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Single, Individual Traps at the SiO_2/Si Interface in Sub-μm MOSFETs

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The alternate capture and emission of mobile charge carriers in the channel at single, individual interface traps generates a random telegraph signal (RTS) in the source-drain conductance of sub-µm sized MOSFETs. The study of the RTS has provided a powerful means of investigating the trapping kinetics of interface states, which involves large Coulomb energies of up to 300meV. The resistance modulations frequently exceed 10% and exhibit a large scatter up to two orders of magnitude. The individual interface trap thus acts as an atomic probe of the strongly nonuniform current distribution.

1. INTRODUCTION

The immense progress in silicon technology and the miniaturization of electronic devices to submicrometer sizes has led to almost defect-free metal-oxide semiconductor field-effect transistors (MOSFETs). The few interface traps remaining in the active gate area are singled out due to the screening of the gate electrode, which is separated from the channel only by a few nanometers. The alternate capture and re-emission of mobile charge carriers in the channel at individual interface traps generates a random telegraph signal (RTS) in the source drain conductance of the MOSFETs. The superposition of many RTSs in large devices is known to create the 1/f noise[1)-3)].

The analysis of RTSs in sub-µm MOSFETs is now established as a powerful method not only to study the behavior of single, individual traps at the Si-SiO_2 interface in equilibrium and the origin of 1/f noise. It is shown in this paper that it may also be utilized as an atomic probe to characterize the strongly nonuniform current distribution in these small MOSFETs[4)].

2. RANDOM TELEGRAPH SIGNALS

When monitoring the source drain conductance of a sub-µm sized MOSFET an RTS like that shown in Fig. 1 is typically observed in n- and in p-channel devices. The observation of RTSs is reported at all temperatures ranging from room temperature down to 4K[2)]. The switching amplitudes are typically of the order of 0.1 to 1%; however, amplitudes of up to 30% have been also reported. The time durations in the up and in the down state may be associated with the charge carrier being in the trap or in the channel. The high-conductance state is frequently, but not necessarily associated with the detrapped charge carrier state as indicated in Fig. 1. Averaging the time durations yields the emission and the capture time constants for capture τ_c and for emission τ_e, respectively, valid for this individual trap under the measurement conditions. A typical experimental result is depicted in Fig. 2. The time constants are usually strongly temperature-activated.

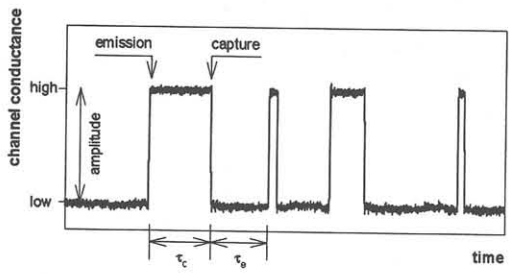

Fig. 1: Example of a random telegraph signal observed in an n-channel MOSFET.

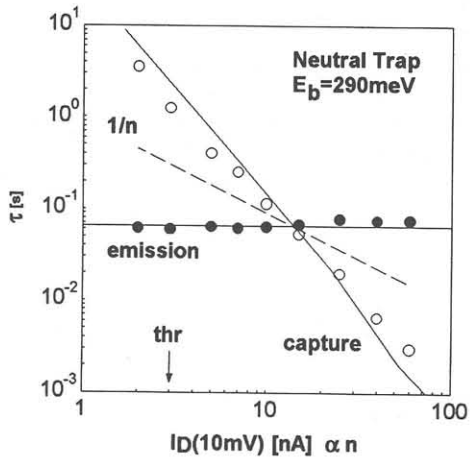

Fig. 2: Capture and emission time constants τ as a function of the free carrier density in the channel. The lines are calculated including the Coulomb energy. The dashed line indicates the slope for a bulk semiconductor trap.

3. CAPTURE AND EMISSION RATES

The major time-constant effects of RTSs were recently explained by the free-energy change of the Coulomb energy induced by the transfer and localization of a single electron into the trap thus charging the capacitor structure[5),6)]. The capture rate $1/\tau_c$ of an interface trap as indicated in Fig. 2, is not proportional to the free carrier density as is known for bulk traps in semiconductors; it rather follows a square law. This effect is due to the Coulomb energy involved in the charge transfer during trapping. The Coulomb energy is frequently discussed for small capacitor structures where it leads to a blockade effect that may be utilized in a single-electron transistor[7)]. The interface trap may be viewed as an extremely small floating capacitor; large Coulomb energy values of the order of 300meV are determined accordingly.

The Coulomb energy was determined for a large number of traps in similar MOSFETs. It only depends on the oxide thickness and on the built-in voltage, i.e., the

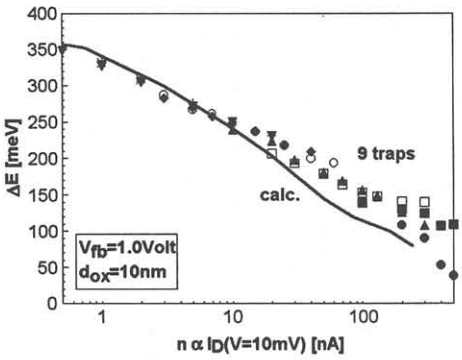

Fig. 3: Coulomb energy at room temperature determined for 9 different trap centers in differing MOSFETs of similar type. The solid line is calculated with the measured parameters given in the insert.

flatband voltage of the device. The Coulomb energy decreases with increasing carrier density in the channel due to screening effects. A typical result is shown in Fig. 3 for 9 different traps. The Coulomb energy determined follows the theoretical curve for all the traps. The unscreened magnitude observed at low carrier densities assumes high values of the order of 350meV.

4. SWITCHING AMPLITUDES

The RTS switching amplitudes were analyzed in various MOS transistors. The devices used were n- and p-channel test structures with active areas ranging from 0.35x0.35 to 0.8x0.8μm² and 10nm gate oxide thickness. Typical switching amplitudes, represented as relative conductance changes ΔG/G, are shown as a function of the channel conductance G in Fig. 4 for 10 different traps marked by two-letter codes.

The amplitude ΔG/G is near constant below threshold (at about I_D=20nA) and shows a roll-off proportional to $I_D^{-1...-2}$ above threshold. A large scatter between different traps is observed, particularly below threshold, which is not solely due to the differences in gate size and channel mobility. Some switching amplitudes exceed 10 % of the channel conductance below or near threshold and exhibit a noticeable decrease with inversion charge density, but no dependence on temperature or only a weak tendency to increase with falling temperature.

A simple estimate of the scattering cross sections of the traps causing large RTSs yields unreasonably high scattering radii approaching or exceeding the device size. The channel mobilities measured of about 200cm²/Vs at room temperature imply a mean free path for the inversion carriers of roughly 5nm, which is of the order of, or smaller than the diameter of the perturbation area of a Coulomb scattering center present at the interface. A model based on a mobility change due to scattering perturbations therefore seems not to be appropriate.

The effect of trapping is better approximated by varying the channel conductivity in a disk of the local potential perturbation. This model is evaluated by using a computer

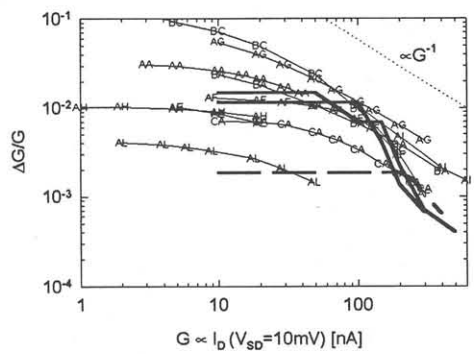

Fig. 4: Relative change in channel conductance ΔG/G versus drain current I_D at constant drain voltage V_{SD}=10mV. Different curves are for different sub-μm MOSFETs at temperatures ranging from 200-300K. The bold lines depict two modeling curves for transistor AF (underlying curve) in a percolation channel. The dashed line shows the predicted modulation of trap AF as estimated for an otherwise uniform channel, and is too small by an order of magnitude in weak inversion.

simulation to solve the resulting current and potential distributions. The total channel conductance is calculated with and without the local conductivity modulation due to a single trap introduced in the channel. For small inversion charge densities below and around threshold, a repulsive elementary charge trapped at the interface effectively punches a hole with a radius of a few nanometers into the sheet of free inversion carriers. From this worst case estimate, it is clear that the maximum conductance modulation due to a single trap in an otherwise homogeneous 0.5x0.5μm² MOS channel cannot exceed 0.5%. This estimate is indicated in Fig. 4 by the dashed line.

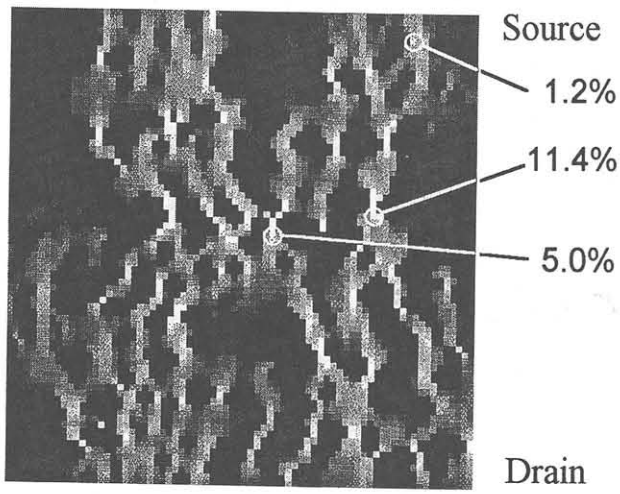

Fig. 5: Modeled distribution of current density in a 0.5x0.5μm² MOS channel with drain current I_D=10nA at drain voltage V_{SD}=10mV in the presence of potential fluctuations due to $4\cdot10^{11}cm^{-2}$ localized elementary charges. Current densities (only source-drain component is shown) range from 0 (black) to 1 mA/cm (white). Indicated are three examples of trap locations and their corresponding relative sub-threshold switching amplitudes.

The modulation of the uniform channel conductance even in this worst case estimate does not yield the magnitude of the modulations observed; furthermore, the modulations calculated are the same for all the traps studied. We conclude from this discussion that the channel is strongly nonuniform and that the modulating trap centers causing RTS are located in percolating current paths. The fixed oxide charges present at a higher density than the interface traps cause similar current modulations which are, however, permanent. The time-dependent modulations visible as RTS probe the percolating current.

High modulations are obtained by simulating an inhomogeneous channel that exhibits potential fluctuations due to a typical interface charge density, here $4\cdot10^{11}cm^{-2}$ potential 'troughs' and 'bumps', each representing the local conductivity fluctuation due to a single, localized elementary charge. With thin oxides (10nm), the gate screens fixed oxide charges so effectively that they become almost isolated. Considerable deviations of the current density from that in a spatially homogeneous channel are observed in the form of percolation paths (cf. Fig. 5). The conductance of such a system was theoretically investigated by Brews[8] using the statistical distribution of fixed charge. Placing single traps into crucial positions of this system causes large conductance modulations as indicated in Fig. 5.

This model predicts the relative conductance change ΔG/G to be constant in the sub-threshold regime in accordance with the experimental observations. The large scatter of the individual traps, particularly in the sub-threshold regime, is readily explained by the individual locations relative to the percolation pattern of each transistor. Additionally, this model correctly describes the ΔG/G roll-off due to screening of the percolation proportional to $I_D^{1...2}$ (varying with different locations) and a decay proportional to I_D^{-1} in strong inversion. Two model curves for the trap named AF are shown bold in Fig. 4; they approximate the underlying experimental curves quite well.

We conclude from this discussion that the channel in sub-μm sized MOSFETs is strongly nonuniform. The RTS is an atomic probe of the channel percolation paths.

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