LANDOLT-BÖRNSTEIN

Numerical Data and Functional Relationships in Science and Technology

Zahlenwerte und Funktionen aus Naturwissenschaften und Technik

Neue Serie

Group III: Crystal and Solid State Physics

Volume 17

Semiconductors

Editors: O. Madelung · M. Schulz · H. Weiss†

Subvolume f

Physics of Non-Tetrahedrally
Bonded Binary Compounds II

Edited by O. Madelung

Springer-Verlag Berlin · Heidelberg · New York · Tokyo 1983

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R. Clasen · G. Harbeke · A. Krost · F. Lévy · O. Madelung
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Gesamtherausgabe: K.-H. Hellwege · O. Madelung

Gruppe III: Kristall- und Festkörperphysik

Band 17

Halbleiter

Herausgeber: O. Madelung · M. Schulz · H. Weiss †

Teilband f

Physik der nicht-tetraedrisch gebundenen Verbindungen II

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Springer-Verlag Berlin · Heidelberg · New York · Tokyo 1983

CIP-Kurztitelaufnahme der Deutschen Bibliothek

Zahlenwerte und Funktionen aus Naturwissenschaften und Technik/Landolt-Börnstein. - Berlin; Heidelberg; New York; Tokyo: Springer Parallelt.: Numerical data and functional relationships in science and technology. - Teilw. mit d. Erscheinungsorten: Berlin, Heidelberg, New York

NE: Landolt, Hans [Begr.]; PT Landolt-Börnstein, ... N.S. Gesamthrsg.: K.-H. Hellwege. Gruppe 3, Kristall- und Festkörperphysik. Bd. 17. Halbleiter/Hrsg.: O. Madelung ... Teilbd. f. Physik der nicht-tetraedrisch gebundenen Verbindungen II/R. Clasen ... Hrsg. von O. Madelung. - 1983.

ISBN 3-540-12160-9 (Berlin, Heidelberg, New York, Tokyo)
ISBN 0-387-12160-9 (New York, Heidelberg, Berlin, Tokyo)

NE: Hellwege, Karl-Heinz [Hrsg.]; Madelung, Otfried [Hrsg.]; Clasen, R. [Mitverf.]

Printed in Germany

Typesetting, printing and bookbinding: Universitätsdruckerei H. Stürtz AG Würzburg

2163/3020 - 543210

Organization of the sections in the chapters on "Physical data of semiconductors"

The data on the physical properties of semiconductors are generally arranged in subsections of the order given below. Since there is some arbitrariness in the assignment of a property to the six subsections physically related properties may appear in different subsections in a few cases.

1. Electronic properties

Information and data about electronic and excitonic energy states as well as electron and hole parameters:

band structure, density of states,
band gaps, exciton data, intraband and interband transition energies, core level transition energies,
effective masses, g-factors, other band parameters, deformation potentials

2. Impurity and defect states

Basic data on shallow and deep states, bound excitons and local modes (data on diffusion and distribution coefficients and on solubilities are presented in subvolumes 17c and d):

shallow impurities, bound excitons, local modes, deep states

3. Lattice properties

Static and dynamic properties of the lattice (for structure, space group, phase transitions, chemical bond, see the 0-section of the respective chapter; for static dielectric constant, see subsection 5; for density and melting point, see subsection 6):

lattice parameter, thermal expansion,
phonon dispersion relations, phonon frequencies, sound velocities,
elastic and other moduli, Grüneisen parameter, effective charges etc.

4. Transport properties

Electronic transport parameters (for thermal conductivity, see subsection 6; for hot carrier effects and electron-hole drops, see special chapter in subvolume 17i):

conductivity, carrier concentrations, mobilities, galvanomagnetic effects,
piezo- and elastoresistance, elastostriction, piezoelectricity etc.,
other transport parameters such as Seebeck coefficient, Nernst coefficient etc.

5. Optical properties

Optical spectra, optical constants, parameters obtained from optical measurements if not already listed in subsections 1 and 2:

optical constants, absorption, reflection,
dielectric constants (including static dielectric constant),
optical spectra (see also figures to subsection 1), other optical coefficients,
Raman and Brillouin scattering, electron energy loss,
Schottky barrier heights (see also special chapter in subvolume 17i)

6. Further properties

Thermal, magnetic, thermodynamic properties, data more completely presented in other Landolt-Börnstein volumes:

thermal conductivity, magnetic susceptibility,
melting point, density, hardness,
thermodynamical data

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Vorwort

In den ersten beiden Teilbänden 17a und 17b des Bandes III/17 „Halbleiter" wurden die physikalischen Eigenschaften der tetraedrisch gebundenen Halbleiter behandelt. Die beiden folgenden Teilbände sind der Halbleiter-Technologie gewidmet: Teilband 17c dem Si, Ge und SiC, Teilband 17d den III–V- und II–VI-Verbindungen sowie einigen anderen technologisch wichtigen Halbleitern.

Die anschließenden Teilbände informieren über die physikalischen Eigenschaften weiterer Halbleitergruppen. Im Teilband 17e beginnt diese Darstellung mit den nicht-tetraedrisch gebundenen Elementen und binären Verbindungen der ersten beiden Gruppen des periodischen Systems. Der vorliegende Teilband 17f bringt die Verbindungen der III., IV. und V. Gruppe.

Auch hier wird wieder eine Fülle von Material vorgelegt. Wenn auch die Autoren die Aufgabe hatten, die Literatur kritisch zu werten, so wird doch der Leser an vielen Stellen unterschiedliche Daten für einen gesuchten Halbleiterparameter nebeneinander aufgeführt finden. Dies ist unvermeidlich. Eine kritische Wertung durch den Autor kann nur bis zu einem gewissen Grad objektiv sein. Das Auswählen der zuverlässigsten Daten ist leicht, die Entscheidung zwischen den verbleibenden, meist an verschiedenen Proben und mit verschiedenen Methoden bestimmten Daten aber oft unmöglich. In solchen Fällen erschien es uns besser, konkurrierende Daten nebeneinander aufzuführen als ein subjektives Urteil zu fällen. Dem Leser wird dann nicht immer erspart bleiben, auf die Originalliteratur zurückzugreifen – es wird ihm aber auch nicht durch Angabe nur eines Wertes vorgespiegelt, dieser Wert sei der einzig zuverlässige.

Viele haben geholfen, diesen Band herzustellen. Allen sei herzlich gedankt, vor allem den Autoren für ihre gründliche und kritische Arbeit, der Landolt-Börnstein Redaktion, insbesondere Herrn Dr. W. Polzin, Frau B. Foltin und Frau R. Lettmann für ihre engagierte Mitarbeit und dem Springer-Verlag für die verständnisvolle Zusammenarbeit bei der Fertigstellung.

Marburg, im August 1983 **Der Herausgeber**

Preface

In the first two subvolumes 17a and 17b of volume III/17 "Semiconductors" the physical properties of the tetrahedrally bonded semiconductors have been discussed. The following two subvolumes present technological data: subvolume 17c covers Si, Ge and SiC, subvolume 17d comprises the III–V and II–VI compounds as well as some other technologically important semiconductors.

In the subsequent volumes the presentation of physical data of further groups of semiconductors will be continued. Subvolume 17e begins the presentation with the non-tetrahedrally bonded semiconducting elements and the binary compounds of elements of the first two groups of the Periodic Table. The present subvolume 17f continues with the presentation of the compounds of the third, fourth and fifth group.

Here again a vast amount of information is presented. Although the authors examined the literature critically, the reader will often find varying data from different sources for a given semiconductor parameter. This is unavoidable, as a critical valuation by the authors can be objective to a certain degree only. It is easy to select the most reliable data. A decision between the remaining ones, mostly measured on different samples and with different methods, often is impossible. In these cases we preferred to publish differing values side by side than to give a biased judgement. We cannot save the reader in such cases to refer to the literature – better than by giving a single figure only to pretend to him that this value is the only reliable one.

Many have helped to produce this subvolume. The editor wishes to thank them, especially the authors for their thorough and critical work, the editorial staff, mainly Dr. W. Polzin, Mrs. B. Foltin and Mrs. R. Lettmann for their engaged cooperation and Springer Verlag for their understanding help in the final preparation.

Marburg, August 1983

The Editor

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(edited by O. MADELUNG)

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A. Introduction

1. List of symbols

In the following list frequently used symbols are specified. The references in the last column refer to the introductory part A in subvolume 17a (cited as 17a/followed by the number for the respective section) or to that section of part B of this subvolume where the quantity is defined or introduced the first time (cited as 17f/followed by the number of the respective section). The units listed in the second-last column are the most frequently used units. In the tables of part B data are generally given in the units of the original paper. To facilitate a conversion from CGS units to SI units or vice versa conversion tables are presented in section 3 below.

Symbol	Property	Unit	Introduced in section
a, b, c	lattice parameters	Å	
A	atomic weight	–	
b	electron-hole mobility ratio (μ_n/μ_p)	–	
$B(B_S, B_T)$	bulk modulus (adiabatic, isothermal)	bar	17a/2.1.2, eq.(A.17)
B	Nernst coefficient	$cm^2 K^{-1} s^{-1}$	17a/2.2.1
$\mathbf{B}$	magnetic induction	T, G	
c	concentration	cm^{-3}	
c_{lm}	elastic moduli (stiffnesses)	$dyn\,cm^{-2}$	17a/2.1.2, eq.(A.19)
c_{ikl}	third order elastic moduli	$dyn\,cm^{-2}$	17a/2.1.2
C	capacity	F	
C_p, C_v	heat capacities	$J\,mol^{-1} K^{-1}$	
d	distance, bond length	cm, Å	
d	density	$g\,cm^{-3}$	
d	thickness of a sample	cm	
d_{opt}	optical density (log I_o/I)	–	
d	non-linear dielectric susceptibility	$cm\,V^{-1}$	17a/2.2.2
$D_{n(p)}$	diffusion coefficient for electrons (holes)	$cm^2 s^{-1}$	
e	elementary charge	C	
$e^*_{(T)}$	(transverse) effective ionic charge	e	17a/2.1.2
$\mathbf{e}$	polarization vector	–	
e_{ik}	strain tensor (6 × 6) (in literature frequently labeled S_{ij})	–	17a/2.1.2
e_{ik}	piezoelectric stress coefficients	$C\,cm^{-2}$	17a/2.2.1, eq.(A.33)
$\mathbf{e}$	strain vector (6-component)	–	17a/2.1.2
$\mathbf{E}$	electric field strength	$V\,cm^{-1}$	
E	energy	eV	
$E_{0,1,2...}$	energies of critical points in optical spectra	eV	17a/2.1.1
$E(\Gamma_6)$...	energy of band edge of type Γ_6...	eV	17a/2.4.1
$E_{[hkl]}$	Young's modulus (measured in [hkl] direktion)	$dyn\,cm^{-2}$	17a/2.4.2, eq.(A.100)
$E_{a(d)}$	energy of acceptor (donor) state measured from the respective band edge	eV	17a/2.3.1
E_A	activation energy (of conductivity or other temperature or pressure dependent properties)	eV	
E_b	binding energy (mostly exciton)	eV	17a/2.1.1
E_{bx}	binding energy of an exciton to an impurity, localization energy of bound exciton	eV	
$E_{c(v)}$	band edge of conduction (valence) band	eV	17a/2.1.1, eq.(A.1)
E_F	Fermi energy	eV	
E_g	energy gap	eV	17a/2.1.1
$E_{g,th}$	energy gap extrapolated to 0 K (thermal energy gap)	eV	17a/2.1.1
$E_{g,dir(ind)}$	direct (indirect) energy gap	eV	17a/2.2.1
E_{gx}	excitonic energy gap ($E_g - E_b$)	eV	17a/2.1.1
E_x	exciton energy level	eV	17f/9.11
E_p	characteristic energy in Kane's theory ($=(2m_o/\hbar^2)P^2$)	eV	17a/2.4.1, eq.(A.79)
$E_{pl(pc)}, E_{peak}$	photoluminescence (photoconductivity) peak energy	eV	

Symbol	Property	Unit	Introduced in section
E_{thr}	photoelectric threshold energy	eV	17f/9.7
$E_{cryst.\,bind.}$	crystal binding energy	eV	17f/9.10
E_t, E_{trap}	energy of trap level	eV	
f	frequency	Hz	
f_i	ionicity	–	
$g(E)$	density of states	$cm^{-3}\,eV^{-1}$	17a/2.1.1, eq. (A.8)
$g_{c(v)}$	density of conduction (valence) band states	$cm^{-3}\,eV^{-1}$	
g^*, g_{eff}	effective *g*-factor	–	17a/2.1.1, eq. (A.15)
g_c, g_n	*g*-factor of conduction electrons	–	
g_v, g_p	*g*-factor of holes (valence band)	–	
$g_{\parallel}$, g_l	longitudinal *g*-factor	–	
$g_{\perp}$, g_t	transverse *g*-factor	–	
$G_{[hkl]}$	torsional (shear) modulus in [hkl] direction	$dyn\,cm^{-2}$	
ΔG_f^0	standard free energy of formation	$J\,mol^{-1}$	
$H_{(B,K,V)}$	hardness (Brinell, Knoop, Vickers)	$kg\,mm^{-2}$	
H	magnetic field strength	$A\,cm^{-1}$, Oe	
ΔH_d	heat of dissociation	$J\,mol^{-1}$	
ΔH_f^0	standard heat of formation	$J\,mol^{-1}$	
ΔH_m	heat of fusion	$J\,mol^{-1}$	
ΔH_v	heat of vaporization	$J\,mol^{-1}$	
ΔH_c	heat of conversion	$J\,mol^{-1}$	
ΔH_s	heat of sublimation	$J\,mol^{-1}$	
ΔH_{tr}	(phase) transformation heat	$J\,mol^{-1}$	
i	current density	$A\,cm^{-2}$	
$I_{(lum,\,R)}$	intensity (of luminescence, Raman intensity)	$cm^{-2}\,s^{-1}$	
I_{ph}	photocurrent	A	
k	extinction coefficient (absorption index)		17a/2.2.2, eq. (A.41)
k	Boltzmann constant	$J\,K^{-1}$	
$\boldsymbol{k}$	wave vector of electrons	cm^{-1}	17a/2.1.1
$k_{0(1)}$	intra (inter) layer force constant	$dyn\,cm^{-1}$	17f/9.11
K	absorption coefficient	cm^{-1}	17a/2.2.2, eq. (A.38)
L	carrier diffusion length	cm	17f/9.7
L	symmetry point in the Brillouin zone	–	17a/2.4, Fig. A.4
$\Delta l/l$	linear thermal elongation	–	
m_0	electron mass	g	
m^*	effective mass	m_0	17a/2.1.1
m^{**}	polaronic mass	m_0	17a/2.1.1, eq. (A.10)
$m_{n(p)}$	effective mass of electrons (holes)	m_0	17a/2.1.1, eq. (A.1)
$m_{p,\,h(l)}$	effective mass of heavy (light) holes	m_0	
$m_{\parallel}$, m_l	longitudinal effective mass	m_0	17a/2.4.1, eq. (A.75)
$m_{\perp}$, m_t	transverse effective mass	m_0	17a/2.4.1, eq. (A.75)
$m(\Gamma_6)$...	effective mass at band edge of type Γ_6...	m_0	17a/2.4.1
m_{ds}	density of states mass	m_0	17a/2.1.1, eq. (A.9)
m_s	effective spin mass	m_0	17f/9.12
m_{ω_p}	effective plasma frequency mass	m_0	17a/2.2.2, eq. (A.50)
m_{ω_c}	effective cyclotron resonance mass	m_0	17a/2.2.2, eq. (A.57)
m_{ik}	elastoresistance coefficient	–	17a/2.2.1, eq. (A.32)
M	molecular weight	–	
n	(real) refractive index	–	17a/2.2.2, eq. (A.37)
n_o	refractive index for ordinary ray	–	
n_e	refractive index for extraordinary ray	–	
$n_{a,b,c}$	refractive index in *a*, *b*, *c* direction	–	
Δn	birefringence ($n_{\parallel} - n_{\perp}$)	–	
n	electron concentration (also carrier concentration in general)	cm^{-3}	
n_i	intrinsic carrier concentration	cm^{-3}	17a/2.1.3, eq. (A.20)
$n_{a(d)}$	acceptor (donor) concentration	cm^{-3}	

Symbol	Property	Unit	Introduced in section
n_H	carrier concentration determined by the Hall effect	cm^{-3}	17f/9.12
n_t	trap concentration	cm^{-3}	
N_{eff}, n_{eff}	effective number of electrons contributing to optical properties	–	17a/2.2.2, eq. (A.60)
N	count rate	–	
N	number of electrons	–	
p	pressure	bar	
p_{tr}	(phase) transition pressure	bar	
p	hole concentration	cm^{-3}	
$p_{l(h)}$	concentration of light (heavy) holes	cm^{-3}	
P	Peltier coefficient	V	17f/9.10
P	Kane's matrix element (see E_p)	eV cm	
P_s	spontaneous polarization	$C m^{-2}$	17f/9.12
q	wave vector of phonons	cm^{-1}	
r_{ex}	exciton radius	Å	
R	resistance	Ω	
R	reflectance	–	17a/2.2.2, eq. (A.42)
R	volume recombination coefficient	$cm^{-3} s^{-1}$	
R_H	Hall coefficient	$cm^3 C^{-1}$	17a/2.2.1
$R_H(\infty)$	Hall coefficient at $B \rightarrow \infty$	$cm^3 C^{-1}$	
R_0	Hall scattering factor	–	17a/2.2.1, eq. (A.26)
S	spin quantum number		
$S_{(A)}$	Seebeck coefficient, thermoelectric power (of material A)	$V K^{-1}$	17a/2.2.1, eq. (A.42)
$S(\infty)$	Seebeck coefficient at $B \rightarrow \infty$	$V K^{-1}$	
s_{ml}	elastic compliances	$cm^2 dyn^{-1}$	17a/2.1.2, eq. (A.19)
S^0	standard entropy (at 298.15 K)	$J mol^{-1} K^{-1}$	
ΔS_f^0	standard entropy of formation	$J mol^{-1} K^{-1}$	
ΔS_m	entropy of fusion	$J mol^{-1} K^{-1}$	
t	time	s	
T	temperature	K, °C	
T_b	boiling temperature	K	
T_m	melting temperature	K	
T_{tr}	transition temperature	K	
T_c	superconductor transition temperature	K	
U	voltage	V	
U_H	Hall voltage	V	
U_{ph}	photovoltage	V	
$v_{L(T)}$, $v_{l(t)}$	velocity of longitudinal (transverse) waves	$cm s^{-1}$	17a/2.1.2
v_{dr}	drift velocity	$cm s^{-1}$	
$V_{(m)}$	(molar) volume	$cm^3 (mol^{-1})$	
V	pseudopotential form factors	eV	17f/9.10
W	width of valence or conduction bands	eV	
x, y, z	fractional coordinates of atoms in unit cell	–	
X	symmetriy point in the Brillouin zone	–	17a/2.4.1, Fig. A.4
X_{ik}	stress tensor (6 × 6) (in the literature often labeled T_{ij})	bar	17a/2.1.2
X_k	stress vector (6-component)	bar	17a/2.1.2
$X_{[hkl]}$	stress in [hkl] direction	bar	
Y	photoyield		17f/9.12
Z	thermoelectric figure of merit ($S^2\sigma/\kappa$)	K^{-1}	17f/9.12
Z	coordination number		
$\alpha(\alpha_F)$	Fröhlich polaron coupling constant	–	17a/2.1.1, eq. (A.11)
α	linear thermal expansion coefficient	K^{-1}	17a/2.1.2, eq. (A.17)
$\alpha_{a,b,c}$	linear thermal expansion coefficient in *a, b, c* direction	K^{-1}	
$\beta(\beta_2)$	two-photon absorption coefficient	$cm W^{-1}$	17a/2.2.2
β	volume thermal expansion coefficient (3 α)	K^{-1}	17a/2.1.2, eq. (A.17)

Symbol	Property	Unit	Introduced in section
γ	Grüneisen constant	–	17a/2.1.2, eq. (A.18)
γ_{jq}	mode Grüneisen parameter	–	17a/2.1.2, eq. (A.18)
$\gamma_{i(e,h)}$	spin splitting factor (in conduction or valence band)	–	17f/9.12
$\mathit{\Gamma}$	linewidth (e.g. of phonon wavenumber)	cm^{-1}	
Γ	center of Brillouin zone	–	17a/2.4.1, Fig. A.4
Δ	[100]-axis in ***k***-space		17a/2.4.1, Fig. A.4
$\mathit{\Delta}_{(0)}$, $\mathit{\Delta}_{so}$	spin-orbit splitting energy at Γ	eV	
$\mathit{\Delta}$	quadrupole splitting	$cm\,s^{-1}$	17f/9.12
$\mathit{\Delta}_{ex}$	excitonic shift	eV	17f/9.11
tan δ	dielectric loss tangent ($=\varepsilon_2/\varepsilon_1$)	–	
ε_0	permittivity of free space	$F\,cm^{-1}$	
ε	dielectric constant		
$\varepsilon_{1(2)}$	real (imaginary) part of dielectric constant		17a/2.2.2, eq. (A.39)
$\varepsilon(0)$	low frequency dielectric constant		17a/2.2.2, eq. (A.53)
$\varepsilon(\infty)$	high frequency dielectric constant	–	17a/2.2.2, eq. (A.53)
ε_{eff}	effective dielectric constant	–	17f/9.12
ζ	reduced wave vector coordinate	–	
η	asymmetry parameter	–	17f/9.12
Θ_{pe}	paraelectric Curie temperature	K	17f/9.8
Θ_D	Debye temperature	K	17a/2.1.2
$\kappa(\kappa_{L,el})$	thermal conductivity (lattice, electronic contribution)	$W\,cm^{-1}\,K^{-1}$	17a/2.2.1, eq. (A.36)
κ	compressibility (=1/bulk modulus)	$cm^2\,dyn^{-1}$	
$\kappa_{v(l)}$	volume (linear) compressibility	$cm^2\,dyn^{-1}$	
λ	wavelength	cm	
$\mu(\mu_{ex})$	reduced mass (of exciton)	m_0	
$\mu_{n(p)}$	electron (hole) mobility	$cm^2\,V^{-1}\,s^{-1}$	17a/2.2.1, eq. (A.25)
μ_{dr}	drift mobility	$cm^2\,V^{-1}\,s^{-1}$	17a/2.2.1
μ_H	Hall mobility	$cm^2\,V^{-1}\,s^{-1}$	17a/2.2.1, eq. (A.27)
ν	Poisson's ratio	–	17a/2.4.2, eq. (A.100)
ν	frequency	s^{-1}	
$\bar{\nu}$	wavenumber	cm^{-1}	
$\bar{\nu}_R$	Raman wavenumber	cm^{-1}	
$\delta\bar{\nu}$, $\mathit{\Delta}$	Davydov splitting	cm^{-1}	17f/9.7
Ξ_d	diagonal component of deformation potential	eV	17a/2.1.1, eq. (A.13)
Ξ_u	deformation potential for pure shear	eV	17a/2.1.1, eq. (A.13)
Ξ_{VC}	interband deformation potential	eV	17f/9.10
π_{ik}	piezoresistance coefficients	$cm^2\,dyn^{-1}$	17a/2.1.1, eq. (A.32)
ϱ	resistivity	Ωcm	
$\varrho_{ik}^{(2)}$	magnetoresistance tensor (6×6)	G^{-2}, T^{-2}	17a/2.2.1, eq. (A.30)
ϱ_{ijkl}, $\varrho_{ijkl}^{(2)}$	fourth-rank tensor components in a power expansion of the resistivity in a magnetic field	$\Omega cm\,G^{-2}$	17a/2.2.1, eq. (A.29)
$\Delta\varrho/\varrho_0$	magnetoresistance		17a/2.2.1, eq. (A.30)
$\sigma_{(i)}$	(intrinsic) conductivity	$\Omega^{-1}\,cm^{-1}$	17a/2.2.1
σ_{ij}	conductivity tensor components	$\Omega^{-1}\,cm^{-1}$	17a/2.2.1, eq. (A.24)
σ_{ph}	photoconductivity	$\Omega^{-1}\,cm^{-1}$	
σ_d	dark conductivity	$\Omega^{-1}\,cm^{-1}$	
$\tau_{(n,p)}$	relaxation time, decay time, rise time, lifetime of carriers	s	
φ_b	Schottky barrier height	eV	
Φ	work function	eV	
χ_v	magnetic volume susceptibility	–	
χ_g, χ	magnetic mass susceptibility	$cm^3\,g^{-1}$	
χ_m	magnetic molar susceptibility	$cm^3\,mol^{-1}$	
ω	circular frequency	$rad\,s^{-1}$	
$\hbar\omega$	photon energy	eV	
ω_c	cyclotron resonance frequency	s^{-1}	17a/2.2.2, eq. (A.56)
ω_p	plasma resonance frequency	s^{-1}	17a/2.2.2, eq. (A.49)