Appendix K

Electronic Properties of Si, Ge, and a Few Binary, Ternary, and Quaternary Compounds

Table K.1 Important Physical Properties[a,b]

Physical Properties	Si	Ge	GaAs	InAs	InP	GaP
Band gap E_g (eV)	(Indirect)	(Indirect)	(Direct)	(Direct)	(Direct)	(Indirect)
0 K	1.170	0.744	1.519	0.42	1.424	2.350
300 K	1.124	0.664	1.424	0.354	1.344	2.272
Dielectric constant ε_s (F/m)	$11.9\varepsilon_0$	$16.2\varepsilon_0$	$13.1\varepsilon_0$	$15.15\varepsilon_0$	$12.56\varepsilon_0$	$11.11\varepsilon_0$
Effective mass (m^*/m_0)						
Electrons						
Longitudinal m_l^*/m_0	0.9163	1.59	0.0665	0.023	0.077	0.254
Transverse m_t^*/m_0	0.1905	0.0823				4.8
Holes						
Heavy, m_{hh}^*/m_0	0.537	0.284	0.50	0.40	0.60	0.67
Light, m_{lh}^*/m_0	0.153	0.043	0.087	0.026	0.12	0.17
Intrinsic carrier concentration n_i (cm^{-3}) at 300 K	1.02×10^{10}	2.33×10^{13}	2.1×10^6	1.3×10^{15}	1.2×10^8	
Lattice constant (Å)	5.43102	5.6579	5.6533	6.0584	5.8688	5.4505
Minority carrier lifetime(s) at 300 K	2.5×10^{-3}	10^{-3}	$\sim 10^{-8}$			
Mobility (cm^2/ Vs) at 300 K						
Electron	1450	3900	9200	$2 \sim 3.3 \times 10^4$	5370	160
Hole	370	1800	400	$100 \sim 450$	150	135

[a]O. Madelung, Ed., *Semiconductors, Group IV Elements and III–V Compounds*, in R. Poerschke, Ed., *Data in Science and Technology*, Springer, Berlin, 1991.

[b]S. Sze, *Physics of Semiconductor Devices*, Wiley, New York, 1982.

Table K.2 Important Band Structure Parameters[a–f] for GaAs, AlAs, InAs, InP, and GaP

	Materials				
	GaAs	AlAs	InAs	InP	GaP
Parameters					
a_0 (Å)	5.6533	5.6600	6.0584	5.8688	5.4505
E_g (eV)					
0 K	1.519	3.13	0.42	1.424	2.90
		2.229*			2.35*
300 K	1.424	3.03	0.354	1.344	2.78
		2.168*			2.27*
Δ (eV)	0.34	0.28	0.38	0.11	0.08
$E_{v,av}$ (eV)	−6.92	−7.49	−6.67	−7.04	−7.40
Optical matrix parameter E_p (eV)	25.7 (25.0)[f]	21.1	22.2	20.7 (16.7)[f]	22.2
Deformation potentials (eV)					
a_c (eV)	−7.17	−5.64	−5.08	−5.04	−7.14
a_v (eV)	1.16	2.47	1.00	1.27	1.70
$a = a_c - a_v$ (eV)	−8.33	−8.11	−6.08	−6.31	−8.83
b (eV)	−1.7	−1.5	−1.8	−1.7	−1.8
d (eV)	−4.55	−3.4	−3.6	−5.6	−4.5
C_{11} (10^{11} dyne/cm^2)	11.879	12.5	8.329	10.11	14.05
C_{12} (10^{11} dyne/cm^2)	5.376	5.34	4.526	5.61	6.203
C_{44} (10^{11} dyne/cm^2)	5.94	5.42	3.96	4.56	7.033
Effective masses					
m_e^*/m_0	0.067	0.15	0.023	0.077	0.25
m_{hh}^*/m_0	0.50	0.79	0.40	0.60	0.67
m_{lh}^*/m_0	0.087	0.15	0.026	0.12	0.17
$m_{hh,z}/m_0 = \dfrac{1}{\gamma_1 - 2\gamma_2}$	0.333	0.478	0.263	0.606	0.326
$m_{lh,z}/m_0 = \dfrac{1}{\gamma_1 + 2\gamma_2}$	0.094	0.208	0.027	0.121	0.199
γ_1	6.8 (6.85)	3.45	20.4	4.95	4.05
γ_2	1.9 (2.1)	0.68	8.3	1.65	0.49
γ_3	2.73 (2.9)	1.29	9.1	2.35	1.25

* Indirect band gap, $E_g(X)$ value.

[a] C. G. Van de Walle, "Band lineups and deformation potentials in the model-solid theory," *Phys. Rev. B* **39**, 1871–1883 (1989).

[b] P. Lawaetz, "Valence-band parameters in cubic semiconductors," *Phys. Rev. B.* **4**, 3460–3467 (1971).

[c] S. Adachi, "GaAs, AlAs, and $Ga_{1-x}Al_xAs$: Material parameters for use in research and device applications," *J. Appl. Phys.* **58**, R1–R28 (1985).

[d] O. Madelung, Ed., *Semiconductors, Group IV Elements and III–V Compounds*, in R. Poerschke, Ed., *Data in Science and Technology*, Springer, Berlin, 1991.

[e] K. H. Hellwege, Ed., *Landolt–Börnstein Numerical Data and Functional Relationships in Science and Technology*, New Series, Group III **17a**, springer, Berlin, 1982; Groups III–V **22a**, Springer, Berlin, 1986.

[f] L. G. Shantharama, A. R. Adams, C. N. Ahmad and R. J. Nicholas, "The **k** · **p** interaction in InP and GaAs from the band-gap dependence of the effective mass," *J. Phys. C: Solid State Phys.* **17**, 4429–4442 (1984).

Table K.3 Important Band Structure Parameters for $Al_xGa_{1-x}As$, $In_{1-x}Ga_xAs$, $Al_xIn_{1-x}As$, and $Ga_xIn_{1-x}As_yP_{1-y}$ Compounds[a-e]

General Interpolation Formula for Ternary Compound Parameters P: $P(A_xB_{1-x}C) = xP(AC) + (1-x)P(BC)$			Ref.
$Al_xGa_{1-x}As$			
$E_g(\Gamma) = 1.424 + 1.247x$ (eV)	at 300 K	for $x < 0.4$	a
$1.519 + 1.447x - 0.15x^2$ (eV)	at 0 K	for $x < 0.4$	b
$m_e^*/m_0 = 0.067 + 0.083x$			a
$m_{hh}^*/m_0 = 0.50 + 0.29x$ (Density of states mass)			interpol.
$m_{lh}^*/m_0 = 0.087 + 0.063x$			f
$m_{so}^*/m_0 = 0.15 + 0.09x$			a
$\gamma_i(x) = x\gamma_i(\text{AlAs}) + (1-x)\gamma_i(\text{GaAs})$	(for calculating transport masses)		interpol.
$In_{1-x}Ga_xAs$			
$E_g(\Gamma) = 0.36 + 0.505x + 0.555x^2$ (eV)	at 300 K		c
$0.324 + 0.7x + 0.4x^2$ (eV)	at 300 K		a
$0.422 + 0.7x + 0.4x^2$ (eV)	at 2 K		
$m_e^*/m_0 = 0.025(1-x) + 0.071x - 0.0163x(1-x)$			
or			
$1/m_e^*(x) = x/m_e^*(\text{GaAs}) + (1-x)/m_e^*(\text{InAs})$			
$In_{0.53}Ga_{0.47}As$			
$E_g(\Gamma) = 0.813$ (eV)	at 2 K		a
0.75 (eV)	at 300 K		
$m_e^*/m_0 = 0.041$			
$m_{hh}^*/m_0 = 0.465$	//[001]		
0.56	//[110]		
$m_{lh}^*/m_0 = 0.0503$			
$Al_xIn_{1-x}As$			
$E_g(\Gamma) = 0.36 + 2.35x + 0.24x^2$ (eV)	at 300 K		a
$0.357 + 2.29x$ (eV)	at 300 K	for $0.44 < x < 0.54$	
$0.447 + 2.22x$ (eV)	at 4 K	for $0.44 < x < 0.54$	
$Al_{0.48}In_{0.52}As$			
$E_g(\Gamma) = 1.508$ (eV)	at 4K		a
1.450 (eV)	at 300 K		
$m_e^*/m_0 = 0.075$			d
$m_{hh}^*/m_0 = 0.41$			
$m_{lh}^*/m_0 = 0.096$			

Table K.3 (*Continued*)

General Interpolation Formula for Quaternary Compound Parameters P: $P(A_xB_{1-x}C_yD_{1-y}) = xyP(AC) + (1-x)(1-y)P(BD) + (1-x)yP(BC) + x(1-y)P(AD)$	
$Ga_xIn_{1-x}As_yP_{1-y}$	
$E_g(x, y) = 1.35 + 0.668x - 1.068y + 0.758x^2 + 0.078y^2 - 0.069xy - 0.322x^2y + 0.03xy^2$ (eV) at 300 K	a
$m_e^*(x, y)/m_0 = 0.08 - 0.116x + 0.026y - 0.059xy + (0.064 - 0.02x)y^2 + (0.06 + 0.032y)x^2$	
$a(x, y) = 5.8688 - 0.4176x + 0.1896y + 0.0125xy$ (Å)	
Lattice-Matched to InP:	
$x = \dfrac{0.1894y}{(0.4184 - 0.013y)}$	a
$E_g(y) = 13.5 - 0.775y + 0.149y^2$ (eV) at 298 K	
$1.425 - 0.7668y + 0.149y^2$ (eV) at 4.2 K	
$m_e^*/m_0 = 0.080 - 0.039y$	e
$m_{hh}^*/m_0 = 0.46$	
$m_{lh}^*/m_0 = 0.12 - 0.099y + 0.030y^2$	
$m_{so}^*/m_0 = 0.21 - 0.01y - 0.05y^2$	
$In_{1-x-y}Al_xGa_yAs$	
$E_g(x, y) = 0.36 + 2.093x + 0.629y + 0.577x^2 + 0.436y^2 + 1.013xy - 2.0xy(1 - x - y)$ (eV) at 300 K	
Lattice-Matched to InP:	
$(In_{0.52}Al_{0.48})_z(In_{0.53}Ga_{0.47})_{1-z}As$	
$x = 0.48z \qquad 0.983x + y = 0.468$	
$E_g(z) = 0.76 + 0.49z + 0.20z^2$ (eV) at 300 K	
$m_e^*/m_0 = 0.0427 + 0.0328z$	

[a] K. H. Hellwege, Ed., *Landolt–Börnstein Numerical Data and Functional Relationships in Science and Technology*, New Series, Group III, **17a**, Springer, Berlin, 1982; Groups III–V **22a**, Springer, Berlin, 1986.
[b] M. El Allai, C. B. Sorensen, E. Veje,and P. Tidemand-Petersson, "Experimental determination of the GaAs and $Ga_{1-x}Al_xAs$ band-gap energy dependence on temperature and aluminum mole fraction in the direct band-gap region," *Phys. Rev. B* **48**, 4398–4404 (1993).
[c] S. Adachi, "Material parameters in $In_xGa_{1-x}As_yP_{1-y}$ and related binaries," *J. Appl. Phys.* **53**, 8775–8792 (1982).
[d] P. Bhattacharya, Ed., *Properties of Lattice-Matched and Strained Indium Gallium Arsenide*, INSPEC, Institute of Electrical Engineers, London, U.K., 1993.
[e] S. Adachi, *Physical Properties of III–V Semiconductor Compounds*, Wiley, New York, 1992.
[f] H. C. Casey, Jr., and M. B. Panish, *Heterostructure Lasers Part A: Fundamental Principles*, Academic Press, Orlando, FL, 1978.