2800-2682

Resistor Theory and Technology

Felix Zandman

Chairman, Scientific Director, and CEO, Vishay Intertechnology, Inc.

Paul-René Simon

Consultant

Joseph Szwarc

Chief Engineer, Vishay Israel Ltd



Distributed by SciTech Publishing, Inc.

Contents

,

	Ρ	reface	xi
	Introduction		1
Part I: Theory		5	
1	O	nm's Law—Resistance	5
	1.	Introduction	5
	2.	Electrokinetics	5
		2.1 Solids, 7	
		2.2 Magnitude of Electric Current, 7	
		2.3 Charge Conservation, 8	
	3.	Steady-State Ohm's Law	9
		3.1 Conductivity, 9	
		3.2 Electrostatic Equilibrium of a Conductor, 10	
		3.3 Conductors in a Steady-State Environment, 10	
	4.	5	11
	5.	Elementary Theory of Conductivity (P. K. Drude	
		Model)	12
		5.1 Conduction in a Sinusoidal Environment, 15	
		5.2 Skin Effect, 17	
	6.	Joule's Law	18
	7.	The Limits of Validity of Ohm's Law	19
	8.	Electrodynamics of Steady-State Environments	20
	9.	Conclusion	21

ľ

Contents	5
----------	---

2		eversible Phenomena Associated with hm's Law	23
	. 1.	Introduction	23
	2.	Matthiessen's Rule	24
	3.	Reversibility Associated with Changes in	
		Temperature	25
	4.	Reversibility Associated with Changes in Electric	
		Field	27
	5.	Reversibility Associated with the Magnetic Field	29
	6.	Reversibility Associated with Mechanical Forces and	
		Deformations	30
	, 7.	Conclusion	31
3	irr	eversible Phenomena Associated with	
•		hm's Law	33
	1.	Introduction	33
	2.	Time-Temperature Effects	34
	4.	2.1 Kinetics and Diffusion Phenomena, 34	54
		2.2 Nature of the Transport Force, 35	
		2.3 Study and Determination of the Diffusion	
		Coefficient, 36	
		2.4 Diffusion Mechanisms, 41	
		2.5 Permanent Changes in Resistivity, 43	
		2.6 Oxidation of a Metal or Alloy, 46	
4	Re	esistive Materials	51
	1.	Introduction	51
	2.	Metals and Solid Alloys	52
		2.1 Copper-Nickel and Copper-Manganese-	
		Nickel Alloys, 52	
		2.2 Nickel-Chrome Alloys, 53	
		2.3 Conduction Mechanism in Magnetic	
		Alloys, 55	
	3.	Thin Films	58
		3.1 Thin Films in Use: Description and	
		Electronic Properties, 58	
		3.2 Conduction Mechanisms in Thin Films and the Origina of Neuroparcials Drift 60	
		the Origins of Nonreversible Drift, 60 3.3 Substrates, 63	
	4.	Thick- and Thin-Film Cermets	64
	4.	4.1 Conductivity Mechanism, 64	04
		4.1 Conductivity Mechanism, 64 4.2 Thick-Film Glass-Metal Cermets, 66	
		me inter i thin Gruss-metal Centers, 66	

Contents

	4.3 Thick-Film Organic Cermets, 68	
	4.4 Thin-Film Cermets, 68	74
	5. Conclusion	74
5	Noise Phenomena	75
	1. Introduction	75
	2. Origins of Noise	75
	2.1 Thermal Noise, 76	
	2.2 Excess Noise, Current Fluctuations, 77	
	2.3 Noise Measurements, 80	
	3. Conclusion	84
6	Heat Transfer	85
	1. Introduction	85
	2. Description of Heat Transfer Mechanisms	86
	2.1 Conduction, 86	
	2.2 Convection, 87	
	2.3 Radiation, 88	
	2.4 Heat Exchange through Phase Changes, 89	
	3. General Equations for Conduction	90
	3.1 Energy Balance, 90	
	3.2 Analytical Expressions for the Heat	
	Equation, 92	
	4. Heating in Resistors	· 93
	4.1 Heating in a Cylindrical Resistor, 93	
	4.2 Heating in Flat Resistors, 98	
	4.3 Components as Shown in Fig. 3, 98	
	4.4 Components as Shown in Fig. 4, 101	
	4.5 Transfer at the Interfaces and Contact Resistances, 103	
	5. Conclusion	106
	5. Conclusion	100
Part	II: Technology	107
	Introduction	107
7	Overview of Fixed and Variable Resistors	109
	1. Fundamental Parameters	109
	1.1 Ohmic Value, 109	
	1.2 Nominal Ohmic Value of a Resistor, 110	
	1.3 Dissipation and Nominal Temperature, 111	

v

ſ

Contents

		1.4 Critical Resistance, 113	
		1.5 Temperature Coefficient, 113	
		1.6 Voltage Coefficient, 114	
	2.	Resistors	115
		2.1 General, 115	
		2.2 Wirewound Resistors, 115	
	3.	Potentiometer Characteristics	117
		3.1 Taper and Conformity, 117	
		3.2 Total Mechanical and Electrical Travel, 118	
		3.3 Contact Resistance, 119	
		3.4 Setting Stability, 120	
	4.	Precision Resistors	120
8	Re	esistive Circuits	123
	1.	Introduction	123
	2.	Parasitic Resistance, Insulation, and Connections	123
		2.1 Influence on Ohmic Values, 123	
	3.	Resistor Assemblies (Ratio, Dividers, Bridges, etc.)	127
		3.1 Ratio, 127	
		3.2 Voltage Divider (Potentiometer, Half-bridge,	
		etc.), 128	
		3.3 Wheatstone Bridge, 129	~
	4.	Frequency Response of Resistors	130
9	Po	ower and Wirewound Resistors	135
	1.	Introduction	135
	2.	Low-Power Resistors	136
		2.1 Electrical and Mechanical	
		Characteristics, 140	
	3.	High-Power Resistors	144
	4.	Low-Ohmic Value Power Resistors	147
	5.	High-Power Surface-Mount Resistors	149
	6.	Measurement of Heat Dissipation during Operation	151
	7.	Conclusion	153
0	Pr	ecision Resistors and Resistor Networks	155
	1.	Introduction	155
	2.	Precision Wirewound Resistors	156
	3.	Foil Resistors	156
		3.1 Physical Principles of TCR Control and Adjustment, 160	

1

,

Conten	ts	vii
	4. Thick-Film Precision Resistors	165
	5. Thin-Film Precision Resistors	171
	6. High Precision Low-Ohmic Value Resistors	176
	7. Thermoelectric Effect	178
	8. Comparison of the Different Technologies	180
	9. Conclusion	180
11	Potentiometers and Potentiometric Position	
	Sensors	183
	1. Introduction	183
	2. Potentiometers and Trimmers	184
	2.1 Track Materials and Characteristics, 185	
	2.2 Wipers: Characteristics and Materials, 185	
	3. Displacement Transducers and Precision	
	Potentiometers	194
	4. Practical Results	196
	4.1 Nature and Structure of the Tracks, 196	
	4.2 Wipers, 198	
	4.3 Adjustment, 199	
	4.4 Nonlinear Laws, 199	
	5. Conclusion	205
12	Magnetoresistance and Its Applications: Anisotropic Magnetoresistance in Ferromagnetic Alloys	[^] 207
	1. Introduction	207
	2. Definitions	207
		210
	3.1 Hysteresis Cycles, 2104. Material Selection	215
	5. Sensor Design	216
	6. Applications	218
	6.1 Incremental Magnetic Encoders, 218	
	6.2 Absolute Magnetic Encoders, 219	221
	7. Conclusion	221
13	Nonlinear Resistors	223
	1. Introduction	223
	 Conductivity Mechanisms in Ceramics and Oxides 2.1 Electrical Conductivity of Ceramics, 224 2.2 Ionic Conductivity in Ceramics, 228 	224

•

	3.	Negative Temperature Coefficient Thermistors		230
		3.1 Production Techniques for Ceramic and for Electrode		
		Deposition, 233		
		3.2 Thermistor Types, 234		
		3.3 Typical Applications, 236		
		3.4 Current-Voltage Characteristics, 237		
		3.5 Temperature Sensors (Low Heat		
		Dissipation), 237 3.6 Applications Based on the Nonlinear b-c		
		Region, 238		
		3.7 Applications Based on Current-Time Relations, 239		
	4.	Positive Temperature Coefficient Thermistors		239
		4.1 Chemical Composition and Electrical		
		Properties, 240		
	5.	PTC Thermistor Types		244
	6.	Applications		244
	7.	Varistors		247
		7.1 Varistor Effects, 247		
		7.2 Varistor Structure and Fabrication, 248		
		7.3 Equivalent Circuit, 251		
		7.4 Applications, 252		~
		7.5 Varistor Types, 253		. \
	8.	7.6 Areas of Application, 253 Gas Sensors		254
				254
	9. 10.	Time Constants for Temperature Measurement Conclusion		250
	10.	Conclusion		- 231
Appen	dix	I: A Precision Film Resistor Exhibiting Bulk		
Pı	rope	erties		259
	A.1	Introduction		259
	A.2	Design Concepts		260
	A.3	•		
		Manufacture		261
	A.4	Some Strain Considerations		263
		Limitations		269
	A.6		/	269
	A .7			273
	A.8			273
Appen	dix	II: Quality Assurance		275
Appen	dix	III: Model for Accelerated Lifetime Testing		277
	A.1	Exponential Distribution		277
	A.1 A.2	-		279
	1 3.4	Trothing and Log Trothing Distributions		419

,

Contents		ix
A.3	The Weibull Distribution	280
A.4	Accelerated Aging and the Arrhenius Model	284
A.5	Other Degradation Models	290
Appendix I	V: The Resistance Strain Gage	291
A.1	Introduction	291
A.2	Strain Gage Construction and Configurations	292
A.3	Significant Characteristics and Parameters	295
A.4	Calibration of Strain Gages	298
A.5	Applications	300
Index		303

Ś

.

(