

# Chapter 1

## Introduction

*The proper conduct of science lies in the pursuit of Nature's puzzles, wherever they may lead.*

J.M. Bishop [2]

**Abstract** Important dates and events in the history of semiconductors are chronologically listed, from the early days (Volta, Seebeck and Faraday) to the latest achievements like the blue and white LED. Many known and not so well known scientists are mentioned. Also a list of semiconductor related Nobel prizes and their winners is given.

The historic development of semiconductor physics and technology began in the second half of the 19th century. Interesting discussions of the history of the physics and chemistry of semiconductors can be found in [3–5]. The development of crystal growth is covered in [6]. The history of semiconductor industry can be followed in [7, 8]. In 1947, the commercial 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 and Key Achievements

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’ [9].

1821

T.J. Seebeck—discovery of thermopower (electrical phenomena upon temperature difference) in metals and PbS, FeS<sub>2</sub>, CuFeS<sub>2</sub> [10].

1833

M. Faraday—discovery of the temperature dependence of the conductivity of Ag<sub>2</sub>S (sulphuret of silver, negative  $dR/dT$ ) [11].

1834

J. Peltier—discovery of the Peltier effect (cooling by current) [12].

1873

W. Smith—discovery of photoconductivity in selenium [13]. Early work on photoconductivity in Se is reviewed in [14, 15].

1874

F. Braun<sup>1</sup>—discovery of rectification in metal–sulfide semiconductor contacts [17], e.g. for CuFeS<sub>2</sub> 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 [18].

W. Siemens—large response from selenium photoconductor [19], 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 [19] and measured to 14.8 in [20].

1879

E.H. Hall—measurement of the transverse potential difference in a thin gold leaf on glass [21, 22]. Experiments were continued by his mentor H.A. Rowland [23]. A detailed account of the discovery of the Hall effect is given in [24, 25].

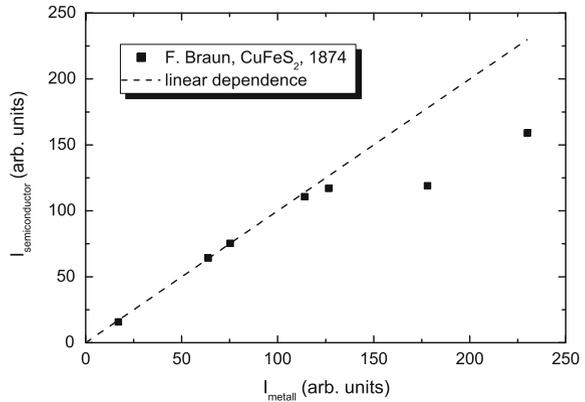
1883

Ch. Fritts—first solar cell, based on an gold/selenium rectifier [20]. The efficiency was below 1 %.

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<sup>1</sup>F. Braun made his discoveries on metal–semiconductor contacts in Leipzig while a teacher at the Thomasschule zu Leipzig [16]. He conducted his famous work on vacuum tubes later as a professor in Strasbourg, France.

**Fig. 1.1** Current through a silver–CuFeS<sub>2</sub>–silver structure as a function of the current through the metal only, 1874. Data points are for different applied voltages. Experimental data from [17]



1901

J.C. Bose—point contact detector for electromagnetic waves based on galena (PbS) [26]. 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’.

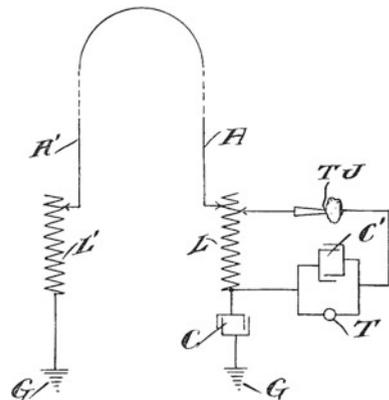
1906

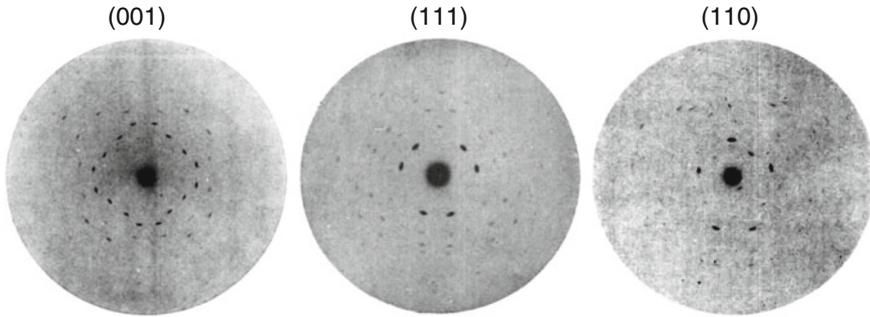
G.W. Pickard—rectifier based on point contact (cat’s whisker) diode on silicon [27-29]. Erroneously, the rectifying effect was attributed to a thermal effect, however, the drawing of the ‘thermo-junction’ (TJ in Fig. 1.2) developed into the circuit symbol for a diode (cmp. Fig. 21.61a).

1907

H.J. Round—discovery of electroluminescence investigating yellow and blue light emission from SiC [30].

**Fig. 1.2** Circuit diagram for a radio receiver with a point-contact diode (TJ). Adapted from [27]





**Fig. 1.3** Laue images of ‘regular’ (cubic) ZnS along three major crystallographic directions, directly visualizing their 4-, 3- and 2-fold symmetry. Adapted from [41]

K. Bädeker—preparation of metal (e.g. Cd, Cu) oxides and sulfides and also CuI from metal layers using a vapor phase transport method [31].<sup>2</sup> CuI is reported transparent ( $\sim 200$  nm thick films) with a specific resistivity of  $\rho = 4.5 \times 10^{-2} \Omega \text{ cm}$ , the first transparent conductor.<sup>3</sup> 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, the first reported TCO (transparent conductive oxide).

1909

K. Bädeker—discovery of doping. Controlled variation of the conductivity of CuI by dipping into iodine solutions (e.g. in chloroform) of different concentrations [34].

1910

W.H. Eccles—negative differential resistance of contacts with galena (PbS), construction of crystal oscillators [38].<sup>4</sup>

1911

The term ‘Halbleiter’ (semiconductor) is introduced for the first time by J. Weiss [39] and J. Königsberger and J. Weiss [40]. Königsberger preferred the term ‘Variabler Leiter’ (variable conductor).

1912

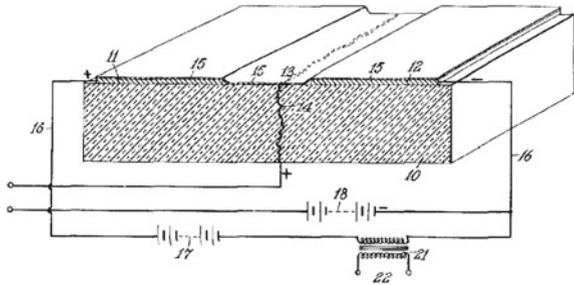
M. von Laue—X-ray diffraction of bulk crystals including ZnS (Fig. 1.3) [41, 42].

<sup>2</sup>This 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 [32, 33].

<sup>3</sup>CuI is actually a p-type transparent conductor; at that time the positive sign of the Hall effect [34, 35] could not be interpreted as hole conduction yet.

<sup>4</sup>Historical remarks on Eccles’ contributions to radio technology can be found in [36, 37].

**Fig. 1.4** Sketch of a field-effect transistor, 1926. From [46]



1925

J.E. Lilienfeld<sup>5</sup>—proposal of the metal-semiconductor field-effect transistor (MES-FET) [46], with suggested copper sulfide thin film channel and aluminum gate.<sup>6</sup> (Fig. 1.4). Lilienfeld was also awarded patents for a depletion mode MOSFET [48] with proposed copper sulfide, copper oxide or lead oxide channel and current amplification with npn- and pnp-transistors [49]. Due to the lack of other publications of Lilienfeld on transistors, it is under discussion whether Lilienfeld just patented ideas or also build working devices with mounting evidence for the latter [44, 47, 50].

1927

A. Schleede, H. Buggisch—synthesis of pure, stoichiometric PbS, influence of sulphur excess and impurities [51].

A. Schleede, E. Körner—activation of luminescence of ZnS [52, 53].

1928

F. Bloch—quantum mechanics of electrons in a crystal lattice, ‘Bloch functions’ [54].

O.V. Losev—description of the light emitting diode<sup>7</sup> (SiC) [58]; light emission was observed in forward direction and close to breakdown (Fig. 1.5a). Also current modulation of LED light output was reported (Fig. 1.5b) [58].

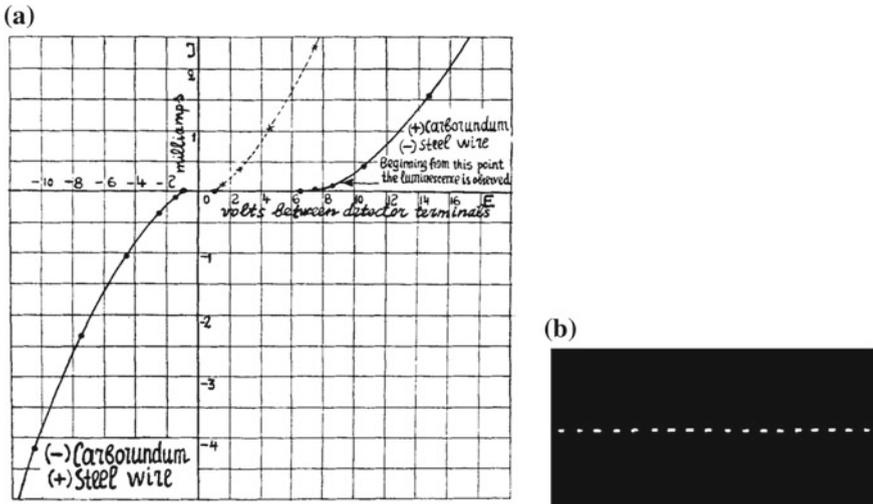
1929

R. Peierls—explanation of positive (anomalous) Hall effect with unoccupied electron states [59, 60].

<sup>5</sup>After obtaining his PhD in 1905 from the Friedrich-Wilhelms-Universität Berlin, Julius Edgar Lilienfeld joined the Physics Department of Universität Leipzig and worked on gas liquefaction and with Lord Zeppelin on hydrogen-filled blimps. In 1910 he became professor at the Universität Leipzig where he mainly researched on X-rays and vacuum tubes [43]. To the surprise of his colleagues he left in 1926 to join a US industrial laboratory [44, 45].

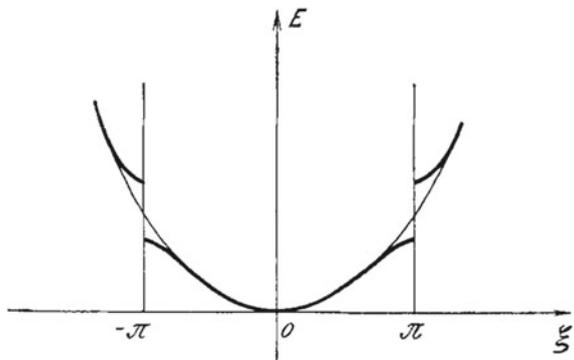
<sup>6</sup>In [44] it is suggested that the device works as a npn transistor, in [47] it is suggested to be a JFET.

<sup>7</sup>The historic role of Losev regarding the invention of the LED and oscillators is discussed in [55–57].



**Fig. 1.5** (a)  $I$ - $V$  characteristic of SiC/steel wire light emitting diode. The *dotted* curve is the flipped curve for negative voltage (3rd quadrant). (b) Recording of current modulated (at 500 Hz) LED on moving photographic plate. Adapted from [58]

**Fig. 1.6** First band structure calculation ( $\xi = k a$ ). Adapted from [62]



1930

R. Peierls—first calculation of a band structure and band gap<sup>8</sup> (Fig. 1.6) [62].

1931

W. Heisenberg—theory of hole (‘Löcher’) states [63].

R. de L. Kronig and W.G. Penney—properties of periodic potentials in solids [64].

A.H. Wilson<sup>9</sup>—development of band-structure theory [67, 68].

<sup>8</sup>Peierls performed this work at suggestion of W. Pauli at ETH Zürich. The mathematical problem of Schrödinger’s equation with a sinusoidal potential had been already treated by M.J.O Strutt in 1928 [61].

<sup>9</sup>Wilson was theoretical physicist in Cambridge, who spent a sabbatical with Heisenberg in Leipzig and applied the brand new field of quantum mechanics to issues of electrical conduction,

1933

C. Wagner—excess ('Elektronenüberschuss-Leitung', n-type) and defect ('Elektronen-Defektleitung', p-type) conduction [69]. Anion deficiency in ZnO causes conducting behavior [70].

1934

C. Zener—Zener tunneling [71].

1936

J. Frenkel—description of excitons [72].

1938

B. Davydov—theoretical prediction of rectification at pn-junction [73] and in  $\text{Cu}_2\text{O}$  [74].

W. Schottky—theory of the boundary layer in metal–semiconductor contacts [75], being the basis for Schottky contacts and field-effect transistors.

N.F. Mott—metal–semiconductor rectifier theory [76, 77].

R. Hilsch and R.W. Pohl—three-electrode crystal (KBr) [78].

1940

R.S. Ohl—Silicon-based photoeffect (solar cell, Fig. 1.7) [79] 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 (boron and phosphorus, cmp. Fig. 4.6b) (J. Scaff and H. Theurer) [80, 81].

1941

R.S. Ohl—Silicon rectifier with point contact [82, 83] (Fig. 1.8), building on work from G.W. Pickard (1906) and using metallurgically refined and intentionally doped silicon (J. Scaff and H. Theurer) [80].

1942

K. Clusius, E. Holz and H. Welker—rectification in germanium [84].

1945

H. Welker—patents for JFET and MESFET [85].

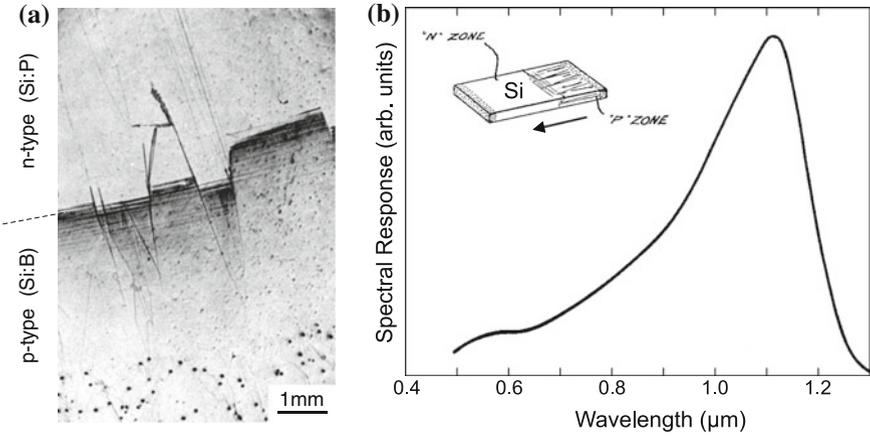
1947

W. Shockley, J. Bardeen and W. Brattain fabricate the first transistor in the AT&T

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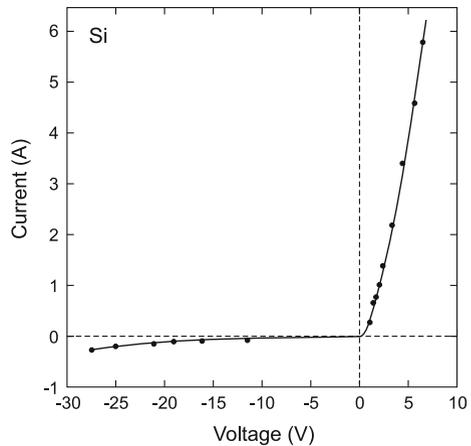
(Footnote 9 continued)

first in metals and then in semiconductors. When he returned to Cambridge, Wilson urged that attention be paid to germanium but, as he expressed it long afterward, 'the silence was deafening' in response. He was told that devoting attention to semiconductors, those messy entities, was likely to blight his career among physicists. He ignored these warnings and in 1939 brought out his famous book 'Semiconductors and Metals' [65] which explained semiconductor properties, including the much-doubted phenomenon of intrinsic semiconductivity, in terms of electronic energy bands. His academic career seems indeed to have been blighted, because despite his great intellectual distinction, he was not promoted in Cambridge (he remained an assistant professor year after year) [66]. Compare the remark of W. Pauli (p. 205).



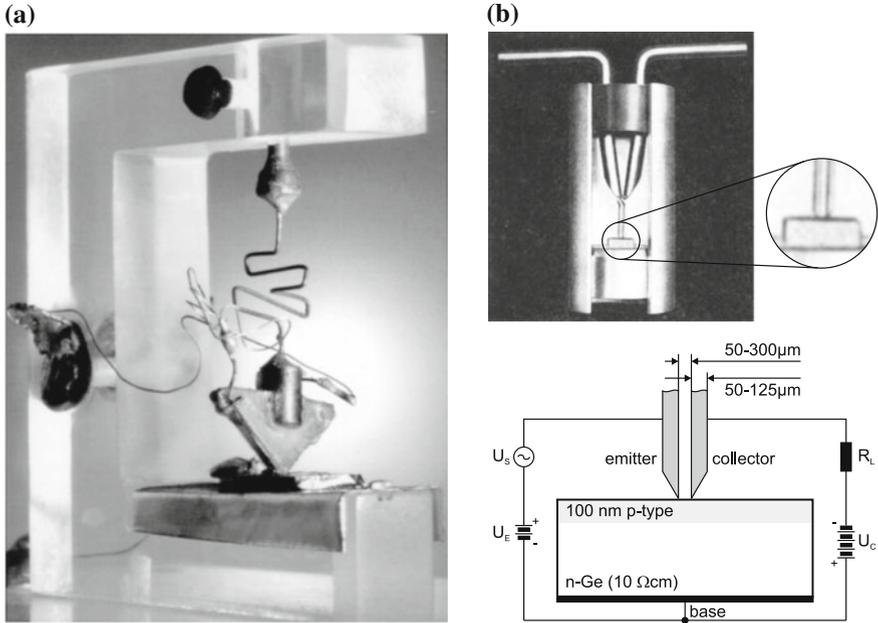
**Fig. 1.7** (a) Optical image of directionally solidified silicon. The lower part contains predominantly boron, the upper part contains predominantly phosphorous. First the growth is porous and subsequently columnar. Adapted from [80]. (b) Spectral response of silicon pn-junction photoelement, 1940. The inset depicts schematically a Si slab with built-in pn-junction formed during directed solidification as shown in panel (a). The arrow denotes the direction of solidification (cmp. Fig. 4.6). Adapted from [79]

**Fig. 1.8** Characteristics of a silicon rectifier, 1941. Adapted from [82]



Bell Laboratories, Holmdel, NJ in an effort to improve hearing aids [86].<sup>10</sup> 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. 1.9a) [87]. The surface region of the germanium is p-type due to surface states and represents an inversion layer. The two gold con-

<sup>10</sup>Subsequently, AT&T, under pressure from the US Justice Department’s antitrust division, licensed the transistor for \$25,000. This action initiated the rise of companies like Texas Instruments, Sony and Fairchild.



**Fig. 1.9** (a) The first transistor, 1947 (length of side of wedge: 32 mm). (b) Cutaway 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 [88]

tacts form emitter and collector, the large-area back contact of the germanium the base contact [88]. For the first time, amplification was observed [89]. Later models use two close point contacts made from wires with their tips cut into wedge shape (Fig. 1.9b) [88].<sup>11</sup> More details about the history and development of the semiconductor transistor can be found in [90], written on the occasion of the 50th anniversary of its invention.

1948

W. Shockley—invention of the bipolar (junction) transistor [91].

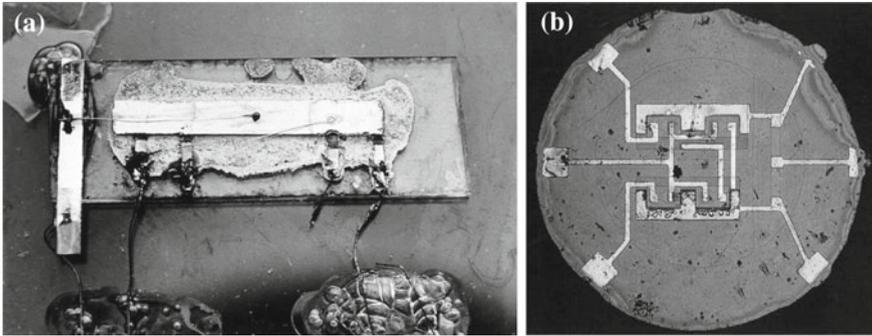
1952

H. Welker—fabrication of III–V compound semiconductors<sup>12</sup> [94–97]

W. Shockley—description of today's version of the (J)FET [98].

<sup>11</sup>The setup of Fig. 1.9b represents a common base circuit. In a modern bipolar transistor, current amplification in this case is close to unity (Sect. 24.2.2). 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  $\sim 125$  was reported [88].

<sup>12</sup>An early concept for III–V semiconductors was developed in [92, 93].



**Fig. 1.10** (a) The first integrated circuit, 1958 (germanium,  $11 \times 1.7 \text{ mm}^2$ ). (b) The first planar integrated circuit, 1959 (silicon, diameter: 1.5 mm)

1953

G.C. Dacey and I.M. Ross—first realization of a JFET [99].

D.M. Chapin, C.S. Fuller and G.L. Pearson—invention of the silicon solar cell at Bell Laboratories [100]. A single  $2 \text{ cm}^2$  photovoltaic cell from Si, Si:As with an ultra-thin layer of Si:B, with about 6% efficiency generated 5 mW of electrical power.<sup>13</sup> Previously existing solar cells based on selenium had very low efficiency (<0.5%).

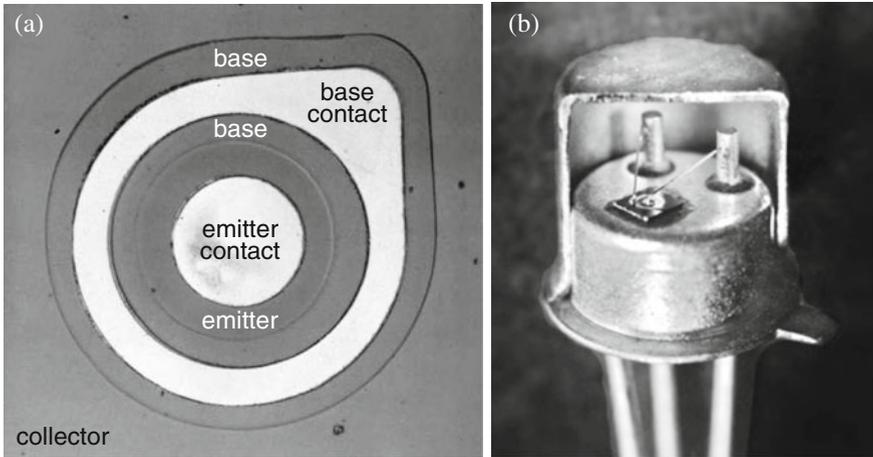
1958

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  $11 \times 1.7 \text{ mm}^2$  Ge platelet (Fig. 1.10a). J.S. Kilby filed in 1959 for a US patent for miniaturized electronic circuits [101]. At practically the same time R.N. Noyce from Fairchild Semiconductors, the predecessor of INTEL, invented the integrated circuit on silicon using planar technology [102]. A detailed and (very) critical view on the invention of the integrated circuit can be found in [103].

Figure 1.10b shows a flip-flop with four bipolar transistors and five resistors. Initially, the invention of the integrated circuit<sup>14</sup> met scepticism because of concerns regarding yield and the achievable quality of the transistors and the other components (such as resistors and capacitors).

<sup>13</sup>A 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.

<sup>14</sup>The 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. 1.11** (a) Optical image of planar pnp silicon transistor (2N1613 [110]), 1959. The contacts are Al surfaces (not bonded). (b) Housing of such transistor cut open

1959

J. Hoerni<sup>15</sup> and R. Noyce—first realization of a planar transistor (in silicon) (Fig. 1.11) [105–109].

1960

D. Kahng and M.M. Atalla—first realization of a MOSFET [111, 112].

1962

The first semiconductor laser on GaAs basis at 77 K at GE [113, 114] (Fig. 1.12) and at IBM [115] and MIT [116].

First visible laser diode [117].<sup>16</sup>

1963

Proposal of a double heterostructure laser (DH laser) by Zh.I. Alferov [120] and H. Kroemer [121].

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) [122].

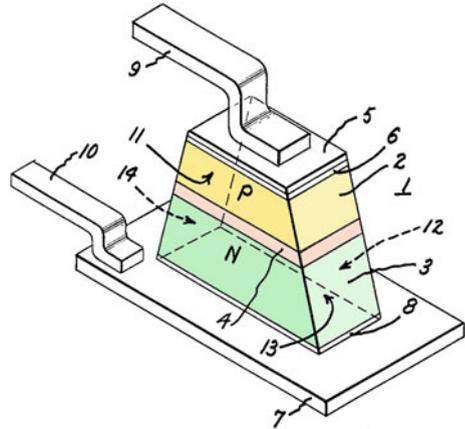
1966

C.A. Mead—proposal of the MESFET (‘Schottky Barrier Gate FET’) [123].

<sup>15</sup>The 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 [104].

<sup>16</sup>Remarks on the discovery and further development of the laser diode can be found in [118, 119].

**Fig. 1.12** Schematics of GaAs-based laser diode. The active layer is highlighted in red. Adapted from [114]



1967

Zh.I. Alferov—report of the first DH laser on the basis of GaAsP at 77 K [124, 125].  
W.W. Hooper and W.I. Lehrer—first realization of a MESFET [126].

1968

DH laser on the basis of GaAs/AlGaAs at room temperature, independently developed by Zh.I. Alferov [127] and I. Hayashi [128].  
GaP:N LEDs with yellow-green emission (550 nm) and 0.3 % efficiency [129].

1968

SiC blue LED with efficiency of 0.005 % [130].

1975

First monolithic microwave integrated circuit (MMIC) (Fig. 1.13) [131]

1992

S. Nakamura—growth of high-quality group-III–nitride thin films [132], blue nitride heterostructure LED with efficiency exceeding 10 % (1995) [133] (Fig. 1.14a). Later the white LED was built by combining a blue LED with yellow phosphors (Fig. 1.14b, c).

## 1.2 Nobel Prize Winners

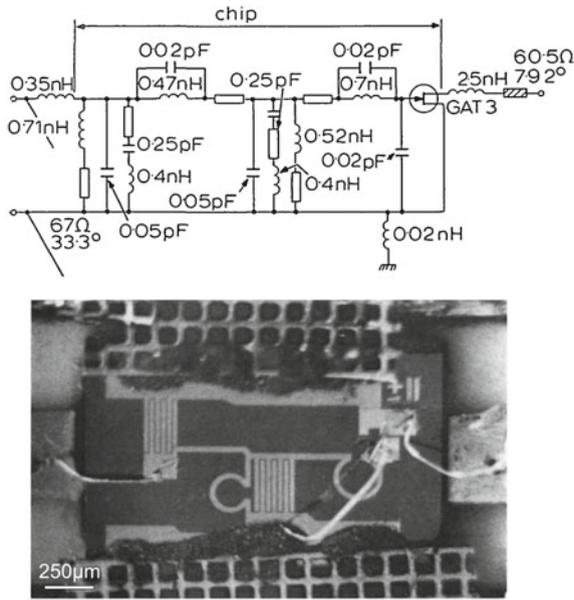
Several Nobel Prizes<sup>17</sup> have been awarded for discoveries and inventions in the field of semiconductor physics (Fig. 1.15).

1909

Karl Ferdinand Braun

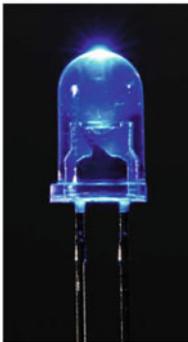
‘in recognition of his contributions to the development of wireless telegraphy’

<sup>17</sup> [www.nobel.se](http://www.nobel.se).



**Fig. 1.13** Equivalent circuit and optical image of first monolithic microwave integrated circuit (exhibiting gain  $(4.5 \pm 0.9\text{dB})$  in the frequency range 7.0–11.7GHz). Adapted from [131]

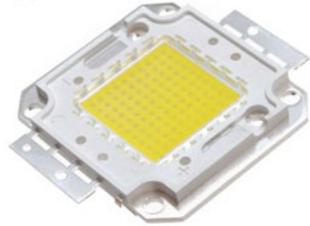
(a)



(b)



(c)



**Fig. 1.14** (a) Blue LED (standard housing). 50 W, 4000lm (b) warm white and (c) cold white LED ( $45 \times 45\text{mm}^2$ )

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’

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’



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)



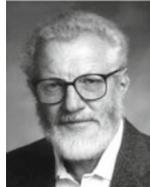
1998  
Horst L. Störmer  
(\*1949)



1998  
Daniel C. Tsui  
(\*1939)



2000  
Zhores I. Alferov  
(\*1938)



2000  
Herbert Kroemer  
(\*1928)



2000  
Jack St. Clair Kilby  
(1923–2005)

**Fig. 1.15** Winners of Nobel Prize in Physics and year of award with great importance for semiconductor physics



2009  
Willard S. Boyle  
(1924–2011)



2009  
George E. Smith  
(\*1930)



2010  
Andre Geim  
\*1958



2010  
Konstantin Novoselov  
\*1974



2014  
Isamu Akasaki  
(\*1929)



2014  
Hiroshi Amano  
(\*1960)



2014  
Shuji Nakamura  
(\*1954)

**Fig. 1.15** (continued)

2010  
Andre Geim  
Konstantin Novoselov  
‘for groundbreaking experiments regarding the two-dimensional material graphene’

2014  
Isamu Akasaki  
Hiroshi Amano  
Shuji Nakamura  
‘for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources’.



Table 1.1 Physical properties of various semiconductors at room temperature

C	S	$a_0$ (nm)	$E_g$ (eV)	$m_e^*$	$m_h^*$	$\epsilon_0$	$n_r$	$\mu_e$ ( $\text{cm}^2/\text{Vs}$ )	$\mu_h$ ( $\text{cm}^2/\text{Vs}$ )
	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 ( $m_{hh}$ ) 0.5 ( $m_{hh}$ )	11.7	3.44	1350	480
Ge	d	0.5646	0.67 (L)	1.58 ( $m_l$ ) 0.08 ( $m_t$ )	0.04 ( $m_{hh}$ ) 0.3 ( $m_{hh}$ )	16.3	4.00	3900	1900
$\alpha$ -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		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	0.39	11	3.4	200	300
GaN	w	0.3189 (a) 0.5185 (c)	3.4 (I)	0.2	0.8	12	2.4	1500	
GaP	zb	0.54506	2.26 (I)	0.13	0.67	10	3.37	300	150
GaAs	zb	0.56533	1.42 (I)	0.067	0.12 ( $m_{lh}$ ) 0.5 ( $m_{hh}$ )	12.5	3.4	8500	400
GaSb	zb	0.60954	0.72 (I)	0.045	0.39	15	3.9	5000	1000

(continued)

Table 1.1 (continued)

	S	$a_0$ (nm)	$E_g$ (eV)	$m_e^*$	$m_h^*$	$\epsilon_0$	$n_r$	$\mu_e$ (cm <sup>2</sup> /Vs)	$\mu_h$ (cm <sup>2</sup> /Vs)
InN	w	0.3533 (a) 0.5693 (c)	0.69 (Γ)						
InP	zb	0.58686	1.35 (Γ)	0.07	0.4	12.1	3.37	4000	600
InAs	zb	0.60584	0.36 (Γ)	0.028	0.33	12.5	3.42	22600	200
InSb	zb	0.64788	0.18 (Γ)	0.013	0.18	18	3.75	100000	1700
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	100
MgO	rs	0.421	7.3						
HgS	zb	0.5852	2.0 (Γ)					50	
HgSe	zb	0.6084	-0.15 (Γ)	0.045		25		18500	
HgTe	zb	0.64616	-0.15 (Γ)	0.029	0.3	20	3.7	22000	100
PbS	rs	0.5936	0.37 (L)	0.1	0.1	170	3.7	500	600
PbSe	rs	0.6147	0.26 (L)	0.07 (m <sub>lh</sub> ) 0.039 (m <sub>hh</sub> )	0.06 (m <sub>lh</sub> ) 0.03 (m <sub>hh</sub> )	250		1800	930

(continued)

Table 1.1 (continued)

	S	$a_0$ (nm)	$E_g$ (eV)	$m_c^*$	$m_h^*$	$\epsilon_0$	$n_r$	$\mu_e$ ( $\text{cm}^2/\text{Vs}$ )	$\mu_h$ ( $\text{cm}^2/\text{Vs}$ )
PbTe	rs	0.645	0.29 (L)	0.24 ( $m_{lh}$ ) 0.02 ( $m_{hh}$ )	0.3 ( $m_{lh}$ ) 0.02 ( $m_{hh}$ )	412		1400	1100
ZnSiP <sub>2</sub>	ch	0.54 ( <i>a</i> ) 1.0441 ( <i>c</i> )	2.96 ( <i>F</i> )	0.07					
ZnGeP <sub>2</sub>	ch	0.5465 ( <i>a</i> ) 1.0771 ( <i>c</i> )	2.34 ( <i>F</i> )		0.5				
ZnSnP <sub>2</sub>	ch	0.5651 ( <i>a</i> ) 1.1302 ( <i>c</i> )	1.66 ( <i>F</i> )						
CuInS <sub>2</sub>	ch	0.523 ( <i>a</i> ) 1.113 ( <i>c</i> )	1.53 ( <i>F</i> )						
CuGaS <sub>2</sub>	ch	0.5347 ( <i>a</i> ) 1.0474 ( <i>c</i> )	2.5 ( <i>F</i> )						
CuInSe <sub>2</sub>	ch	0.5784 ( <i>a</i> ) 1.162 ( <i>c</i> )	1.0 ( <i>F</i> )						
CuGaSe <sub>2</sub>	ch	0.5614 ( <i>a</i> ) 1.103 ( <i>c</i> )	1.7 ( <i>F</i> )						

'S' denotes the crystal structure (*d* diamond, *w* wurtzite, *zb* zinblende, *ch* chalcopyrite, *rs* rocksalt)

## 1.3 General Information

In Fig. 1.16, the periodic table of elements is shown.

In Table 1.1 the physical properties of various semiconductors are summarized. Data on semiconductors can be found in [134–146].