Semiconductors | n, k database | InGaAsP | Equivalents

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 colleages 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 reseach, we would appreciate acknowledging it in your papers.

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

Authors

mytrix

$Al_x Ga_{1-x} As$

- *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 $Al_xGa_{1-x}As$/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*

$Al_x Ga_{1-x} As$

Basic Parameters at 300 K

Crystal structure	Zinc Blende
Group of symmetry	T_d^2-F43m
Number of atoms in 1 cm^3	$(4.42-0.17x)\cdot 10^{22}$
Debye temperature	$370+54x+22x^2$ K
Density	$5.32-1.56x$ $g\cdot cm^{-3}$
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 eV ($x<0.45$) 3.64-0.14x eV ($x>0.45$)
Lattice constant	5.6533+0.0078x A
Optical phonon energy	$36.25+1.83x+17.12x^2-5.11x^3$ meV

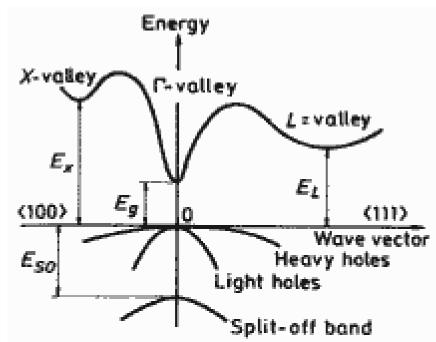
$Al_x Ga_{1-x} As$

Band structure and carrier concentration

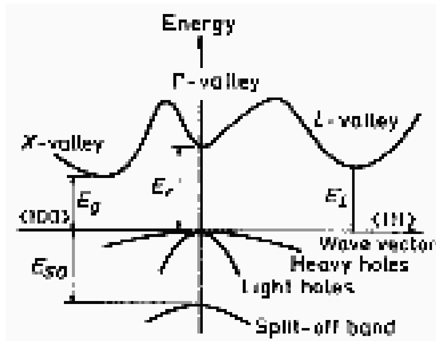
Basic Parameters
Temperature Dependences
Dependence on Hydrostatic Pressure
Energy Gap Narrowing at High Doping Levels
Band Discontinuities at $Al_xGa_{1-x}As$/GaAs Heterointerface

Basic Parameters

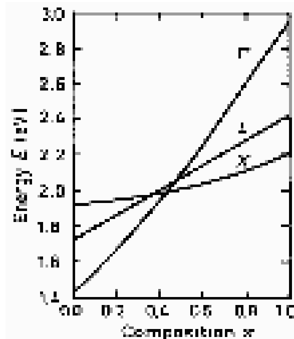
Energy gap	x<0.45	1.424+1.247x eV
	x>0.45	$1.9+0.125x+0.143x^2$
Energy separation ($E_{•L}$) between • and L valleys	0.29 eV	
Energy separation ($E_•$) between • and top of valence band	$1.424+1.155x+0.37x^2$ eV	
Energy separation (E_X) between X-valley and top of valence band	$1.9+0.124x+0.144x^2$ eV	
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	$4•10^9$ ••cm
	x=0.3	$1•10^{12}$ ••cm
	x=0.5	$1•10^{14}$ ••cm
	x=0.8	$5•10^{14}$ ••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 condition band and maxima of the valence band

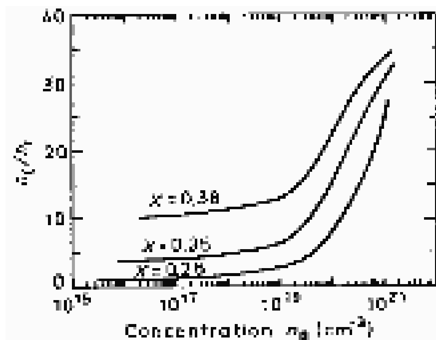


Band structure Al_xGa_{1-x} for x>0.45. Important minima of the condition band and maxima of the valence band



Energy separation between •-, X-, and L- conduction band minima and top of the valence band versus composition.
Crossover points:

x_c(L-X) = 0.35 eV $E_L=E_X$ = 1.95 eV
x_c(•-X) = 0.41 eV $E_•=E_X$ = 1.97 eV
x_c(•-L) = 0.47 eV $E_•=E_L$ = 2.04 eV
(Saxena [1980]).



Ratio of the total carrier concentration to the carrier concentration in •-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 •, X, and L valleys of the conduction band $E_•$, E_X and E_L one can use the data for GaAs *(Aspnes [1976])*.

$E_• = E_•(0) - 5.41•10^{-4}• T^2/(T+204)$ (eV)
where $E_•(0) = 1.519 + 1.155x + 0.37x^2$ (eV)

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

where $E_X(0) = 1.981 + 0.124x + 0.144x^2$ (eV)

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

where $E_L(0) = 1.815 + 0.0.69x$ (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

$E_L = 1.815 - 6.05•10^{-4}• T^2/(T+204)$ (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

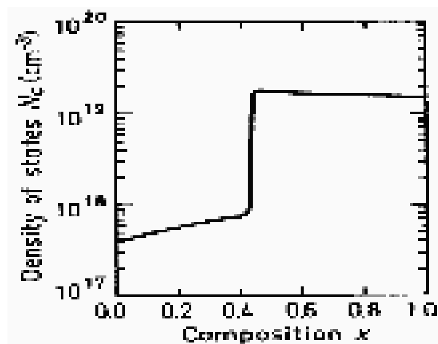
$E_L=1.981-4.60\cdot 10^{-4}\cdot T^2/(T+204)$ (eV)

Effective density of states in the conduction band N_c

X<0.41 $N_c=4.82\cdot10^{15}\cdot(m_\bullet/m_o)^{3/2}\cdot T^{3/2} = 4.82\cdot10^{15}\cdot T^{3/2}\cdot(0.063+0.083x)^{3/2}$ (cm^{-3})

X>0.41 $N_c=4.82\cdot10^{15}\cdot(m_{cd}/m_o)^{3/2}\cdot T^{3/2} = 4.82\cdot10^{15}\cdot T^{3/2}\cdot(0.85-0.14x)^{3/2}$ (cm^{-3})

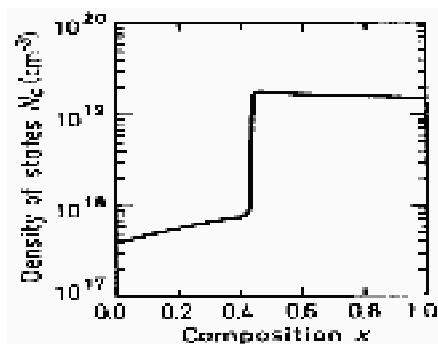
where m_{cd} is effective mass of the density of states;



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

Effective density of states in the valence band N_v

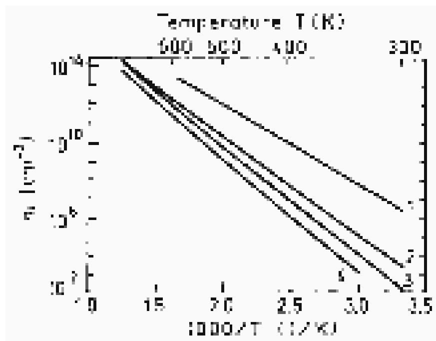
$N_v = 4.82\cdot10^{15}\cdot T^{3/2}\cdot(0.51+0.25x)^{3/2}$ (cm^{-3}) **X>0.41** $N_c=4.82\cdot10^{15}\cdot(m_{cd}/m_o)^{3/2}\cdot T^{3/2} = 4.82\cdot10^{15}\cdot T^{3/2}\cdot(0.85-0.14x)^{3/2}$ (cm^{-3})



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

Intrinsic Carrier Concentration

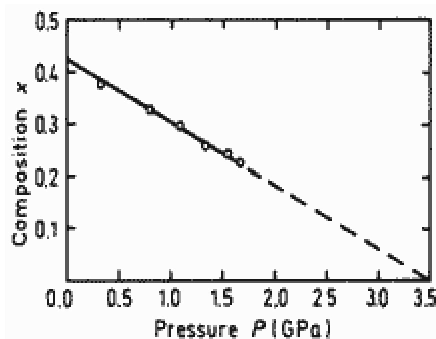
$n_i = (N_c\cdot N_v)^{1/2}\exp[-E_g/(2k_bT)]$



The temperature dependences of the intrinsic carrier concentration.
1. x=0
2. x=0.3
3. x=0.6
4. x=1

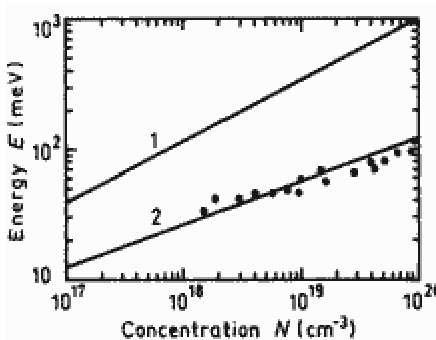
Dependences on Hydrostatic Pressure

$E_{\bullet} = (11.5 - 1.3\,x)\bullet 10^{-3}\bullet P$ *(eV)*
$E_X = -0.8\bullet 10^{-3}\bullet P$ *(eV)*
$E_L = 2.8\bullet 10^{-3}\bullet P$ *(eV)*
where P is pressure in kbar. (Adachi [1985])

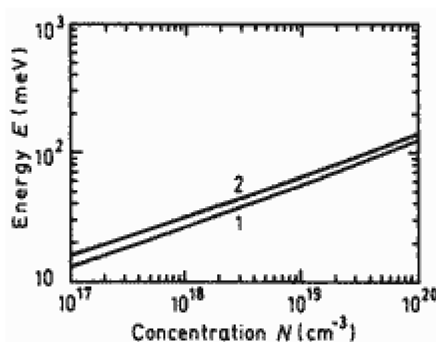


Pressure dependence of the •-X crossover. 300 K
(Saxena [1980])

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 curvesare calculated according *(Jain et al. [1990])*

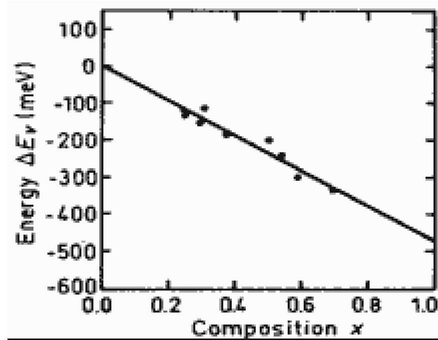
Band Discontinuities at $Al_xGa_{1-x}As$/GaAs Heterointerface

Valence band discontinuity:

- $E_v = -0.46x$ (eV)

Conduction band discontinuity:

x<0.41	•$E_c = 0.79x$ (eV)
x>0.41	•$E_c = 0.475-0.335x+0.143x^2$ (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])*

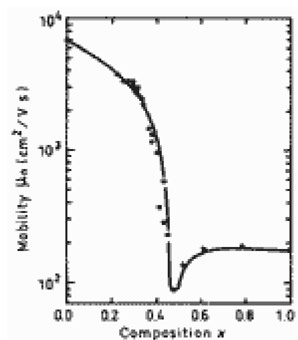
$Al_x Ga_{1-x} As$

Electrical properties - Basic Parameters

Breakdown field	$\bullet(4\div6)\ \bullet10^5$ V/cm
Mobility electrons	
0<x<0.45	$8\bullet10^3-2.2\bullet10^4x+10^4\bullet x^2$ $cm^2\ V^{-1}\ s^{-1}$
0.45<x<1	$-255+1160x-720x^2$ $cm^2\ V^{-1}\ s^{-1}$
Mobility holes	$370-970x+740x^2$ $cm^2\ V^{-1}\ s^{-1}$
Diffusion coefficient electrons	
0<x<0.45	$200-550x+250x^2$ cm^2/s
0.45<x<1	$-6.4+29x-18x^2$ cm^2/s
Diffusion coefficient holes	$9.2-24x+18.5x^2$ cm^2/s
Electron thermal velocity	
0<x<0.4	$(4.4-2.1x)\bullet10^5$ m/s
0.45<x<1	$2.3\bullet10^5$ m/s
Hole thermal velocity	$(1.8-0.5x)\bullet10^5$ m/s

$Al_x Ga_{1-x} As$

Mobility and Hall Effect



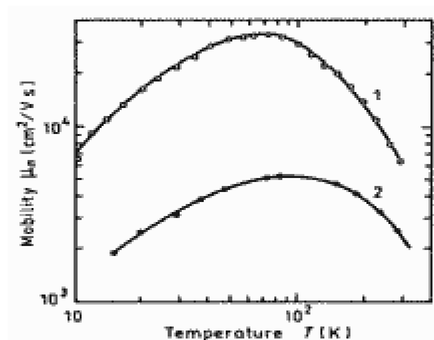
Electron Hall mobility versus alloy composition x. T=300 K.
Electron concentration $n_o=(5\div10)\bullet10^{15}$ cm^{-3}.
(Saxena (1981b).

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

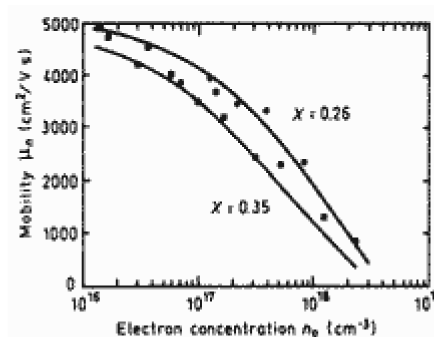
0<x<0.45 $\mu_H=-8000 - 22000x+ 10000x^2$

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

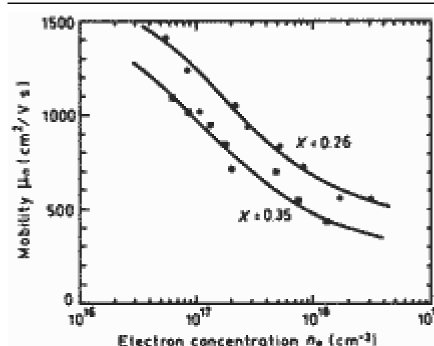
(Shur (1990)).



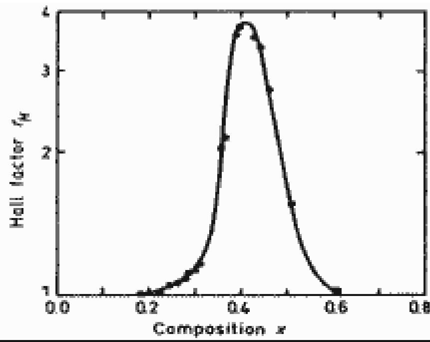
Electron Hall mobility versus temperature.
Curve 1 x=0; $n=0.5\bullet10^{16}$ cm^{-3} *(Stillman et al. (1970))*.
Curve 2 x=0.32; $n=(0.5\div1)\bullet10^{16}$ cm^{-3} *(Saxena (1981b))*.



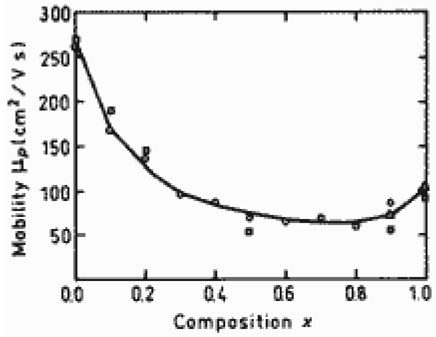
Electron Hall mobility versus electron concentration for two values of x. T=77 K.
(Liu (1990)).



Electron Hall mobility versus electron concentration for two values of x. T=300 K.
(Liu (1990)).



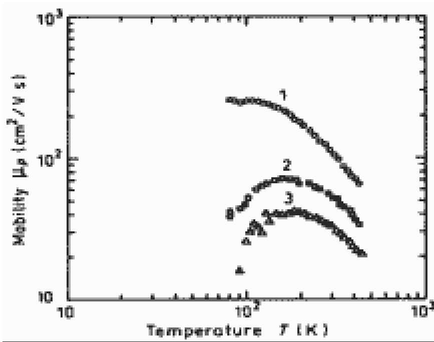
Hall factor versus alloy composition x for n-type $Al_xGa_{1-x}As$ T=300 K
Electron concentration $n_o=(5\div10)\cdot10^{15}$ cm^{-3}.
(Saxena (1981a).



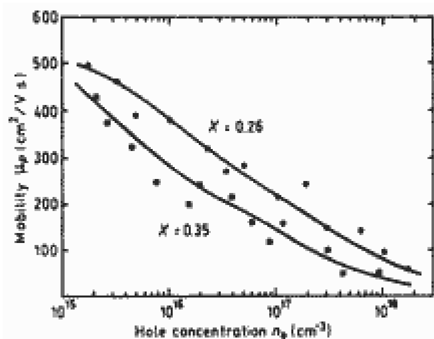
Hole Hall mobility versus alloy composition x. 296 K.
Acceptor density N_a•$2.5\cdot10^{17}$ cm^{-3}.
(Look et al. (1992)).

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

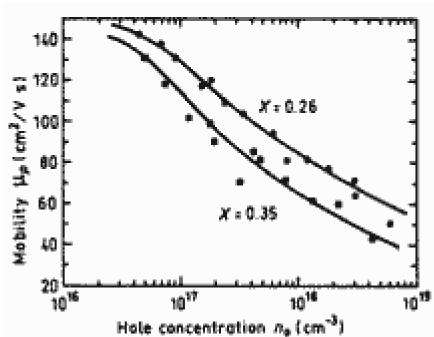
μ_H=-370-970x+740x^2
(Shur (1990)).



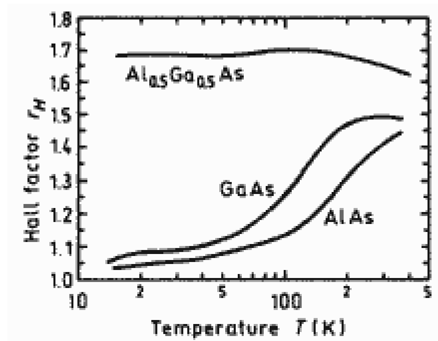
Hole Hall mobility versus temperature.
Curve 1 - x=0; $p_o=7\cdot10^{17}$ cm^{-3}
Curve 2 - x=0.41; $p_o=4.65\cdot10^{17}$ cm^{-3}
Curve 3 - x=0.75; $p_o=2.4\cdot10^{17}$ cm^{-3}
(Yang et al. (1981)).



Hole Hall mobility versus hole concentration for two values of x. T=77 K.
(Liu (1990)).



Hole Hall mobility versus hole concentration for two values of x. T=300 K.
(Liu (1990)).

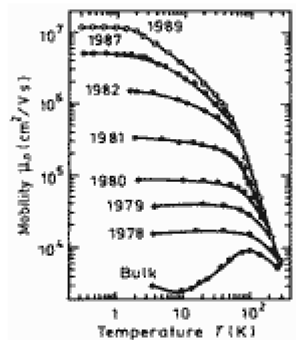


Hall factor versus temperature x for p-type GaAs, AlAs and $Al_{0.5}Ga_{0.5}As$.

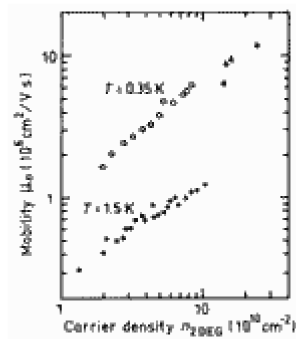
Curves are calculated for acceptor concentration N_a•6.5•10^{13} cm^{-3}.
(Look et al. (1992)).

$Al_x Ga_{1-x} As$

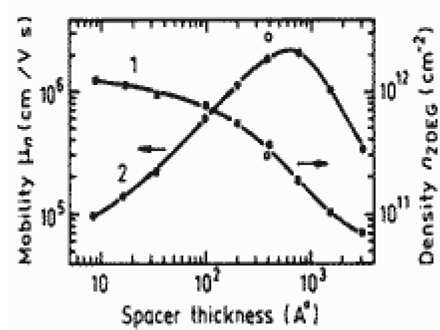
Two-dimensional electron and hole gas mobility at $Al_xGa_{1-x}As/GaAs$ interface



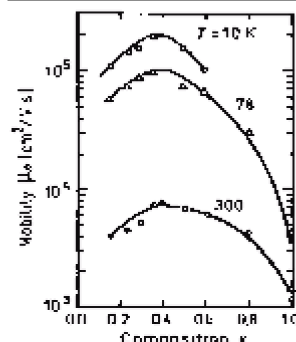
Temperature dependences of the electron Hall mobility in the modulation-doped two-dimensional gas.
(Pfeiffer et al. (1989)).



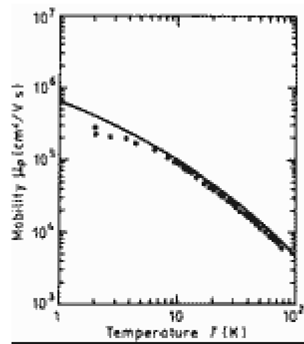
Dependences of electron mobility versus surface carrier density 2D electron gas in the modulation-doped two-dimensional gas.
(Pfeiffer et al. (1989)).



Dependences of surface electron density (Curve 1) and mobility (Curve 2) versus undoped spacer thickness. T=4 K.
(Harris et al. (1987)).



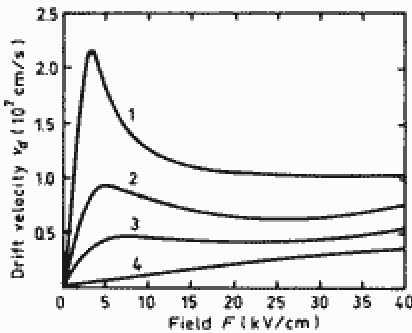
Electron mobility in 2D-electron gas versus Al fraction x at three different temperatures.
(Drummond et al. (1982)).



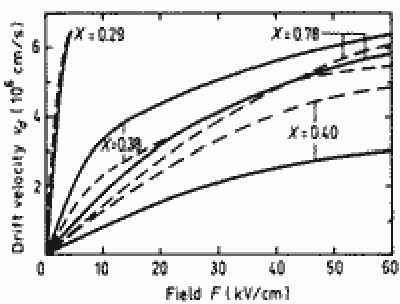
Hole mobility in 2D-hole gas versus temperature.
Solid line shows theoretical calculation.
Points show experimental data for hole surface density 2•10^{11} cm^{-2} *(Walukiewicz (1996))*.

$Al_x Ga_{1-x} As$

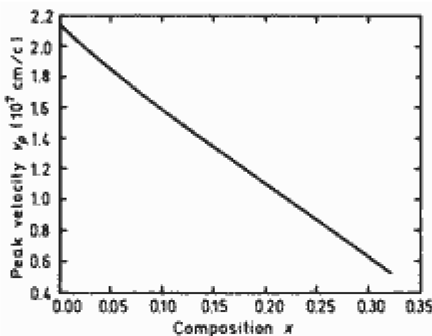
Transport Properties in High Electric Fields



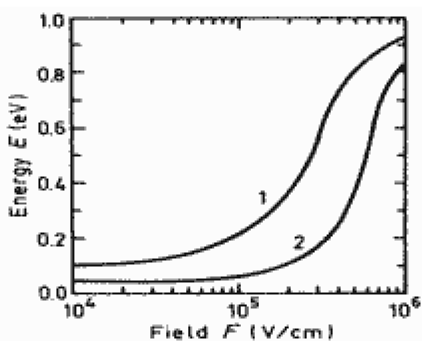
Field dependences of the electron drift velocity for different values of x.
Curves are calculated according displaced Maxwellian approximation. T=300 K.
1 - x=0;
2 - x=0.225;
3 - x=0.325;
4 - x=0.5.
(Hava and Auslender (1993)).



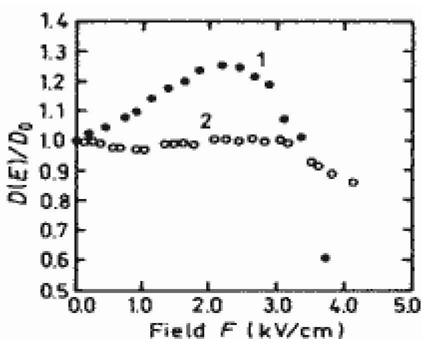
Field dependences of the electron drift velocity for different values of x.
Solid curves - show experimental results (electron concen tration $n_o=(2\div10)\cdot10^{15}$ cm^{-3}
Dashed curves show results of Monte-Carlo calculations.
(Hill and Robson (1981)).



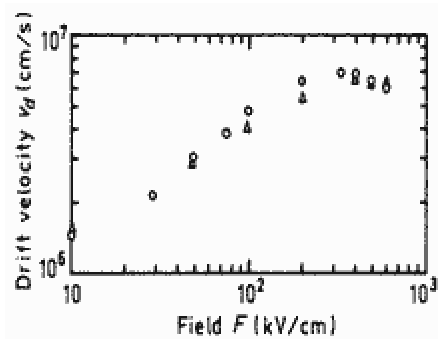
Dependences of peak electron velocity versus x.
(Hava and Auslender (1993)).



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



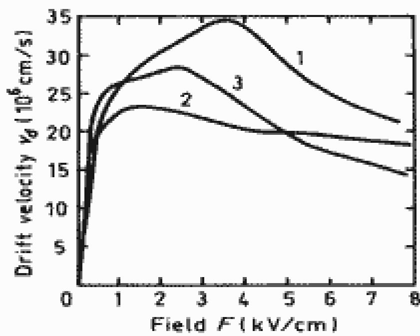
The field dependences of normalized longitudinal diffusion coefficient. T=300 K.
1 - x=0;
2 - x=0.25. *(de Murcia et al. (1993))*.



Field dependence of hole drift velocity. Monte-Carlo calculations. T=300 K.
(Brennan and Hess (1986)).

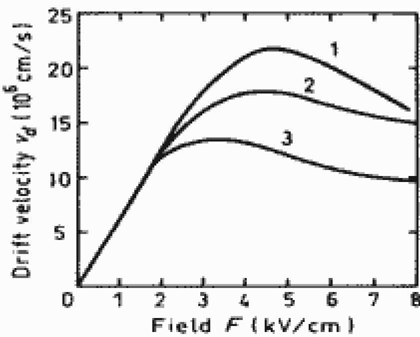
$Al_x Ga_{1-x} As$

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



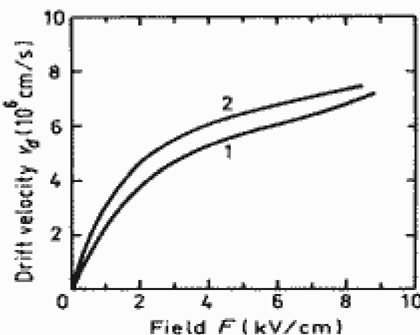
Experimental field dependences dependences of electron velocity. T=77 K.

1 - for bulk GaAs with $n_o=10^{15}$ cm^{-3}
2, 3 - for two-dimensional modulation - doped heterostructures $Al_xGa_{1-x}As/GaAs$.
2 - x=0.3;
3 - x=0.5.
(Masselink (1989)).



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

1 - for bulk GaAs with $n_o=10^{15}$ cm^{-3}
2, 3 - for two-dimensional modulation - doped heterostructures $Al_xGa_{1-x}As/GaAs$.
2 - x=0.3;
3 - x=0.5.
(Masselink (1989)).

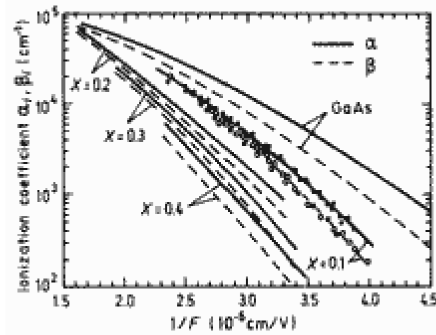


Experimental field dependences of hole velocity for two-dimensional hole gas. Single heterointerface samples. x=0.5. T=77 K.

1 - $p=3.3\cdot10^{11}$ cm^{-2}, $\mu=3300$ cm^2 Vs
2 - $p=4.2\cdot10^{11}$ cm^{-2}, $\mu=4000$ cm^2 Vs
(Masselink et al. (1987)).

$Al_x Ga_{1-x} As$

Impact Ionization



Fits to experimental values of electron and hole ionization coefficients for $Al_xGa_{1-x}As$ with x=0.1÷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:

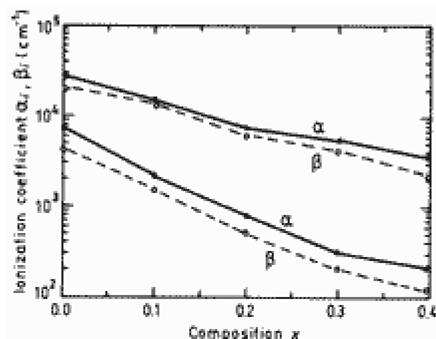
$$\alpha_i = \alpha_0 \exp[-(F_{n_0}/F)^m]$$

x	• $_o$ (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:

$$\beta_i = \beta_0 \exp[-(F_{p_0}/F)^m]$$

x	• $_o$ (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



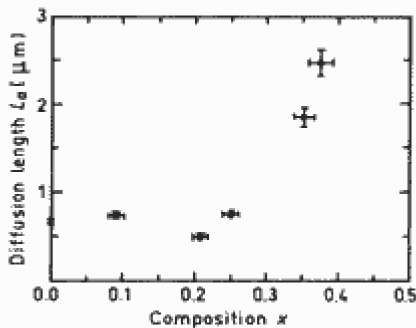
Experimental ionization coefficients versus x for electric fields
Bottom curves - $3 \cdot 10^5$ V/cm
Upper curves - $4 \cdot 10^5$ V/cm
T=300 K. *(Robbins et al. (1988))*.

Breakdown voltage and breakdown field of n-GaAs/p-$Al_{0.3}Ga_{0.7}As$ heterojunctions T=300 K.
(Hur et al. (1990))

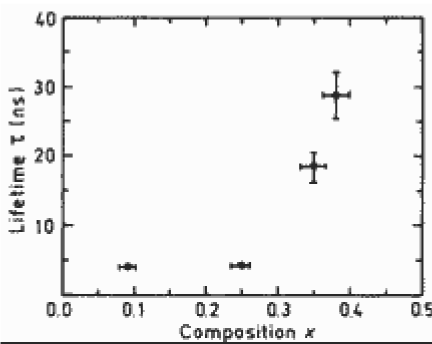
$N_a=10^{14}$ cm^{-3}	$V_i=2.8$ kV	$E_i=2.8\cdot10^5$ V cm^{-1}
$N_a=10^{16}$ cm^{-3}	$V_i=70$ V	$E_i=4.5\cdot10^5$ V cm^{-1}

$Al_x Ga_{1-x} As$

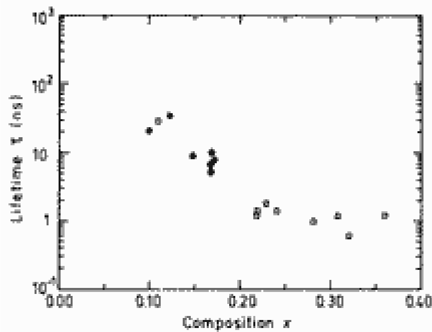
Recombination Parameter



Ambipolar diffusion length at a carrier density of $10^{17}÷10^{18}$ cm^{-3} versus x. T= 300K.
Determination was accomplished by catodoluminescene technique *(Zarem et al. (1989))*.



Carrier lifetimes at carrier density of ~3•10^{18} cm^{-3} (high injection level) versus versus x. T= 300K.
Determination was accomplished by photoluminiscence decay signal technique.
(Zarem et al. (1989)).



Hole lifetime versus x for n-$Al_xGa_{1-x}As$
N_d-N_a~$10^{15}÷10^{16}$ cm^{-3}. T= 300K.
(Timmons et al. (1988)).

Radiative recombination coefficient at 300K ~1.8•10^{-10} cm^3/s

Auger coefficient at T=300 K *(Timmons (1985))*.

x	C_n (cm^6/s)	C_p (cm^6/s)
0	1.9•10^{-31}	12•10^{-31}
0.1	1.2•10^{-31}	8.5•10^{-31}
0.2	0.7•10^{-31}	6.1•10^{-31}

Cn (for n - doped samples)
Cp (for p - doped samples)

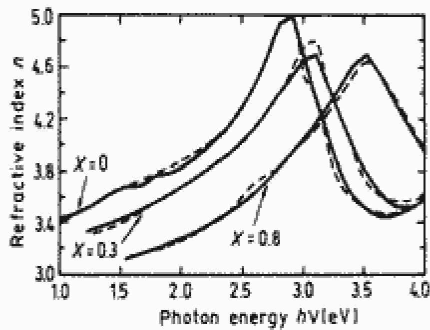
Surface and interface recombination velocities in GaAs and $Al_xGa_{x-1}As$
(Pavesi and Guzzi (1994)).

x	S (cm/s)	
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 $Al_xGa_{1-x}As/Al_{0.88}Ga_{0.22}As$ undoped
0.28	4200	interface between $Al_xGa_{1-x}As/Al_{0.5}Ga_{0.5}As$ undoped

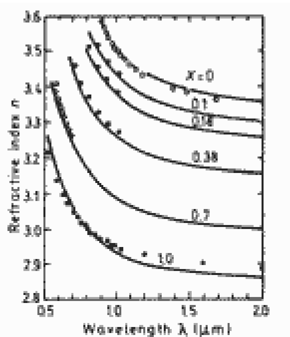
$Al_x Ga_{1-x} As$

Optical properties

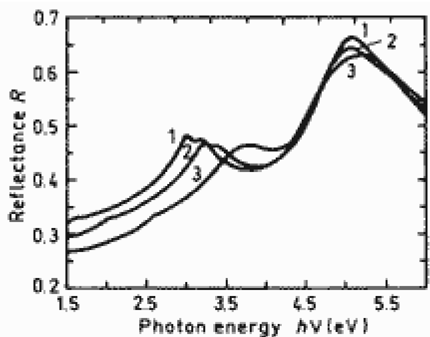
Infrared refractive index (300 K)
$n=3.3-0.53x+0.09x^2$



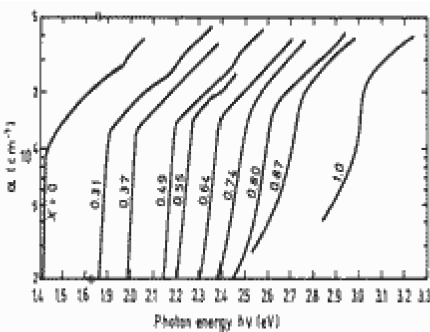
Refractive index *n* versus photon energy for three values of *x*.
Solid lines are calculated.
Dashed lines are experimental data. 300 K.
(Jenkins (1990)).



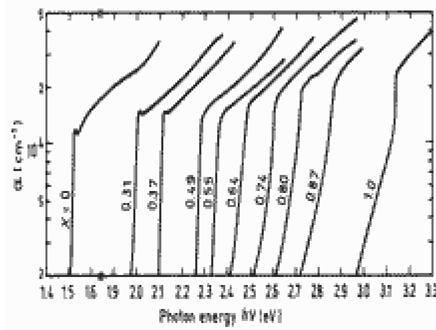
Refractive index *n* versus wavelength for different values of *x*. 300 K.
(Pikhtin and Yas'kov (1980)).



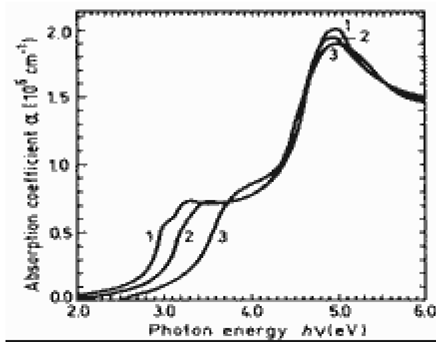
Normal incidence reflectivity versus photon energy. 300 K.
1 x~0.1,
2 x~0.42,
3 x~0.8.
(Aspnes et al. (1986))).



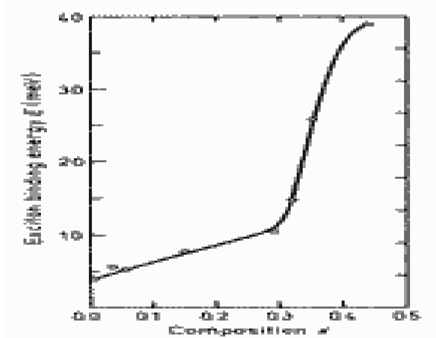
Intrinsic absorption coefficient near the intrinsic absorption edge for different values of *x*. 300 K.
(Monemar et al. (1976)).



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~0.1,
2 x~0.42,
3 x~0.8.
(Aspnes et al. (1986))).

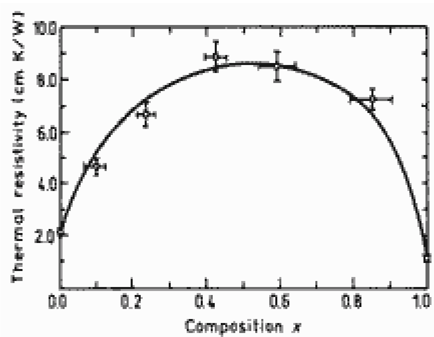


Free exciton binding energy versus Al mole fraction *x*.
(Pearah et al. (1985)).

$Al_x Ga_{1-x} As$

Thermal properties

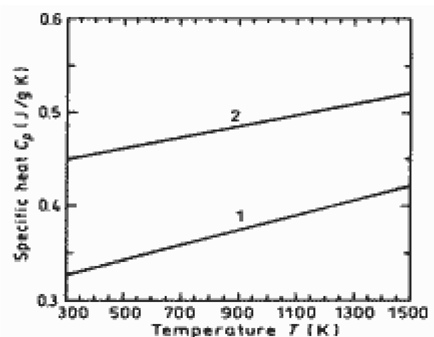
Bulk modulus	$(7.55+0.26x)\cdot10^{11}$ dyn cm^{-2}
Melting point	$1240-58x+558x^2$ °C *(solidus curve)* $12401082x+582x^2$ °C *(liquidus curve)*
Specific heat	$0.33+0.12x$ J g^{-1}°C^{-1}
Thermal conductivity	$0.55-2.12x+2.48x^2$ W cm^{-1} °C^{-1}
Thermal diffusivity	$0.31-1.23x+1.46^2$ $cm^2 s^{-1}$
Thermal expansion, linear	$(5.73-0.53x)\cdot10^{-6}$ °C^{-1}



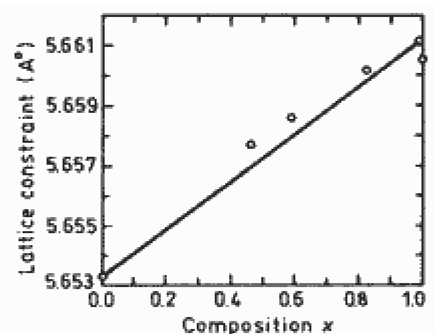
Thermal resistivity versus Al fraction x. 300K.
Solid curve is a theoretical fit to the experimental data.
(Afromowitz [1973]).

Approximate formula for the lattice thermal resistivity:

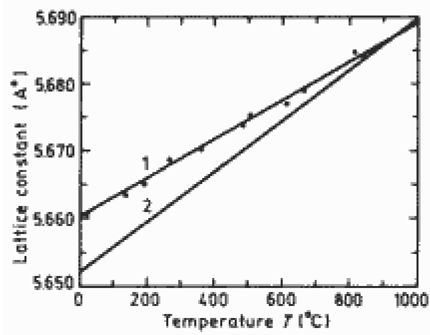
$R_{th}=2.27+28.83x-30x^2$ cm••W^{-1}



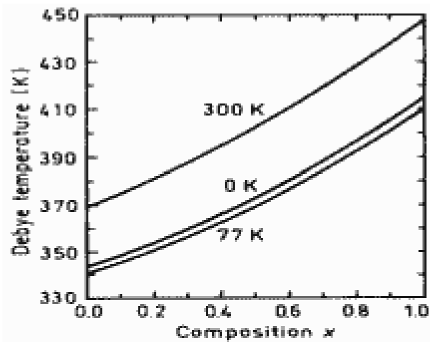
Temperature dependences of specific heat at constant pressure.
1. GaAs *(Lichter and Sommelet [1969])*;
2. AlAs *(Barin et al. [1977])*.



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 °C - *(solidus curve)*
T_m=1240+1082x-582x^2 °C *(liquidus curve)*

$Al_x Ga_{1-x} As$

Mechanical properties, elastic constants, lattice vibrations

[Basic Parameter](#)
[Elastic constants](#)
[Acoustic Wave Speeds](#)
[Phonon frequencies](#)

Basic Parameter

Bulk modulus	$(7.55+0.26x)\cdot10^{11}$ dyn cm^{-2}
Density	5.32-1.56x g cm^{-3}
Hardness on the Mohs scale	~ 5
Cleavage plane	{110}
Piezoelectric constant	e_{14}= -0.16-0.065x C m^{-2}

Elastic constants 300 K.

$C_{11}=(11.88+0.14x)\cdot10^{11}$ dyn/cm^2
$C_{12}=(5.38+0.32x)\cdot10^{11}$ dyn/cm^2
$C_{44}=(5.94-0.05x)\cdot10^{11}$ dyn/cm^2
(Adachi [1985]).

For T = 300 K

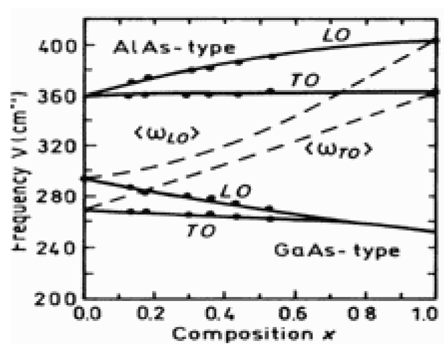
Bulk modulus (compressibility^{-1})	B_s= =$(7.55+0.26x)\cdot10^{11}$dyn/cm^2
Anizotropy factor	A=0.55-0.01x
Shear modulus	C'=$(3.25-0.09x)\cdot10^{11}$dyn/cm^2
[100] Young's modulus	$Y_o=(8.53-0.18x)\cdot10^{11}$dyn/cm^2
[100] Poisson ratio	$\bullet_o$=(0.31+0.1x)

(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	$(C_{11}/\bullet)^{1/2}$	$4.73+0.68x+0.24x^2$
	V_T	$(C_{44}/\bullet)^{1/2}$	$3.34+0.46x+0.16x^2$
[110]	V_l	$[(C_{11}+C_{12}+2C_{44})/2\bullet]^{1/2}$	$5.24+0.78x+0.24x^2$
	$V_{t\parallel}$	$V_{t\parallel}=V_T=(C_{44}/\bullet)^{1/2}$	$3.34+0.46x+0.16x^2$
	$V_{t\perp}$	$[(C_{11}-C_{12})/2\bullet]^{1/2}$	$2.47+0.33x+0.10x^2$
[111]	V_l'	$[(C_{11}+2C_{12}+4C_{44})/3\bullet]^{1/2}$	$5.40+0.79x+0.26x^2$
	V_t'	$[(C_{11}-C_{12}+C_{44})/3\bullet]^{1/2}$	$2.79+0.38x+0.12x^2$

Phonon frequencies



Optical phonon energy as a function of x.
The compositional dependence of the effective phonon energy <•$_{L0}$> and < • $_{T0}$> are shown by the dashed lines.
(Adachi [1985]).

$Al_x Ga_{1-x} As$

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GaAs - Gallium Arsenide

- *Basic Parameters at 300 K*
- *Band structure and carrier concentration*
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  - *Temperature Dependences*
  - *Energy Gap Narrowing at High Doping Levels*
  - *Effective Masses and Density of States*
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- *Electrical Properties*
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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 A
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	$0.063 m_o$
Effective hole masses m_h	$0.51 m_o$
Effective hole masses m_{lp}	$0.082 m_o$
Electron affinity	4.07 eV
Lattice constant	5.65325 A
Optical phonon energy	0.035 eV

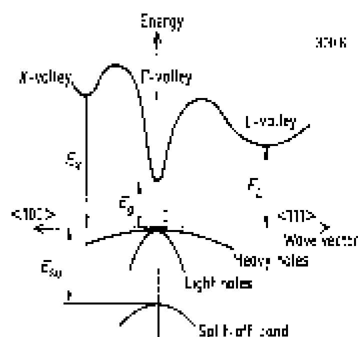
GaAs - Gallium Arsenide

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 ($E_{\bullet L}$) between • and L valleys	0.29 eV
Energy separation ($E_{\bullet X}$) between • and X valleys	0.48 eV
Energy spin-orbital splitting	0.34 eV
Intrinsic carrier concentration	$2.1\bullet10^{6}$ cm^{-3}
Intrinsic resistivity	$3.3\bullet10^{8}$ ••cm
Effective conduction band density of states	$4.7\bullet10^{17}$ cm^{-3}
Effective valence band density of states	$9.0\bullet10^{-18}$ cm^{-3}



Band structure and carrier concentration of GaAs. 300 K
E_g = 1.42 eV
E_L = 1.71 eV
E_X= 1.90 eV
E_{so} = 0.34 eV

Temperature Dependences

Temperature dependence of the energy gap

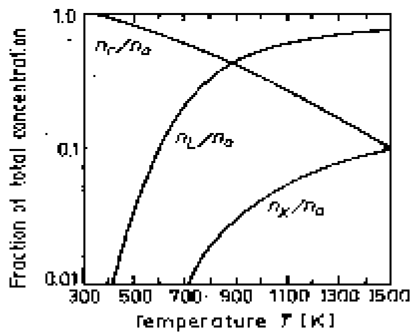
$E_g=1.519-5.405\bullet10^{-4}\bullet T^2/(T+204)$ (eV)
where T is temperatures in degrees K ($0 < T < 10^3$).

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

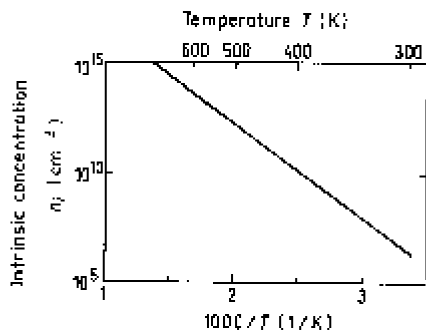
$E_L=1.815-6.05\bullet10^{-4}\bullet T^2/(T+204)$ (eV)

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• 10^{-4}• $T^2/(T+204)$ (eV)



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



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

Intrinsic Carrier Concentration

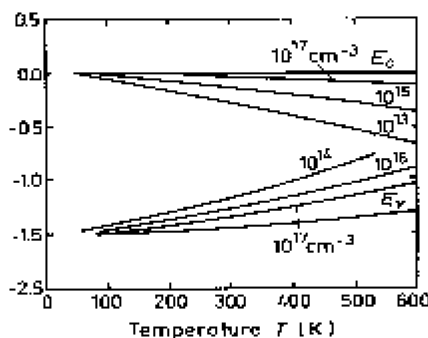
$n_i = (N_c \bullet N_\bullet)^{1/2} exp(-E_g/(2k_bT))$

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

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

Effective density of states in the valence band

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

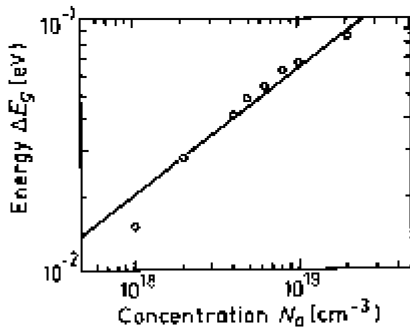


Fermi level versus temperature for different concentrations of shallow donors and acceptors.

Dependences on Hydrostatic Pressure

$E_g = E_g(0) + 0.0126 \bullet P - 3.77 \bullet 10^{-5} P^2$ (eV)
$E_L = E_L(0) + 5.5 \bullet 10^{-3} P$ (eV)
$E_X = E_X(0) + 1.5 \bullet 10^{-3} P$ (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])

•Eg • $2•10^{-11}•N_a^{-1/2}$ (eV) (N_a- in cm.$^{-3}$)

Effective Masses

Electrons:

For •-valley	$m_•$ = 0.063m_o
In the L-valley the surfaces of equal energy are ellipsoids	
	m_l= 1.9m_o
	m_t= 0.075m_o
Effective mass of density of states	
$m_L=(16m_lm_t^2)^{1/3}$	m_L=0.85m_o
In the X-valley the surfaces of equal energy are ellipsoids	
	m_l= 1.9m_o
	m_t= 0.19m_o
Effective mass of density of states	
$m_X=(9m_lm_t^2)^{1/3}$	m_X=0.85m_o

Holes:

Heavy	m_h = 0.51m_o
Light	m_{lp} = 0.082m_o
Split-off band	m_{so} = 0.15m_o
Effective mass of density of states	m_v = 0.53m_o

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

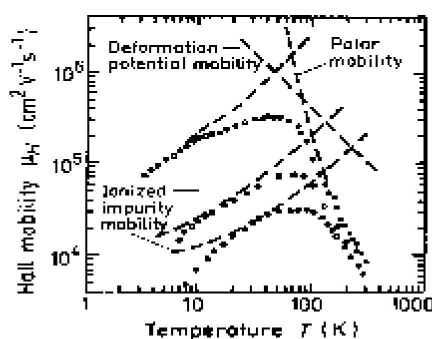
Electrical properties

[Basic Parameters](#)
[Mobility and Hall Effect](#)
[Transport Properties in High Electric Fields](#)
[Impact Ionization](#)
[Recombination Parameters](#)

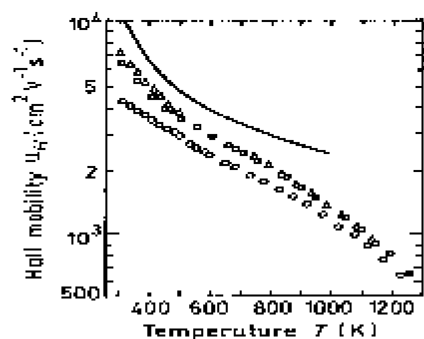
Basic Parameters

Breakdown field	•4•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•10^5 m/s
Hole thermal velocity	1.8•10^{5}m/s

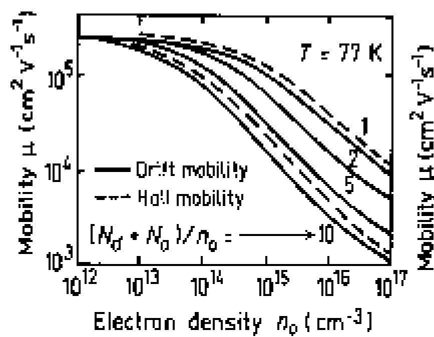
Mobility and Hall Effect



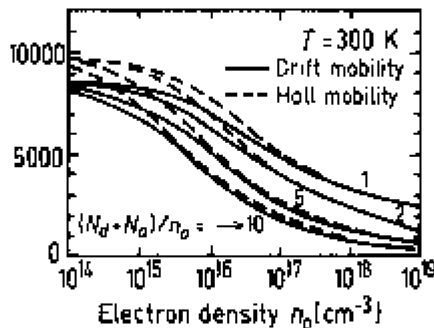
Electron Hall mobility versus temperature for different doping levels.
[(Stillman et al. [1970]](#)
1. Bottom curve: N_d=5•10^{15}cm^{-3};
2. Middle curve : N_d=10^{15}cm^{-3};
3. Top curve : N_d=5•10^{15}cm^{-3}
For weakly doped GaAs at temperature close to 300 K, electron Hall mobility
μ_H=9400(300/T) cm^2 V^{-1} 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•10^{17} cm^{-3};
Open squares: N_d=4N_a=10^{16} cm^{-3};
Open triangles: N_d=3N_a=2•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
μ_n=8000(300/T)$^{2/3}$ cm^2 V^{-1} s^{-1}



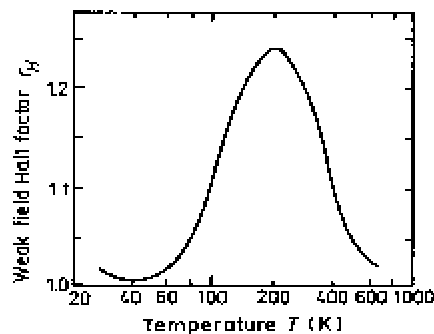
Drift and Hall mobility versus electron concentration for different degrees of compensation T= 77 K
(Rode [1975]).



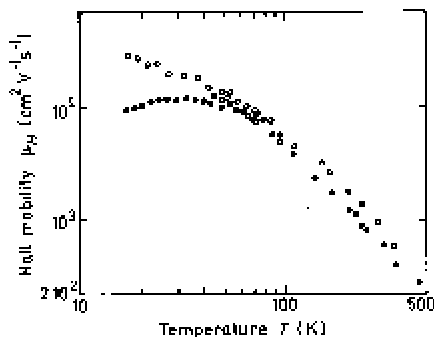
Drift and Hall mobility versus electron concentration for different degrees of compensation T= 300 K
(Rode [1975]).

Approximate formula for the Hall mobility

. $\mu_n = \mu_{OH}/(1+N_d \cdot 10^{-17})^{1/2}$, where $\mu_{OH} \cdot 9400$ (cm^2 V^{-1} 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]).

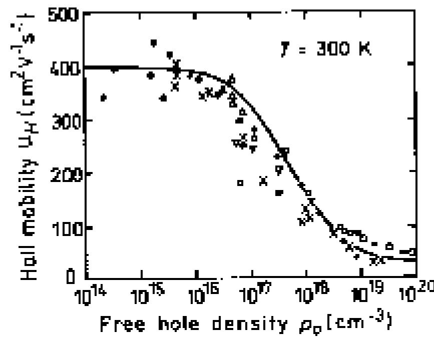


Temperature dependence of the Hall mobility for three high-purity samples
(Wiley [1975])

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

$$\mu_{pH} = \left[0.0025\left(\frac{T}{300}\right)^{2.3} + 4\times10^{21}\,p\left(\frac{T}{300}\right)^{1.5}\right]^{-1}$$ (cm^{2}V^{-1}s^{-1}), (p - in cm^{-3})

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

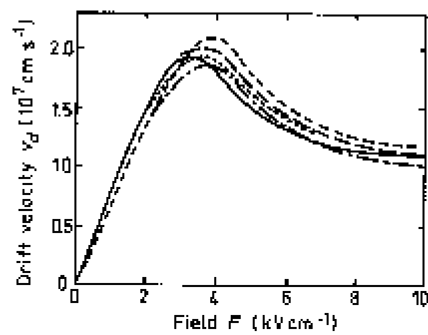


The hole Hall mobility versus hole density.
(Wiley [1975])

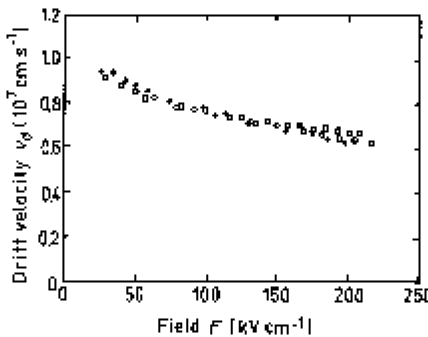
At T= 300 K, the Hall factor in pure GaAs

r_H=1.25.

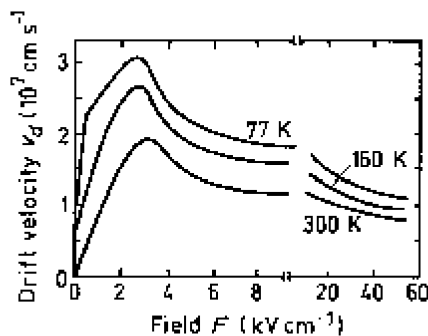
Transport Properties in High Electric Fields



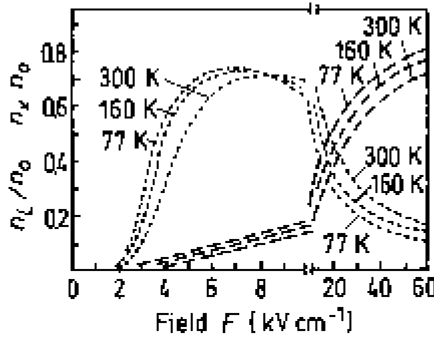
Field dependences of the electron drift velocity.
(Blakemore[1982]).
Solid curve was calculated by (Pozhela and Reklaitis[1980]).
Dashed and dotted curves are measured data, 300 K



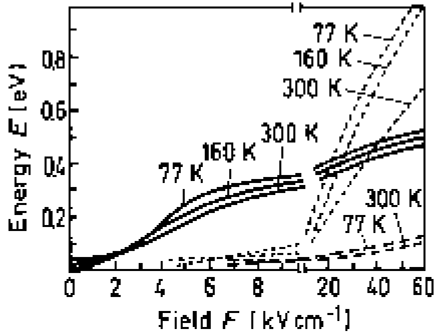
Field dependences of the electron drift velocity for high electric fields, 300 K.
(Blakemore[1982]).



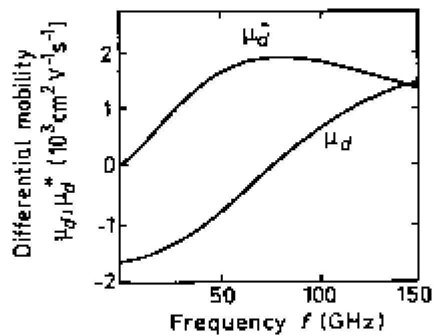
Field dependences of the electron drift velocity at different temperatures.
(Pozhela and Reklaitis[1980]).



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 • , *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 - • valleys, dotted curve - *L* valleys, dashed curve - *X* valleys.

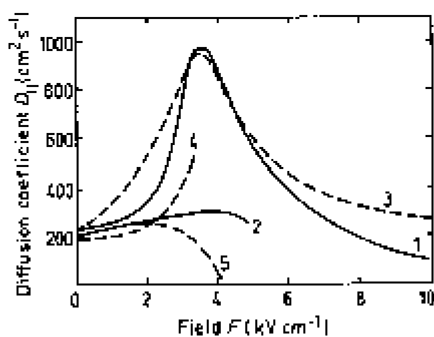


Frequency dependences of electron differential mobility.

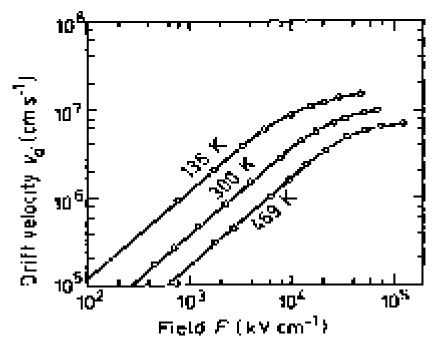
μ_d is real part of the differential mobility; μ_d^* is imaginary part of differential mobility.

F= 5.5 kV cm^{-1}

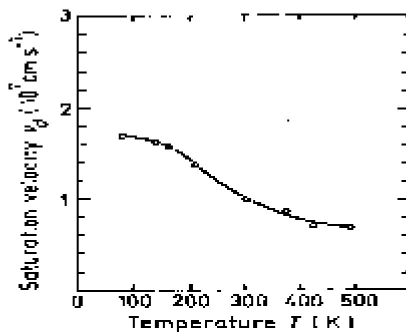
(Rees[1969]).



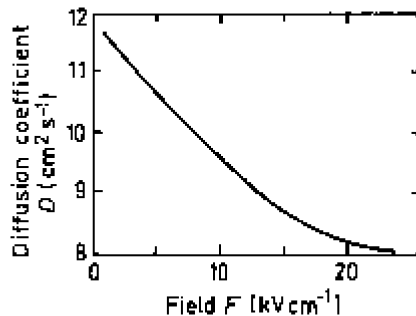
The field dependence of longitudinal electron diffusion coefficient *D||F*.
Solid curves 1 and 2 are theoretical calculations. Dashed curves 3, 4, and 5 are experimental data.
Curve 1 - from *(Pozhela and Reklaitis[1980])*.
Curve 2 - from *(Fauquembergue et al.[1980])*.
Curve 3 - from *(Ruch and Kino[1968])*.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

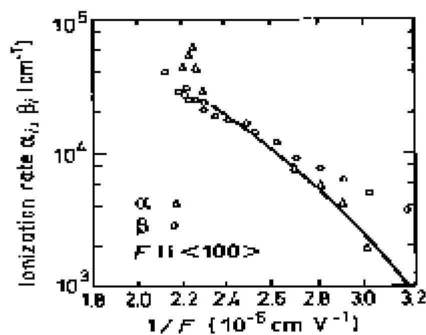


The field dependence of the hole diffusion coefficient.
(Joshi and Crendin [1989]).

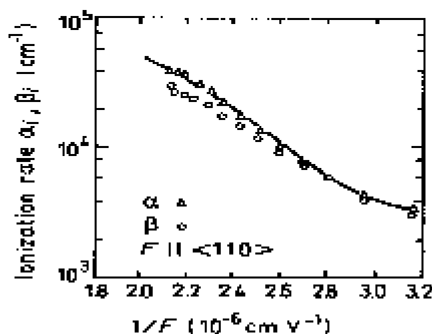
Impact Ionization

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

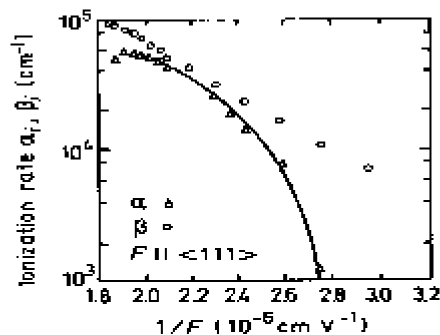
The first one states that impact ionization rates • $_i$ and • $_i$ for electrons and holes in GaAs are known accurately enough to distinguish such subtle details such as the anisothropy of • $_i$ and • $_i$ for different crystallographic directions. This approach is described in detail in the work by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



Experimental curves • $_i$ and • $_i$ versus *1/F* for GaAs.
(Pearsall et al. [1978]).



Experimental curves • $_i$ and • $_i$ versus *1/F* for GaAs.
(Pearsall et al. [1978]).

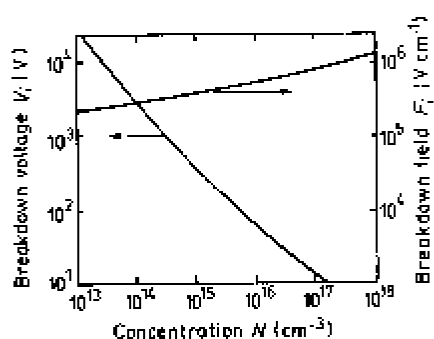


Experimental curves •$_i$ and •$_i$ versus *1/F* for GaAs.
(Pearsall et al. [1978]).

The second school focuses on the values of •$_i$ and •$_i$ 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 •$_i$ = •$_i$. Approximate formula for the field dependence of ionization rates:

•$_i$ = •$_i$ =•$_o$$exp[\bullet - (\bullet^2 + (F_0/F)^2)^{1/2}]$

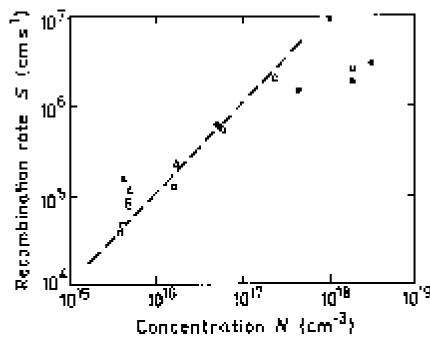
where •$_o$ = 0.245•10^6 cm^{-1}; • = *57.6* F_o = 6.65•10^6 V cm^{-1} (Kyuregyan and Yurkov [1989]).



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_o ~ 10^{14}cm^{-3})	
The longest lifetime of holes	•$_p$ ~3•10^{-6} s
Diffusion length $L_p = (D_p \bullet \bullet_p)^{1/2}$	L_p ~30-50 µm.
Pure p-type material	
(a)Low injection level	
The longest lifetime of electrons	•$_n$ ~ 5•10^{-9} s
Diffusion length $L_n = (D_n \bullet \bullet_n)^{1/2}$	L_n ~10 µm
(b) High injection level (filled traps)	
The longest lifetime of electrons	• ~2.5•10^{-7} s
Diffusion length L_n	L_n ~ 70 µm



Surface recombination velocity versus doping density
(Aspnes [1983]).
Different experimental points correspond to different surface treatment methods.

Radiative recombination coefficient *(Varshni[1967])*

90 K	$1.8 \cdot 10^{-8} cm^3/s$
185 K	$1.9 \cdot 10^{-9} cm^3/s$
300 K	$7.2 \cdot 10^{-10} cm^3/s$

Auger coefficient

300 K	$\sim 10^{-30} cm^6/s$
500 K	$\sim 10^{-29} cm^6/s$

GaAs - Gallium Arsenide

Optical properties

Infrared refractive index	3.3
Radiative recombination coefficient	$7\cdot10^{-10}$ cm^3/s

Infrared refractive index

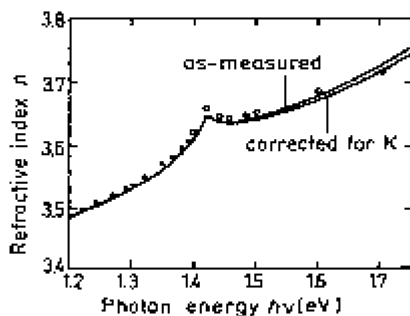
$n = k^{1/2} = 3.255\cdot(1 + 4.5\cdot10^{-5}T)$
for 300 K n= 3.299

Long-wave *TO* phonon energy

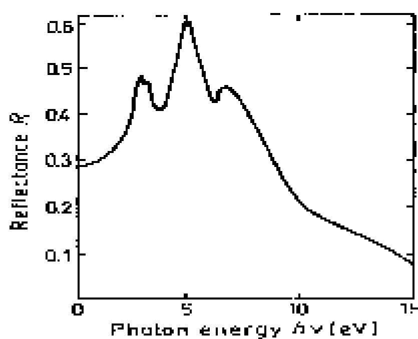
$h\cdot_{TO} = 33.81\cdot(1 - 5.5\cdot10^{-5} T)$ (meV)
for 300 K $h\cdot_{TO}$ = 33.2 meV

Long-wave *LO* phonon energy

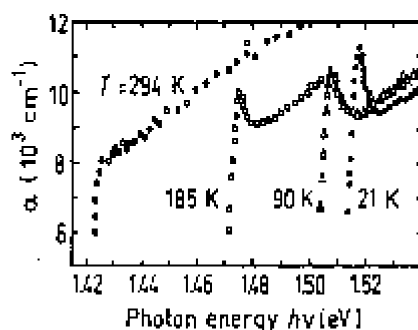
$h\cdot_{LO} = 36.57\cdot(1 - 4\cdot10^{-5} T)$ (meV)
for 300 K $h\cdot_{LO}$ = 36.1 meV



Refractive index *n* versus photon energy for a high-purity GaAs.(n_o~$5\cdot10^{13}$ 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]).

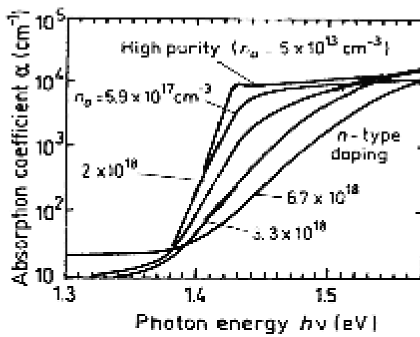


Normal incidence reflectivity versus photon energy.
(Phillip and Ehrenreich [1963]).

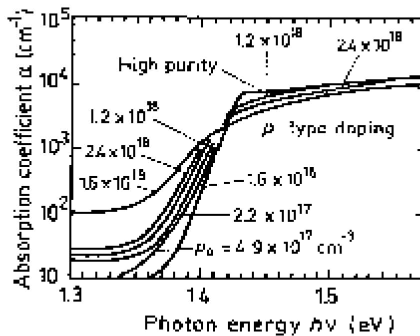


Intrinsic absorption coefficient near the intrinsic absorption edge for different temperatures.
(Sturge [1962]).

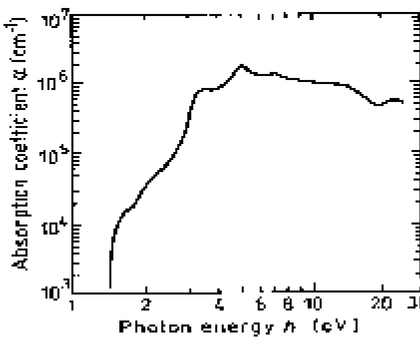
A ground state Rydberg energy R_{X1}= 4.2 meV



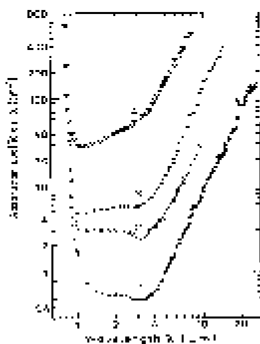
Intrinsic absorption edge at 297 K at different doping levels. *n*-type doping
(Casey et al. [1975]).



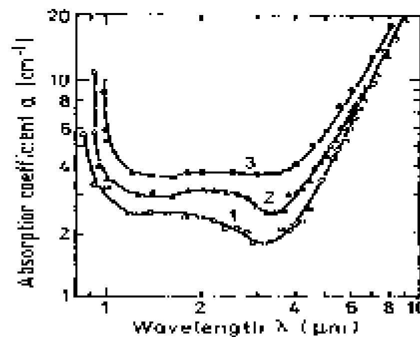
Intrinsic absorption edge at 297 K at different doping levels. *p*-type doping
(Casey et al. [1975]).



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



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

At 300 K

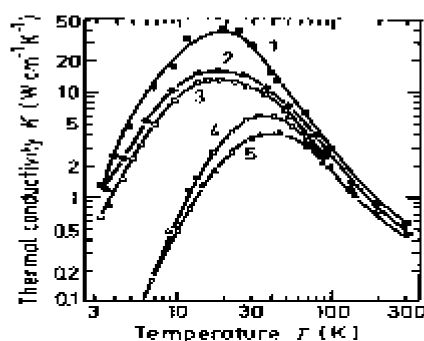
For •~2 µm • $=6 \cdot 10^{-18} n_o$ (cm^{-1}) (n_o - in cm^{-1})
For • > 4µm and $10^{17} < n_o < 10^{18} cm^{-3}$• • $7.5 \cdot 10^{-20} n_o$• •^{3} (cm^{-1}) (n_o - in cm^{-3}, • - µm)

mytrix

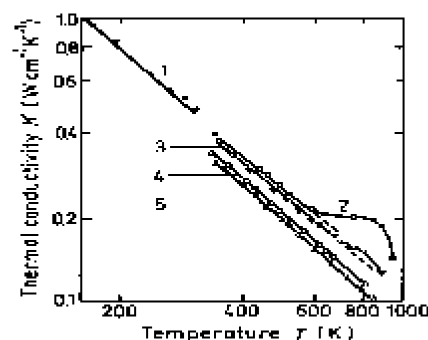
GaAs - Gallium Arsenide

Thermal properties

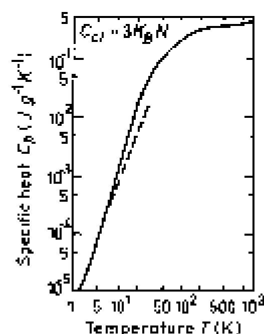
Bulk modulus	$7.53 \bullet 10^{11}$ dyn cm^{-2}
Melting point	1240 °C
Specific heat	0.33 J g^{-1}°C^{-1}
Thermal conductivity	0.55 W cm^{-1} °C^{-1}
Thermal diffusivity	0.31cm^{2}s^{-1}
Thermal expansion, linear	$5.73 \bullet 10^{-6}$ °C^{-1}



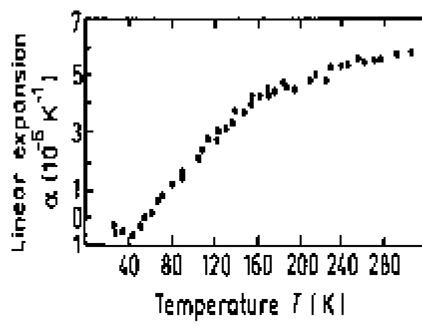
Temperature dependence of thermal conductivity
n-type sample, n_o (cm^{-3}): **1**. 10^{16}; **2**. $1.4 \bullet 10^{16}$; **3**. 10^{18};
p-type sample, p_o (cm^{-3}): **4**. $3 \bullet 10^{18}$; **5**. $1.2 \bullet 10^{19}$.
(Carlson et al [1965]).



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



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



Temperature dependence of linear expansion coefficient • *(Novikova[1961])*.

Melting point	T_m=1513 K
For 0 < P < 45 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

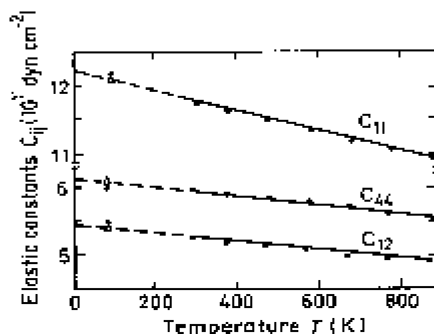
Basic Parameter
Elastic constants
Acoustic Wave Speeds
Phonon frequencies

Basic Parameter

Bulk modulus	$7.53 \cdot 10^{11}$ 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 C m^{-2}

Elastic constants 300 K.

$C_{11}=11.90 \cdot 10^{11}$ dyn/cm^2
$C_{12}=5.34 \cdot 10^{11}$ dyn/cm^2
$C_{44}=5.96 \cdot 10^{11}$ dyn/cm^2



Temperature dependences of elastic constants.
For $0<T<T_m$=1513K (in units of 10^{11} dyn cm^{-2})
C_{11}= 12.17 - 1.44•10^{-3}T
C_{12}= 5.46 - 0.64•10^{-3}T
C_{44}= 6.16 - 0.70•10^{-3}T
(Burenkov et al. [1973])

For T = 300 K

Bulk modulus (compressibility^{-1})	B_s= 7.53•10^{11}dyn/cm^2
Shear modulus	C'= 3.285•10^{11}dyn/cm^2
[100] Young's modulus	Y_o= 8.59•10^{11}dyn/cm^2
[100] Poisson ratio	$\bullet_o$ = 0.31

Acoustic Wave Speeds

Wave	Wave	Expression for wave speed	Wave speed

propagation Direction	character		(in units of 10^5 cm/s)
[100]	V_L	$(C_{11}/\bullet)^{1/2}$	4.73
	V_T	$(C_{44}/\bullet)^{1/2}$	3.35
[110]	V_l	$[(C_{11}+C_{12}+2C_{44})/2\bullet]^{1/2}$	5.24
	$V_{t\Vert}$	$V_{t\Vert}=V_T=(C_{44}/\bullet)^{1/2}$	3.35
	$V_{t\perp}$	$[(C_{11}-C_{12})/2\bullet]^{1/2}$	2.48
[111]	V_l'	$[(C_{11}+2C_{12}+4C_{44})/3\bullet]^{1/2}$	5.4
	V_t'	$[(C_{11}-C_{12}+C_{44})/3\bullet]^{1/2}$	2.8

Phonon frequencies

(in units of 10^{12} Hz) *(Waugh and Dolling [1963])*

- TO(•) 8.02 • LO (X) 7.22
- LO(•) 8.55 • TA(L) 1.86
- TA(X) 2.36 • LA(L) 6.26
- LA(X) 6.80 • TO(L) 7.84
- TO(X) 7.56 • LO(L) 7.15

GaAs - Gallium Arsenide

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