ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Microelectronics Reliability 47 (2007) 839–840

MICROELECTRONICS RELIABILITY

www.elsevier.com/locate/microrel

Editorial

During the last decades CMOS technology has witnessed a breathtaking progress ushered in by the invention of the integrated circuit. Since then many roadblocks had to be overcome on the way to modern technology, the benefits of which we all enjoy today. In order to save valuable chip area and to boost device performance, critical device dimensions have been reduced to incredibly small values in the nanometer regime. As technology was pushed closer and closer to the fundamental limits of available material systems, it was realized that device reliability was becoming more and more critical.

Device reliability issues have always been part and parcel of technology development and controllability often a requirement for the introduction of a refined and further scaled technology. In particular, at the time of its discovery 40 years ago negative bias temperature instability (NBTI) was one of many reliability issues and only received moderate attention. However, this has changed dramatically as also manifested by an exponential increase in the number of publications on the subject starting from the year 2000. Nowadays, of all the known instabilities, NBTI has turned out to be indeed very critical for highly scaled pMOSFETS, displaying a shift in important device parameters – such as the threshold voltage – when a large negative voltage is applied at the gate. The increasing importance of NBTI in modern technology has been largely attributed to the ever increasing electric fields inside the gate-oxide, the omnipresence of nitrogen, and the increasing operating temperatures, all as a result of device scaling.

Many explanations of NBTI have been given over the years, where often the depassivation of dangling bonds at the Si/SiO_2 interface during stress was used as the main ingredient. These dangling bonds are present in a considerable number at any Si/SiO_2 interface. During device fabrication they have to be passivated through some sort of hydrogen anneal, thereby eliminating the electrically active trap levels. Although the resulting silicon–hydrogen bonds are rather stable, at elevated temperatures and higher electric fields they can be broken, thus reactivating the electrically active trap levels. On top of that, fixed positive charges might be created, the origin of which has been attributed to trapped protons or trapped holes, although this issue is still controversial.

Of particular importance in that context is the relaxation of the induced damage, which is observed as soon as the stress is removed. This recovery can be quite large, but the microscopic origin is not completely understood. It was found in 2003 that this effect is extremely important in the understanding of NBTI, because during measurements unintentional recovery had distorted practically all previously available measurement data.

Although a lot of progress has been made in the theoretical understanding of NBTI, an universally accepted theory is still missing. Many publications focus on refining the classic reaction–diffusion model originally proposed by Jeppson and Svensson 30 years ago. However, recently a variety of other explanations have been put forward, using for instance dispersive trap-controlled transport of the hydrogen species released from the dangling bond, creation of hole traps, a broad distribution of dissociation rates at the interface, and interactions with hydrogen from the inversion layer. Some of these extended/alternative models rely on a different microscopic picture, sometimes augmenting – but not always compatible with – the standard reaction–diffusion model.

This plethora of explanations and possible physical models is confusing not only to device engineers but also to researchers having worked on the topic for a longer period. In addition, this might reflect the fact that NBTI is despite all efforts not yet fully understood. Therefore, we decided to bring together world leading experts to a Companion Workshop during the International Workshop on Computational Electronics in Vienna (www.iwce.org) to summarize their current understanding of the phenomenon, in order to pave the way towards a more complete understanding. Based on this Companion Workshop it was tried to identify leading researchers with different backgrounds, who would naturally have diverging ideas on the importance of various aspects of the problem in order to cover a broad range of interesting facets in this special section of Microelectronics Reliability.

0026-2714/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.microrel.2006.10.005

The opening paper is given by Dieter Schroder whose NBTI review written together with Jeff Babcock in 2002 belongs to the most cited NBTI publications. Since a lot of progress in the understanding of NBTI has been made during the last four years, a broad review which covers the recent advances in the state-of-the-art was considered a timely idea.

One of the most prominent NBTI models is the reaction–diffusion model based on the ideas of Jeppson and Svensson proposed back in the 70s. These ideas have been continuously refined with Muhammad A. Alam and Souvik Mahapatra being amongst the most prominent advocates. They review their current understanding and give possible explanations for seven key aspects of NBTI using the reaction–diffusion model.

Although analytical NBTI models based on the reaction–diffusion theory give a pretty good idea of the capabilities of the model, they leave several questions unanswered. A quantitative statement on the saturation behavior, influence of traps, layout effects, regions with different power-law slopes, etc. can be given through a careful numerical analysis of the problem. This issue is tackled in the work of Chakravarthi et al., where a wide range of possible model variations consistent with the reaction–diffusion theory is explored.

In the paper by Helmut Puchner aspects important for a product oriented point of view are presented. The impact of transistor reliability data on standby currents and regulator design is investigated, including the correlation between transistor, circuit, and product level NBTI reliability. In particular, the relative importance of NBTI, hot carrier injection (HCI), and time-dependent dielectric breakdown is assessed, for instance by studying the degradation of ring-oscillator performance.

The incorporation of nitrogen as a performance booster is one of the reasons, why NBTI has become actually worse in modern technologies. An increased sensitivity to NBTI is also observed, when high-k gate stacks are introduced to replace silicon dioxide. This issue is investigated for gate stacks using HfSiO(N) in the work of Michel Houssa et al., who identify a slow bulk trap component in addition to fast interface states. They also summarize their model based on dispersive transport of hydrogen in addition to a hole trapping model for the slow bulk states.

One of the difficulties related to NBTI modeling is the validation of the microscopic picture underlying the model equations. A particularly intriguing way to experimentally investigate the nature of the defects created during NBT stress is the use of the electron paramagnetic resonance (EPR) technique. Patrick Lenahan who is one of the pioneers in this field gives a review of the applicability of the EPR technique to the special problem of NBTI degradation. Although these studies confirm the widely held view that P_b centers are important, it is also argued that this is not always the case.

Most NBTI models published so far rely heavily on the properties of hydrogen in silicon-based materials. For instance, the way hydrogen diffuses in silicon dioxide or polycrystalline silicon (that is, in the gate, since the oxides are extremely thin) is of fundamental importance for the reaction–diffusion model and models using dispersive transport equations. However, the link to the vast amount of literature existing on that topic is still not clear, and one of the leading experts on hydrogen transport, Norbert Nickel, summarizes some of the complexities of hydrogen transport in polycrystalline silicon.

First-principles simulations provide an interesting means to study the microscopic details related to the chemical reactions assumed to happen during NBT stress. Sokrates Pantelides, a pioneer in first-principles techniques, discusses the application of density-functional-theory (DFT) calculations to NBTI modeling. It is argued that the reaction–diffusion model in its present form is not compatible with the results obtain from DFT simulations. In addition, DFT studies of other hydrogen related reliability issues are summarized.

We had a great time, both, organizing the Companion Workshop and putting together this special section. It was a pleasure to work with the authors on this effort and we wish to thank them all for their dedication to the subject. We sincerely hope that you enjoy this special section on 'Modeling of Negative Bias Temperature Instability' as much as we do, that it will help to get a better understanding of the current state-of-the-art, and that it triggers further research in that field.

Tibor Grasser
Siegfried Selberherr
Technische Universitäet Wien,
Institute for Microelectronics,
Gusshaussstrasse 27-29/E360,
1040 Vienna,
Austria
Tel.: +43 1 58801 36023; fax: +43 1 58801 36099
E-mail addresses: grasser@iue.tuwien.ac.at (T. Grasser)
selberherr@iue.tuwien.ac.at (S. Selberherr)

Available online 1 December 2006