論　文　の　要　旨

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論 文 題 目

Development and Verification of Compact Model for NBTI (Negative Bias Temperature Instability) Effect Observed in p-MOSFET

(p-MOSFET における NBTI (Negative Bias Temperature Instability) 効果のモデル開発)

Background

In the post decades, the dimension of semiconductor devices continuously scales following Moore's Law and approaching to its limit. A definition of "equivalent scaling" has been proposed for several years. New materials and novel structures are invented for MOSFET manufacturing, providing possibilities to extend Moore's Law beyond its limitation. On the other hand, reliability issues are getting more inevitable due to the increased defect density within the high-K materials as well as the evidently enlarged electric field due to the ultra-thin gate oxide. During the circuit operation, carriers have increased opportunity to be captured by the existing and newly generated defects under high electric field. Such condition raises the reliability problems such as the hot carrier effect, the negative bias temperature instability (NBTI) effect, as well as gate leakage current and dielectric break down.

Among the above reliability issues, the NBTI effect is one of the most important concerns since it deteriorates the drive-capability of the p-MOSFETs by degrading the threshold voltage, drain current, transconductance, and even the circuit output delay. The accurate predictive model for the NBTI effect is required for circuit protective design and reducing the design tolerance for saving the layout area. At present, numerous NBTI predictive models based on different concepts have been developed, including the hydrogen reaction-diffusion theory, hole-trapping theory and the energy transfer based theory. However, none of them are able to balance both the consistency of the theory as well as the practical application. An efficient NBTI model must be able to accurately predict the following features: 1) Long term degradation under DC stress conditions. 2) AC degradation with various frequencies and duty cycle. 3) The recovery characteristic in short term and long term regions. 4) Temperature dependence.

Purpose

The purpose of this study is developing a NBTI predictive model validated under any stress and temperature conditions. Besides of figuring out the physical mechanisms behind the NBTI degradation, the practicality of the compact predictive model is also highly concerned. The novel proposals to approach the purpose are as follows:

1. Developed NBTI model with the improved reaction-diffusion (RD) theory. The traditional RD theory assumes that the hydrogen diffusion in the gate oxide is the fundamental reason of the threshold voltage degradation under negative gate bias. Such hypothesis is validated only under the conditions of high stress bias and long time duration. In this thesis, the procedure of Si-H bond reaction is investigated in detail, and modeled using a logarithmic time dependent equation, which is physically derived from the classical reaction equation.
2. However, the assumption of hydrogen diffusion is still open for discuss, the hole-trapping/detrapping theory attracts close attention recently. In this thesis, the NBTI model is improved by combining the reaction of silicon bonds at the interface with the hole-trapping in the gate oxide. Based on the observation of the experimental results, the short term degradation is dominated by hole-trapping mechanism, while the long term degradation is induced by interface state generation.
3. In the real circuit, the drain of p-MOSFET is usually biased at the applied voltage. Such condition is different from the ideal NBTI measurement condition that drain bias equals zero. In order to ensure the NBTI model applicable under any practical operation conditions, the drain bias dependent hot carrier effect model coupling with NBTI model is developed. With the increased drain bias, the threshold voltage shift firstly decreases in the low drain bias region due to the weakened NBTI effect, and then increases in the high drain bias region due the enhanced hot carrier effect.
4. Temperature is the other significant factor responsible for p-MOSFET degradation. This thesis considers the temperature as another component of the developed NBTI model. The modeling results are consistent with the experimental results with various temperatures.
5. The NBTI model is implemented into the advanced compact MOSFET model HiSIM for circuit simulation. The output-delay of inverter, ring oscillator, NAND, NOR, SRAM after certain time operation is simulated.