

LANDOLT-BÖRNSTEIN

Zahlenwerte und Funktionen
aus Naturwissenschaften und Technik

Neue Serie

Gesamtherausgabe: K.-H. Hellwege · O. Madelung

Gruppe III: Kristall- und Festkörperphysik

Band 17
Halbleiter

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

Teilband c

Technologie von Si, Ge und SiC

W. Dietze · E. Doering · P. Glasow · W. Langheinrich
A. Ludsteck · H. Mader · A. Mühlbauer · W. v. Münch
H. Runge · L. Schleicher · M. Schnöller
M. Schulz · E. Sirtl · E. Uden · W. Zulehner

Herausgegeben von M. Schulz · H. Weiss †



Springer-Verlag Berlin · Heidelberg · New York · Tokyo 1984

Table of contents

Semiconductors

Subvolume c: Technology of Si, Ge and SiC (edited by M. SCHULZ · H. WEISS †)

A Introduction (M. SCHULZ)		
1 General remarks	1	
2 Frequently used symbols	2	
3 Conversion of units	5	
4 Abbreviations frequently used in semiconductor technology	6	
 B Technology of semiconductors	 Data	 Figures
6 Tetrahedrally bonded semiconductors	12	—
 6.1 Silicon and germanium	12	—
6.1.1 Technological data (A. MÜHLBAUER).	12	417 ff.
6.1.1.0 Introduction	12	—
6.1.1.1 Phase diagrams and liquidus curves	12	417 ff.
6.1.1.2 Solubility in solid Si and Ge	13	419 ff.
6.1.1.3 Equilibrium distribution coefficient	14	420 ff.
6.1.1.4 Melt diffusion coefficient	16	423
6.1.1.5 Evaporation rate	16	—
6.1.1.6 Tetrahedral covalent radius	17	422
6.1.1.7 Thermophysical properties	17	421 ff.
6.1.1.8 Properties of liquid Si and Ge	19	—
References for 6.1.1	20	—
6.1.2 Crystal growth.	23	—
6.1.2.1 Deposition of polycrystalline silicon (W. DIETZE).	23	—
6.1.2.1.0 Introduction	23	—
6.1.2.1.1 Deposition technology	23	425
6.1.2.1.2 Processes connected to deposition	25	425
6.1.2.1.3 Deposition conditions	26	426
6.1.2.1.4 Alternative processes	26	—
6.1.2.2 Preparation and purification methods of Ge (W. DIETZE).	28	—
6.1.2.3 Czochralski growth of Si and Ge (W. ZULEHNER).	28	—
6.1.2.3.0 Introduction	28	—
6.1.2.3.1 Czochralski pulling technique	28	427 ff.
6.1.2.3.2 Starting materials	32	428 ff.
6.1.2.3.3 Crucible materials	33	429
6.1.2.3.4 Heating and furnace equipment	35	429
6.1.2.3.5 Growth ambients	36	447
6.1.2.3.6 Automatic control	37	430 ff.
6.1.2.3.7 Recharging methods	37	430 ff.
6.1.2.3.8 Czochralski pulling apparatus	38	429 ff.
6.1.2.3.9 Impurity incorporation	39	432 ff.
6.1.2.3.10 Oxygen incorporation	39	429 ff.
6.1.2.4 Zone melting (A. MÜHLBAUER, subsection 6.1.2.4.6 P. GLASOW).	41	—
6.1.2.4.0 Introduction	41	434 ff.
6.1.2.4.1 Silicon float-zone technology	41	434 ff.

	Data	Figures
6.1.2.4.2 Forces in a floating zone	43	435
6.1.2.4.3 Doping of float-zone grown crystals	43	436
6.1.2.4.4 Redistribution of impurities	45	436 ff.
6.1.2.4.5 Faceting	46	439
6.1.2.4.6 Growth of high purity germanium	47	437 ff.
6.1.2.5 Unconventional Si crystallization techniques (M. SCHULZ, E. SIRTL)	50	-
6.1.2.5.1 Directional solidification	50	441
6.1.2.5.2 Mould casting	51	441 ff.
6.1.2.5.3 Sheet growth	52	442 ff.
6.1.2.6 Wafer preparation (W. ZULEHNER)	54	-
6.1.2.6.1 Ingot preparation	54	444 ff.
6.1.2.6.2 Slicing, lapping, and edge rounding	55	445
6.1.2.6.3 Etching, polishing, wafer finishing	56	445
References for 6.1.2	57	-
6.1.3 Characterization of crystal properties	62	-
6.1.3.1 Properties of polycrystalline silicon (W. DIETZE)	62	446
6.1.3.2 Properties of Czochralski silicon (W. ZULEHNER)	62	-
6.1.3.2.1 Doping profiles	63	446 ff.
6.1.3.2.2 Oxygen in CZ silicon	64	449 ff.
6.1.3.2.3 Impurities in CZ silicon	66	453
6.1.3.2.4 Lattice defects	67	453 f.
6.1.3.3 Properties of float-zone silicon (A. MÜHLBAUER)	69	-
6.1.3.3.1 Doping profiling	69	455 ff.
6.1.3.3.2 Impurity striations	70	460 ff.
6.1.3.3.3 Impurities	71	462
6.1.3.3.4 Defects	72	462 ff.
6.1.3.4 Properties of high purity germanium (P. GLASOW)	73	-
6.1.3.4.1 Impurities in the starting material	73	-
6.1.3.4.2 Impurities in purified Ge	73	465 ff.
6.1.3.5 Diagnostic techniques (A. MÜHLBAUER, subsection 6.1.3.5.3 P. GLASOW)	77	-
6.1.3.5.1 Doping profiling	77	-
6.1.3.5.2 Impurity and defect analysis	77	466
6.1.3.5.3 Characterization - techniques for high purity germanium	82	466
References for 6.1.3	83	-
6.1.4 Device technology	90	-
6.1.4.0 Basic device structures (H. MADER, subsection 6.1.4.0.9 P. GLASOW)	90	-
6.1.4.0.0 Introduction	90	467 ff.
6.1.4.0.1 Diodes	91	468 ff.
6.1.4.0.2 Transistors	94	-
6.1.4.0.3 Bipolar transistors	101	470 ff.
6.1.4.0.4 MOS-transistors	101	471 ff.
6.1.4.0.5 Thyristors	102	473 ff.
6.1.4.0.6 Bipolar integrated circuits	102	474 ff.
6.1.4.0.7 MOS-integrated circuits	103	476 ff.
6.1.4.0.8 CMOS integrated circuits	104	479 ff.
6.1.4.0.9 Nuclear radiation detectors	104	481 ff.
References for 6.1.4.0	115	-
6.1.4.1 Diffusion (W. LANGHEINRICH under assistance of K. HABERLE)	118	-
6.1.4.1.0 Introduction	118	-

	Data	Figures
6.1.4.1.1 Diffusion coefficients	119	494ff.
6.1.4.1.2 Introduction of impurities by diffusion	129	497ff.
6.1.4.1.3 Properties of diffusion source material	134	502
6.1.4.1.4 Diffusion in the system SiO ₂ /Si	135	499ff.
6.1.4.1.5 Diffusion profiles	139	500ff.
6.1.4.1.6 Properties of masking layers	141	502ff.
6.1.4.1.7 Gettering	144	504ff.
References for 6.1.4.1	145	-
6.1.4.2 Ion implantation (H. RUNGE)	150	-
6.1.4.2.0 Introduction	150	-
6.1.4.2.1 Depth distribution of implanted ions	150	506ff.
6.1.4.2.2 Annealing	154	-
6.1.4.2.3 Implantation of dopants in Si	154	507ff.
6.1.4.2.4 Implantation of dopants in Ge	156	-
6.1.4.2.5 Useful formulas	156	509ff.
6.1.4.2.6 Range tables	157	-
6.1.4.2.7 Evaluation of ion implanted layers	166	511
6.1.4.2.8 Implantation apparatus	170	511ff.
References for 6.1.4.2	179	-
6.1.4.3 Nuclear transmutation doping (M. SCHNÖLLER)	185	-
6.1.4.3.0 Introduction	185	513ff.
6.1.4.3.1 Nuclear transmutation	185	-
6.1.4.3.2 Radiation defects	185	-
6.1.4.3.3 Side reactions of neutron irradiation	186	-
6.1.4.3.4 Irradiation exposure time	188	514
6.1.4.3.5 Selection and preparation of the starting silicon	188	514
6.1.4.3.6 Neutron irradiation	188	515
6.1.4.3.7 Radioactivity of the irradiated silicon	189	515
6.1.4.3.8 Annealing	189	515ff.
References for 6.1.4.3	190	-
6.1.4.4 Silicon epitaxy (A. LUDSTECK)	192	-
6.1.4.4.1 Introduction	192	-
6.1.4.4.2 Basic technology	193	517
6.1.4.4.3 Scope of the data collection	196	-
6.1.4.4.4 Properties of materials used in Si epitaxy	197	518ff.
6.1.4.4.5 Epitaxial silicon growth	202	527ff.
6.1.4.4.6 Doping during epitaxy	205	528
6.1.4.4.7 Low-pressure deposition	206	-
6.1.4.4.8 Defects in epitaxial layers	207	528
6.1.4.4.9 Evaluation of epitaxial silicon films	207	528
References for 6.1.4.4	210	-
6.1.4.5 Fabrication of layers (subsections 6.1.4.5.0–7, E. DOERING, 6.1.4.5.8–12 L. SCHLEICHER)	213	529ff.
6.1.4.5.0 Introduction to insulating films	213	-
6.1.4.5.1 Thermal oxidation of silicon	213	529ff.
6.1.4.5.2 Modified thermal oxidation processes	217	533ff.
6.1.4.5.3 Chemical vapour deposition	219	538ff.
6.1.4.5.4 Evaporation	223	-
6.1.4.5.5 Sputtering	224	541
6.1.4.5.6 Anodization	225	-
6.1.4.5.7 Properties of insulating films	225	541
References for 6.1.4.5.0–6.1.4.5.7	233	-
6.1.4.5.8 Requirements on metal layers	593	624
6.1.4.5.9 Metal deposition	595	625ff.
6.1.4.5.10 Properties of metals used for deposition	604	634ff.
6.1.4.5.11 Intrinsic properties of metal layers	610	636ff.

	Data	Figures
6.1.4.5.12 Residual gas dependent properties of metal layers	613	639 ff.
References for 6.1.4.5.8–6.1.4.5.12	621	–
6.1.4.6 Litography (H. MADER)	250	542 ff.
6.1.4.6.0 Introduction	250	542 ff.
6.1.4.6.1 Resists	250	543 ff.
6.1.4.6.2 Photolithography	251	542 ff.
6.1.4.6.3 Electron-beam lithography	260	548 ff.
6.1.4.6.4 X-ray lithography	265	551 ff.
6.1.4.6.5 Ion-beam lithography	270	553 ff.
References for 6.1.4.6	274	–
6.1.4.7 Etching processes (H. MADER)	280	556 ff.
6.1.4.7.1 Wet etching	280	–
6.1.4.7.2 Wet etching techniques	281	–
6.1.4.7.3 Wet etching processes for pattern generation	281	556
6.1.4.7.4 Wet etchants	282	–
References for 6.1.4.7.1–6.1.4.7.4	301	–
6.1.4.7.5 Dry etching	305	–
6.1.4.7.6 Ion etching processes	307	556 ff.
6.1.4.7.7 Reactive dry etching processes	319	558 ff.
6.1.4.7.8 Systems used for reactive dry etching	325	566 ff.
6.1.4.7.9 Gases used in reactive dry etching	328	–
References for 6.1.4.7.5–6.1.4.7.9	351	–
6.1.4.8 Final device preparation (E. UDEN)	367	569 ff.
6.1.4.8.1 Survey of package groups	367	569 ff.
6.1.4.8.2 Package components and materials	375	569 ff.
6.1.4.8.3 Assembly methods	387	571 ff.,
6.1.4.8.4 Properties of packages	395	584
References for 6.1.4.8	398	–
6.2 Silicon carbide (W. v. MÜNCH)	403	585 ff.
6.2.0 Introduction	403	–
6.2.1 Technological data	404	585 ff.
6.2.1.1 Figures of merit for devices	404	–
6.2.1.2 SiC phase diagram	404	585
6.2.1.3 Solubility of carbon in silicon	404	585
6.2.1.4 Vapour pressure of silane compounds	404	586
6.2.2 Crystal growth	404	585 ff.
6.2.2.0 Introductory remarks	404	–
6.2.2.1 Melt growth	405	585 ff.
6.2.2.2 Vapour growth	405	586 ff.
6.2.2.2.1 Deposition of polycrystalline SiC	405	586
6.2.2.2.2 Lely technique	406	586 ff.
6.2.3 Characterization of crystal properties	407	587 ff.
6.2.3.1 Polytype verification and crystal defects	407	587
6.2.3.2 Electrical properties	408	587 ff.
6.2.3.3 Luminescence	408	588
6.2.4 Devices technology	408	588 ff.
6.2.4.0 Introductory remarks	408	588 ff.
6.2.4.0.1 General processing steps	408	–
6.2.4.0.2 Diode-(rectifier)-fabrication	409	588
6.2.4.0.3 Field-effect transistor fabrication	409	589
6.2.4.0.4 Light-emitting diode fabrication	409	589
6.2.4.1 Diffusion	410	589 ff.
6.2.4.2 Ion implantation	410	590
6.2.4.3 Epitaxy	411	590 ff.

Table of contents

XIII

	Data	Figures
6.2.4.3.1 Vapour-phase epitaxy (VPE)	411	590ff.
6.2.4.3.2 Liquid-phase epitaxy (LPE)	412	591
6.2.4.4 Thermal oxidation	412	591 ff.
6.2.4.5 Surface preparation	413	592
6.2.4.5.0 Introductory remarks.	413	592
6.2.4.5.1 Gaseous etching	413	592
6.2.4.5.2 Molten salt etching.	414	592
6.2.4.5.3 Electrolytic etching.	414	-
6.2.4.6 Contact fabrication	414	-
References for 6.2.	415	-