Switching Characteristics of a 4H-SiC IGBT with Interface Defects
Up to the Nonquasi-Static Regime

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Abstract
The switching characteristics of a 4H-SiC IGBT with interface defects are analyzed up to the nonquasi-static (NQS) regime using reported interface density measurements and device simulation. A threshold voltage shift and current degradation are observed under quasi-static (QS) condition. At fast switching, the trapping effect is observed as a surge of current at the initial gate voltage switch-on, and the NQS behavior itself conceals the trapping effect.

1. Introduction
The 4H-SiC/SiO₂ interface has a high interface defect density $D_D$, characterized by distinct deep and shallow traps as shown in the measurements in Fig. 1. The previous work of the author investigated the effects of the measured interface density on the static threshold characteristics of a 4H-SiC IGBT device shown in Fig. 2. The collector current $I_C$ is severely degraded. The deep trap $D_{2a}$ causes the threshold voltage to shift to higher gate voltages while the shallow trap $D_{2a}$ causes current degradation as shown in Fig. 3a and b [2].

The extension from static to transient analysis, however, is not straightforward. The static results cannot be used directly to predict transient device characteristics because the dynamics of carriers are governed not only by the applied voltages but also by: (1) the time to charge/discharge the channel and base regions, and (2) the time for trapping/detrapping of carriers due to interface defects. It is the aim of this work to characterize the dynamic response of 4H-SiC IGBT in the presence of traps when fast switching is applied with the device simulation. The work is relevant since power devices are mainly used as switches in power circuits.

2. Transient Device Simulation with Measured Defects
Device simulation involves solving the Poisson equation consistently with the continuity equations to describe the carrier dynamics [3]. The space charge density $ρ$ which is the sum of all contributing charges is

$$ ρ = q\left(\rho - n + N_D^+ + N_A^-\right) + Q_T \tag{1} $$

where $q$ is the unit electronic charge, $\rho$ is the concentration of holes, $n$ is the concentration of electrons, $N_D^+$ is the concentration of ionized donors, $N_A^-$ is the concentration of ionized acceptors, and $Q_T$ is the density of charges due to contributions from interfacial trap states. The defects existing within the bandgap as reported in the measurement are included as interface defects. For this work, only the acceptor-like traps $D_{1a}$ and $D_{2a}$ are considered because the carriers in the device are electrons. $D_{1a}$ is modeled as a Gaussian distribution as

$$ g_{1a}(E) = N_{GA} \exp\left(-\frac{\left(E - E_{GA}\right)}{W_{GA}}\right) \tag{2} $$

where $E$ is the energy level of the trap state, $E_{GA}$ is the energy level where the distribution peaks, $N_{GA}$ is the trap density per unit energy at the peak of the distribution and $W_{GA}$ is the characteristic decay energy for the distribution.

$D_{2a}$ near the conduction band edge is modeled as an exponential distribution given by

$$ g_{2a}(E) = N_{TA} \exp\left(-\frac{E - E_{TA}}{W_{TA}}\right) \tag{3} $$

where $E_{TA}$ is the energy at the semiconductor conduction band edge, $N_{TA}$ is the trap density per unit energy at the semiconductor conduction band edge and $W_{TA}$ is the characteristic decay energy. The values of the constants in the equations are extracted from the reported measurement.

The total contribution from the defect states to the charge density is then calculated as $p_T = p_{TA} + p_{GA}$

$$ p_{TA} = \int_{E_C}^{E_{FA}} g_{TA}(E) \cdot f_{1,TA}(E,n,p) \, dE \tag{4} $$

$$ p_{GA} = \int_{E_C}^{E_{GA}} g_{GA}(E) \cdot f_{1,GA}(E,n,p) \, dE \tag{5} $$

where $f_{1,TA}$ and $f_{1,GA}$ are the probabilities of occupation of a trap level at energy $E$ for the exponential and Gaussian acceptor and donor states. $f_{1,TA}$ is given as

$$ f_{1,TA} = \frac{v_{TA} \cdot SIGTA \cdot n \cdot \exp\left(-\frac{E - E_{TA}}{kT}\right)}{v_{TA} \cdot SIGTA \cdot n + v_{TA} \cdot SIGTAH \cdot n \cdot \exp\left(-\frac{E - E_{TA}}{kT}\right) + v_{TA} \cdot SIGTAH \cdot \left(\left(p + n\right) \cdot \exp\left(-\frac{E - E_{TA}}{kT}\right)\right)} \tag{6} $$

In the transient simulation case, additional rate equation is given for $p_{TA}$ and $p_{GA}$. For $p_{TA}$,

$$ \frac{d}{dt}(p_{TA}) = \frac{1}{\tau_{TA}} \left[ g_{TA}(E) \cdot v_{TA} \cdot SIGTA \left(\left(1 - f_{1,TA}(E)\right) - f_{1,TA}(E)\right) \cdot n \cdot \exp\left(-\frac{E - E_{TA}}{kT}\right) \right] \tag{7} $$

Similar forms of Eq. 6 and 7 are followed for $f_{1,GA}$ and $p_{GA}$, respectively.

A step function of varying rise times and gate voltages is used as input. The collector voltage $V_C$ is fixed to 15V to ensure current conduction for switching evaluation. The capture cross section parameters are set to 1e18.

3. Results and Discussion
Fig. 4a shows the transient current at $V_C=25V$ with a slow input rise time $t_{rise}$ of 20μs. For slow switching, the current with combined $D_{1a}$ and $D_{2a}$ starts to increase according to the applied $V_C$ with the waveform showing no trapping effects. A surge of current becomes visible due to carriers being trapped until it decays and reaches the static
value in Fig. 3b. The shallow trap $D_{2a}$ introduced a larger influence to degrade the current because the high density of carriers is in the conduction band where $D_{2a}$ is located.

At $t_{\text{rise}} = 200\text{ns}$, the surge of current is bounded by the transient current without the defects as shown in Fig. 4b. This current without defects is governed only by the dynamics of charging/discharging of the channel and base, or the nonquasi-static (NQS) characteristics. This means that the magnitude of current due to the trapping effect is limited by the NQS current.

Fig. 5a shows the current characteristics with total defects for different switching times at the NQS regime. The initial surges are all bounded by the NQS current. Fig. 5b shows the switching characteristics as a function of normalized transient time by $t_{\text{rise}}$. Due to the stronger NQS effect the current decay occurs much later for faster switching. The NQS effect observed for the $t_{\text{rise}} = 1000\text{ns}$ occurs frequently for normal device operation conditions. The observed phenomena are summarized in Fig. 6. The maximum effect of trapping is governed by the NQS current. Therefore, any measurement of current with carrier trapping in the static case (quasi-static or QS approximation) does not necessarily appear as degradation in the transient current during switching. Calculation of transient current using QS with trapping effects introduces a maximum difference of $\Delta I = I_{\text{QS}} - I_{\text{NQS}}$. In compact modeling, $I_{\text{NQS}} = I_{\text{QS}} + dQ/dt$ where $Q$ is the charge responsible for charging. So a first-order approximation of $\Delta I$ gives $dQ/dt$, which is the charging current. This correction is important in circuit simulation for correct prediction of waveform of SiC-IGBT during switching characteristics.

4. Summary

Investigation of the switching characteristics of a 4H-SiC IGBT with interface defects showed threshold voltage shift and current degradation under quasi-static (QS) condition. At nonquasi-static (NQS) switching, the surge of current due to trapping effects is concealed by the NQS current. The NQS behavior itself limits the trapping of carriers.

References


Fig. 1. SiC/SiO$_2$ measured interface defect density [1].