

# Preface

Simplicity is prerequisite for reliability.

Edsger Dijkstra (1930–2002)

Today’s integrated circuits are among the most complex engineering products ever built by mankind. Every day and around the world, seemingly without notice, *billions* of transistors work flawlessly in our cell phones and other electronic gadgets; the failure of a single transistor alone could render the entire system useless. Having these systems work at all is a testament to the elevated reliability of the components of which they are composed, commonly expressed in “failure in time (FIT)” units. That we define a single unit of FIT as the number of failures that occurs in  $10^9$  device-hours of operation, which is approximately 114,000 years, is no accident—it impressively illustrates the huge reliability requirement of today’s microelectronic components.

Today’s microelectronics revolution all started with the so-called first generation of modern electronics, the invention of electronic switches and miniature vacuum tubes by 1942. The first large-scale computing device, the Electronic Numerical Integrator and Computer (ENIAC), which contained 20,000 vacuum tubes, was an early and extraordinarily impressive result. However, it had reliability issues right from the start—several tubes burned out almost every day, leaving ENIAC non-functional about fifty percent of the time.

Then came the second generation, based on the discovery of the transistor in 1948. This period was mainly characterized by the switch from vacuum tubes to smaller, and much more reliable, transistors.

The 1960s saw the dawn of the third generation of electronics, ushered in by the development of integrated circuits (IC). Together with semiconductor memories, such as random-access memory (RAM) and read-only memory (ROM), they enabled increasingly complex system designs. Subsequently, we witnessed the first microprocessor in 1971. Then in 1973, Motorola developed the first prototype mobile phone, in 1976 Apple Computer introduced the *Apple I*, and in 1981 IBM introduced the *IBM PC*. These developments foreshadowed the *iPhones* and *iPads* that became ubiquitous at the turn of the twenty-first century.

As semiconductor fabrication improved, enabling larger and larger numbers of transistors to be integrated on a single chip, it became imperative for the design community to turn to computer-aided design to address the resulting problem of scale. It was an amazing self-supporting cycle: computer-aided design was facilitated by the improvements in the speed of computers, which were in turn used to create the next generation of computer chips, resulting in their own further improvement!

Throughout history, no other technical law has been as reliable and influential as Moore's Law. It fueled the PC revolution in the 1980s, the Internet in the 1990s, social media in the 2000s, and now the machine learning revolution. New electronic systems extend our senses, helping us see, helping us navigate, and helping us drive safely. Their impact reaches far beyond gadgets: electronic systems affect the way humans work and live. We have truly become a society immersed in mobile electronic devices.

Our increased dependence on electronic systems shines an intense light on their reliability. After all, a system is only as reliable as its weakest link. For example, as our chip structures become smaller and smaller, causing interconnect cross-sections to be continuously scaled down in size, we face increased migration problems, notably electromigration (EM), within our circuit interconnects. Hence, the last several years have seen a tremendous increase in electromigration-aware design approaches. It is now well-accepted wisdom that EM risks arising from ever-smaller structure sizes will become increasingly prominent in the future. If we want to continue producing working circuits in ever-decreasing sizes, we must significantly increase investment in reliability-promoting design methodologies.

This is where this book comes in. The aim is to examine the measures available for designing and manufacturing an electromigration-robust, and hence, reliable integrated circuit; to compare such measures with one another; and to investigate their use in practical, up-to-date design flows. The book not only provides a comprehensive overview of electromigration and its effects on the reliability of electronic circuits, it also introduces the physical process of electromigration and its crucial relationship with current density. The overall goal is to give the reader the requisite understanding and knowledge for adopting appropriate countermeasures.

A book of such considerable scope and depth requires the support of many. The authors wish to express their warm appreciation and thanks to all who helped produce this publication. We would like to mention in particular Martin Forrestal for his key role in writing a proper English version of our manuscript. Our warm thanks go to Dr. Mike Alexander who has greatly assisted in the preparation of the English text; his knowledge on the subject of this book has been appreciated. We thank Andreas Krinke for his contribution to analog design issues and Dr. Frank Reifegerste for the cover design. We also wish to sincerely thank Göran Jerke of Robert Bosch GmbH for his input on determining application-robust design rules, such as current-density limits (Sect. 3.4). Thanks are also due to VDI Verlag for allowing us to reprint excerpts from Matthias Thiele's PhD thesis (VDI Series 9, No. 395). We also thank Petra Jantzen of Springer for being very supportive and going beyond her call of duty to help out with our requests.

Rapid progress will continue to be made in electromigration research and electromigration-aware design in the years to come, perhaps by some of the readers of this humble book. The authors are always grateful for any comments or ideas for the future development of the topic and wish you good luck in your careers.

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