

COURSE NOTES

LOW-TEMPERATURE ELECTRONICS

DISCLAIMER

These are *notes* only, not a formal or rigorous document. I have worked to ensure that the information in these Course Notes correct, but I make no claims regarding the accuracy, completeness, or suitability of the contents of these Course Notes. I have intended the information to be taken in the context of the Course. – R.K.K.

Randall K. Kirschman, Ph.D.

Silicon Valley, California

P.O. Box 391716

Mountain View, CA 94039

U. S. A.

ExtElect@gmail.com

www.ExtremeTemperatureElectronics.com

+1-650-962-0200

Version 5, October 2011

Copyright © 2011 Randall K. Kirschman

CONTENTS

Course Description.....	iv
Course Objectives	iv
Biography of Presenter.....	v
I. About This LTE Course.....	1
II. What is Low-Temperature Electronics?	2
a. “Categories” of low-temperature electronics	2
b. Ingredients & parameters	2
c. Temperatures	3
d. Brief history	6
e. Technologies	7
III. Reasons for Low-Temperature Operation.....	8
IV. Applications of LTE	9
a. Space exploration	10
b. Cold environment.....	10
c. Sensor signal-processing	15
d. Space observatories.....	17
e. Detector array readout.....	22
f. Wind tunnels.....	24
g. Magnetic resonance (NMR, MRI) & spectrometry.....	26
h. Pulse preamps.....	29
i. Microwave-mm waves.....	30
j. Electric power & magnets.....	38
k. Digital circuits & systems	39
l. Cryopreservation of biological specimens.....	48
m. Unique (LT) phenomena, R&D on low-temp phenomenon	48
n. In combination with superconducting materials, devices, circuits or systems.....	48
o. Summary	49
V. General Effects of Reducing Environmental/Operating Temperature	50
a. Benefits of LT operation	50
b. Difficulties, costs/drawbacks	51
VI. Materials Behavior – Semiconductors.....	52
a. Carrier concentration.....	52
b. Mobility.....	57
c. Electrical conduction.....	59
VII. Semiconductor Devices – General	60
a. Device families/classes/types	60
b. Materials.....	60
VIII. Diodes	61
a. General	61
b. P-N junctions.....	61
c. Specific types of diodes.....	62
d. Power diodes.....	62
e. Light-emitting diodes (LEDs).....	64
IX. Optoelectronic ICs.....	66
a. Experimental reports	66
b. Conclusion/summary.....	67

X. Bipolar Transistors	68
a. General	68
b. Conventional silicon & germanium	69
c. Silicon-germanium HBTs.....	71
d. Other types & materials	73
XI. Field-Effect Transistors (FETs).....	74
a. JFETs & MESFETs.....	74
b. MOSFETs (MISFETs, IGFETs).....	78
c. Power MOSFETs	82
d. Other power devices.....	84
e. Power circuits.....	86
f. III-V devices	88
g. Heterojunction FETs	88
XII. Difficulties.....	89
a. Freeze-out.....	89
b. Hot-carrier effects	89
XIII. Noise	92
a. Types of noise	92
b. Factors affecting noise	95
c. Transistor comparison	96
d. Factors of merit FOMs.....	103
e. Measuring low-frequency noise	104
XIV. Design Issues	106
a. Choosing components	106
b. Factors.....	106
c. Temperature/temperature range.....	106
d. Environment – additional stresses.....	106
e. Electrical noise	107
f. Mechanical.....	107
g. Resources	107
h. Custom vs commercial.....	107
XV. Modeling & Simulation.....	108
a. Device and circuit modeling.....	108
b. Assemblies	108
XVI. Measurements	109
a. Temperature measurement	109
b. Cooling.....	109
c. Examples of measurement techniques.....	110
XVII. Materials Behavior – Non-Semiconductors.....	117
a. Thermomechanical – thermal expansion.....	117
b. Thermal conduction, heat capacity, thermal diffusivity	119
c. Electrical conduction.....	122
d. Summary	125
XVIII. Passive Electronic Components	126
a. General	126
b. Resistors.....	126
c. Dielectric properties	128
d. Capacitors.....	130
e. Magnetic properties.....	135
f. Inductors & transformers.....	135

XIX. Wire, Coax, Waveguide, Stripline, Switches, Relays	138
a. General	138
b. Wire.....	138
c. Shielded wire.....	138
d. Coax & waveguide.....	139
e. Connectors, low-frequency	139
f. Connectors, high-frequency	139
g. Switches & relays.....	139
XX. Assembly & Packaging	140
a. General	140
b. Packages & circuit boards	141
c. Die attach.....	141
d. Bonding/microwelding.....	142
e. Soldering & brazing	142
f. Interfacing low temperature–room temperature	143
XXI. Reliability & Aging.....	144
a. How is low-temperature different from room temperature?	144
b. Mechanical stress	144
c. Failure rates	145
d. Temperature cycling studies	146
e. Adaptive circuitry	148
XXII. Radiation Effects	149
a. General	149
b. Radiation effects & management.....	150
c. Ionization effects	150
d. Modification & damage effects.....	151
e. Radiation examples	152
f. Summary	154
XXIII. “Hybrid” LTE – Combining Semiconductor & Superconductor	156
a. General	156
b. Semiconductor – superconductor comparison	157
c. Device level – “Intra-chip”	157
d. Circuit level, microwave	159
e. Circuit level, preamps for SQUIDS	160
f. System level, digital.....	161
g. System level, power	162
XXIV. Concluding Thoughts.....	163
a. Summary	163
b. Future possibilities	163
XXV. Acknowledgements	164
XXVI. Acronyms	165
XXVII. References & Bibliography	R-1

COURSE DESCRIPTION

Operation of electronics at low temperatures is a valuable option for substantially improving performance. Temperature may be thought of as an additional design choice when justified by system performance requirements.

Low-Temperature Electronics (LTE) may be based on semiconductors or on superconductors, or a combination of the two. The focus of this course is *semiconductor* electronics at low temperatures: device behavior, applications, advantages and drawbacks, technical issues and present situation. Basic materials characteristics related to electronics at low temperatures and passive electronic components are included. The temperature range covered in this course extends from room temperature down to absolute zero (0 K), with emphasis on the cryogenic range, approximately -150°C (~ 120 K) and below.

Applications include many areas of science and technology, including astrophysics, particle physics, computing, microwaves, communications, electric power, and biotech. Supercomputers have been built in which critical subsystems are cooled by liquid nitrogen at 77 K (-196°C). LTE microwave receivers for radio astronomy and deep-space communication, as well as signal-conditioning circuits for low-temperature infrared sensors and other cryogenic devices have been in use for decades, operating at temperatures throughout the LTE range. Superconducting and “hybrid” semiconducting/superconducting systems have been applied to cell-phone receivers, and LTE tracking is being developed for cryopreservation of biological specimens.

Benefits from cooling include faster switching, higher efficiency, and lower noise and higher sensitivity. At the same time there are technical challenges, related to component behavior circuit design, integrating the electronic system with the cooling system and overcoming difficulties related to thermal effects.

LTE has been primarily based on the field-effect transistor, of one type or another (JFET, MOSFET, MFSFET, MODFET). Conventional bipolar devices have not been satisfactory, but advanced types such as SiGe HBTs are proving valuable for low-temperature applications.

Although future developments in electronics are difficult to predict, it is likely that low-temperature operation will continued to be used when ultimate performance and operation in extreme environments is needed from devices, circuits, and systems.

COURSE OBJECTIVES

Provide an overview of situations where the technologies of electronics and low temperatures are brought together.

Provide an overview of the applications for low temperature electronics.

Survey the relationships between fundamental phenomena, materials behavior, and device and system characteristics and performance at low temperatures.

Overview the behavior of materials and components used in electronics at low temperatures: metals, ceramics, plastics, passive components, semiconductor materials and devices, and electronic circuits and assemblies.

Provide practical information on materials, devices, circuits and techniques for those involved in low-temperature electronics.

BIOGRAPHY OF PRESENTER

Randall Kirschman is an internationally recognized authority on low temperature electronics. He has been consulting to industry, government and academe since 1980 in the areas of microelectronic materials and fabrication technology, and electronics for extreme temperatures.

Before going into business for himself, he managed the processing laboratory at the R&D Center at a division of Eaton Corporation, where he was responsible for the fabrication of thin-film hybrids for microwave components. Prior to that he was on the staff of the Jet Propulsion Laboratory, performing research on a variety of superconductor and semiconductor materials and devices. During 1990-91 he was a Visiting Senior Research Fellow at the Institute of Cryogenics, University of Southampton, England. and between 1998-2005 was a member of the Physics Department at Oxford University.

He completed his undergraduate studies at the University of California, and earned his Ph.D. in Physics and Electrical Engineering at the California Institute of Technology in 1972.

He edited the 1986 IEEE Press book *Low-Temperature Electronics* and was on the International Advisory Board of *Cryogenics* journal (1988-2010). He has been on the organizing committees of more than half of the meetings on Low Temperature Electronics from 1983 to the present.