Electronic Thin-Film Reliability

Thin films are widely used in the electronic device industry. As the trend for miniaturization of electronic devices moves into the nanoscale domain, the reliability of thin films becomes an increasing concern. Building on the author's previous book, *Electronic Thin Film Science* by Tu, Mayer, and Feldman, and based on a graduate course at UCLA given by the author, this new book focuses on reliability science and the processing of thin films. Early chapters address fundamental topics in thin-film processes and reliability, including deposition, surface energy, and atomic diffusion, before moving on to systematically explain irreversible processes in interconnect and packaging technologies. Describing electromigration, thermomigration, and stress-migration, with a closing chapter dedicated to failure analysis, the reader will come away with a complete theoretical and practical understanding of electronic thin-film reliability. Kept mathematically simple, with real-world examples, this book is ideal for graduate students, researchers, and practitioners.

King-Ning Tu is a Professor in the Department of Materials Science and Engineering at the University of California at Los Angeles. Since receiving his Ph.D. in Applied Physics from Harvard University in 1968, he has gained 25 years' experience at IBM T.J. Watson Research Center as a Research Staff Member in the Physical Science Department. He is a Fellow of the American Physical Society, the Metallurgical Society, the Material Research Society, and an Overseas Fellow of Churchill College, Cambridge. He is also an academician of Academia Sinica of the Republic of China. Professor Tu has published over 450 journal papers, authored a book (*Solder Joint Technology*, 2007) and co-authored a textbook (*Electronic Thin Film Science*, 1992).

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Dedicated to my wife, Ching Chiao Tu

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Preface

The book is intended as a textbook for first and second year graduate students in the Department of Materials Science and Engineering. It can also be used as a reference book for self-study by engineers in the microelectronic industry. The early chapters in this book evolve from *Electronic Thin Film Science*, by K. N. Tu, J. W. Mayer, and L. C. Feldman, and published by MacMillan in 1993. The contents of this book have been taught in a graduate class on “Thin film materials science” at UCLA for over 15 years.

The emphasis in thin-film research is twofold: (1) to invent or to process new thin-film materials having useful functions in applications, and (2) to improve the reliability of functional thin films in large-scale applications, for example, in consumer electronic products. To achieve these goals, on the basis of the discipline of thin-film materials science, requires the study of correlation among structure—properties—processing—performance—reliability of thin films. There are textbooks on the processing of thin films, such as deposition methods by sputtering, electroplating, and MBE growth. There are also textbooks on characterization techniques such as SEM, TEM, RBS, XPS, UPS, Auger, and STM, etc. However, there is no textbook on thin-film reliability science.

When a technology is mature and in mass production, and has widespread application, reliability issues become crucial. As the trend of miniaturization of electronic devices moves into the nanoscale region, the reliability concern of nanotechnology will become serious in the near future. Reliability of nanotechnology may depend on the experience and understanding of reliability in microelectronic technology.

To have a reliable device, it is important to include the concept of reliability into the design and processing of materials in making the device. Thus, there is a strong link between the processing and reliability. It is the goal of this book to combine the science therein, but the emphasis will be on reliability.

What is reliability science? Typically, we tend to assume that the microstructure in a device is stable in its lifetime of usage. Unfortunately, this is not true. In most electronic applications, we must apply an electric field or an electric current. Under a high current density, electromigration occurs in the microstructure and induces circuit failure due to opening by void formation or shorting by extrusion. The high current density causes joule heating and the temperature rise will lead to thermal stress in the device between different materials having different thermal expansion coefficients. The stress gradient and temperature gradient, in addition to electromigration, may induce atomic diffusion and lead to microstructure change and phase transformations. Under a stress gradient or temperature gradient, it means that pressure or temperature is not constant. What is unique in these changes is that they occur in the domain of non-equilibrium thermodynamics or irreversible processes. The basic science that is needed in order to develop an understanding of these reliability problems and to find a way to prevent them from occurring is reliability science.

At the start of the book, the fundamental subjects needed in thin-film processes and reliability such as deposition, surface energy, atomic diffusion, and elastic stress–strain in thin films will be reviewed. The essence of irreversible processes and entropy production will be covered in Chapter 10. This is followed by chapters on electromigration, thermomigration, and stress-migration, with a few examples of reliability failure. The final chapter will discuss failure analysis on the basis of both physical and statistical analyses. Appendixes A–G cover some of the very basic and useful topics and data related to this book.

It is worth mentioning that electromigration itself does not necessarily lead to microstructure failure. Only when there is atomic flux divergence in the microstructure may failure occur. Furthermore, even flux divergence is not enough to cause failure. We require a non-constant volume process in which lattice shift does not occur. In the absence of lattice shift, the non-constant volume change can lead to the generation of extra lattice sites which account for void and hillock or whisker formation.

In preparing the book, I have been helped greatly by students in my classes and in my research group. In particular, I would like to thank Miss Hsin-Ping Chen, Miss Tian Tian, and Mr. Daechul Choi at UCLA for typing part of the text, and revising figures and references. Mr. Choi proofread the book. I would also like to thank Professor Andriy M. Gusak at Cherkasy National University, Ukraine, for a review of Chapter 10 and Chapter 15. Appendix C on the derivation of electron windforce was taken from the lecture notes of Prof. Gusak. Research funding support on reliability study from NSF, SRC, National Semiconductor Corporation, Hitachi (Japan), Seoul Technopark (South Korea), and Advanced Semiconductor Engineering (Taiwan, ROC) is acknowledged.

King-Ning Tu, October 2009.