

1 Introduction

The proper conduct of science
lies in the pursuit of Nature's puzzles,
wherever they may lead.
J.M. Bishop [1]

The historic development of semiconductor physics and technology began in the second half of the 19th century. Interesting discussions of the early history of the physics and chemistry of semiconductors can be found in treatises of G. Busch [2] and Handel [3]. The history of semiconductor industry can be followed in the text of Morris [4] and Holbrook et al. [5]. In 1947, the realization of the transistor was the impetus to a fast-paced development that created the electronics and photonics industries. Products founded on the basis of semiconductor devices such as computers (CPUs, memories), optical-storage media (lasers for CD, DVD), communication infrastructure (lasers and photodetectors for optical-fiber technology, high frequency electronics for mobile communication), displays (thin film transistors, LEDs), projection (laser diodes) and general lighting (LEDs) are commonplace. Thus, fundamental research on semiconductors and semiconductor physics and its offspring in the form of devices has contributed largely to the development of modern civilization and culture.

1.1 Timetable

In this section early important milestones in semiconductor physics and technology are listed.

1782

A. Volta – coins the phrase ‘semicoibente’ (semi-insulating) which was translated then into English as ‘semiconducting’ [6].

1821

T.J. Seebeck – discovery of semiconductor properties of PbS [7].

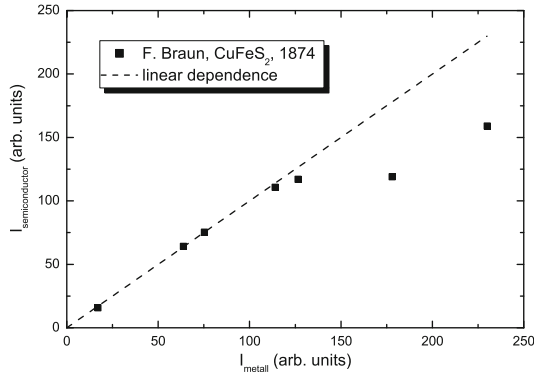


Fig. 1.1. Current through a silver–CuFeS₂–silver structure as a function of the current through the metal only, 1874. Data points are for different applied voltages. Experimental data from [12]

1833

M. Faraday – discovery of the temperature dependence of the conductivity of Ag₂S (negative dR/dT) [8].

1873

W. Smith – discovery of photoconductivity in selenium [9]. Early work on photoconductivity in Se is reviewed in [10, 11].

1874

F. Braun¹ – discovery of rectification in metal–sulfide semiconductor contacts [12], e.g. for CuFeS₂ and PbS. The current through a metal–semiconductor contact is nonlinear (as compared to that through a metal, Fig. 1.1), i.e. a deviation from Ohm’s law. Braun’s structure is similar to a MSM diode.

1876

W.G. Adams and R.E. Day – discovery of the photovoltaic effect in selenium [14].

W. Siemens – large response from selenium photoconductor [15], made by winding two thin platinum wires to the surface of a sheet of mica, and then covering the surface with a thin film of molten selenium. Resistance ratio between dark and illuminated by sunlight was larger than ten [15] and measured to 14.8 in [16].

1879

E.H. Hall – measurement of the transverse potential difference in a thin gold leaf on glass [17, 18]. Experiments were continued by his mentor H.A.

¹F. Braun made his discoveries on metal–semiconductor contacts in Leipzig while a teacher at the Thomasschule zu Leipzig [13]. He conducted his famous work on vacuum tubes later as a professor in Strasbourg, France.

Rowland [19]. A detailed account of the discovery of the Hall effect is given in [20, 21].

1883

Ch. Fritts – first solar cell, based on an gold/selenium rectifier [16]. The efficiency was below 1%.

1901

J.C. Bose – point contact detector for electromagnetic waves based on galena (PbS) [22]. At the time, the term semiconductor was not introduced yet and Bose speaks about ‘substances of a certain class (...) presenting a decreasing resistance to the passage of the electric current with an increasing impressed electromotive force’.

1906

G.W. Pickard – rectifier based on point contact (cat’s whisker) diode on silicon [23–25]. Erroneously, the rectifying effect was attributed to a thermal effect, however, the drawing of the ‘thermo-junction’ (TJ in Fig. 1.2) developed into the circuit symbol for a diode (cmp. Fig. 20.56a).

1907

H.J. Round – discovery of electroluminescence investigating yellow and blue light emission from SiC [26].

K. Bädeker – preparation of metal (e.g. Cd, Cu) oxides and sulfides and also CuI from metal layers using a vapor phase transport method [27].²

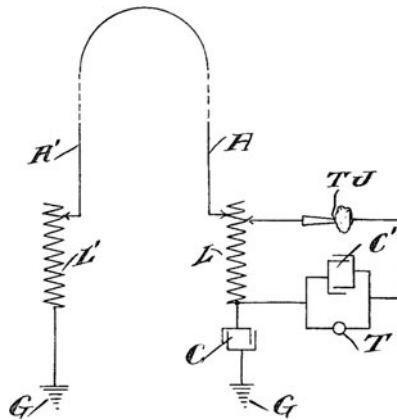


Fig. 1.2. Circuit diagram for a radio receiver with a point-contact diode (TJ). Adapted from [23]

²This work was conducted as Habilitation in the Physics Institute of Universität Leipzig. Bädeker became subsequently professor in Jena and fell in WW I. His scientific contribution to semiconductor physics is discussed in [28].

CuI is reported transparent (~ 200 nm thick films) with a specific resistivity of $\rho = 4.5 \times 10^{-2} \Omega \text{ cm}$, the first transparent conductor.³ Also CdO (films of thickness 100–200 nm) is reported to be highly conductive, $\rho = 1.2 \times 10^{-3} \Omega \text{ cm}$, and orange-yellow in color, probably the first reported TCO (transparent conductive oxide). Anion deficiency in CuI causes insulating behavior.

1911

The term ‘Halbleiter’ (semiconductor) is introduced for the first time by J. Weiss [29] and J. Königsberger and J. Weiss [30]. Königsberger preferred the term ‘Variabler Leiter’ (variable conductor).

1925

J.E. Lilienfeld⁴ – proposal of the metal-semiconductor field-effect transistor (MESFET) [33] (Fig. 1.3). He was also awarded patents for a depletion mode MOSFET [34] and current amplification with npn- and pnp-transistors [35].

1927

A. Schleede, H. Buggisch – synthesis of pure, stoichiometric PbS, influence of sulphur excess and impurities [36].

A. Schleede, E. Körner – activation of luminescence of ZnS [37, 38].

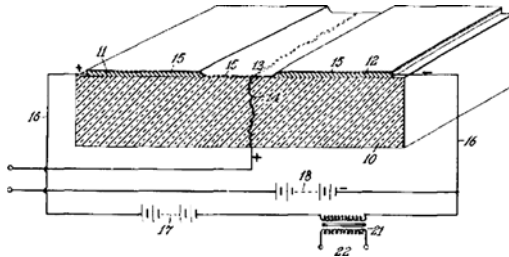


Fig. 1.3. Sketch of a field-effect transistor, 1926. From [33]

³CuI is actually a p-type transparent conductor; at that time the reverse sign of the Hall effect could not be interpreted as hole conduction yet although Bädcker considered positive charges [28].

⁴After obtaining his PhD in 1905 from the Friedrich-Wilhelms-Universität Berlin, J.E. Lilienfeld joined the Physics Department of University of Leipzig and worked on gas liquefaction and with Lord Zeppelin on hydrogen-filled blimps. In 1910 he became professor at the University of Leipzig where he mainly researched on X-rays and vacuum tubes. To the surprise of his colleagues he left in 1926 to join a US industrial laboratory [31, 32].

1928

F. Bloch – quantum mechanics of electrons in a crystal lattice, ‘Bloch functions’ [39].

1929

R. Peierls – explanation of positive (anomalous) Hall effect with unoccupied electron states [40, 41].

1931

W. Heisenberg – theory of hole (‘Löcher’) states [42].

R. de L. Kronig and W.G. Penney – properties of periodic potentials in solids [43].

A.H. Wilson – development of band-structure theory [44].

C. Zener – Zener tunneling [45].

1933

C. Wagner – excess (‘Elektronenüberschuss-Leitung’, n-type) and defect (‘Elektronen-Defektleitung’, p-type) conduction [46]. Anion deficiency in ZnO causes conducting behavior [47].

1936

J. Frenkel – description of excitons [48].

1938

B. Davydov – theoretical prediction of rectification in Cu_2O [49].

W. Schottky – theory of the boundary layer in metal–semiconductor contacts [50], being the basis for Schottky contacts and field-effect transistors.

N.F. Mott – metal–semiconductor rectifier theory [51].

R. Hilsch and R.W. Pohl – three-electrode crystal (KBr) [52].

1940

R.S. Ohl – Silicon-based photoeffect (solar cell, Fig. 1.4) [53] from a pn-junction formed within a slab of polycrystalline Si fabricated with directed solidification due to different distribution coefficients of p- and n-dopants (e.g. boron and phosphorus, cmp. Fig. 4.7b) (J. Scaff and H. Theurer) [54, 55].

1941

R.S. Ohl – Silicon rectifier with point contact [56] (Fig. 1.5), building on work from G.W. Pickard (1906) and using metallurgically refined and intentionally doped silicon (J. Scaff and H. Theurer) [54].

1942

K. Clusius, E. Holz and H. Welker – rectification in germanium [57].

1945

H. Welker – patents for JFET and MESFET [58].

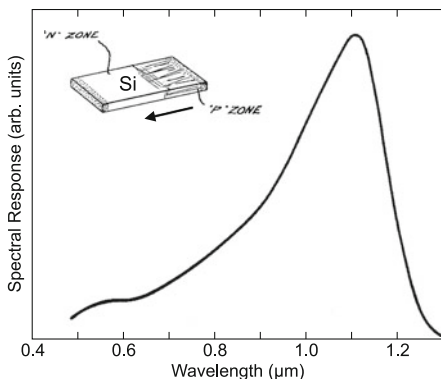


Fig. 1.4. Spectral response of silicon pn-junction photoelement, 1940. The *inset* depicts schematically a Si slab with built-in pn-junction formed during directed solidification (cmp. Fig. 4.7). The *arrow* denotes the direction of solidification. Adapted from [53]

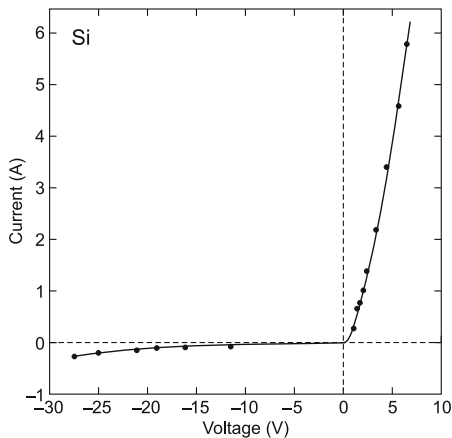


Fig. 1.5. Characteristics of a silicon rectifier, 1941. Adapted from [56]

1947

W. Shockley, J. Bardeen and W. Brattain fabricate the first (point contact) Transistor in the AT&T Bell Laboratories, Holmdel, NJ in an effort to improve hearing aids [59].⁵ Strictly speaking the structure was a point-contact transistor. A 50- μm wide slit was cut with a razor blade into gold foil over a plastic (insulating) triangle and pressed with a spring on n-type germanium (Fig. 1.6a) [63]. The surface region of the germanium is p-type due to

⁵Subsequently, AT&T, under pressure from the US Justice Department's anti-trust division, licensed the transistor for \$25,000. This action initiated the rise of companies like Texas Instruments, Sony and Fairchild.

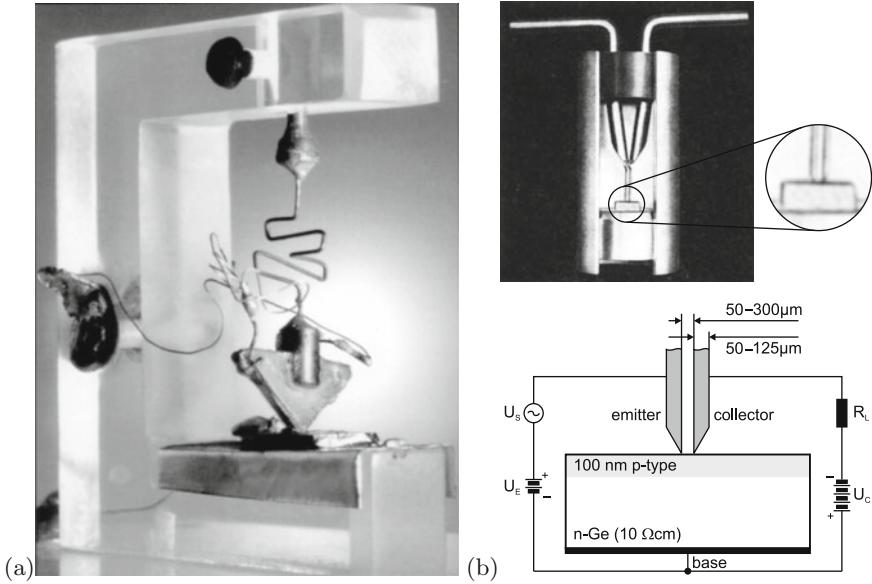


Fig. 1.6. (a) The first transistor, 1947 (length of side of wedge: 32 mm). (b) Cut-away model of a 1948 point contact transistor ('Type A') based on n-type bulk Ge ($n = 5 \times 10^{14} \text{ cm}^{-3}$) and common base circuit diagram. The surface region ($\sim 100 \text{ nm}$ depth) of the Ge is p-type due to surface states and represents an inversion layer. The two wires are made from phosphor bronze. Adapted from [61]

surface states and represents an inversion layer. The two gold contacts form emitter and collector, the large-area back contact of the germanium the base contact [61]. For the first time, amplification was observed [62]. Later models use two close point contacts made from wires with their tips cut into wedge shape (Fig. 1.6b) [61].⁶ More details about the history and development of the semiconductor transistor can be found in [63], written on the occasion of the 50th anniversary of its invention.

1948

W. Shockley – invention of the bipolar (junction) transistor [64].

1952

H. Welker – fabrication of compound semiconductors [65–68]

W. Shockley – description of today's version of the (J)FET [69].

⁶The setup of Fig. 1.6b represents a common base circuit. In a modern bipolar transistor, current amplification in this case is close to unity (Sect. 23.2.2). In the 1948 germanium transistor, the reversely biased collector contact is influenced by the emitter current such that current amplification $\partial I_C / \partial I_E$ for constant U_C was up to 2–3. Due to the collector voltage being much larger than the emitter voltage, a power gain of ~ 125 was reported [61].

1953

G.C. Dacey and I.M. Ross – first realization of a JFET [70].

D.M. Chapin, C.S. Fuller and G.L. Pearson – invention of the silicon solar cell at Bell Laboratories [71]. A single 2-cm² photovoltaic cell from Si, Si:As with an ultrathin layer of Si:B, with about 6% efficiency generated 5 mW of electrical power.⁷ Previously existing solar cells based on selenium had very low efficiency (<0.5%).

1958

J.S. Kilby made the first integrated circuit at Texas Instruments. The simple 1.3 MHz RC-oscillator consisted of one transistor, three resistors and a capacitor on a 11 × 1.7 mm² Ge platelet (Fig. 1.7a). J.S. Kilby filed in 1959 for a US patent for miniaturized electronic circuits [72]. At practically the same time R.N. Noyce from Fairchild Semiconductors, the predecessor of INTEL, invented the integrated circuit on silicon using planar technology [73]. A detailed view on the invention of the integrated circuit can be found in [74]. Figure 1.7b shows a flip-flop with four bipolar transistors and five resistors. Initially, the invention of the integrated circuit⁸ met scepticism because of concerns regarding yield and the achievable quality of the transistors and the other components (such as resistors and capacitors).

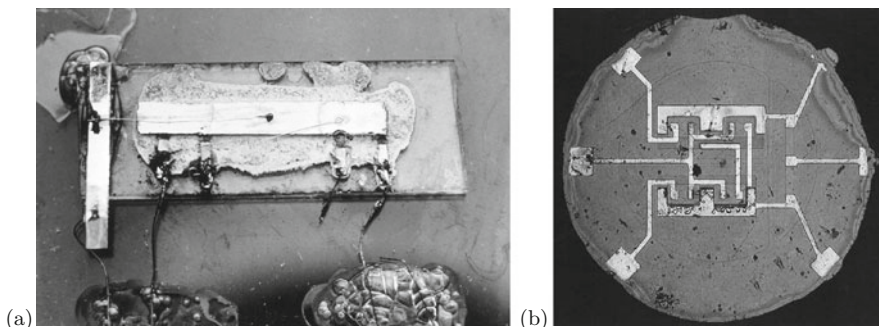


Fig. 1.7. (a) The first integrated circuit, 1958 (germanium, 11 × 1.7 mm²). (b) The first planar integrated circuit, 1959 (silicon, diameter: 1.5 mm)

⁷A solar cell with 1 W power cost \$300 in 1956 (\$3 in 2004). Initially, ‘solar batteries’ were only used for toys and were looking for an application. H. Ziegler proposed the use in satellites in the ‘space race’ of the late 1950s.

⁸The two patents led to a decade-long legal battle between Fairchild Semiconductors and Texas Instruments. Eventually, the US Court of Customs and Patent Appeals upheld R.N. Noyce’s claims on interconnection techniques but gave J.S. Kilby and Texas Instruments credit for building the first working integrated circuit.

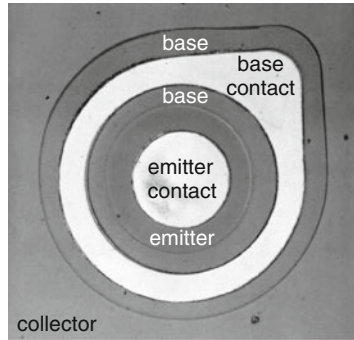


Fig. 1.8. Planar pnp silicon transistor, 1959. The contacts are Al surfaces (not bonded)

1959

J. Hoerni⁹ and R. Noyce – first realization of a planar transistor (in silicon) (Fig. 1.8) [76–79].

1960

D. Kahng and M.M. Atalla – first realization of a MOSFET [80, 81].

1962

The first semiconductor laser on GaAs basis at 77K at GE [82] and at IBM [83]. First visible laser diode [84].

1963

Proposal of a double heterostructure laser (DH laser) by Zh.I. Alferov [85] and H. Kroemer [86].

J.B. Gunn – discovery of the Gunn effect, the spontaneous microwave oscillations in GaAs and InP at sufficiently large applied electric field (due to negative differential resistance) [87].

1966

Zh.I. Alferov – report of the first DH laser on the basis of GaInP at 77 K [88].
C.A. Mead – proposal of the MESFET (‘Schottky Barrier Gate FET’) [89].

1967

W.W. Hooper and W.I. Lehrer – first realization of a MESFET [90].

1968

DH laser on the basis of GaAs/AlGaAs at room temperature, independently developed by Zh.I. Alferov [91] and I. Hayashi [92].

GaP:N LEDs with yellow-green emission (550 nm) and 0.3% efficiency [93].

⁹The Swiss born Jean Hoerni also contributed \$12000 for the building of the first school in the Karakoram Mountain area in Pakistan and has continued to build schools in Pakistan and Afghanistan as described in [75].

1968

SiC blue LED with efficiency of 0.005% [94].

1975

First monolithic microwave integrated circuit (MMIC) [95].

1995

S. Nakamura – blue GaN heterostructure LED with efficiency exceeding 10% [96].

1.2 Nobel Prize Winners

Several Nobel Prizes¹⁰ have been awarded for discoveries and inventions in the field of semiconductor physics (Fig. 1.9).

1909

Karl Ferdinand Braun

‘in recognition of his contributions to the development of wireless telegraphy’

1914

Max von Laue ‘for his discovery of the diffraction of X-rays by crystals’

1915

Sir William Henry Bragg

William Lawrence Bragg

‘for their services in the analysis of crystal structure by means of X-rays’

1946

Percy Williams Bridgman

‘for the invention of an apparatus to produce extremely high pressures, and for the discoveries he made therewith in the field of high pressure physics’

1953

William Bradford Shockley

John Bardeen

Walter Houser Brattain

‘for their researches on semiconductors and their discovery of the transistor effect’

1973

Leo Esaki

‘for his experimental discoveries regarding tunneling phenomena in semiconductors’

1985

Klaus von Klitzing

‘for the discovery of the quantized Hall effect’

¹⁰www.nobel.se

1998

Robert B. Laughlin

Horst L. Störmer

Daniel C. Tsui

‘for their discovery of a new form of quantum fluid with fractionally charged excitations’

2000

Zhores I. Alferov

Herbert Kroemer

‘for developing semiconductor heterostructures used in high-speed and optoelectronics’

Jack St. Clair Kilby

‘for his part in the invention of the integrated circuit’

2009

Willard S. Boyle

George E. Smith

‘for the invention of an imaging semiconductor circuit – the CCD sensor’

2010

Andre Geim

Konstantin Novoselov

‘for groundbreaking experiments regarding the two-dimensional material graphene’

1.3 General Information

In Fig. 1.10, the periodic table of elements is shown. In Table 1.1 the physical properties of various semiconductors are summarized.



1909
Karl Ferdinand Braun
(1850–1918)



1914
Max von Laue
(1879–1960)



1915
Sir William Henry Bragg
(1862–1942)



1915
William Laurence Bragg
(1890–1971)



1946
Percy Williams Bridgman
(1882–1961)



1953
William B. Shockley
(1910–1989)



1953
John Bardeen
(1908–1991)



1953
Walter Hauser Brattain
(1902–1987)



1973
Leo Esaki
(*1925)



1985
Klaus von Klitzing
(*1943)



1998
Robert B. Laughlin
(*1930)



1998
Horst L. Störmer
(*1949)



1998
Daniel C. Tsui
(*1939)



2000
Zhores I. Alferov
(*1938)



2000
Herbert Kroemer
(*1928)



2000
Jack St. Clair Kilby
(1923–2005)



2009
Willard S. Boyle
(*1924)



2009
George E. Smith
(*1930)



2010
Andre Geim
(*1958)



2010
Konstantin Novoselov
(*1974)

Fig. 1.9. Winners of Nobel Prize in Physics and year of award with great importance for semiconductor physics

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103	104	Rf	105	Db	106	Sg	107	Bh	108	Hs	109	Mt	110	Uun	111	Uuu	112	Uub	113	Uuq	114	Uuq	115	Uuh	116	Uuq	117	Uuo	118	Uuo	119	Uuu	120	Uuq	121	Uub	122	Uub	123	Uub	124	Uub	125	Uub	126	Uub	127	Uub	128	Uub	129	Uub	130	Uub	131	Uub	132	Uub	133	Uub	134	Uub	135	Uub	136	Uub	137	Uub	138	Uub	139	Uub	140	Uub	141	Uub	142	Uub	143	Uub	144	Uub	145	Uub	146	Uub	147	Uub	148	Uub	149	Uub	150	Uub	151	Uub	152	Uub	153	Uub	154	Uub	155	Uub	156	Uub	157	Uub	158	Uub	159	Uub	160	Uub	161	Uub	162	Uub	163	Uub	164	Uub	165	Uub	166	Uub	167	Uub	168	Uub	169	Uub	170	Uub	171	Uub	172	Uub	173	Uub	174	Uub	175	Uub	176	Uub	177	Uub	178	Uub	179	Uub	180	Uub	181	Uub	182	Uub	183	Uub	184	Uub	185	Uub	186	Uub	187	Uub	188	Uub	189	Uub	190	Uub	191	Uub	192	Uub	193	Uub	194	Uub	195	Uub	196	Uub	197	Uub	198	Uub	199	Uub	200	Uub	201	Uub	202	Uub	203	Uub	204	Uub	205	Uub	206	Uub	207	Uub	208	Uub	209	Uub	210	Uub	211	Uub	212	Uub	213	Uub	214	Uub	215	Uub	216	Uub	217	Uub	218	Uub	219	Uub	220	Uub	221	Uub	222	Uub	223	Uub	224	Uub	225	Uub	226	Uub	227	Uub	228	Uub	229	Uub	230	Uub	231	Uub	232	Uub	233	Uub	234	Uub	235	Uub	236	Uub	237	Uub	238	Uub	239	Uub	240	Uub	241	Uub	242	Uub	243	Uub	244	Uub	245	Uub	246	Uub	247	Uub	248	Uub	249	Uub	250	Uub	251	Uub	252	Uub	253	Uub	254	Uub	255	Uub	256	Uub	257	Uub	258	Uub	259	Uub	260	Uub	261	Uub	262	Uub	263	Uub	264	Uub	265	Uub	266	Uub	267	Uub	268	Uub	269	Uub	270	Uub	271	Uub	272	Uub	273	Uub	274	Uub	275	Uub	276	Uub	277	Uub	278	Uub	279	Uub	280	Uub	281	Uub	282	Uub	283	Uub	284	Uub	285	Uub	286	Uub	287	Uub	288	Uub	289	Uub	290	Uub	291	Uub	292	Uub	293	Uub	294	Uub	295	Uub	296	Uub	297	Uub	298	Uub	299	Uub	300	Uub	301	Uub	302	Uub	303	Uub	304	Uub	305	Uub	306	Uub	307	Uub	308	Uub	309	Uub	310	Uub	311	Uub	312	Uub	313	Uub	314	Uub	315	Uub	316	Uub	317	Uub	318	Uub	319	Uub	320	Uub	321	Uub	322	Uub	323	Uub	324	Uub	325	Uub	326	Uub	327	Uub	328	Uub	329	Uub	330	Uub	331	Uub	332	Uub	333	Uub	334	Uub	335	Uub	336	Uub	337	Uub	338	Uub	339	Uub	340	Uub	341	Uub	342	Uub	343	Uub	344	Uub	345	Uub	346	Uub	347	Uub	348	Uub	349	Uub	350	Uub	351	Uub	352	Uub	353	Uub	354	Uub	355	Uub	356	Uub	357	Uub	358	Uub	359	Uub	360	Uub	361	Uub	362	Uub	363	Uub	364	Uub	365	Uub	366	Uub	367	Uub	368	Uub	369	Uub	370	Uub	371	Uub	372	Uub	373	Uub	374	Uub	375	Uub	376	Uub	377	Uub	378	Uub	379	Uub	380	Uub	381	Uub	382	Uub	383	Uub	384	Uub	385	Uub	386	Uub	387	Uub	388	Uub	389	Uub	390	Uub	391	Uub	392	Uub	393	Uub	394	Uub	395	Uub	396	Uub	397	Uub	398	Uub	399	Uub	400	Uub	401	Uub	402	Uub	403	Uub	404	Uub	405	Uub	406	Uub	407	Uub	408	Uub	409	Uub	410	Uub	411	Uub	412	Uub	413	Uub	414	Uub	415	Uub	416	Uub	417	Uub	418	Uub	419	Uub	420	Uub	421	Uub	422	Uub	423	Uub	424	Uub	425	Uub	426	Uub	427	Uub	428	Uub	429	Uub	430	Uub	431	Uub	432	Uub	433	Uub	434	Uub	435	Uub	436	Uub	437	Uub	438	Uub	439	Uub	440	Uub	441	Uub	442	Uub	443	Uub	444	Uub	445	Uub	446	Uub	447	Uub	448	Uub	449	Uub	450	Uub	451	Uub	452	Uub	453	Uub	454	Uub	455	Uub	456	Uub	457	Uub	458	Uub	459	Uub	460	Uub	461	Uub	462	Uub	463	Uub	464	Uub	465	Uub	466	Uub	467	Uub	468	Uub	469	Uub	470	Uub	471	Uub	472	Uub	473	Uub	474	Uub	475	Uub	476	Uub	477	Uub	478	Uub	479	Uub	480	Uub	481	Uub	482	Uub	483	Uub	484	Uub	485	Uub	486	Uub	487	Uub	488	Uub	489	Uub	490	Uub	491	Uub	492	Uub	493	Uub	494	Uub	495	Uub	496	Uub	497	Uub	498	Uub	499	Uub	500	Uub	501	Uub	502	Uub	503	Uub	504	Uub	505	Uub	506	Uub	507	Uub	508	Uub	509	Uub	510	Uub	511	Uub	512	Uub	513	Uub	514	Uub	515	Uub	516	Uub	517	Uub	518	Uub	519	Uub	520	Uub	521	Uub	522	Uub	523	Uub	524	Uub	525	Uub	526	Uub	527	Uub	528	Uub	529	Uub	530	Uub	531	Uub	532	Uub	533	Uub	534	Uub	535	Uub	536	Uub	537	Uub	538	Uub	539	Uub	540	Uub	541	Uub	542	Uub	543	Uub	544	Uub	545	Uub	546	Uub	547	Uub	548	Uub	549	Uub	550	Uub	551	Uub	552	Uub	553	Uub	554	Uub	555	Uub	556	Uub	557	Uub	558	Uub	559	Uub	560	Uub	561	Uub	562	Uub	563	Uub	564	Uub	565	Uub	566	Uub	567	Uub	568	Uub	569	Uub	570	Uub	571	Uub	572	Uub	573	Uub	574	Uub	575	Uub	576	Uub	577	Uub	578	Uub	579	Uub	580	Uub	581	Uub	582	Uub	583	Uub	584	Uub	585	Uub	586	Uub	587	Uub	588	Uub	589	Uub	590	Uub	591	Uub	592	Uub	593	Uub	594	Uub	595	Uub	596	Uub	597	Uub	598	Uub	599	Uub	600	Uub	601	Uub	602	Uub	603	Uub	604	Uub	605	Uub	606	Uub	607	Uub	608	Uub	609	Uub	610	Uub	611	Uub	612	Uub	613	Uub	614	Uub	615	Uub	616	Uub	617	Uub	618	Uub	619	Uub	620	Uub	621	Uub	622	Uub	623	Uub	624	Uub	625	Uub	626	Uub	627	Uub	628	Uub	629	Uub	630	Uub	631	Uub	632	Uub	633	Uub	634	Uub	635	Uub	636	Uub	637	Uub	638	Uub	639	Uub	640	Uub	641	Uub	642	Uub	643	Uub	644	Uub	645	Uub	646	Uub	647	Uub	648	Uub	649	Uub	650	Uub	651	Uub	652	Uub	653	Uub	654	Uub	655	Uub	656	Uub	657	Uub	658	Uub	659	Uub	660	Uub	661	Uub	662	Uub	663	Uub	664	Uub	665	Uub	666	Uub	667	Uub	668	Uub	669	Uub	670	Uub	671	Uub	672	Uub	673	Uub	674	Uub	675	Uub	676	Uub	677	Uub	678	Uub	679	Uub	680	Uub	681	Uub	682	Uub	683	Uub	684	Uub	685	Uub	686	Uub	687	Uub	688	Uub	689	Uub	690	Uub	691	Uub	692	Uub	693	Uub	694	Uub	695	Uub	696	Uub	697	Uub	698	Uub	699	Uub	700	Uub	701	Uub	702	Uub	703	Uub	704	Uub	705	Uub	706	Uub	707	Uub	708	Uub	709	Uub	710	Uub	711	Uub	712	Uub	713	Uub	714	Uub	715	Uub	716	Uub	717	Uub	718	Uub	719	Uub	720	Uub	721	Uub	722	Uub	723	Uub	724	Uub	725	Uub	726	Uub	727	Uub	728	Uub	729	Uub	730	Uub	731	Uub	732	Uub	733	Uub	734	Uub	735	Uub	736	Uub	737	Uub	738	Uub	739	Uub	740	Uub	741	Uub	742	Uub	743	Uub	744	Uub	745	Uub	746	Uub	747	Uub	748	Uub	749	Uub	750	Uub	751	Uub	752	Uub	753	Uub	754	Uub	755	Uub	756	Uub	757	Uub	758	Uub	759	Uub	760	Uub	761	Uub	762	Uub	763	Uub	764	Uub	765	Uub	766	Uub	767	Uub	768	Uub	769	Uub	770	Uub	771	Uub	772	Uub	773	Uub	774	Uub	775	Uub	776	Uub	777	Uub	778	Uub	779	Uub	780	Uub	781	Uub	782	Uub	783	Uub	784	Uub	785	Uub	786	Uub	787	Uub	788	Uub	789	Uub	790	Uub	791	Uub	792	Uub	793	Uub	794	Uub	795	Uub	7

Table 1.1. Physical properties of various semiconductors at room temperature. ‘S’ denotes the crystal structure (d: diamond, w: wurzite, zb: zincblende, ch: chalcopyrite, rs: rocksalt)

	S	a_0 (nm)	E_g (eV)	m_e^*	m_h^*	ϵ_0	η_r	μ_e (cm^2/Vs)	μ_h (cm^2/Vs)
C	d	0.3567	5.45 (I)			5.5	2.42	2200	1600
Si	d	0.5431	1.124 (X)	0.98 (m_l) 0.19 (m_t)	0.16 (m_{lh}) 0.5 (m_{hh})	11.7	3.44	1350	480
Ge	d	0.6461	0.67 (L)	1.58 (m_l) 0.08 (m_t)	0.04 (m_{lh}) 0.3 (m_{hh})	16.3	4.00	3900	1900
α -Sn	d	0.64892	0.08 (I)	0.02				2000	1000
3C-SiC	zb	0.436	2.4			9.7	2.7	1000	50
4H-SiC	w	0.3073 (a) 1.005 (c)	3.26			9.6	2.7	1000	120
6H-SiC	w	0.30806 (a) 1.5117 (c)	3.101			10.2	2.7	1140	850
AlN	w	0.3111 (a) 0.4978 (c)	6.2			8.5	3.32		
AlP	zb	0.54625	2.43 (X)	0.13		9.8	3.0	80	
AlAs	zb	0.56605	2.16 (X)	0.5	0.49 (m_{lh}) 1.06 (m_{hh})	12		1000	80
AlSb	zb	0.61335	1.52 (X)	0.11		11	3.4	200	300
GaN	w	0.3189 (a) 0.5185 (c)	3.4 (I)	0.2	0.8	12	2.4	1500	

Table 1.1. (continued)

S	a_0 (nm)	E_{g} (eV)	m_e^*	m_h^*	ϵ_0	n_r	μ_e (cm^2/Vs)	μ_h (cm^2/Vs)
GaP	zb	0.54506	2.26 (Γ)	0.13	0.67	10	3.37	300
GaAs	zb	0.56533	1.42 (Γ)	0.067	0.12 (m_{hh})	12.5	3.4	8500
GaSb	zb	0.60954	0.72 (Γ)	0.045	0.39	15	3.9	5000
InN	w	0.3533 (a) 0.5693 (c)	0.9 (Γ)					1000
InP	zb	0.58686	1.35 (Γ)	0.07	0.4	12.1	3.37	4000
InAs	zb	0.60584	0.36 (Γ)	0.028	0.33	12.5	3.42	22600
InSb	zb	0.64788	0.18 (Γ)	0.013	0.18	18	3.75	100000
ZnO	w	0.325 (a) 0.5206 (c)	3.4 (Γ)	0.24	0.59	6.5	2.2	220
ZnS	zb	0.54109	3.6 (Γ)	0.3		8.3	2.4	110
ZnSe	zb	0.56686	2.58 (Γ)	0.17		8.1	2.89	600
ZnTe	zb	0.61037	2.25 (Γ)	0.15		9.7	3.56	
CdO	rs	0.47	2.16					
CdS	w	0.416 (a) 0.6756 (c)	2.42 (Γ)	0.2	0.7	8.9	2.5	250
CdSe	zb	0.650	1.73 (Γ)	0.13	0.4	10.6		650
CdTe	zb	0.64816	1.50 (Γ)	0.11	0.35	10.9	2.75	1050

Table 1.1. (continued)

S	a_0 (nm)	E_g (eV)	m_e^*	m_h^*	ϵ_0	n_r	μ_e (cm^2/Vs)	μ_h (cm^2/Vs)
MgO	rs	7.3						
HgS	zb	2.0 (<i>F</i>)					50	
HgSe	zb	-0.15 (<i>F</i>)	0.045		25		18500	
HgTe	zb	-0.15 (<i>F</i>)	0.029	0.3	20	3.7	22000	100
PbS	rs	0.37 (<i>L</i>)	0.1	0.1	170	3.7	500	600
PbSe	rs	0.26 (<i>L</i>)	0.07 (m_{lh})	0.06 (m_{lh})	250		1800	930
			0.039 (m_{hh})	0.03 (m_{hh})				
PbTe	rs	0.29 (<i>L</i>)	0.24 (m_{lh})	0.3 (m_{lh})	412		1400	1100
			0.02 (m_{hh})	0.02 (m_{hh})				
			0.07					
ZnSiP ₂	ch	0.54 (<i>a</i>)						
		1.0441 (<i>c</i>)						
ZnGeP ₂	ch	0.5465 (<i>a</i>)						
		1.0771 (<i>c</i>)		0.5				
ZnSnP ₂	ch	0.5651 (<i>a</i>)						
		1.1302 (<i>c</i>)						
CuInS ₂	ch	0.523 (<i>a</i>)						
		1.113 (<i>c</i>)						
CuGaS ₂	ch	0.5347 (<i>a</i>)						
		1.0474 (<i>c</i>)						
CuInSe ₂	ch	0.5784 (<i>a</i>)						
		1.162 (<i>c</i>)						
CuGaSe ₂	ch	0.5614 (<i>a</i>)						
		1.103 (<i>c</i>)						