

Materialwerte - Zusammenstellung zum Optoelektronikseminar GaAs - $\text{Ga}_x\text{In}_{1-x}\text{As}$ - $\text{Al}_x\text{In}_{1-x}\text{As}$ - InP

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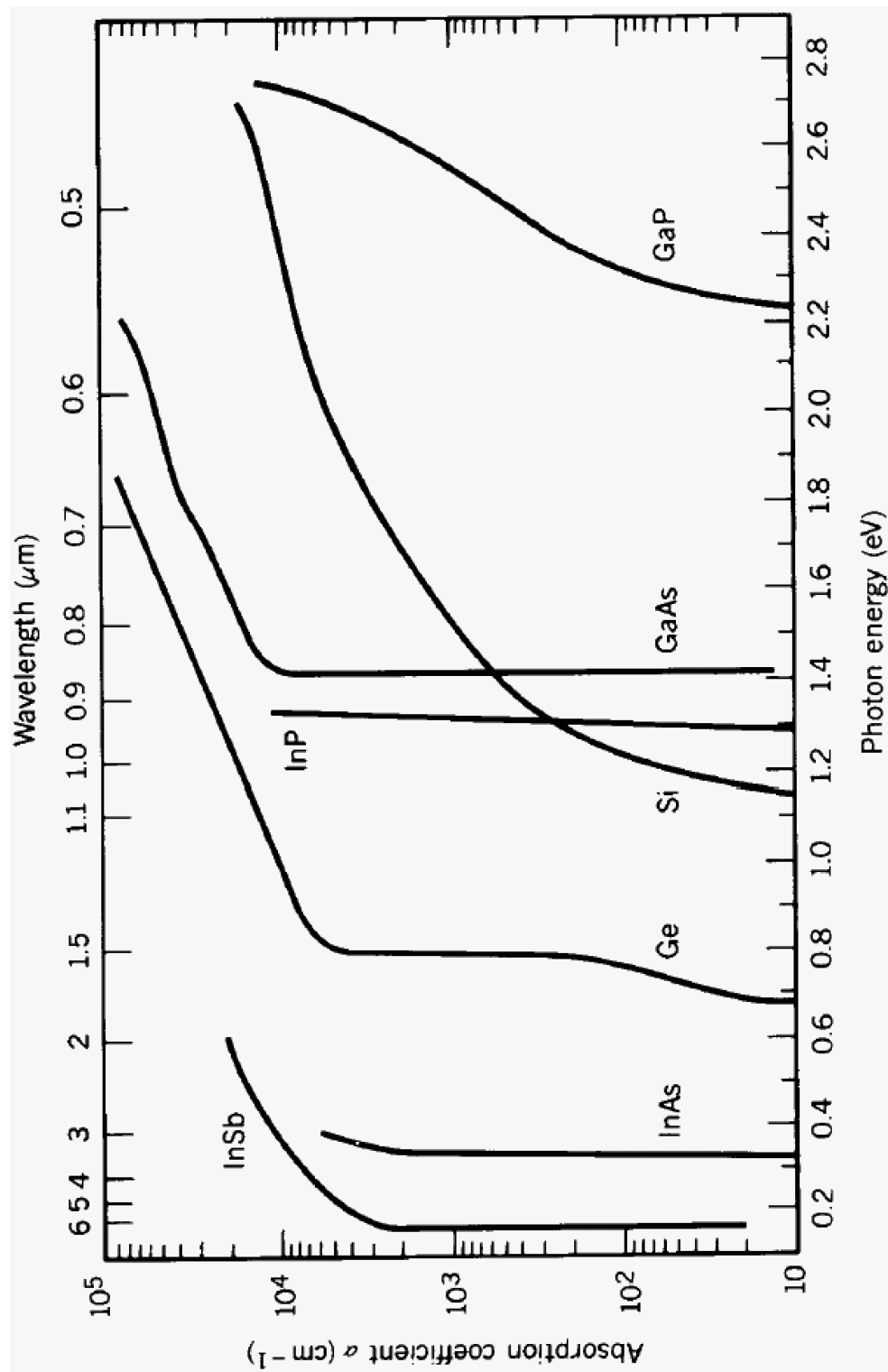
Erstellt: 1. Oktober 2009 – Letzte Revision: 30. Juni 2021

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Literatur

[002] <http://www.ioffe.ru/SVA/NSM/Semicond/>.



1 GaAs

[002]ff.

1.1 Originaltexte

Dokument nächste Seite folgend.

Si	- Silicon	Ge	- Germanium
GaP	- Gallium Phosphide	GaAs	- Gallium Arsenide
InAs	- Indium Arsenide	C	- Diamond
GaSb	- Gallium Antimonide	InSb	- Indium Antimonide
InP	- Indium Phosphide	GaAs_{1-x}Sb_x	- Gallium Arsenide Antimonide
Al_xGa_{1-x}As	- Aluminium Gallium Arsenide		
AlN	- Aluminium Nitride	InN	- Indium Nitride
BN	- Boron Nitride	GaN	- Gallium Nitride

We are going to add new data for:

Ga_xIn_{1-x}As_ySb_{1-y}	- Gallium Indium Arsenide Antimonide	Ga_xIn_{1-x}P	- Gallium Indium Phosphide
Ga_xIn_{1-x}As	- Gallium Indium Arsenide	Ga_xIn_{1-x}Sb	- Gallium Indium Antimonide
InAs_{1-x}Sb_x	- Indium Arsenide Antimonide	Ga_xIn_{1-x}As_yP_{1-y}	- Gallium Indium Arsenide Phosphide
Si_{1-x}Ge_x	- Silicon Germanium	SiC	- Silicon Carbide

This section is intended to systematize parameters of semiconductor compounds and heterostructures based on them. Such a WWW-archive has a number of advantages: in particular, it enables physicists, both theoreticians and experimentalists, to rapidly retrieve the semiconducting material parameters they are interested in. In addition, physical parameters - optical, electrical, mechanical, etc. - will be presented in the framework of the electronic archive for both the known and new semiconducting compounds. As the starting point in creating the database served the voluminous reference book *"Handbook Series on Semiconductor Parameters"* vol. 1,2 edited by M. Levinstein, S. Rumyantsev and M. Shur, World Scientific, London, 1996, 1999. We express sincere gratitude to M.E. Levinstein for help and attention to this work. A great number of reference books and original papers cited at the end of this section have been used in compiling the information database.

We would like to express our warmest gratitude to all colleagues presented their original data and literature references to complete these archive. If you find these archive pages helpful, and use the data retrieved through the server for your research, we would appreciate acknowledging it in your papers.

We would be indebted very much for any of your further suggestions and comments.

[Authors](#)

GaAs - Gallium Arsenide

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GaAs - Gallium Arsenide

Basic Parameters at 300 K

Crystal structure	Zinc Blende
Group of symmetry	T_d^2-F43m
Number of atoms in 1 cm^3	$4.42 \cdot 10^{22}$
de Broglie electron wavelength	240 Å
Debye temperature	360 K
Density	5.32 g cm^{-3}
Dielectric constant (static)	12.9
Dielectric constant (high frequency)	10.89
Effective electron mass m_e	$0.063m_0$
Effective hole masses m_h	$0.51m_0$
Effective hole masses m_{lp}	$0.082m_0$
Electron affinity	4.07 eV
Lattice constant	5.65325 Å
Optical phonon energy	0.035 eV

GaAs - Gallium Arsenide

Band structure and carrier concentration

[Basic Parameters](#)

[Temperature Dependences](#)

[Dependence of the Energy Gap on Hydrostatic Pressure](#)

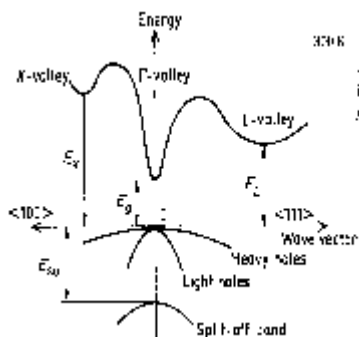
[Energy Gap Narrowing at High Doping Levels](#)

[Effective Masses](#)

[Donors and Acceptors](#)

Basic Parameters

Energy gap	1.424 eV
Energy separation ($E_{\Gamma L}$) between Γ and L valleys	0.29 eV
Energy separation ($E_{\Gamma X}$) between Γ and X valleys	0.48 eV
Energy spin-orbital splitting	0.34 eV
Intrinsic carrier concentration	$2.1 \cdot 10^6 \text{ cm}^{-3}$
Intrinsic resistivity	$3.3 \cdot 10^8 \Omega \cdot \text{cm}$
Effective conduction band density of states	$4.7 \cdot 10^{17} \text{ cm}^{-3}$
Effective valence band density of states	$9.0 \cdot 10^{18} \text{ cm}^{-3}$



Band structure and carrier concentration of GaAs. 300 K

$E_g = 1.42 \text{ eV}$
 $E_L = 1.71 \text{ eV}$
 $E_X = 1.90 \text{ eV}$
 $E_{so} = 0.34 \text{ eV}$

Temperature Dependences

Temperature dependence of the energy gap

$$E_g = 1.519 - 5.405 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

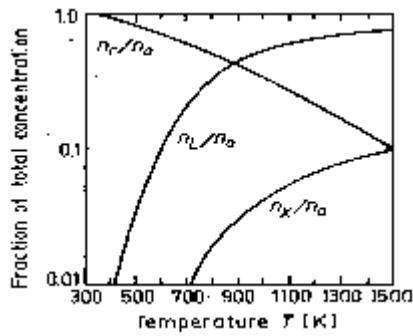
where T is temperatures in degrees K ($0 < T < 10^3$).

Temperature dependence of the energy difference between the top of the valence band and the bottom of the L-valley of the conduction band

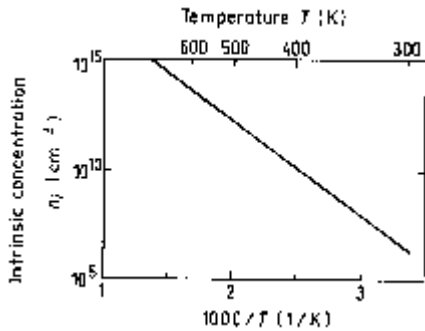
$$E_L = 1.815 - 6.05 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

Temperature dependence of the energy difference between the top of the valence band and the bottom of the X-valley of the conduction band

$$E_X = 1.981 - 4.60 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$



The temperature dependences of the relative populations of the Γ , L and X valleys.
([Blakemore \[1982\]](#)).



The temperature dependences of the intrinsic carrier concentration.
([Shur \[1990\]](#)).

Intrinsic Carrier Concentration

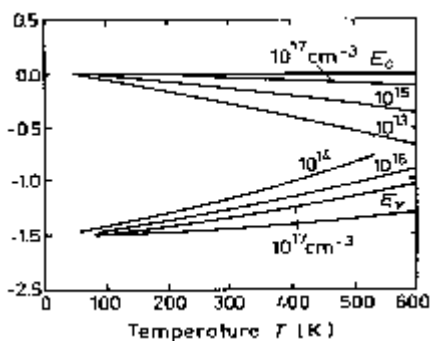
$$n_i = (N_c \cdot N_v)^{1/2} \exp(-E_g/(2k_b T))$$

Effective density of states in the conduction band taking into account the nonparabolicity of the Γ -valley and contributions from the X and L-valleys

$$N_c = 8.63 \cdot 10^{13} \cdot T^{3/2} [1 - 1.9310^{-4} \cdot T - 4.19 \cdot 10^{-8} \cdot T^2 + 21 \cdot \exp(-E_{\Gamma L}/(2k_b T)) + 44 \cdot \exp(-E_{\Gamma X}/(2k_b T))] \text{ (cm}^{-3}\text{)}$$

Effective density of states in the valence band

$$N_v = 1.83 \cdot 10^{15} \cdot T^{3/2} \text{ (cm}^{-3}\text{)}$$



Fermi level versus temperature for different concentrations of shallow donors and acceptors.

Dependences on Hydrostatic Pressure

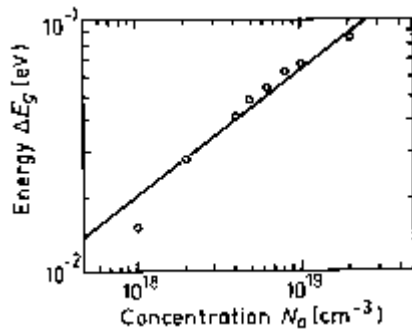
$$E_g = E_g(0) + 0.0126 \cdot P - 3.77 \cdot 10^{-5} P^2 \text{ (eV)}$$

$$E_L = E_L(0) + 5.5 \cdot 10^{-3} P \text{ (eV)}$$

$$E_X = E_X(0) + 1.5 \cdot 10^{-3} P \text{ (eV)}$$

where P is pressure in kbar.

Energy Gap Narrowing at High Doping Levels



Energy gap narrowing at high doping levels.

([Tiwari and Wright \[1990\]](#))

$$\Delta E_g \approx 2 \cdot 10^{-11} \cdot N_a^{-1/2} \text{ (eV) } (N_a \text{ in cm}^{-3})$$

Effective Masses

Electrons:

For Γ -valley $m_\Gamma = 0.063m_0$

In the L-valley the surfaces of equal energy are ellipsoids

$$m_l = 1.9m_0$$

$$m_t = 0.075m_0$$

Effective mass of density of states

$$m_L = (16m_l m_t^2)^{1/3} \quad m_L = 0.85m_0$$

In the X-valley the surfaces of equal energy are ellipsoids

$$m_l = 1.9m_0$$

$$m_t = 0.19m_0$$

Effective mass of density of states

$$m_X = (9m_l m_t^2)^{1/3} \quad m_X = 0.85m_0$$

Holes:

Heavy $m_h = 0.51m_0$

Light $m_{lp} = 0.082m_0$

Split-off band $m_{so} = 0.15m_0$

Effective mass of density of states $m_v = 0.53m_0$

Donors and Acceptors

Ionization energies of shallow donors (eV)

([Milnes \[1973\]](#))

S Se Si Ge Sn Te

~0.006 ~0.006 ~0.006 ~0.006 ~0.006 ~0.03

Ionization energies of shallow acceptors (eV)

([Milnes \[1973\]](#))

C Si Ge Zn Sn

~0.02 ~0.03/0.1/0.22 ~0.03 ~0.025 ~0.2

GaAs - Gallium Arsenide

Electrical properties

[Basic Parameters](#)

[Mobility and Hall Effect](#)

[Transport Properties in High Electric Fields](#)

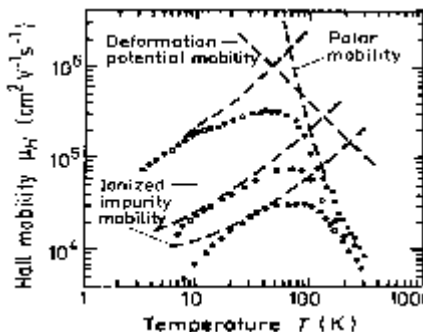
[Impact Ionization](#)

[Recombination Parameters](#)

Basic Parameters

Breakdown field	$\approx 4 \cdot 10^5$ V/cm
Mobility electrons	≤ 8500 cm ² V ⁻¹ s ⁻¹
Mobility holes	≤ 400 cm ² V ⁻¹ s ⁻¹
Diffusion coefficient electrons	≤ 200 cm ² /s
Diffusion coefficient holes	≤ 10 cm ² /s
Electron thermal velocity	$4.4 \cdot 10^5$ m/s
Hole thermal velocity	$1.8 \cdot 10^5$ m/s

Mobility and Hall Effect



Electron Hall mobility versus temperature for different doping levels.

([Stillman et al. \[1970\]](#))

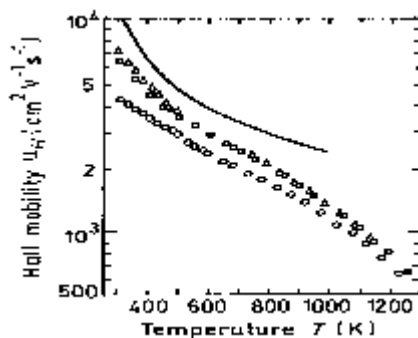
1. Bottom curve: $N_d = 5 \cdot 10^{15}$ cm⁻³;

2. Middle curve: $N_d = 10^{15}$ cm⁻³;

3. Top curve: $N_d = 5 \cdot 10^{15}$ cm⁻³

For weakly doped GaAs at temperature close to 300 K, electron Hall mobility

$$\mu_H = 9400(300/T) \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$



Electron Hall mobility versus temperature for different doping levels and degrees of compensation (high temperatures):

Open circles: $N_d = 4N_a = 1.2 \cdot 10^{17}$ cm⁻³;

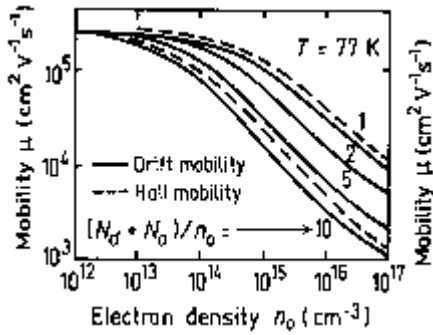
Open squares: $N_d = 4N_a = 10^{16}$ cm⁻³;

Open triangles: $N_d = 3N_a = 2 \cdot 10^{15}$ cm⁻³;

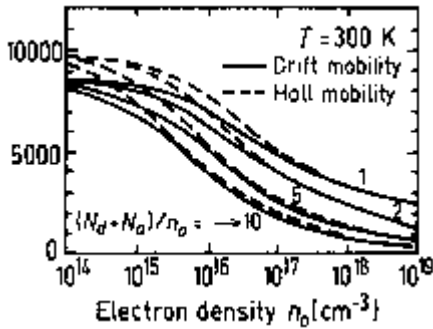
Solid curve represents the calculation for pure GaAs ([Blakemore \[1982\]](#)).

For weakly doped GaAs at temperature close to 300 K, electron drift mobility

$$\mu_n = 8000(300/T)^{2/3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$



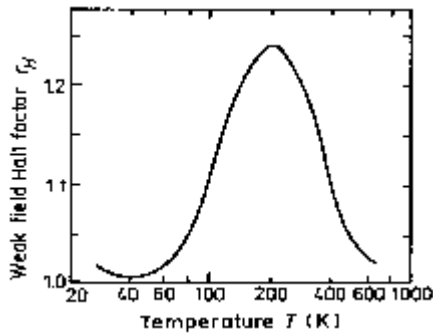
Drift and Hall mobility versus electron concentration for different degrees of compensation $T = 77$ K
(Rode [1975]).



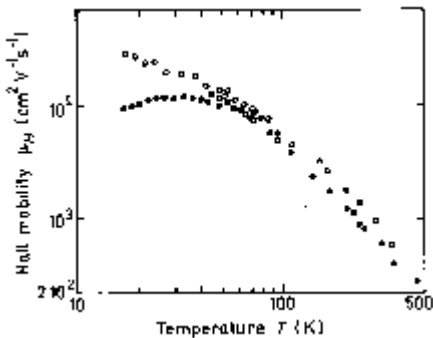
Drift and Hall mobility versus electron concentration for different degrees of compensation $T = 300$ K
(Rode [1975]).

Approximate formula for the Hall mobility

$\mu_n = \mu_{OH} / (1 + N_d \cdot 10^{-17})^{1/2}$, where $\mu_{OH} \approx 9400$ ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$), N_d in cm^{-3}
(Hilsum [1974]).



Temperature dependence of the Hall factor for pure n -type GaAs in a weak magnetic field
(Rode [1975]).

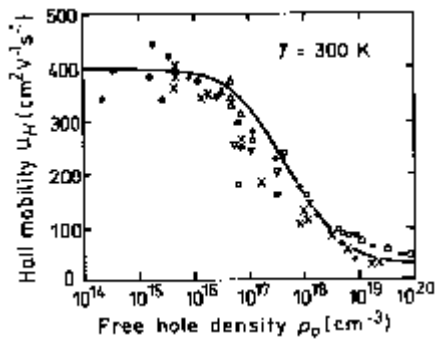


Temperature dependence of the Hall mobility for three high-purity samples
(Wiley [1975]).

For GaAs at temperatures close to 300 K, hole Hall mobility

$$\mu_{pH} = \left[0.0025 \left(\frac{T}{300} \right)^{2.3} + 4 \times 10^{21} p \left(\frac{T}{300} \right)^{1.5} \right]^{-1} (\text{cm}^2 \text{V}^{-1} \text{s}^{-1}), (p - \text{in cm}^{-3})$$

For weakly doped GaAs at temperature close to 300 K, Hall mobility
 $\mu_{pH} = 400(300/T)^{2.3}$ ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$).

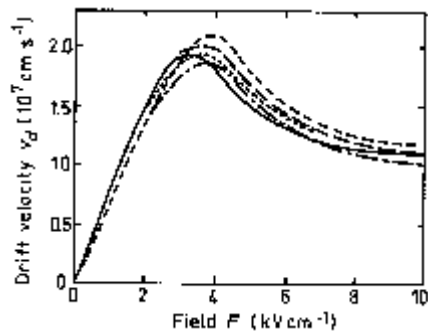


The hole Hall mobility versus hole density.
(Wiley [1975])

At $T = 300 \text{ K}$, the Hall factor in pure GaAs

$$r_H = 1.25.$$

Transport Properties in High Electric Fields

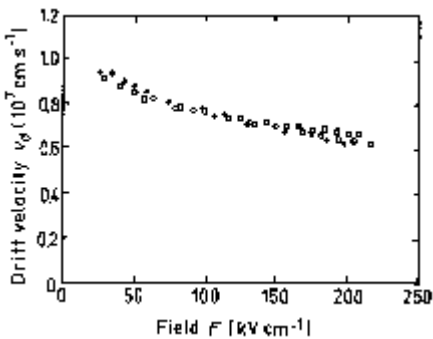


Field dependences of the electron drift velocity.

(Blakemore [1982]).

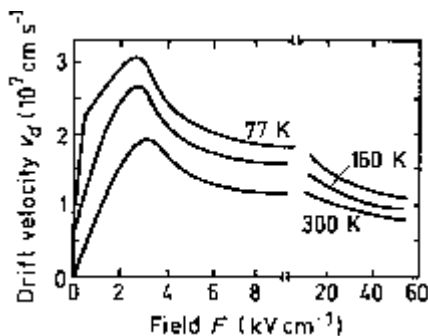
Solid curve was calculated by (Pozhela and Reklaitis [1980]).

Dashed and dotted curves are measured data, 300 K



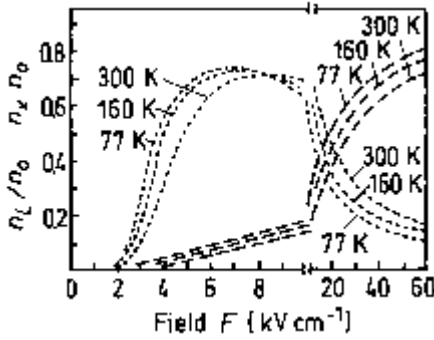
Field dependences of the electron drift velocity for high electric fields, 300 K.

(Blakemore [1982]).

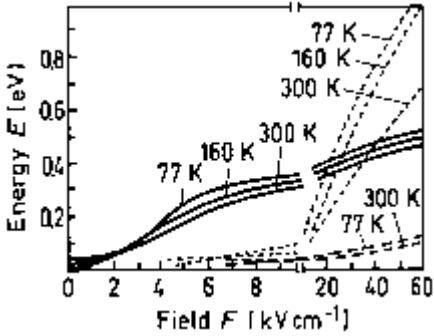


Field dependences of the electron drift velocity at different temperatures.

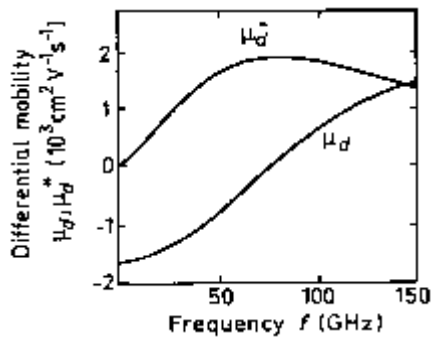
(Pozhela and Reklaitis [1980]).



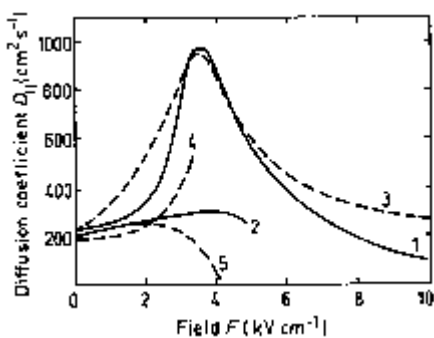
Fraction of electrons in L and X valleys. n_L and n_X as a function of electric field F at 77, 160, and 300 K, $N_d=0$
[\(Pozhela and Reklaitis\[1980\]\).](#)
Dotted curve - L valleys, dashed curve - X valleys.



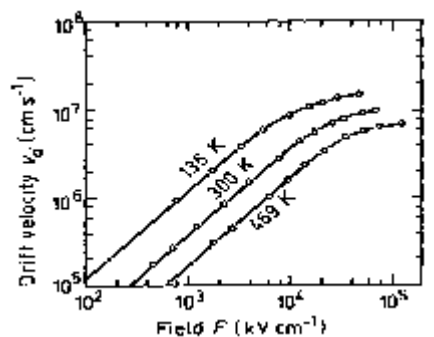
Mean energy E in Γ , L , and X valleys as a function of electric field F at 77, 160, and 300 K, $N_d=0$
[\(Pozhela and Reklaitis\[1980\]\).](#)
Solid curve - Γ valleys, dotted curve - L valleys, dashed curve - X valleys.



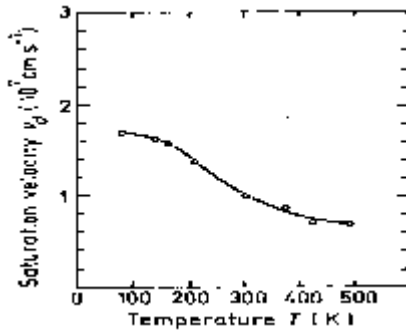
Frequency dependences of electron differential mobility.
 μ_d is real part of the differential mobility; μ_d^* is imaginary part of differential mobility.
 $F=5.5 \text{ kV cm}^{-1}$
[\(Rees\[1969\]\).](#)



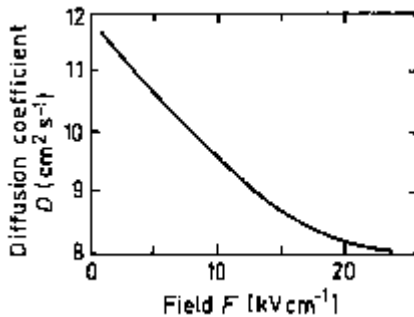
The field dependence of longitudinal electron diffusion coefficient $D||F$.
Solid curves 1 and 2 are theoretical calculations. Dashed curves 3, 4, and 5 are experimental data.
Curve 1 - from [\(Pozhela and Reklaitis\[1980\]\).](#)
Curve 2 - from [\(Fauquembergue et al.\[1980\]\).](#)
Curve 3 - from [\(Ruch and Kino\[1968\]\).](#)
Curve 4 - from [\(Bareikis et al.\[1978\]\).](#)
Curve 5 - [\(from de Murcia\[1991\]\).](#)



Field dependences of the hole drift velocity at different temperatures.
[\(Datal et al. \[1971\]\).](#)



Temperature dependence of the saturation hole velocity in high electric fields
([Datal et al. \[1971\]](#)).

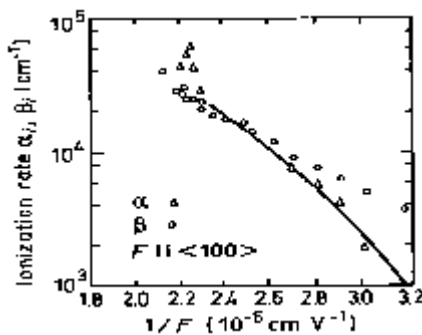


The field dependence of the hole diffusion coefficient.
([Joshi and Crendin \[1989\]](#)).

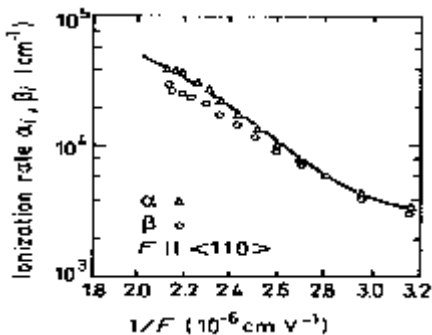
Impact Ionization

There are two schools of thought regarding the impact ionization in GaAs.

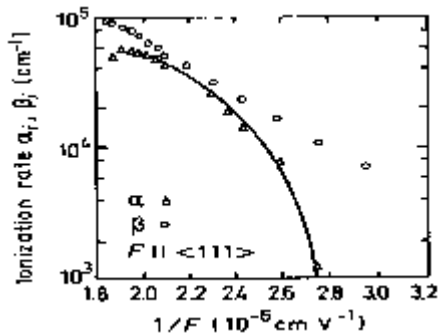
The first one states that impact ionization rates α_i and β_i for electrons and holes in GaAs are known accurately enough to distinguish such subtle details such as the anisotropy of α_i and β_i for different crystallographic directions. This approach is described in detail in the work by Dmitriev et al.[1987].



Experimental curves α_i and β_i versus $1/F$ for GaAs.
([Pearsall et al. \[1978\]](#)).



Experimental curves α_i and β_i versus $1/F$ for GaAs.
([Pearsall et al. \[1978\]](#)).



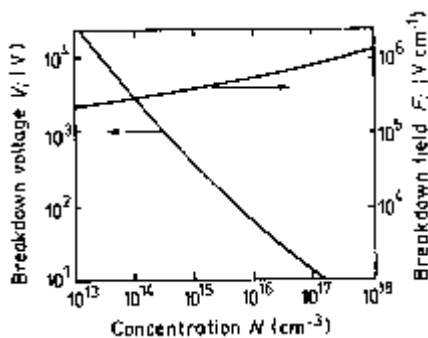
Experimental curves α_i and β_i versus $1/F$ for GaAs.

([Pearsall et al. \[1978\]](#)).

The second school focuses on the values of α_i and β_i for the same electric field reported by different researches differ by an order of magnitude or more. This point of view is explained by Kyuregyan and Yurkov [1989]. According to this approach we can assume that $\alpha_i = \beta_i$. Approximate formula for the field dependence of ionization rates:

$$\alpha_i = \beta_i = \alpha_0 \exp[\delta - (\delta^2 + (F_0/F)^2)^{1/2}]$$

where $\alpha_0 = 0.245 \cdot 10^6 \text{ cm}^{-1}$; $\beta = 57.6 F_0 = 6.65 \cdot 10^6 \text{ V cm}^{-1}$ (Kyuregyan and Yurkov [1989]).



Breakdown voltage and breakdown field versus doping density for an abrupt p - n junction.

([Kyuregyan and Yurkov \[1989\]](#)).

Recombination Parameter

Pure n-type material ($n_0 \sim 10^{14} \text{ cm}^{-3}$)

The longest lifetime of holes $\tau_p \sim 3 \cdot 10^{-6} \text{ s}$

Diffusion length $L_p = (D_p \cdot \tau_p)^{1/2}$ $L_p \sim 30\text{-}50 \text{ }\mu\text{m}$.

Pure p-type material

(a) Low injection level

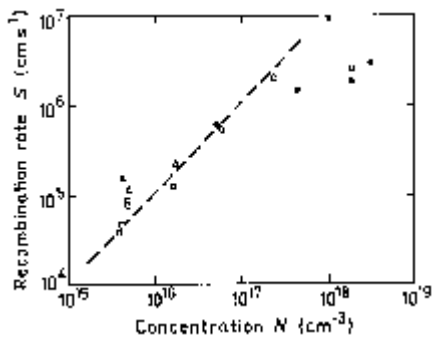
The longest lifetime of electrons $\tau_n \sim 5 \cdot 10^{-9} \text{ s}$

Diffusion length $L_n = (D_n \cdot \tau_n)^{1/2}$ $L_n \sim 10 \text{ }\mu\text{m}$

(b) High injection level (filled traps)

The longest lifetime of electrons $\tau \sim 2.5 \cdot 10^{-7} \text{ s}$

Diffusion length L_n $L_n \sim 70 \text{ }\mu\text{m}$



Surface recombination velocity versus doping density

([Aspnes \[1983\]](#)).

Different experimental points correspond to different surface treatment methods.

Radiative recombination coefficient ([Varshni\[1967\]](#))

90 K $1.8 \cdot 10^{-8} \text{cm}^3/\text{s}$

185 K $1.9 \cdot 10^{-9} \text{cm}^3/\text{s}$

300 K $7.2 \cdot 10^{-10} \text{cm}^3/\text{s}$

Auger coefficient

300 K $\sim 10^{-30} \text{cm}^6/\text{s}$

500 K $\sim 10^{-29} \text{cm}^6/\text{s}$

GaAs - Gallium Arsenide

Optical properties

Infrared refractive index 3.3

Radiative recombination coefficient $7 \cdot 10^{-10} \text{ cm}^3/\text{s}$

Infrared refractive index

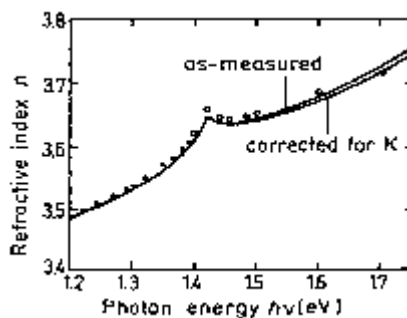
$n = k^{1/2} = 3.255 \cdot (1 + 4.5 \cdot 10^{-5} T)$
for 300 K $n = 3.299$

Long-wave TO phonon energy

$h\nu_{TO} = 33.81 \cdot (1 - 5.5 \cdot 10^{-5} T) \text{ (meV)}$
for 300 K $h\nu_{TO} = 33.2 \text{ meV}$

Long-wave LO phonon energy

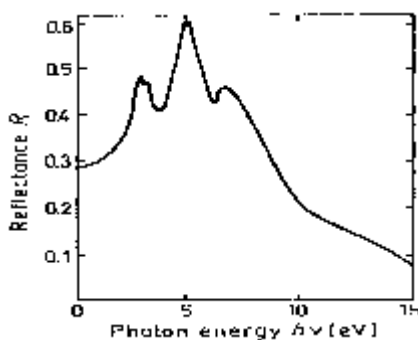
$h\nu_{LO} = 36.57 \cdot (1 - 4 \cdot 10^{-5} T) \text{ (meV)}$
for 300 K $h\nu_{LO} = 36.1 \text{ meV}$



Refractive index n versus photon energy for a high-purity

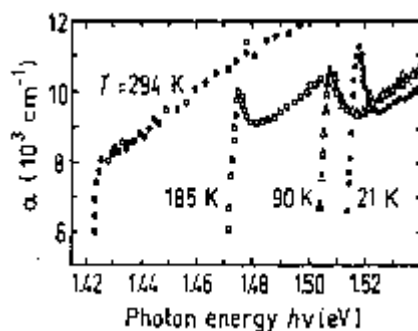
GaAs. ($n_0 \sim 5 \cdot 10^{13} \text{ cm}^{-3}$).

Solid curve is deduced from two-beam reflectance measurements at 279 K. Dark circles are obtained from refraction measurements. Light circles are calculated from Kramers-Kronig analysis ([Blakemore \[1982\]](#)).



Normal incidence reflectivity versus photon energy.

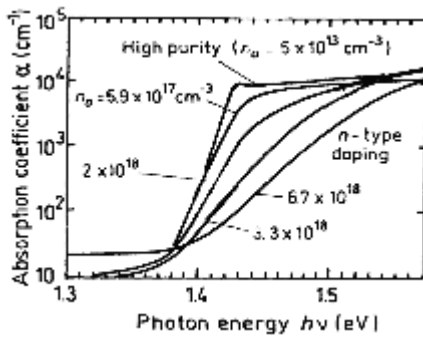
([Phillip and Ehrenreich \[1963\]](#)).



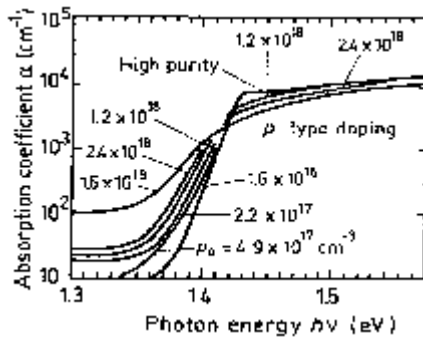
Intrinsic absorption coefficient near the intrinsic absorption edge for different temperatures.

([Sturge \[1962\]](#)).

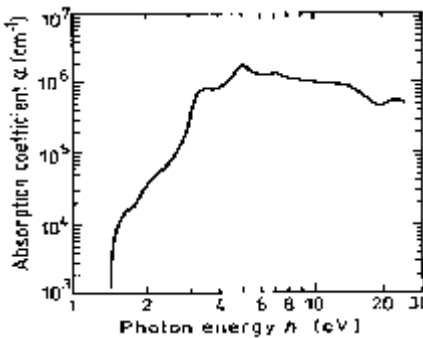
A ground state Rydberg energy $R_{XI} = 4.2 \text{ meV}$



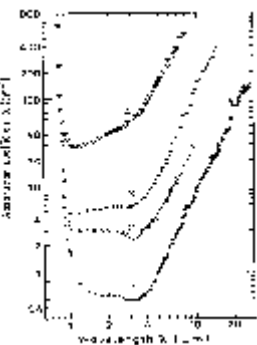
Intrinsic absorption edge at 297 K at different doping levels. *n*-type doping
(Casey et al. [1975]).



Intrinsic absorption edge at 297 K at different doping levels. *p*-type doping
(Casey et al. [1975]).



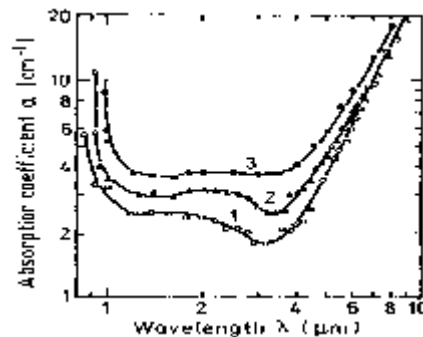
The absorption coefficient versus photon energy from intrinsic edge to 25 eV.
(Casey et al. [1975]).



Free carrier absorption versus wavelength at different doping levels, 296 K
(Spitzer and Whelan [1959]).

Conduction electron concentrations are:

1. $1.3 \cdot 10^{17} \text{ cm}^{-3}$; 2. $4.9 \cdot 10^{17} \text{ cm}^{-3}$; 3. 10^{18} cm^{-3} ; 4. $5.4 \cdot 10^{18} \text{ cm}^{-3}$



Free carrier absorption versus wavelength at different temperatures.
 $n_0 = 4.9 \cdot 10^{17} \text{ cm}^{-3}$ (Spitzer and Whelan [1959])
Temperatures are: 1. 100 K; 2. 297 K; 3. 443 K.

At 300 K

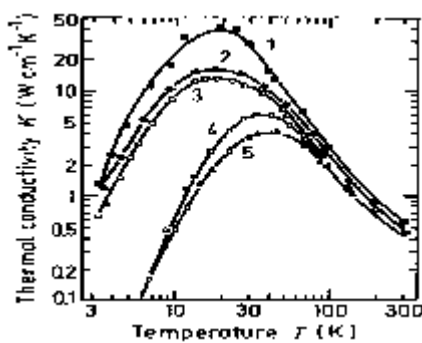
For $\lambda \sim 2 \mu\text{m}$ $\alpha = 6 \cdot 10^{-18} n_0 \text{ (cm}^{-1}\text{)}$ (n_0 - in cm^{-3})

For $\lambda > 4 \mu\text{m}$ and $10^{17} < n_0 < 10^{18} \text{ cm}^{-3}$ $\alpha \approx 7.5 \cdot 10^{-20} n_0 \cdot \lambda^3 \text{ (cm}^{-1}\text{)}$ (n_0 - in cm^{-3} , λ - μm)

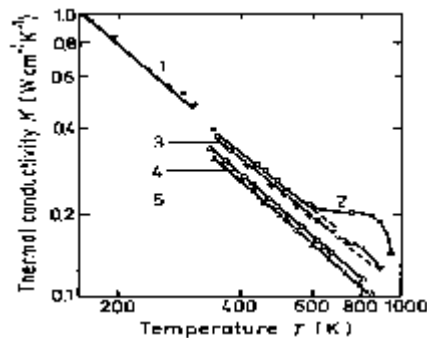
GaAs - Gallium Arsenide

Thermal properties

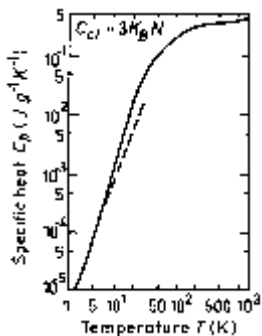
Bulk modulus	$7.53 \cdot 10^{11} \text{ dyn cm}^{-2}$
Melting point	$1240 \text{ }^{\circ}\text{C}$
Specific heat	$0.33 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$
Thermal conductivity	$0.55 \text{ W cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$
Thermal diffusivity	$0.31 \text{ cm}^2 \text{ s}^{-1}$
Thermal expansion, linear	$5.73 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$



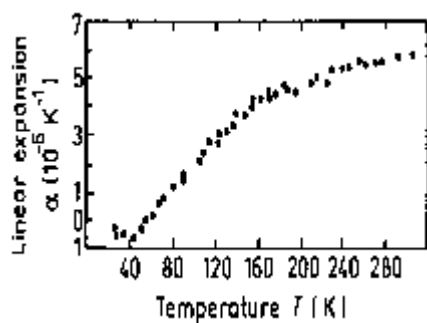
Temperature dependence of thermal conductivity
n-type sample, $n_0 \text{ (cm}^{-3}\text{)}$: 1. 10^{16} ; 2. $1.4 \cdot 10^{16}$; 3. 10^{18} ;
p-type sample, $p_0 \text{ (cm}^{-3}\text{)}$: 4. $3 \cdot 10^{18}$; 5. $1.2 \cdot 10^{19}$.
[\(Carlson et al \[1965\]\).](#)



Temperature dependence of thermal conductivity (for high temperature)
n-type sample, $n_0 \text{ (cm}^{-3}\text{)}$: 1. $7 \cdot 10^{15}$; 2. $5 \cdot 10^{16}$; 3. $4 \cdot 10^{17}$; 4. $8 \cdot 10^{18}$;
p-type sample, $p_0 \text{ (cm}^{-3}\text{)}$: 5. $6 \cdot 10^{19}$.
[\(Blakemore \[1982\]\).](#)



Temperature dependence of specific heat at constant pressure C_p
 $3k_B N = 0.345 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$.
 N is the number of atoms in 1 g of GaAs.
Dashed line: $C_p = (4\pi^2 C_{cl} / 5\theta_0^3) \cdot T^3$ for $\theta_0 = 345 \text{ K}$.
[\(Blakemore \[1982\]\).](#)



Temperature dependence of linear expansion coefficient α
[\(Novikova \[1961\]\).](#)

Melting point	$T_m=1513\text{ K}$
For $0 < P < 45\text{ kbar}$	$T_m= 1513 - 3.5P$ (P in kbar)
Saturated vapor pressure (in Pascals)	
1173 K	1
1323 K	100

GaAs - Gallium Arsenide

Mechanical properties, elastic constants, lattice vibrations

[Basic Parameter](#)

[Elastic constants](#)

[Acoustic Wave Speeds](#)

[Phonon frequencies](#)

Basic Parameter

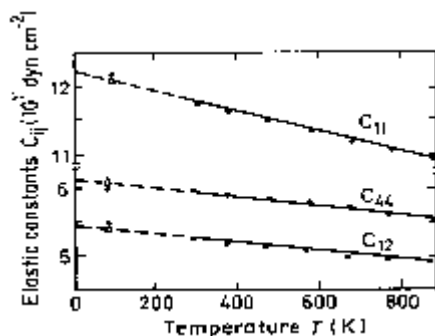
Bulk modulus	$7.53 \cdot 10^{11} \text{ dyn cm}^{-2}$
Density	5.317 g cm^{-3}
Hardness on the Mohs scale	between 4 and 5
Surface microhardness (using Knoop's pyramid test)	750 kg mm^{-2}
Cleavage plane	{110}
Piezoelectric constant	$e_{14} = -0.16 \text{ C m}^{-2}$

Elastic constants 300 K.

$$C_{11} = 11.90 \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{12} = 5.34 \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{44} = 5.96 \cdot 10^{11} \text{ dyn/cm}^2$$



Temperature dependences of elastic constants.

For $0 < T < T_m = 1513 \text{ K}$ (in units of $10^{11} \text{ dyn cm}^{-2}$)

$$C_{11} = 12.17 - 1.44 \cdot 10^{-3} T$$

$$C_{12} = 5.46 - 0.64 \cdot 10^{-3} T$$

$$C_{44} = 6.16 - 0.70 \cdot 10^{-3} T$$

(Burenkov et al. [1973])

For T = 300 K

Bulk modulus (compressibility ⁻¹)	$B_s = 7.53 \cdot 10^{11} \text{ dyn/cm}^2$
Shear modulus	$C' = 3.285 \cdot 10^{11} \text{ dyn/cm}^2$
[100] Young's modulus	$Y_0 = 8.59 \cdot 10^{11} \text{ dyn/cm}^2$
[100] Poisson ratio	$\sigma_0 = 0.31$

Acoustic Wave Speeds

Wave propagation	Wave character	Expression for wave speed	Wave speed (in units of
------------------	----------------	---------------------------	-------------------------

Direction			10 ⁵ cm/s)
[100]	V _L	$(C_{11}/\rho)^{1/2}$	4.73
	V _T	$(C_{44}/\rho)^{1/2}$	3.35
[110]	V _l	$[(C_{11}+C_{12}+2C_{44})/2\rho]^{1/2}$	5.24
	V _t	$V_{t }=V_T=(C_{44}/\rho)^{1/2}$	3.35
	V _{t⊥}	$[(C_{11}-C_{12})/2\rho]^{1/2}$	2.48
[111]	V _{l'}	$[(C_{11}+2C_{12}+4C_{44})/3\rho]^{1/2}$	5.4
	V _{t'}	$[(C_{11}-C_{12}+C_{44})/3\rho]^{1/2}$	2.8

Phonon frequencies

(in units of 10¹² Hz) ([Waugh and Dolling, \[1963\]](#))

$\nu_{TO}(\Gamma)$ 8.02 $\nu_{LO}(X)$ 7.22

$\nu_{LO}(\Gamma)$ 8.55 $\nu_{TA}(L)$ 1.86

$\nu_{TA}(X)$ 2.36 $\nu_{LA}(L)$ 6.26

$\nu_{LA}(X)$ 6.80 $\nu_{TO}(L)$ 7.84

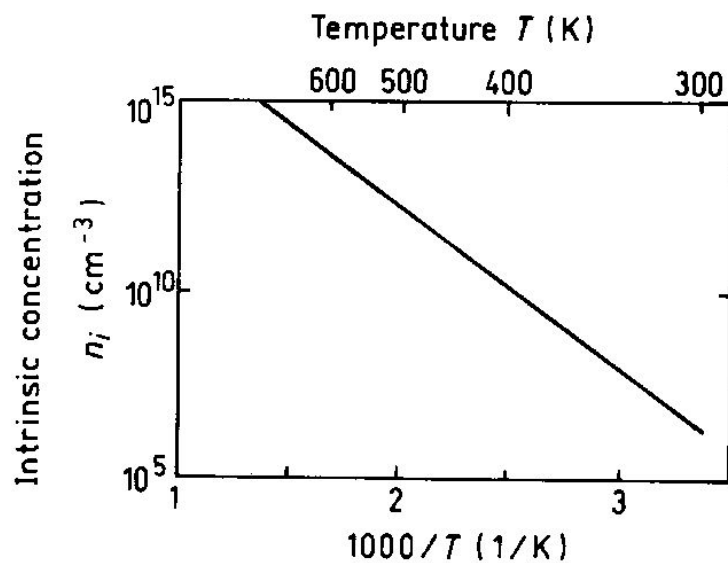
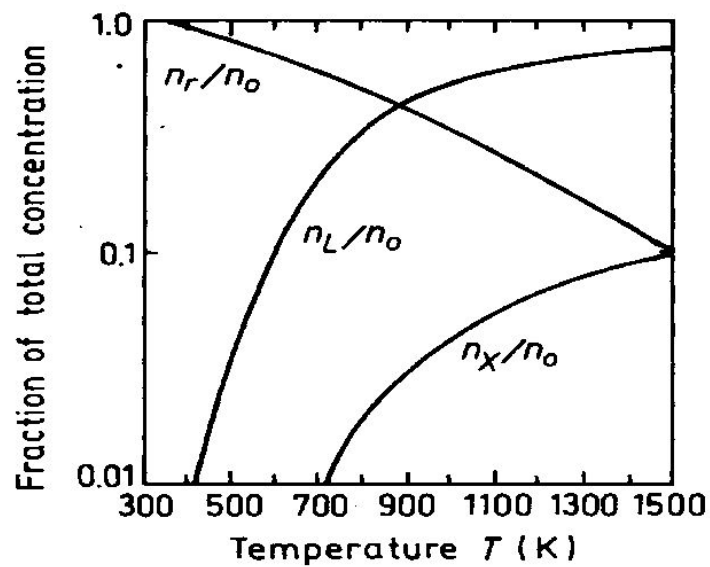
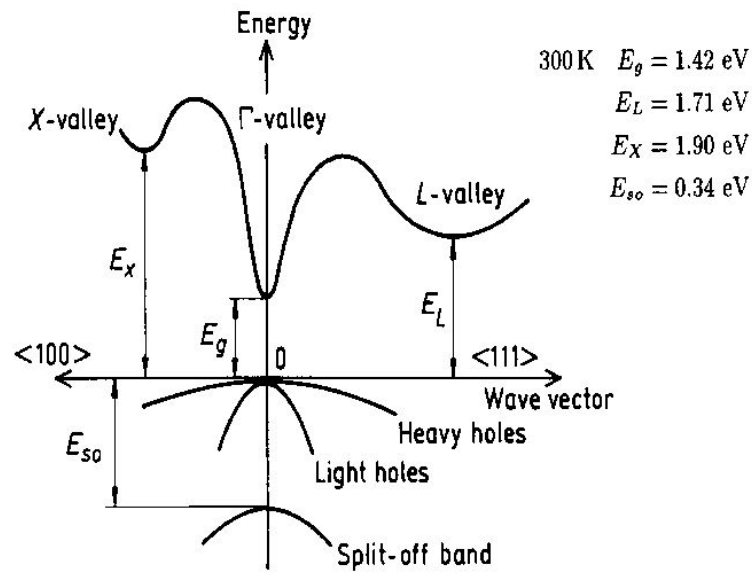
$\nu_{TO}(X)$ 7.56 $\nu_{LO}(L)$ 7.15

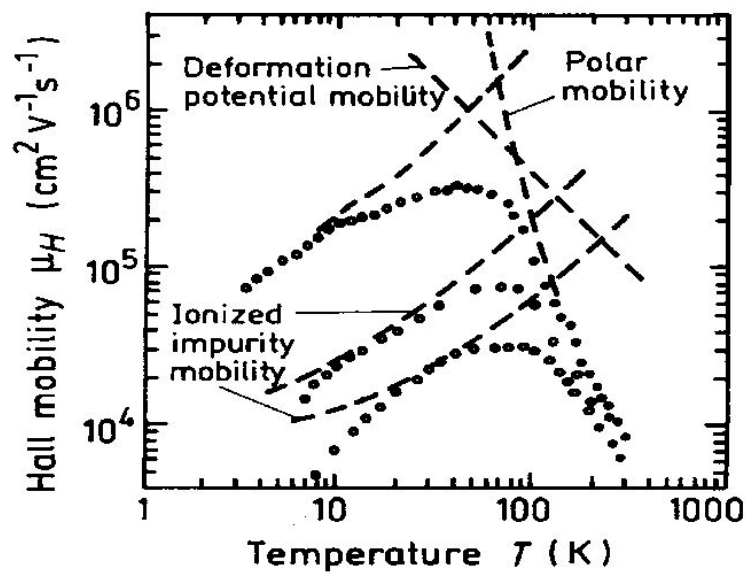
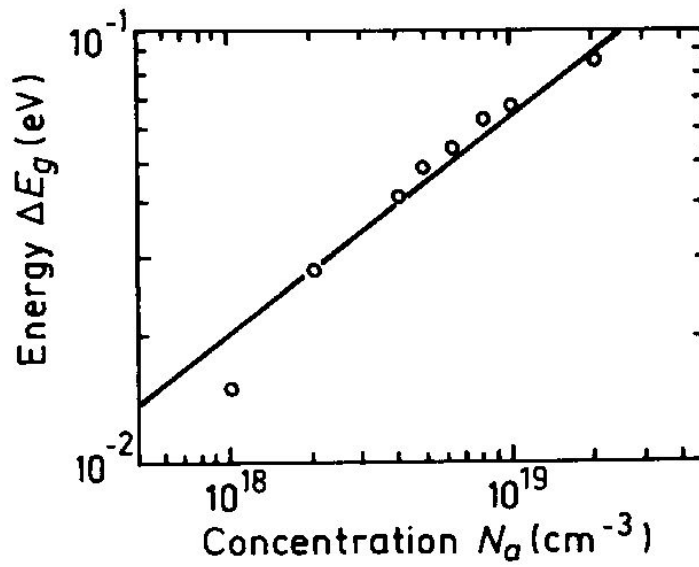
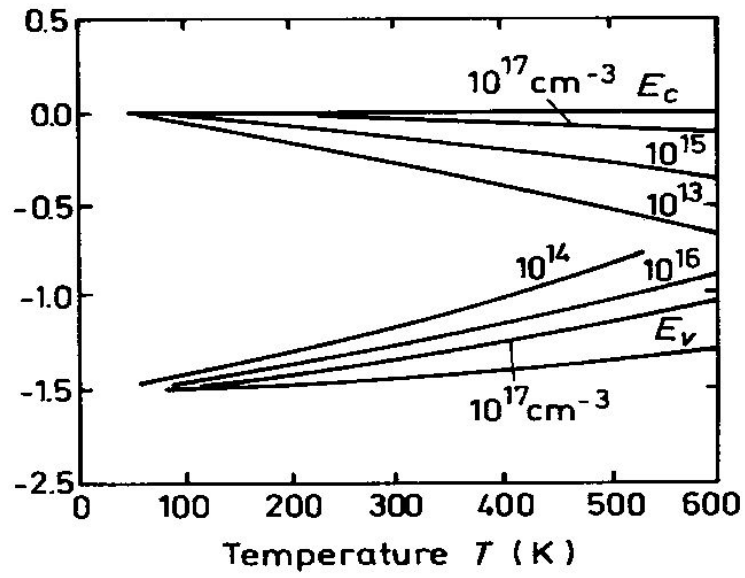
GaAs - Gallium Arsenide

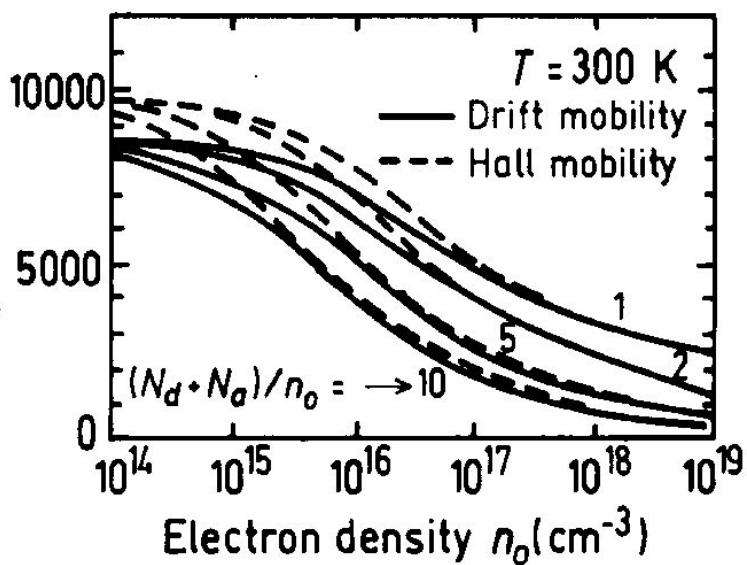
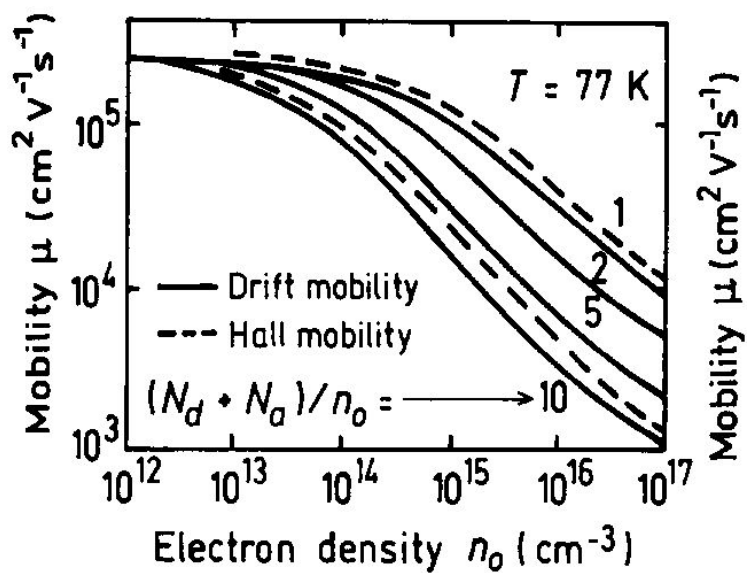
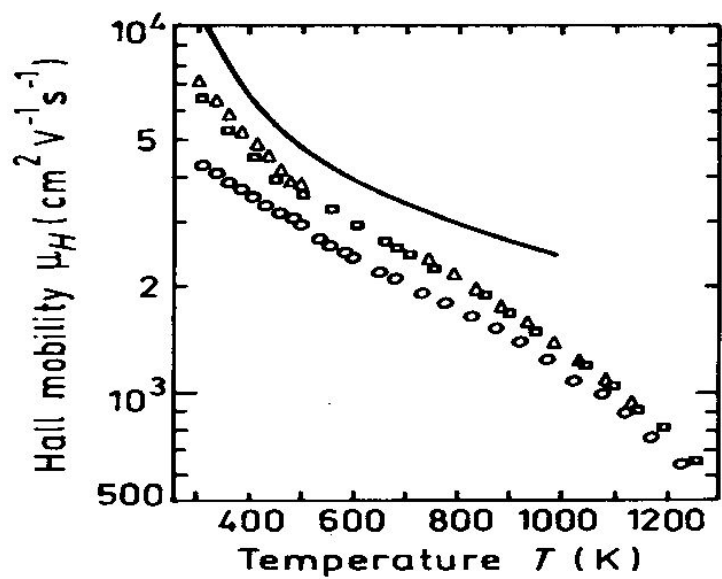
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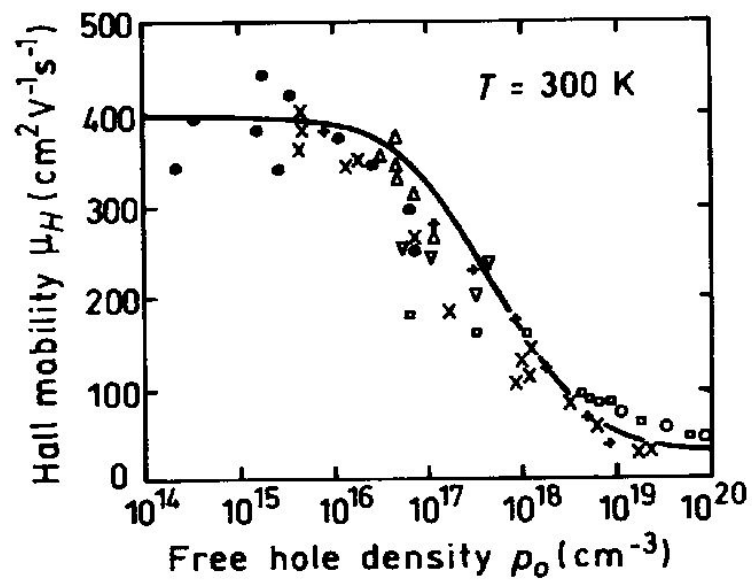
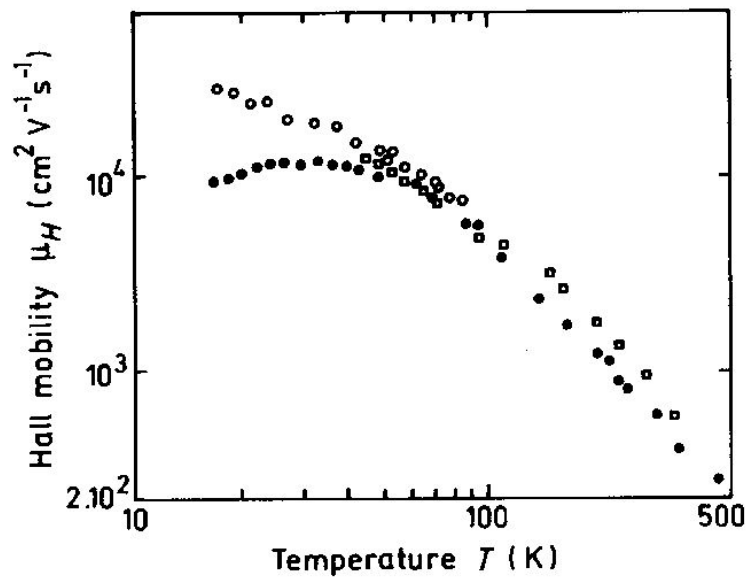
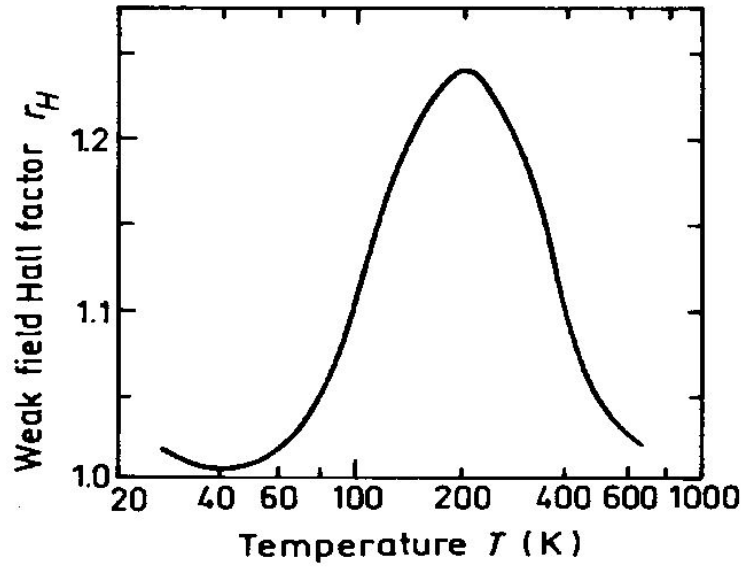
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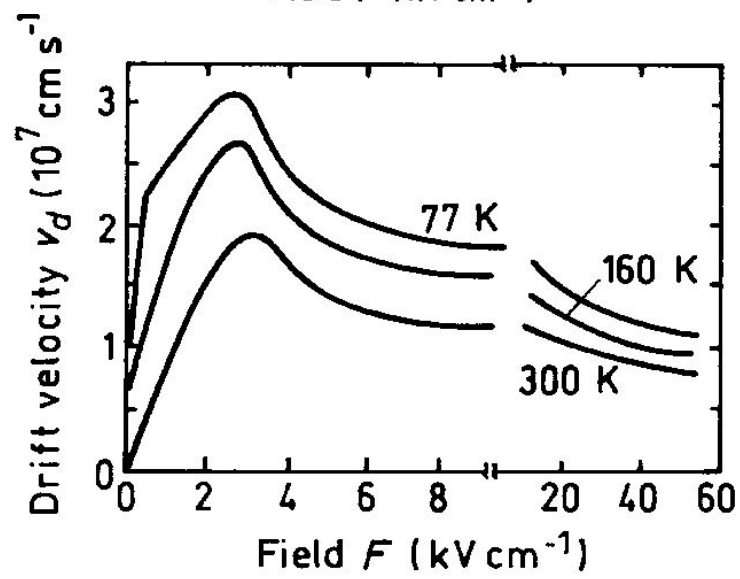
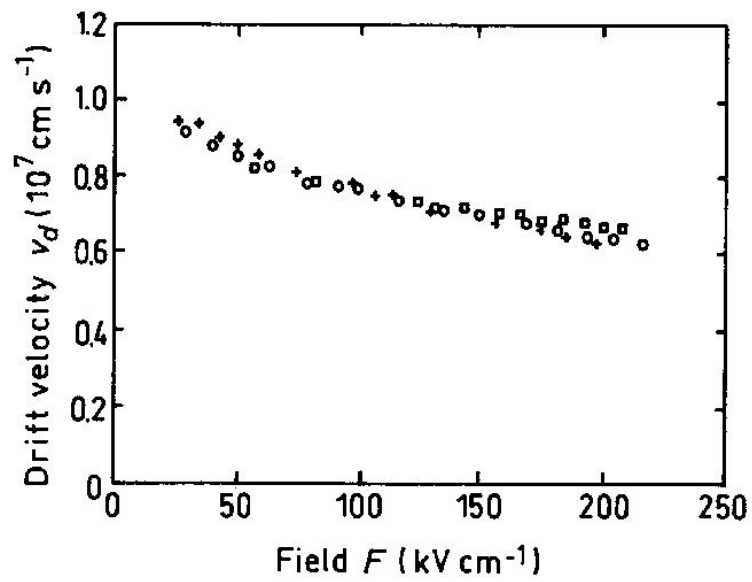
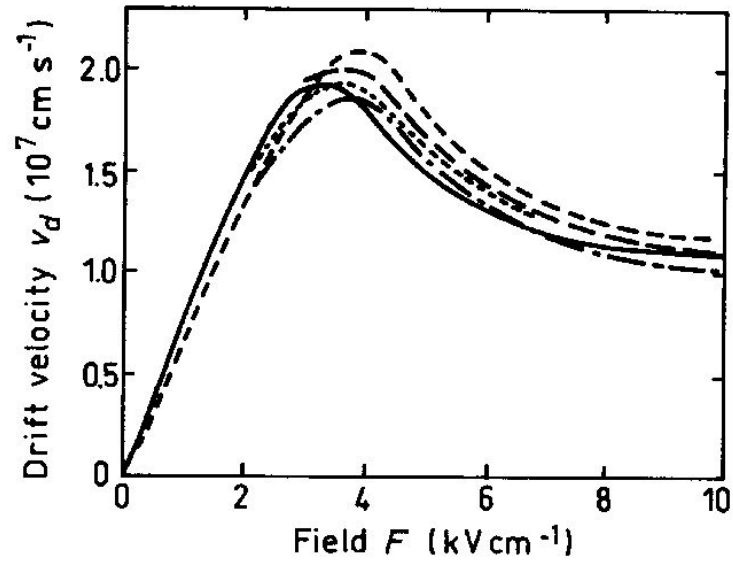
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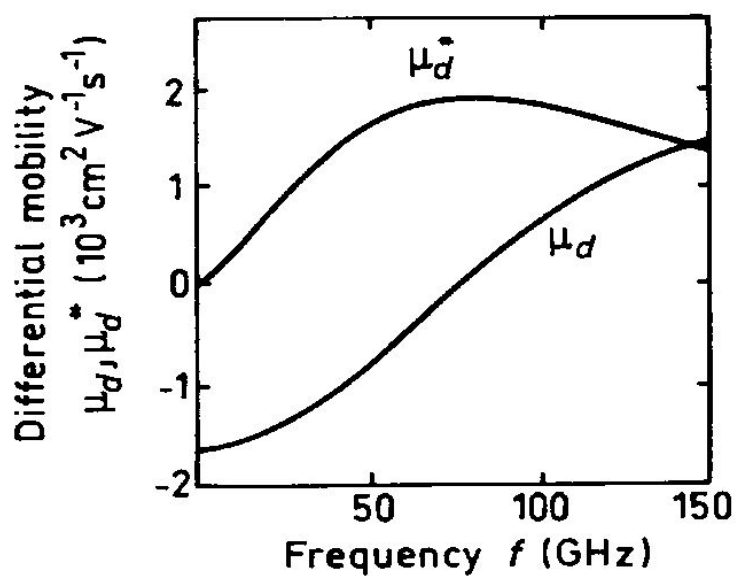
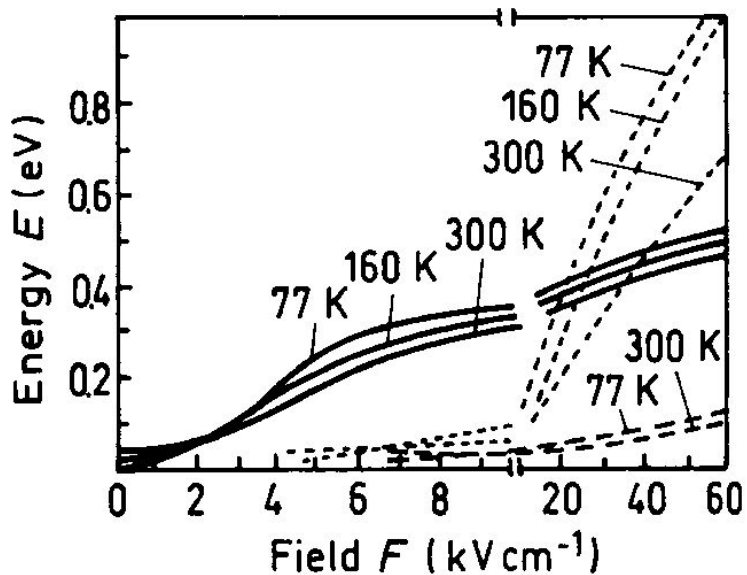
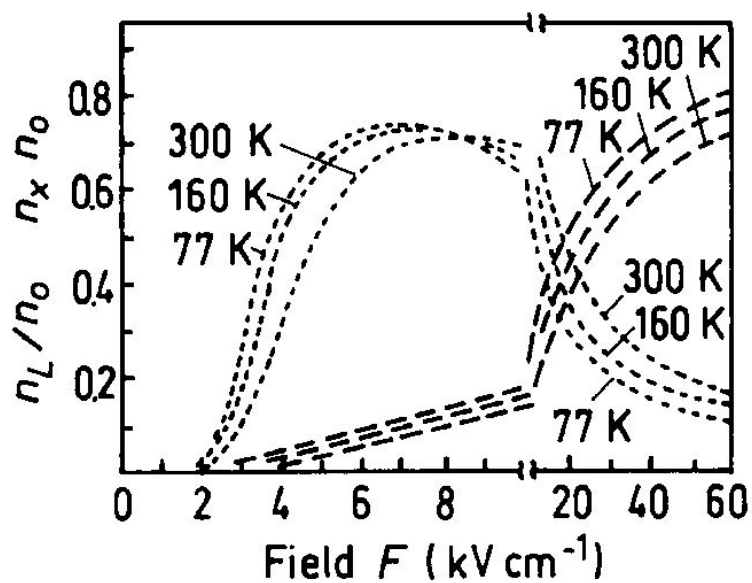


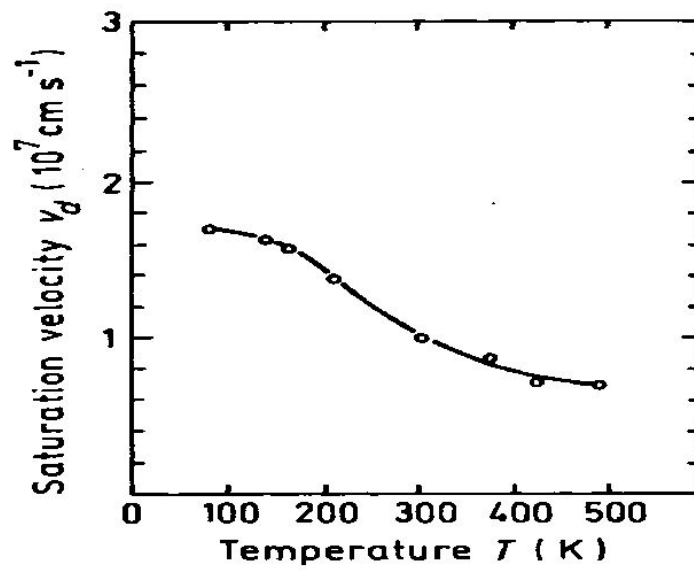
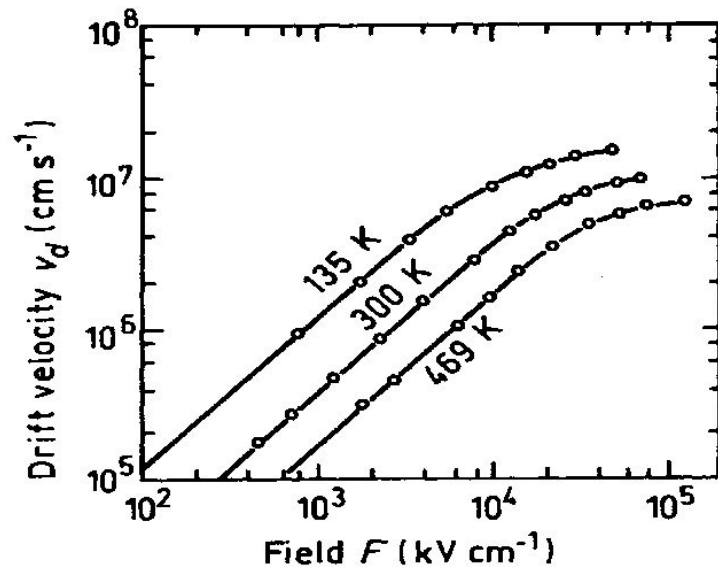
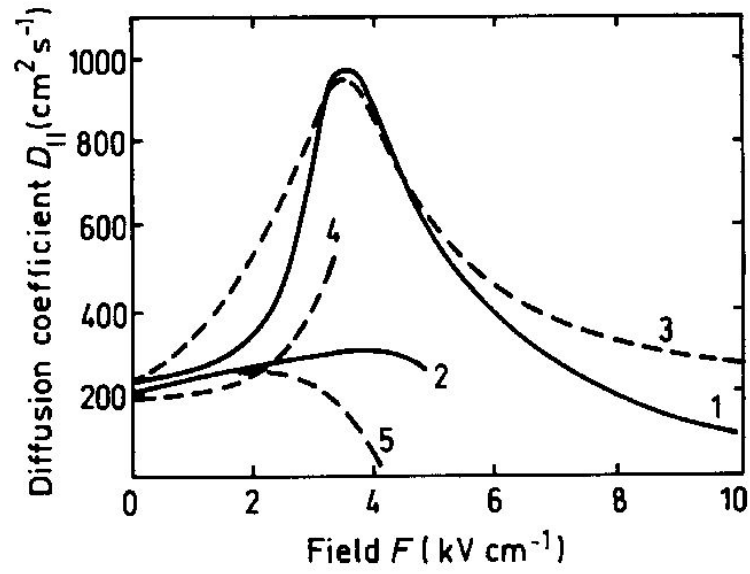


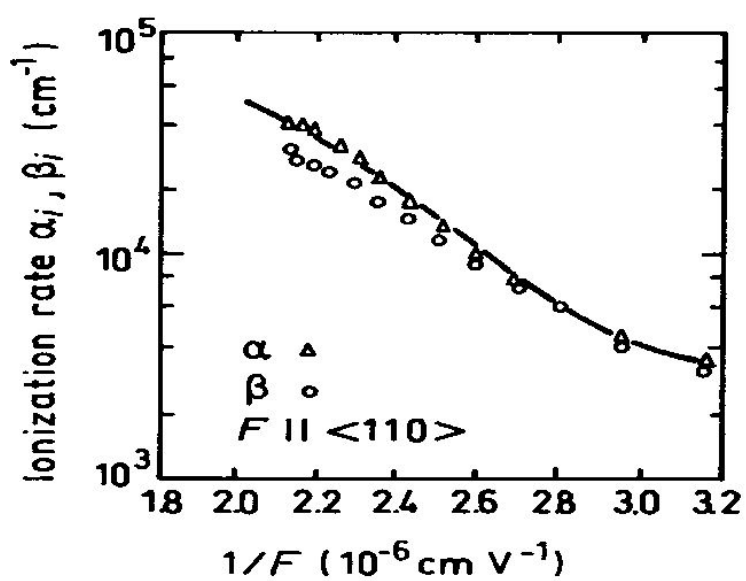
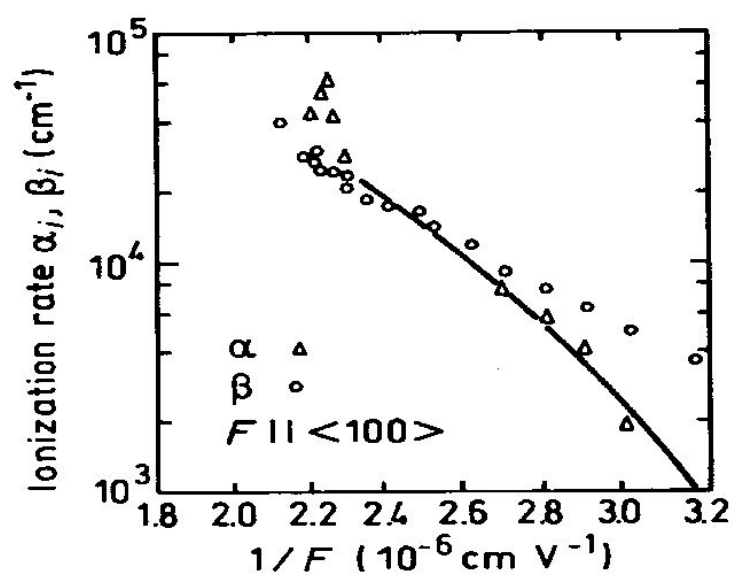
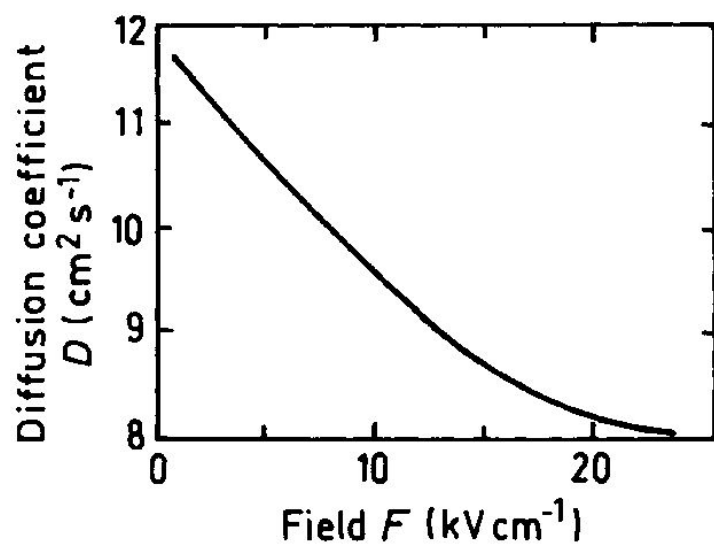


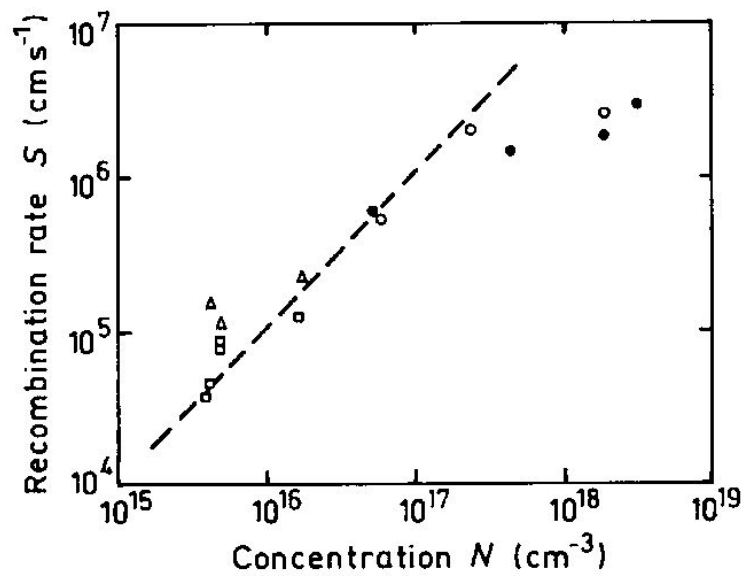
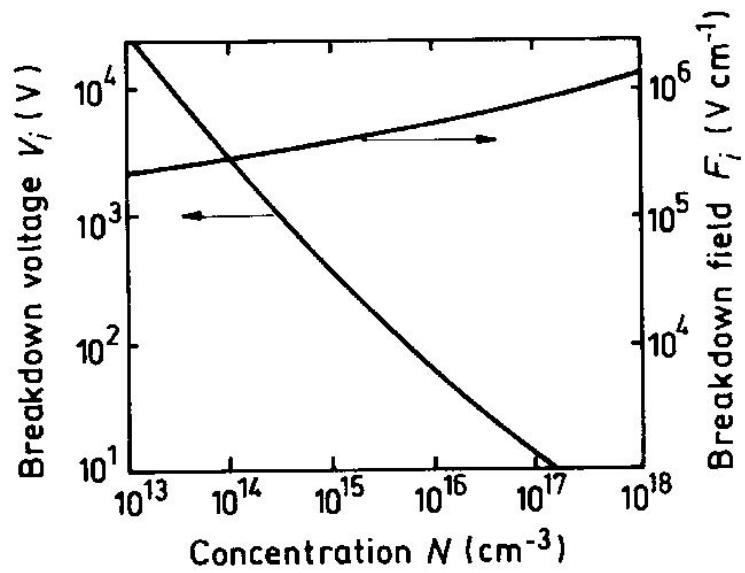
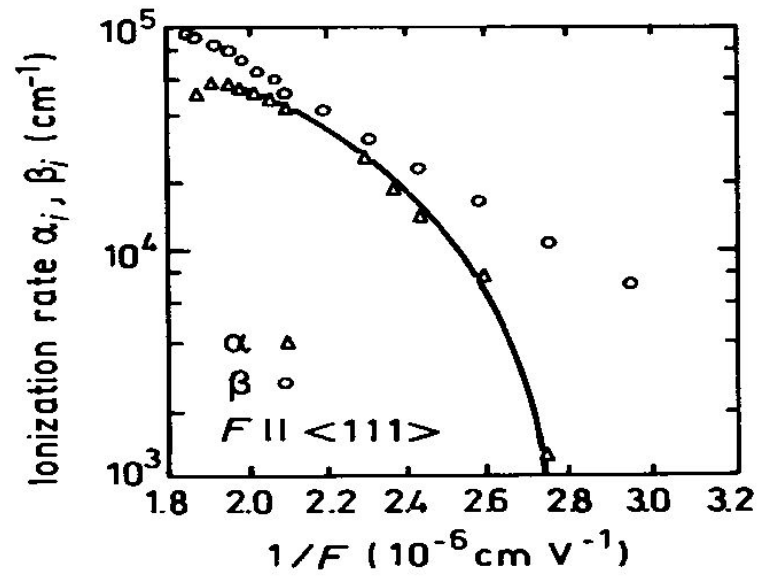


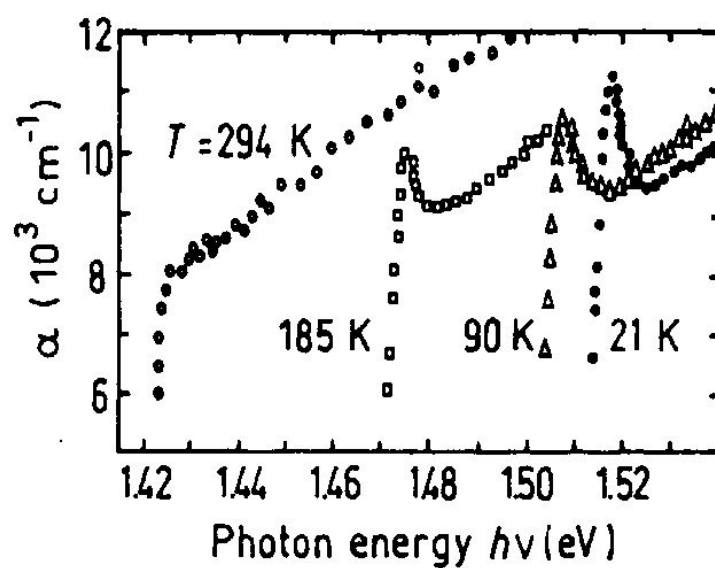
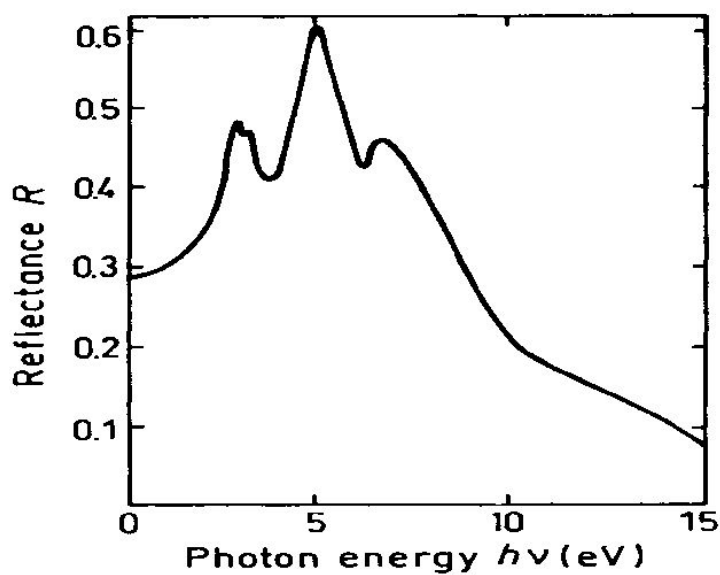
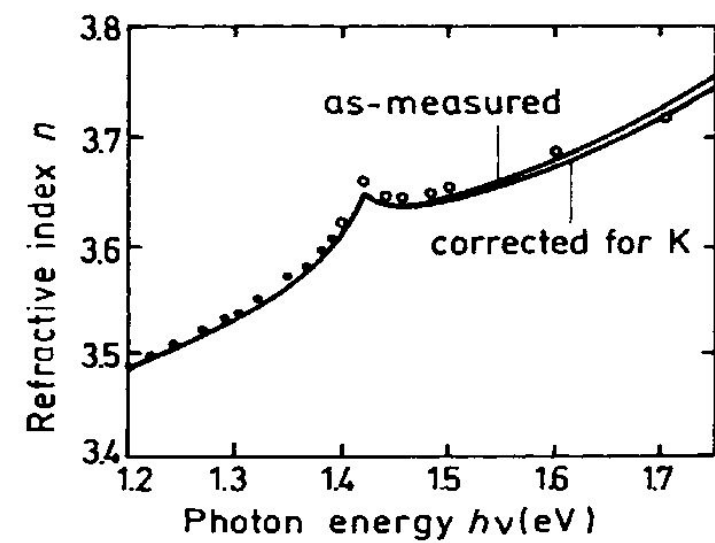


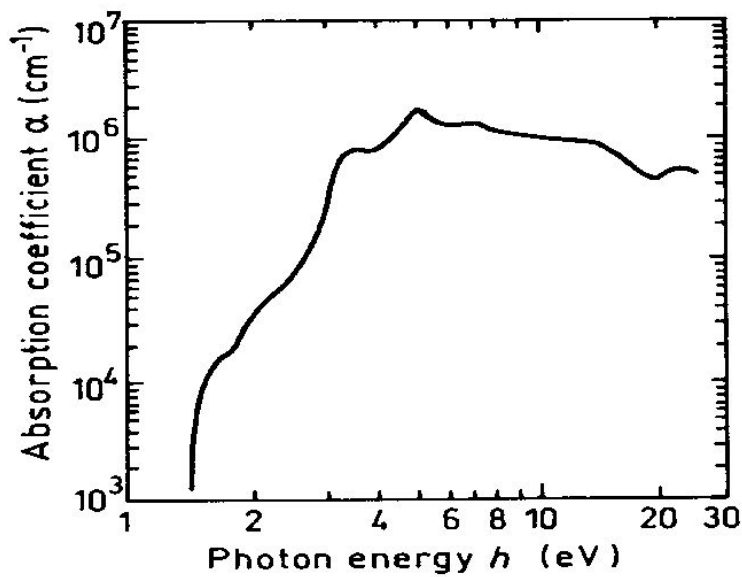
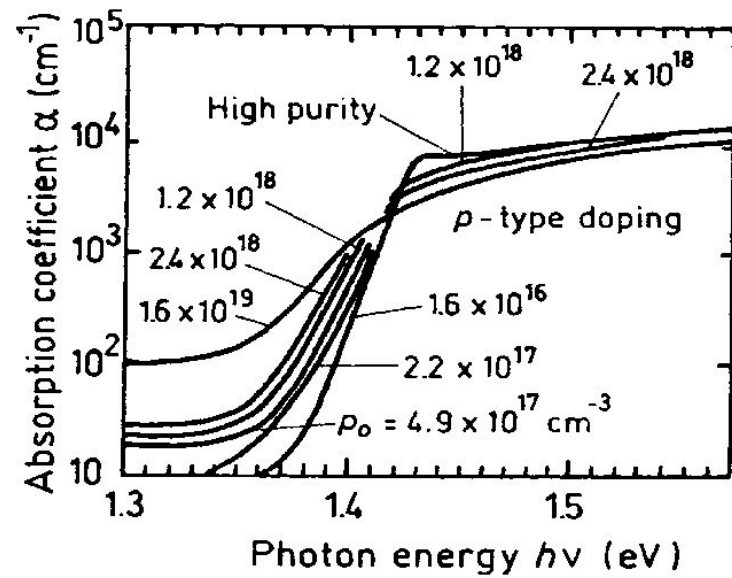
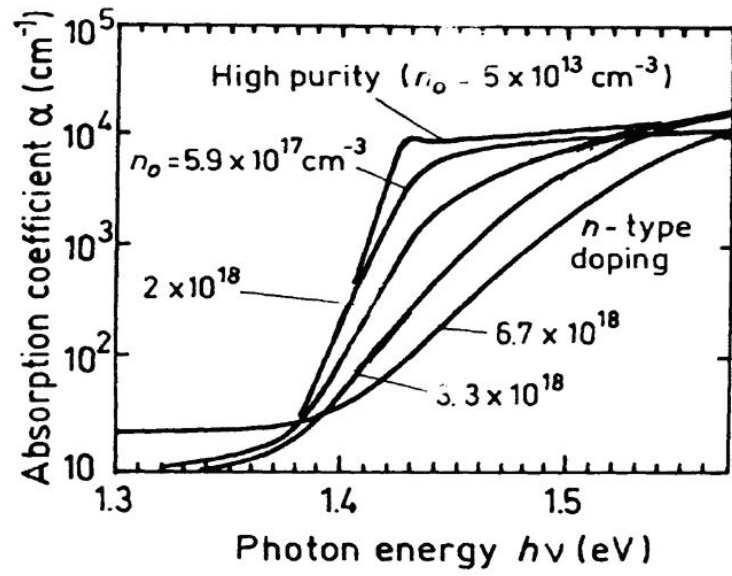


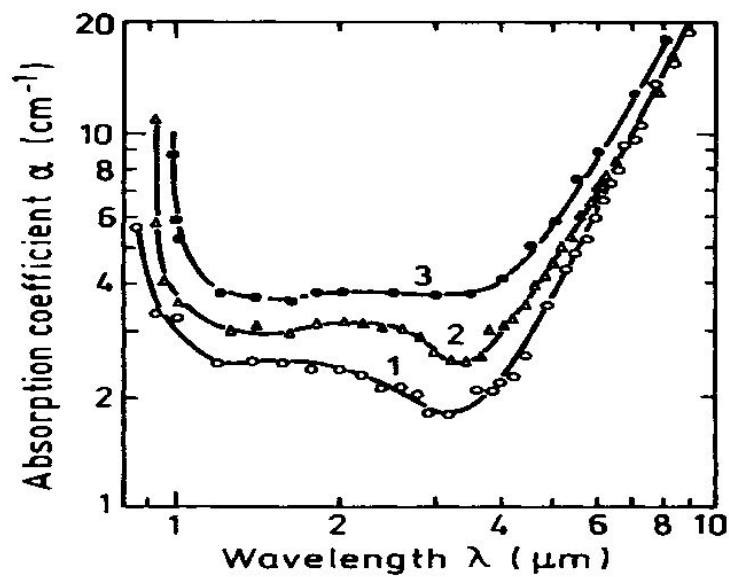
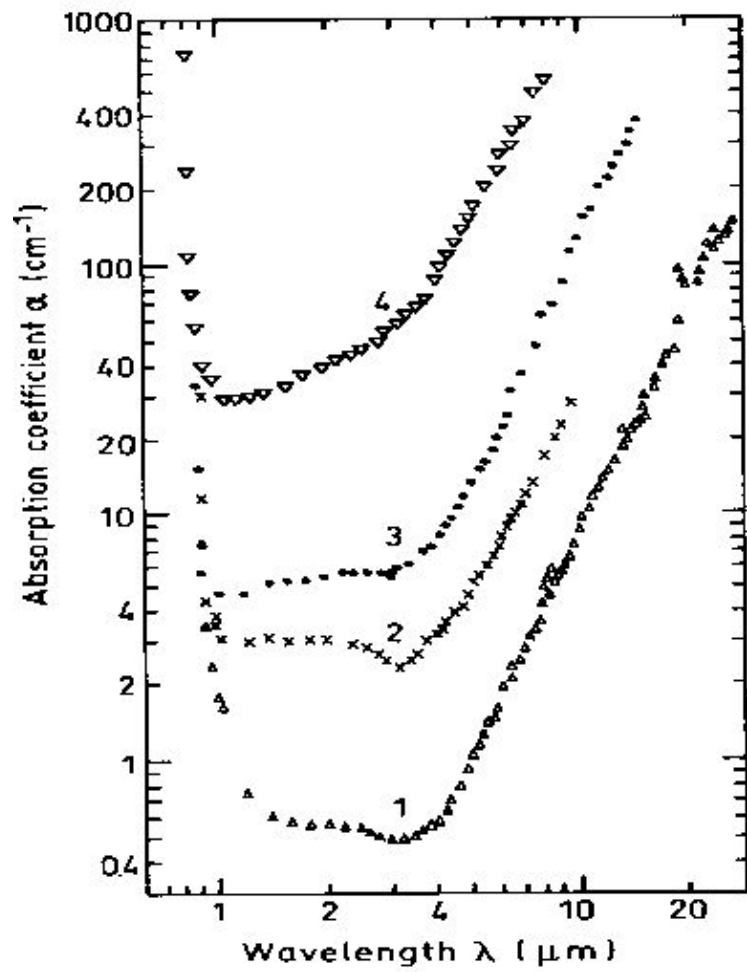


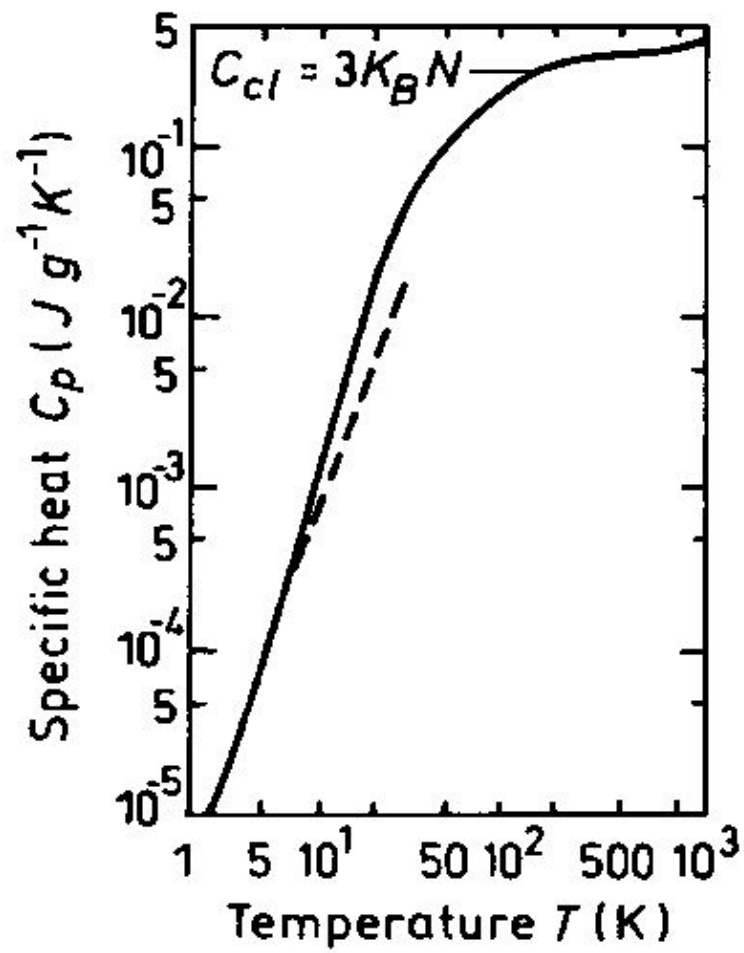
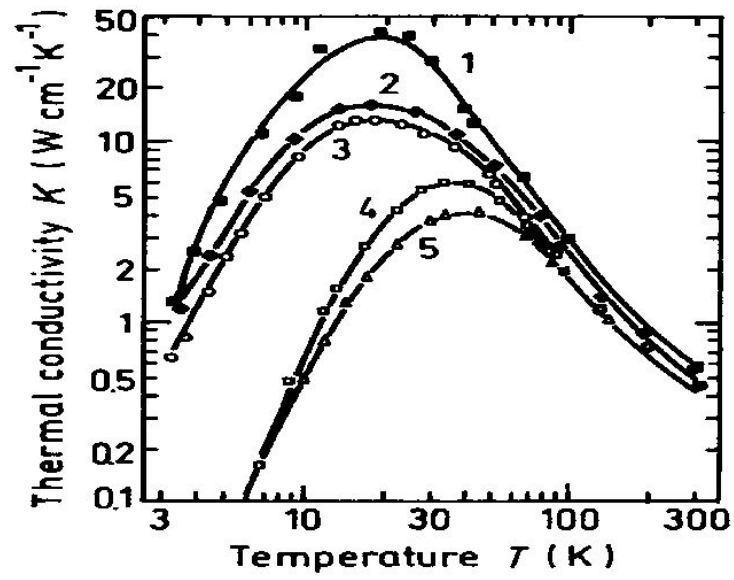


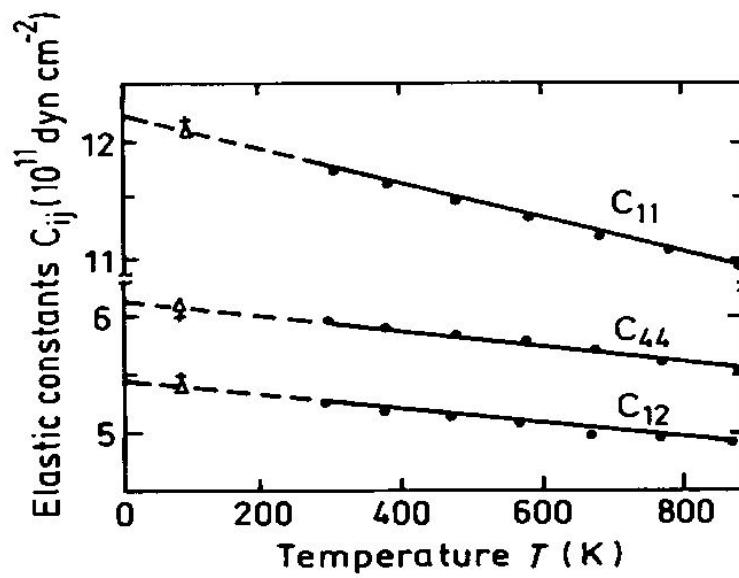
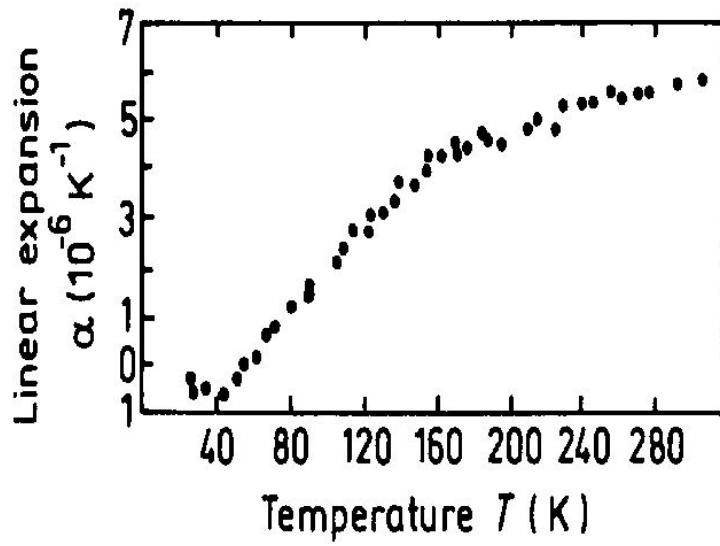
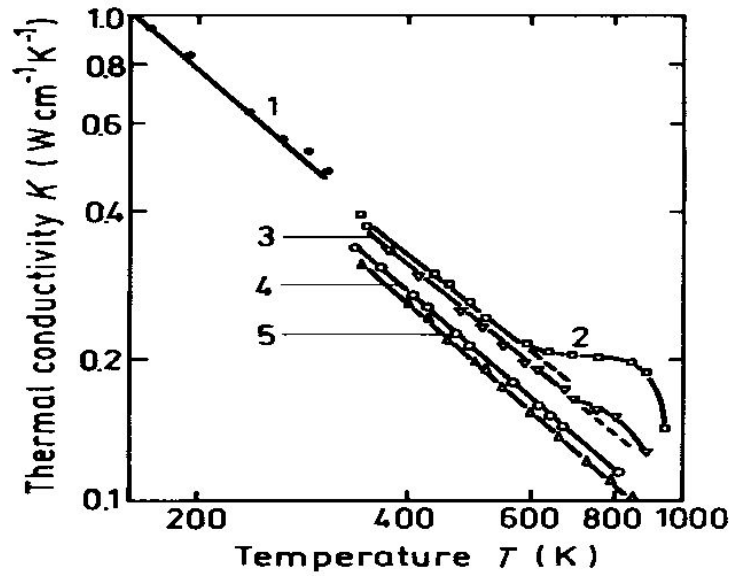












2 $\text{Ga}_x\text{In}_{1-x}\text{As}$

[002]ff.

2.1 Originaltexte

Dokument nächste Seite folgend.

$\text{Ga}_x\text{In}_{1-x}\text{As}$

- [Basic Parameters at 300 K](#)
- [Band structure and carrier concentration](#)
 - [Basic Parameters](#)
 - [Band Structure](#)
 - [Intrinsic carrier concentration](#)
 - [Effective Density of States in the Conduction and Valence Band](#)
 - [Temperature Dependences](#)
 - [Dependence on Hydrostatic Pressure](#)
 - [Band Discontinuities at Heterointerfaces](#)
 - [Energy gap narrowing at high doping levels](#)
 - [Effective Masses and Density of States](#)
 - [Donors and Acceptors](#)
- [Electrical Properties](#)
 - [Basic Parameters of Electrical Properties](#)
 - [Mobility and Hall Effect](#)
 - [Two-Dimensional Electron and Hole Gas Mobility in Heterostructures](#)
 - [Transport Properties in High Electric Fields](#)
 - [Impact Ionization](#)
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 - [Micro Hardness](#)
 - [Acoustic Wave Speeds](#)
 - [Phonon Frequencies](#)
- [Magnetic properties](#)
- [References](#)

Ga_xIn_{1-x}As

Basic Parameters at 300 K

	Ga_{0.47}In_{0.53}As	Ga_xIn_{1-x}As	Remarks Referens
Crystal structure	Zinc Blende	Zinc Blende	300 K
Group of symmetry	T _d ² -F43m	T _d ² -F43m	300 K
Number of atoms in 1 cm ³	3.98 · 10 ²²	(3.59-0.83x) · 10 ²²	300 K
Bulk modulus	6.62 · 10 ¹¹ dyn/cm ²	(5.81+1.72x) · 10 ¹¹ dyn/cm ²	300 K Goldberg Yu.A. & N.M. Schmidt (1999)
Debye temperature	330 K	(280+110x) K	300 K
Density	5.50 g · cm ⁻³	(5.68-0.37x) g · cm ⁻³	300 K
Melting point, T _m		~ 1100° C	
Specific heat	0.3 J g ⁻¹ °C ⁻¹		300 K
Thermal conductivity	0.05 W cm ⁻¹ °C ⁻¹	see Temperature dependences	
Thermal expansion coefficient, linear	5.66x10 ⁻⁶ °C ⁻¹	see Temperature dependences	
Dielectric constant (static)	13.9	15.1-2.87x+0.67x ²	300 K
Dielectric constant (high frequency)	11.6	12.3-1.4x	300 K
Infrared refractive index n	3.43 cm ² V ⁻¹ s ⁻¹	(3.51-0.16x) V ⁻¹ s ⁻¹	300 K
Radiative recombination coefficient	0.96 x 10 ⁻¹⁰ cm ² /s	see Impact Ionization	300 K
Energy gaps, E _g	0.74 eV	(0.36+0.63x+0.43x ²) eV (0.4105+0.6337x+0.475x ²) eV	300 K Goetz et al.(1983) 2 K
Effective electron mass m _e	0.041 m _o (at n= 2 · 10 ¹⁷ cm ⁻³)	(0.023+0.037x+0.003x ²) m _o	300 K Pearsall (1982)
Effective hole masses m _h	0.45 m _o	(0.41+0.1x) m _o	300 K Goldberg Yu.A. & N.M. Schmidt (1999)
Effective hole masses m _{lp}	0.052 m _o	(0.026+0.056x) m _o	300 K
Effective hole masses (split-off band) m _{so}		~ 0.15 m _o	300 K
Electron affinity	4.5 eV	(4.9-0.83x) eV	300 K
Lattice constant	5.8687 Å	(6.0583-0.405x) Å	300 K
Piezoelectric constant		e ₁₄ = -(0.045+0.115x) C/m ²	300 K
Optical phonon energy	34 meV	see Raman-active phonon modes	300 K

Ga_xIn_{1-x}As

Band structure and carrier concentration

[Basic Parameters](#)

[Band structure](#)

[Intrinsic carrier concentration](#)

[Lasing wavelength](#)

[Effective Density of States in the Conduction and Valence Band](#)

[Temperature Dependences](#)

[Dependences on Hydrostatic Pressure](#)

[Band Discontinuities at Heterointerfaces](#)

[Energy gap narrowing at high doping levels](#)

[Effective Masses and Density of States](#)

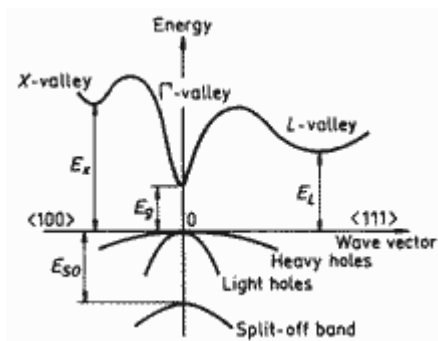
[Donors and Acceptors](#)

Basic Parameters for Ga_xIn_{1-x}As_yP_{1-y}

Zinc Blende crystal structure

	Ga _{0.47} In _{0.53} As	Ga _x In _{1-x} As	Remarks	Referens
Energy gaps, E _g	0.74 eV	(0.36+0.63x+0.43x ²) eV	300 K	Goetz et al.(1983)
Energy gaps, E _g		(0.4105+0.6337x+0.475x ²) eV	2 K	Goetz et al.(1983)
Electron affinity	4.5 eV	(4.9-0.83x) eV	300 K	
Conduction band				
Energy separation between X valley and top of the valence band E _X	1.33 eV	(1.37-0.63x+1.16x ²) eV	300 K	Goetz et al.(1983)
Energy separation between L valley and top of the valence band E _L	1.2 eV	(1.08-0.02x+0.65x ²) eV	300 K	Goetz et al.(1983)
Effective conduction band density of states	2.1·10 ¹⁷ cm ⁻³	see Temerature dependences		
Valence band				
Energy separation of spin-orbital splitting E _{so}	***	***		
Effective valence band density of states	7.7·10 ¹⁸ cm ⁻³	see Temerature dependences		
Intrinsic carrier concentration	6.3·10 ¹¹ cm ⁻³	see Temerature dependences		

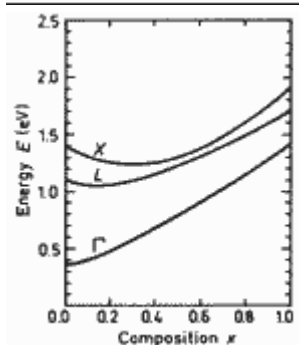
Band structure for Ga_xIn_{1-x}As



Ga_xIn_{1-x}As (zinc blende, cubic). Band structure

Important minima of the conduction band and maxima of the valence band..

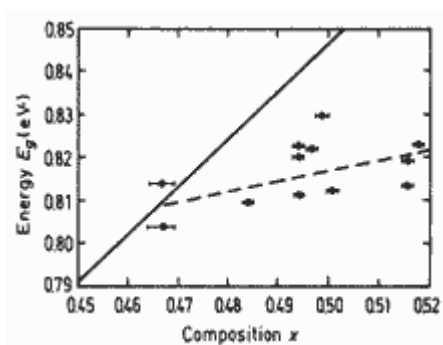
For details see [Goldberg Yu.A. & N.M. Schmidt \(1999\)](#).



Ga_xIn_{1-x}As. Energy gap E_g Energy separations between Γ-, X-, and L-conduction band minima and top of the valence band vs. composition parameter x.

[Porod and Ferry \(1983\)](#)

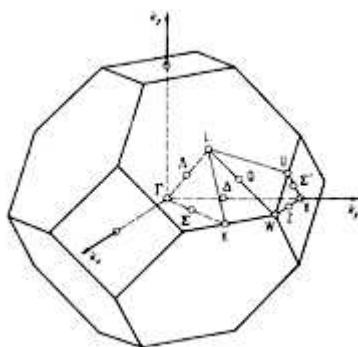
Interfacial elastic strain induced by lattice parameter mismatch between epilayer and substrate results in significant band-gap shifts:



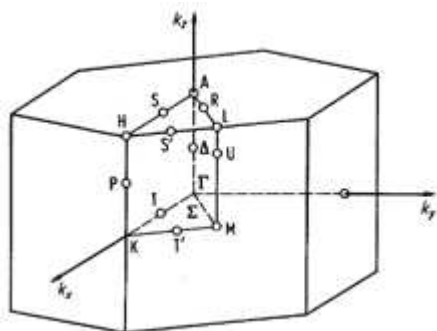
Ga_xIn_{1-x}As. Energy band gap E_g of unstrained (solid line) and strained (dashed line and experimental points) vs. composition parameter x.

Solid line is calculated according to $E_g = (0.4105 + 0.6337x + 0.475x^2)$ eV. Experimental points are obtained at 4K.

[Kuo et al.\(1985\)](#)



Brillouin zone of the face centered cubic lattice, the Bravais lattice of the diamond and zincblende structures.



Brillouin zone of the hexagonal lattice.

Temperature Dependences

$$E_g(x,T) = 0.42 + 0.625x - [5.8/(T+300) - 4.19/(T+271)] \cdot 10^{-4} T^2 x - 4.19 \cdot 10^{-4} T^2/(T+271) + 0.475x^2 \text{ (eV)}$$

Ga_xIn_{1-x}As [Paul et al.\(1991\)](#)

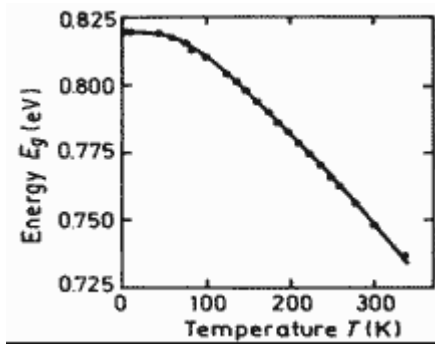
$$E_g(x,T) = E_g(0) + (6x^2 - 8.6x + 5.2) \cdot 10^{-4} T^2/(337x^2 - 455x + 196)$$

Ga_xIn_{1-x}As on GaAs [Karachevtseva et al.\(1994\)](#)

$$E_g(x,T) = 0.42 + 0.625x - [5.8/(T+300) - 4.19/(T+271)] \cdot 10^{-4} T^2 x - 4.19 \cdot 10^{-4} T^2/(T+271) + 0.475x^2 \text{ (eV)}$$

Ga_xIn_{1-x}As

where T is temperature in degrees K



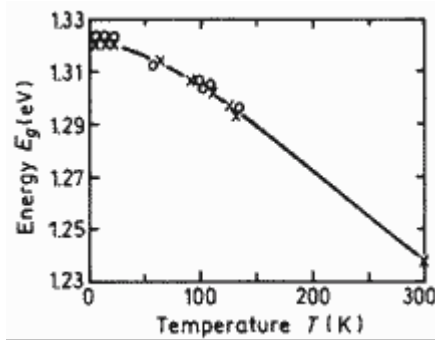
Ga_{0.47}In_{0.53}As. Energy gap E_g of vs. temperature

Points are experimental data.

Solid line is theoretical calculation.

$E_g(0) = 821.5 \pm 0.2$ meV.

[Zielinski et al.\(1986\)](#)



Ga_{0.87}In_{0.13}As. Energy gap E_g of vs. temperature

Points are experimental data.

Solid line -- $1.321 - 4.1 \cdot 10^{-4} T^2/(T+139)$

[Karachevtseva et al.\(1994\)](#)

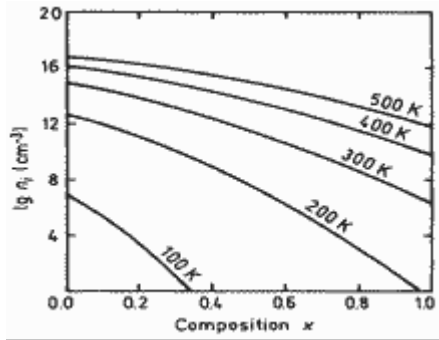
Lasing wavelength λ_0

Intrinsic carrier concentration:

$$n_i = (N_c \cdot N_v)^{1/2} \exp(-E_g/(2k_B T)) \approx 4.82 \times 10^{15} \cdot [(0.41 - 0.09x)^{3/2} + (0.027 + 0.047x)^{3/2}]^{1/2} \times x(0.025 + 0.043x)^{3/4} [T^{3/2} \exp(-v/2)(1 + 3.75/v + 3.28/v^2 - 2.46/v^3)^{1/2}] \text{ (cm}^{-3}\text{)},$$

where $v = E(x,T)/2kT$

[Paul et al.\(1991\).](#)



Ga_xIn_{1-x}As. Intrinsic carrier concentration vs. temperature for Ga_xIn_{1-x}As.

T = 100K; 200K; 300K; 400K; 500K;

[Paul et al.\(1991\)](#)

$n_i = 6.3 \times 10^{11} \text{ cm}^{-3}$ for **Ga_{0.47}In_{0.53}As** at **300K**

Effective density of states in the conduction band: N_c

$$N_c \sim 4.82 \times 10^{15} \cdot (m_{\Gamma}/m_0)^{3/2} T^{3/2} (\text{cm}^{-3}) \sim 4.82 \times 10^{15} \cdot (0.023 + 0.037x + 0.003x^2)^{3/2} T^{3/2} (\text{cm}^{-3}) :$$

Effective density of states in the valence band: N_v

$$N_v \sim 4.82 \times 10^{15} \cdot (m_h/m_0)^{3/2} T^{3/2} (\text{cm}^{-3}) = 4.82 \times 10^{15} \cdot (0.41 - 0.1x)^{3/2} T^{3/2} (\text{cm}^{-3}) :$$

Dependence on Hydrostatic Pressure

$$E_g(0.47, P) \sim (0.796 + 10.9 \times 10^{-3} \cdot P - 30 \times 10^{-6} \cdot P^2) \text{ eV} \quad 80\text{K, Ga}_{0.47}\text{In}_{0.53}\text{As} \quad x=0.47 \quad \text{Lambkin and Dunstan (1988)}$$

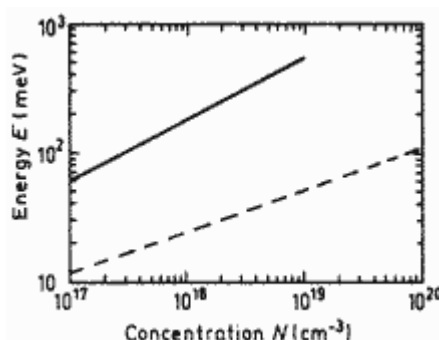
$$E_g(0.47, P) \sim (0.733 + 11.0 \times 10^{-3} \cdot P - 27 \times 10^{-6} \cdot P^2) \text{ eV} \quad 300\text{K, Ga}_{0.47}\text{In}_{0.53}\text{As} \quad x=0.47$$

$$E_g(0.0, P) \sim (E_g(0) + 4.8 \times 10^{-3} \cdot P) \text{ eV} \quad 300\text{K, InAs} \quad x=0.$$

$$E_g(1.0, P) \sim (E_g(0) + 12.6 \times 10^{-3} \cdot P - 37.7 \times 10^{-6} \cdot P^2) \text{ eV} \quad 300\text{K, GaAs} \quad x=1.$$

where P is pressure in kbar.

Energy gap narrowing at high doping levels



Ga_{0.47}In_{0.53}As. Energy gap narrowing E_g vs. donor (solid line) and acceptor (dashed line) doping density

solid line -- donor doping density;

dashed line -- acceptor doping density

[Jain et al. \(1990\)](#)

$$\Delta E_g \approx (A \cdot N^{1/3} 10^{-9} + B \cdot N^{1/4} 10^{-7} + C \cdot N^{1/2} 10^{-12}) \text{ meV} \quad 300\text{K, Ga}_{0.47}\text{In}_{0.53}\text{As } x=0.47$$

where

$$n : A=15.5; \quad B=1.95; \quad C=159$$

$$300\text{K, Ga}_{0.47}\text{In}_{0.53}\text{As } x=0.47$$

$$p : A=9.2; \quad B=3.57; \quad C=3.65$$

$$300\text{K, Ga}_{0.47}\text{In}_{0.53}\text{As } x=0.47$$

N -- carrier concentration in cm^{-3}

Band Discontinuities at Heterointerfaces

Band discontinuities at $\text{Ga}_x\text{In}_{1-x}\text{As}/\text{Al}_y\text{Ga}_{1-y}\text{As}$ heterointerface [Shur \(1990\)](#).

Referens

Conduction band discontinuity $\Delta E_v = (\Delta E_g - \Delta E_v) \text{ eV}$

[Shur \(1990\)](#)

Valence band discontinuity $\Delta E_c = (0.44 \Delta E_{gg}) \text{ eV}$

[Shur \(1990\)](#)

where $\Delta E_{gg} \text{ (eV)} = [1.247y + 1.5(1-x) - 0.4(1-x)^2] \text{ (eV)}$ is the difference between Γ -valleys in $\text{Ga}_x\text{In}_{1-x}\text{As}$ and $\text{Al}_y\text{Ga}_{1-y}\text{As}$.

Energy gap E_g discontinuity : $\Delta E_g = \Delta E_{gg}$ for $y < 0.45$

Energy gap E_g discontinuity : $\Delta E_g = 0.476 + 0.125y + 0.143y^2 + 1.5(1-x) - 0.4(1-x)^2$ for $y > 0.45$

Band discontinuities $\Delta E_v \approx 0.38 \text{ eV}$
 $\Delta E_c \approx 0.22 \text{ eV}$ at $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{InP}$ heterointerface

[Adachi \(1992\);](#)
[Hybertsen \(1991\)](#)

Band discontinuities $\Delta E_v \approx 0.2 \text{ eV}$
 $\Delta E_c \approx 0.52 \text{ eV}$ at $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ heterointerface

[Adachi \(1992\);](#)
[Hybertsen \(1991\)](#)

$\Delta E_c / \Delta E_g = [0.653 + 0.1(1-x)] \text{ eV}$ at $\text{Ga}_x\text{In}_{1-x}\text{As}/\text{Al}_x\text{In}_{1-x}\text{As}$ heterointerface

[Wolak et al. \(1991\)](#)

Effective Masses and Density of States:

Electrons

For wurtzite crystal structure the surfaces of equal energy in Γ valley should be ellipsoids, but effective masses in z direction and perpendicular directions are estimated to be approximately the same:

Effective Electron Masses

Remarks

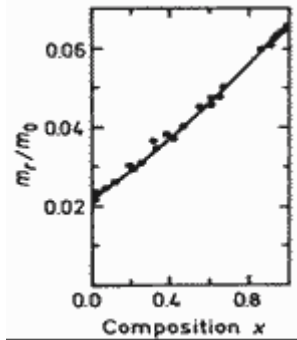
Referens

Effective electron mass $m_e = m_{\Gamma}$ $0.023 - 0.037x + 0.003x^2$
 m_0

$\text{Ga}_x\text{In}_{1-x}\text{As}$; 300K; for Γ - valley

[Goldberg Yu.A. & N.M. Schmidt \(1999\)](#)

Effective electron mass m_e	$m_I = 0.041 m_0$ at $n = 2 \times 10^{17} \text{ cm}^{-3}$ $m_I = 0.074 m_0$ at $n = 6 \times 10^{18} \text{ cm}^{-3}$ $m_L = 0.29 m_0$; (L - valley) $m_X = 0.68 m_0$; (X - valley)	$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	Pearsall (1982)
		$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	Pearsall (1982)



$\text{Ga}_x\text{In}_{1-x}\text{As}$. Electron effective mass vs. concentration x for $\text{Ga}_x\text{In}_{1-x}\text{As}$; 300K
[Adachi \(1992\)](#)

Holes

Effective Masses for Zinc Blende GaN

		Remarks	Referens
Effective hole masses (heavy) m_h	$m_h \approx (0.41 - 0.1x) m_0$	$\text{Ga}_x\text{In}_{1-x}\text{As}$; 300K;	Goldberg Yu.A. & N.M. Schmidt (1999)
Effective hole masses (light) m_{lp}	$m_{lp} \approx (0.026 - 0.056x) m_0$	$\text{Ga}_x\text{In}_{1-x}\text{As}$; 300K;	
Effective hole masses (split-off band) m_s	$m_{so} \approx 0.15 m_0$	$\text{Ga}_x\text{In}_{1-x}\text{As}$; 300K;	

Donors and Acceptors

Ionization energies of Shallow Donors

		Remarks	
Sn, Ge, Si, C	$\sim 5 \text{ meV}$	$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	Goldberg Yu.A. & N.M. Schmidt (1999)
Sn, Ge, Si, S, Se, Te	$> 1 \text{ meV}$	InAs; $x=0$	
Sn, Ge, Si, S, Se, Te	$\sim 6 \text{ meV}$	GaAs; $x=1$	

Ionization energies of Shallow Acceptor

Mg	$\sim 25 \text{ meV}$	$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	Goldberg Yu.A. & N.M. Schmidt (1999)
Zn	$\sim 20 \text{ meV}$	$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	
Cd	$\sim 30 \text{ meV}$	$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$; $x=0.47$	

Mn ~ 50 meV Ga_{0.47}In_{0.53}As;
 $x=0.47$

Fe ~ 150 meV Ga_{0.47}In_{0.53}As;
x=0.47

(above valence band), 280, 370, and 440 below conduction band

Mg ~ 25 meV $\text{Ga}_x\text{In}_{1-x}\text{As}$; $0 < x < 1$

Be ~ 25 meV $\text{Ga}_x\text{In}_{1-x}\text{As}$; $0 < x < 1$

Cd $\sim 8-20$ meV Ga_xIn_{1-x}As; 0<x<1

(above valence band), 280, 370, and 440 below conduction band

Sn-10; Ge-14; Si-20; Cd-15; Zn-10 meV InAs; x=0

C - 20, Si - three acceptor levels $\sim 30, 100$, and 220, GaAs; $x=1$

Ge - 30, Zn - 25, Sn - 20.

Ga_xIn_{1-x}As

Electrical properties

[Basic Parameters](#)

[Mobility and Hall Effect](#)

[Two-dimensional electron and hole gas mobility in heterostructures](#)

[Transport Properties in High Electric Fields](#)

[Impact Ionization](#)

[Recombination Parameters](#)

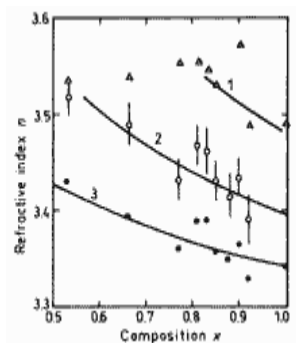
Basic Parameters

	Ga_{0.47}In_{0.53}As	Ga_xIn_{1-x}As	Remarks	Referens
Breakdown field	$\approx 2 \cdot 10^5$ V/cm	$\approx (2 \div 4) \cdot 10^5$ V/cm	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Mobility electrons	$< 12 \cdot 10^3$ cm ² V ⁻¹ s ⁻¹	$(40 - 80.7x + 49.2x^2) \cdot 10^3$ cm ² V ⁻¹ s ⁻¹	300 K	
Mobility holes	< 300 cm ² V ⁻¹ s ⁻¹	$\sim 300 \div 400$ cm ² V ⁻¹ s ⁻¹	300 K	
Diffusion coefficient electrons	< 300 cm ² /s	$(10 - 20.2x + 12.3x^2) \cdot 10^2$ cm ² /s	300 K	
Diffusion coefficient holes	< 7.5 cm ² /s	$\sim 7 \div 12$ cm ² /s	300 K	
Electron thermal velocity	$5.5 \cdot 10^5$ m/s	$(7.7 - 5.9x + 2.6x^2) \cdot 10^5$ m/s	300 K	
Hole thermal velocity	$2 \cdot 10^5$ m/s	$(1.8 \div 2) \cdot 10^5$ m/s	300 K	
Surface recombination velocity		$< 10^6$ cm/s	300 K	
Radiative recombination coefficient	$0.96 \cdot 10^{-10}$ cm ³ /s		300 K	
Auger coefficient	$7 \cdot 10^{-29}$ cm ⁶ /s		300 K	

Ga_xIn_{1-x}As

Optical properties

	Ga _{0.47} In _{0.53} As	Ga _x In _{1-x} As	Remarks	Referens
Dielectric constant (static)	13.9	$15.1 - 2.87x + 0.67x^2$	300 K	
Dielectric constant (high frequency)	11.6	$12.3 - 1.4x$	300 K	
Infrared refractive index n	$3.43 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$	$(3.51 - 0.16x) \text{ V}^{-1} \text{ s}^{-1}$	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Radiative recombination coefficient	$0.96 \times 10^{-10} \text{ cm}^2/\text{s}$	see Impact Ionization	300 K	
Optical phonon energy	34 meV	see Raman-active phonon modes	300 K	



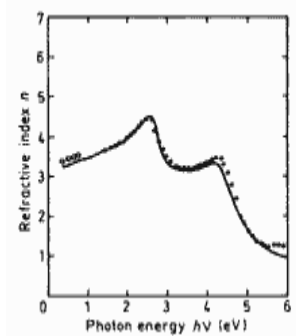
Refractive index n versus alloy composition x at different photon energies

1 1.2 eV

2 0.9 eV

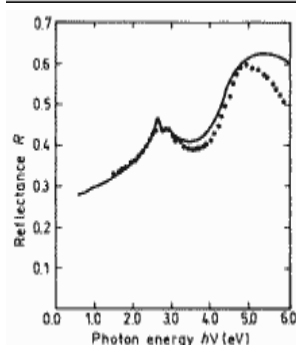
3 0.6 eV.

[Takagi \(1978\)](#)



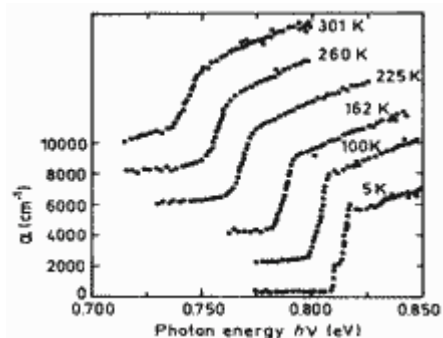
Refractive index n versus photon energy for $x=0.47$. 300 K.

[Adachi \(1992\)](#)



Normal incidence reflectivity versus photon energy for $x=0.47$. 300 K.

[Adachi \(1992\)](#)

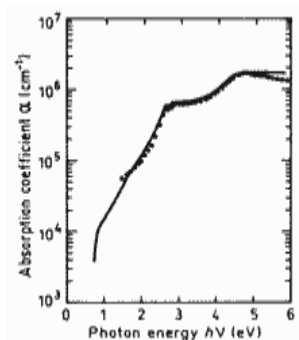


The absorption coefficient versus photon energy at different temperatures for $x=0.47$.

Electron concentration $n_0=8 \cdot 10^{14} \text{ cm}^{-3}$.

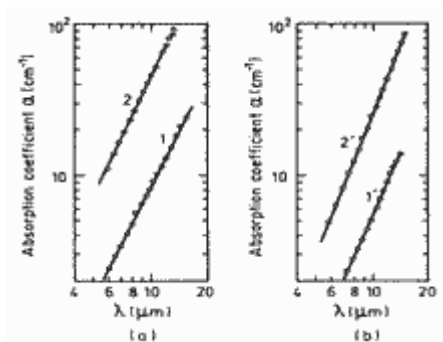
Curves are shifted vertically for clarity.

[Zielinski et al. \(1986\)](#)



The absorption coefficient versus photon energy for $x=0.47$, 300 K.

[Adachi \(1992\)](#)



Free carrier absorption coefficient versus wavelength.

a - $T=300 \text{ K}$, b - $T=92 \text{ K}$.

1 $x=0.08$, $N_d=1.4 \cdot 10^{17} \text{ cm}^{-3}$

2 $x=0.1$ $N_d=5.4 \cdot 10^{17} \text{ cm}^{-3}$.

[Aliev et al. \(1987\)](#)

A ground state Rydberg energy $R_{x1}=2.5 \text{ meV}$ (for $x=0.47$).

Ga_xIn_{1-x}As

Thermal properties

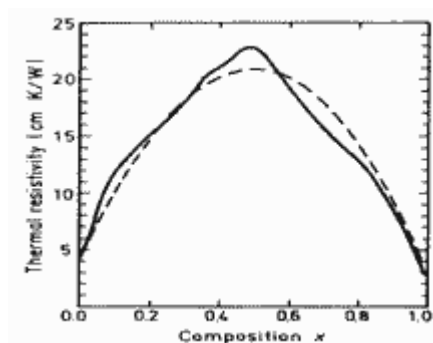
- [Basic parameters](#)
- [Thermal conductivity](#)
- [Lattice properties](#)

Basic parameters

	Ga _{0.47} In _{0.53} As	Ga _x In _{1-x} As	Remarks	Referens
Bulk modulus	$6.62 \cdot 10^{11}$ dyn/cm ²	$(5.81+1.72x) \cdot 10^{11}$ dyn/cm ²	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Debye temperature	330 K	(280+110x) K		
Density	5.50 g/cm ³	5.68-0.37x g/cm ³	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Melting point, T _m		≈ 1100° C		
Specific heat	0.3 J g ⁻¹ °C ⁻¹			
Thermal conductivity	0.05 W cm ⁻¹ °C ⁻¹	see Temperature dependences		
Thermal expansion coefficient, linear	5.66x10 ⁻⁶ °C ⁻¹	see Temperature dependences		
Lattice constant	5.8687 Å	(6.0583-0.405x) Å		

Thermal conductivity

Thermal conductivity 0.05 W cm⁻¹ °C⁻¹

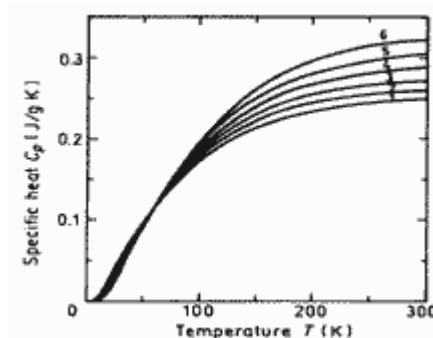


Ga_xIn_{1-x}As. Thermal resistivity vs. composition parameter x 300K

Solid lines shows the experimental data.

Dashed lines are the results theoretical calculation.

[Adachi \(1983\)](#)



Ga_xIn_{1-x}As. Specific heat at constant pressure vs. temperature for different concentrations x.

1 - x=0.0;

2 - x=0.2;

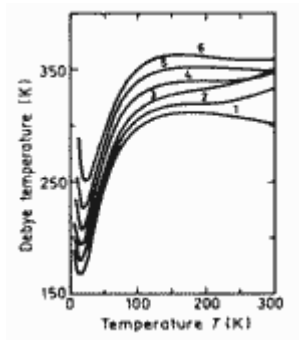
3 - x=0.4;

4 - x=0.6;

5 - x=0.8.

6 - x=1.0.

[Sirota et al. \(1982\)](#)



Ga_xIn_{1-x}As. Debye temperature vs. temperature for different concentrations x .

1 - $x=0.0$;

2 - $x=0.2$;

3 - $x=0.4$;

4 - $x=0.6$;

5 - $x=0.8$.

6 - $x=1.0$.

[Sirota et al. \(1982\)](#)

Lattice properties

Lattice parameters

	Remarks	Referens
Lattice constant, a ($6.0583-0.405x$) Å	Ga _{x} In _{$1-x$} As; 300K	Adachi (1982)
5.8687 Å	Ga _{0.47} In _{0.53} As; 300K, $x=0.47$	

Linear thermal expansion coefficient

Ga_xIn_{1-x}As

Mechanical properties, elastic constants, lattice vibrations

[Basic Parameter](#)

[Elastic constants](#)

[Micro Hardness](#)

[Acoustic Wave Speeds](#)

[Phonon frequencies](#)

Basic Parameter

	Ga_{0.47}In_{0.53}As	Ga_xIn_{1-x}As	Remarks	Referens
Bulk modulus	$6.62 \cdot 10^{11}$ dyn/cm ²	$(5.81+1.72x) \cdot 10^{11}$ dyn/cm ²	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Debye temperature	330 K	$(280+110x)$ K		
Density	5.50 g/cm ³	$5.68-0.37x$ g/cm ³	300 K	Goldberg Yu.A. & N.M. Schmidt (1999)
Melting point, T _m		~ 1100° C		
Specific heat	$0.3 \text{ J g}^{-1} \text{ } ^\circ\text{C}^{-1}$			
Thermal conductivity	$0.05 \text{ W cm}^{-1} \text{ } ^\circ\text{C}^{-1}$	see Temperature dependences		
Thermal expansion coefficient, linear	$5.66 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$	see Temperature dependences		
Hardness on the Mohs scale		***		
Surface microhardness (using Knoop's pyramid test)		see Micro Hardness		
Piezoelectric constant		$e_{14} = -(0.045+0.115x)$ C/m ²		
Cleavage plane	{110}	{110}		
Lattice constant	5.8687 Å	$(6.0583-0.405x)$ Å		

Elastic constants at 300K

$$C_{11} = (8.34 + 3.56x) \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{12} = (4.54 + 0.8x) \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{44} = (3.95 + 2.01) \cdot 10^{11} \text{ dyn/cm}^2$$

Cleavage plane {110}

Bulk modulus (compressibility⁻¹)

$$B_s = (C_{11} + 2C_{12})/3 \quad B_s = (5.81+1.72x) \cdot 10^{11} \text{ dyn/cm}^2$$

Anisotropy factor

$$C' = (C_{11} - C_{12})/2 \quad A = (0.48+0.07x)$$

Shear modulus

$$C' = (C_{11} - C_{12})/2 \quad C' = (1.9+1.38x) \cdot 10^{11} \text{ dyn/cm}^2$$

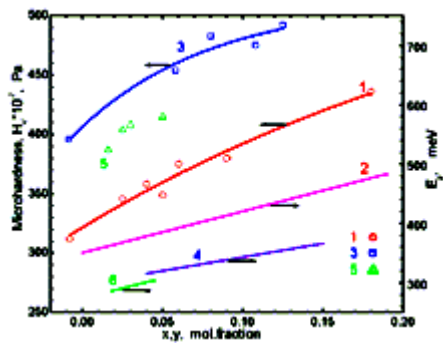
[100] Young's modulus

$Y_0=(C_{11}+2C_{12})\cdot(C_{11}-C_{12})/(C_{11}+C_{12})$ $Y_0= (5.14+3.39x)\cdot 10^{11}$ dyn/cm²

[100] Poisson ratio

$\sigma_o=C_{12}/(C_{11}+C_{12})$ $\sigma_o= (0.35-0.04x)$

Micro Hardness



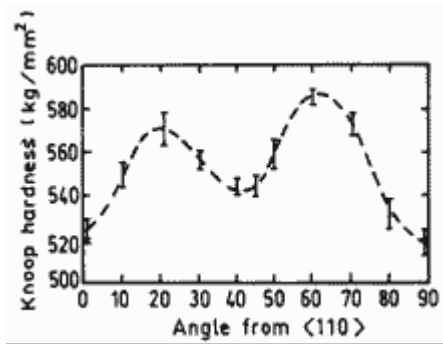
Micro hardness (Hv) and energy gap values E_g vs composition of three alloy systems:

$In_{1-x}Ga_xAs$ (1, 2),
 $In_{1-x}Ga_xAs_{0.9}Sb_{0.1}$ (3, 4) and
 $InAs_{1-x-0.1}Sb_{0.1}Py$ (5, 6).

Measured using (111) oriented epilayers at 50 g weight (stress) on Vickers pyramid

[B.A.Matveev et al. Izv.Akad.Nauk SSSR, Neorg.Mater, 26 \(1990\), 639](#)

Contact authors: [B.A.Matveev](#)



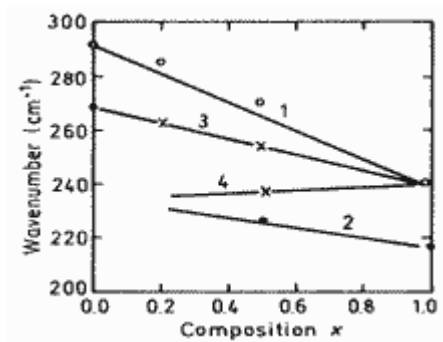
Knoop microhardness anisotropy on the {100} plane for $Ga_{0.47}In_{0.53}As$.

[Adachi \(1992\)](#)

Acoustic Wave Speeds

Wave propagation Direction	Wave character	Expression for wave speed	Wave speed (in units of 10^5 cm/s)
[100]	V_L (longitudinal)	$(C_{11}/\rho)^{1/2}$	$3.83+0.90x$
	V_T (transverse)	$(C_{44}/\rho)^{1/2}$	$2.64+0.71x$
[100]	V_l	$[(C_{11}+C_{12}+2C_{44})/2\rho]^{1/2}$	$4.28+0.96x$
	$V_{t\parallel}$	$V_{t\parallel}=V_T=(C_{44}/\rho)^{1/2}$	$2.64+0.71x$
	$V_{t\perp}$	$[(C_{11}-C_{12})/2\rho]^{1/2}$	$1.83+0.65x$
[111]	V_l'	$[(C_{11}+2C_{12}+4C_{44})/3\rho]^{1/2}$	$4.41+0.99x$
	V_t'	$[(C_{11}-C_{12}+C_{44})/3\rho]^{1/2}$	$2.13+0.67x$

Phonon frequencies



Raman-active phonon modes in $\text{Ga}_x\text{In}_{1-x}\text{As}$.

The symbols show experimental results.

1 - LO phonon behavior,

2 - TO phonon behavior,

3,4 - mixed mode behavior.

[Pearsall et al. \(1983\)](#)

$\text{Ga}_x\text{In}_{1-x}\text{As}$

Piezoelectric, Thermoelectric and Magnetic Properties

Piezoelectric constant

Remarks Referens

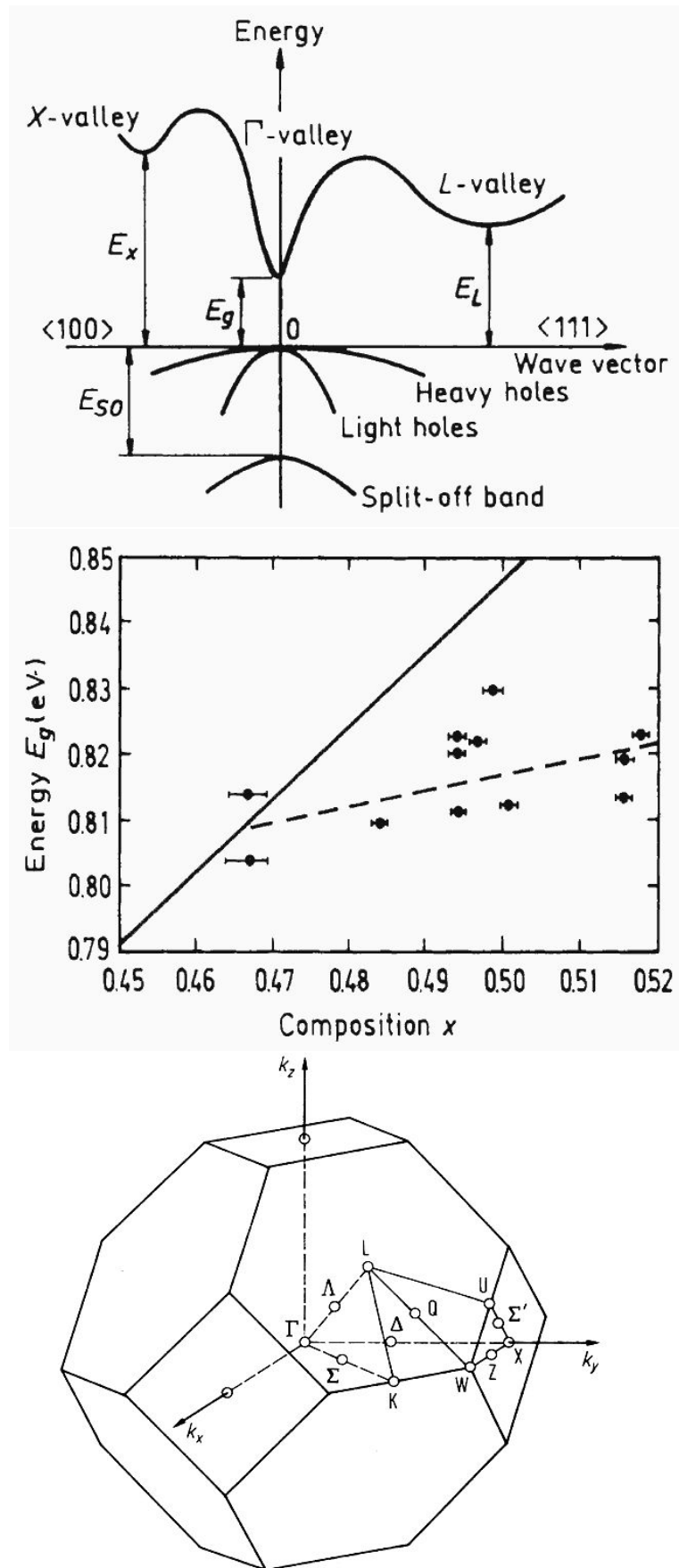
Piezoelectric constant $e_{14} = -(0.045 + 0.115x) \text{ C/m}^2$ 300 K [*Goldberg Yu.A. & N.M. Schmidt \(1999\)*](#)

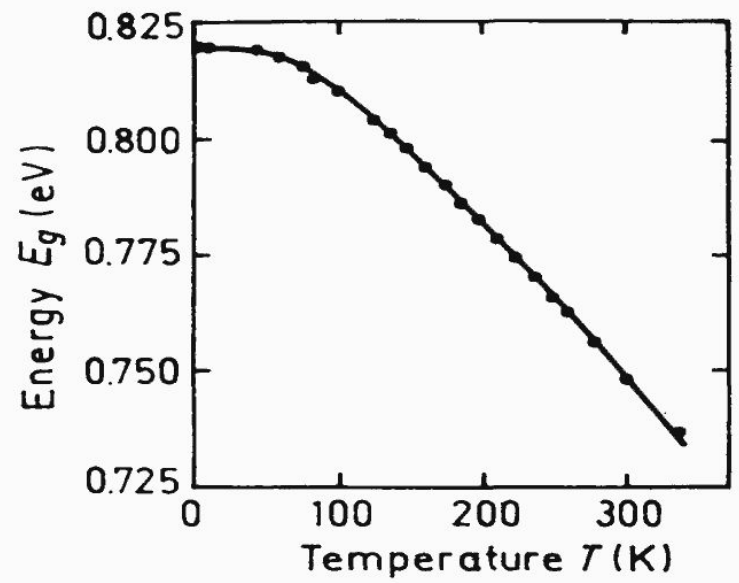
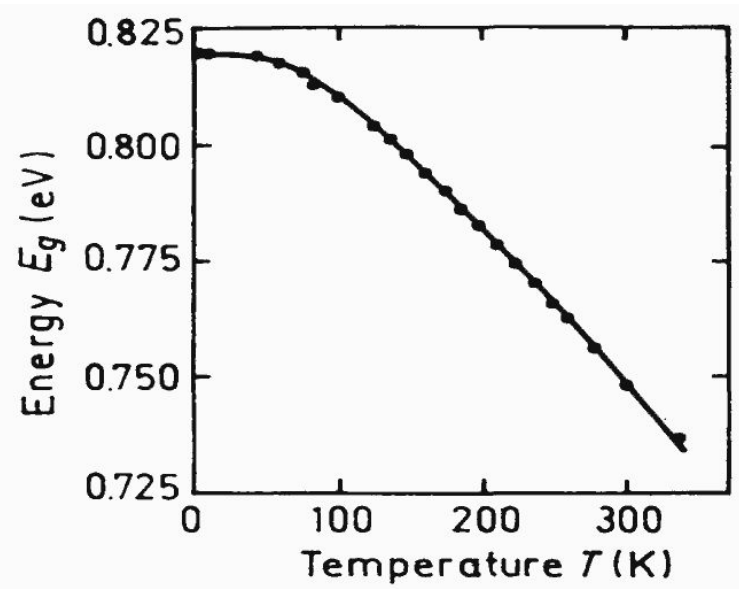
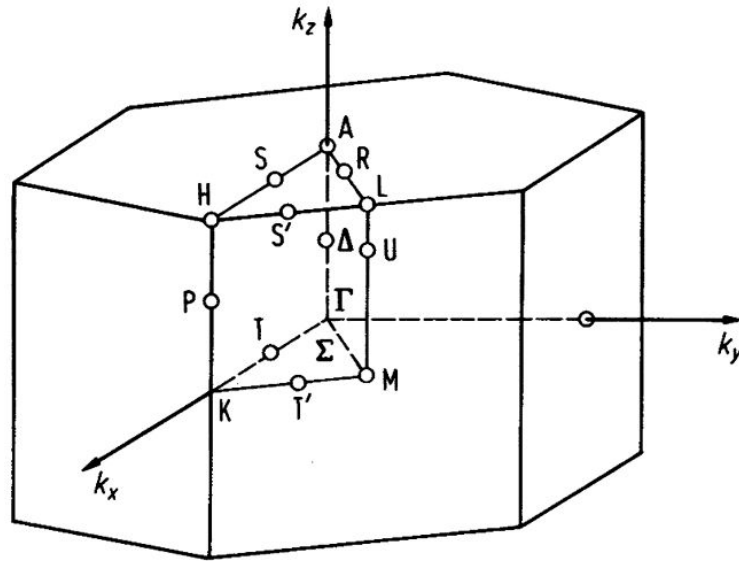
Ga_xIn_{1-x}As

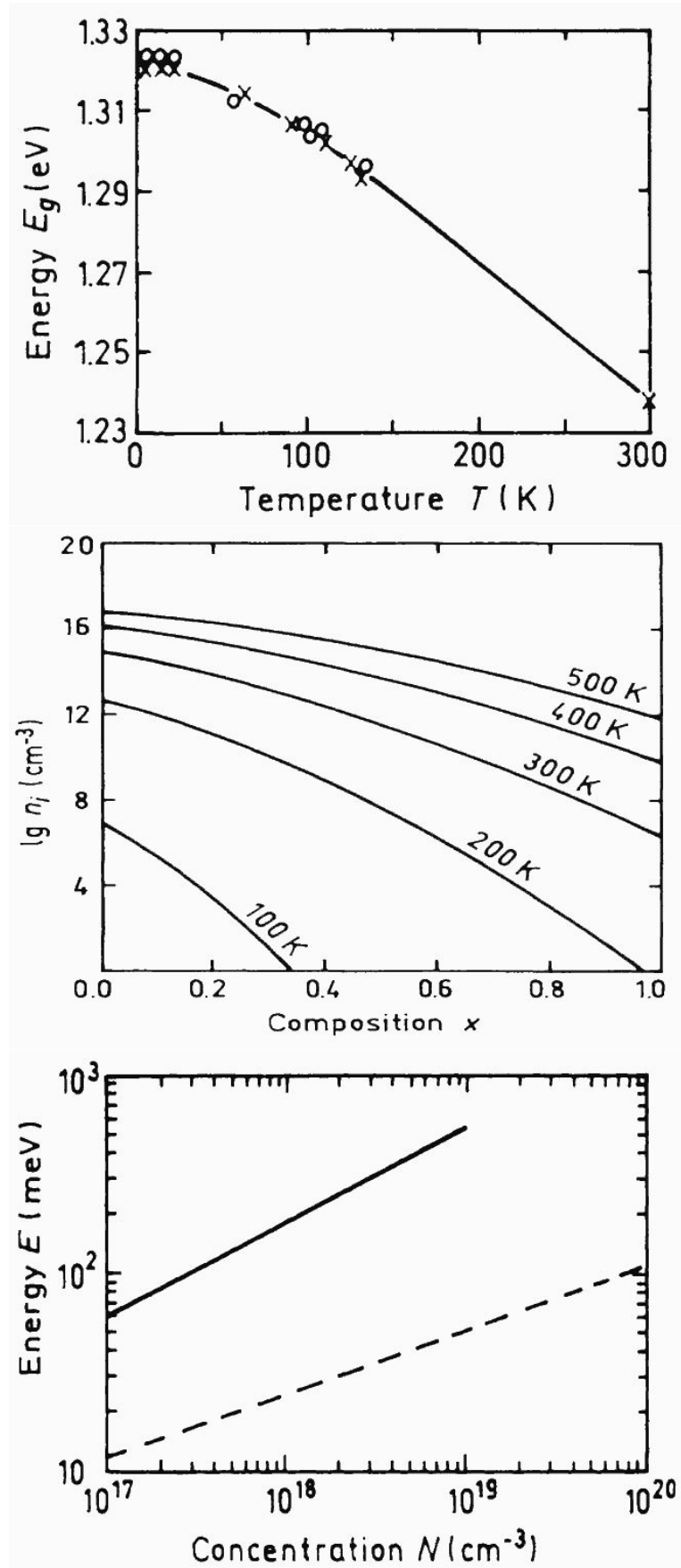
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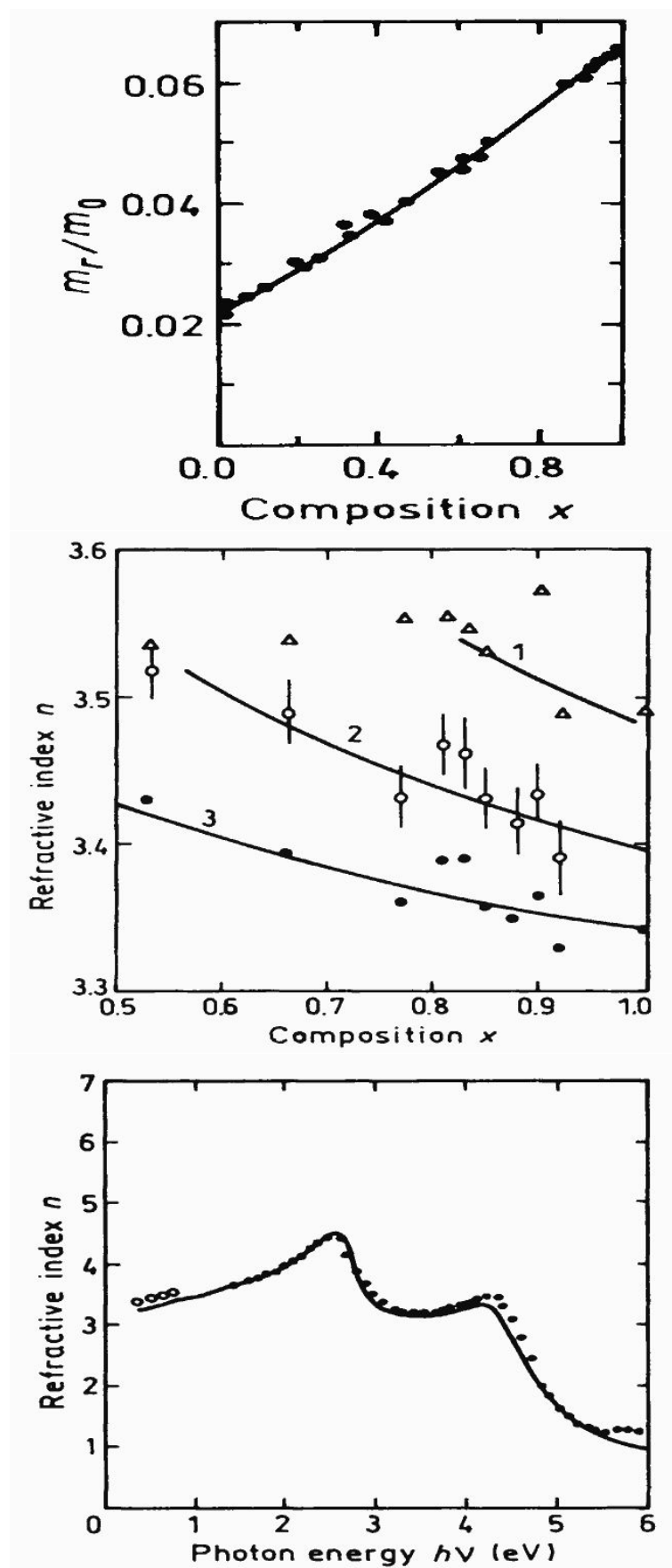
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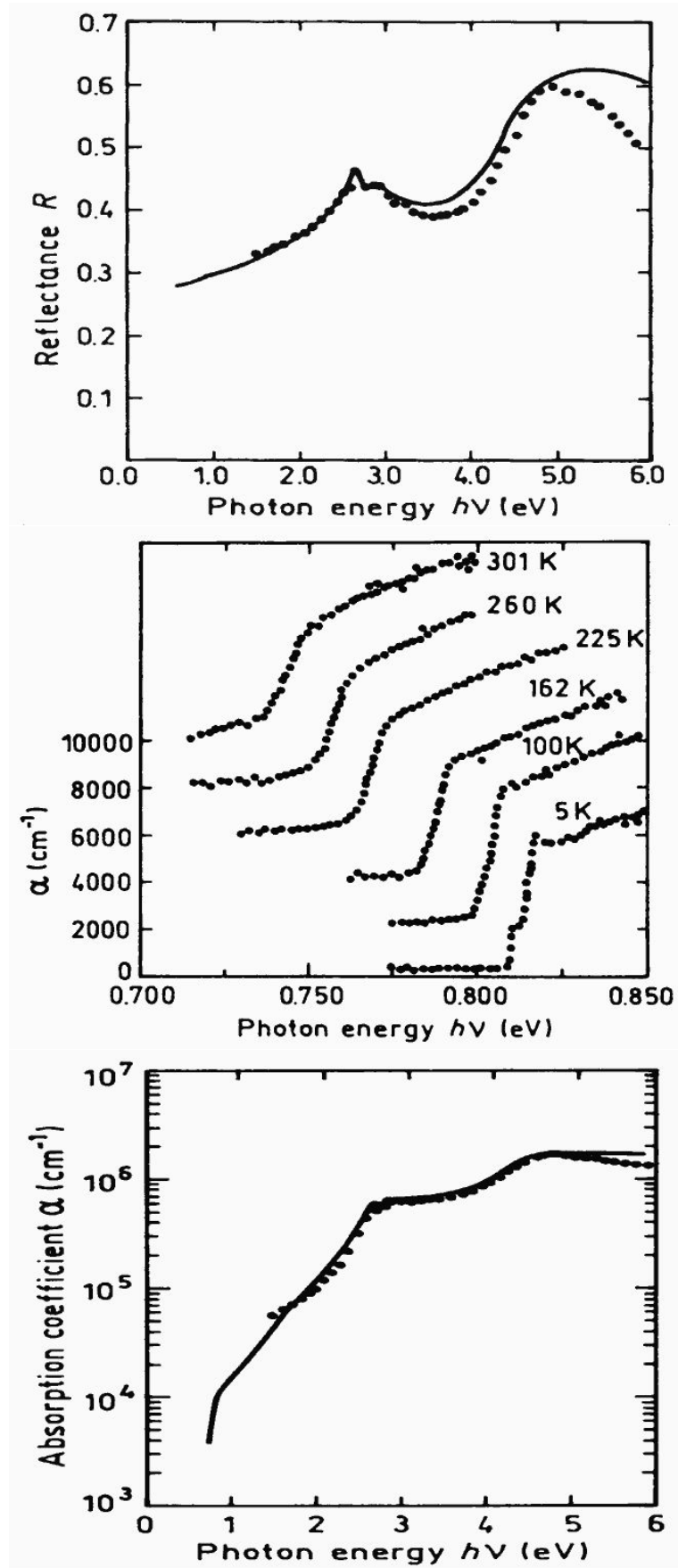
2.2 Bildvergrößerungen

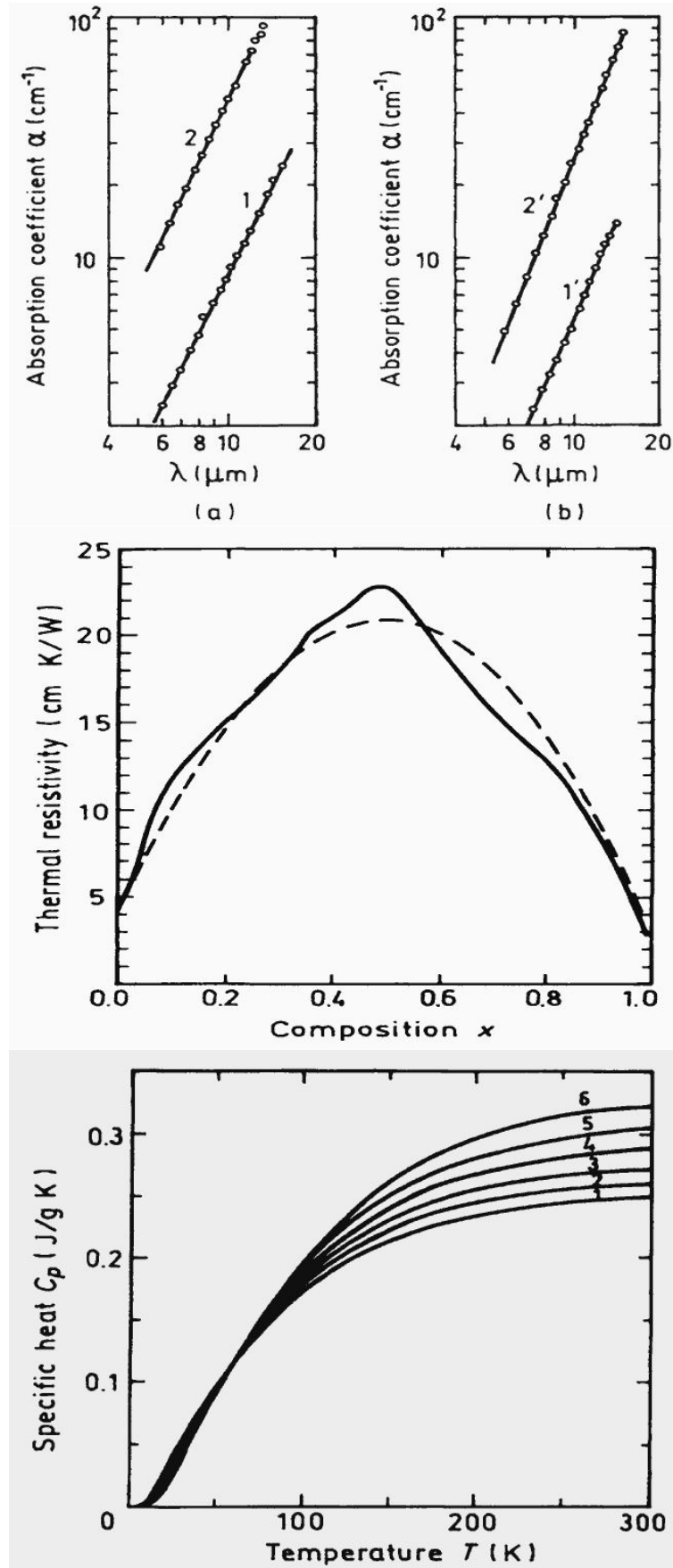


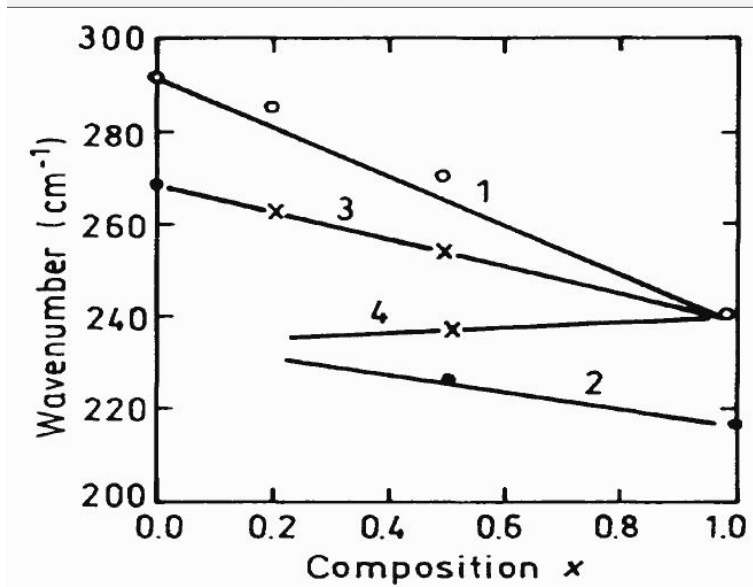
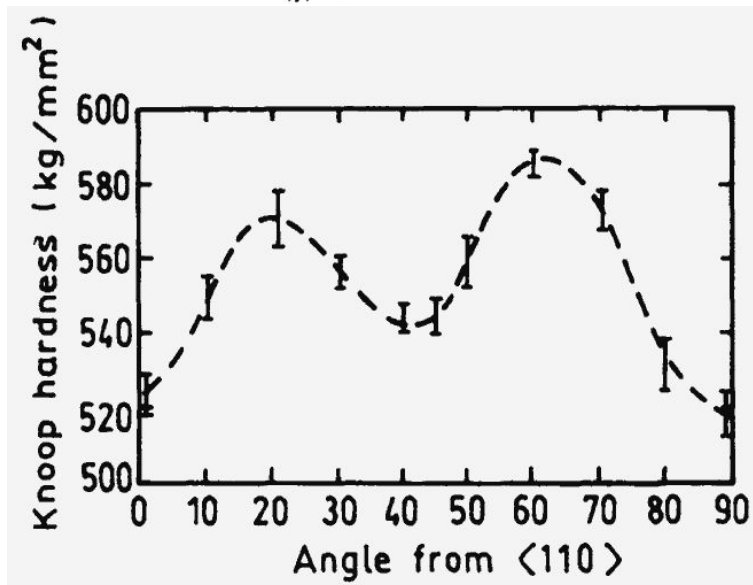
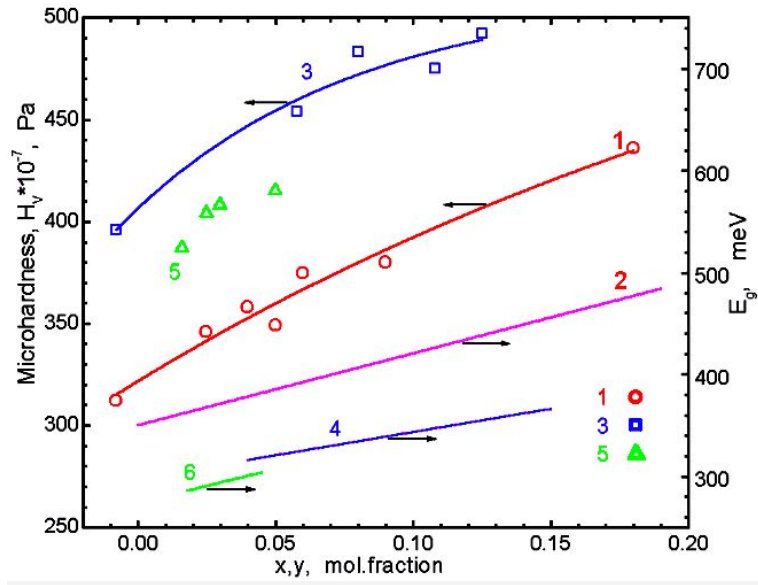


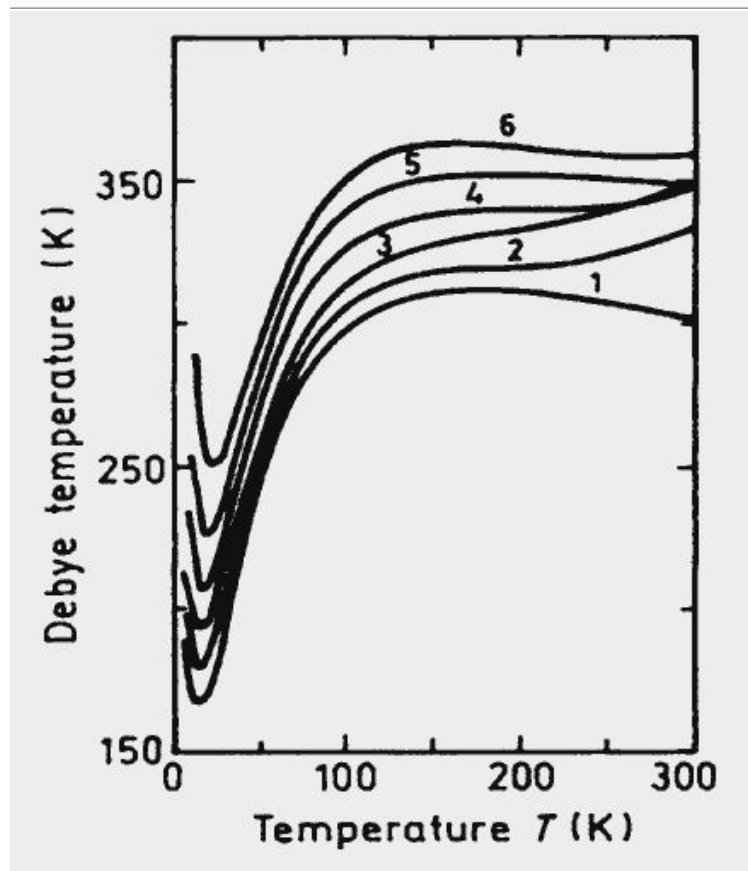
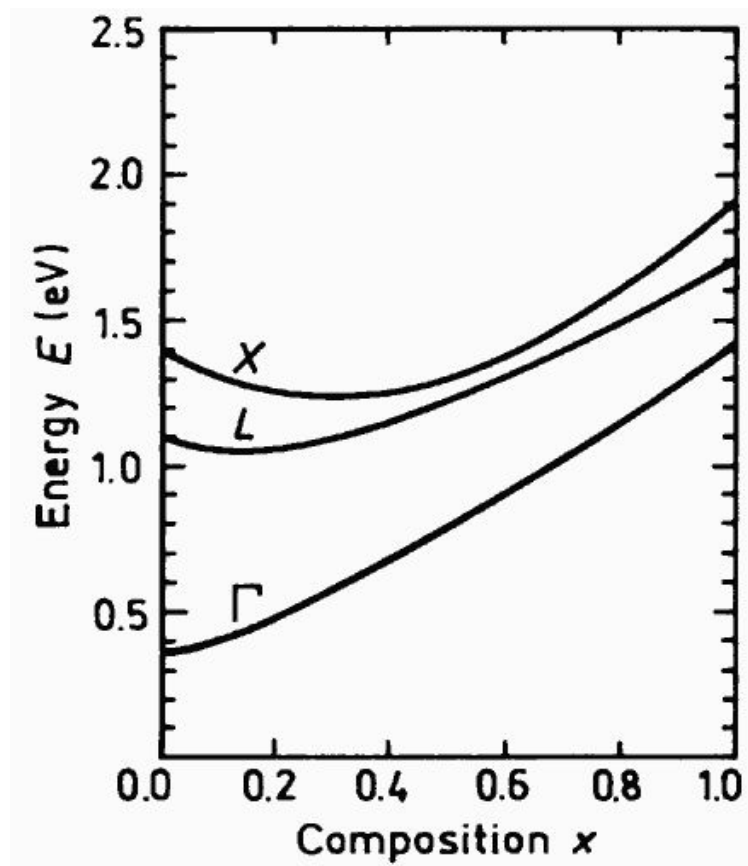












3 $\text{Al}_x\text{In}_{1-x}\text{As}$

[002]ff.

3.1 Originaltexte

Dokument nächste Seite folgend.

$\text{Al}_x\text{Ga}_{1-x}\text{As}$

- [Basic Parameters at 300 K](#)
- [Band structure and carrier concentration](#)
- [Electrical Properties](#)
 - [Basic Parameters of Electrical Properties](#)
 - [Mobility and Hall Effect](#)
 - [Two-dimensional electron and hole gas mobility at \$\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}\$ interface](#)
 - [Transport Properties in High Electric Fields](#)
 - [Transport properties of electron and hole two-dimensional gas in high electric field](#)
 - [Impact Ionization](#)
 - [Recombination Parameters](#)
- [Optical properties](#)
- [Thermal properties](#)
- [Mechanical properties](#)
- [References](#)

$\text{Al}_x\text{Ga}_{1-x}\text{As}$

Basic Parameters at 300 K

Crystal structure	Zinc Blende
Group of symmetry	$T_d^2\text{-F43m}$
Number of atoms in 1 cm^3	$(4.42-0.17x) \cdot 10^{22}$
Debye temperature	$370+54x+22x^2\text{ K}$
Density	$5.32-1.56x\text{ g}\cdot\text{cm}^{-3}$
Dielectric constant (static)	$12.90-2.84x$
Dielectric constant (high frequency)	$10.89-2.73x$
Effective electron mass m_e	$0.063+0.083x\ m_o\ (x<0.45)$
Density-of-states electron mass m_{cd}	$0.85-0.14x\ m_o\ (x>0.45)$
Conductivity effective mass m_{cc}	$0.26\ m_o\ (x>0.45)$
Effective hole masses m_h	$0.51+0.25x\ m_o$
Effective hole masses m_{lp}	$0.082+0.068x\ m_o$
Electron affinity	$4.07-1.1x\text{ eV}\ (x<0.45)$ $3.64-0.14x\text{ eV}\ (x>0.45)$
Lattice constant	$5.6533+0.0078x\ \text{\AA}$
Optical phonon energy	$36.25+1.83x+17.12x^2-5.11x^3\text{ meV}$

Al_xGa_{1-x}As

Band structure and carrier concentration

[Basic Parameters](#)

[Temperature Dependences](#)

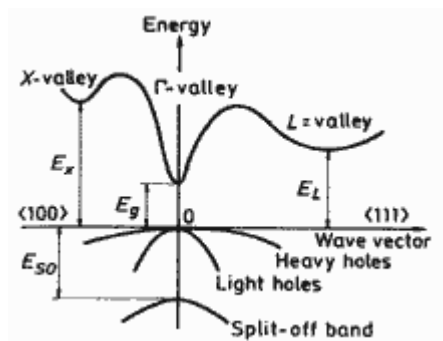
[Dependence on Hydrostatic Pressure](#)

[Energy Gap Narrowing at High Doping Levels](#)

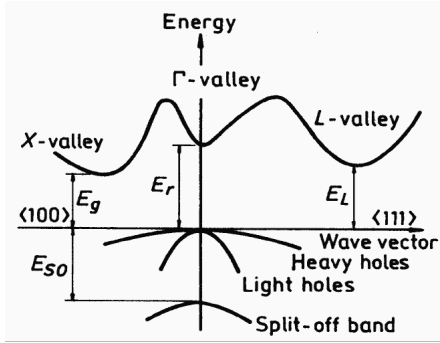
[Band Discontinuities at Al_xGa_{1-x}As/GaAs Heterointerface](#)

Basic Parameters

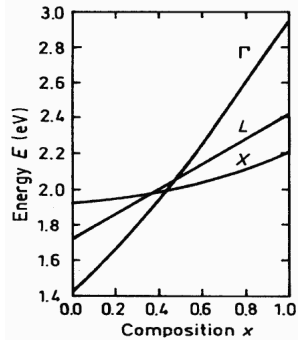
Energy gap	x<0.45	1.424+1.247x eV
	x>0.45	1.9+0.125x+0.143x ²
Energy separation (E _{ΓL}) between Γ and L valleys		0.29 eV
Energy separation (E _Γ) between Γ and top of valence band		1.424+1.155x+0.37x ² eV
Energy separation (E _X) between X-valley and top of valence band		1.9+0.124x+0.144x ² eV
Energy separation (E _L) between L-valley and top of valence band		1.71+0.69x eV
Energy spin-orbital splitting		0.34-0.04x eV
Intrinsic carrier concentration	x=0.1	2.1·10 ⁵ cm ⁻³
	x=0.3	2.1·10 ³ cm ⁻³
	x=0.5	2.5·10 ² cm ⁻³
	x=0.8	4.3·10 ¹ cm ⁻³
Intrinsic resistivity	x=0.1	4·10 ⁹ Ω·cm
	x=0.3	1·10 ¹² Ω·cm
	x=0.5	1·10 ¹⁴ Ω·cm
	x=0.8	5·10 ¹⁴ Ω·cm
Effective conduction band density of states	x<0.41	2.5·10 ¹⁹ ·(0.063+0.083x) ^{3/2} cm ⁻³
	x>0.45	2.5·10 ¹⁹ ·(0.85-0.14x) ^{3/2} cm ⁻³
Effective valence band density of states		2.5·10 ¹⁹ ·(0.51+0.25x) ^{3/2} cm ⁻³



Band structure Al_xGa_{1-x} for x<0.41-0.45. Important minima of the conduction band and maxima of the valence band



Band structure $\text{Al}_x\text{Ga}_{1-x}$ for $x > 0.45$. Important minima of the conduction band and maxima of the valence band



Energy separation between Γ -, X-, and L- conduction band minima and top of the valence band versus composition.

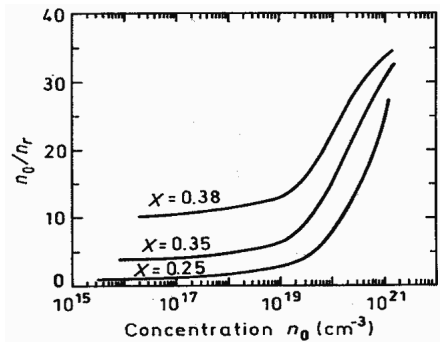
Crossover points:

$$x_c(\text{L-X}) = 0.35 \text{ eV } E_L = E_X = 1.95 \text{ eV}$$

$$x_c(\Gamma\text{-X}) = 0.41 \text{ eV } E_\Gamma = E_X = 1.97 \text{ eV}$$

$$x_c(\Gamma\text{-L}) = 0.47 \text{ eV } E_\Gamma = E_L = 2.04 \text{ eV}$$

(Saxena [1980]).



Ratio of the total carrier concentration to the carrier concentration in Γ -valley as a function of equilibrium carrier concentration at 300K

(Zarem et al. [1989]).

Temperature Dependences

To estimate the temperature dependences of energy difference between the top of the valence band and the bottom of the Γ , X, and L valleys of the conduction band E_Γ , E_X and E_L one can use the data for GaAs (Aspnes [1976]).

$$E_\Gamma = E_\Gamma(0) - 5.41 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

$$\text{where } E_\Gamma(0) = 1.519 + 1.155x + 0.37x^2 \text{ (eV)}$$

$$E_X = E_X(0) - 4.6 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

$$\text{where } E_X(0) = 1.981 + 0.124x + 0.144x^2 \text{ (eV)}$$

$$E_L = E_L(0) - 6.05 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

$$\text{where } E_L(0) = 1.815 + 0.069x \text{ (eV)}$$

Temperature dependence of the energy difference between the top of the valence band and the bottom of the L-valley of the conduction band

$$E_L = 1.815 - 6.05 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

Temperature dependence of the energy difference between the top of the valence band and the bottom of the X-valley of the conduction band

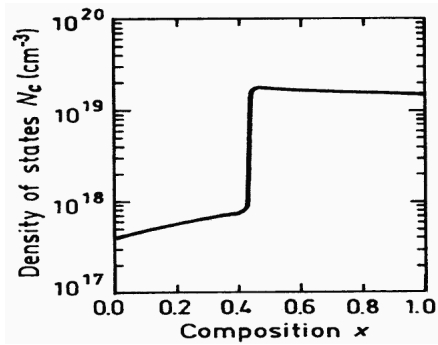
$$E_L = 1.981 - 4.60 \cdot 10^{-4} \cdot T^2 / (T + 204) \text{ (eV)}$$

Effective density of states in the conduction band N_c

$$X < 0.41 \quad N_c = 4.82 \cdot 10^{15} \cdot (m_\Gamma/m_0)^{3/2} \cdot T^{3/2} = 4.82 \cdot 10^{15} \cdot T^{3/2} \cdot (0.063 + 0.083x)^{3/2} \text{ (cm}^{-3}\text{)}$$

$$X > 0.41 \quad N_c = 4.82 \cdot 10^{15} \cdot (m_{cd}/m_0)^{3/2} \cdot T^{3/2} = 4.82 \cdot 10^{15} \cdot T^{3/2} \cdot (0.85 - 0.14x)^{3/2} \text{ (cm}^{-3}\text{)}$$

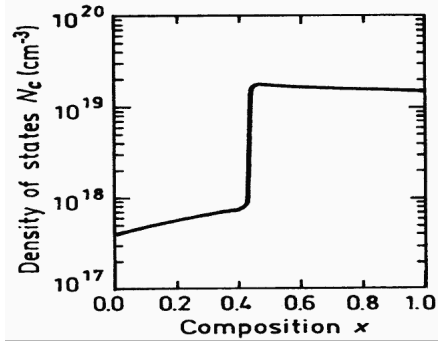
where m_{cd} is effective mass of the density of states;



Effective density of states in the conduction band versus x .
(Calculated)

Effective density of states in the valence band N_v

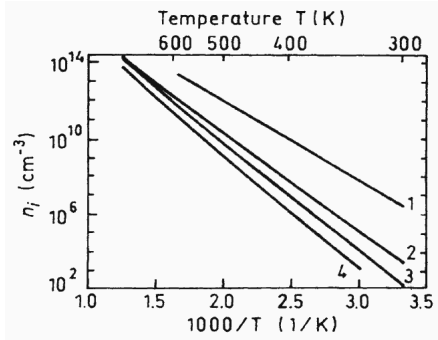
$$N_v = 4.82 \cdot 10^{15} \cdot T^{3/2} \cdot (0.51 + 0.25x)^{3/2} \text{ (cm}^{-3}\text{)} \quad X > 0.41 \quad N_c = 4.82 \cdot 10^{15} \cdot (m_{cd}/m_0)^{3/2} \cdot T^{3/2} = 4.82 \cdot 10^{15} \cdot T^{3/2} \cdot (0.85 - 0.14x)^{3/2} \text{ (cm}^{-3}\text{)}$$



Effective density of states in the conduction band versus x .
(Calculated)

Intrinsic Carrier Concentration

$$n_i = (N_c \cdot N_v)^{1/2} \exp[-E_g / (2k_b T)]$$



The temperature dependences of the intrinsic carrier concentration.

1. $x=0$
2. $x=0.3$
3. $x=0.6$
4. $x=1$

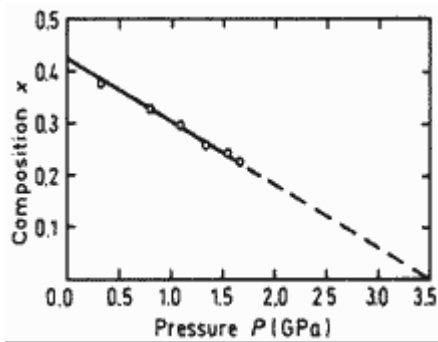
Dependences on Hydrostatic Pressure

$$E_{\Gamma} = (11.5 - 1.3x) \cdot 10^{-3} \cdot P \text{ (eV)}$$

$$E_X = -0.8 \cdot 10^{-3} \cdot P \text{ (eV)}$$

$$E_L = 2.8 \cdot 10^{-3} \cdot P \text{ (eV)}$$

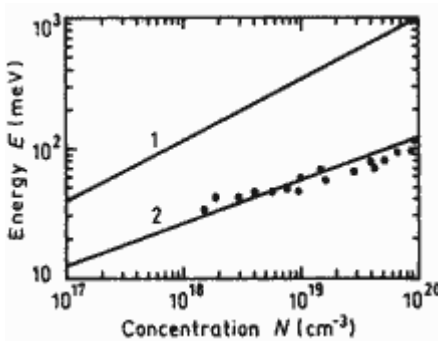
where P is pressure in kbar. ([Adachi \[1985\]](#))



Pressure dependence of the Γ -X crossover. 300 K

([Saxena \[1980\]](#))

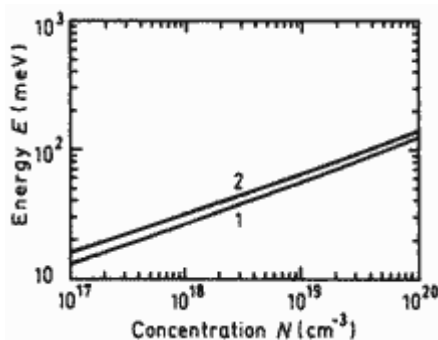
Energy Gap Narrowing at High Doping Levels



Energy gap narrowing versus donor (curve 1) and acceptor (curve 2) doping density for GaAs ($x=0$).

Experimental points for p-GaAs are taken from four different papers

([Jain and Roulston \[1991\]](#))



Energy gap narrowing versus donor (curve 1) and acceptor (curve 2) doping density for AlAs ($x=1$).

The curves are calculated according ([Jain et al. \[1990\]](#))

Band Discontinuities at $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ Heterointerface

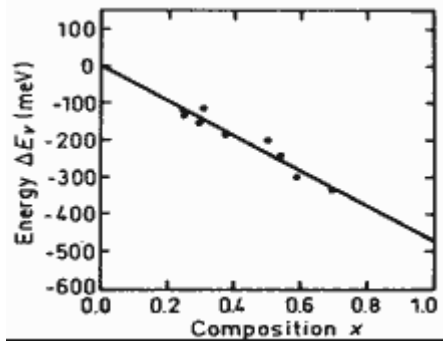
Valence band discontinuity:

$$\Delta E_v = -0.46x \text{ (eV)}$$

Conduction band discontinuity:

$$x < 0.41 \quad \Delta E_c = 0.79x \text{ (eV)}$$

$$x > 0.41 \quad \Delta E_c = 0.475 - 0.335x + 0.143x^2 \text{ (eV)}$$



Energy gap narrowing versus donor (curve 1) and acceptor (curve 2) doping density for GaAs (x=0).

Experimental points for p-GaAs are taken from four different papers
([Jain and Roulston \[1991\]](#))

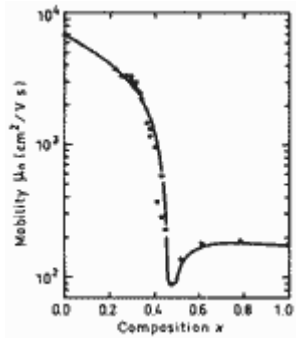
$\text{Al}_x\text{Ga}_{1-x}\text{As}$

Electrical properties - Basic Parameters

Breakdown field	$\approx(4\div6) \cdot 10^5 \text{ V/cm}$
Mobility electrons	
$0 < x < 0.45$	$8 \cdot 10^3 - 2.2 \cdot 10^4 x + 10^4 \cdot x^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
$0.45 < x < 1$	$-255 + 1160x - 720x^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Mobility holes	$370 - 970x + 740x^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Diffusion coefficient electrons	
$0 < x < 0.45$	$200 - 550x + 250x^2 \text{ cm}^2/\text{s}$
$0.45 < x < 1$	$-6.4 + 29x - 18x^2 \text{ cm}^2/\text{s}$
Diffusion coefficient holes	$9.2 - 24x + 18.5x^2 \text{ cm}^2/\text{s}$
Electron thermal velocity	
$0 < x < 0.4$	$(4.4 - 2.1x) \cdot 10^5 \text{ m/s}$
$0.45 < x < 1$	$2.3 \cdot 10^5 \text{ m/s}$
Hole thermal velocity	$(1.8 - 0.5x) \cdot 10^5 \text{ m/s}$

Al_xGa_{1-x}As

Mobility and Hall Effect



Electron Hall mobility versus alloy composition x . $T=300$ K.

Electron concentration $n_0 = (5 \div 10) \cdot 10^{15} \text{ cm}^{-3}$.

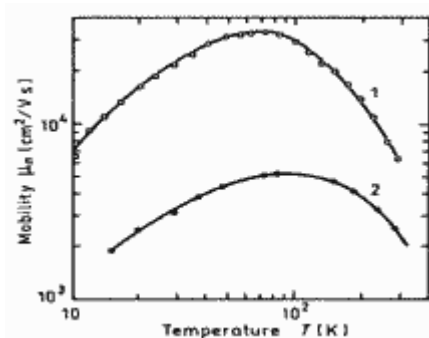
([Saxena \(1981b\)](#)).

For weakly doped Al_xGa_{1-x}As at 300 K electron Hall mobility.

$$0 < x < 0.45 \quad \mu_H = -8000 - 22000x + 10000x^2$$

$$0.45 < x < 1 \quad \mu_H = -255 + 1160x - 720x^2$$

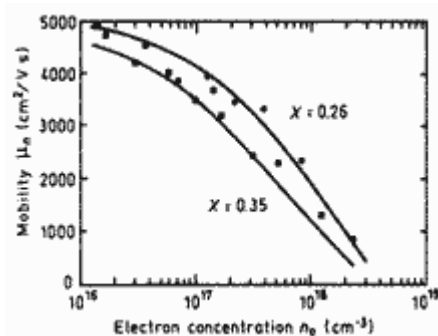
([Shur \(1990\)](#)).



Electron Hall mobility versus temperature.

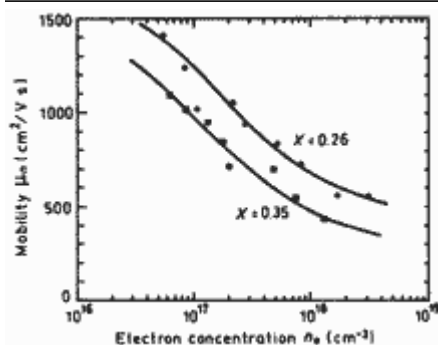
Curve 1 $x=0$; $n=0.5 \cdot 10^{16} \text{ cm}^{-3}$ ([Stillman et al. \(1970\)](#)).

Curve 2 $x=0.32$; $n=(0.5 \div 1) \cdot 10^{16} \text{ cm}^{-3}$ ([Saxena \(1981b\)](#)).



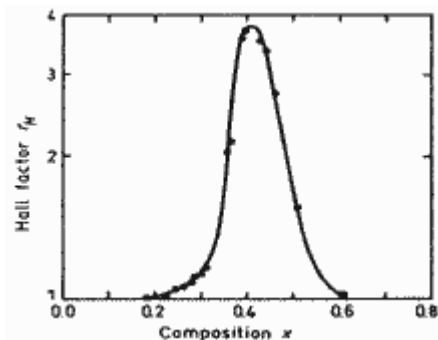
Electron Hall mobility versus electron concentration for two values of x . $T=77$ K.

([Liu \(1990\)](#)).



Electron Hall mobility versus electron concentration for two values of x . $T=300$ K.

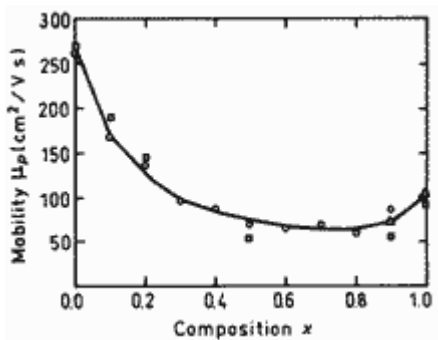
([Liu \(1990\)](#)).



Hall factor versus alloy composition x for n-type $\text{Al}_x\text{Ga}_{1-x}\text{As}$ $T=300\text{ K}$

Electron concentration $n_0 = (5 \div 10) \cdot 10^{15} \text{ cm}^{-3}$.

([Saxena \(1981a\)](#)).



Hole Hall mobility versus alloy composition x. 296 K.

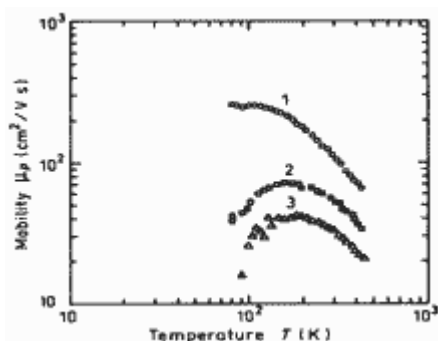
Acceptor density $N_a \approx 2.5 \cdot 10^{17} \text{ cm}^{-3}$.

([Look et al. \(1992\)](#)).

For weakly doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ at 300 K hole Hall mobility.

$$\mu_H = -370 - 970x + 740x^2$$

([Shur \(1990\)](#)).



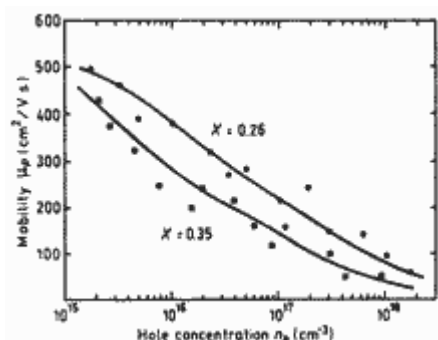
Hole Hall mobility versus temperature.

Curve 1 - $x=0$; $p_0 = 7 \cdot 10^{17} \text{ cm}^{-3}$

Curve 2 - $x=0.41$; $p_0 = 4.65 \cdot 10^{17} \text{ cm}^{-3}$

Curve 3 - $x=0.75$; $p_0 = 2.4 \cdot 10^{17} \text{ cm}^{-3}$

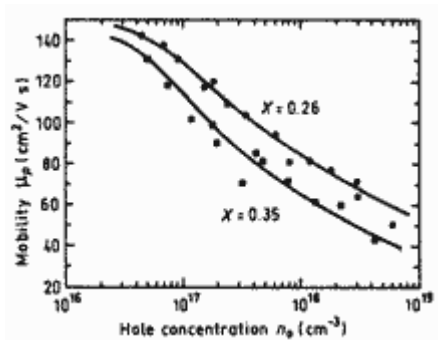
([Yang et al. \(1981\)](#)).



Hole Hall mobility versus hole concentration for two values of x.

$T=77\text{ K}$.

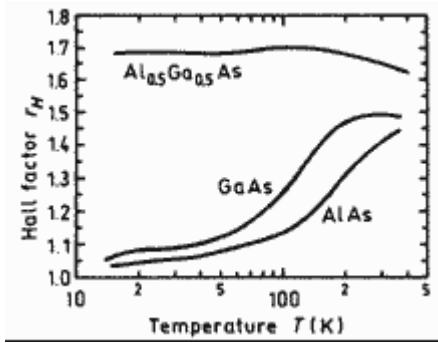
([Liu \(1990\)](#)).



Hole Hall mobility versus hole concentration for two values of x.

$T=300\text{ K}$.

([Liu \(1990\)](#)).

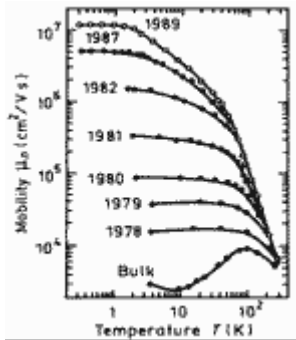


Hall factor versus temperature x for p-type GaAs, AlAs and $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$.

Curves are calculated for acceptor concentration $N_a \approx 6.5 \cdot 10^{13} \text{ cm}^{-3}$.
[\(Look et al. \(1992\)\).](#)

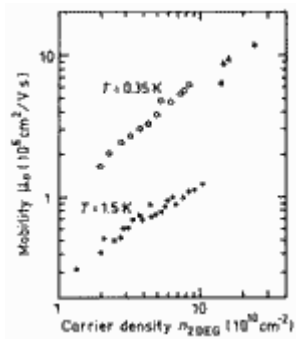
Al_xGa_{1-x}As

Two-dimensional electron and hole gas mobility at Al_xGa_{1-x}As/GaAs interface



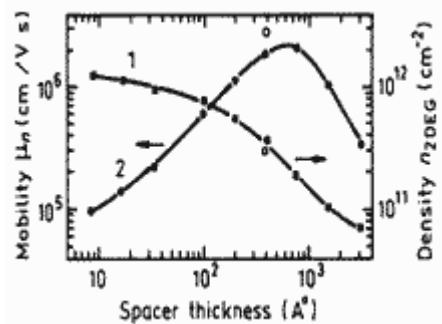
Temperature dependences of the electron Hall mobility in the modulation-doped two-dimensional gas.

([Pfeiffer et al. \(1989\)](#)).



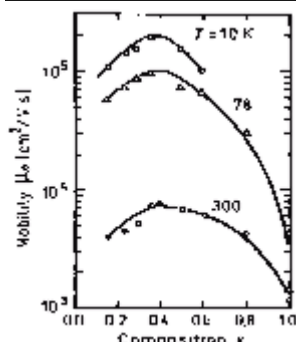
Dependences of electron mobility versus surface carrier density 2D electron gas in the modulation-doped two-dimensional gas.

([Pfeiffer et al. \(1989\)](#)).



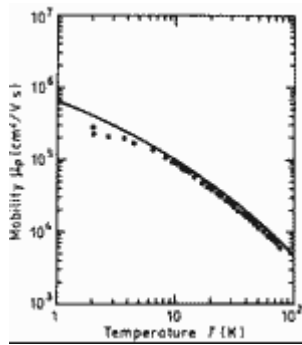
Dependences of surface electron density (Curve 1) and mobility (Curve 2) versus undoped spacer thickness. T=4 K.

([Harris et al. \(1987\)](#)).



Electron mobility in 2D-electron gas versus Al fraction x at three different temperatures.

([Drummond et al. \(1982\)](#)).



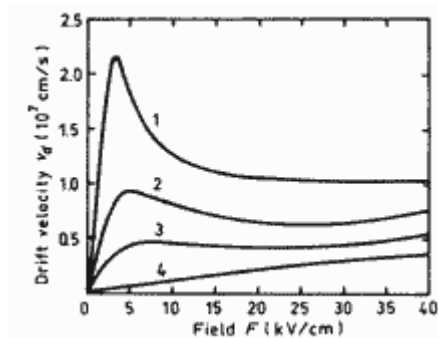
Hole mobility in 2D-hole gas versus temperature.

Solid line shows theoretical calculation.

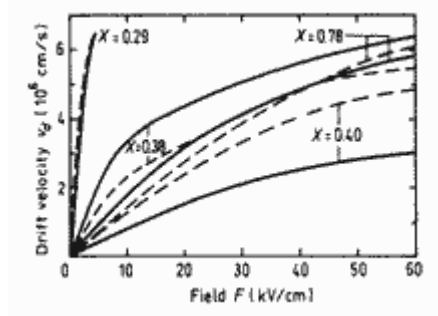
Points show experimental data for hole surface density $2 \cdot 10^{11} \text{ cm}^{-2}$ ([Walukiewicz \(1996\)](#)).

Al_xGa_{1-x}As

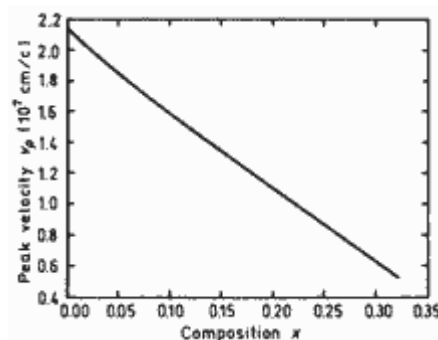
Transport Properties in High Electric Fields



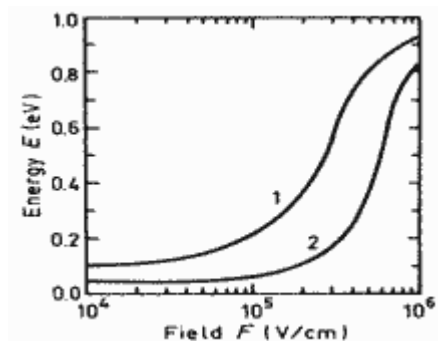
Field dependences of the electron drift velocity for different values of x . Curves are calculated according displaced Maxwellian approximation. $T=300$ K.
 1 - $x=0$;
 2 - $x=0.225$;
 3 - $x=0.325$;
 4 - $x=0.5$.
 ([Hava and Auslender \(1993\)](#)).



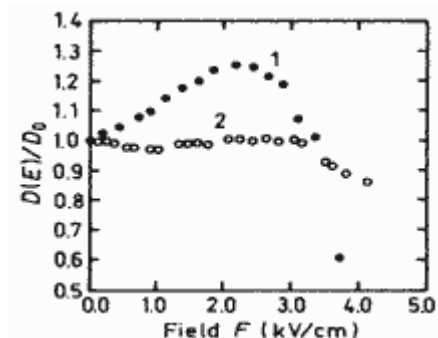
Field dependences of the electron drift velocity for different values of x . Solid curves - show experimental results (electron concentration $n_0=(2\div 10)\cdot 10^{15}$ cm⁻³). Dashed curves show results of Monte-Carlo calculations.
 ([Hill and Robson \(1981\)](#)).



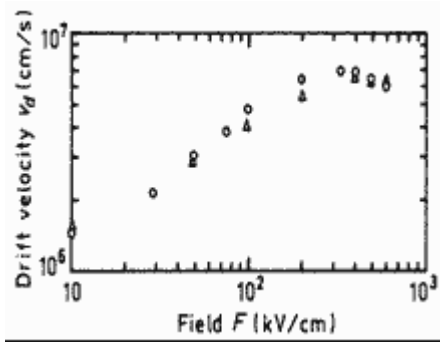
Dependences of peak electron velocity versus x .
 ([Hava and Auslender \(1993\)](#)).



Average electron energy as a function of electric field. $T=300$ K.
 1 - $x=0.25$;
 2 - $x=0.45$. ([Lippens and Vanbesien \(1987\)](#)).



The field dependences of normalized longitudinal diffusion coefficient. $T=300$ K.
 1 - $x=0$;
 2 - $x=0.25$. ([de Murcia et al. \(1993\)](#)).



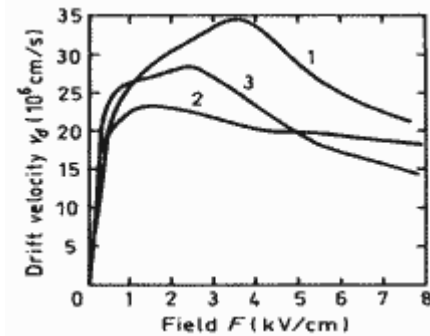
Field dependence of hole drift velocity. Monte-Carlo calculations.

T=300 K.

[\(Brennan and Hess \(1986\)\).](#)

$\text{Al}_x\text{Ga}_{1-x}\text{As}$

Transport properties of electron and hole two-dimensional gas in high electric field



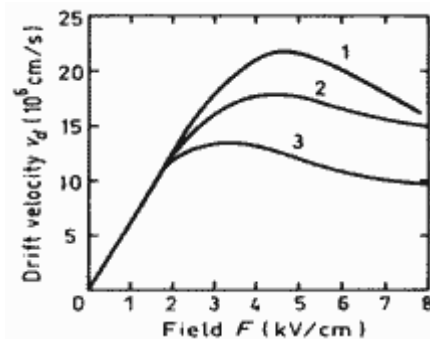
Experimental field dependences of electron velocity.
T=77 K.

1 - for bulk GaAs with $n_0=10^{15} \text{ cm}^{-3}$
 2, 3 - for two-dimensional modulation - doped heterostructures $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$.

2 - $x=0.3$;

3 - $x=0.5$.

([Masselink \(1989\)](#)).



Experimental field dependences of electron velocity.
T=300 K.

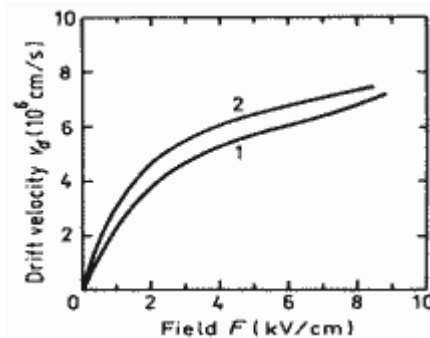
1 - for bulk GaAs with $n_0=10^{15} \text{ cm}^{-3}$

2, 3 - for two-dimensional modulation - doped heterostructures $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$.

2 - $x=0.3$;

3 - $x=0.5$.

([Masselink \(1989\)](#)).



Experimental field dependences of hole velocity for two-dimensional hole gas. Single heterointerface samples. $x=0.5$. T=77 K.

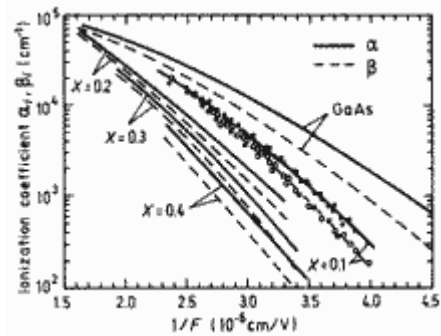
1 - $p=3.3 \cdot 10^{11} \text{ cm}^{-2}$, $\mu=3300 \text{ cm}^2 \text{ Vs}$

2 - $p=4.2 \cdot 10^{11} \text{ cm}^{-2}$, $\mu=4000 \text{ cm}^2 \text{ Vs}$

([Masselink et al. \(1987\)](#)).

Al_xGa_{1-x}As

Impact Ionization



Fits to experimental values of electron and hole ionization coefficients for Al_xGa_{1-x}As with $x=0.1 \div 0.4$. $T=300$ K.

Experimental points are shown only for $x=0.1$ ([Robbins et al. \(1988\)](#)).

Parametrizations of the electron and hole ionization coefficients. $T=300$ K. ([Robbins et al. \(1988\)](#))

For electrons:

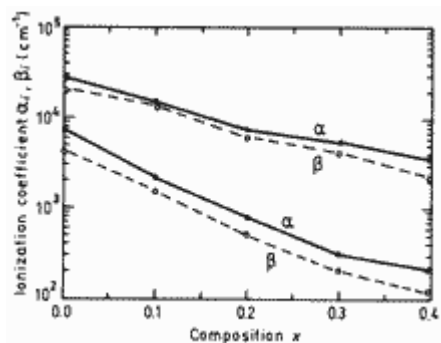
$$\alpha_i = \alpha_0 \exp\left[-\left(F_{no}/F\right)^m\right]$$

x	α_0 (cm ⁻¹)	F_{no} (V cm ⁻¹)	m
0.1	$1.81 \cdot 10^5$	$6.31 \cdot 10^5$	2.0
0.2	$1.09 \cdot 10^6$	$1.37 \cdot 10^6$	1.3
0.3	$2.21 \cdot 10^5$	$7.64 \cdot 10^5$	2.0
0.4	$1.74 \cdot 10^7$	$3.39 \cdot 10^6$	1.0

For holes:

$$\beta_i = \beta_0 \exp\left[-\left(F_{po}/F\right)^m\right]$$

x	β_0 (cm ⁻¹)	F_{po} (V cm ⁻¹)	m
0.1	$3.05 \cdot 10^5$	$7.22 \cdot 10^5$	1.9
0.2	$6.45 \cdot 10^5$	$1.11 \cdot 10^6$	1.5
0.3	$2.791 \cdot 10^5$	$8.47 \cdot 10^5$	1.9
0.4	$3.06 \cdot 10^6$	$2.07 \cdot 10^6$	1.2



Experimental ionization coefficients versus x for electric fields

Bottom curves - $3 \cdot 10^5$ V/cm

Upper curves - $4 \cdot 10^5$ V/cm

$T=300$ K. ([Robbins et al. \(1988\)](#)).

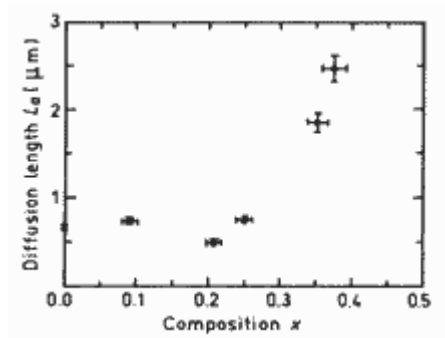
Breakdown voltage and breakdown field of n-GaAs/p-Al_{0.3}Ga_{0.7}As heterojunctions $T=300$ K.

(Hur et al. (1990))

$N_a=10^{14} \text{ cm}^{-3}$	$V_i=2.8 \text{ kV}$	$E_i=2.8 \cdot 10^5 \text{ V cm}^{-1}$
$N_a=10^{16} \text{ cm}^{-3}$	$V_i=70 \text{ V}$	$E_i=4.5 \cdot 10^5 \text{ V cm}^{-1}$

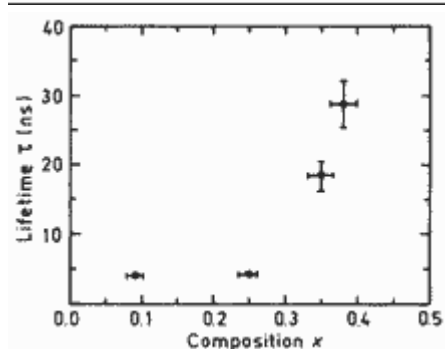
Al_xGa_{1-x}As

Recombination Parameter



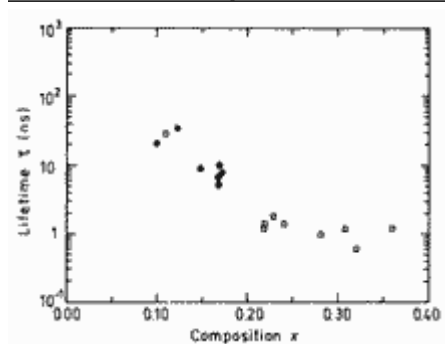
Ambipolar diffusion length at a carrier density of $10^{17} \div 10^{18} \text{ cm}^{-3}$ versus x. T= 300K.

Determination was accomplished by catodoluminescence technique ([Zarem et al. \(1989\)](#)).



Carrier lifetimes at carrier density of $\sim 3 \cdot 10^{18} \text{ cm}^{-3}$ (high injection level) versus x. T= 300K.

Determination was accomplished by photoluminescence decay signal technique. ([Zarem et al. \(1989\)](#)).



Hole lifetime versus x for n-Al_xGa_{1-x}As

$N_d - N_a \sim 10^{15} \div 10^{16} \text{ cm}^{-3}$. T= 300K.

([Timmons et al. \(1988\)](#)).

Radiative recombination coefficient at 300K $\sim 1.8 \cdot 10^{-10} \text{ cm}^3/\text{s}$

Auger coefficient at T=300 K ([Timmons \(1985\)](#)).

x	C _n (cm ⁶ /s)	C _p (cm ⁶ /s)
0	$1.9 \cdot 10^{-31}$	$12 \cdot 10^{-31}$
0.1	$1.2 \cdot 10^{-31}$	$8.5 \cdot 10^{-31}$
0.2	$0.7 \cdot 10^{-31}$	$6.1 \cdot 10^{-31}$

C_n (for n - doped samples)

C_p (for p - doped samples)

Surface and interface recombination velocities in GaAs and Al_xGa_{1-x}As

([Pavesi and Guzzi \(1994\)](#)).

x	S (cm/s)
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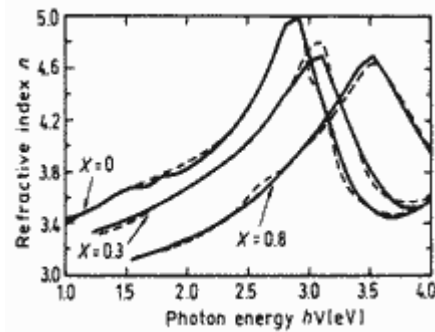
0	$4 \cdot 10^5$	free surface
0	45	interface between GaAs/Al _{0.3} Ga _{0.7} As
0	450±100	interface between GaAs/Al _{0.5} Ga _{0.5} As p-type
0.08	$4 \cdot 10^5$	free surface
0.08÷0.18	$\sim 3 \cdot 10^4$	interface between Al _x Ga _{1-x} As/Al _{0.88} Ga _{0.22} As undoped
0.28	4200	interface between Al _x Ga _{1-x} As/Al _{0.5} Ga _{0.5} As undoped

Al_xGa_{1-x}As

Optical properties

Infrared refractive index (300 K)

$$n=3.3-0.53x+0.09x^2$$

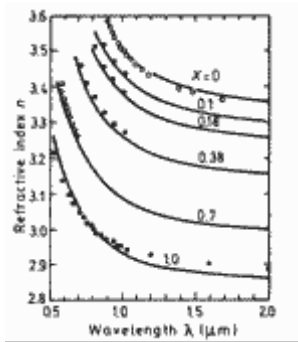


Refractive index n versus photon energy for three values of x .

Solid lines are calculated.

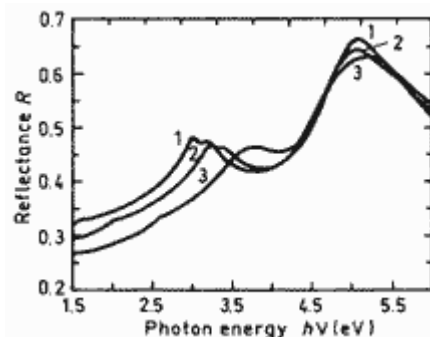
Dashed lines are experimental data. 300 K.

([Jenkins \(1990\)](#)).



Refractive index n versus wavelength for different values of x . 300 K.

([Pikhtin and Yas'kov \(1980\)](#)).



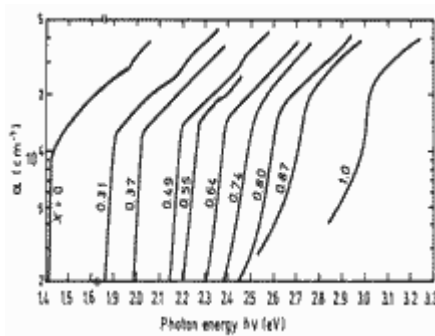
Normal incidence reflectivity versus photon energy. 300 K.

1 $x \sim 0.1$,

2 $x \sim 0.42$,

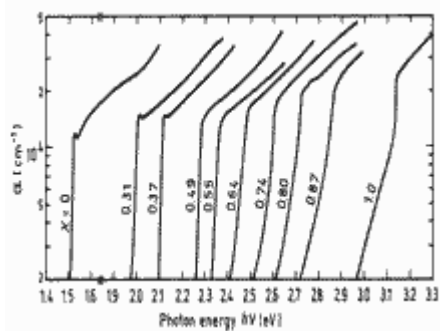
3 $x \sim 0.8$.

([Aspnes et al. \(1986\)](#))).

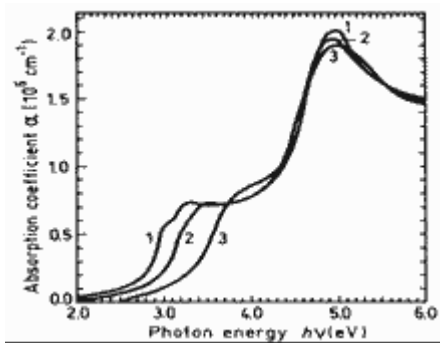


Intrinsic absorption coefficient near the intrinsic absorption edge for different values of x . 300 K.

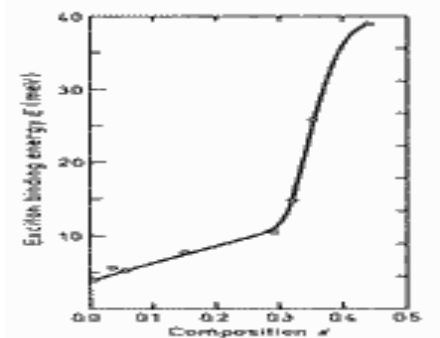
([Monemar et al. \(1976\)](#)).



Intrinsic absorption coefficient near the intrinsic absorption edge for different values of x . 4 K.
[\(Monemar et al. \(1976\)\).](#)



The absorption coefficient versus photon energy. 300 K.
1 $x \sim 0.1$,
2 $x \sim 0.42$,
3 $x \sim 0.8$.
[\(Aspnes et al. \(1986\)\).](#)

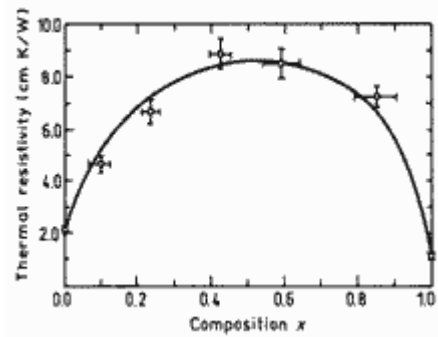


Free exciton binding energy versus Al mole fraction x .
[\(Pearah et al. \(1985\)\).](#)

Al_xGa_{1-x}As

Thermal properties

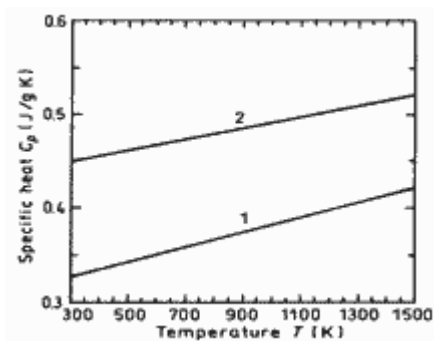
Bulk modulus	$(7.55+0.26x) \cdot 10^{11} \text{ dyn cm}^{-2}$
Melting point	$1240-58x+558x^2 \text{ }^{\circ}\text{C}$ (solidus curve) $12401082x+582x^2 \text{ }^{\circ}\text{C}$ (liquidus curve)
Specific heat	$0.33+0.12x \text{ J g}^{-1}\text{ }^{\circ}\text{C}^{-1}$
Thermal conductivity	$0.55-2.12x+2.48x^2 \text{ W cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$
Thermal diffusivity	$0.31-1.23x+1.46^2 \text{ cm}^2\text{s}^{-1}$
Thermal expansion, linear	$(5.73-0.53x) \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$



Thermal resistivity versus Al fraction x. 300K.
Solid curve is a theoretical fit to the experimental data.
([Afromowitz \[1973\]](#)).

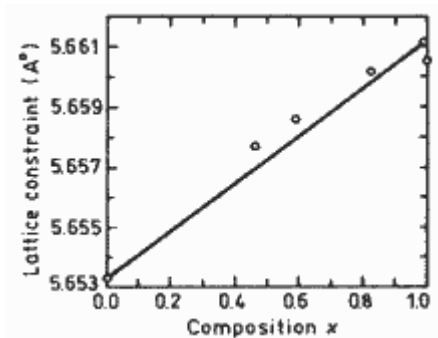
Approximate formula for the lattice thermal resistivity:

$$R_{\text{th}} = 2.27 + 28.83x - 30x^2 \text{ cm} \cdot \text{W}^{-1}$$

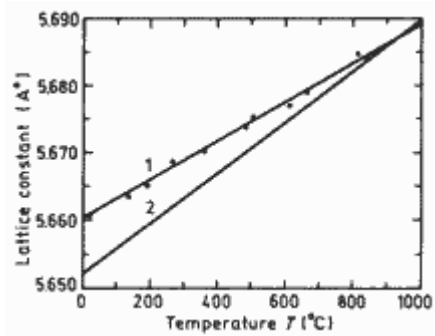


Temperature dependences of specific heat at constant pressure.

1. GaAs ([Lichter and Sommelet \[1969\]](#));
2. AlAs ([Barin et al. \[1977\]](#)).



Lattice constant as a function of x. 300K.
([Adachi \[1985\]](#)).

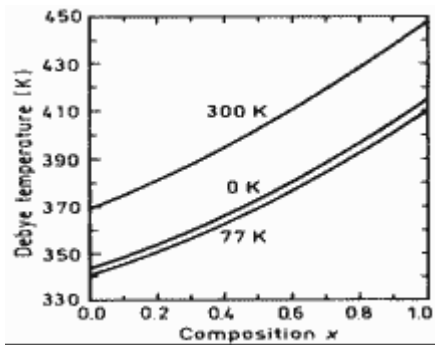


Lattice constants versus temperature.

1. AlAs;

2. GaAs;

([Ettenberg and Paff \[1970\]](#)).



Debye temperature as a function of x for three different temperatures.

([Adachi \[1985\]](#)).

Melting point:

$$T_m = 1240 - 58x + 558x^2 \text{ } ^\circ\text{C} \text{ - (solidus curve)}$$

$$T_m = 1240 + 1082x - 582x^2 \text{ } ^\circ\text{C} \text{ (liquidus curve)}$$

Al_xGa_{1-x}As

Mechanical properties, elastic constants, lattice vibrations

[Basic Parameter](#)

[Elastic constants](#)

[Acoustic Wave Speeds](#)

[Phonon frequencies](#)

Basic Parameter

Bulk modulus	$(7.55+0.26x) \cdot 10^{11} \text{ dyn cm}^{-2}$
Density	$5.32-1.56x \text{ g cm}^{-3}$
Hardness on the Mohs scale	~ 5
Cleavage plane	$\{110\}$
Piezoelectric constant	$e_{14} = -0.16-0.065x \text{ C m}^{-2}$

Elastic constants 300 K.

$$C_{11} = (11.88+0.14x) \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{12} = (5.38+0.32x) \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{44} = (5.94-0.05x) \cdot 10^{11} \text{ dyn/cm}^2$$

[\(Adachi \[1985\]\)](#).

For T = 300 K

Bulk modulus (compressibility ⁻¹) $B_s =$	$(7.55+0.26x) \cdot 10^{11} \text{ dyn/cm}^2$
Anisotropy factor	$A = 0.55-0.01x$
Shear modulus	$C' = (3.25-0.09x) \cdot 10^{11} \text{ dyn/cm}^2$
[100] Young's modulus	$Y_o = (8.53-0.18x) \cdot 10^{11} \text{ dyn/cm}^2$
[100] Poisson ratio	$\sigma_o = (0.31+0.1x)$

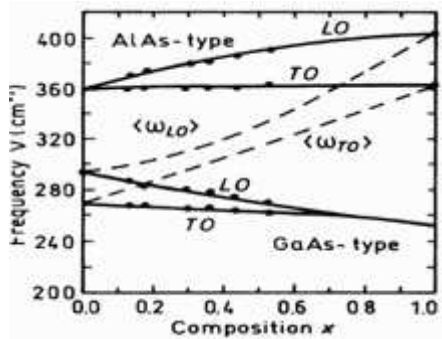
[\(Adachi \[1985\]\)](#).

Acoustic Wave Speeds

Wave propagation Direction	Wave character	Expression for wave speed	Wave speed (in units of 10^5 cm/s)
[100]	V_L	$(C_{11}/\rho)^{1/2}$	$4.73+0.68x+0.24x^2$
	V_T	$(C_{44}/\rho)^{1/2}$	$3.34+0.46x+0.16x^2$
[110]	V_l	$[(C_{11}+C_{12}+2C_{44})/2\rho]^{1/2}$	$5.24+0.78x+0.24x^2$
	$V_{t\parallel}$	$V_{t\parallel} = V_T = (C_{44}/\rho)^{1/2}$	$3.34+0.46x+0.16x^2$
	$V_{t\perp}$	$[(C_{11}-C_{12})/2\rho]^{1/2}$	$2.47+0.33x+0.10x^2$

[111]	V_l'	$[(C_{11}+2C_{12}+4C_{44})/3\rho]^{1/2}$	$5.40+0.79x+0.26x^2$
	V_t'	$[(C_{11}-C_{12}+C_{44})/3\rho]^{1/2}$	$2.79+0.38x+0.12x^2$

Phonon frequencies



Optical phonon energy as a function of x .

The compositional dependence of the effective phonon energy $\langle\omega_{LO}\rangle$ and $\langle\omega_{TO}\rangle$ are shown by the dashed lines.

([Adachi \[1985\]](#)).

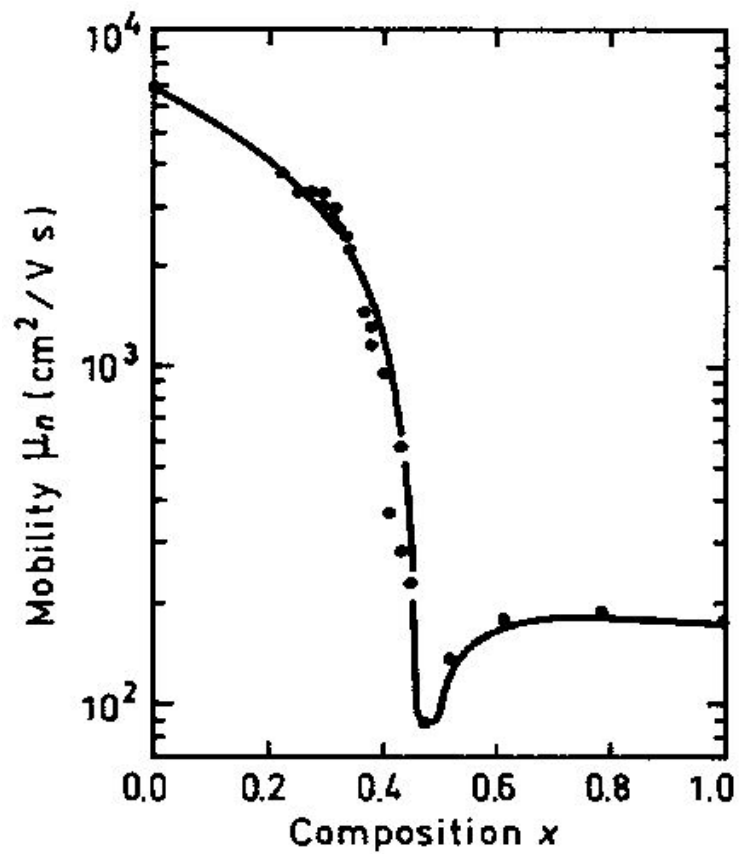
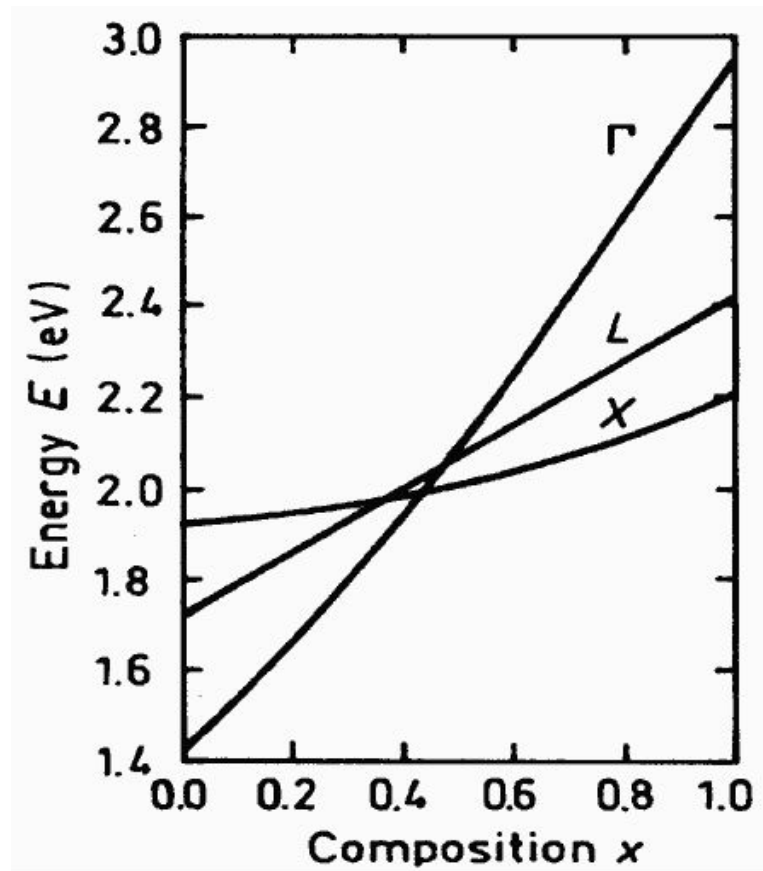
Al_xGa_{1-x}As

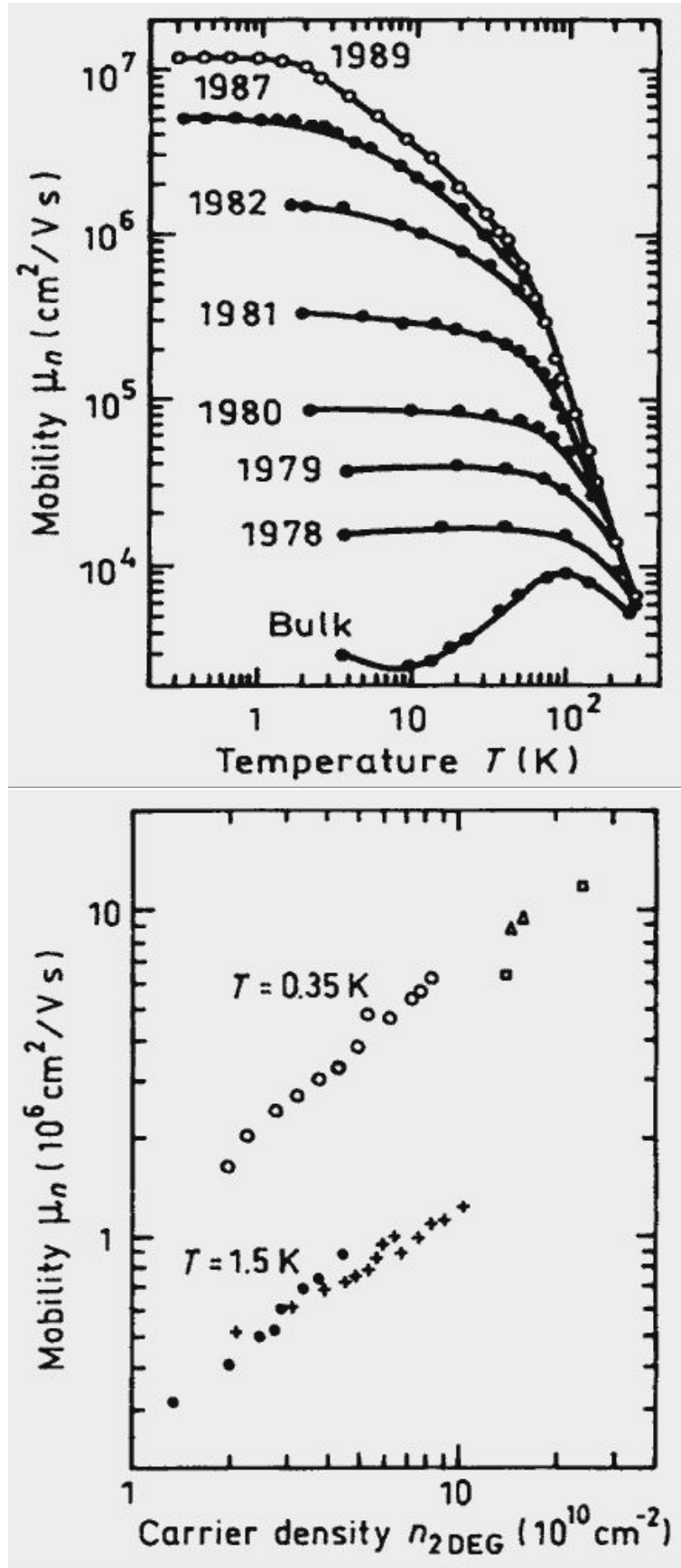
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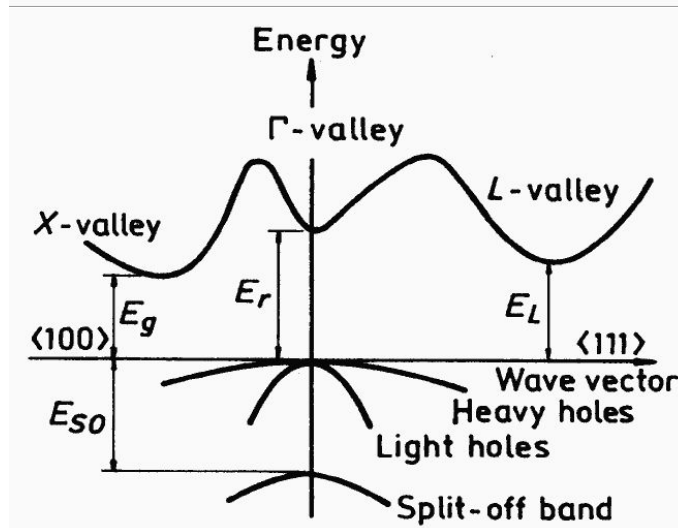
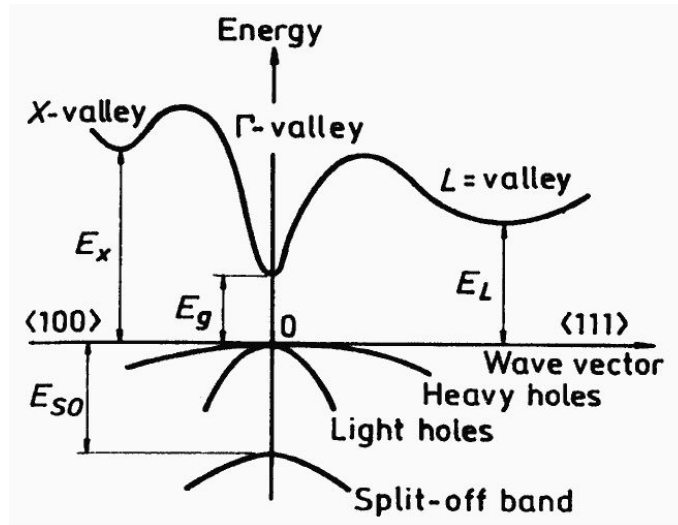
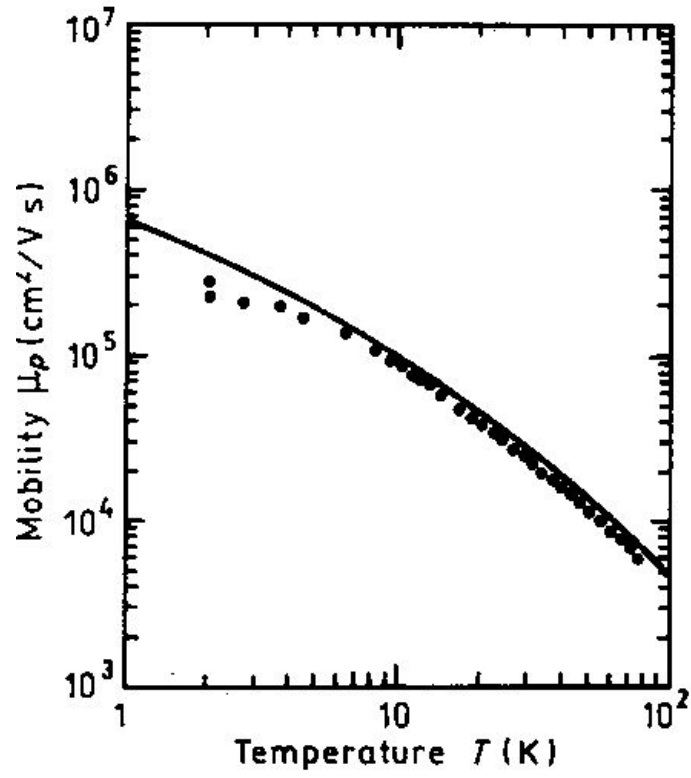
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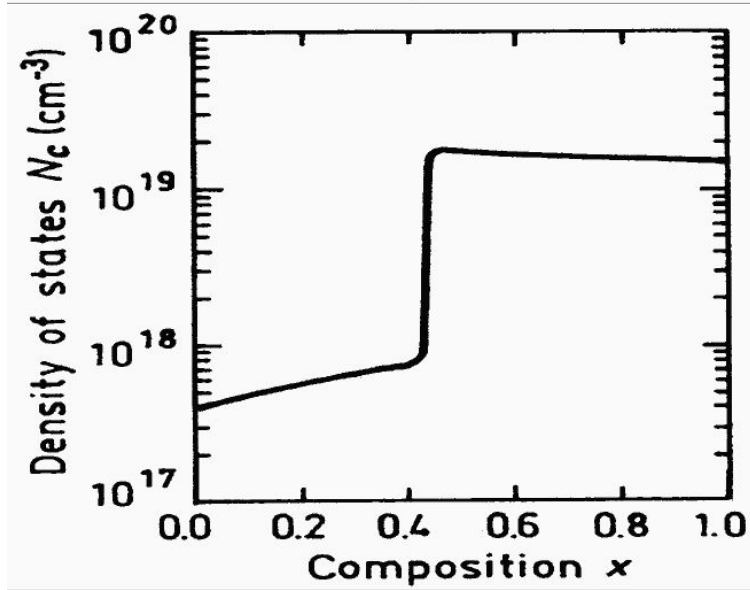
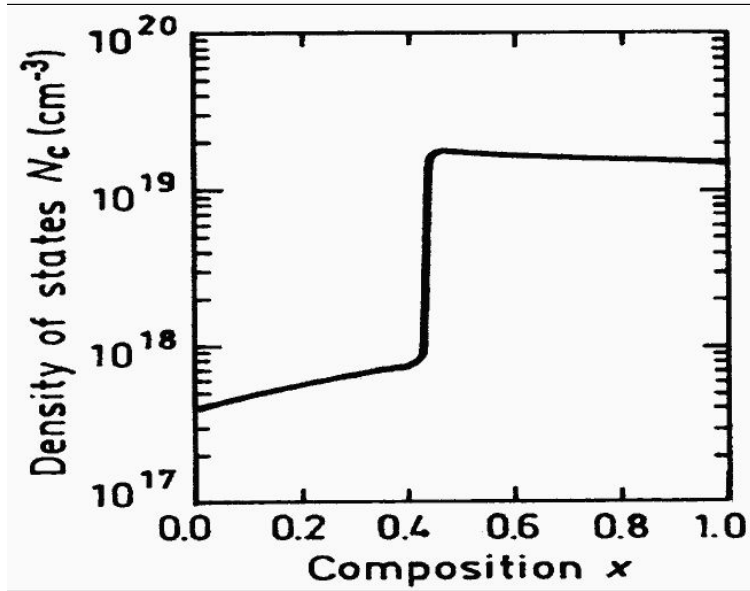
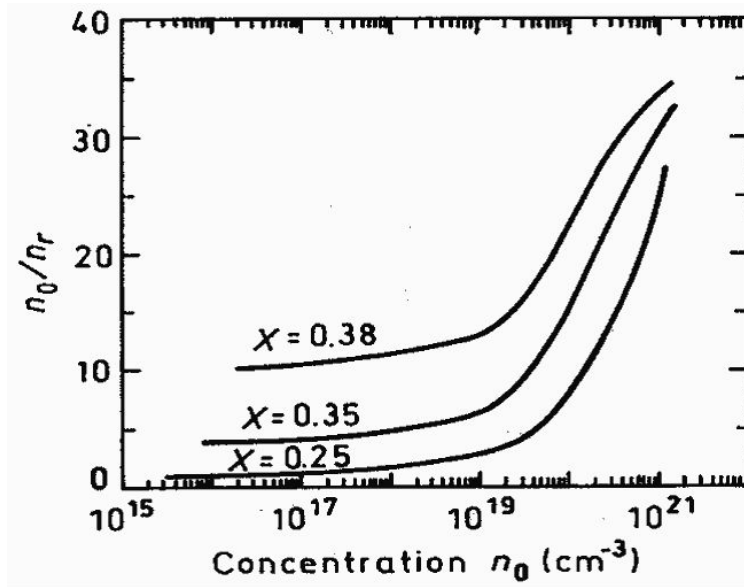
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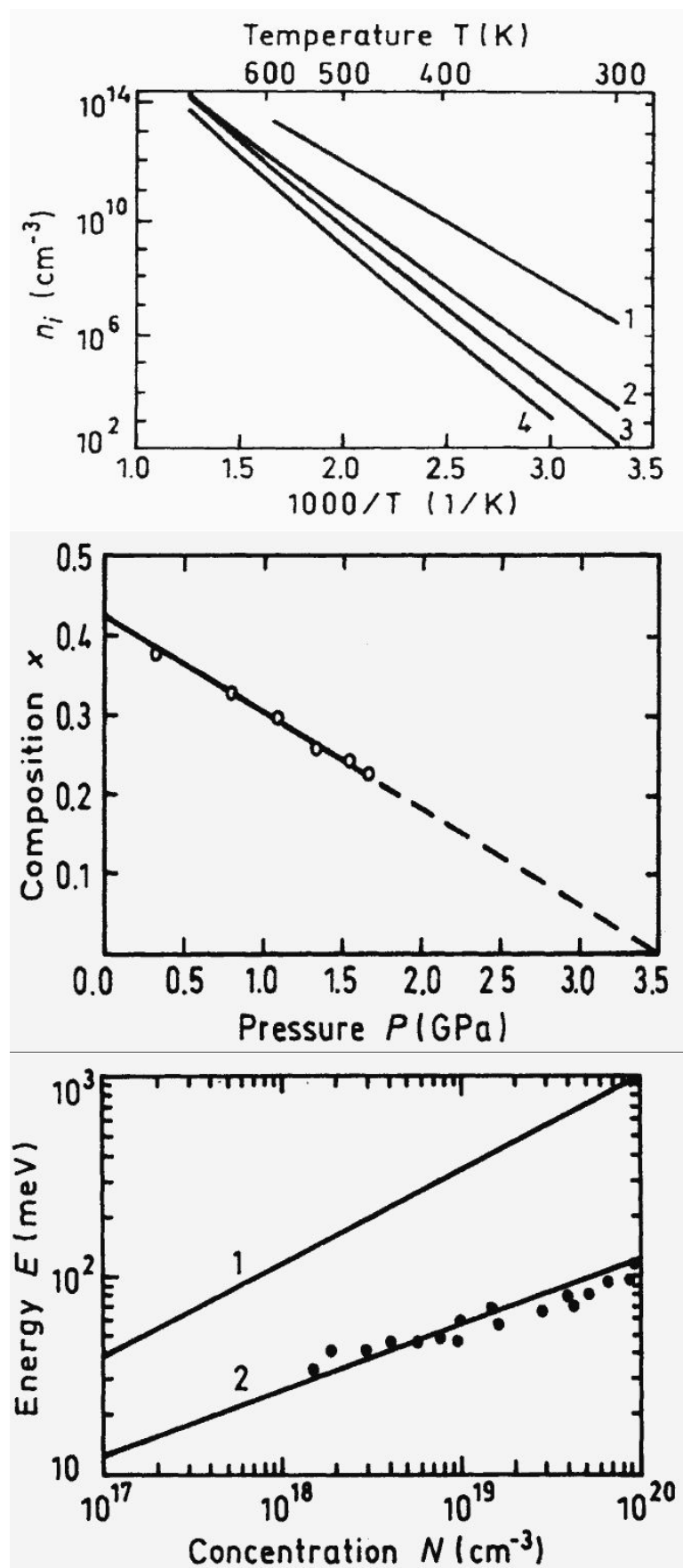
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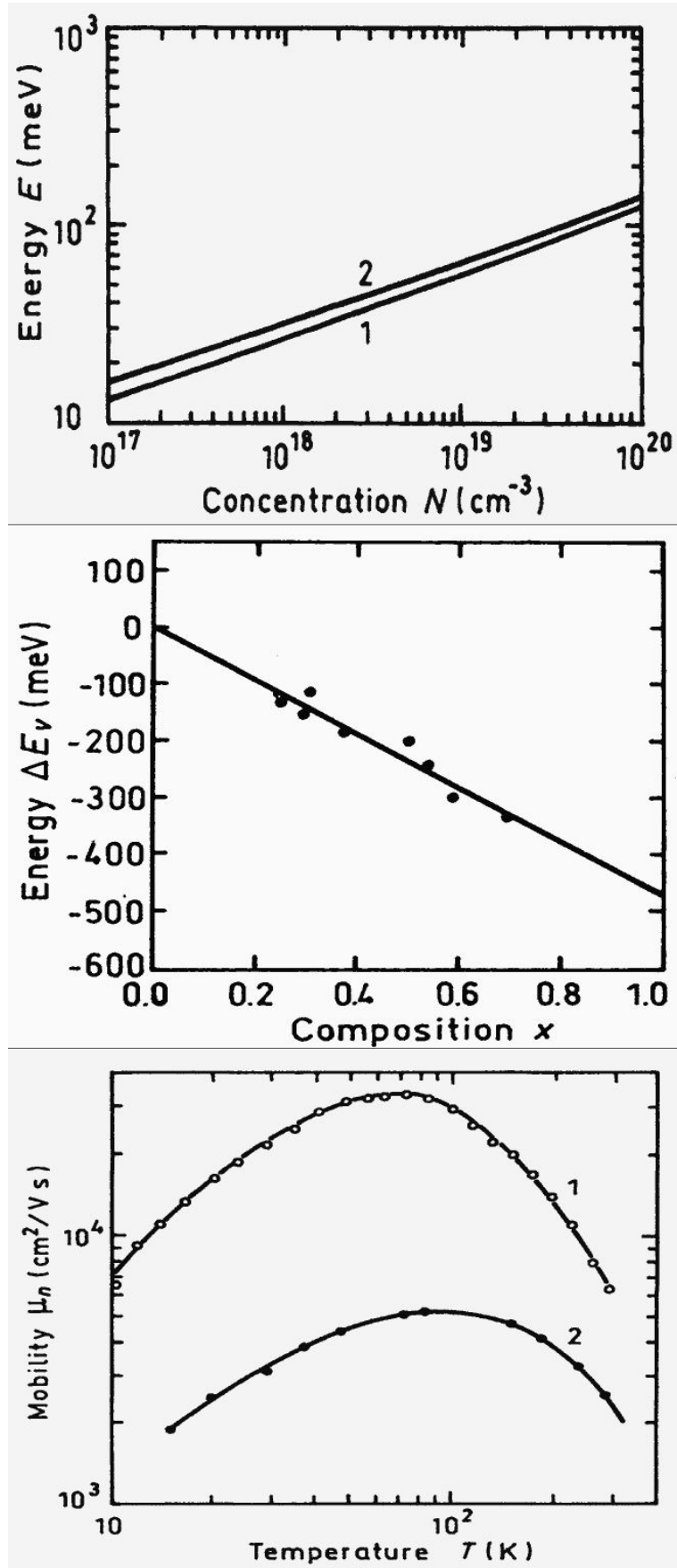


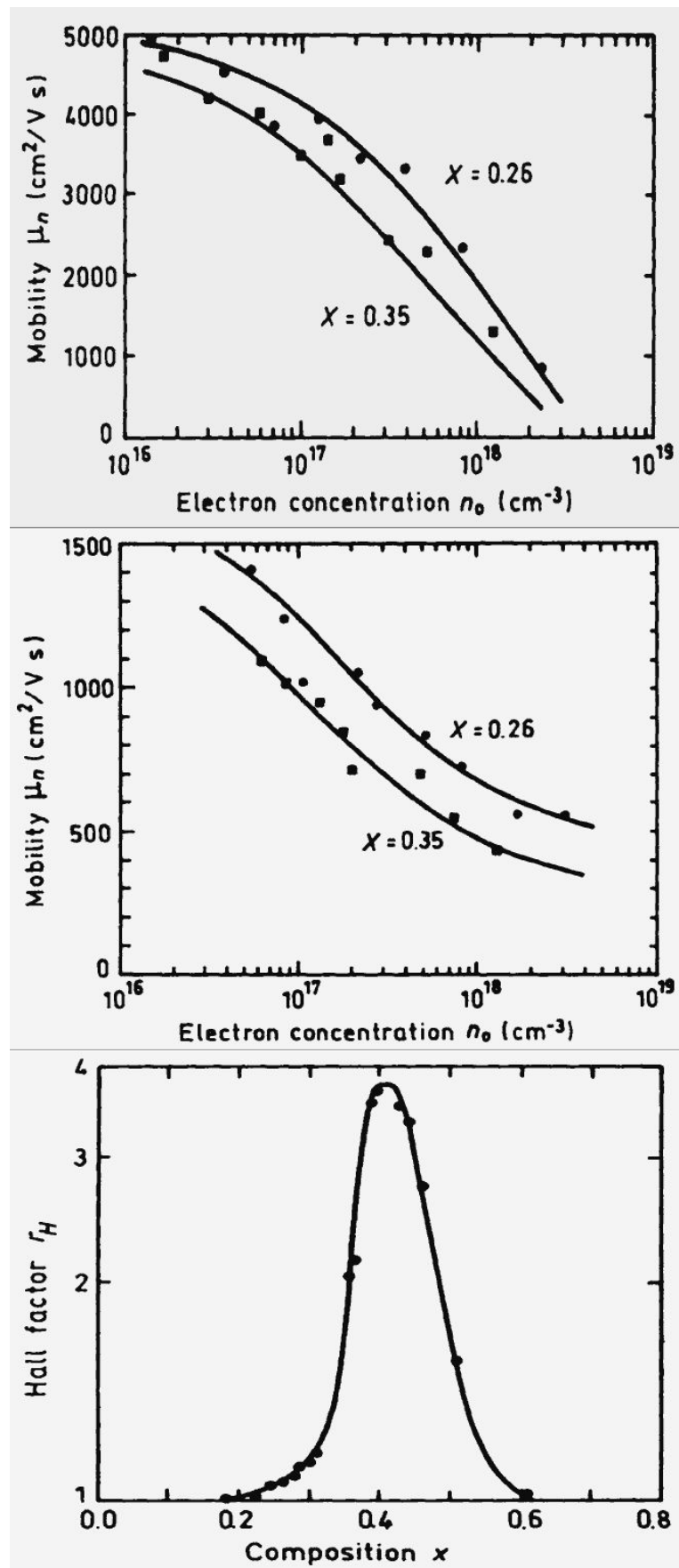


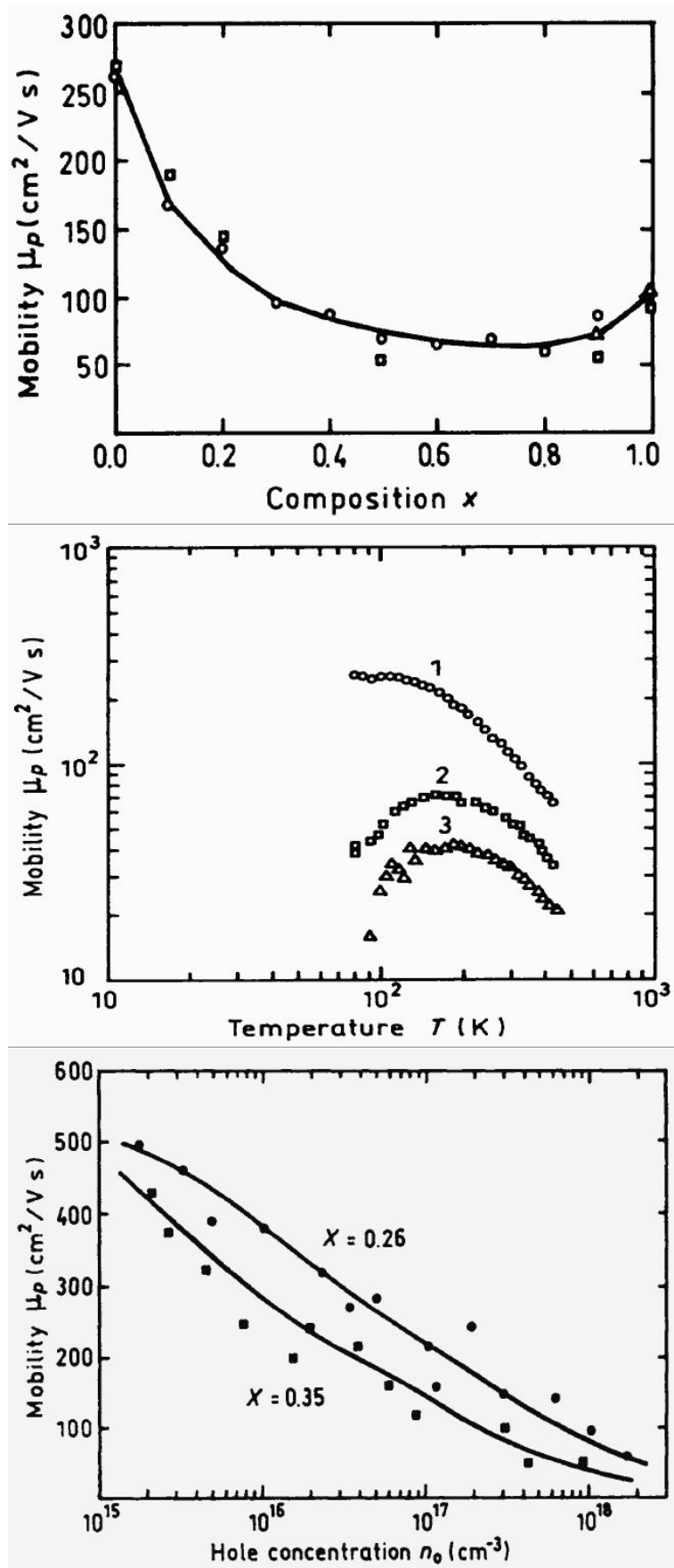


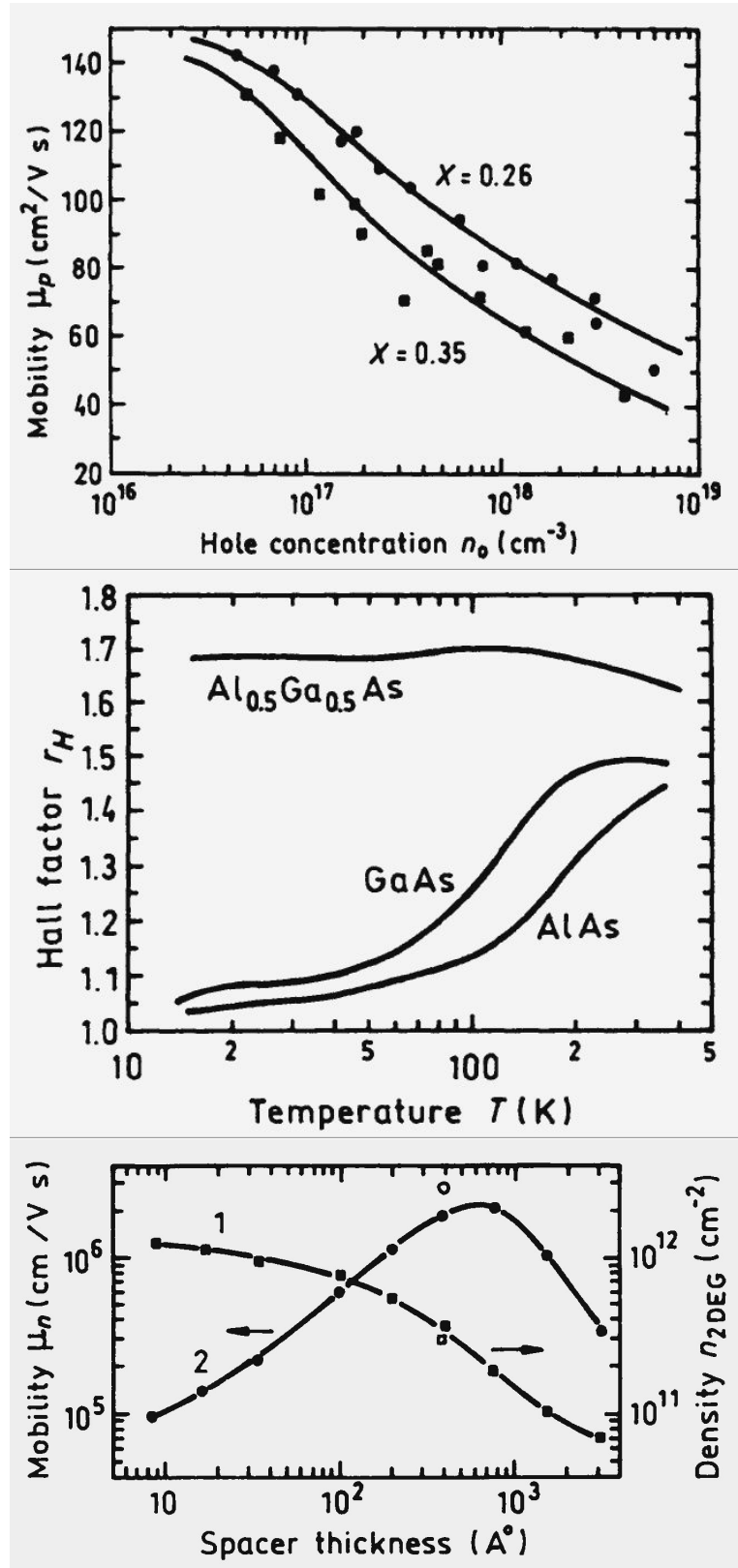


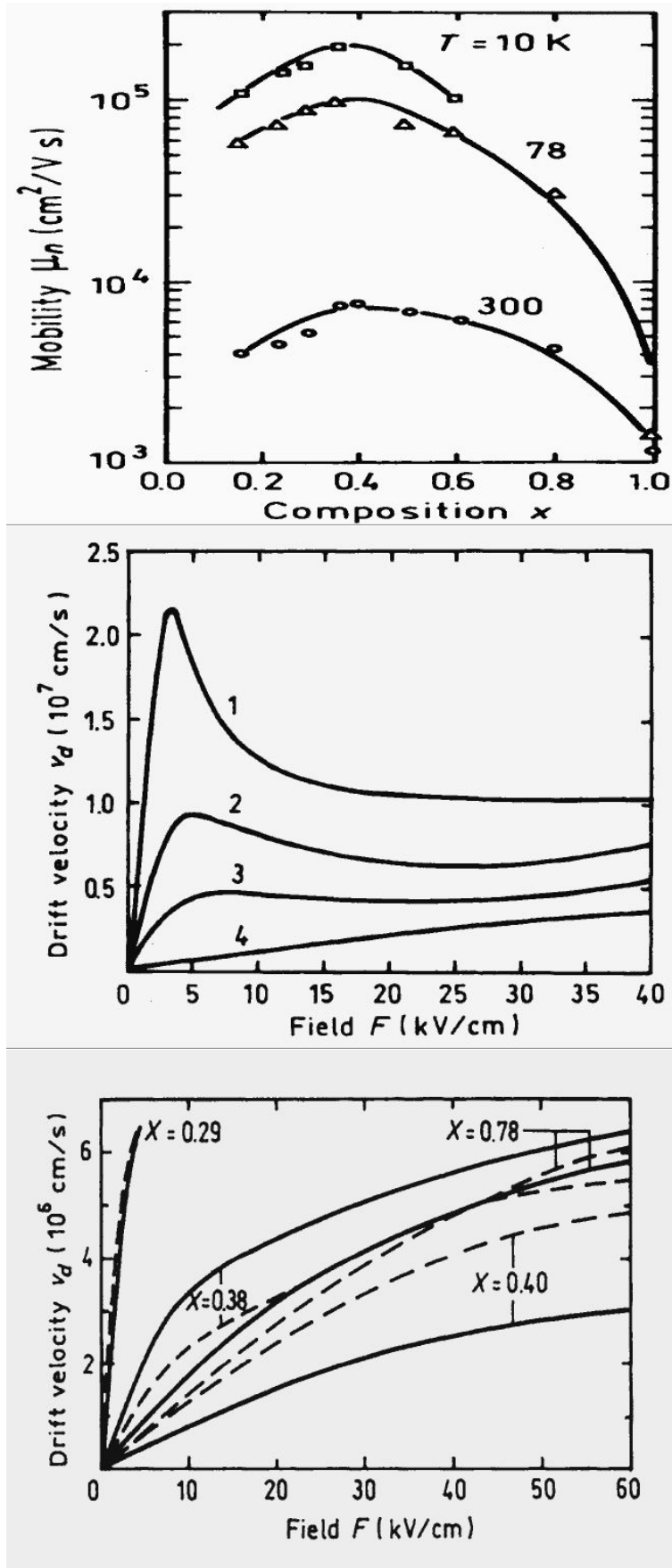


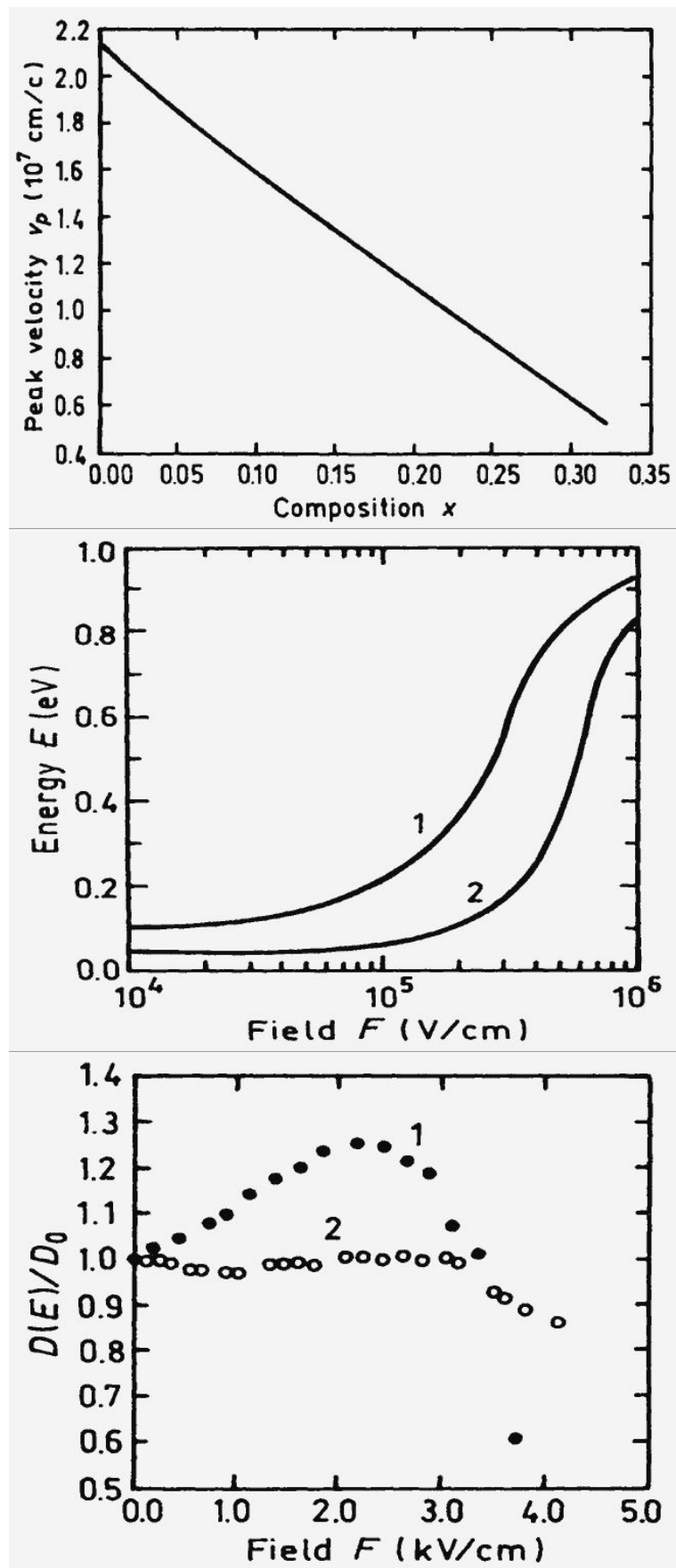


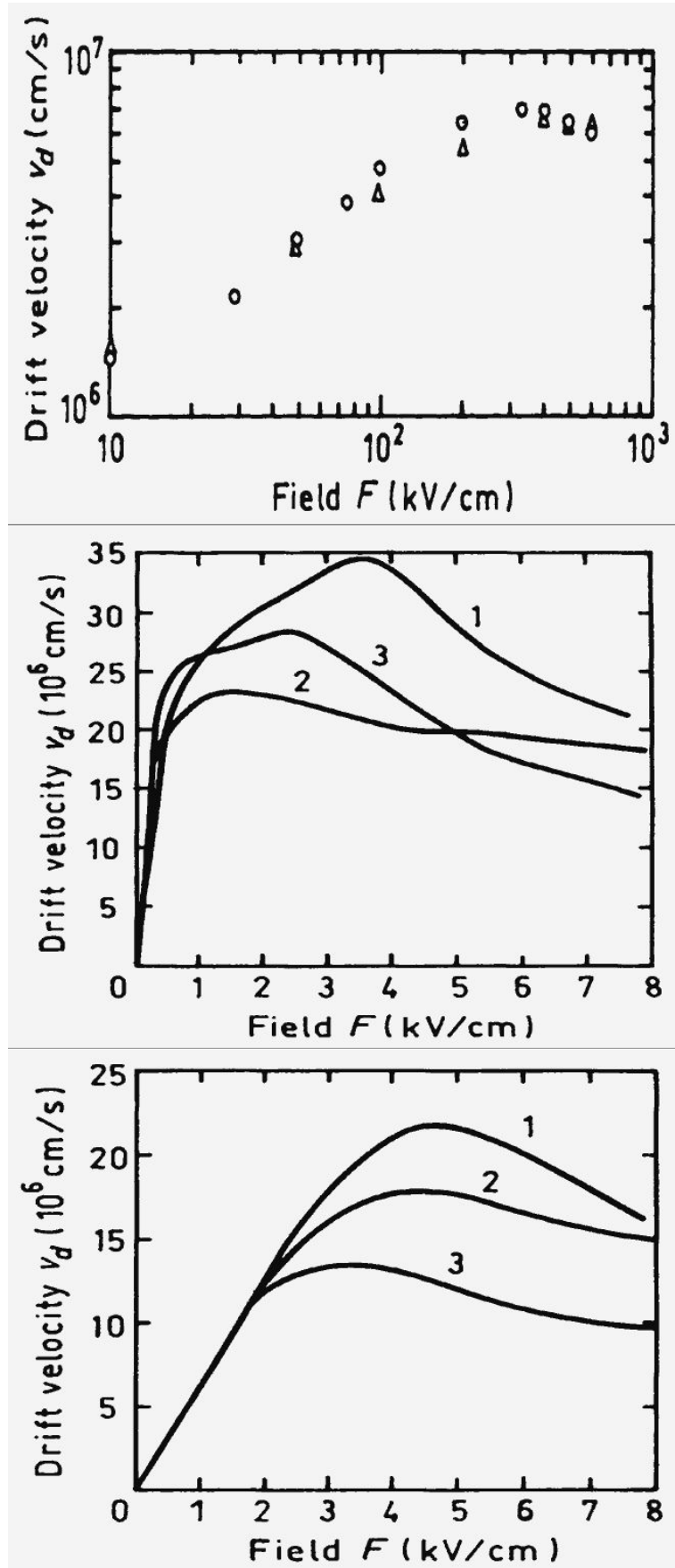


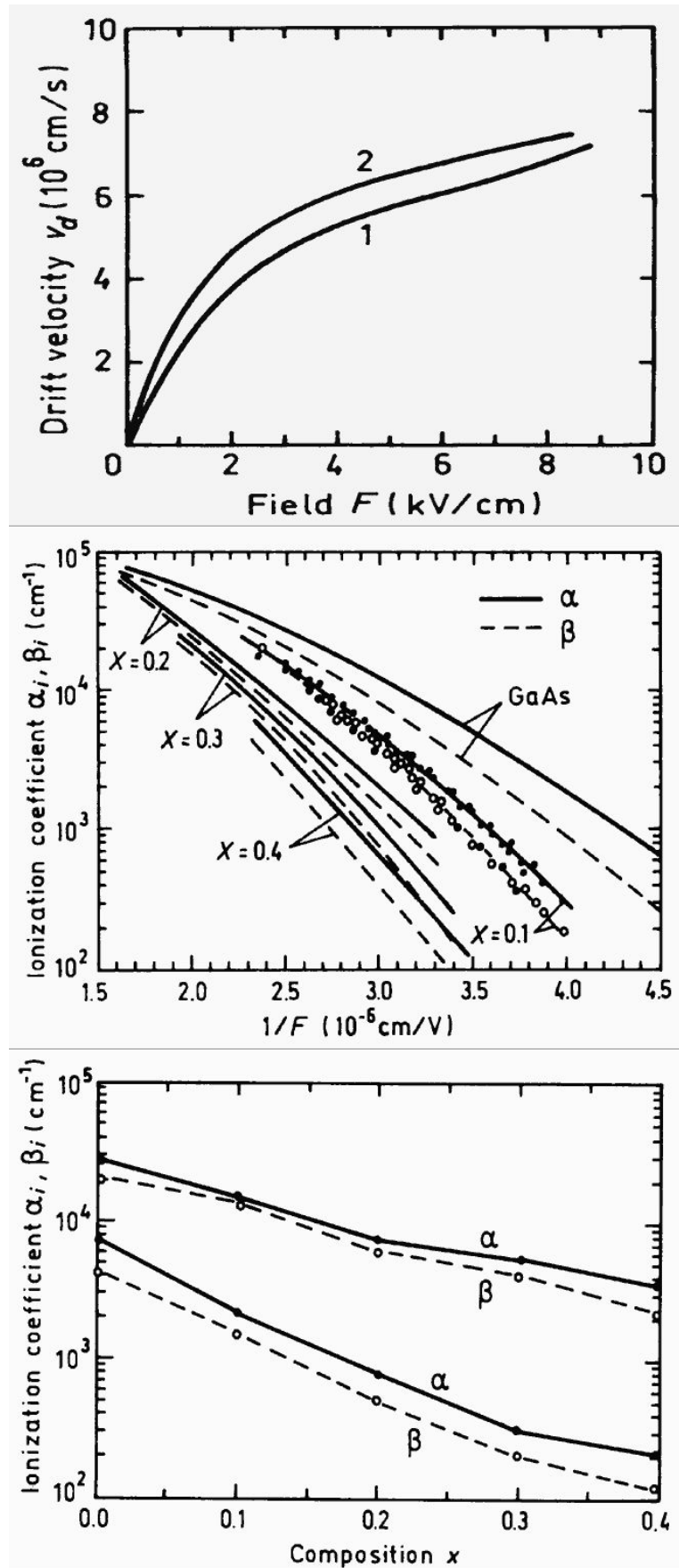


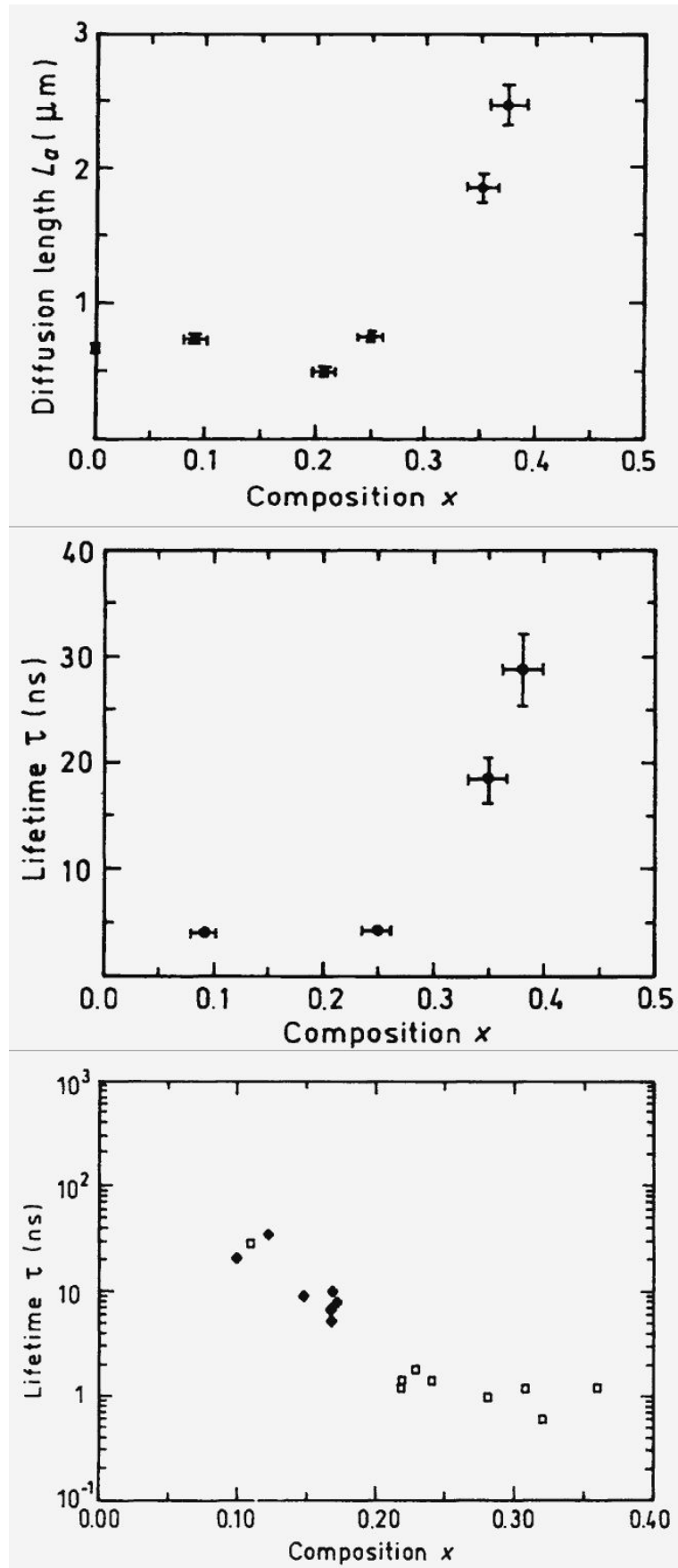


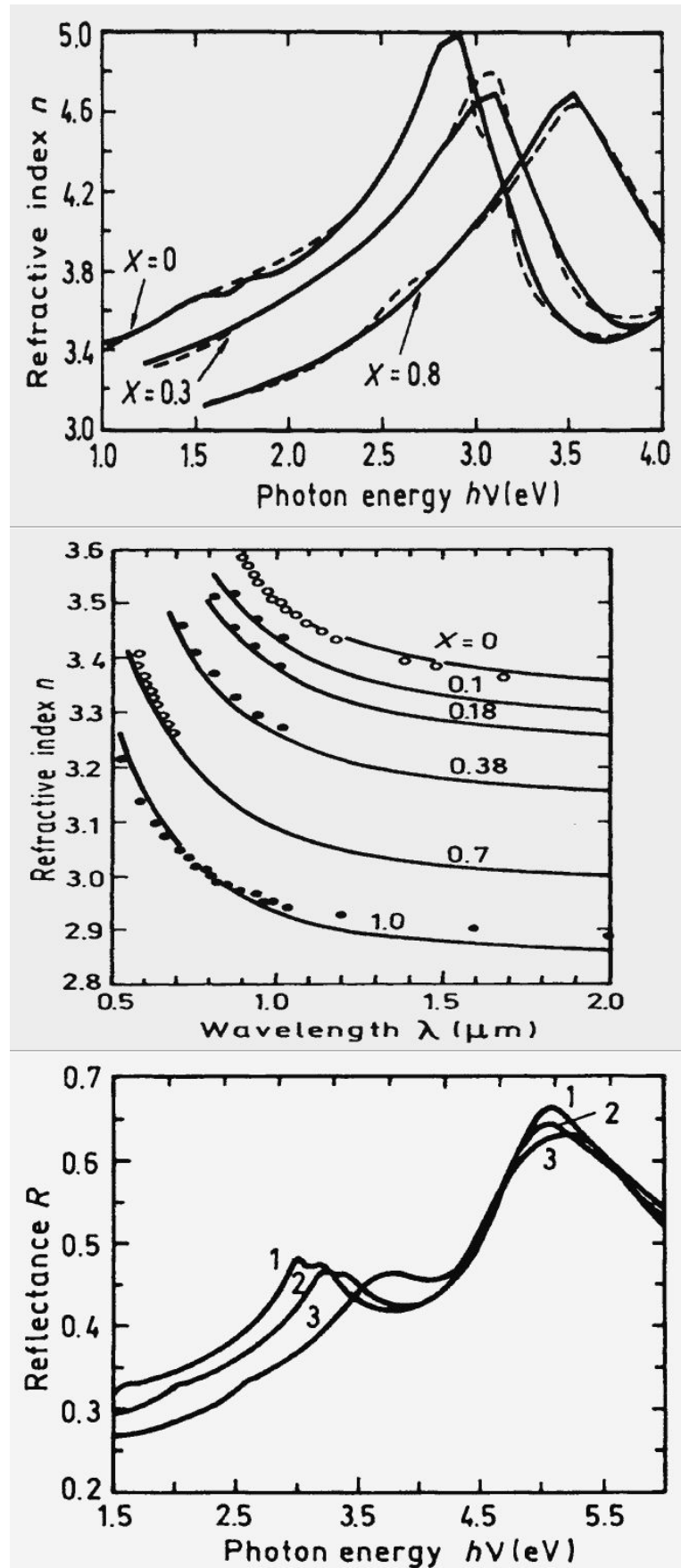


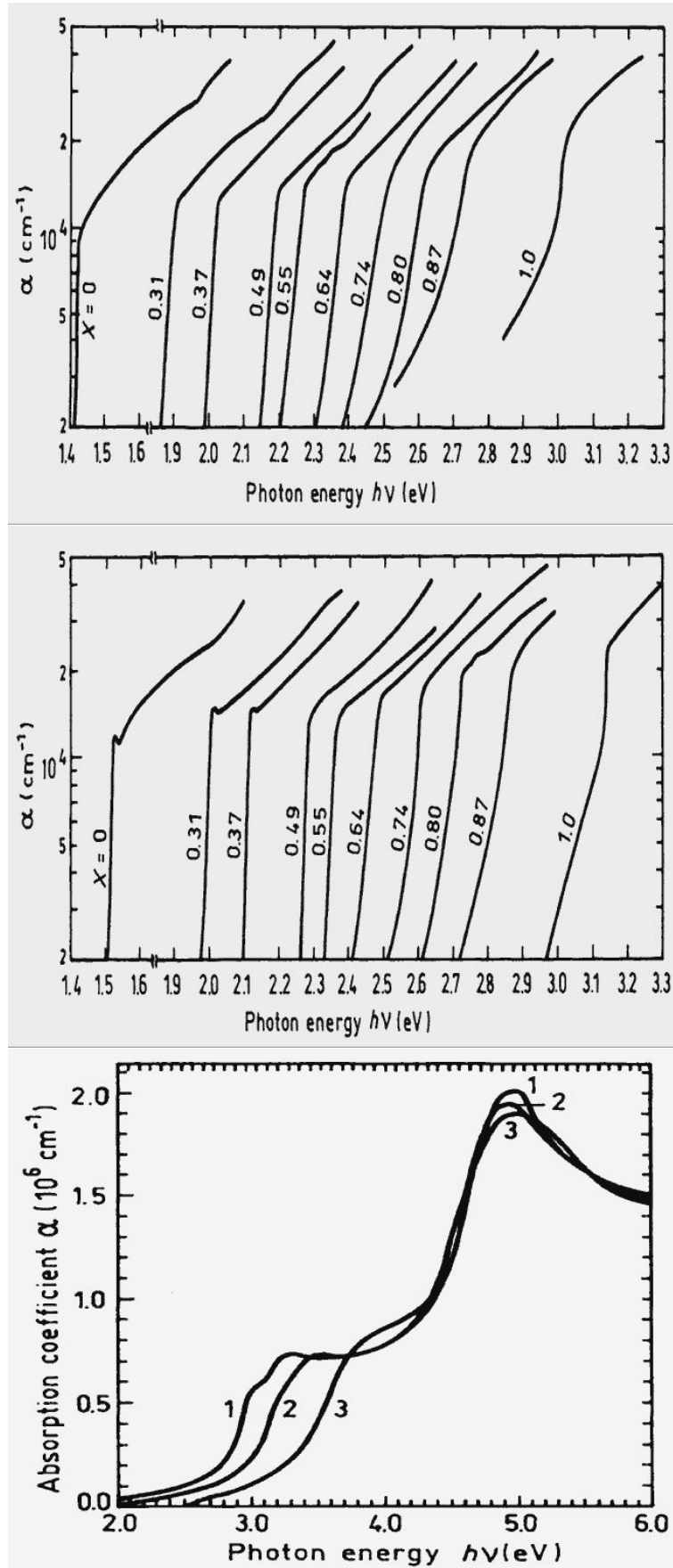


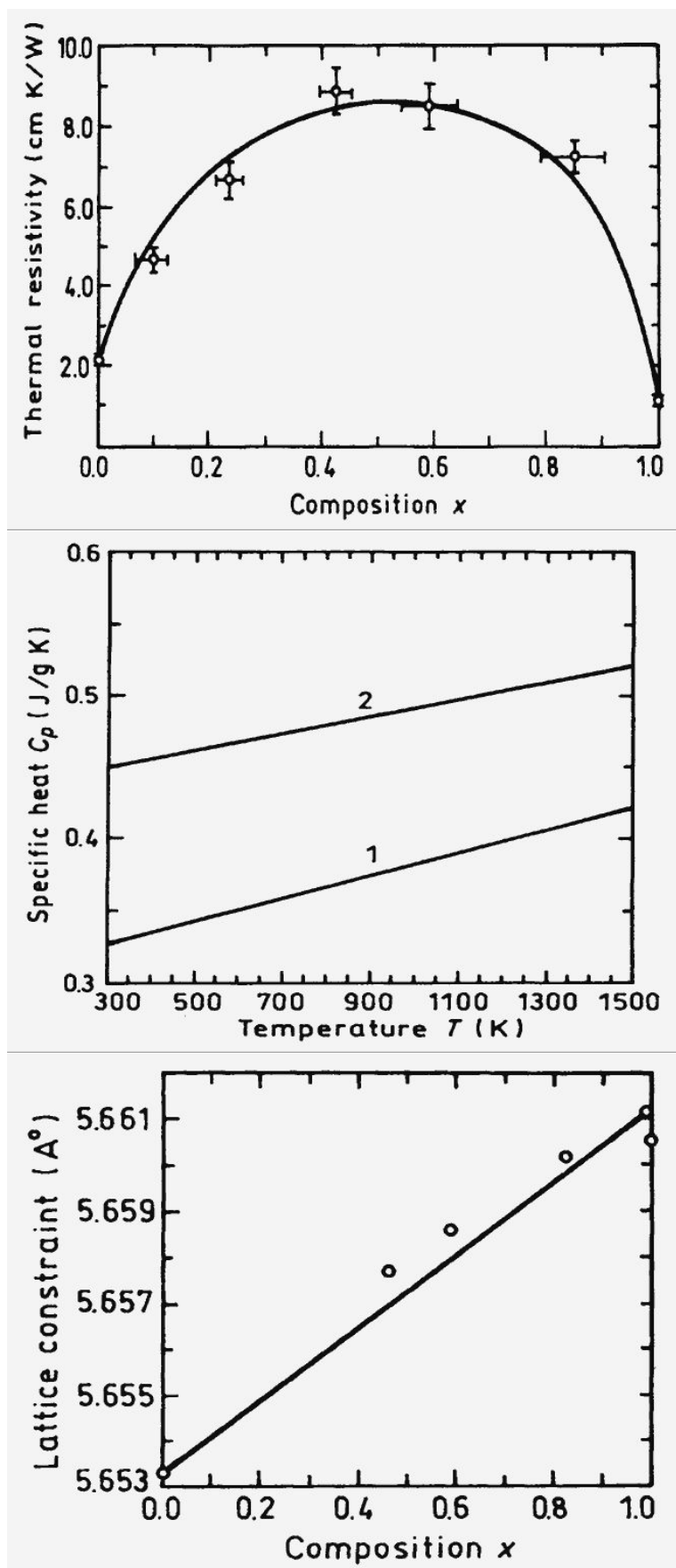


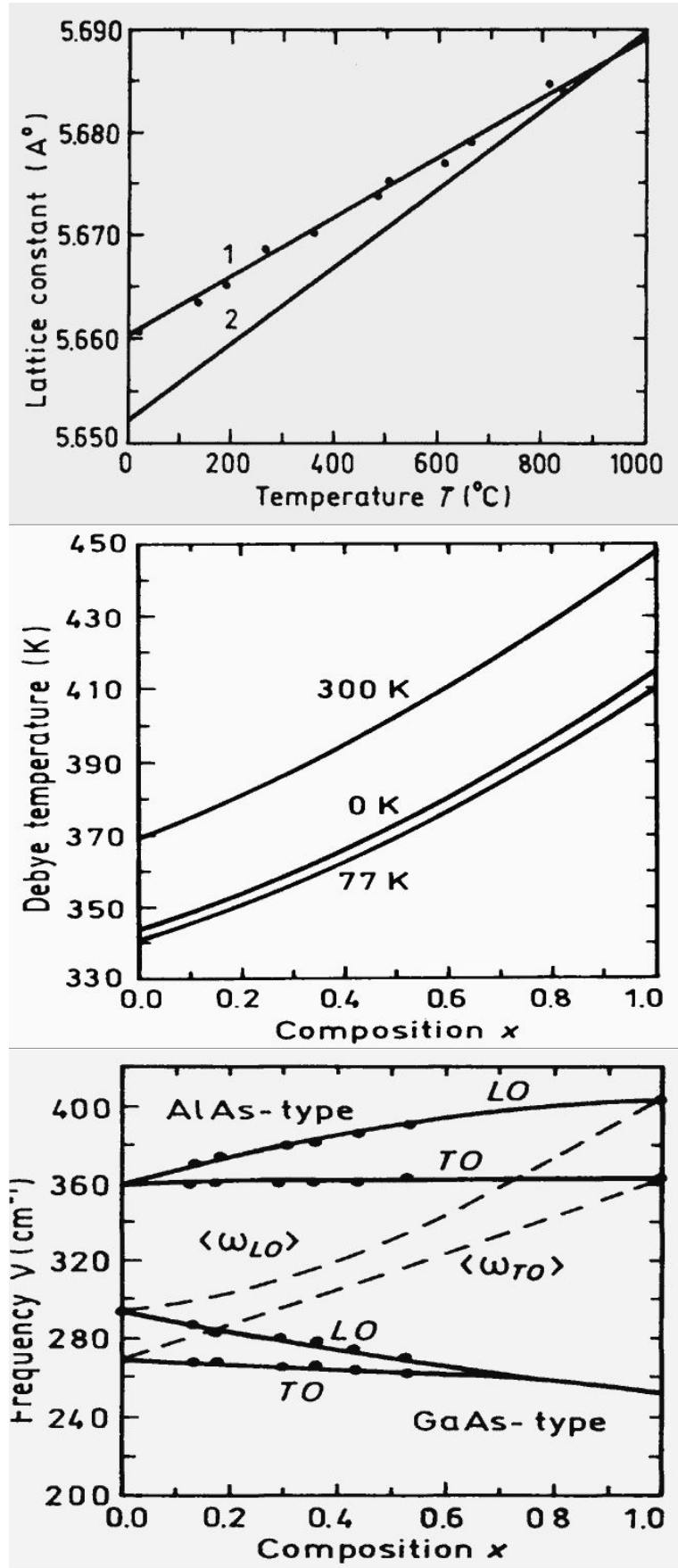












4 InP

[002]ff.

4.1 Originaltexte

Dokument nächste Seite folgend.

InP - Indium Phosphide

- [Basic Parameters at 300 K](#)
- [Band structure and carrier concentration](#)
 - [Basic Parameters of Band Structure and carrier concentration](#)
 - [Temperature Dependences](#)
 - [Energy Gap Narrowing at High Doping Levels](#)
 - [Effective Masses and Density of States](#)
 - [Donors and Acceptors](#)
- [Electrical Properties](#)
 - [Basic Parameters of Electrical Properties](#)
 - [Mobility and Hall Effect](#)
 - [Transport Properties in High Electric Fields](#)
 - [Impact Ionization](#)
 - [Recombination Parameters](#)
- [Optical properties](#)
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- [Mechanical properties, elastic constants, lattice vibrations](#)
 - [Basic Parameters](#)
 - [Elastic Constants](#)
 - [Acoustic Wave Speeds](#)
 - [Phonon Frequencies](#)
- [References](#)

InP - Indium Phosphide

Basic Parameters at 300 K

Crystal structure	Zinc Blende
Group of symmetry	T_d^2-F43m
Number of atoms in 1 cm^3	$3.96 \cdot 10^{22}$
Debye temperature	425 K
Density	4.81 g/cm^3
Dielectric constant (static)	12.5
Dielectric constant (high frequency)	9.61
Effective electron mass	$0.08m_0$
Effective hole masses m_h	$0.6m_0$
Effective hole masses m_{lp}	$0.089m_0$
Electron affinity	4.38 eV
Lattice constant	5.8687 Å
Optical phonon energy	0.043 eV

InP - Indium Phosphide

Band structure and carrier concentration

[Basic Parameters](#)

[Temperature Dependences](#)

[Dependences on Hydrostatic Pressure](#)

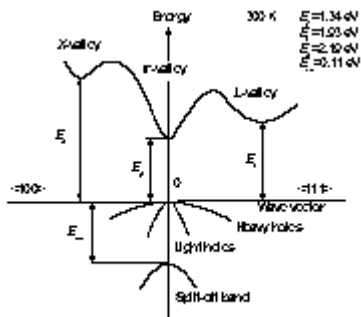
[Energy Gap Narrowing at High Doping Levels](#)

[Effective Masses](#)

[Donors and Acceptors](#)

Basic Parameters

Energy gap	1.344 eV
Energy separation ($E_{\Gamma L}$) between Γ and L valleys	0.59 eV
Energy separation ($E_{\Gamma X}$) between Γ and X valleys	0.85 eV
Energy spin-orbital splitting	0.11 eV
Intrinsic carrier concentration	$1.3 \cdot 10^7 \text{ cm}^{-3}$
Intrinsic resistivity	$8.6 \cdot 10^7 \Omega \cdot \text{cm}$
Effective conduction band density of states	$5.7 \cdot 10^{17} \text{ cm}^{-3}$
Effective valence band density of states	$1.1 \cdot 10^{19} \text{ cm}^{-3}$



Band structure and carrier concentration of InP.

Important minima of the conduction band and maxima of the valence band. 300 K.

$$E_g = 1.34 \text{ eV};$$

$$E_L = 1.93 \text{ eV};$$

$$E_X = 2.19 \text{ eV};$$

$$E_{so} = 0.11 \text{ eV}$$

Temperature Dependences

Temperature Dependences Temperature dependence of the energy gap

$$E_g = 1.421 - 4.9 \cdot 10^{-4} \cdot T^2 / (T + 327) \text{ (eV)},$$

where T is temperature in degrees K ($0 < T < 800$).

Temperature dependence of the energy separation between Γ and X valleys

$$E_{\Gamma X} = 0.96 - 3.7 \cdot 10^{-4} \cdot T \text{ (eV)},$$

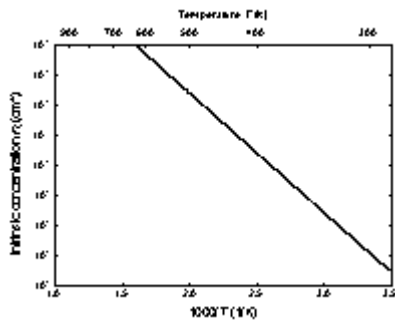
where T is temperature in degrees K ($0 < T < 300$).

Effective density of states in the conduction band

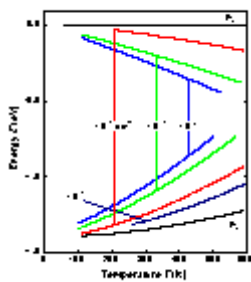
$$N_c \approx 1.1 \cdot 10^{14} \cdot T^{3/2} \text{ (cm}^{-3}\text{)}.$$

Effective density of states in the valence band

$$N_v \approx 2.2 \cdot 10^{15} \cdot T^{3/2} \text{ (cm}^{-3}\text{)}.$$



The temperature dependence of the intrinsic carrier concentration.



Fermi level versus temperature for different concentrations of shallow donors and acceptors.

Dependences on Hydrostatic Pressure

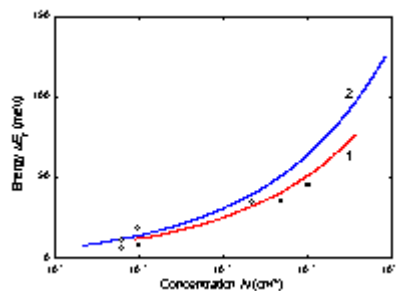
$$E_g = E_g(0) + 8.4 \cdot 10^{-3}P - 1.8 \cdot 10^{-5}P^2 \text{ (eV)}$$

$$E_L = E_L(0) + 4.6 \cdot 10^{-3}P \text{ (eV)},$$

$$E_X = E_X(0) + 2 \cdot 10^{-3}P \text{ (eV)},$$

where P is pressure in kbar.

Energy Gap Narrowing at High Doping Levels



Energy gap narrowing versus donor (curve 1 and experimental points) and acceptor (curve 2) doping density, $T = 300 \text{ K}$.

Curve 1 and experimental points ([Bugajski and Lewandowski \[1985\]](#));

Curve 2 ([Jain et al. \[1990\]](#)).

For *n*-type InP:

$$\Delta E_g \approx 22.5 \cdot 10^{-9} \cdot N_d^{1/3} \text{ (eV)}$$

([Bugajski and Lewandowski \[1985\]](#))

For *p*-type InP

$$\Delta E_g \approx 10.3 \cdot 10^{-9} \cdot N_a^{1/3} + 4.43 \cdot 10^{-7} \cdot N_a^{1/4} + 3.38 \cdot 10^{-12} \cdot N_a^{1/2} \text{ (eV)}$$

(Jain et al. [1990]).

Effective Masses

Electrons:

For Γ -valley	$m_\Gamma = 0.08m_0$
The are 4 equivalent L-valleys in the conduction band:	
<i>in one L-valley</i>	$m_L = 0.25m_0$
<i>for all L-valley</i>	$m_{Ld} = 0.63m_0$
The are 3 equivalent X-valleys in the conduction band:	
<i>in one X-valley</i>	$m_X = 0.32m_0$
<i>for all X-valley</i>	$m_{Xd} = 0.66m_0$

Holes:

Heavy	$m_h = 0.6m_0$
Light	$m_{lp} = 0.089m_0$
Split-off band	$m_{so} = 0.17m_0$
Effective mass of density of states	$m_v = 0.6m_0$

Donors and Acceptors

Ionization energies of shallow donors (eV) ~0.0057:

S, Si, Sn, Ge

Ionization energies of shallow acceptors (eV):

C	Hg	Zn	Cd	Si	Cu	Be	Mg	Ge	Mn
0.04	0.098	0.035	0.057	0.03	0.06	0.03(MBE)	0.03(MBE)	0.021	0.27

InP - Indium Phosphide

Electrical properties

[Basic Parameters](#)

[Mobility and Hall Effect](#)

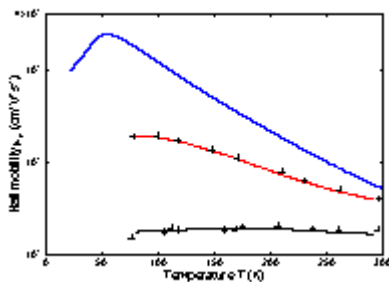
[Transport Properties in High Electric Fields](#)

[Impact Ionization](#)

[Recombination Parameters](#)

Basic Parameters

Breakdown field	$\approx 5 \cdot 10^5 \text{ V cm}^{-1}$
Mobility electrons	$\leq 5400 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Mobility holes	$\leq 200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Diffusion coefficient electrons	$\leq 130 \text{ cm}^2 \text{ s}^{-1}$
Diffusion coefficient holes	$\leq 5 \text{ cm}^2 \text{ s}^{-1}$
Electron thermal velocity	$3.9 \cdot 10^5 \text{ m s}^{-1}$
Hole thermal velocity	$1.7 \cdot 10^5 \text{ m s}^{-1}$



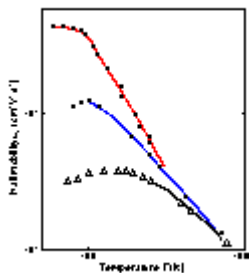
Electron Hall mobility versus temperature for different doping levels.

Bottom curve - $n_0 = N_d - N_a = 8 \cdot 10^{17} \text{ cm}^{-3}$;

Middle curve - $n_0 = 2 \cdot 10^{15} \text{ cm}^{-3}$;

Top curve - $n_0 = 3 \cdot 10^{13} \text{ cm}^{-3}$.

([Razeghi et al. \[1988\]](#)) and ([Walukiewicz et al \[1980\]](#)).



Electron Hall mobility versus temperature (high temperatures):

Bottom curve - $n_0 = N_d - N_a \sim 3 \cdot 10^{17} \text{ cm}^{-3}$;

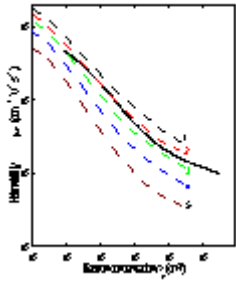
Middle curve - $n_0 \sim 1.5 \cdot 10^{16} \text{ cm}^{-3}$;

Top curve - $n_0 \sim 3 \cdot 10^{15} \text{ cm}^{-3}$.

([Galavanov and Siukaev \[1970\]](#)).

For weakly doped n -InP at temperatures close to 300 K electron drift mobility:

$$\mu_n = (4.2 \div 5.4) \cdot 10^3 \cdot (300/T) \text{ (cm}^2 \text{ V}^{-1} \text{ s}^{-1}\text{)}$$



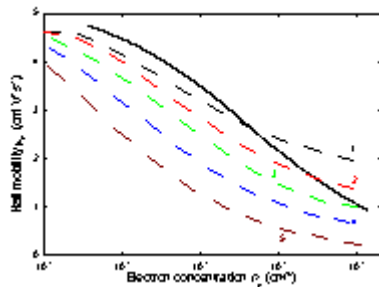
Hall mobility versus electron concentration for different compensation ratios.

$\theta = N_a/N_d$, 77 K.

Dashed curves are theoretical calculations: 1. $\theta = 0$; 2. $\theta = 0.2$; 3. $\theta = 0.4$; 4. $\theta = 0.6$; 5. $\theta = 0.8$;

([Walukiewicz et al. \[1980\]](#)).

Solid line is mean observed values ([Anderson et al. \[1985\]](#)).



Hall mobility versus electron concentration for different compensation ratios

$\theta = N_a/N_d$, 300 K.

Dashed curves are theoretical calculations: 1. $\theta = 0$; 2. $\theta = 0.2$; 3. $\theta = 0.4$; 4. $\theta = 0.6$; 5. $\theta = 0.8$;

([Walukiewicz et al. \[1980\]](#)).

Solid line is mean observed values ([Anderson et al. \[1985\]](#)).

Approximate formula for electron Hall mobility

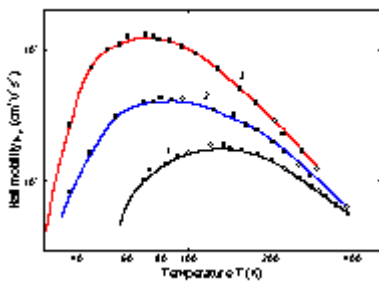
$$\mu = \mu_{OH} / [1 + (N_d / 10^7)^{1/2}],$$

where $\mu_{OH} = 5000 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$,

N_d - in cm^{-3} ([Hilsum \[1974\]](#))

At 300 K, the electron Hall factor $r_n \approx 1$ in n -InP.

for $N_d > 10^{15} \text{ cm}^{-3}$.



Hole Hall mobility versus temperature for different doping (Zn) levels.

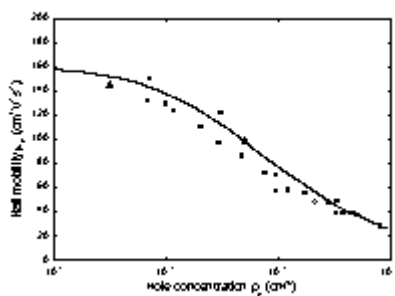
Hole concentration at 300 K: 1. $1.75 \cdot 10^{18} \text{ cm}^{-3}$; 2. $3.6 \cdot 10^{17} \text{ cm}^{-3}$; 3. $4.4 \cdot 10^{16} \text{ cm}^{-3}$.

$\theta = N_a/N_d \sim 0.1$.

([Kohanyuk et al. \[1988\]](#)).

For weakly doped p -InP at temperature close to 300 K the Hall mobility

$$\mu_{pH} \sim 150 \cdot (300/T)^{2.2} (\text{cm}^2 \text{V}^{-1} \text{s}^{-1}).$$



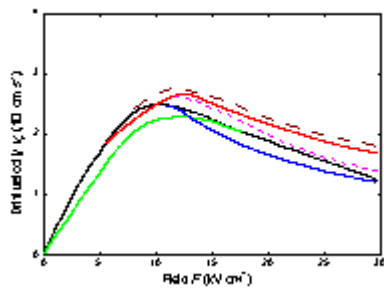
Hole Hall mobility versus hole density, 300 K (Wiley [1975]).

The approximate formula for hole Hall mobility:

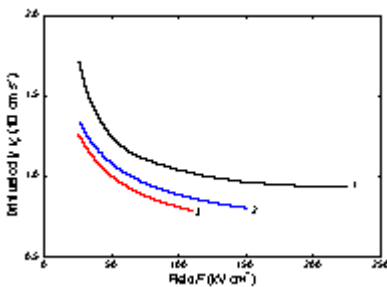
$$\mu_p = \mu_{p0} / [1 + (N_a / 2 \cdot 10^{17})^{1/2}], \text{ where } \mu_{p0} \sim 150 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}, N_a - \text{in cm}^{-3}$$

At 300 K, the hole factor in pure p -InP: $r_p \sim 1$

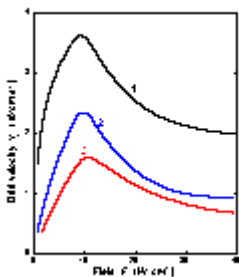
Transport Properties in High Electric Fields



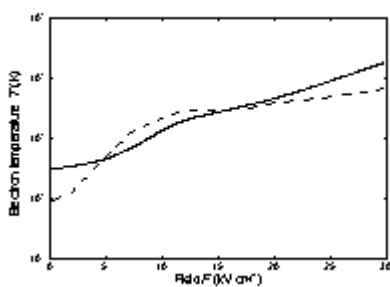
Field dependences of the electron drift velocity in InP, 300 K.
Solid curve are theoretical calculation.
Dashed and dotted curve are measured data.
([Maloney and Frey \[1977\]](#)) and ([Gonzalez Sanchez et al. \[1992\]](#)).



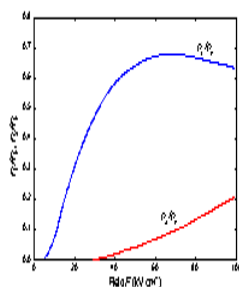
The field dependences of the electron drift velocity for high electric fields.
T(K): 1. 95; 2. 300; 3. 400.
([Windhorn et al. \[1983\]](#)).



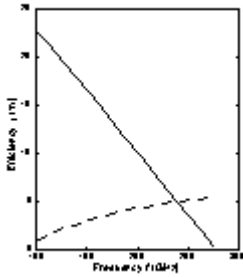
Field dependences of the electron drift velocity at different temperatures.
Curve 1 - 77 K ([Gonzalez Sanchez et al. \[1992\]](#)).
Curve 2 - 300 K, Curve 3 - 500 K ([Fawcett and Hill \[1975\]](#)).



Electron temperature versus electric field for 77 K and 300 K.
([Maloney and Frey \[1977\]](#))



Fraction of electrons in L and X valleys n_L/n_0 and n_X/n_0 as a function of electric field, 300 K.
([Borodovskii and Osadchii \[1987\]](#)).



Frequency dependence of the efficiency η at first (solid line) and at the second (dashed line) harmonic in LSA mode.

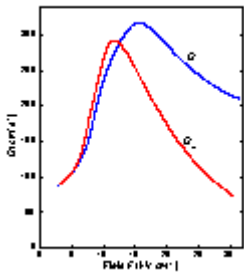
Monte Carlo simulation.

$$F = F_0 + F_1 \cdot \sin(2\pi \cdot ft) + F_2 \cdot [\sin(4\pi \cdot ft) + 3\pi/2],$$

$$F_0 = F_1 = 35 \text{ kV cm}^{-1},$$

$$F_2 = 10.5 \text{ kV cm}^{-1}$$

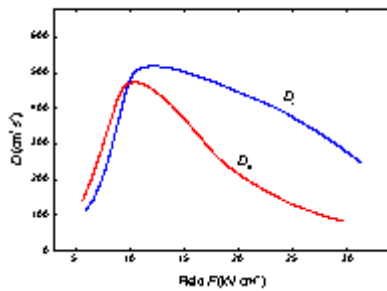
([Borodovskii and Osadchii \[1987\]](#)).



Longitudinal ($D \parallel F$) and transverse ($D \perp F$) electron diffusion coefficients at 300 K.

Ensemble Monte Carlo simulation.

([Aishima and Fukushima \[1983\]](#)).

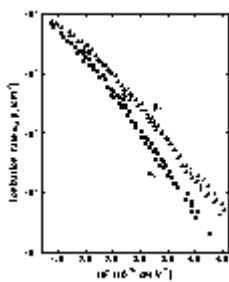


Longitudinal ($D \parallel F$) and transverse ($D \perp F$) electron diffusion coefficients at 77K.

Ensemble Monte Carlo simulation.

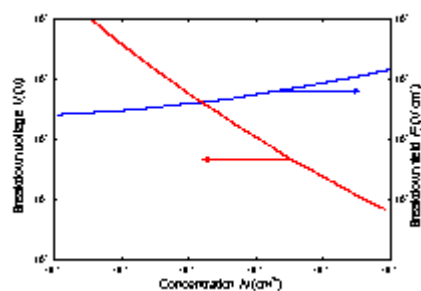
([Aishima and Fukushima \[1983\]](#)).

Impact Ionization



The dependence of ionization rates for electrons α_i and holes β_i versus $1/E$, 300 K.

([Cook et al. \[1982\]](#)).



Breakdown voltage and breakdown field versus doping density for an abrupt p - n junction, 300 K

([Kyuregyan and Yurkov \[1989\]](#)).

Recombination Parameters

Pure *n*-type material ($n_0 \sim 10^{14} \text{ cm}^{-3}$)

The longest lifetime of holes $\tau_p \sim 3 \cdot 10^{-6} \text{ s}$

Diffusion length $L_p = (D_p \cdot \tau_p)^{1/2}$ $L_p \sim 40 \text{ } \mu\text{m}$.

Pure *p*-type material ($p_0 \sim 10^{15} \text{ cm}^{-3}$)

(a) Low injection level

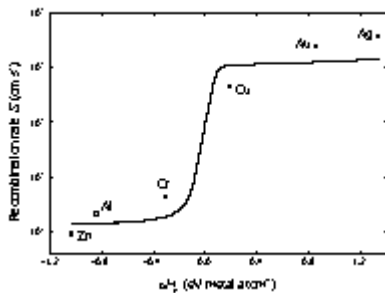
The longest lifetime of electrons $\tau_n \sim 2 \cdot 10^{-9} \text{ s}$

Diffusion length $L_n = (D_n \cdot \tau_n)^{1/2}$ $L_n \sim 8 \text{ } \mu\text{m}$

(b) High injection level (filled traps)

The longest lifetime of electrons $\tau \sim 10^{-8} \text{ s}$

Diffusion length L_n $L_n \sim 25 \text{ } \mu\text{m}$



Surface recombination velocity versus the heat of reaction per atom of each metal phosphide ΔH_R

([Rosenwaks et al. \[1990\]](#)).

If the surface Fermi level E_{FS} is pinned close to midgap ($E_{FS} \sim E_g/2$) the surface recombination velocity increases from $\sim 5 \cdot 10^{-3} \text{ cm/s}$ for doping level $n_0 \sim 3 \cdot 10^{15} \text{ cm}^{-3}$ to $\sim 10^6 \text{ cm/s}$ for doping level $n_0 \sim 3 \cdot 10^{18} \text{ cm}^{-3}$ ([Bothra et al. \[1991\]](#)).

Radiative recombination coefficient (300 K) $1.2 \cdot 10^{-10} \text{ cm}^3/\text{s}$

Auger coefficient (300 K) $\sim 9 \cdot 10^{-31} \text{ cm}^6/\text{s}$

InP - Indium Phosphide

Optical properties

Infrared refractive index 3.1

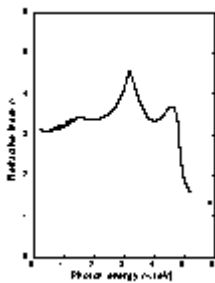
Radiative recombination coefficient $1.2 \cdot 10^{-10} \text{ cm}^3/\text{s}$

Infrared refractive index

$$n = k^{1/2} = 3.075 \cdot (1 + 2.7 \cdot 10^{-5} T)$$

Long-wave TO phonon energy at 300 K $h\nu_{\text{TO}} = 38.1 \text{ meV}$

Long-wave LO phonon energy at 300 K $h\nu_{\text{LO}} = 42.6 \text{ meV}$

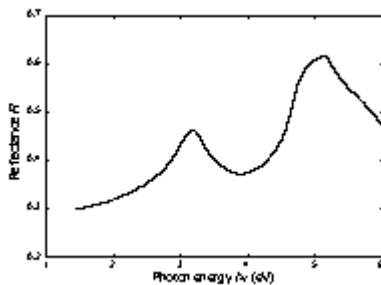


Refractive index n versus photon energy.

Solid curve is theoretical calculation.

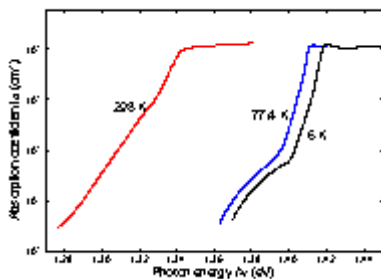
Points represent experimental data, 300 K

([Adachi \[1989\]](#)).



Normal incidence reflectivity versus photon energy, 300 K

([Aspnes and Studna \[1983\]](#)).

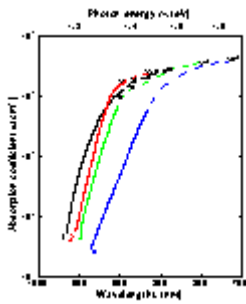


Intrinsic absorption coefficient near the intrinsic absorption edge for different temperatures.

$n\text{-InP}$, $n_0 = 5 \cdot 10^{15} \text{ cm}^{-3}$

([Turner et al. \[1964\]](#)).

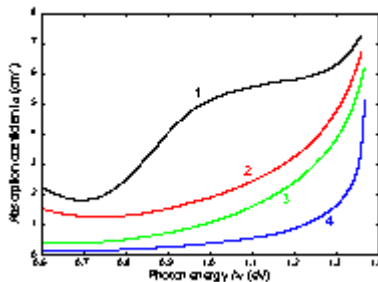
A ground state Rydberg energy $R_{X1} = 5.0 \text{ meV}$.



Intrinsic absorption edge at 296 K at different doping levels

1. p -type sample, $p_0 = 1.1 \cdot 10^{18} \text{ cm}^{-3}$
3. n -type sample, $n_0 = 1.9 \cdot 10^{18} \text{ cm}^{-3}$
2. n -type sample, $n_0 = 7.4 \cdot 10^{16} \text{ cm}^{-3}$
4. n -type sample, $n_0 = 7 \cdot 10^{18} \text{ cm}^{-3}$

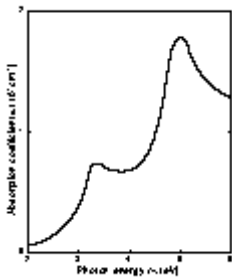
([Burkhard et al. 1982](#)).



Intrinsic absorption edge at 77 K for n -InP at different doping levels

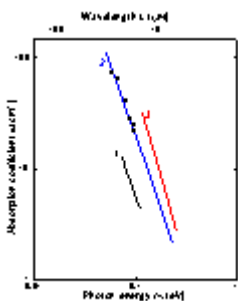
1. $n_0 = 10^{19} \text{ cm}^{-3}$;
2. $n_0 = 5 \cdot 10^{18} \text{ cm}^{-3}$;
3. $n_0 = 2 \cdot 10^{18} \text{ cm}^{-3}$;
4. $n_0 = 9.6 \cdot 10^{16} \text{ cm}^{-3}$

([Bugajski and Lewandowski 1985](#)).



The absorption coefficient versus photon energy, 300 K

([Aspnes and Studna 1983](#)).



Free carrier absorption versus photon energy at different doping levels, 300 K.

Electron concentration $n_0 \text{ (cm}^{-3}\text{)}$: 1. $4 \cdot 10^{16}$; 2. $2 \cdot 10^{17}$; 3. $4 \cdot 10^{17}$

([Newman 1958](#)).

InP - Indium Phosphide

Thermal properties

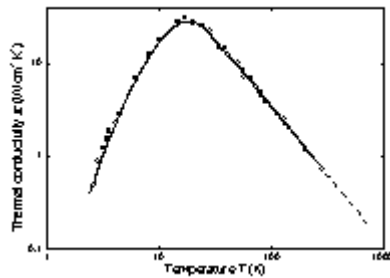
Bulk modulus	$7.1 \cdot 10^{11} \text{ dyn cm}^{-2}$
Melting point	1060 °C
Specific heat	$0.31 \text{ J g}^{-1} \text{ °C}^{-1}$
Thermal conductivity	$0.68 \text{ W cm}^{-1} \text{ °C}^{-1}$
Thermal diffusivity	$0.372 \text{ cm}^2 \text{ s}^{-1}$
Thermal expansion, linear	$4.60 \cdot 10^{-6} \text{ °C}^{-1}$

Melting point $T_m = 1333 \text{ K}$

For $0 < P < 40 \text{ kbar}$

$$T_m = 1333 - 2.0 \cdot P \text{ (P in kbar)}$$

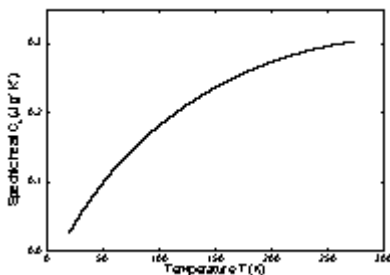
([Glasov et al. \[1977\]](#)).



Temperature dependence of thermal conductivity.

n -type samples, $n_0 = 2 \cdot 10^{16} \text{ cm}^{-3}$

([Aliev et al \[1965\]](#)).



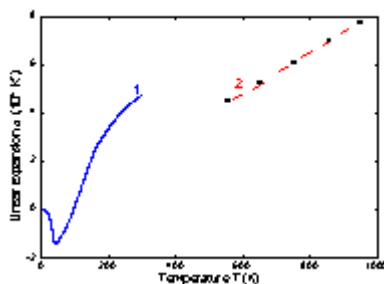
Temperature dependence of specific heat at constant pressure

([Piesbergen \[1963\]](#)).

For $298 < T < 910 \text{ K}$

$$C_p = 0.28 + 10^{-4} \cdot T \text{ (J g}^{-1} \text{ K}^{-1}\text{)}$$

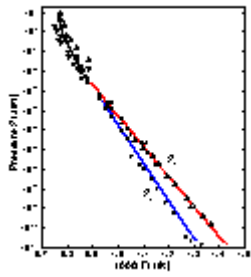
([Barin et al. \[1977\]](#)).



Temperature dependence of linear expansion coefficient α .

1. ([Soma et al. \[1982\]](#)),
2. ([Glazov et al. \[1977\]](#)).

Temperature dependence of saturation vapor pressure.
([Panish and Arthur\[1970\]](#)).



InP - Indium Phosphide

Mechanical properties, elastic constants, lattice vibrations

[Basic Parameter](#)

[Elastic constants](#)

[Acoustic Wave Speeds](#)

[Phonon frequencies](#)

Basic Parameter

Bulk modulus	$7.1 \cdot 10^{11} \text{ dyn cm}^{-2}$
Density	4.81 g cm^{-3}
Surface microhardness (using Knoop's pyramid test)	$\sim 460 \text{ kg mm}^{-2}$
Cleavage plane	{100}
Piezoelectric constant	$e_{14} = -3.5 \cdot 10^{-2} \text{ C m}^{-2}$

Elastic constants at 300 K

$$C_{11} = 10.11 \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{12} = 5.61 \cdot 10^{11} \text{ dyn/cm}^2$$

$$C_{44} = 4.56 \cdot 10^{11} \text{ dyn/cm}^2$$

[\(Nichols et al. \[1980\]\).](#)

Bulk modulus (compressibility ⁻¹) B_s	$7.11 \cdot 10^{11} \text{ dyn/cm}^2$
Shear modulus	$C' = 2.25 \cdot 10^{11} \text{ dyn/cm}^2$
[100] Young's modulus	$Y_0 = 6.11 \cdot 10^{11} \text{ dyn/cm}^2$
[100] Poisson ratio	$\sigma_0 = 0.36$

Acoustic Wave Speeds

Wave propagation Direction	Wave character	Expression for wave speed	Wave speed (in units of 10^5 cm/s)
[100]	V_L	$(C_{11}/\rho)^{1/2}$	4.58
	V_T	$(C_{44}/\rho)^{1/2}$	3.08
[100]	V_l	$[(C_{11}+C_{12}+2C_{44})/2\rho]^{1/2}$	5.08
	$V_{t\parallel}$	$V_{t\parallel}=V_T=(C_{44}/\rho)^{1/2}$	3.08
	$V_{t\perp}$	$[(C_{11}-C_{12})/2\rho]^{1/2}$	2.16
[111]	V_l'	$[(C_{11}+2C_{12}+4C_{44})/3\rho]^{1/2}$	5.23
	V_t'	$[(C_{11}-C_{12}+C_{44})/3\rho]^{1/2}$	2.51

Phonon frequencies (in units of 10^{12} Hz)

$$v_{\text{TO}}(\Gamma) \ 9.2 \quad v_{\text{LO}}(\text{X}) \ 9.95$$

$v_{LO}(\Gamma)$ 10.3 $v_{TA}(L)$ 1.65

$v_{TA}(X)$ 2.05 $v_{LA}(L)$ 5.0

$v_{LA}(X)$ 5.8 $v_{TO}(L)$ 9.5

$v_{TO}(X)$ 9.7 $v_{LO}(L)$ 10.2

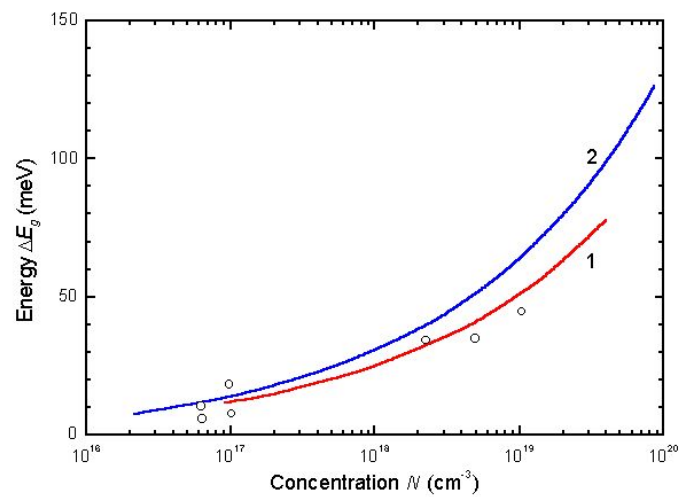
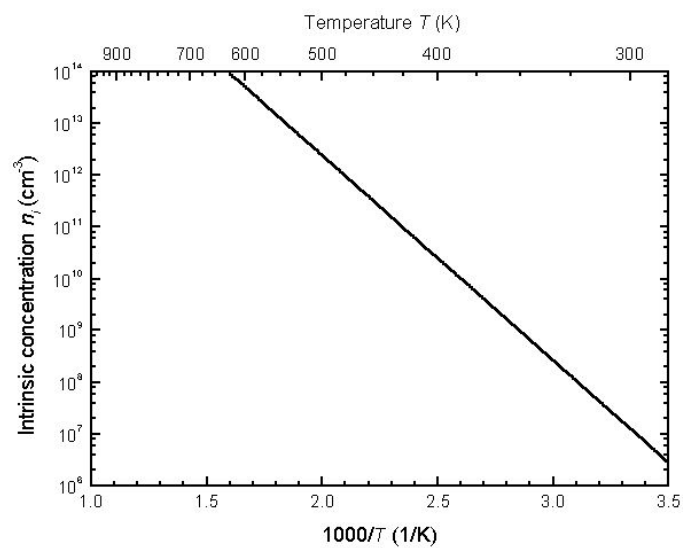
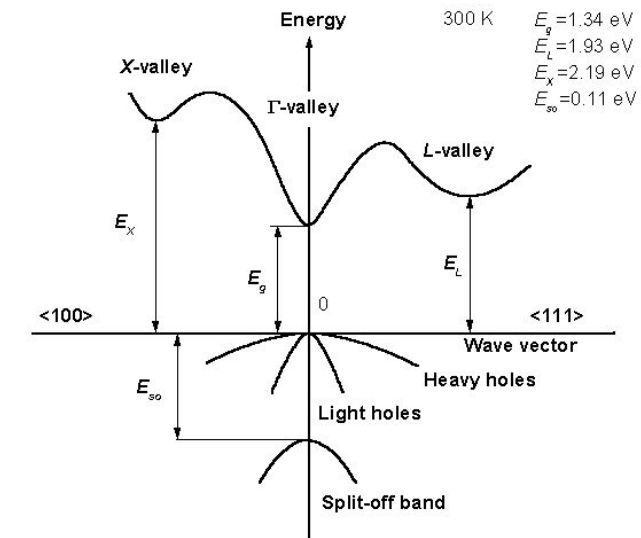
[*\(Suto and Nashizawa \[1990\]\).*](#)

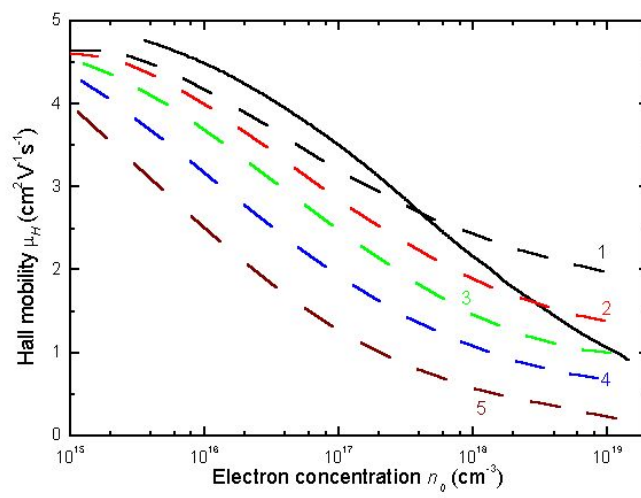
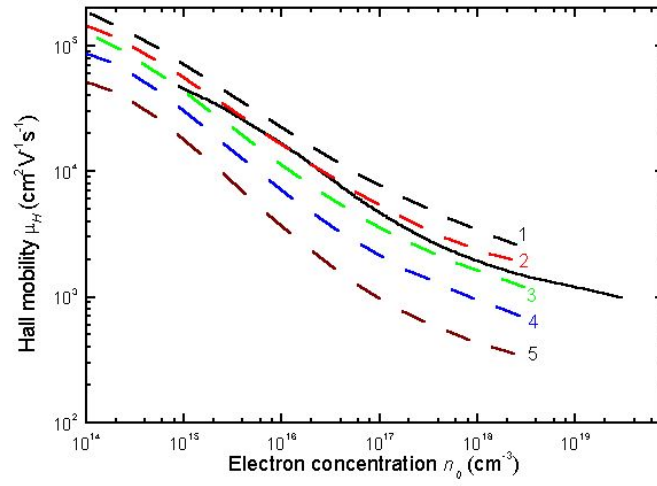
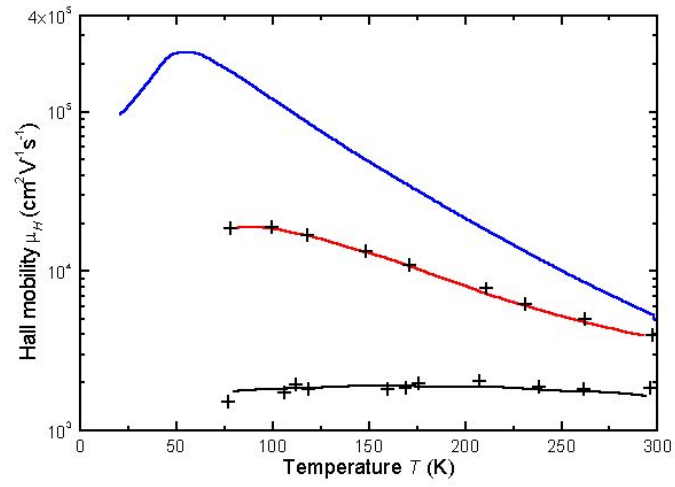
InP - Indium Phosphide

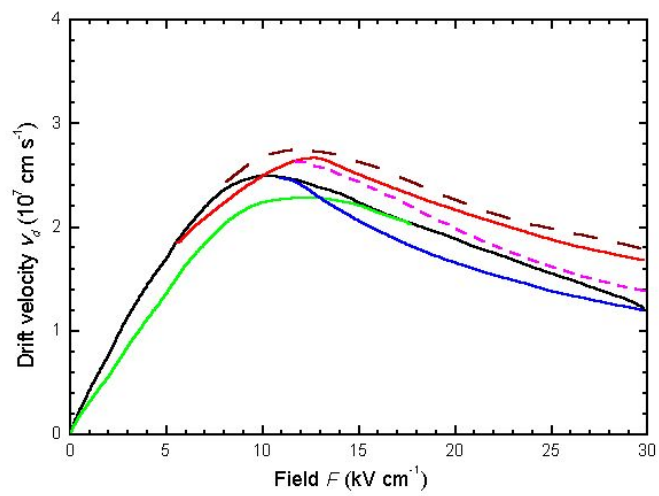
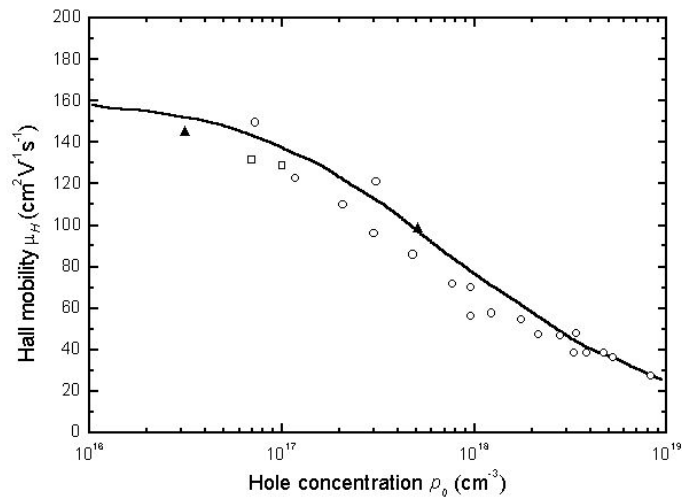
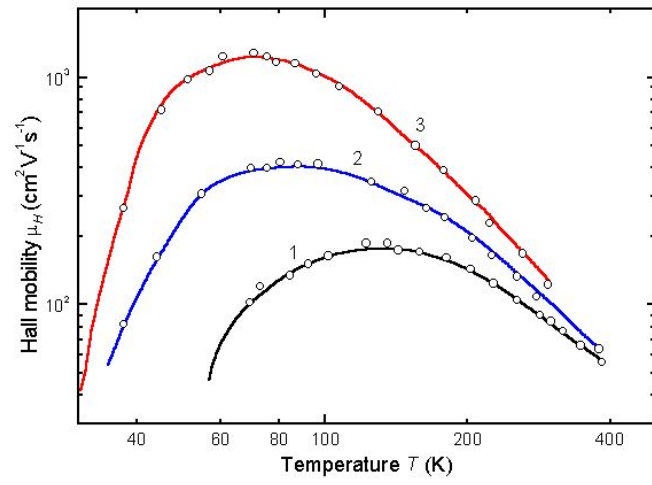
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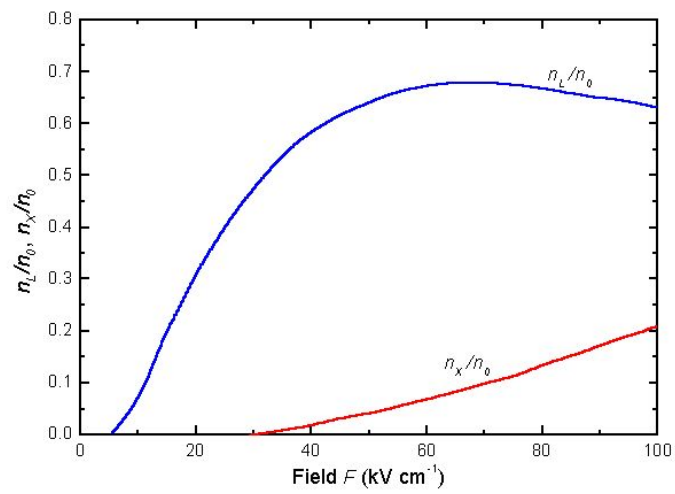
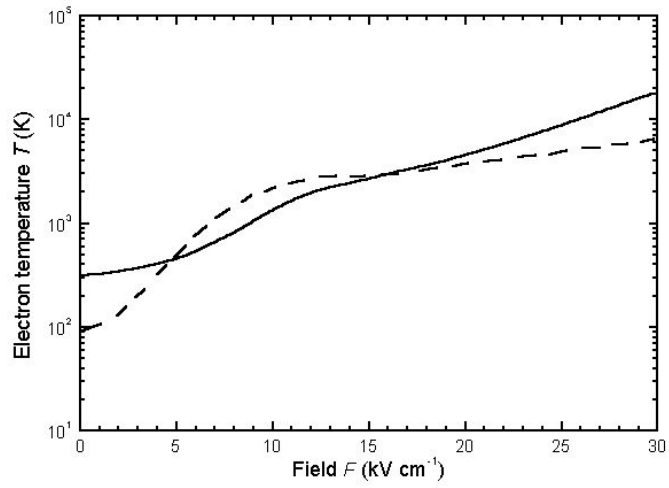
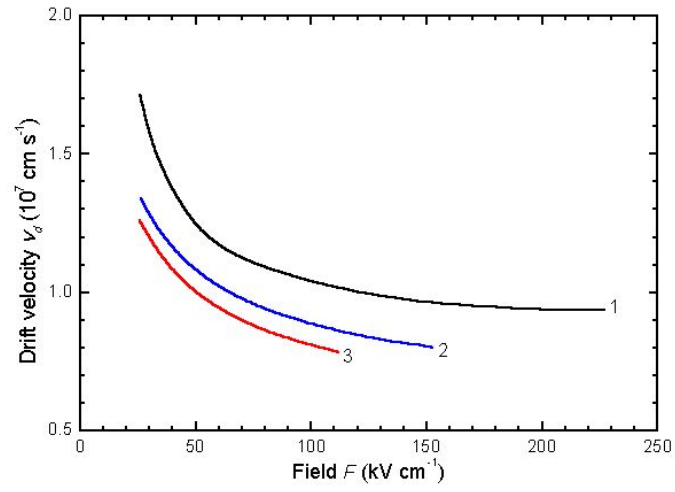
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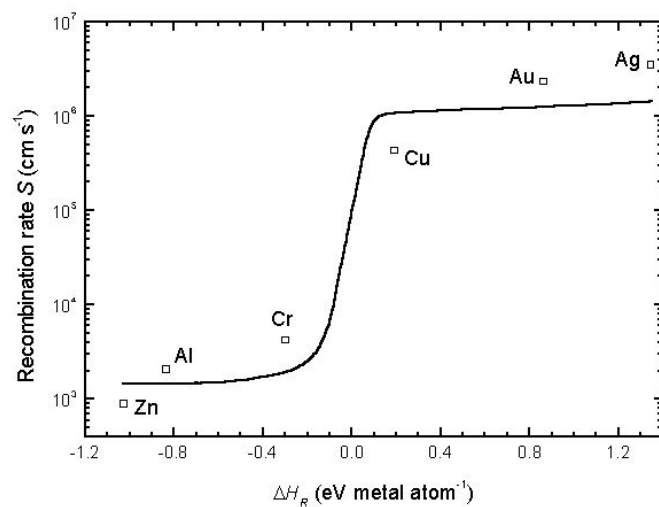
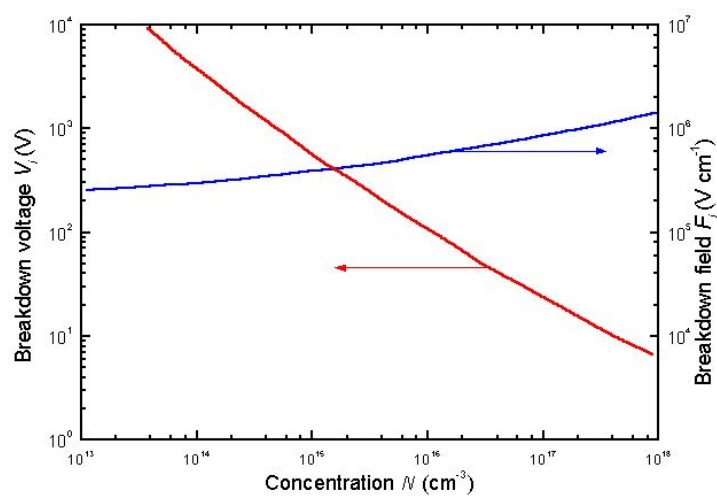
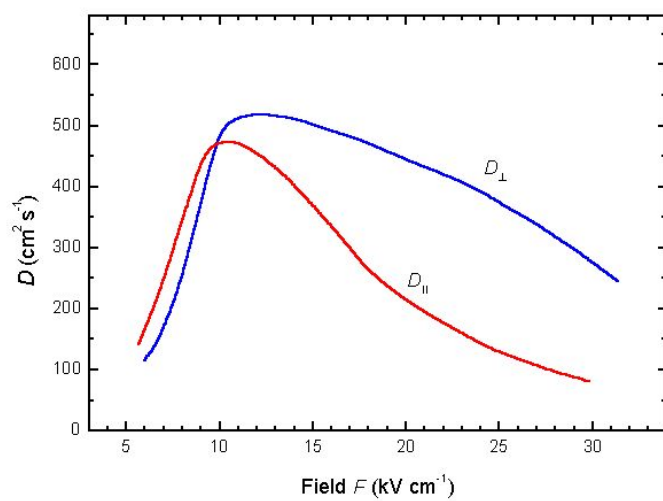
4.2 Bildvergrößerungen

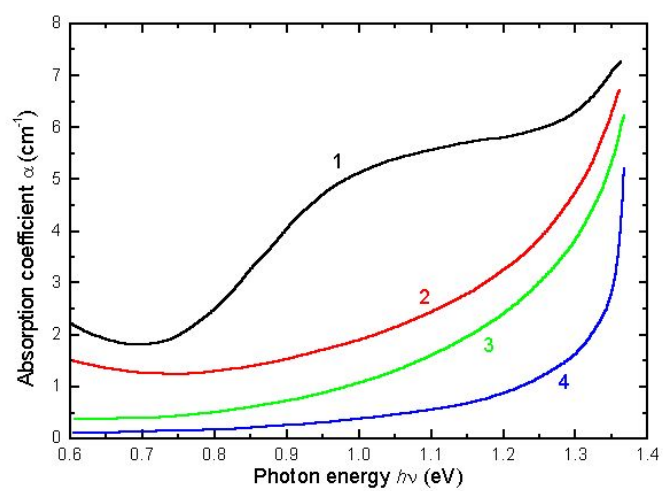
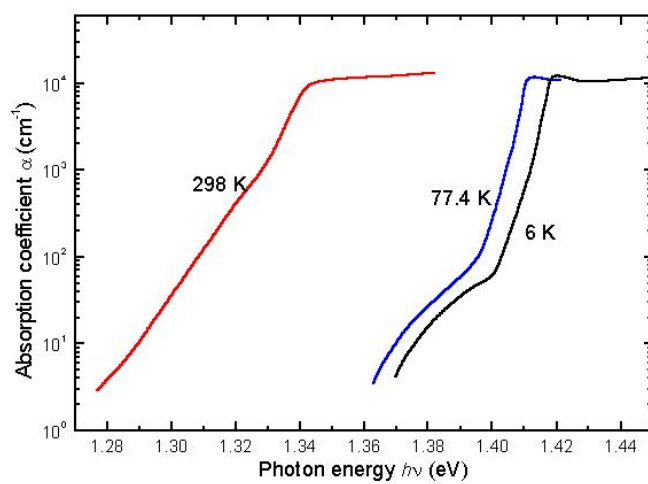
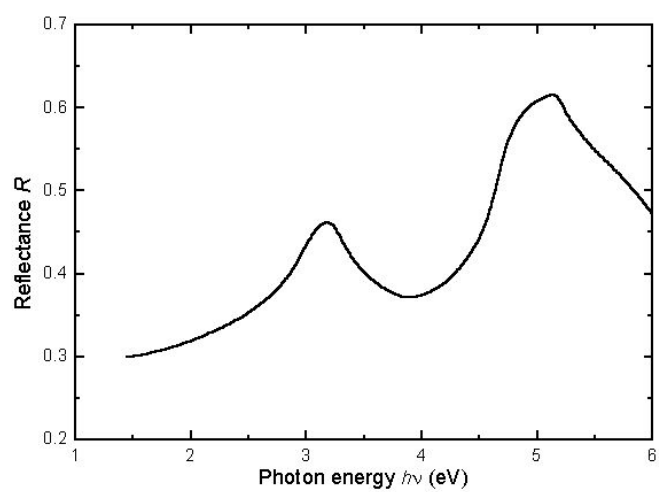


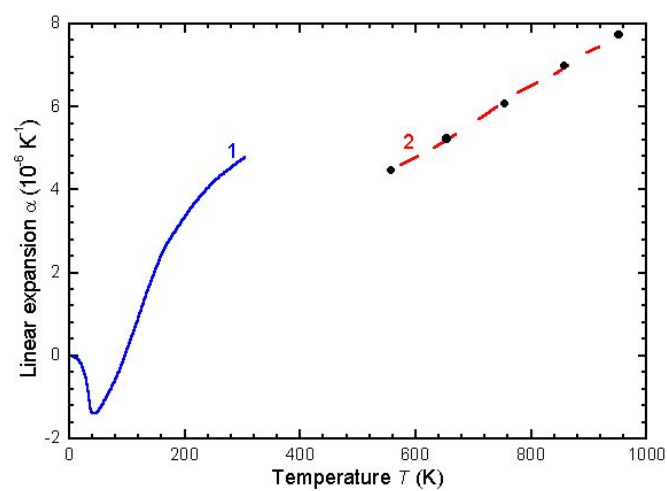
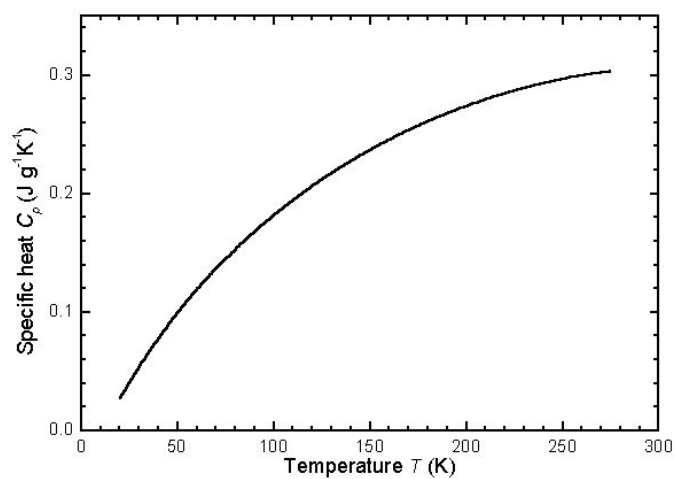
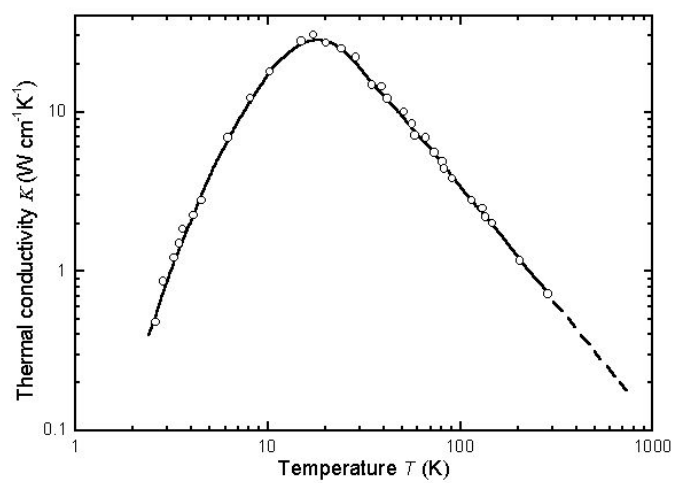


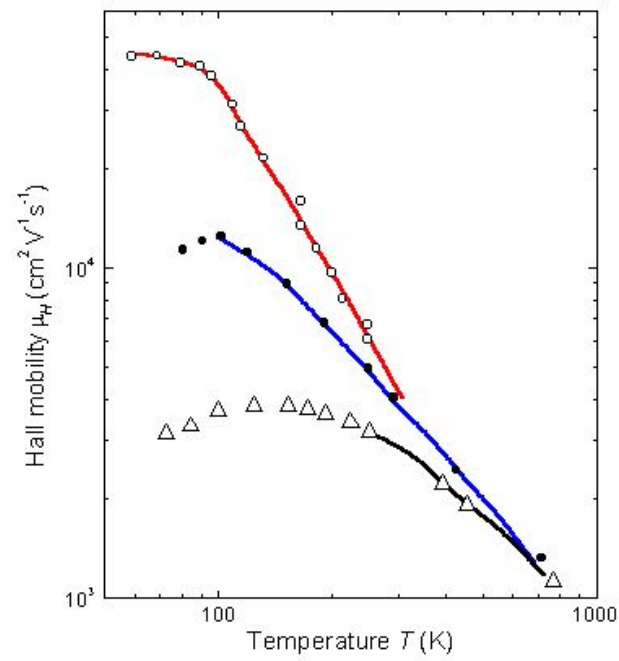
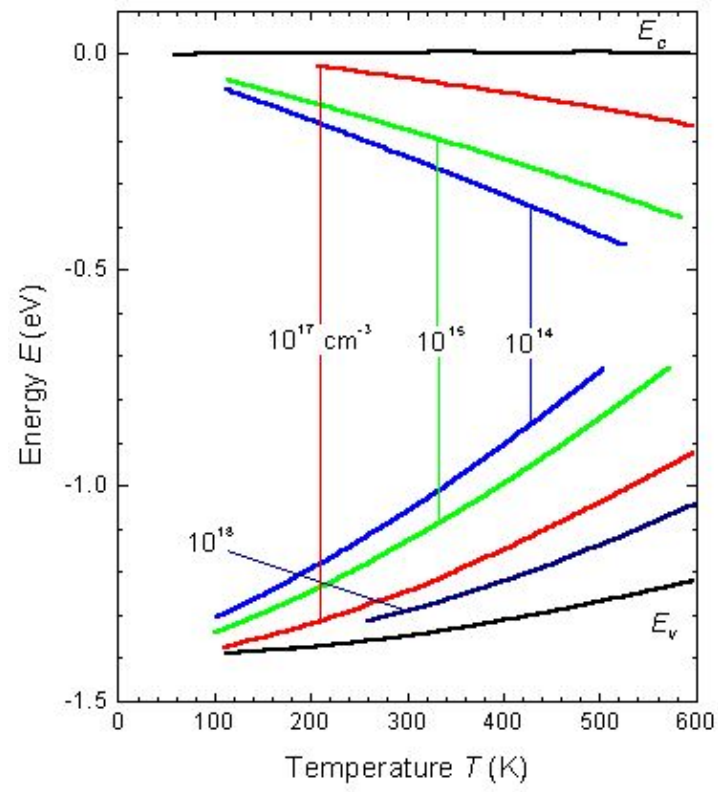


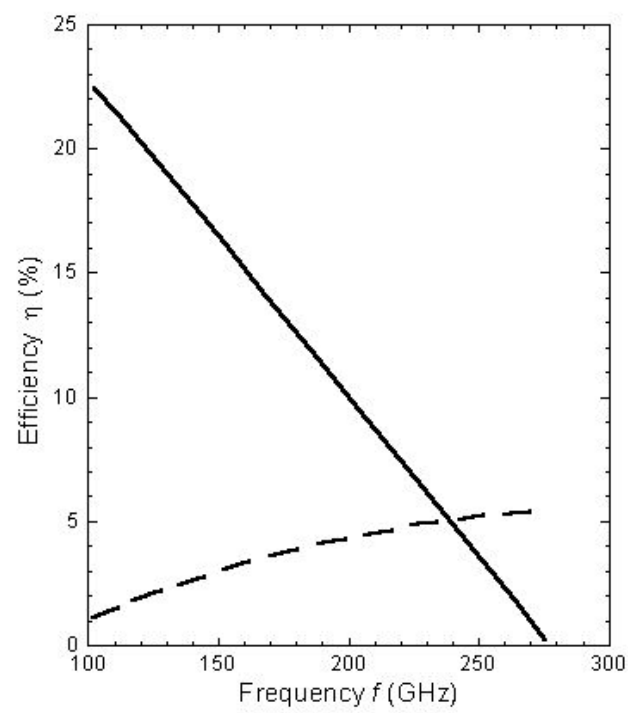
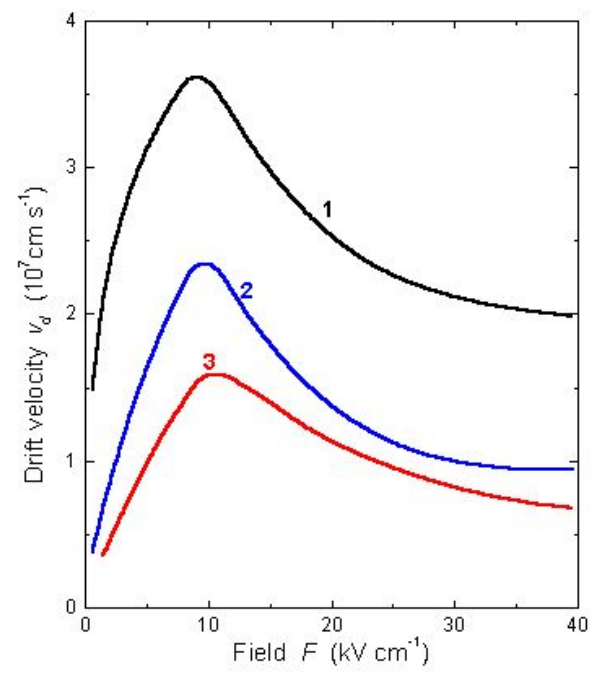


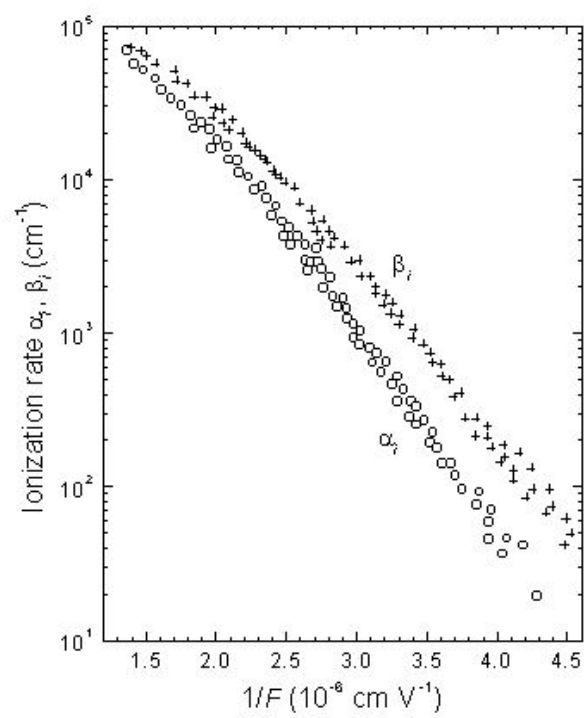
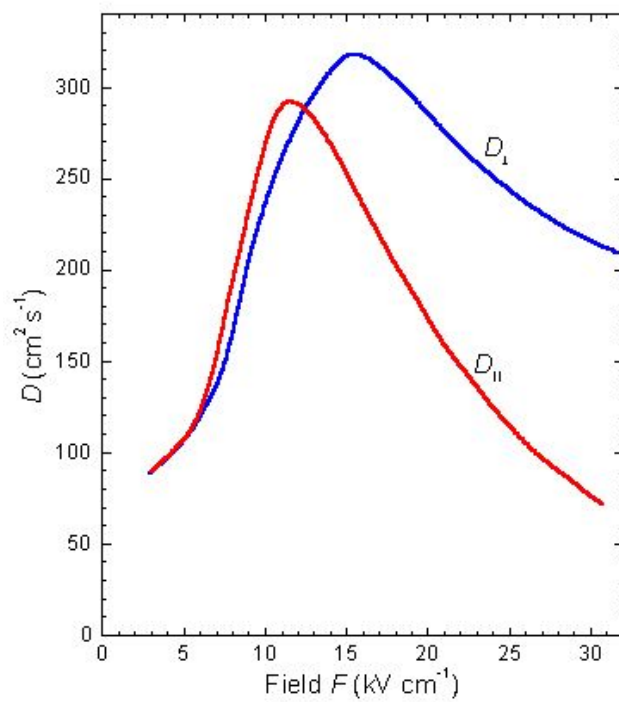


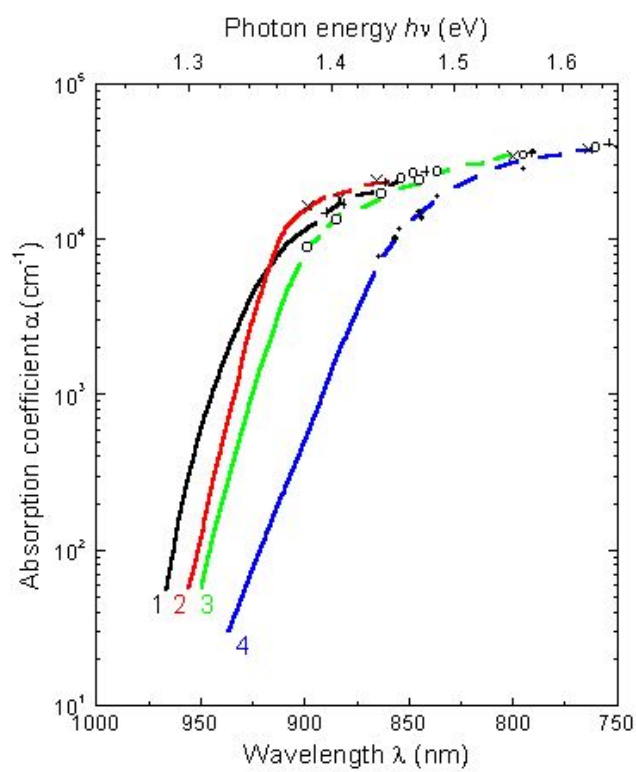
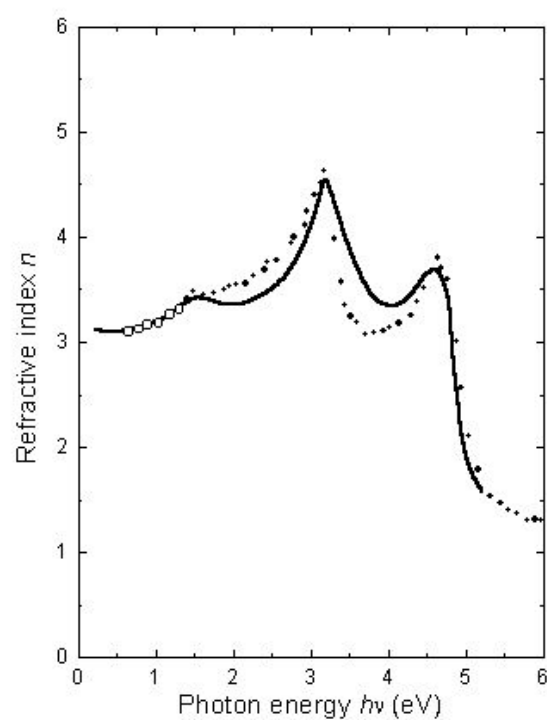


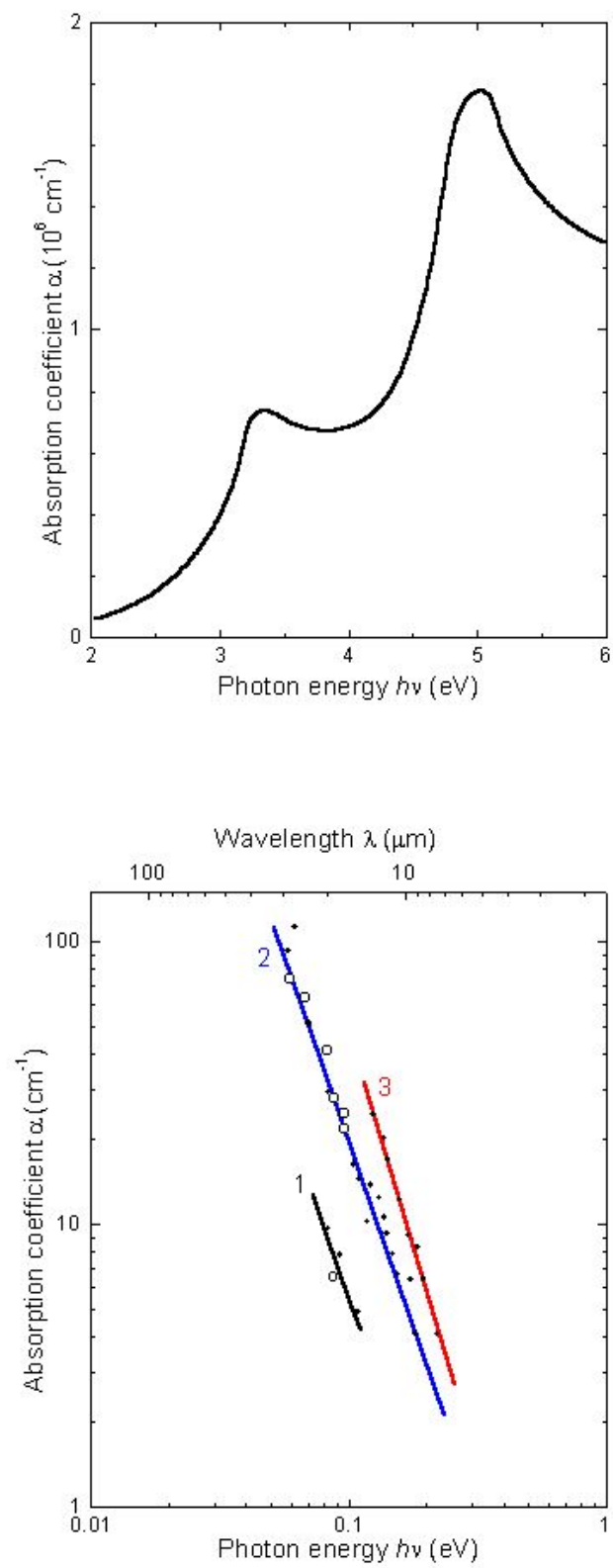


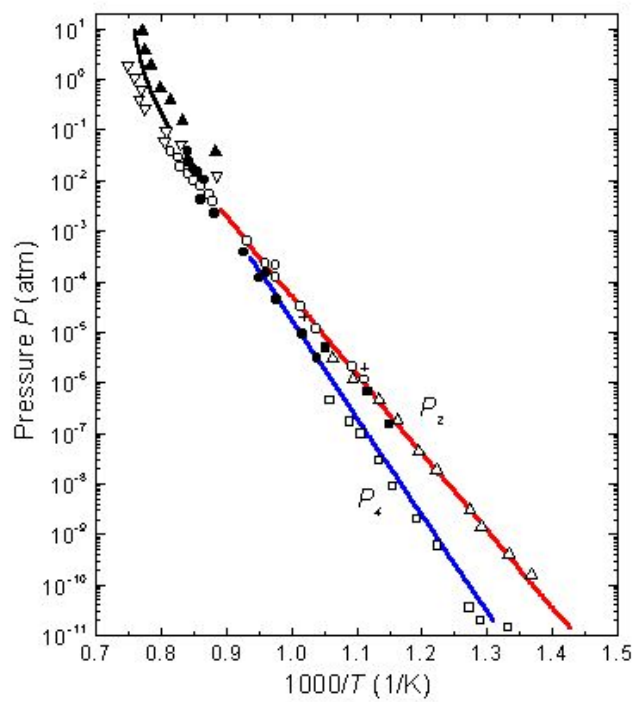












LaTeX 2_ε

