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Charge Trapping and the Negative Bias Temperature Instability

W. Goes*, F. Schanovsky°, Ph. Hehenberger°,
P.J. Wagner*, and T. Grasser°

* Christian Doppler Laboratory for TCAD at the Institute for Microelectronics, TU Wien, Austria
° Institute for Microelectronics, TU Wien, Austria

I. INTRODUCTION

The negative bias temperature instability (NBTI) belongs to the most challenging reliability concerns in present-day semiconductor devices and thus has aroused intense industrial as well as scientific interest. However, despite of a high research activity in this field over years, the knowledge about the physical origin of this phenomenon has remained vague. The cause is partially related to the prevalence of electrical measurements which are indirect and have left room for various distinct modelling attempts. The popularized reaction-diffusion (RD) model [1, 2] has long been regarded as the explanation of NBTI. Recently, a lot of concerns have been raised as the RD model is incapable of accurately describing the recovery phase [3]. Other models have focussed on the role of the interface reaction [4] rather than the diffusion of hydrogen. In addition to interface state creation, quantum mechanical tunneling of charge carriers into defects within the oxide has been put forward by several authors. However, no satisfying agreement with experimental data using simple tunneling models [5] has been achieved which triggered investigations on more complex trapping processes. Therein, the trapping mechanism has taken the role of a recoverable degradation part, vanishing quickly as soon as the stress conditions are removed. Recently published models indicate that NBTI recovery is due to a superposition of individual charge trapping events which rules out the RD model and any variant thereof. In this study, several different charge trapping models are inspected with respect to their basic tendency and their compatibility with experimental findings.

II. EXPERIMENTAL

Despite of the imperfect assessment of the real device degradation, the fast on-the-fly [6] and the extended stress-measure-stress [7] method have been established as measurement techniques to assess device degradation. Detailed experimental studies have revealed particular stress-recovery patterns described by a log-like behavior during the initial stress phase and a universal relaxation function during recovery. These patterns only differ by a scaling factor which follows a quadratic temperature activation and field acceleration. The results have been interpreted assuming a superposition of a quickly recoverable and a nearly permanent component that might be either closely coupled or coexistent independently. A recently devised measurement method, termed the time-dependent defect spectroscopy (TDDS) [8], is capable of tracing the charging of single defects that appear as steps in the monitored recovery. The acquired experimental data is undoubtedly shown to be incompatible with the RD model and has been associated with a mechanism of independently occuring trapping processes.

III. TRAPPING MODELS

Any trapping mechanism requires a quantum mechanical tunneling process for the charge carriers to enter into the dielectric. A simple but physics-based trapping model assuming elastic tunneling of charge carriers was developed by Tewksbury [4, 5]. Therein, variations in trap locations bring about a broad distribution of trapping times as required for NBTI. However, such a model starts to fail when oxide thicknesses enter the nanometer range — especially when interactions of charge carriers with the gate contact are taken into account. In addition, another weakness of the model lies in the weak temperature dependence associated with the change in interfacial charge carrier concentration. This shortcoming has been remedied by a thermally activated hole trapping process as has been proposed in [9]. In agreement with experimental findings, the trapping process is coupled to a hydrogen reaction representing the permanent or slowly recoverable component. Although the experimental stress-relaxation data could be reproduced with remarkable accuracy, the description of hole capture in the model relies on an physically ill-defined stress-parameter. In a new modeling attempt resulting in the so-called two-stage model [10], the physical picture of the inelastic hole trapping process was associated with a nonradiative multiphonon process (NMP), which accounts for the unavoidable lattice relaxation involved in the trapping process. This model has not only been able to reproduce the experimentally observed quadratic temperature activation and field acceleration but also to explain the unexpectedly quick response after short bias switches. With the emergence of the TDDS, new insights into the behavior of traps have been gained allowing to put the theory behind NBTI on a sound and physical foundation [8]. In a recent investigation, the involved traps were identified as defects with a bistable configuration in both their neutral and positive charge state. These findings led to an extension of the previous model relying on a more rigorous formulation of the nonradiative multiphonon transitions.

IV. CONCLUSION

We have thoroughly analyzed the existing trapping models proposed in the context of NBTI, pointed out their basic features and evaluated them against measurements for various stress and relaxation conditions. Furthermore, the physical meaningfulness of the underlying assumptions for the different models has been examined and the historical progression of trapping models with a refined two-stage model as the most promising candidate have been discussed.

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