Radioisotope Thin-Film Powered Microsystems

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To my grandparents
Ammamma and Tatagaru
and my parents
Usha Rani and Vijaya Sekhar Duggirala

Rajesh

I am thankful to my family and grateful to my friends. I am thankful and grateful to my wife for being both.

Shankar

Preface

This book presents the technical accomplishments of research that started with the intent of realizing radioisotope micro-power sources suitable for microelectromechanical systems, and subsequently broadened into exploring other micro-scale applications of the unique properties of radioactivity. The text primarily discusses the radioisotope powered electromechanical micro power generators developed as part of the research, and their applications in long lifetime wireless sensors. These electromechanical micro power generators utilize very low quantities of radioisotope fuels, to minimize radiation hazard and safety concerns, and use high efficiency pulsed release of energy to amplify the low power output of low activity radioisotopes by 10^3–10^5 to power microsystems. The text also introduces other micro-scale applications of radioactivity by presenting radioactivity based counting clocks. The success in the demonstration of the above two applications have encouraged us in the SonicMEMS Laboratory at Cornell University to successfully explore new and exciting micro-scale applications of radioisotopes such as massively parallel nano-scale lithography, self-powered lamps, and self-powered ultra-high vacuum pumps and gauges.

This research started in year 2000 when we were investigating micro power generators suitable for long lifetime microsystems including wireless sensor networks. Reliable, compact, and long lifetime micro power sources are needed to successfully deploy wireless sensor networks for applications ranging from environmental monitoring to national security. Our investigations revealed that there were no commercial or even research stage micro power sources available that could satisfy the requirements of the wireless sensor networks. We identified that the main limitation of the available micro power sources was the low energy density of fuels being used, and started exploring the use of high energy density radioisotope fuels to micro power sources. Radioisotope fuels also have the advantage of being very reliable under a wide range of environmental conditions, as the rate of isotope disintegration does not change with ambient conditions. Initially guided by our nuclear engineering colleagues at University of Wisconsin-

Madison, we embarked on this exciting area of research, and to our surprise and delight, discovered new and exciting phenomenon in electrostatics, vacuum science, surface science, and materials science, that led to the research and development of novel applications of radioisotopes at the micro scale.

While we are successfully solving the technological problems currently limiting microsystems by applying the unique properties of radioisotopes, we are aware that the biggest hurdle to the widespread adoption of radioisotope technologies is the perception that radioisotopes are unsafe and should be avoided as much as possible. This is both because of a lack of general knowledge about radioisotopes, and a lack of awareness among the public about the widespread use of radioisotopes around us. In spite of radioisotopes and their applications ranging from nuclear power to nuclear arms playing an important role in all our lives, even engineering students rarely get exposed and educated in the basics of radioactivity. The physics and health-physics of radioisotopes are only taught on a need-to-know basis to people experimenting with radioisotopes in medical and biological sciences. The science and technology of producing and handling radioisotopes is even more elusive, due to the small number of companies that produce radioisotopes commercially. This lack of knowledge prevents a rational cost benefit analysis for every radioisotope application, as was done in the past, where several radioisotope based commercial devices were approved by the Nuclear Regulatory Commission and Food and Drug Administration, including:

1. Tritium powered light sources: These include self-powered exit signs, and watches. These sources use tritium with activities in the range from microCuries to 10–20 Curies. These light sources are regulated by the Nuclear Regulatory Commission and have been approved for use even in elementary schools and airplanes, where highly reliable function is needed to potentially save lives.
2. Gas ionizers: Nickel-63 is used in airport gas detectors to ionize the gas atoms, effusing off the wipes that are used to collect samples from luggage. Although other technologies for gas ionization are possible, the ultimate reliability and

decreased chances of false-negatives in testing provide the justification for the use of radioisotopes to potentially save lives.

3. Smoke detectors: Americium-241 (10 microCurie) is used in smoke detectors for its alpha radiation, which is directed toward an alpha particle detector placed across an air chamber. When smoke enters the air chamber, the smoke particles stop the alpha particles from the crossing the air chamber and being incident on the detector. The lack of alpha particle radiation at the detectors serves as a smoke signal. The stability of alpha particle emission by Americium-241, compared to other ion-emission technologies, enables a highly reliable smoke detector that can save lives.
4. Radioisotope power sources on space missions: NASA uses radioisotope sources (based on plutonium alpha emission), that provide power for several years to tens of years required for mission. Here, no other source would provide the reliability needed for such missions.
5. Radioisotopes in Medicine: Radioisotopes are used everyday in various medical procedures to save lives. These procedures include Positron Emission Tomography (PET) and radiation therapies for many types of cancer. In PET therapy, the specific positron generated by radioisotopes is detected by the resulting gamma particles. In cancer therapy, neutron–boron reaction is used to cause local damage to tissue. Additionally, radioisotopes are used in the discovery of biological phenomena. In many biological labs, radioisotope labeling is used to trace proteins and DNA by size and mass on X-ray film.

In all of the above cases, a risk-benefit analysis led to the commercial acceptance of the devices, because these devices were reliable, and had the potential to save lives. In the case of microsystems such as sensor networks, we face the same choice. Can we develop a technology that might provide high reliability and operation in harsh environments, such that the true benefit of sensor networks to mankind can be achieved? We answer this in the affirmative, with the material in this text. We also introduce the basics of the physics and the health physics of spontaneous disintegration, so the public can make a rational risk-benefit assessment of all the new applications.

We hope that this new area of radioisotope based micro-power sources and this text book will excite educators, policy makers, environmentalists, and the public at large to appreciate radioisotopes and their various applications that might make our lives safer in the future.

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Acknowledgement

We would greatly like to thank the tax-payers of the United States of America and the program managers at DOE and DARPA who funded this work. Without their support, this idea would have remained an interesting curiosity.

We would also to thank the team of Nuclear Engineers at University of Wisconsin-Madison, Prof. Michael Corradini, Prof. James Blanchard, and Prof. Douglas Henderson, who had the courage to support a MEMS group to start radioisotope based microsystem research. We would also like to thank Dr. Madan Dubey and Dr. Ron Polcawich who supported the fabrication of micro fabricated devices at the Army Research Labs. Numerous industrial engineers at Isotope Products Labs and NRD helped in realizing how much we needed to rediscover about radioisotope thin films.

The material presented in this book is a culmination of work and intellectual contributions from several current and previous students of the SonicMEMS Laboratory, including Dr. Hui Li, Prof. Hang Guo, Dr. Norimasa Yoshimizu, Dr. Shyi-Herng Kan, Steven Tin, and Yuerui Liu, in addition to the authors of this book.

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