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Physics-Based Hot-Carrier Degradation Modeling

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1. Introduction

Over the last decades, hot-carrier degradation (HCD) modeling has evolved from simple empirical models to a more detailed understanding of the microscopic physics involving single- and multiple-carrier processes (SC- and MC-mechanisms) [1-4]. A detailed description of the physics requires knowledge of the carrier energy distribution function (DF) which can only be obtained from a solution of the Boltzmann transport equation [3,5]. Most models in use today employ simplified solutions based on the average energy or, even more dramatic, the electric field, while in the ultimate simplification it is tried to capture the physics using closed analytic expressions [4,6]. Although computationally more efficient, these approaches are inevitably inaccurate, even though their limitations might not be that obvious when a limited range of bias conditions, temperatures, and channel-lengths is investigated. We present a careful study on the various models, highlighting their limits of validity as well as the resulting implications for lifetime prediction.

2. Main Peculiarities of HCD

Nowadays it is commonly assumed that hot-carrier degradation is linked to the breakage of Si-H bonds at or near the Si/SiO_2 interface [2,4,7]. The driving force behind this mechanism is the energy deposited by hot carriers. By "hot" we understand carriers accelerated by the electric field up to energies required to trigger bond dissociation. As a result, the most intensive bond-breakage occurs near the electric field peak which also determines the position of the severest degradation spot.

This scenario was typical for several generations of transistors. However, due the continued scaling of MOSFETs, a reduction of the supply voltage below 1.0 V would have been necessary [2,4]. With such small voltages, the probability to induce bond dissociation by the impact of a single particle is rather low, as the average activation energy of this process is around 3.0-3.5 eV [3,4,7,8]. If only SC-induced bond rapture was possible, one would expect negligible HCD. In reality, however, hot-carrier damage remains rather severe even for CMOS transistors with drain voltages V_{ds} below 1.0 V [3,4].

In an attempt to understand this behavior, the group of Hess [8] suggested that two so far neglected physical phenomena are to be taken into account: first, electron-electron scattering can populate the "hot" carrier fraction of the DF even at $V_{ds} < 1.0$V, resulting in a hump in the high-energy tail [7]. Second, the bond rupture is possible by interaction of a bond with several "colder" carriers. Thus, the vibrational energy of the bond is successively increased as a consequence of the carrier bombardement. Such a highly excited bond is already rather weak, i.e. the hydrogen is able to overcome the potential barrier between this state and the transport mode. Thus, a reduction of the channel length and the supply V_{ds} decreases the dominance of the SC- in favor of the MC-process.. An intimately linked circumstance is the change of the HCD worst-case conditions [4,7], which occur at $V_{gs}=V_{ds}$ rather than at $V_{gs}=V_{ds}/2$ (for nMOSFETs).

3. Hot-Carrier Degradation models

A number of HCD models have been suggested recently which will be given in a unified formalism and compared.

Hess model

The idea to incorporate the information about the DF into a HCD model was first expressed by the group of Hess [3]. Another important novelty of their work was that the concept of two competing mechanisms of bond dissociation was mathematically formalized using an information on H desorption induced by electrons tunneling from the STM tip [10,11].

Penzin model

Although the Hess model provides a sound physical picture of interface state build-up, a complete analysis of device characteristics degradation was not performed. A successor of the Hess approach, the Penzin model, tries to relate defect generation with device characteristics, thereby propagating the Hess concept to the device level [6]. Penzin *et al* employed first-order kinetics to describe defect build-up and regarding a dispersion of the Si-H bond-breakage activation energy (inherited from the Hess model). Another advantage of the model is that the mobile hydrogen introduced into the system hampers further H release. Since HCD is driven by the energy delivered by carriers, the model estimates an acceleration factor based on the "hot carrier current" calculated by the simplified drift-diffusion scheme [12].

Reaction-Diffusion (RD) Based Model

Another approach connecting the microscopic and device levels is the extension of the reaction-diffusion framework of NBTI to HCD [13]. The RD approach assumes that the degradation is a diffusion-limited process. This implies, however, that once stress is removed, a quick recovery should be observable. In reality, the recovery of HCD is very slow, thus suggesting that HCD is a reaction-limited process [14].

Rauch's Energy-Driven Paradigm

Rauch and co-workers proposed a so-called "energy-driven paradigm" [7]. For channel lengths less than 180 nm, the HCD was shown to be controlled by the single "knee" energy. This energy is related to the stress bias. Therefore, instead of operating with coordinate-dependent quantities (electric field, dynamic temperature, DF, etc) only a single bias-dependent parameter is considered.

Bravaix Model

The peculiarities of the Hess and Rauch strategies (i.e. SC vs. MC-mechanisms of Si-H bond rapture and energy-driven paradigm) were incorporated into the Bravaix model [4]. The main shortcoming of this model (inherited from the Rauch approach) is that the DF information is substituted by some empirical factors. As a result, the model provides no information on the coordinate-dependent interface state concentration, i.e. one of the main features of HCD, its strong localization, is lost.

Model based on the Evaluation of the DF

Keeping all the shortcomings of the HCD models in mind, we have developed our own approach [5], which uses the carrier DF provided by a solution of the Boltzmann transport equation. As an essential aspect, the interplay between the SC- and MC- bond-breakage mechanisms is considered and controlled by the carrier acceleration integral. The model is able to represent the linear drain current degradation in a wide range of stress/operation conditions and is applicable for a wide class of transistors. In order to assess the severity of the various employed approximations for the DF, we have also substituted the Monte-Carlo based transport kernel of our model by drift-diffusion and/or hydrodynamic schemes. We have calibrated the model and compared it with the Penzin and Bravaix approaches to understand their limitations.

4. Conclusion

An exhaustive analysis and comparison of hot-carrier degradation models has been carried out. We provide a strict hierarchy of the existing approaches reflecting their shortcomings and applicability limits. All these findings have finally proven that the thorough evaluation of the carrier energy distribution function is the vital component of a comprehensive HCD model.

5. Referencess

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