Gate current random telegraph noise and single defect conduction

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ABSTRACT

The properties of Random Telegraph Noise (RTN) in the gate current of nanoscaled Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET) are discussed. While the gate current RTN capture and emission times depend strongly on temperature and gate voltage, the RTN amplitude, corresponding to single gate oxide leakage path, appears independent of temperature and scaling with the gate current. The RTN amplitude is observed to reach up to tens of percent of gate current. In carrier separation measurements the fluctuations typically appear in one component only. A correlation of drain and gate current fluctuations allows linking the charge and conduction states of a single gate oxide trap. A model for drain current RTN involving a metastable state is extended to include conduction through the single trap and gate current RTN.

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1. Introduction

Although only a few defects will be present in the gate dielectric of deeply-downscaled CMOS devices, their relative impact will be considerable [1]. For example, an individual charged trap can significantly alter the channel current I_D of a nm-sized FET, thus affecting the performance of the entire circuit [2]. The ability to observe these single-carrier events has one advantage—it allows us to study time-dependent degradation mechanisms at the ultimate, "atomistic" level. In this "bottom-up" approach, the overall degradation is then described as a concomitant impact of an ensemble of individual defects, naturally yielding a physically-based description of the time-dependent variability.

The properties of individual defects and their impact on I_D have been investigated in great detail [3–7]. Recently reported observations linked the same defects to fluctuations in another important FET parameter—gate current I_G [8,9]. Here we discuss the mechanism responsible for gate leakage through an individual defect in both n- and pFETs, attempting to provide a unified picture for these fluctuations. Insights into the mechanism controlling individual defect conduction should in turn lead to better general understanding of gate leakage and its degradation during FET operation [10].

2. Experimental

Both n- and p-channel FET devices were investigated with EOT = 2.3 nm SiON gate oxide, 70 nm nominal gate length corre-

sponding to ∼35 nm effective channel length and 90 nm gate width [9]. The FET currents were simultaneously measured with a pair of Keithley 2636 units with a sampling rate of 20 ms. All measurements reported here were done at 25 °C unless noted otherwise.

3. Results and discussion

Intermittent capture and emission of charge in a single gate oxide defect will result in so-called random telegraph noise in the drain current (I_D-RTN; Fig. 1a). Note that the lower I_D level corresponds to the trap being occupied, resulting in Coulombic blocking of a part of the FET conduction channel (Fig. 2a). The process is characterized by defect capture time τ_c, emission time τ_e, and the change in I_D due to the single trap ΔI_D (Fig. 1a).

Trapping and detrapping into this defect also result in *fluctuations in the gate current* ΔI_G (Figs. 1b and 2b) [11]. Most notably, the I_G and I_D *fluctuations are correlated* [9], allowing us to link the charged state of the defect with the lower I_G-RTN level. This crucial information could not be obtained in previous work on large-area? MOS *capacitors* [11].

The τ_c and τ_e characterizing *both correlated RTN processes* are strongly voltage and temperature dependent [9] (widely distributed $E_A \sim 0.1$–1.5 eV), the latter suggesting exchange of energy with the lattice during the charge capture/emission process [12,13].

The crucial issue is the mechanism through which the captured charge affects I_G. Here we note the large magnitude of ΔI_G fluctuations in Fig. 1b (about 70% of I_G). The distribution of these fluctuations in other devices is shown in Fig. 3. We note that a change of 30% in $\Delta I_G/I_G$ would correspond to uniform gate leakage being dis-
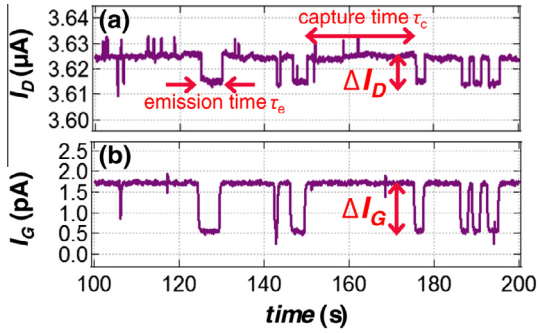
Fig. 1. Random telegraph noise (RTN) in (a) the drain current I_D (V_D = 100 mV) and (b) the gate current I_G (V_G = 0.7 V) is correlated in a deeply scaled nFET [9]. Data obtained at 45 °C.
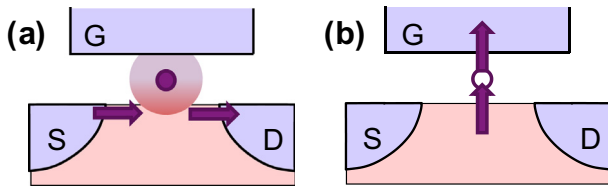

Fig. 2. A schematic illustration of a single trap influencing both (a) the channel and (b) the gate currents.
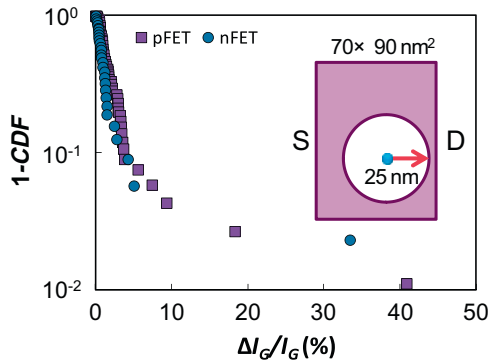

Fig. 3. The relative magnitude of gate current fluctuations can reach more than 10% in about 3% of devices. Inset: $\Delta I_G/I_G$ = 30% corresponds to I_G being "disabled" over an area with ~25 nm radius around the charged defect.

Fig. 4. Carrier separation experiment ($V_D = V_S = V_B = 0$ V) in nm-sized (a) nFET and (b) pFET in accumulation. In most cases, fluctuations in I_G are correlated with one component only.

Fig. 5. Schematic of the process in an nFET. (a) An *unoccupied* trap locally contributes to the extra current ΔI_G, cf. Fig. 1. Overall direct tunneling (DT) component forms the background. (b) The *occupied* trap disables ΔI_G conduction path. A local oxide barrier increase and a repulsion of supply carriers are also shown but are ruled out as decisive, cf. Fig. 3.

abled over a circular area with ~25 nm radius around the charged defect in our 70×90 nm^2 devices [14]. Although a charge capture does result in the local increase of the gate oxide tunneling barrier, such extent suggests that this is an unlikely scenario. The same argument also rules out local electrostatic repelling of supply carriers in the injection electrode in the vicinity of the trapped charge as the origin of the fluctuations. This view is further corroborated by charge-separation experiments (Fig. 4) in which I_G-RTN is reflected in *either* hole *or* electron components (the above barrier modulation would affect both components).

A more likely process involves enhanced conduction through the trap when it is unoccupied by an electron (Fig. 5 for nFET, pFET not shown). Such a process would be most efficient for traps close to the center of the oxide [15], readily explaining why there are no defects causing *both* large ΔI_G and large ΔI_D (Fig. 6a) [9]. The same correlation (Fig. 6b) can be qualitatively constructed using this assumption, combined with the impact of a charged trap on I_D depending on the distance of the trap from the critical point of a source-drain percolation path [16].
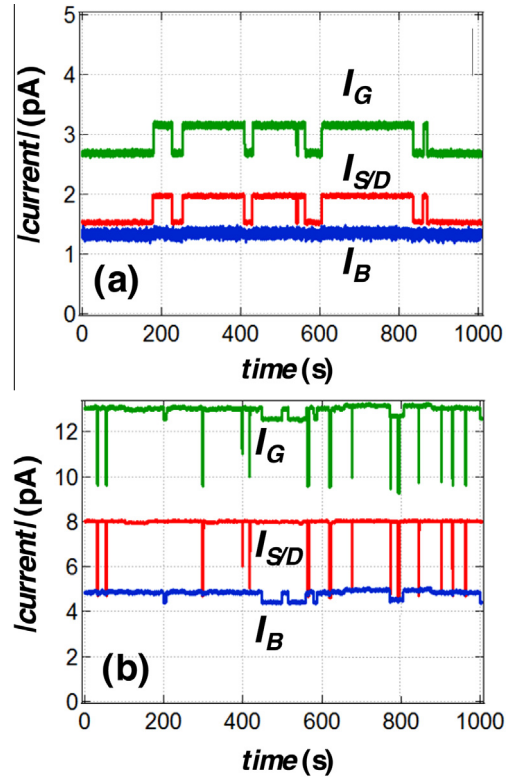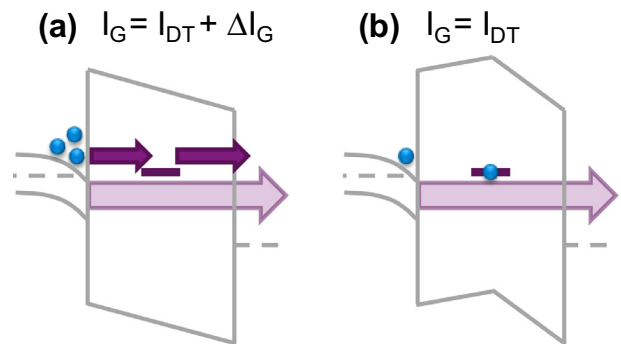
Decoherent tunneling through a trap near the center of the oxide (Fig. 7) will also result in a similar voltage dependence of the background I_G and the ΔI_G component—an observation recorded (but not fully appreciated) already in [11] and confirmed in [9].

Finally, following the model in [4], the state diagram describing the entire I_G-RTN mechanism relying on a metastable state is shown in Fig. 8. In this picture, the temperature *independence* of the ΔI_G component (observed in a T range of ~50 K [9,11]) is associated with the very fast time constants τ_{tc} and τ_{te} ($\Delta I_G \sim 10$ pA corresponds to ~10^{-8} s) describing tunneling into and out of the trap. The strong T dependence of the RTN constants τ_c and τ_e is then due to thermal barriers between the metastable and stable charged states of the trap [4].
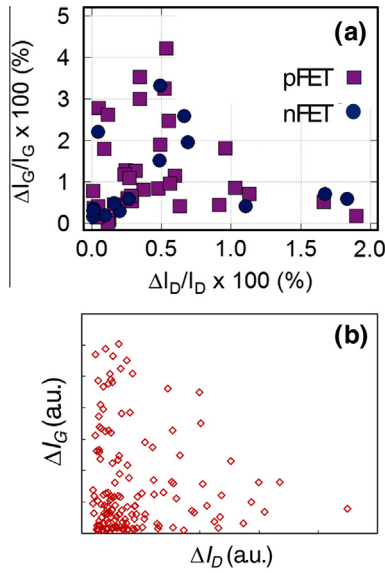
Fig. 6. (a) Correlation plot of relative changes in I_D and I_G ($I_G = \sim 10$ pA). Note that upper right corner (large I_D and large I_G fluctuations) is unpopulated. (b) The same trend can be qualitatively reproduced by the proposed picture.
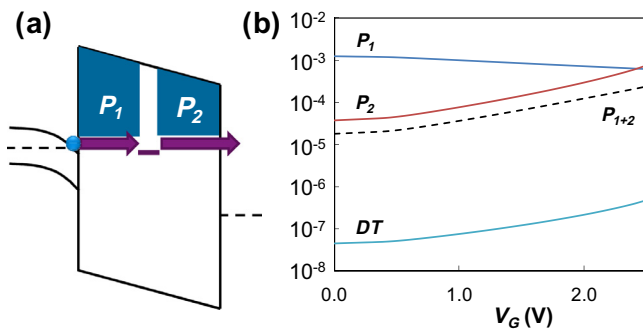
Fig. 7. (a) Band diagram showing the tunneling probabilities into and out of the trap P_1 and P_2. (b) A first-passage-time combination of P_1 and P_2 (for a trap positioned 25% into the oxide) will have voltage dependence very similar to the direct tunneling probability ($\sim I_G$).
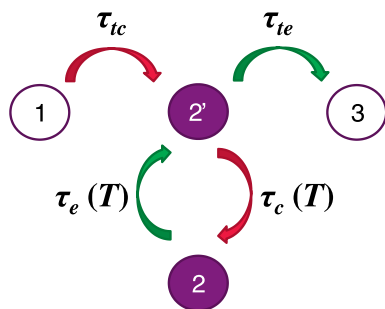
Fig. 8. State diagram describing the I_G-RTN process. A carrier tunnels from injecting electrode 1 into metastable state 2' and either continues to the opposite electrode 3, contributing to ΔI_G, or becomes captured in state 2, disabling the conduction path.

4. Conclusions

The properties of Random Telegraph Noise (RTN) in the gate current of nanoscaled Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET) have been discussed. A correlation of drain and gate current fluctuations allows us to link the charge and conduction states of a single gate oxide trap. A model for drain current RTN involving a metastable state is extended to include conduction through the single trap and gate current RTN.

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