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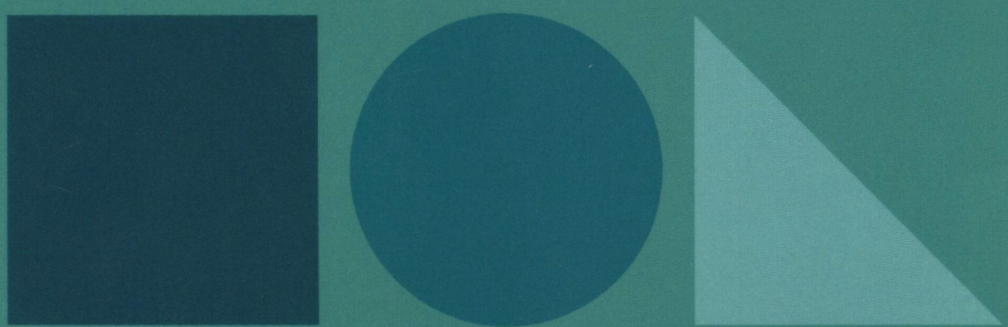
The Physics of Thermoelectric Energy Conversion

H Julian Goldsmid



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The Physics of Thermoelectric Energy Conversion

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This book outlines the principles of thermoelectric generation and refrigeration from the discovery of the Seebeck and Peltier effects in the 19th century through the introduction of semiconductor thermoelements in the mid-20th century to the more recent development of nanostructured materials. It is shown that the efficiency of a thermoelectric generator and the coefficient of performance of a thermoelectric refrigerator can be related to a quantity known as the figure of merit. The figure of merit depends on the Seebeck coefficient and the ratio of the electrical to thermal conductivity. It is shown that expressions for these parameters can be derived from the band theory of solids. The conditions for favourable electronic properties are discussed. The methods for selecting materials with a low lattice thermal conductivity are outlined and the ways in which the scattering of phonons can be enhanced are described. The application of these principles is demonstrated for specific materials including the bismuth telluride alloys, bismuth-antimony, alloys based on lead telluride, silicon-germanium and materials described as phonon-glass electron-crystals. It is shown that there can be advantages in using the less familiar transverse thermoelectric effects and the transverse thermomagnetic effects. Finally, practical aspects of thermoelectric generation and refrigeration are discussed. The book is aimed at readers who do not have a specialised knowledge of solid state physics.

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The Physics of Thermoelectric Energy Conversion

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The Physics of Thermoelectric Energy Conversion

This book is dedicated to my wife, Joan.

Preface

For many years after their discovery in the early part of the nineteenth century the thermoelectric effects were not much more than a scientific curiosity. They eventually found application in the measurement of temperature and in the detection of thermal radiation. However, thermoelectricity is now regarded as a serious means for the conversion of heat into electricity and for heat pumping and refrigeration. The present-day thriving thermoelectric industry has come about through the dedicated research of materials scientists from all disciplines with a major contribution coming from solid state physicists. Considerable advances have been made since the introduction of semiconductor thermoelements in the middle of the twentieth century but much more needs to be done and it is hoped that this book will encourage a new generation of experimental and theoretical physicists to use their talents in the study of thermoelectricity.

Julian Goldsmid
Kingston Beach, Tasmania, Australia
March 2017

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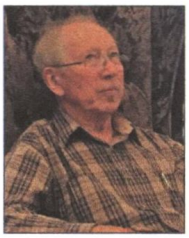
Author biography

H Julian Goldsmid



After graduating from Queen Mary College, University of London in 1949 Julian Goldsmid joined the scientific staff of the General Electric Company in their Wembley laboratories. In 1964 he was appointed Reader in Solid State Physics at the University of Bath and in 1969 he became Professor of Experimental Physics at the University of New South Wales in Sydney. After retiring from his chair in1988 he was appointed Emeritus Professor. From 1989 to 1995 he was Chairman of the Australian National Standards Commission.

Julian Goldsmid has been a Visiting Professor at the universities of Karlsruhe, Sussex, Southampton and the Southern Methodist University in Dallas. Until recently he was a consultant for Marlow Industries. He is a Fellow of the Institute of Physics and Honored Academician of the International Thermoelectric Academy. In 2002 he was awarded the Golden Prize of that organisation. In 2012 he received the Outstanding Achievement Award of the International Thermoelectric Society. He also received the Lightfoot Medal of the Institute of Refrigeration in 1959. He was awarded his PhD degree by the University of London in 1958 and his DSc in 1966. He has been author or joint author of about 200 publications. He is credited with many developments in the field of thermoelectricity, including the first demonstration in 1954 of practical refrigeration using the Peltier effect in bismuth telluride.

List of symbols

A	Cross-section area, mean atomic weight
a	Lattice constant
B	Magnetic field
C	Thermal capacity
c	Diameter of defect
c_V	Specific heat per unit volume
D^*	Detectivity
d	Width
E	Electric field, energy
E_F	Fermi energy
E_g	Energy gap
e	Electronic charge
F_n	Fermi–Dirac integral
f	Fermi distribution function
f_0	Equilibrium Fermi distribution function
g	Density of electron states
h	Planck's constant
$\hbar$	$h/2\pi$
I	Electric current
I_ϕ	Current for maximum COP
i	Electric current density
j	Heat flux density
K	Thermal conductance
K_c	Thermal conductance per unit area of end plates
K_s	Transport integral
k	Boltzmann's constant
L	Length, Lorenz number
l_e	Mean free path of charge carriers
l_t	Mean free path of phonons
M	$(1 + ZT_m)^{1/2}$
m	Mass of free electron
m^*	Density-of-states effective mass
m_I	Inertial mass
m_N	Density-of-states mass for a single valley
N	Nernst coefficient, total number of modes of vibration, number of unit cell per unit volume, number of couples in a module, number of stages in cascade
N_A	Avogadro's number
N_v	Number of valleys in an energy band
n	Subscript for electrons
n	Electron concentration, ratio of layer thicknesses in a synthetic transverse thermoelement
P	Ettingshausen coefficient, Poisson's ratio
p	Subscript for positive holes
$\boldsymbol{p}$	Phonon momentum
q	Rate of heat flow, phonon wave number
Q_1	Rate of heat flow from source
R	Electrical resistance, gas constant, responsivity

R_H	Hall coefficient
R_L	Load resistance
r	Scattering law parameter
S	Righi–Leduc coefficient
s	Compatibility factor
T	Temperature
T_1	Temperature of heat source
T_2	Temperature of heat sink
T_m	Mean temperature, melting point
ΔT	Temperature difference
ΔT^*	Temperature difference between sink and source
ΔT_{max}	Maximum temperature difference
t	Time
u	Velocity of carriers
V	Voltage, mean atomic volume
v	Speed of sound
w	Electrical power
x	$\hbar\omega/kT$
Z	Thermoelectric figure of merit for couple
Z_{NE}	Thermomagnetic or Nernst–Ettingshausen figure of merit
z	Figure of merit for single material
z_d	Phonon drag figure of merit
z_{trans}	Transverse figure of merit
α	Seebeck coefficient
α_d	Phonon drag Seebeck coefficient
α_T	Thermal expansion coefficient
β	Chasmar and Stratton's materials parameter, phase difference
Γ	Gamma function
γ	Grüneisen's parameter
ε	Emissivity
ε_m	Parameter in melting rule
η	Efficiency, reduced Fermi energy
η_g	Reduced energy gap
θ_D	Debye temperature
κ	Thermal diffusivity
λ	Thermal conductivity
λ_e	Electronic thermal conductivity
λ_I	Thermal conductivity of insulation
λ_L	Lattice conductivity
μ	Carrier mobility
ν	Frequency
ξ	Reduced energy
π	Peltier coefficient
π_d	Phonon drag Peltier coefficient
ρ	Electrical resistivity, density
σ	Electrical conductivity
τ	Thomson coefficient, relaxation time
τ_0	Scattering law constant
τ_d	Relaxation time for phonon drag
τ_e	Relaxation time for charge carriers
τ_{eff}	Effective relaxation time for charge carriers

τ_N	Relaxation time for normal processes
τ_R	Relaxation time for umklapp processes
ϕ	Coefficient of performance, angle of transverse thermoelement with normal to layers
ϕ_{max}	Maximum coefficient of performance
χ	Compressibility
ω	Angular frequency
ω_D	Debye angular frequency

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