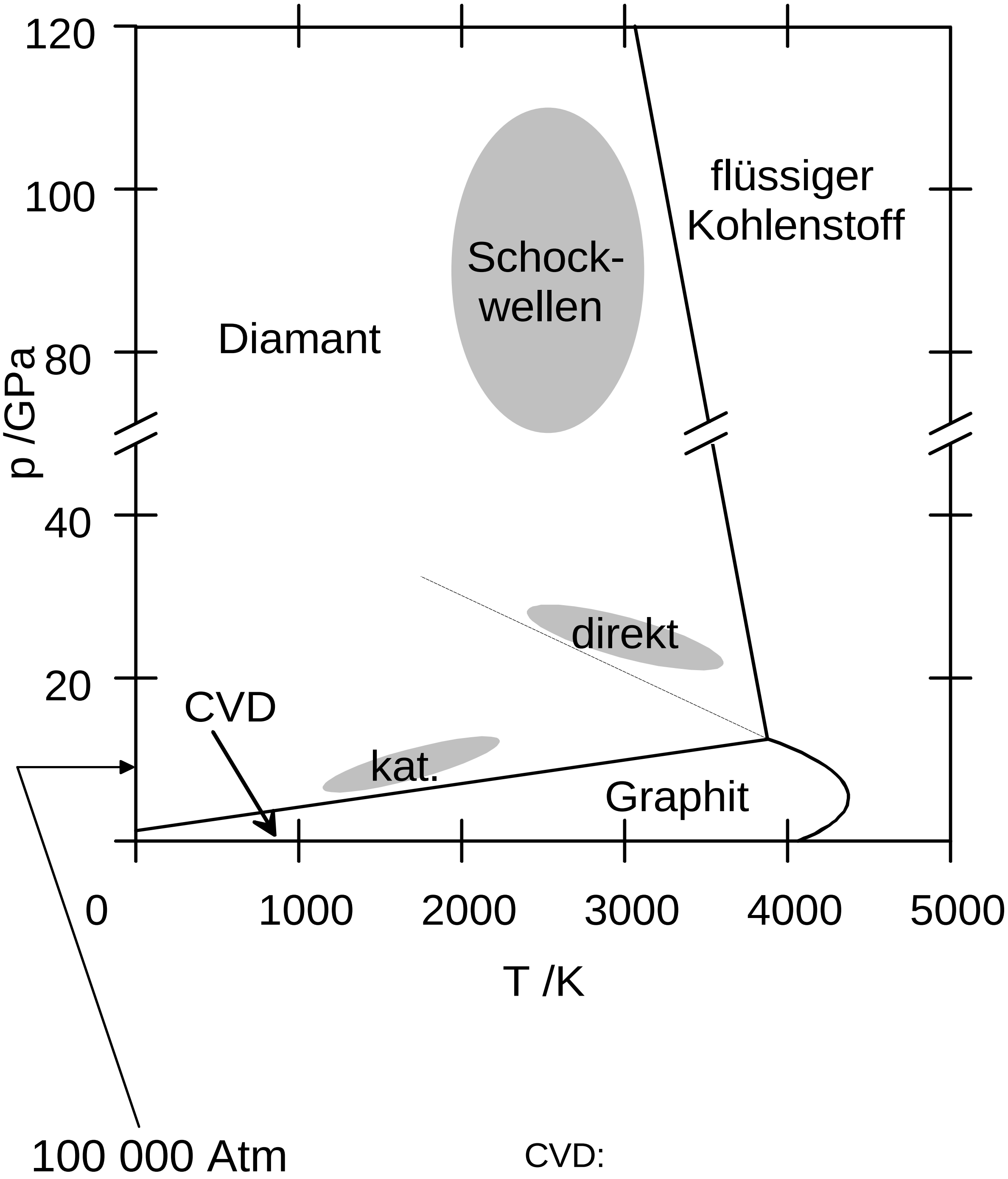
Programm

- Herstellung von Diamantschichten
- Diamantschichten als Halbleiter:
- Dotierung
- Schottky-Dioden
- Feldeffektstrukturen
- Besondere Oberflächeneigenschaften:
  Elektronenaffinität und
  Oberflächenleitfähigkeit

Key Material Parameters of Diamond and Competing Semiconductors

	Diamond	**Si**	b**-SiC**	**h-GaN**	**c-BN**
fcc lattice constant (Å)	3.56	5.43	4.36	3.2/5.2*	3.62
density (gcm^{-3})	3.515	2.4	3.216	6.1	3.49
energy gap (eV)	5.48	1.107	2.86	3.5	6.4
dielectric constant	5.8	11.8	9.7	10	7.1
refractive index (at 589 nm)	2.42	3.5	2.65	2.3	2.1
electron mobiliy (cm^2/(Vs))	2200	1500	400	100	-
hole mobility (cm^2/(Vs))	1800	495	50	-	-
breakdown field strength (MV/cm)	10	0.3	4	-	-
hardness (kg/mm^2)	10000	1000	3500	-	6500
heat conductivity (W/(Kcm))	20	1.5	5	1.3	-

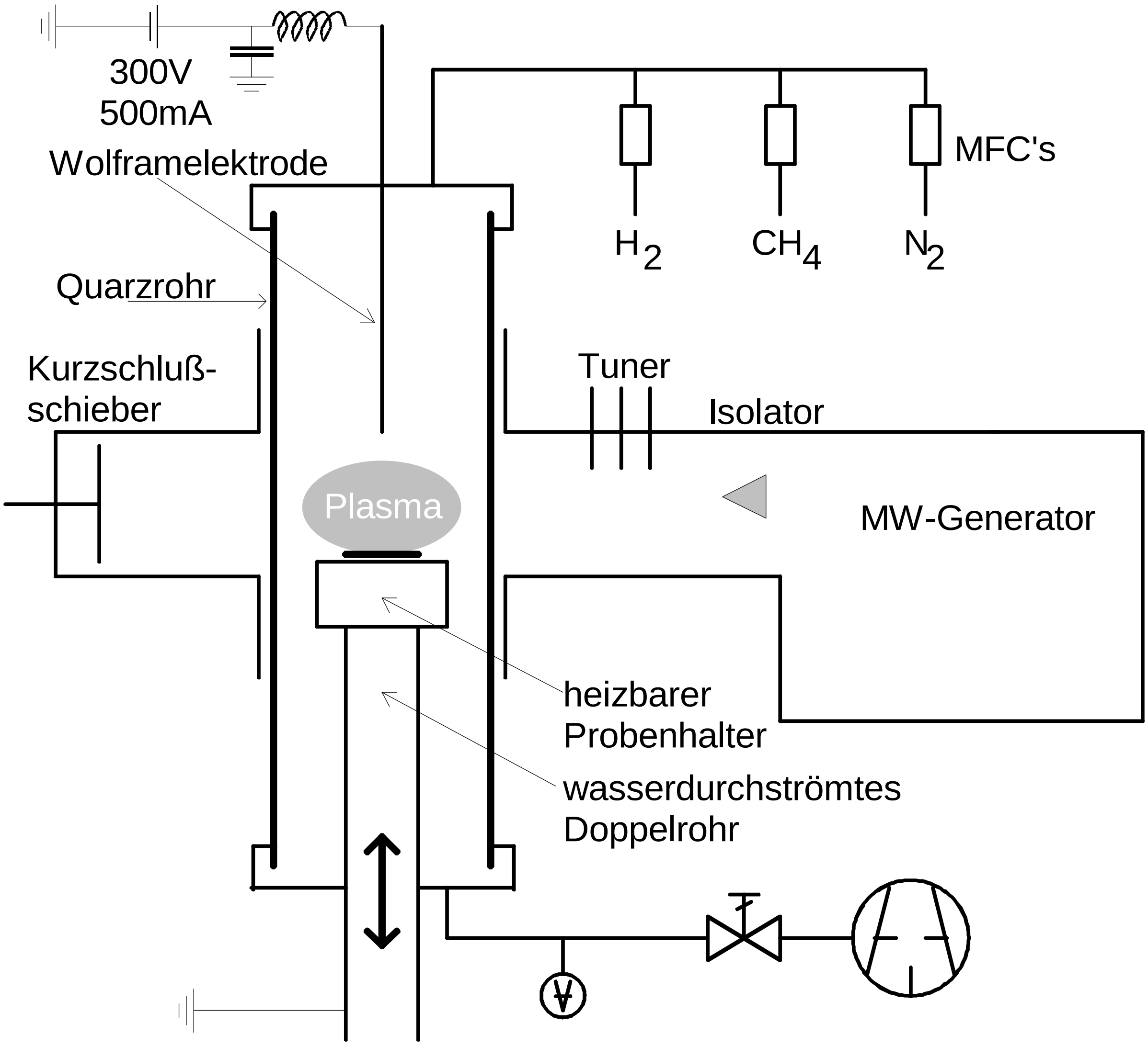
Das Phasendiagramm von Kohlenstoff

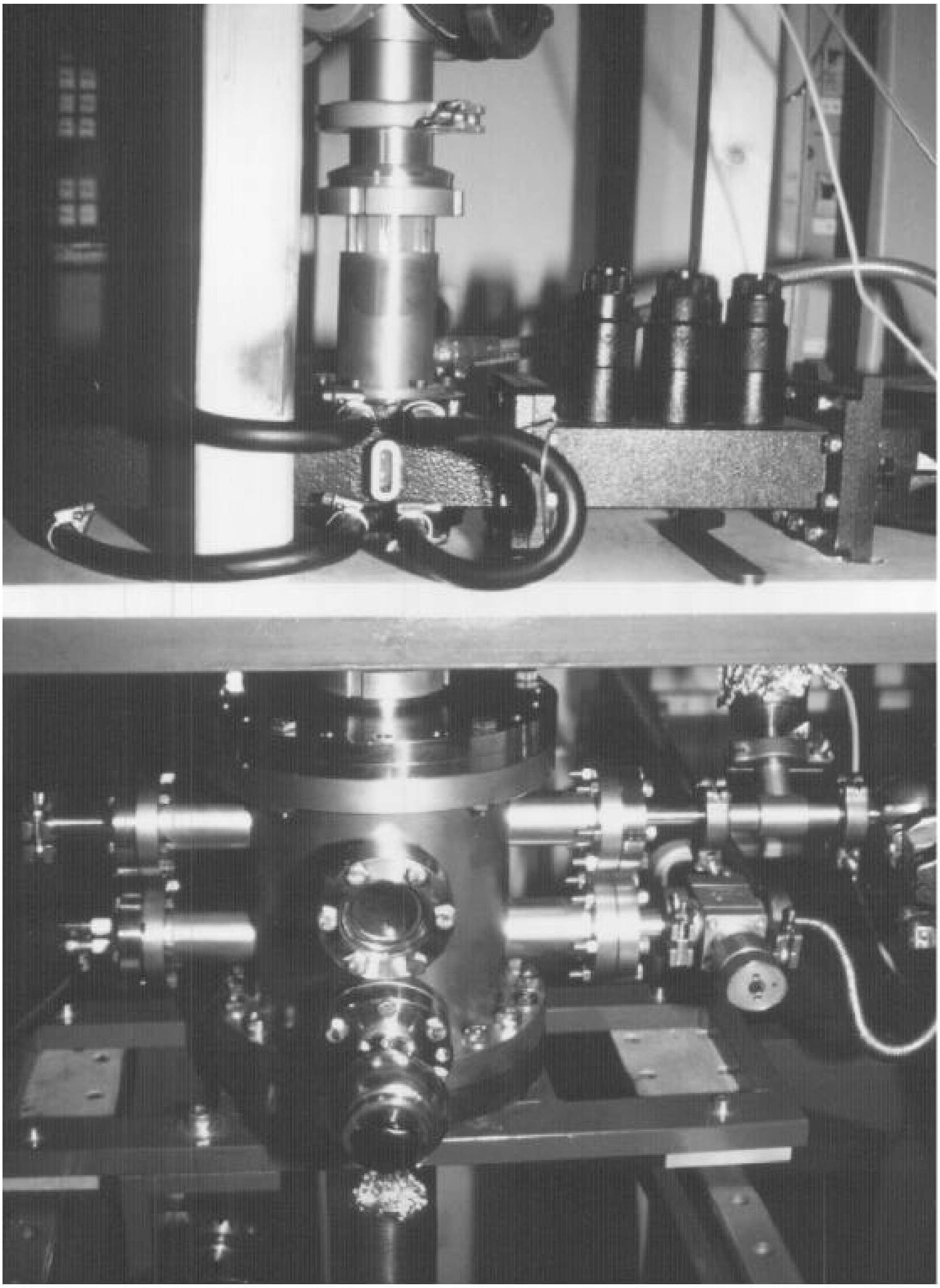


CVD:

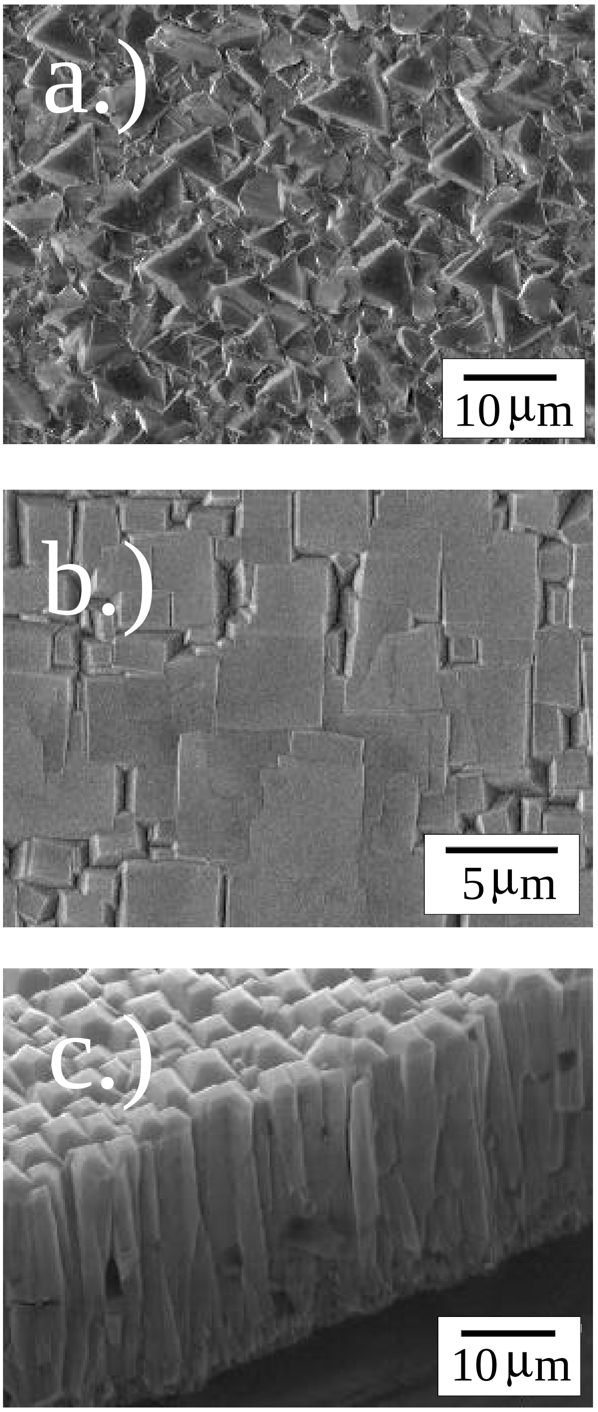
Druck: 30 mbar
Temp.: 850 °C

Mikrowellen-Plasma Depositionsanlage zur Gasphasenabscheidung von Diamant





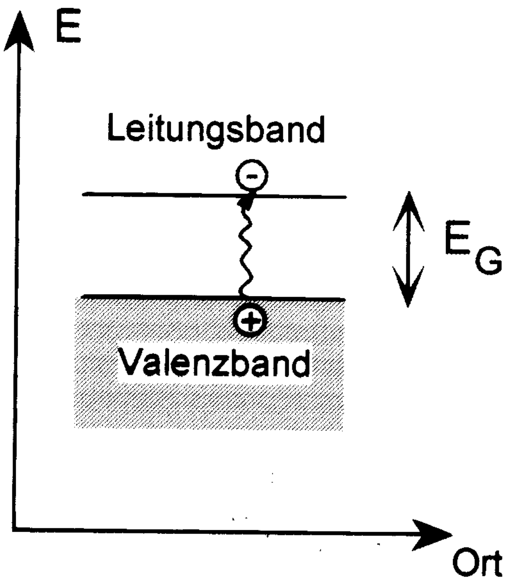
Hetero-epitaxial CVD Diamond Layers



Scanning Electron Micrograph (SEM) of a state of the art hetero-epitaxial CVD diamond film (a) on a Si (111) and (b) on a silicon (100) substrate. The homogenous orientation of the large crystallites forming the surface of the films (especially panel b) is achieved by overgrowing misoriented nuclei through an appropriate choice of the deposition parameters. As a consequence the first few hundred nm of the diamond film contain predominantly small crystallites of random orientation and a high volume fraction of grain boundaries with non-diamond material in between (panel c). The thickness of the films in a.) and b.) is about 80µm

Halbleiter:

> *Bezeichnung für alle kristallinen Stoffe, die sich bei tiefen Temperaturen wie Isolatoren verhalten, bei Zimmertemperatur eine merkliche Leitfähigkeit zeigen und deren Widerstand mit zunehmender Temperatur abnimmt. ....*
>
> Meyers Grosses Taschenlexikon, Mannheim 1983



$$n_i = p_i = \underset{\substack{\uparrow \\ \approx 10^{20}\,/\,\mathrm{cm}^3}}{\sqrt{N_L N_V}} \cdot e^{-\frac{E_G}{2kT}}$$

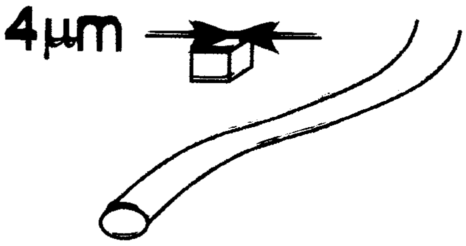
Bei Zimmertemperatur:

$$V_{1\mathrm{Elektron}} \approx 10^{-20}\,\mathrm{cm}^3 \times e^{\frac{E_G}{2\cdot(1/40)\mathrm{eV}}}$$

$$V_{1\mathrm{Elektron}} \approx 10^{-20}\,\mathrm{cm}^3 \times e^{20\cdot(E_G/\mathrm{eV})}$$

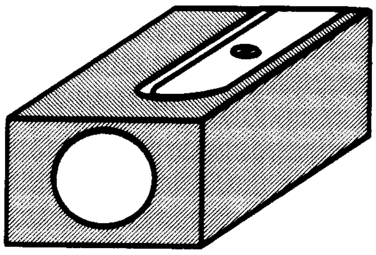
Si:

$E_G = 1.1$ eV → $\times\, e^{22}$



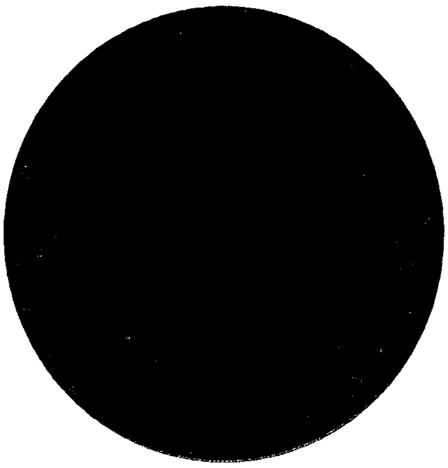
β–SiC:

$E_G = 2.2$ eV → $\times\, e^{44}$



Diamant:

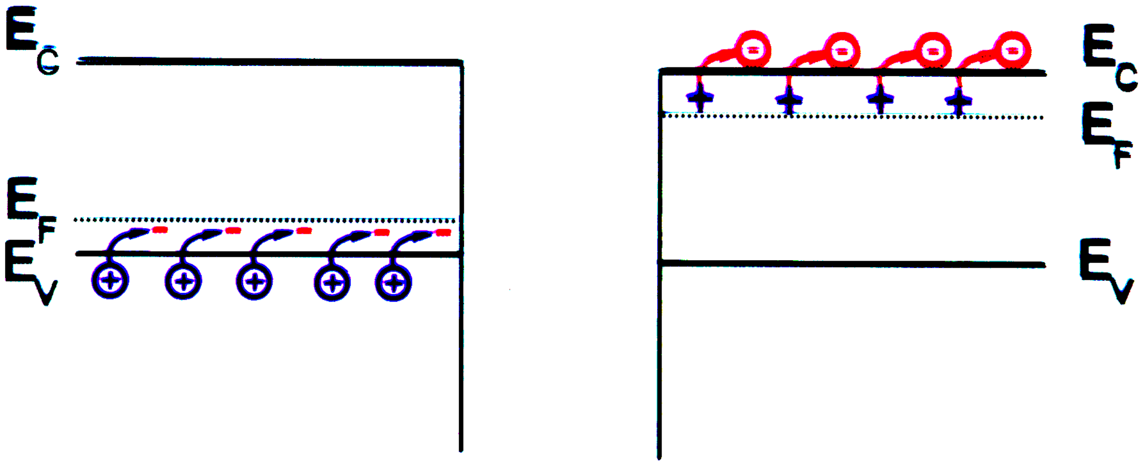
$E_G = 5.5$ eV → $\times\, e^{110}$



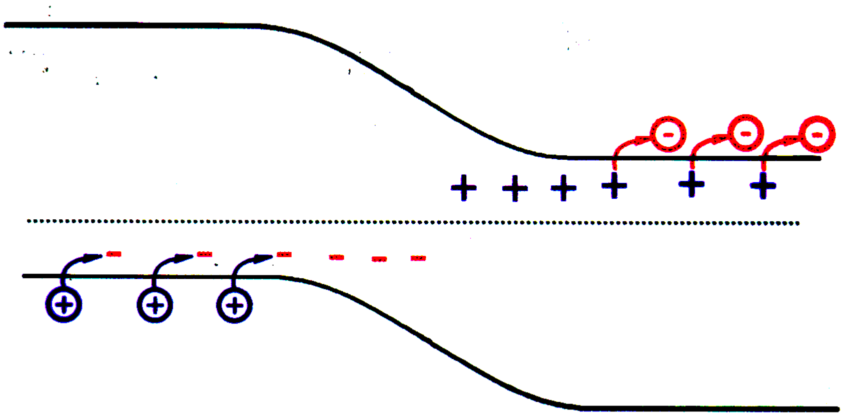
Doping of Semiconductors

p-type

n-type



p-n junction



Doping of Silicon

⋮

Ref. p. 77] 1.2 Silicon (Si) **Fig. p. 363**

Impurity	Ionization energy	Remarks	Ref.
V_2	$E_c - 0.24$	di-vacancy, V_2^-	76E
	$E_c - 0.23$	di-vacancy, V_2^-	78K
	$E_c - 0.43$	V_2^0, stable at RT, anneals at 610 K	76E
	$E_c - 0.41$	V_2^0	78K
	$E_v + 0.20$	V_2^+, anneals at 570 K	76K4
	$E_v + 0.21$		78K
V	$E_v + 0.13$	V^{++}, negative Hubbard-U V^+ metastable	80W1
Ge		isoelectronic, substitutional	
	$E_c - 0.14$	acceptor, implantation, anneals at 500 °C	73S2
	$E_c - 0.27$	donor	72F, 73S2
	$E_c - 0.55$	donor, implantation, anneals at 500 °C	
Sn	$E_v - 0.17$	MOS-CV, implantation	72F
	$E_v + 0.37$	anneals at 500 °C	
Sn − V	$E_v + 0.32$	$Sn - V^+$, anneals at 500 K	79T2
	$E_v + 0.07$	$Sn - V^{++}$	
Pb	$E_c - 0.17$	ion implantation, anneals at 500 °C MOS-CV	72H
Ti	$E_c - 0.21$	ion implantation, anneals at 500 °C	72F
group V			
N	$E_c - 0.14$	donor, substitutional	73M
	$E_c - 0.045$	N^--center [74P]	68C, 68Z
P	$E_c - 0.0453$	donor, substitutional IR-absorption + electrical, Fig. 19	56P, 65A2
	$E_c - 0.0458$	IR-absorption, 4 K	79P1
P^-	$E_c - 0.0037$	photoconductivity, 1.6 K	76N2, 77N2
P − V	$E_c - 0.40$	E-center, anneals at 420 K	69K
As	$E_c - 0.0537$	substitutional donor, IR-absorption	56P, 65A2
	$E_c - 0.05377$	IR-absorption, 4 K	79P1
As − V	$E_c - 0.47$	E-center, anneals at 450 K	79T2
Sb	$E_c - 0.0427$	substitutional donor, IR-absorption	65A2
	$E_c - 0.04277$	IR-absorption, 4 K	79P1
Sb − V	$E_c - 0.44$	E-center, anneals at 460 K	79T2
Bi	$E_c - 0.0706$	substitutional donor, IR-absorption	59H
	$E_c - 0.069$	electrical	76S1
	$E_c - 0.0710$	IR-absorption, 4 K	79P1
V	$E_c - 0.49$	MOS-CV, ion implantation, anneals at 500 °C	72F
	$E_v + 0.40$		
Ta	$E_c - 0.14$	MOS-CV, ion implantation, anneals at 500 °C	72F
	$E_c - 0.43$		

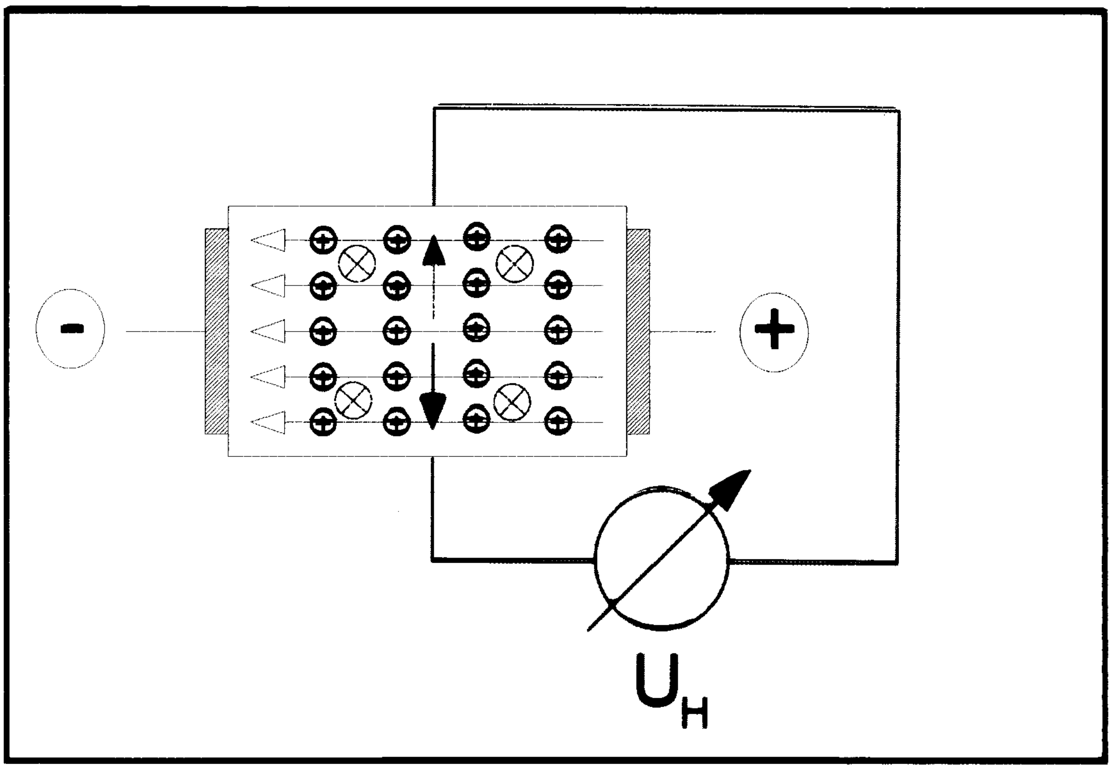
⋮

$\sum_{Si} = 80\ (18)$

$\sum_{SiC} = 6$

$\sum_{Dia} = B + \left\{ \begin{array}{l} P\ (1997) \\ S\ (1999) \end{array} \right.$

The Hall Experiment



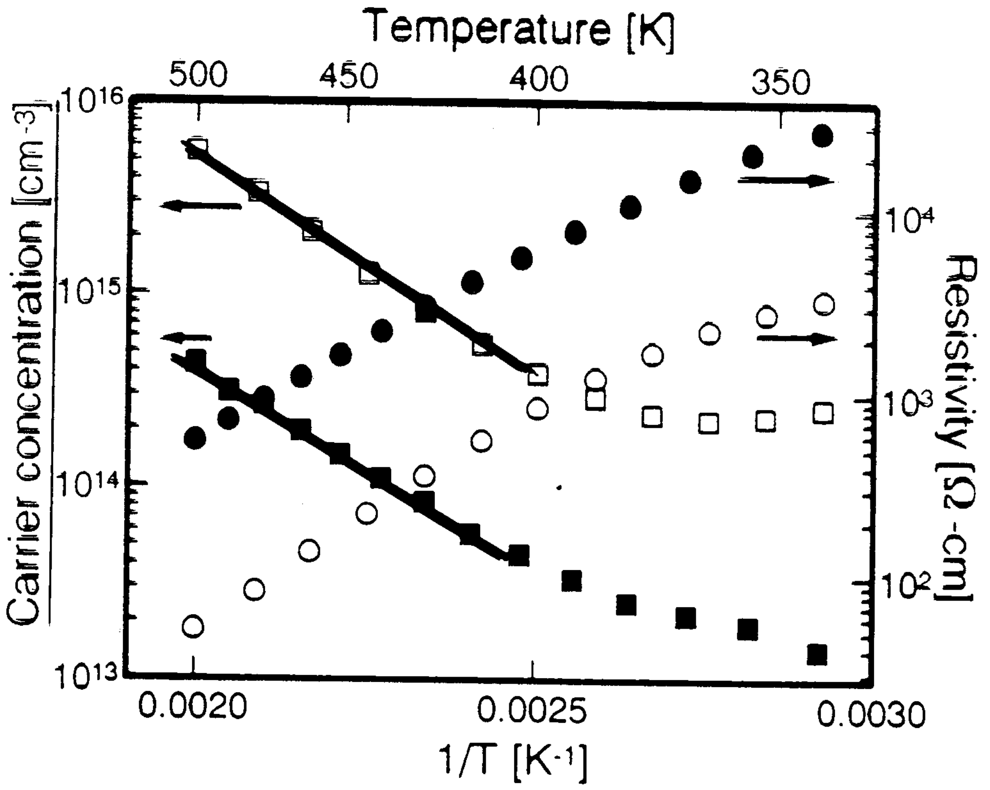
$$j = e \cdot v \cdot p \qquad = e \cdot \underset{\uparrow}{p} \cdot \underset{\uparrow}{\mu} \cdot E_D$$

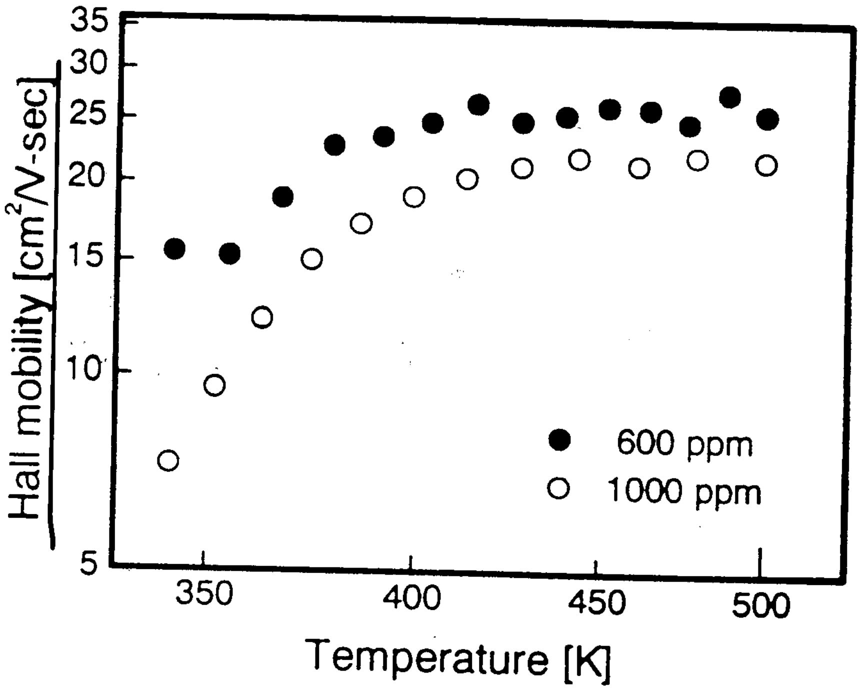
$$F_L = \underbrace{e \cdot v}_{j/p} \cdot B = e \cdot \underline{E_H} = \underline{F_{el}}$$

$$\rightarrow \qquad \frac{E_H}{j \cdot B} = H = \frac{1}{e \cdot \underset{\uparrow}{p}}$$

$$\rightarrow \qquad \underbrace{\frac{j}{E_D}}_{\sigma} \cdot H = \underset{\uparrow}{\mu}$$

Phosphorous Doping of Diamond





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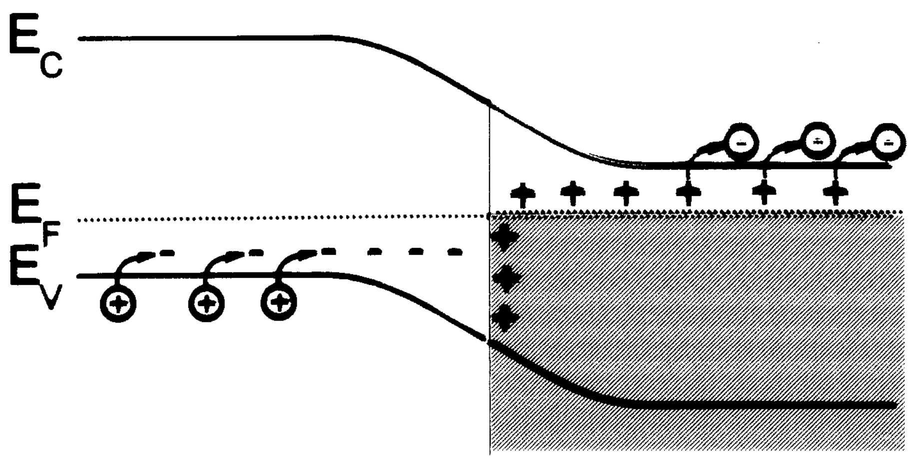
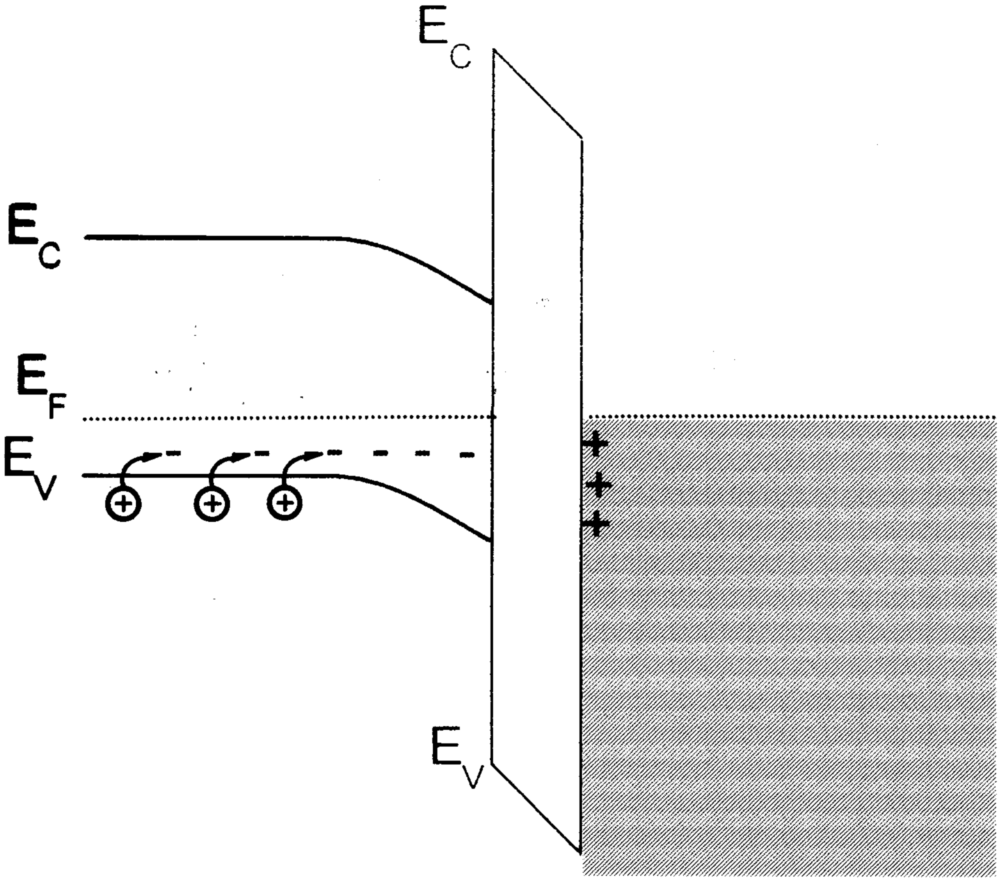
Schottky Diode

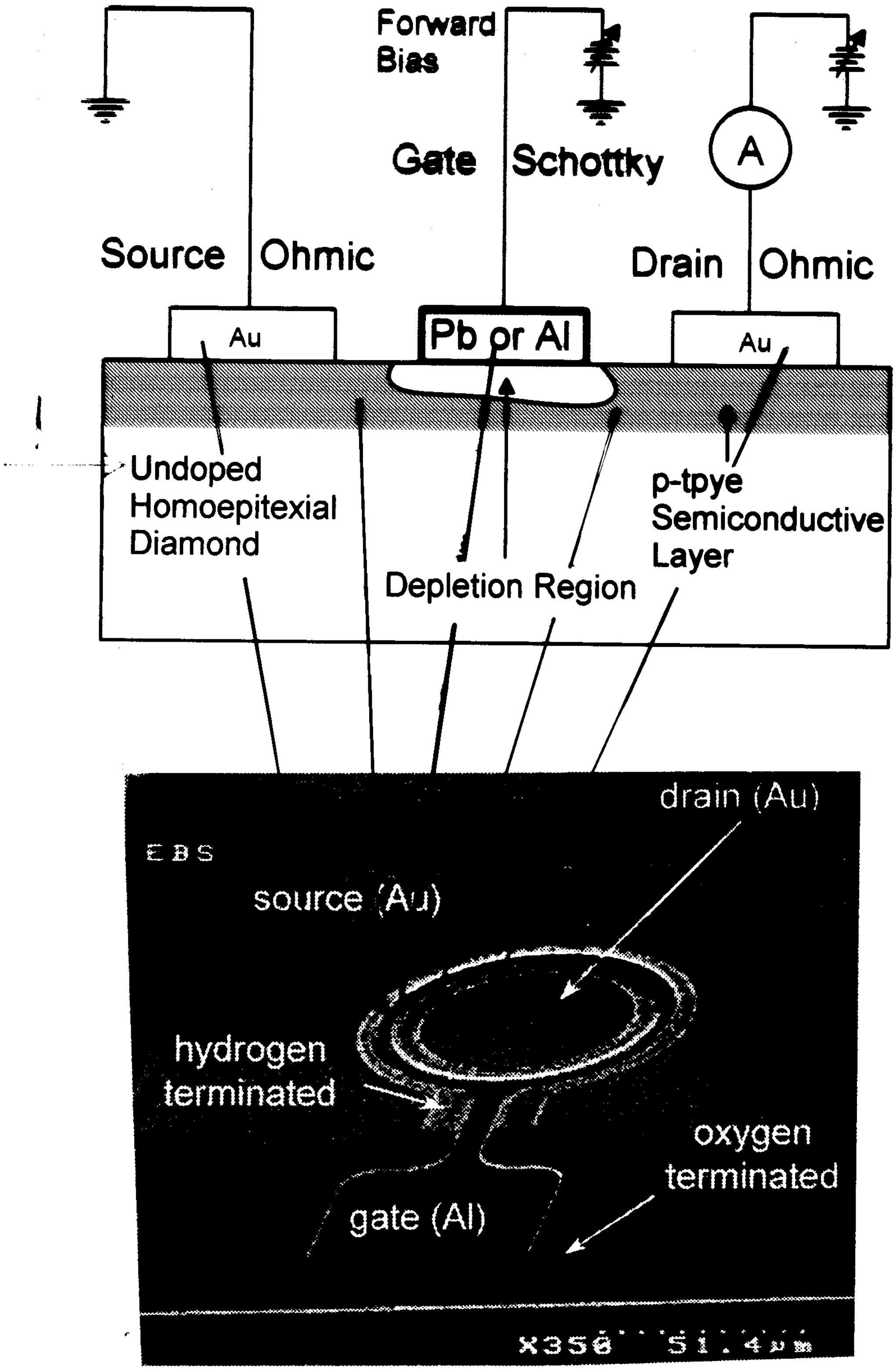
p-n junction



Field Effect Transistor



The Diamond Surface-Channel FET



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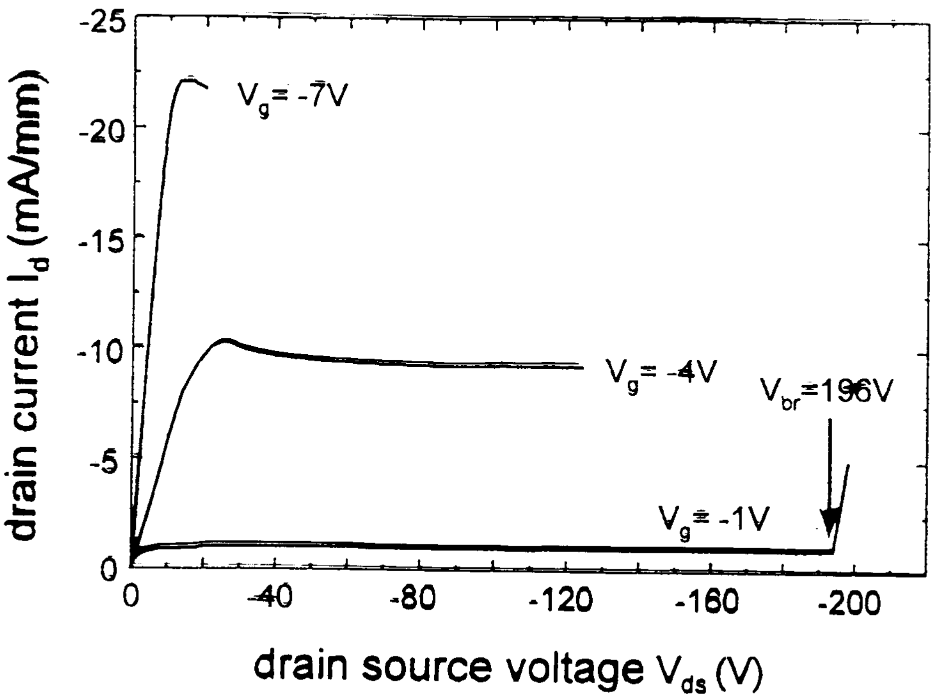
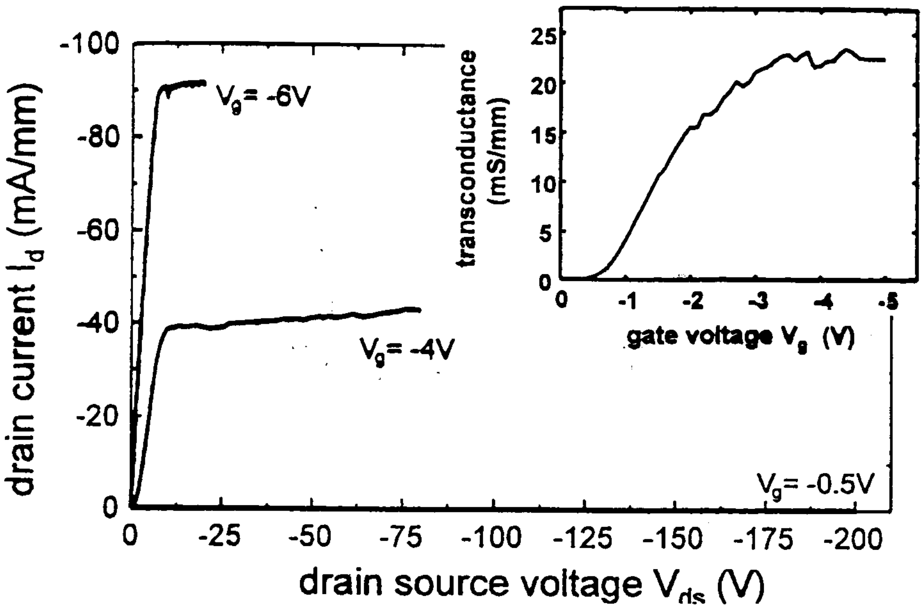
Output Characteristics of the Diamond Surface-Channel FET



circular

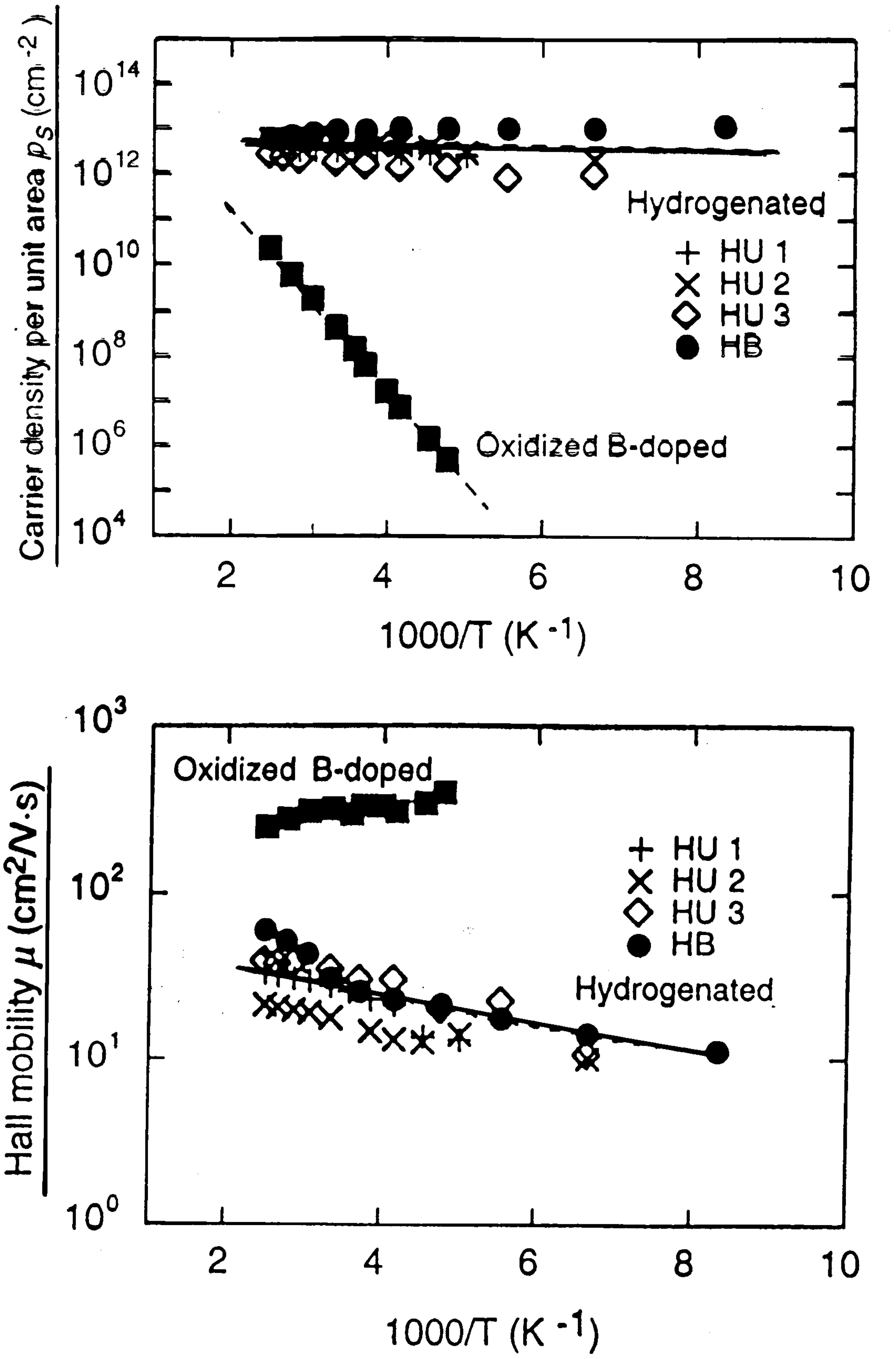


linear

$$U_{SD,max} = 196V$$

$$\rightarrow \quad g_{max} = 25mS / mm$$

Surface Conductivity of Hydrogenated Diamond



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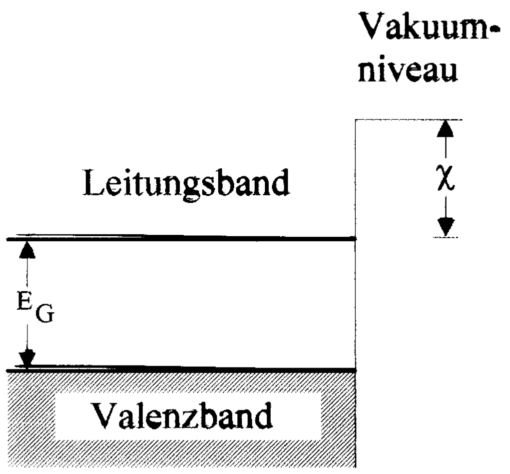
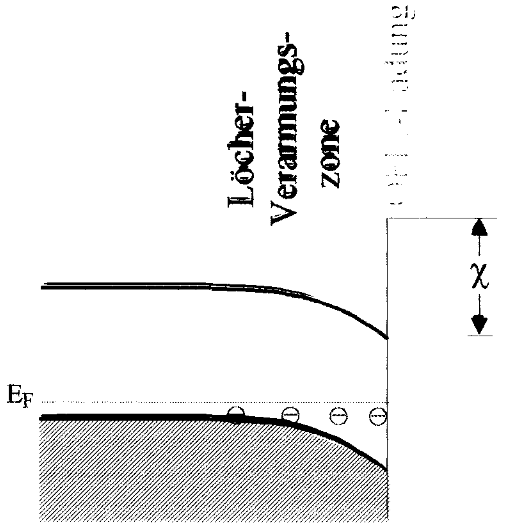
Elektronenaffinität konventioneller Halbleiter

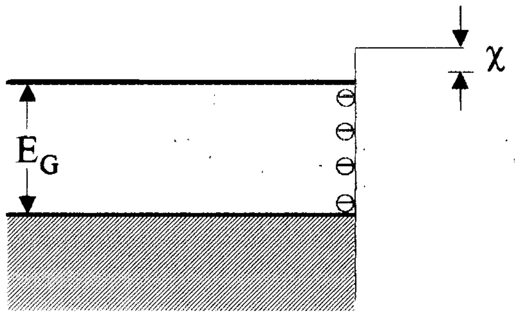
Positive Elektronenaffinität



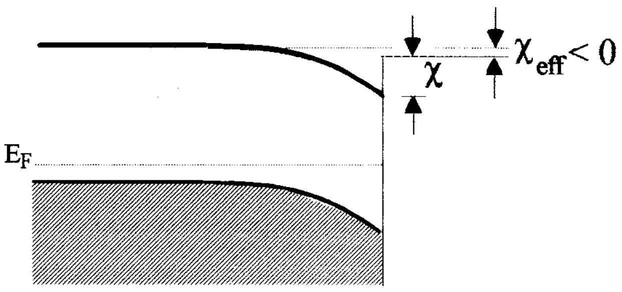
Bandverbiegung



Oberflächen-Dipolschicht

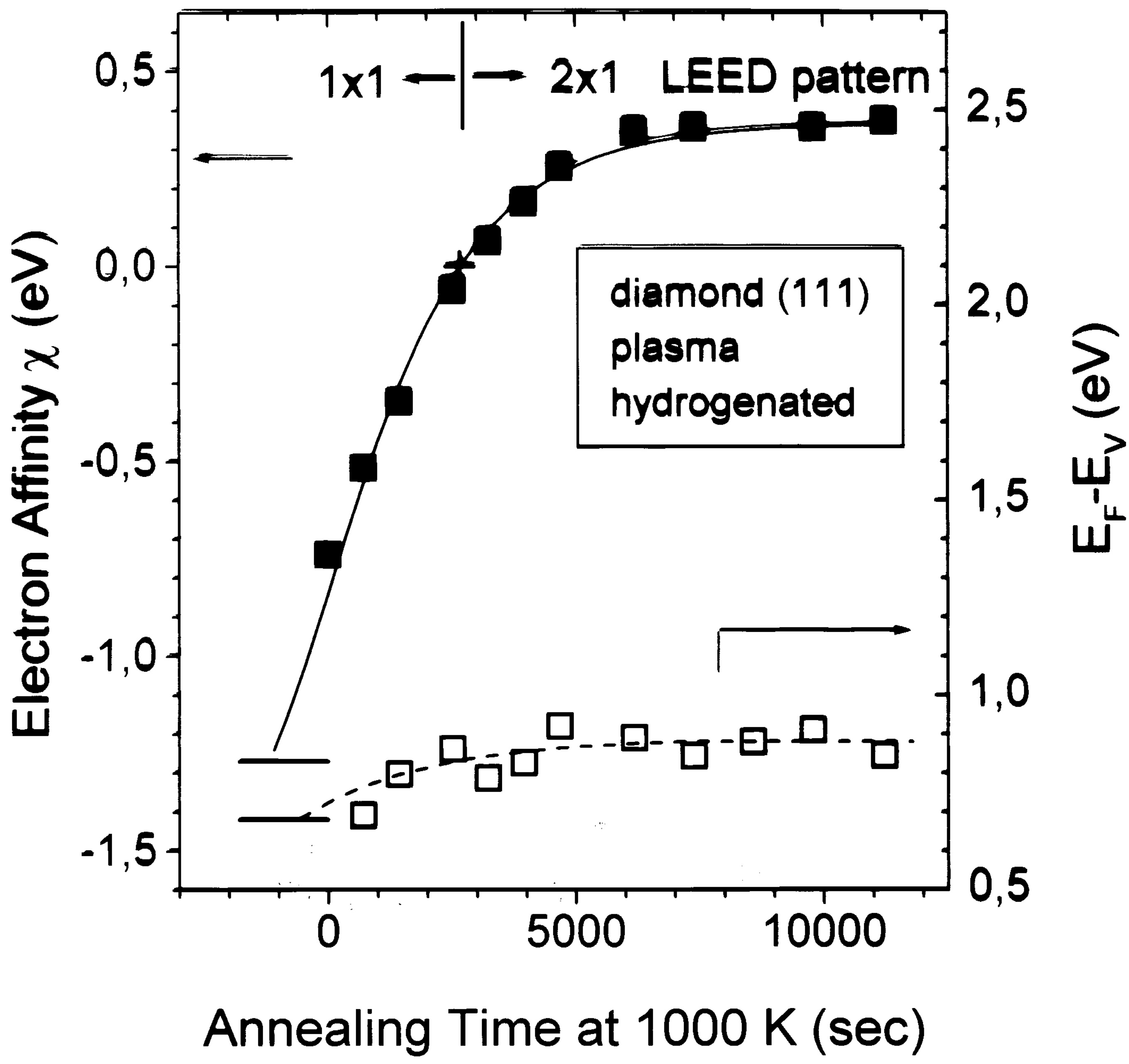


Bandverbiegung
+
Oberflächen-Dipolschicht

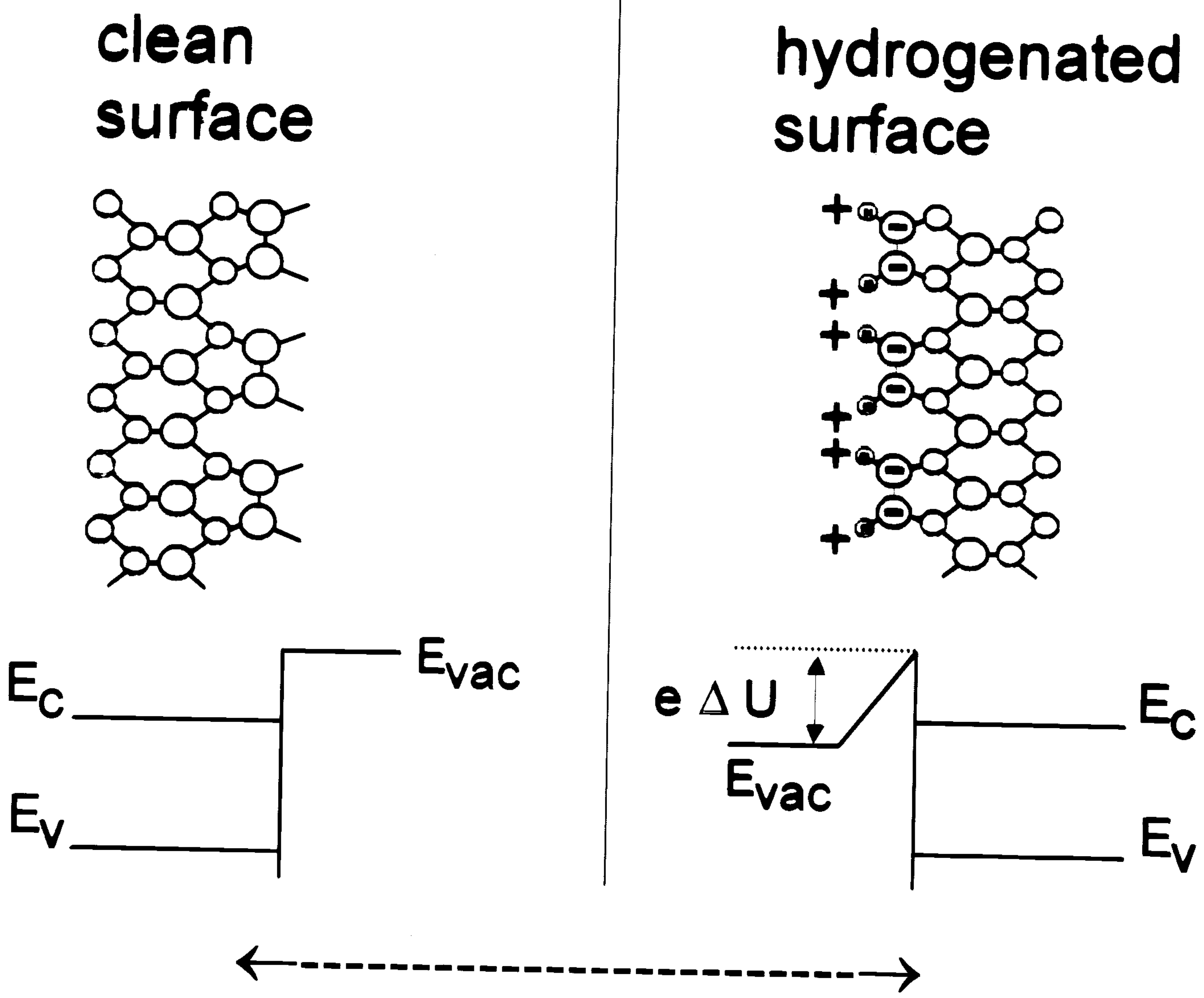


→ effektive negative Elektronenaffinität

Electron Affinity and Surface Fermi Level Position



Hydrogen Adsorption ←→ Electron Affinity



Charge transfer due to different electronegativities:
→ each C-H bond carries a dipole moment p

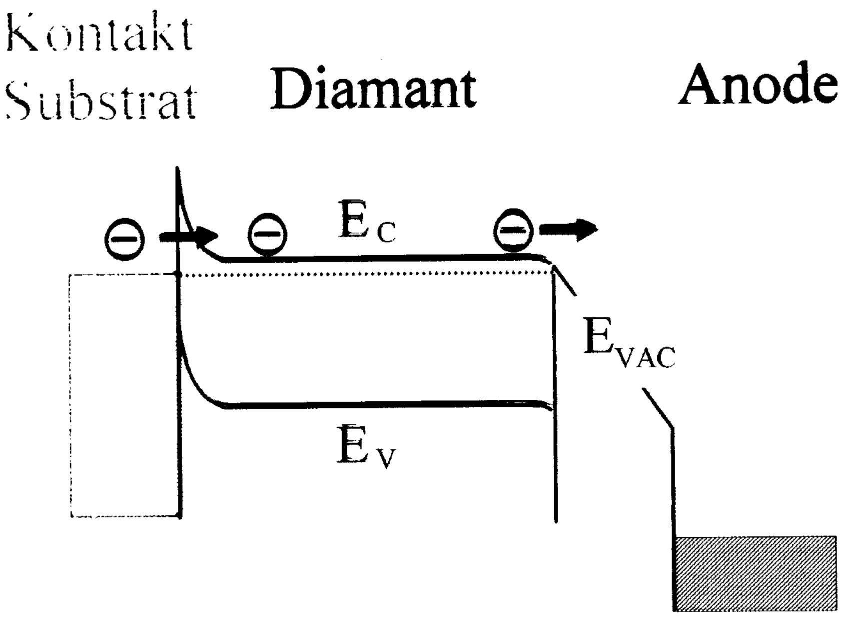
$$\rightarrow \quad e\Delta U = \chi(n) - \chi_0 = -\frac{e}{\varepsilon_0} \cdot n \cdot p \cdot f(n)$$

with the depolarization function as a small correction*

* J. Topping, Proc. Royal Soc. London, **A 114**, (1927)

Elektronenemission aus Diamant

Tunnelstrom durch Schottky-Diode auf n-Typ Halbleiter:



Vorwärtsstrom durch Schottky-Diode auf p-Typ Halbleiter: