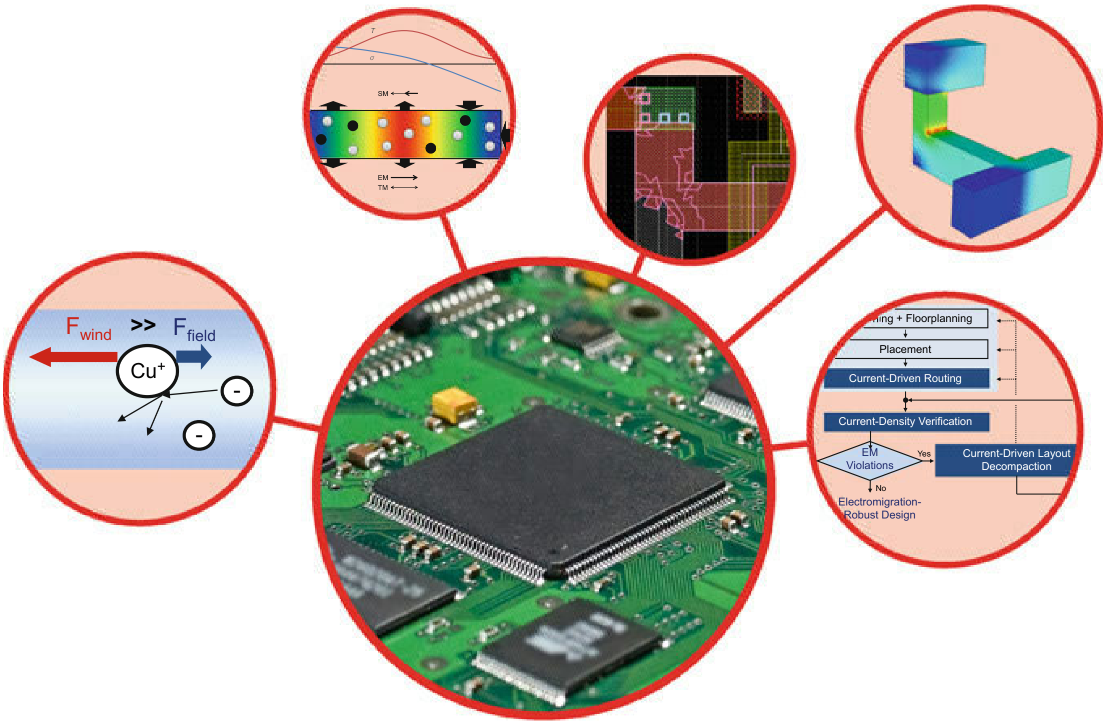
Jens Lienig · Matthias Thiele

Fundamentals of Electromigration-Aware Integrated Circuit Design



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Foreword

The stunning continued reduction in the size of IC structures is bringing interconnect reliability at the scale of individual atoms to the forefront of concern in the dependability of fielded electronic devices. That observation includes several important aspects. First is that the concern is for fielded devices, that is for voids and other material defects that come to exist and affect the component after the overall product is in operation for days, weeks, or months. Second is that the concern is for the anticipated integrity of the interconnect at the scale of individual atoms.

The physical processes responsible for these concerns are not new. These processes have always been present in fielded devices; however, the IC designs implemented by earlier technologies were robust to the defects introduced. Whereas with the present and planned IC structure scales, the material defects constitute dramatic damage or resistance change in the interconnect, thus possible failure or incorrect operation of the IC.

Specifically of concern here are migration processes: electro-, thermal, and stress migrations. The authors of this volume bring years of experience in academic and industrial circuit layout design and in the operational integrity of implemented designs to the elucidation of the current and coming design problems associated with electromigration. In particular, the authors have extensive experience in investigating devices (ICs and PCBs) that failed—often exposed to high current densities, amplified by extreme environmental conditions, for example the electronic devices that are omnipresent in automobile electronics. In this book, the authors present their knowledge for a broad audience. The information is well structured and written in a style professionals and engineering students will find accessible.

However, for both professional designers and engineering students, a full appreciation of design countermeasures for electromigration-induced defects is only possible with a deep understanding of the inner workings of electromigration. To this end, a thorough introduction to electromigration is presented and set in its relationships to thermal and stress migration processes that are also critical in this small scale. The authors augment the fundamental introduction to electromigration with the presentation of finite element modeling for analyzing electromigration effects in specific design situations.

The authors correctly argue that in the overall IC design process, the phase in which attention to electromigration mitigation should be focused is the layout-synthesis stage. In this context, present design methodology is described with options for modifying that methodology to encompass design principles for the prevention of debilitating defects due to electromigration. In addition, measures indicating the robustness of the resulting interconnect to electromigration effects are formulated from an analysis of relevant technological developments.

The extensive experience of the authors provides the basis for their advice on detailed applications for the principles in very specific and important components of ICs. Their skills as educators are evident in the presentation, as circuit designers will certainly be able to use the advice in their own designs requiring increased current-density limits with the overall goal of reducing the negative impact of electromigration on the circuit's reliability. Thus, professionals and engineering students will find it possible to apply the advice in today's IC layout design.

The continued progression of reductions in the size of IC structures expected due to developments in micro- and nanoelectronics, however, will soon require new methods. The authors, thus, turn to the future making proposals for further electromigration-aware IC design principles. These proposals are placed in the context of the future outlook in this field as a whole.

This unique book provides the fundamental science necessary for a sound grounding from which to make practical use of the complete and indispensable application-oriented information regarding the electromigration-aware design of electronic systems. It is a foundational reference for today's design professionals, as well as for the next generation of engineering students.

Charlottesville, VA, USA

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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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