SEMICONDUCTOR MATERIAL AND DEVICE CHARACTERIZATION

THIRD EDITION

DIETER K. SCHRODER

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Third Edition

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Physical Constants		
Symbol	Name	Value
q	Magnitude of electronic charge	1.60218×10^{-19} C
m_o	Electron mass in free space	9.10938×10^{-31} kg
q/m_o	Charge/mass ratio (electron)	1.75882×10^{11} C/kg
c	Speed of light in vacuum	2.99792×10^{8} m/s
ε_o	Permittivity of vacuum	8.8542×10^{-12} F/m
k	Boltzmann's constant	1.38065×10^{-23} J/K
		8.61734×10^{-5} eV/K
h	Planck's constant	6.62607×10^{-34} J · s
		4.13567×10^{-15} eV · s
A_o	Avogadro's constant	6.02214×10^{26} molecules/kg · mole
kT	Thermal energy	0.02586 eV ($T = 27°$C)
		0.02526 eV ($T = 20°$C)

Source: `http://physics.nist.gov/constants`

Conversion Factors	
1 Å	= 0.1 nm
	$= 10^{-4}$ μm
	$= 10^{-8}$ cm
	$= 10^{-10}$ m
1 μm	$= 10^{4}$ Å
	$= 10^{3}$ nm
	$= 10^{-4}$ cm
	$= 10^{-6}$ m
1 mil	$= 10^{-3}$ in
	= 25.4 μm
1 eV	$= 1.60218 \times 10^{-19}$ J
λ (μm)	= 1.2398/E (eV)
λ (Å)	$= 1.2398 \times 10^{4}$/E (eV)
	= 12.398/E (keV)

Selected Properties of Some Semiconductors at $T = 300$ K.

Semicond	Band Gap (eV)	Electron Mobility* ($cm^2/V \cdot s$)	Hole Mobility* ($cm^2/V \cdot s$)	Static Dielectric Constant	Lattice Constant (Å)	Density (g/cm^3)	Melting Point (K)
Si	1.12	1,500	470	11.7	5.43095	2.328	1685
Ge	0.67	3,900	1,900	16	5.64613	5.327	1231
Diamond	5.45	1,900	1,600	5.5	3.57	3.5	~4000
3C-SiC	2.3	800	40	9.7	4.36	3.2	sublimes
6H-SiC (Hexagonal)	3.03	400	100	9.7	a = 3.081 c = 15.17	3.2	>2100
GaAs	1.42	8,500	400	12.8	5.6533	5.32	1510
GaN (Wurtzite)	3.39	1,500	30	9	a = 3.189 c = 5.185	6.10	1500
GaP	2.26	110	75	11.2	5.4512	4.13	1750
GaSb	0.72	5,000	1,000	15.7	6.0959	5.619	980
InAs	0.36	33,000	460	15.1	6.0584	5.66	1215
InP	1.35	4,600	150	12.4	5.8693	4.787	1330
InSb	0.17	77,000	1,000	17.9	6.4794	5.775	798
AlAs	2.16	1,200	400	10.1	5.6622	3.81	1870
AlSb	1.6	200	420	14.4	6.1355	4.218	1330
AlP	3.0			9.8	5.4510	2.85	1770
CdS	2.5	300	50	11.6	5.8320	4.82	1750
CdTe	1.5	1,000	100	10.8	6.482	5.86	1365
PbS	0.41	600	700	175	5.9362	7.61	1390
PbSe	0.26	1,000	900	250	6.1243	8.15	1340
PbTe	0.32	1,800	900	400	6.4620	8.16	1180
ZnO	3.35	200	180	8.5	a = 3.252 c = 5.213	5.66	—
ZnS	3.66	165	5	8.3	5.410	4.079	2100
ZnSe	2.67	540	30	9.25	5.6676	5.42	1790
ZnTe	2.26	340	100	9.7	6.101	5.72	1568

* Drift mobilities in the purest materials.

Powers of Ten

10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	K
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

SEMICONDUCTOR MATERIAL AND DEVICE CHARACTERIZATION

PREFACE TO THIRD EDITION

Semiconductor characterization has continued its relentless advance since the publication of the second edition. New techniques have been developed, others have been refined. In the second edition preface I mentioned that techniques such as scanning probe, total-reflection X-ray fluorescence and contactless lifetime/diffusion length measurements had become routine. In the intervening years, probe techniques have further expanded, charge-based techniques have become routine, as has transmission electron microscopy through the use of focused ion beam sample preparation. Line width measurements have become more difficult since lines have become very narrow and the traditional SEM and electrical measurements have been augmented by optical techniques like scatterometry and spectroscopic ellipsometry. In addition to new measurement techniques, the interpretation of existing techniques has changed. For example, the high leakage currents of thin oxides make it necessary to alter existing techniques/theories for many MOS-based techniques.

I have rewritten parts of each chapter and added two new chapters, deleted some outdated material, clarified some obscure/confusing parts that have been pointed out to me. I have redone most of the figures, deleted some outdated ones or replaced them with more recent data. The third edition is further enhanced through additional problems and review questions at the end of each chapter and examples throughout the book, to make it a more attractive textbook. I have added 260 new references to bring the book as up-to-date as possible. I have also changed the symbol for sheet resistance from ρ_s to R_{sh}, to bring it in line with more accepted use.

I list the main additional or expanded material here briefly by chapter. There are many other smaller changes throughout the book.

Chapter 1
New sheet resistance explanation; new 4-point probe derivation; use of 4-point probe for shallow junctions and high sheet resistance sample; added the *Carrier Illumination* method.

Chapter 2
Contactless $C-V$ added; integral capacitance augmented; series capacitance added/augmented; free carrier absorption augmented; new lateral profiling section; added Appendix 2—equivalent circuit derivations.

Chapter 3
Augmented circular contact resistance section; added considerations of parasitic resistance in TLM method; expanded barrier height section by adding BEEM; added Appendix dealing with parasitic resistance effects.

Chapter 4
Added section of pseudo MOSFETs for silicon-on-insulator characterization; added several MOSFET effective channel length measurement methods and deleted some of the older methods.

Chapter 5
Added Laplace DLTS; added a section to the time constant extraction portion in Appendix 5.2.

Chapter 6
Expanded the section on oxide thickness measurements; added considerations for the effect of leaky gate oxides on conductance and charge pumping; added the DC-IV method; expanded the section on gate oxide leakage currents; added Appendix 6.2 considering the effects of wafer chuck parasitic capacitance and leakage current.

Chapter 7
Clarified the optical lifetime section; added *Quasi-steady-state Photoconductance*; augmented the free carrier absorption and diode current lifetime method; added leaky oxide current considerations to the pulsed MOS capacitor technique.

Chapter 8
Added the effects of gate depletion, channel location, gate current, interface traps, and inversion charge frequency response to the extraction of the effective mobility. I also added a section on contactless mobility measurements.

Chapter 9
This chapter is new and introduces charge-based measurement and Kelvin probes. I have also included probe-based measurements here and expanded these by including scanning capacitance, scanning Kelvin force, scanning spreading resistance, and ballistic electron emission microscopy.

Chapter 10
Expanded confocal optical microscopy, photoluminescence, and line width measurement.

Chapter 11
Made some small changes.

Chapter 12
This is a new chapter, dealing with *Failure Analysis and Reliability*. I have taken some sections from other chapters in the second edition and expanded them. I introduce failure times and distribution functions here, then discuss electromigration; hot carriers; gate oxide integrity; negative bias temperature instability; stress induced leakage current; electrostatic discharge that are of concern for device reliability. The rest of this chapter deals with the more common failure analysis techniques: quiescent drain current; mechanical probes; emission microscopy; fluorescent microthermography; infrared thermography; voltage contrast; laser voltage probe; liquid crystals; optical beam induced resistance change and noise.

Several people have supplied experimental data and several concepts were clarified by discussions with experts in the semiconductor industry. I acknowledge their contributions in the figure captions. Tom Shaffner from the National Institute of Standards and Technology has continued to be an excellent source of knowledge and a good friend and Steve Kilgore from Freescale Semiconductor has helped with electromigration concepts. The recent book *Handbook of Silicon Semiconductor Metrology*, edited by Alain Diebold, is an excellent companion volume as it gives many of the practical details of semiconductor metrology missing here. I thank executive editor G. Telecki, R. Witmer and M. Yanuzzi from John Wiley & Sons for editorial assistance in bringing this edition to print.

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