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This book is dedicated to the giants of science whose shoulders we stand up on and who continue to be the immortal guides to the progress of science and technology and to the creation of a better world.

Contents

Preface

Optical properties, particularly in the infrared range of wavelengths, continue to be of enormous interest to both material scientists and device engineers. The need for the development of standards for data of optical properties in the infrared range of wavelengths is very timely considering the on-going transition of nano-technology from fundamental R&D to manufacturing. The recent progress in two-dimensional materials is an example of this evolution in materials science and engineering.

Radiative properties play a critical role in the processing, process control and manufacturing of semiconductor materials, devices, circuits and systems. The design and implementation of real-time, non-contact process monitoring and control methods in manufacturing, such as multi-wavelength imaging pyrometry, spectroscopic ellipsometry and reflectometry, require the knowledge of the radiative properties of materials.

The design and manufacturing of sensors, imagers, waveguides, filters, anti-reflection coatings and lenses, operating in the infrared range of wavelengths, requires a reliable database of the radiative properties of materials.

This book reviews the optical properties of various semiconductors in the infrared range of wavelengths. Some fundamental and experimental studies of the radiative properties of semiconductors are presented. Previous studies, potential applications and future developments are outlined.

In chapter 1, an introduction to the radiative properties is presented. A brief overview of the optical and thermal properties is presented in chapter 2. Examples of the instrumentation for the measurements of the radiative properties are described in chapter 3. In chapters 4–13, case studies of the radiative properties of several semiconductors are elucidated. The modeling and applications of these properties are explained in chapters 14 and 15, respectively. In chapter 16, examples of the global infrastructure for these measurements are illustrated.

Foreword

This year marks the 25th anniversary [1] since the Defense Advanced Research Projects Agency (DARPA) and the US Air Force Wright Laboratory contracted with Texas Instruments (TI) [2, 3] to develop a next generation flexible semiconductor wafer fabrication system called the Microelectronics Manufacturing Science & Technology (MMST). The $100 million, MMST Program, was a 5-year R&D effort, initiated under the leadership of Dr Arati Prabhakar (Director, DARPA, July 2012–January 2017), to develop a wide range of new technologies for advanced semiconductor manufacturing. The major highlight of the program was the demonstration, in 1993, of sub-3-day cycle time for manufacturing 350-nm CMOS integrated circuits. This was mainly enabled by the development of 100% single-wafer processing.

Around the same time, work had begun on the development of a Multi-Wavelength Imaging Pyrometer (M-WIP) (figure 1), at the New Jersey Institute of Technology (NJIT), under the sponsorship of the US Air Force Wright Laboratory and DARPA (then ARPA)—Microelectronics Technology Office.

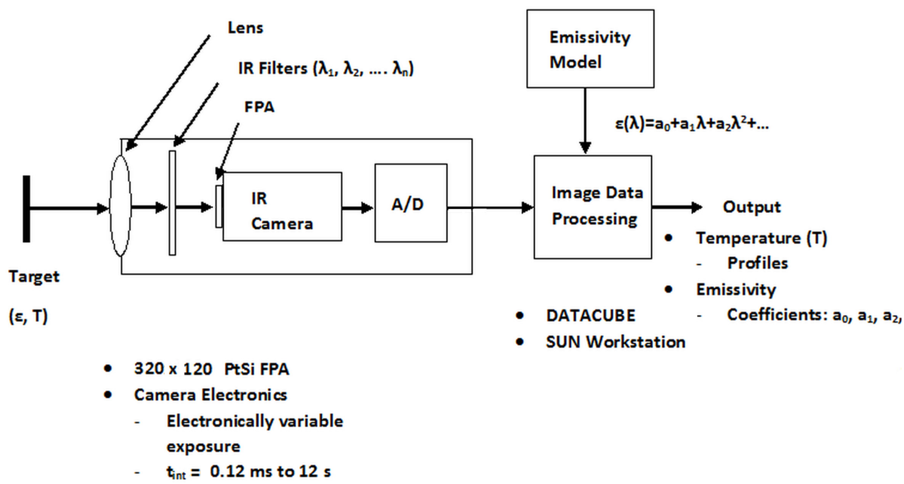

Figure 1. Multi-Wavelength Imaging Pyrometer [4].

The main components for the development of M-WIP for applications in remote sensing of temperature profiles of targets with unknown emissivity were as follows:

- Lens or array of micro lenses
- Infrared filters
- IR Camera/Focal Plane Array (FPA)
- Read Out Integrated Circuits/Electronics
- Image Data Processing Unit
- Control System Software
- Emissivity Model.

Under the sponsorship of the US Department of Defense/Defense University Research Instrumentation Program (DURIP), NJIT acquired a Spectral Emissometer (SE). By utilizing an in-line Fourier transform infrared (FTIR) spectrometer, SE was designed specifically to facilitate simultaneous measurements of surface spectral emittance and temperature by using optical techniques over the near and mid-IR spectral range and temperatures ranging from 300 K to 2000 K [5]. This non-contact, real-time technique enabled the measurements of the radiative properties of materials as a function of temperature and wavelength. Advanced Fuel Research (James Markham) [6] was responsible for the development of the Spectral Emissometer.

The US Department of Energy/National Renewable Energy Laboratory (NREL), Sematech (Don Lindholm, Arun Nanda, T Speranza) and several Semiconductor Research Corporation (William T Lynch, William Holton) member companies joined in this effort.

I acknowledge with thanks the fruitful discussions, over the years, with Advanced Fuel Research (James Markham); BTL Fellows Inc. (Martin P Lepselter); Cavendish Labs, Cambridge University (Paul Timans, K U Ahmed); City University of New York (Jacob Trevino); David Sarnoff Research Center (Bawa Singh, Michael Leahy, David Richman, Jon Thomas); D2IR Inc. (Peter Kaufman); Georgia Tech (Zhuomin Zhang); Harmon Sensors (Alex Stein); Massachusetts Institute of Technology (Jeff Hebb); National Institute of Standards and Technology (NIST—the late David Dewitt, Raju Datla, Benjamin K Tsai, Leonard M Hanssen); National Renewable Energy Laboratory (Bhushan Sopori); Online Technologies (Peter Solomon); Rochester Institute of Technology (Lynn Fuller and Santosh Kurinec); Stanford University (Krishna Saraswat, Mehrdad Moslehi); US Army at Fort Monmouth (Richard Lareau); Wright Patterson Air Force Base; several companies including Advanced Micro Devices; Applied Materials (Bruce Adams); AST-Steag (Jeff Gelpey); CVC (Mehrdad Moslehi); Dainippon Screen; Emcore; Epitax (Greg Olson, Krishna Linga); IBM; Intel; Lucent Technologies (Anthony T Fiory); Luxtron (Charles Schittinger); Philips (Fred Roozeboom); Rockwell International (Krishna Bajaj, Stuart Irvine); Sensarray; Texas Instruments (Pallab Chatterjee) and Vortek.

The participation and support of the late Chancellor Gary Thomas, late Raymond Balcerack (DARPA), late Walter F Kosonocky, late Eugene Gordon, late Constantin Manikopoulos, John C Hensel, Edwin Hou and Bernard Friedland is acknowledged with thanks. The team at NJIT consisted of a large number of scientists including Sergej Belikov, Oktay Gokce, Viphul Patel and Feiming Tong. Some of the research summarized in this book is based on the results that were obtained by an inter-disciplinary team of graduate students from the College of Computing Sciences, College of Engineering and the College of Science and Liberal Arts at NJIT. This includes Sufian Abedrabbo (U. Jordan), Wei Chen, Michael Kaplinsky (Arecont Vision), Chiranjivi Lamsal (Fort Peck Community College and U. Montana), Jun Li (Tsinghua), Nathaniel Mcaffrey (New Hampshire), Sarang Muley (National Standard), Yi Zhang and many others.

The late 1980s witnessed a flurry of activities on research relating to single wafer processing—with a goal to reduce the thermal budget (temperature time product), reduce process-induced contamination and increase process yield. Several equipment manufacturers focused on rapid thermal processing (RTP) as the approach to single-wafer manufacturing. These manufacturers included AET Thermal, AG Associates, Applied Materials, AST Steag, BCT Spectrum, CVC, Dainippon Screen, Eaton, G Squared Semiconductor Corp, General Electric, Jiplec, LEISK, Matson, Peak Systems, Process Products, Tamarack, TEL/Thermco, Texas Instruments, Varian and Vortek. Several tungsten–halogen lamp configurations were implemented in these RTP units [7]—these included linear lamps and multi-zone configuration of lamps in circular geometry. This resulted in demands on thermal management of the lamp/processing chamber as well as the need for real-time monitoring of temperature using pyrometers [8] that operated in a range of wavelengths in the infrared. Vortek proposed a single-lamp approach. These technologies continue to be practiced in the industry today.

As new materials begin to evolve, the radiative properties of semiconductors will continue to be of enormous interest to material scientists, engineers and technologists. The challenges will be to address issues such as surface/interface roughness, free carrier absorption in bulk/multi-layers as well as in two-dimensional materials and structures [9, 10]. Some efforts have been made in the literature to address surface roughness using the bidirectional reflectance distribution function (BRDF) via Monte Carlo simulations [11].

Radiative properties of semiconductors have direct applications in the design and fabrication of materials, devices, circuits and systems, particularly in the infrared, such as bolometers/microbolometers [12, 13], coatings, detectors/imagers, filters, lenses, light emitting diodes, photonic crystals, selective absorbers/emitters and solar cells/thermophotovoltaics [14]. They are critical for real-time process monitoring and control in manufacturing.

Next year, DARPA celebrates sixty years since its inception in 1958 [15]. Its efforts to bring convergence to a variety of technologies and products of interest to the Department of Defense and the civilian sector have been unique and unparalleled. At the same time, DARPA has been the major force in minimizing the time of transition from fundamental R&D to manufacturing to product availability in the market.

In putting together the various components of this overview, I thank NSF I-Corps (Michael A Ehrlich, Judith A Sheft), US Army Research Office, US Air Force Office of Scientific Research/Wright-Patterson Air Force Base, the US Department of Defense, DARPA, US Department of Energy/National Renewable Energy Laboratory, New Jersey Commission on Science and Technology (Jay Brandinger), Semiconductor Research Corporation and Sematech for the financial as well as the intellectual support.

Much of the write-up of this Foreword has taken place during flights between Newark, NJ and Dallas, TX. I thank Russ George for sharing his work on the oceans [16] and Randell Mill's work on the SunCell [17] and magnetic polymers [18] during one of these flights.

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10 May 2017

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Author biographies

N M Ravindra

N M Ravindra (Ravi) is Professor of Physics at the New Jersey Institute of Technology (NJIT). He was the Chair of the Physics Department (2009–13) and Director, Interdisciplinary Program in Materials Science and Engineering at NJIT (2009–2016).

Ravi is the Editor-in-Chief of *Emerging Materials Research* (www.icevirtuallibrary.com/content/serial/emr). He is Series Editor of *Emerging Materials: Processing, Performance and Applications*, Momentum Press (www.momentumpress.net/). He has been a frequent Guest Editor of *JEM*, the *Journal of Electronic Materials* (www.tms.org/pubs/journals/JEM/jem.aspx); *JOM* (www.tms.org/pubs/journals/JOM/JOMhome.aspx). He serves on the editorial board of several international journals and book series that are dedicated to materials science and engineering.

Before joining NJIT in 1987, Ravi had been associated with Vanderbilt University, the Microelectronics Center of North Carolina (MCNC), North Carolina State University, International Center for Theoretical Physics (ICTP-Trieste), Politecnico di Torino, CNRS associated labs in Paris and Montpellier.

Ravi holds a PhD in Physics from Indian Institute of Technology (Roorkee, India), MS & BS in Physics from Bangalore University, India. Ravi and his research team have published over 300 papers in international journals, books and conference proceedings; his team has several pending and two issued patents; he has organized over 30 international conferences; and he has given over 75 talks in international meetings.

His research activities have been sponsored by agencies including the US Department of Defense (DOD), Defense Advanced Research Projects Agency (DARPA), SEMATECH, Semiconductor Research Corporation, US Department of Energy/National Renewable Energy Laboratory (DOE/NREL), US Department of Education, National Aeronautics & Space Administration (NASA), US Army Research Office, US Air Force of Scientific Research, New Jersey Commission on Science and Technology and the National Science Foundation.

Ravi's research interests include education, energy, health, materials, manufacturing and the Physics of Sports. He has been a frequent keynote speaker in several international conferences and has won several awards in the US and abroad.

Ravi is the co-editor of Transient Thermal Processing Techniques in Electronic Materials (TMS—The Minerals, Metals, Materials Society, 1997); he is the co-author of *Black Silicon: Processing, Properties and Applications* (Momentum Press, 2016).

Here are some of the links to Ravi's Papers etc:

https://scholar.google.com/citations?user=MNoHLhys8zkC&hl=en

https://www.researchgate.net/profile/Nuggehalli_Ravindra

https://njit.academia.edu/RavindraNuggehalli

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Sita Rajyalaxmi Marthi (Laxmi) received a BSc in Physics and MSc in Applied Physics from Osmania University, Hyderabad, India, in 2006 and 2009, respectively. Laxmi is currently pursuing a PhD in Materials Science and Engineering at the New Jersey Institute of Technology. Her research interests are related to the optical properties of Black silicon, related materials and device structures. Laxmi is a co-author of *Black Silicon: Processing, Properties and Applications* (Momentum Press, 2016).

Asahel Bañobre

Asahel Bañobre received his BS with Honors and MS in Applied Physics from the New Jersey Institute of Technology (NJIT) in 2003 and 2006, respectively. From 2005 to 2015, Asahel worked as a Test Engineer at Kulite Semiconductor Inc. where he contributed to the optimization and automation of device test procedures and the development of custom product prototypes. Currently, he is pursuing his PhD in Materials Science and Engineering at NJIT. His doctoral study focuses on the design, modeling, fabrication and characterization of uncooled infrared microbolometers. His research interests include semiconductors, MEMS integrated sensors and transducers such as pressure and temperature sensors, and infrared detectors.