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A reversible first-order dispersive model of parametric instability

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ABSTRACT

A general purpose instability model is derived for the variation of device parameters which is related to the activation–deactivation of statistically independent microscopic defects, with reversible first-order reaction kinetics and distributed rate constants. The model is aimed at predicting the parametric instability of electronic devices under periodic AC stimulus of arbitrary waveform over a wide time-scale range covering the whole device lifetime. As a practical application, we extracted a model for the negative-bias temperature instability of a p-channel type silicon MOSFET, including both the recovery effects and the voltage–temperature dependence. The model can be implemented in commercially available tools for the compact simulation of integrated circuits.

1. Introduction

Operation of electronic devices typically implies the ageing of elementary components that can be described as the variation of their characteristic parameters with time. In order to evaluate those parametric variations early in the product design stage, modern CAD circuit simulators of microelectronic devices are conveniently featured with device degradation tools [1,2] aimed at predicting the parametric evolution of elementary devices under the foreseen device operation profile. The task of device wear out simulation gets more complicated if recovery effects are present [3], i.e. if a device parameter appears to recover towards its initial value upon 'relieving the stressing condition'. Such behaviour is called parametric instability: its modelling is the main subject of this work.

One of the most important concerns in modern electronic devices is the threshold voltage instability of the p-channel type silicon MOSFET under negative gate bias and high temperature, known as Negative-Bias Temperature Instability (NBTI). The debate about the microscopic processes behind NBTI and about the modelling of its kinetics is still presently open. According to the recent literature, up to two [4,5] or even three [6] different microscopic processes are suggested to cause NBTI, depending on the gate dielectric material. Recent advances [7] have revealed that a relevant fraction of the threshold voltage instability is due to the reversible capture-emission of charge carriers, at pre-existing defects of the gate dielectrics, associated with the microscopic structural relaxation of the dielectric lattice. The capture-emission process was described in terms of the field-assisted non-radiative multi-phonon theory. Accordingly, both the capture and the emission would be thermally activated, at least in the common operating temperature range, with distributed, bias-dependent, activation energy. It was shown [8] that a reversible first-order dispersive kinetic model derived from a simplified application of those findings was adequate for describing the threshold voltage instability of a p-channel MOSFET with 2.2 nm thick plasma-nitride (gate) oxide under a wide duration range of step-wise stress–relax, and low-frequency AC NBT stimuli. By resorting to a different physical model, but still based on the same kinetics, other authors [9] were able to account for the time and temperature dependence of NBTI stress and recovery, including the effect of the thickness and nitridation recipe of the gate oxide, in p-channel MOSFETs with gate dielectric thickness between 2.2 nm and 15 nm.

The laboratory characterization conditions typically comprise relatively high oxide electric field and rather limited cumulative stress duration. Should reversible first-order dispersive kinetics be suitable for describing the NBTI of the actual device operating conditions and lifetime scale too, one could predict, in principle, the parametric instability of devices under time-dependent NBT stimuli of arbitrary waveform. In order to be effective in supporting the design of microelectronic circuits, such model should be (i) suitable for implementation in common CAD software environment and (ii) able to produce its predictions with reasonable computational efforts.

With the continuous decrease of electronic device size the number of microscopic defects per individual component may well decrease to a few units. The related stochastic effects may lead to non-negligible device-to-device and time-to-time variations in the instability behaviour. Recently, a noticeable effort has been devoted to account for the stochastic effects in the circuit simulation of bias-temperature instability of very small devices [10–12]. Those models are based on an 'atomistic' or 'defect-based'

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approach and address the case of ideal 'digital' waveform consisting of a two-level periodic stimulus. The focus of this work is somehow complementary: while we will consider only large size devices such that all the stochastic variations can be assumed to be averaged out, the aspect of continuous variation of the stimulus conditions is included. The latter feature may be of interest for the purposes of digital modelling since the switching rise and fall times may well be a significant fraction of the clock period.

We will show that if the generic device parametric instability actually results from the additive effect of a large number of statistically independent activation–deactivation microscopic events following reversible first-order kinetics with distributed reaction rate constants then an exact kinetic solution can be actually found, yielding the variation of the device parameter under time-depending stimuli of arbitrary waveform. We will then propose suitable manipulation and approximation of the exact solution to make it compatible with its implementation in commercial CAD simulators. The proposed formulation allows for the calculation of a parametric drift induced by any periodic stimulus with arbitrary waveform over the whole device lifetime.

The instability model explained in Section 2 can be considered an extension of the first-order dispersive ageing model developed by some of these authors [13,14] where a parametric degradation was treated as the superposition of different first order kinetics. It is worth to mention that different physical models have been proposed for explaining dispersive instability kinetics, which do not follow the present approach. That would be the case, for instance, of the well-known reaction–diffusion NBTI model [4], or even the case whether the charge capture-emission process contributing to the NBTI would take place on defects possessing more than two states, like in the 'switching trap' model proposed for explaining the high-frequency properties of NBTI [15]. We will present in Section 5 the extraction of the model parameters for the threshold voltage instability of a p-channel MOSFET under homogeneous NBT stress, with the gate voltage and temperature dependence included. The purpose of the extraction example is to highlight practical aspects and to prove the model effectiveness, not to bring any experimental evidence or to advance any conclusion about the microscopic mechanisms behind the NBTI.

2. Model

The instability model developed in this work relies on the following assumptions: (i) the generic device parameter drift Δ of the device under stress is proportional to the fraction of a large number of microscopic defects which gets activated independently, (ii) the distribution D of the defect parameters relevant to the reaction rates does not change upon stressing (and no extra defects are generated), and (iii) the activation–deactivation reaction obeys reversible first-order kinetics. According to the latter assumption, the probability p that a given defect is found activated at the time t is a solution of the first order differential equation:

$$\frac{dp}{dt} = k_f(1-p) - k_b p \tag{1}$$

where k_f and k_b are the forward and backward rate constants of the reaction, which depend on the defect properties, and are arbitrary continuous positive functions of time depending on the variation of the applied stimulus. According to Eq. (1), the instantaneous defect activation rate is proportional to the probability $1-p$ that the defect has not yet been activated, and the instantaneous defect deactivation rate is proportional to the probability p, that the defect has already been activated. According to this perspective, both the 'degradation' and 'recovery' processes should be thought as being active at the same time, although with different instantaneous rates, under any condition. Moreover, it should be clear that whether the application of any stimulus would result in a 'build-up' or in a 'recovery' effect, it does depend on the stimulus waveform history too.

Eq. (1) may be considered as the equation governing the transition probability of a two-state system. In Fig. 1, "0" and "1" may represent, for instance, the non-activated and the activated states of a microscopic defect.

The rate constants k_f and k_b are also functions of the parameters η_f and η_b, which represent some physical property of the defects (e.g. forward and backward activation energies in a thermally activated process such as NBTI), and which are distributed according to D. Hence, the drift Δ of the generic parameter of a device under time-dependent stimulus is expressed as an integral transformation:

$$\Delta(t) = \Delta_0 + \Delta_{sat}\int_{-\infty}^{+\infty} d\eta_f \int_{-\infty}^{+\infty} d\eta_b D(\eta_f,\eta_b)[p(\eta_f,\eta_b,t) - p_0(\eta_f,\eta_b)] \tag{2}$$

where Δ_0 is the 'time-zero' parameter drift

$$\Delta_0 = \Delta_{sat}\int_{-\infty}^{+\infty} d\eta_f \int_{-\infty}^{+\infty} d\eta_b D(\eta_f,\eta_b)p_0(\eta_f,\eta_b) \tag{3}$$

and Δ_{sat} a saturation value corresponding to the case of all the defects activated. The distribution D is intended to be normalised such that its integral over the full range of η_f and η_b is equal to unity.

Once a solution of Eq. (1) is determined, Eq. (2) provides the general form of a reversible first-order dispersive instability model for time-dependent stimulus. In order to fit this model to a real device the initial activation probability $p_0(\eta_f,\eta_b)$ must be known. In addition, the distribution D and the dependence of the reaction rate constants k_f and k_b on both η_f and η_b and the stress conditions have to be either specified in advance or determined. As a useful and plausible approximation, we shall assume $p_0 = 0$ (hence $\Delta_0 = 0$) for a virgin or fully relaxed device.

A natural extension of Eq. (2) is used in the case more than one kind of defects or mechanisms would contribute to the instability of the same parameter. The extension is obtained by plain summation:

$$\Delta(t) = \sum_{i=1}^{m}\left\{\Delta_{0i} + \Delta_{sat,i}\int_{-\infty}^{+\infty} d\eta_f \int_{-\infty}^{+\infty} d\eta_b D_i(\eta_f,\eta_b)[p_i(\eta_f,\eta_b,t) - p_{0i}(\eta_f,\eta_b)]\right\} \tag{4}$$

where m is the number of different kinds of defects, $\Delta_{sat,i}$, D_i and p_i are the saturation value, distribution and activation probability of the different kinds of defect.

2.1. The exact solution

Given the initial condition $p(t=0) = p_0$, the solution of Eq. (1) is known from calculus:

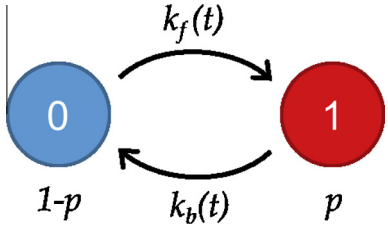

Fig. 1. The generic two-state system. The instantaneous transition rate constants k_f and k_b are arbitrary functions of time. Both forward and backward transitions are possible.