

Preface

Together with bias temperature instabilities and time-dependent dielectric breakdown, hot carrier degradation has been at the forefront of critical reliability issues for half a century. In earlier technologies, devices were operated at relatively high voltages in which highly energetic (“hot”) carriers are created in a rather straight forward manner. Using some *lucky-electron* arguments, where a solitary “lucky” hot carrier is able to cause device degradation, simple yet accurate reliability models could be constructed. In modern scaled technologies, however, the true origin of hot carrier degradation is much more subtle, requiring more detailed knowledge of the multi layered physics of defect creation. A lot of research has been carried out in this field during the last 15 years, triggered significantly by the pioneering work of the group of Karl Hess. During recent years, the rapid introduction of new materials and other technological options has raised a number of new issues and challenges which have to be addressed urgently.

While a lot of progress has been made in the understanding of device degradation brought about by hot carriers, the topic is far from being fully understood, in particular when challenges in future technologies must be resolved. As such, I felt that a thorough and comprehensive collection of the state of the art would be a valuable resource for scientists and engineers working on this phenomenon. I have therefore invited leading authors in the field to summarize their current understanding and review the state of the art in greater detail than is possible in regular journal and conference publications.

The book is structured in three parts and encompasses characterization, defect/device modeling, technological impact, and circuit/compact modeling aspects. In the opening chapter, McMahon et al. (GlobalFoundries) provide an overview of modeling attempts going beyond the simple lucky-electron picture. They summarize the theoretical foundations and contrast these models to those often used in industry to eventually arrive at a qualification scheme compatible with industrial needs. In the next chapter, Rauch and Guarin (State University of New York/IBM) describe the ground breaking energy-driven hot carrier paradigm,

which acknowledges the fact that the energy distribution of the carriers plays a crucial role in degradation. They provide simple and effective approximations to the carrier energy distribution function and demonstrate how they can be used to accurately model hot carrier degradation. In the chapter by Bravaix et al. (ISEN/ST Microelectronics), the authors build on the energy-driven paradigm by Rauch and LaRosa and the work of the Hess group on defect breakage dynamics to construct a refined hot carrier degradation model. They compare their model with simpler models and validate it for numerous technologies and use cases. Based on these fundamental contributions, Tyaginov (TU Wien) summarizes his efforts in creating a comprehensive TCAD model for hot carrier degradation which utilizes a solver for the Boltzmann transport equation for the accurate determination of the carrier distribution function. A detailed study of the impact of the various contributors to the carrier energy distribution function and the peculiarities of the defect generation kinetics as well as their impact on degradation is provided.

As outlined above, detailed knowledge of the carrier distribution function is essential for accurate hot carrier degradation modeling. Unfortunately, this distribution function is the solution of the seven-dimensional Boltzmann transport equation and as such very difficult to obtain. Although this has been a standard TCAD problem for many decades by now, an efficient and user-friendly solution scheme for this highly complex problem remains a challenge. Zaka et al. (GlobalFoundries/University of Udine/IMEP/Institut d'Optique Graduate School/ST Microelectronics) suggest a highly efficient semi-analytic solution scheme for the Boltzmann equation, which is capable of considering full-band aspects as well as various challenging scattering mechanisms including impact ionization and carrier-carrier scattering. In the next chapter, Bina and Rupp (TU Wien) describe their efforts in creating an efficient direct solver for the Boltzmann equation based on a spherical harmonics expansion of the distribution function, under the inclusion of the Pauli Principle, impact ionization, and electron-electron scattering. Contrary to the conventionally used Monte Carlo approaches, this approach allows a deterministic solution of the Boltzmann equation, which is extremely beneficial for the elimination of the noise in the all-important tails of the distribution function.

While recovery of hot carrier degradation is typically neglected for reliability assessment, it can be shown that the degradation is not fully permanent and can be recovered by increasing the temperature. Recent results are summarized by Pobegen (K-AI) who demonstrates that the distribution of reaction barriers is consistent with results of electron-spin resonance measurements on P_b centers, which are silicon dangling bonds at the interface. It is furthermore shown that quite different results are obtained after bias temperature stress, indicating that the link between these two degradation modes is not yet fully understood. In the final chapter of the first part of the book, Aichinger and Nelhiebel (Infineon) provide a detailed tutorial on the charge-pumping technique, which is the most commonly used method to analyze interface states in MOS devices and as such of immense value to our understanding of the time-dependent evolution of the defect profiles. The various suggested modifications of the method are summarized, using hot carrier degradation as an example.

In the second part of the book, the opening chapter by Franco and Kaczer (imec) studies hot carrier degradation in high-mobility SiGe and Ge channel MOSFETs, in which a more severe degradation is expected due to the smaller bandgap compared to Si. They suggest and study gate stack optimization methods which are demonstrated to reduce not only hot carrier degradation but also bias temperature instabilities. Next, Cho et al. (imec) investigate hot carrier degradation in FinFETs, which are the likely end-of-the-road map CMOS architecture. Given the small channel volume and the poor thermal coupling to the substrate, FinFETs (as well as SOI technologies) are prone to increased self-heating effects, which are shown to unfavorably interact with degradation mechanisms.

Lateral double-diffused MOS (LDMOS) transistors have been an important component in the microelectronics industry for decades. Reggiani et al. (University of Bologna/Texas Instruments) present their TCAD approach aimed at the understanding of hot carrier degradation in these complicated structures in terms of the safe operating area. Using a drift-diffusion approach, the impact of device geometry and in particular of the corners around shallow trench isolations is studied and the accuracy of the methodology demonstrated via comparison to experiment. The chapter of Alagi investigates the applicability of a dispersive rate-limited modeling approach to the case of LDMOSFETs. Particular care is taken to capture the degradation for varying bias conditions, which is essential for understanding the behavior of a device in a circuit. Given the large dimensions, the rates can be successfully described by an extended lucky-electron description, and a compact model suitable for the implementation into standard circuit simulators is suggested. In the final chapter of this part, Chakraborty and Cressler (Georgia Institute of Technology) look into hot carrier degradation in silicon-germanium heterojunction bipolar transistors (HBTs), the understanding of which has significantly evolved during the last few years. The authors review experimental evidence, summarize the physics of degradation for these devices based on vertical current transport, and eventually develop and validate an accurate TCAD modeling approach.

The third part of the book is devoted to circuit-related aspects of hot carrier degradation. In the first chapter, Huard et al. (ST Microelectronics) develop a bottom-up modeling approach for circuit reliability prediction for general stress patterns. The model is validated in detail with a particular focus on the interaction with the bias temperature instability, and the authors demonstrate how this methodology can be used to determine accurate design margins. The chapter by Schluender (Infineon) focuses on the identification of the relative impact of hot carrier degradation and the bias temperature instability. It is suggested that depending on the application field, a circuit can be more prone to one of these degradation modes. However, a number of exceptions are highlighted which demonstrate that no conclusions on the dominance of one mechanism can be provided for the general case. In the last chapter, Scholten et al. (NXP) discuss compact modeling approaches to hot carrier degradation and how to guarantee that the conventional DC degradation models remain accurate under transient conditions. The methodology is successfully validated for three rather different devices, namely, HBTs, MOSFETs, and LDMOS devices.

I sincerely hope that the information provided in these chapters proves useful to scientists and engineers working in this challenging field by accurately capturing the state of the art. Furthermore, it is hoped that this book triggers further research into this elusive phenomenon.

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