OXIDE RELIABILITY

A Summary of Silicon Oxide Wearout, Breakdown, and Reliability

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FOREWORD

The metal-oxide-semiconductor (MOS) transistor was invented in 1960 and by the mid 1960s integrated circuits (ICs) using these new transistors were commercially available. Since the earliest days of the manufacture of MOS ICs there have been three major yield and reliability concerns. One concern involved the metallization, including step coverage, electromigration, metal-migration, metal reliability, and other problems. A second concern involved the oxide, including bias-temperature stability, uniformity, interface properties, leakage currents, endurance, ever-thinner oxides, reliability and other issues. The third concern involved the semiconductor being used, silicon, and issues such as manufacturing large (100) wafers when all that was available in 1960 was 3/4" (111) silicon, oxygen content, substrate defects, keeping the substrate defect free during processing, gettering of defects, etc. This issue of the *International Journal of High Speed Electronic Systems* is devoted to the second of the three issues raised above, that is, oxide reliability. Much effort has been expended by others resolving the first and third concerns.

Before introducing this issue of IJHSES we should recognize that, as an industry over the past 40 years, we have done an outstandingly good job producing high quality, highly reliable oxides in whatever thicknesses today's IC technologies required. This record of performance was not obtained lightly. The semiconductor industry has invested billions of dollars in research, development and manufacture of high quality oxides. This investment has resulted in ever thinner oxides operating in higher performance ICs. We are now being faced with some fundamental limits on oxide thickness reduction. The quantum mechanical and wave like properties of the electron mean that oxides thinner than about 3 nm are now partially transparent to electron flow, and the almost ideal insulating oxide of earlier times is no longer realized in these ultra-thin oxides. The wave properties of the electron mean that oxides thinner than 1 nm are no longer insulators and oxides much thinner than 1 nm may never find extensive use in ICs because of excessively high oxide currents. While some high speed logic circuits may use ultra-thin oxides, reducing oxide thicknesses below 5 nm is very difficult in dynamic random memory (DRAM) applications and using oxides thinner than 8 – 10 nm in non-volatile memory applications involve serious data retention – endurance – reliability trade-offs.

Since oxide thicknesses are now reaching some fundamental thickness limitations and since much very good work has been done in the past in the area of oxide reliability, it is appropriate at this time to attempt to summarize our knowledge of oxide reliability. Dr. Iwai asked me at the 1999 International Reliability Physics Symposium (IRPS) to try to put together a special issue of IJHSES devoted to oxide reliability. He gave me considerable latitude in editing this special issue. I was able to convince some of the world's experts in this field to contribute their thoughts on the subject, by basically giving them *carte blanche* freedom over the content and length of their individual contributions. The contributing authors agreed to share their expertise with us and

responded with the excellent articles that appear below. These authors are well known in the field of oxide reliability. They have contributed many invited tutorials to IRPS and have been awarded “Outstanding Paper” and “Best Paper” awards many times by IRPS for their past works. This issue is the result of a great deal of effort on the part of these experts.

The first article in this special issue is my own. I’ve tried to provide a short summary of the field of oxide wearout, breakdown and reliability. The article is broader than it is deep. Five topics are summarized in this work. They are oxide breakdown, oxide leakage currents, trap generation, statistics, and reliability. The individual topics that are included in this article are much more interesting and exciting than the cursory presentation received here. However, I aimed this paper primarily at the new oxide reliability engineer who needs a short, concise overview of the field so he doesn’t spend much of his time repeating the works of others, but rather, uses past knowledge to help him produce new insights and more reliable oxides. There is a second audience for this paper, that is, the oxide reliability engineer who would like to know what work has been done in the past and needs a list of references to that work. Of the over 3,000 papers and presentations that I have in my files, I included 890 references. I was not able to include all of the good references due to lack of space. I hope someone working in this field who does not see their favorite piece of work referenced will understand that not all references were able to be included. I think the reference list does provide a good first place to go to find out what work has been done in the past.

The second article is by Neal Mielke and Jian Chen of Intel and Sandisk. I put this article second because of the practical nature of the paper. The oxide in a non-volatile memory is operated at fields that are more normally associated with high-field accelerated oxide testing. The authors have studied the oxide degradation mechanisms as they apply to cell programming, cell erasing, and data retention. The authors describe how an understanding of oxide degradation can be applied to aid in the manufacture of highly reliable oxides. These authors have done an outstanding job describing how an oxide can be used in an environment close to its ultimate reliability limits. They have spend considerable time describing the IC upset conditions that can be related back to the changes that occur in the oxide properties as it ages. Neal was the first person to confirm some ideas we had on the possibility that dielectric breakdown might be very rare in ultra small devices with ultra thin oxides operating in high impedance environments due to energy and power limitations during the thermal breakdown event.

The third article is by Joe McPherson of Texas Instruments. Joe was the first person to relate oxide reliability to the fundamental physics and chemistry of the Si-O-Si system on a molecular basis. He used very simple thermodynamic principles to describe oxide reliability. His original insights into the importance of an Eyring formulation for the description of oxide reliability have proven to be valid over time. He has related oxide reliability to the fundamental nature of the silicon oxide structure and has used an open approach to explore differences in the various models of oxide reliability projection. His paper describes how fundamental knowledge of the physics of the Si-O-Si system can be used to resolve controversies in the field acceleration parameters of oxide breakdown.

The fourth article was contributed by Jordi Sune and David Jimenez of the Universitat Autònoma de Barcelona and Enrique Miranda of the Universidad de Buenos Aires. Jordi was the first person to supply us with a model that coupled the deterministic nature of trap generation with the statistical distributions of breakdown. Since the publication of his original work, many others have developed more advanced models, but his model still remains one of the easiest to use and one that provides much insight into the physics coupling wearout to breakdown. He has also done extensive thinking on the subject of early, non-destructive breakdowns and how these breakdowns are related to the final, thermal, destructive breakdown. The article contributed by these authors addresses, in detail, the two topics of statistical/physical modeling and the relationships between soft breakdown and hard breakdown.

The fifth article was written by Yee-Chia Yeo, Qiang Lu, and Chenming Hu from the University of California at Berkeley. Dr. Hu and his students have been continuous contributors to the area of oxide reliability since the early 1980s. Chenming and his students have probably published more articles in this field than any other group in either industry or academia. The subject of their paper is a review of their anode hole injection model and the other work done by the Berkeley team. They were able to couple their effective oxide thickness model to the development of reliability simulators and to the development of oxide screening techniques. Dr. Hu has taken an engineering approach to the field of oxide reliability, using measured data and simple models to project reliability. This article was chosen to wrap-up the presentations since the authors have contributed so much to this field.

It is with a great deal of gratitude that I thank these authors for helping make this issue of *IJHSES* a major contribution to the archival literature of oxide reliability. I can not thank these authors enough for the time and effort they put into their contributions. Their accumulated knowledge and their willingness to spend the time to describe their thoughts in clear and concise papers will help others use their accumulated knowledge. I again want to thank them.

I also want to thank some of the people who made my contribution possible. My work in the area of oxide reliability started when Jay Lathrop, a Clemson University professor since retired, ask me and several other faculty to join him in a new center, the Center for Semiconductor Device Reliability Research (CSDRR) at Clemson University. He was able to obtain long term funding for this project from the Semiconductor Research Corporation and other governmental and industrial sources. Jay and my other colleagues in this Center, Mike Bridgwood, Bill Harrison, and Kelvin Poole, although working on other reliability projects, provided many insights into the approaches that could be taken to defining oxide reliability. Many industries provided devices for our study. In particular, Texas Instruments provided oxides that ranged from 80 nm to 1.6 nm, all of these oxides being high quality. George Brown at Texas Instruments was responsible for providing many of these devices. George has probably forgotten more about oxides and oxide reliability than most of us will ever know. Dave Baglee, when at Texas Instruments, helped us build our test station and provided us with many software programs to use on this system. P. B. Ghate, retired now from Texas Instruments, provided to me, and many others, some invaluable insights into the physics of reliability.

Over the 15 years that the CSDRR was in existence 32 graduate students received degrees based on their oxide reliability work. Most of these students were Master Degree students. They did outstanding work. I want to acknowledge just a few of them and comment on their contributions. Akram Ditali and Tom Taylor built the test station that we all used during this 15 years. There was only one test station with one pA meter that supported all of the 32 students, a most efficient provider of graduate students to the semiconductor industry. They were able to construct a measurement system that had 1 pA resolution in current measurement. Without their efforts most of our detailed measurements and insights would not have been possible. Kenan Dickerson took some very careful measurements of interface trap densities after very low stresses and of long term, low voltage changes in oxide currents. These measurements helped us define the fluence and time dependencies of oxide wearout. I still use his data today. Jay Maddux showed us how to use the change in oxide transient response of oxide current from an $\exp^{-(t/RC)}$ form to a t^{-1} form to determine the stress generated bulk oxide trap densities. Rajaram Subramonium used this trap generation data, coupled it with Jordi Sune's statistical model, to show us how to use wearout data to describe the statistics of breakdown. Ron Scott studied the properties of the stress generated traps and showed how their tunnel charge/discharge properties could account for the different currents that flowed following stresses. Troy Robinson, Carl Jackson, and Omer Oralkan studied the non-destructive and destructive breakdowns in oxides. Their works emphasized the thermal nature of breakdown and it's fun to see how many present day authors have adopted many of these students' ideas. The other students all contributed significant pieces in the quest to define oxide reliability, but the students mentioned above provided the corner stones of our approach. I'd also like to thank Sally Surver for proof reading the references in my paper and helping me assure that they contained a minimum of errors.

Thanks go to my wife, Mariel, for encouraging me during the writing of my manuscript. I retired on 01/01/01 and she's been a constant fan of my work during the last 7 months while I was working on this manuscript. Now it's time for the two of us to move on to other fun things.

To everyone mentioned above, thanks, friends.

D. J. Dumin, July, 2001.

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