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# Solder Joint Technology

## Materials, Properties, and Reliability

Springer

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# Preface

The trend in consumer electronic products will be more and more wireless, portable, and handheld. To manufacture these multifunctional products, high-density circuit interconnections between a Si chip and its substrate are needed. Flip chip solder joint technology, by which an area array of solder bumps is used to join a chip to its substrate, is growing rapidly in demand. Flip chip technology is the only technology that can provide a large number of such interconnections with reliability. Solder joints are ubiquitous in electronic products.

Due to environmental concerns regarding the toxicity of Pb-based solders, the European Union Parliament issued a directive to ban the use of Pb-based solders in consumer products on July 1, 2006. The application of Pb-free solder joints to a wide range of devices is urgent, and R&D of Pb-free solders for electronic manufacturing is thus very active at the moment. While solder joint technology is mature, Pb-free solder technology is not, hence its reliability must be proven. For example, electrical shorting due to Sn whiskers, electrical opening due to electromigration, and joint fracture due to dropping of handheld devices to the ground are challenging reliability problems in the application of Pb-free solders. To solve these problems in a largely technology-based manufacturing industry, scientific understanding and solutions are required. The copper–tin reaction is essential in the formation of a solder joint and the failure of such joints is due to externally applied forces as in electromigration. A fundamental understanding of the copper–tin reaction and the effect of external forces on solder joint reliability is critical and is emphasized in this book.

There are two themes in this book. The first is the copper–tin reaction as a function of time and temperature, and the second is the effect of external forces on the reaction. Actually the second theme also emphasizes phase transformations under an inhomogeneous boundary condition. Typically, metallurgical phase transformations occur under constant temperature and constant pressure so that Gibbs free energy is minimized. However, in thermomigration or stress migration (creep) of a solder joint, the temperature or the pressure is not constant because there exists a temperature gradient or a stress gradient to drive the phase change, so an equilibrium state with a minimum free energy will not be reached. In electromigration, a potential gradient exists across the sample too. These are irreversible processes.

The contents of the book are divided into two parts. Part I, from Chapters 2 to 7, covers copper–tin reactions, and Part II, from Chapters 8 to 12, covers electromigration and thermomigration of solder joints.

Chapter 1 is an overview of flip chip technology. Why it is important and the known reliability problems are explained. The future trend in electronic packaging technology and its effect on solder joint technology are covered. Chapter 2 concerns wetting reactions between molten eutectic solder and bulk Cu foils. The unique morphology of scallop-type Cu-Sn intermetallic compound formation is emphasized and analyzed. Chapter 3 considers about Cu-Sn reactions in thin films. Thin-film reactions are important since most metallization on Si devices to be joined by solder is in thin film form. Spalling of thin-film intermetallic compounds is a unique reliability phenomenon. Chapter 4 covers solder reaction in a flip chip configuration in which the reaction occurs on two interfaces. The two interfacial reactions interact with each other and the interaction is a reliability issue. Chapter 5 presents a theoretical analysis of flux-driven ripening of scallop-type growth of Cu-Sn intermetallic compounds under the constraint of a constant surface area. Theoretically derived and experimentally measured distribution functions of scallops are compared. Chapter 6 examines spontaneous Sn whisker growth which is a creep phenomenon. The necessary and sufficient conditions of whisker growth are discussed, and how to conduct an accelerated test of Sn whisker growth and how to prevent its growth are presented. Chapter 7 discusses briefly solder reactions on nickel, palladium, and gold surfaces. In addition to copper, these metals are used as under-bump metallization in devices. Chapter 8 covers the fundamentals of electromigration and the differences between electromigration in solder alloys and in Al or Cu interconnects. Why electromigration in solder joints has only recently become a reliability problem is explained. Chapter 9 concerns the unique behavior of electromigration in flip chip solder joints, especially the effect of current crowding. It is a key chapter of the book. The unique failure model due to pancake-type void formation at the cathode contact interface is presented. Chapter 10 examines the interaction between electrical and chemical forces in solder joints. The polarity effect of electromigration on intermetallic compound formation at the cathode and the anode interfaces of a solder joint is presented. Chapter 11 describes the interaction between electrical and mechanical forces. An accidental drop to the ground is the most frequent cause of failure of portable devices. Impact test and drop test of solder joints are analyzed, and the effect of electromigration on these tests is discussed. Chapter 12 considers thermomigration in solder joints, and the interaction between electrical and thermal forces is analyzed. Microstructure instability in a eutectic two-phase structure driven by a temperature gradient is adressed.

I started solder research in 1965, when I began my Ph.D. dissertation on cellular precipitation of Sn lamellae in SnPb alloys. However, the contents of this book are based on thirteen Ph.D. dissertations finished in the University of California at Los Angeles since 1996, supported by the National Science Foundation (Dr. Bruce MacDonald), Semiconductor Research Corporation (Dr. Harold Hosack), and several microelectronic companies (especially Dr. Paul A. Totta of IBM East Fishkill, NY, Dr. Fay Hua of Intel, Santa Clara, CA, Dr. Luu Nguyen at NSC, Santa Clara, CA, Dr. Darrel Frear at Freescale, Phoenix, AZ, and Dr. Yi-Shao Lai at ASE, Taiwan). The dissertations of H. K. Kim, Patrick Kim, Cheng-Yi Liu, Taek Yeong Lee, Woo-Jin Choi, Hua Gan, Albert T. Wu, Emily Shengquan Ou, Minyu Yan, Fei Ren, Jong-ook Suh, Annie Huang, and Tiffany Fan-Yi Ouyang are acknowledged. Also included are the work of several postdocs (Grant Pan, J. W. Jang, Everett C. C. Yeh, Kejun Zeng, J. W. Nah, and L. Y. Zhang) and M.Sc. students (Wang Yang, Ann A. Liu, Jessica P. Almaraz, Quyen Tang Huynh, Xu Gu, Rajat Agarwal, Joanne Huang, and Jackie Preciado). I acknowledge the generous support of these students and postdocs and thank them. It is their dedication and hard work that made this book possible.

Many outstanding contributions to solder research have been made by other researchers. Since this book is an introduction to solder joint technology and covers only a small part of the literature on the subject, I was unable to include much of the published work on solder joints in the literature.
I apologize to those colleagues whose work is not included here. Still I hope the book may serve as a steppingstone to reach out to a much broader field of solder and as a reference to future R&D in the field. Indeed, much work on the reliability of Pb-free solder joints remains undone.

While this book is intended for engineers and scientists working on solder joint technology in the electronic manufacturing industry, it might be used as a reference book in a course on reliability science of electronic packaging technology for seniors and graduate students. Because very few textbooks on the subject of electronic packaging technology and reliability science are available, I include in the appendixes the derivations of the diffusion coefficient in vacancy mechanism of diffusion in a face-centered-cubic lattice, the growth and dissolution equation of a spherical particle in the ripening process, and Huntington's electron wind force in electromigration. They are convenient references for analyzing the basic kinetic behaviors of solder joints discussed in this book. This derivation on electron wind force has been taken from the lecture notes of Professor A. M. Gusak at Cherkasy National University, Ukraine. He has been very helpful regarding the kinetic analyses presented in this book, for example, irreversible processes. I am also grateful to Dr. Yuhuan Xu at UCLA and Professor Yiping Wu at Huazhong University of Science and Technology, China, for helpful comments on the drop test in Chapter 11. I thank Professor Chih Chen, National Chiao Tung University, Hsinchu, Taiwan, ROC, and Professor Cheng-Yi Liu, National Central University, Chungli, Taiwan, ROC, for a critical review of the book, and Mr. Jong-ook Suh at UCLA for preparation of all the figures and Miss Fan-Yi Ouyang for revision corrections. Finally, I thank Professor Y. C. Chan of the Department of Electrical Engineering, City University of Hong Kong, and Professor Weijia Wen of the Department of Physics, Hong Kong University of Science and Technology, for hosting my two-month visit to Hong Kong so that I could concentrate on finishing the final version of the book.

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