Entropy measurements on slow Si/SiO$_2$ interface states

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Using telegraph noise measurements on small n- and p-channel metal-oxide-silicon field-effect transistors, we have measured the entropy change associated with the change of the charge state of individual slow Si/SiO$_2$ surface states. In n-channel devices we find that the entropy change is positive on electron emission to the silicon conduction band, while in p-channel devices it is positive on hole emission to the valence band. The results suggest that the slow states in the upper and lower regions of the silicon band gap are of a different type.

The electrical properties of slow states at the Si/SiO$_2$ interface have been studied in large-area devices by a wide range of techniques, including deep level transient spectroscopy (DLTS),[1] conductance,[2] and noise[3,4] measurements. In the conventional model[5] these states arise from defects distributed more or less uniformly into the oxide and with a broad distribution of energies, in contrast with the more extensively studied fast states which have a single (smeared) time constant at any particular energy in the band gap.[6] This explains the observed nearly featureless distribution of trapping times, which has made unambiguous interpretation of results very difficult. However, over the last few years, additional information has come from the analysis of discrete switching, or random telegraph signals (RTSs), in the drain current of submicron metal-oxide-silicon field-effect transistors (MOSFETs).[7-12] This switching is caused by the alternate capture and emission of charge carriers at a single slow interface defect.

The main points that have emerged from experiments carried out on n-channel devices, and which were obscured in the measurements on large devices which contain ensembles of these defects, are the following: (i) carrier capture is thermally activated[7]; (ii) in large devices, the distribution of the properties of these slow states is such that the RTSs sum up to give $1/f$ noise[8]; and (iii) it has been inferred that the capture process is inelastic, the defects showing large lattice relaxation after capture by tunneling, and that the defects have a large entropy of ionization.[9] This entropy change is simply manifested experimentally as a linear temperature dependence of the Gibbs free energy level of a trap.

In the present letter, our previous measurements on n-channel MOSFETs are extended to p-channel devices in order to investigate the slow states close to the silicon valence-band edge. These states are found to behave in a way very similar to those in the n-channel devices, as has been noted previously by other workers,[10,11] when considered as capturing holes rather than electrons. However, the new important result that emerges from our analysis is that the entropy change ΔS, associated with the emission of a hole from a trap into the inversion layer in a p-channel device, is of the same sign as that for the emission of an electron into the inversion layer in an n-channel device, and is also of the same magnitude (of order[12] $5k_B$ to $10k_B$, where k_B is the Boltzmann constant). In other words, the entropy change associated with emission of an electron in the two cases is of opposite sign. Thus the energy level of the defect in the n-channel case moves upwards towards the silicon conduction-band edge with increasing temperature, whereas that of the defect in the p-channel case moves downwards towards the valence-band edge. This fact indicates strongly that the transitions occurring in the two situations are of a different type.

The devices used for all measurements were conventional n- and p-channel MOSFETs produced by a 1.5 μm p-well complementary MOS process and were all from a single wafer. The gate oxide thickness was 32 nm and the drawn channel length and width were of various values between 1.5 and 20 μm. Standard threshold-control implants resulted in a region of the p-channel devices adjacent to the silicon/oxide interface actually being converted to p type, so that in the subthreshold regime the devices operated in a buried-channel manner and therefore could not be simply modeled until they were operating in strong inversion. The effective electrical lengths and widths, as obtained by comparing the room-temperature transconductance characteristics of devices of different sizes, were somewhat smaller than the drawn dimensions. Following the method applied previously to n-channel MOSFETs,[12] the $1/f$ spectrum below 100 Hz, obtained by averaging the spectra of a set of devices of the same size, was found to scale with channel dimensions in the way expected for a macroscopically uniform distribution of incoherent noise sources within the channel. This shows that the traps involved were associated with the electrically active channel area rather than with any other part of the devices.

RTSs were found in p-channel devices with approximately the same frequency as in n-channel devices. Only those detectable at room temperature were analyzed, to extract the mean capture and emission times, over a range of temperatures and gate voltages determined by the background noise level and the experimental bandwidth (about 1 ms to 100 s).

Schematic electron free energy diagrams for n- and p-channel traps are given in Fig. 1. Treating the p-channel

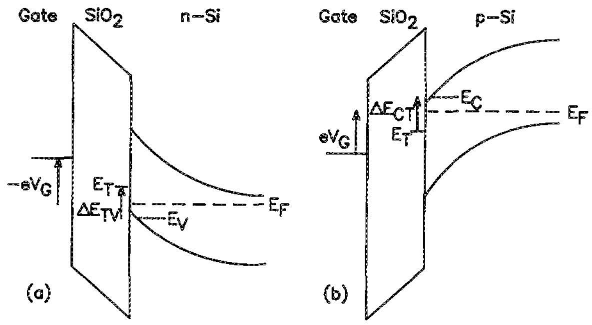

FIG. 1. Schematic electron energy-band diagrams indicating the definitions of the various Gibbs free energies used in the text for typical traps in (a) a p-channel device and (b) an n-channel device, operating in strong inversion.

traps as hole traps, in close analogy with the n-channel electron trap analysis,[9,12] gives the following pair of equations for the mean hole capture and emission times τ_c and τ_e:

$$I_D T\tau_c = \exp(\Delta E_B/k_B T)\sigma_0\chi \tag{1}$$

and

$$T^2\tau_e = \exp(-\Delta S/k_B)\exp[(\Delta E_B + \Delta H_{TV})/k_B T]/\sigma_0\eta. \tag{2}$$

Here T is the temperature, I_D is the drain current, σ_0 is the hole capture cross-section prefactor, ΔE_B is the activation energy for capture, and η and χ are constants for a given device.[12] The Gibbs free energy change for hole emission to the valence band is $\Delta E_{TV} = E_T - E_V$, where E_T is the trap energy level and E_V is the energy of the inversion layer charge centroid. ΔE_{TV} can be written as $\Delta E_{TV} = \Delta H_{TV} - T\Delta S$, where ΔH_{TV} is the enthalpy change for the transition and ΔS is the corresponding entropy change. Both ΔH_{TV} and ΔS are assumed temperature independent over the experimental range. Since the experiments independently measure the capture and emission times under equilibrium conditions, fits to Arrhenius plots at a given gate voltage V_G yield from these equations the values of ΔE_B, ΔH_{TV}, σ_0, and ΔS. From the V_G dependences of τ_c and τ_e the variation of ΔE_{TV} with V_G can then be found, and this, if attributed to a simple electrostatic displacement of the trap energy, can be used to obtain a rough value for the depth d of the trap into the oxide.[7,12]

The values of these various quantities for four p-channel traps and two n-channel traps are displayed in Table I. All are active in strong inversion. The quantities given for the n-channel traps are those analogous to the quantities for the p-channel traps given at the heads of the columns, i.e., ΔH_{CT} for ΔH_{TV} and ΔE_{CF} for ΔE_{FV} (see Fig. 1). The values of ΔS, σ_0, and ΔH_{TV} lie in the same range as has been found previously for n-channel traps,[12] with the exception of those for device N3N22, which has an unusually temperature-insensitive σ and a small ΔS. The values obtained for d, ranging from 0.8 to 3.5 nm, are typical for such traps and demonstrate that the process involves single electron rather than multielectron trapping,[12] as has been proposed for the possibly different set of defects involved in oxide tunneling experiments.[13] They cannot, however, be taken as accurate depth measurements, as it has been shown that the trap energy levels may have an additional gate-voltage dependence apart from the simple electrostatic variation expected.[12]

In this letter we concentrate on the quantity ΔS, which we believe to be meaningful for the following reasons. First, ΔS could not be a manifestation of any of the following processes: (1) A temperature-dependent silicon/oxide work function; this would result in all defect energy levels having the same temperature coefficient, as is far from the case. (2) The sensitivity of the energy levels to the temperature-dependent mechanical strain near the interface; this should be a small effect, and furthermore if the same type of defect transition is always involved this could not explain the observed difference in behavior between the n- and p-channel traps. (3) A surface potential fluctuation $\delta\phi_s$ in the inversion layer adjacent to a trap, due for instance to a fixed oxide charge; this would cause the measured value of ΔH_{TV} to be too small by $q\delta\phi_s$ and that of ΔE_B to be too large by the same amount, but would not affect the values of ΔS and σ_0.

Second, the values of ΔS found here are not unreason-

TABLE I. Data obtained from the investigation of slow traps in four p-channel (Q2P22 to Q4P22) and two n-channel (N3N22 and N4N18) MOSFETs. L and W are the electrical length and width of the channel, and the parameters given in columns 5–10 were deduced from sweeps over the temperature range indicated in column 3 at the single gate voltage given in column 4. The estimated depth d was obtained from the gate-voltage dependence at the temperature T, given in column 11, and the parameters in columns 12–14 were also calculated at this temperature. The error in the measurement of ΔS, given in column 9, was obtained from a least-squares analysis of the data. The similarity between ΔE_{TV} and ΔE_{FV} $(= E_V - E_V)$ is to be expected, as the trap will only produce a measurable RTS when it lies close in energy to the silicon Fermi level.

1 Device label	2 Size L, W (μm)	3 Temp. range (K)	4 V_G (V)	5 σ_0 (cm^2)	6 ΔH_{TV} (meV)	7 ΔE_B (meV)	8 ΔS (k_B)	9 Error in ΔS (k_B)	10 d (nm)	11 T (K)	12 ΔE_{TV} (meV)	13 ΔE_{FV} (meV)	14 σ (cm^2)
Q2P22	1.4, 0.8	260–330	−2.5	1.3×10^{-19}	394	332	12.9	1.1	3.5	310	49	59	2.6×10^{-25}
Q1P17	1.9, 1.3	260–300	−1.5	2.3×10^{-16}	144	503	3.8	1.0	0.8	280	51	96	4.6×10^{-26}
Q4P21	1.9, 0.8	290–345	−2.4	7.6×10^{-16}	314	640	9.5	0.9	2.6	310	60	61	3.0×10^{-26}
Q4P22	1.4, 0.8	290–335	−3.0	8.3×10^{-16}	306	619	9.7	1.0	2.1	297	59	50	5.3×10^{-26}
N3N22	1.4, 0.8	260–348	1.7	2.4×10^{-24}	114	69	1.5	0.5	2.0	300	75	81	3.1×10^{-25}
N4N18	1.4, 1.3	260–340	1.55	2.5×10^{-17}	181	411	4.6	0.5	1.4	292	65	89	4.3×10^{-24}

able for the entropy change associated with a process involving significant lattice relaxation, especially in a material with strong ionicity.[14,15] It may not be exactly the entropy change of the transition, as it may contain a component from a temperature dependence of the enthalpy, but it should nevertheless be related principally to the changing hardness of the lattice and the corresponding phonon mode changes[16] via the electron-phonon interaction.

We will now discuss the implications of our result that the average entropy change for electron *emission* from the slow traps in the n-channel case, $\Delta S \sim +5k_B$, is of the same sign and magnitude as that for electron *capture* in the p-channel case (i.e., the entropy change for hole emission given in Table I). First we assume that the defects are all of the same chemical origin and are undergoing the same occupancy level transition. The contribution to ΔS from the oxide lattice can then be of the same sign in the above two cases only if the defect energy levels are highly sensitive to the direction of the electric field in the oxide, and unless the defects are highly anisotropic and always have the same orientation with respect to the interface this will not be so. In both types of devices one would also expect a contribution to ΔS from the silicon inversion layer. However, the capture of an electron from the valence band, followed by emission to the conduction band, should result in a total entropy change equal to the silicon band-gap value, which is about $3k_B$ in the bulk.[16] This is much smaller than the sum of the entropy changes measured for the two processes separately, which is of order $5k_B + 5k_B = 10k_B$. Thus with the assumption of only one type of defect transition our results cannot be explained.

The transitions occurring in the n- and p-channel devices must therefore be associated either with different defects, or with different charge (occupancy) levels of the same defect. There are two possible scenarios which could account for this: (1) There could be a roughly uniform distribution of the energy levels of the two transition types across the silicon band gap, but with a large difference in capture cross section for each type between the n- and p-channel situations.[17] However, any asymmetry would have to be large compared with the range of measured cross sections for slow traps in each case, and this is not feasible because no lower limit on this range has been observed; it encompasses, for example, the very slow stress-induced defects,[18] and ultimately the effectively "fixed" (mainly positive) oxide charge. (2) There could be a concentration towards opposite sides of the silicon band gap of the energy levels corresponding to the two types of transitions. In this case, if the defects are bulk oxide defects as previously thought, it seems overly fortuitous that they should line up in such a way with the silicon band gap. The significant implication is that the intrinsic slow states are in fact connected to the silicon band structure. A possible model is of the defects being located close enough to the interface to hybridize strongly with the silicon bands, producing different occupancy levels in the upper and lower halves of the silicon band gap. If the levels in the upper half have charge assignment $(-/0)$ and those in the lower half have assignment $(0/+)$, this is entirely consistent with our entropy measurements; the $(-/0)$ n-channel defects will then go from a charged to a neutral state on electron *emission*, with an accompanying softening of the surrounding lattice and a positive entropy change, while the $(0/+)$ p-channel defects will go from charged to neutral on *capture* of an electron, again with a lattice softening and a positive entropy change.

This distribution resembles that found for P_{b0} centers at the interface,[19] and is consistent with an increase of the slow state density towards the silicon band edges, as has been well established for the fast interface states and has been proposed on several occasions to explain the results of noise measurements on slow states.[3,4] These results therefore indicate that the wide range of capture cross sections observed reflects a range of trap environments rather than a range of tunneling distances as in the conventional picture.

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