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Near Surface Oxide Trap Density Profiling in NO and Remote Plasma Nitrided Oxides in Nano-Scale MOSFETs, Using Multi-Temperature Charge Pumping Technique: N_{ot} *vs*. Oxide Processing

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1. Introduction

The increased gate leakage current and impurity penetration in ultrathin silicon dioxide (SiO_2) have impeded the scaling down of CMOS devices [1]. The NO oxide and remote plasma nitrided oxide (RPNO) have been proposed to circumvent these problems. In ultrathin gate dielectric, the primary mechanism of gate leakage is the trap assisted tunneling (TAT) [2]. Therefore, an accurate extraction of oxide trap density in NO oxide and RPNO is crucial for realizing reliable nano-scale CMOSFETs.

We have examined in this work the profiles of oxide trap density, N_{ot} near the interface in NO thermal oxide and RPNO's having two different nitrogen concentrations. The trechnique used for the investigation is the multi-frequency, multi-temperature charge pumping (CP).

2. Scheme for N_{ot} Profiling

Recently Paulsen and White examined N_{ot}, using the multi-frequency charge pumping technique [3]. In this scheme, the CP current (I_{CP}) has to be measured with frequency low enough to accommodate the tunneling time from oxide traps, typically less than 1KHz [4]. However, as the minimum feature size of the device shrinks, the large gate current through the ultra-thin oxide significantly masks the low frequency I_{CP}, especially its maximum, I_{CPmax} (Fig. 1(a)). On the other hand, in devices with small geometry but thick gate oxide, such as flash memory cells, I_{CP} is too low to be measured or is subject to large fluctuations unless the frequency is made sufficiently high (Fig. 1(b)).

We circumvent these difficulties by using the multi-T CP measurement, invoking the temperature enhanced tunneling. The model of Paulsen and White is based on the maximum tunneling distance x_{max} given by

$$x_{\max}(f,T) = \frac{1}{\alpha}\ln\left(\frac{1}{f\cdot\tau}\right) \qquad (1)$$

where f is the CP frequency, and the attenuation coefficient in SiO_2, α is given by the mass of electron in the oxide, m_{ox} and barrier height, $q\Phi_{itf}$ as $\alpha = 2(2m_{ox}q\Phi_{itf})^{1/2}/\hbar$ with $m_{ox} = 0.4m_0$, m_0 being the electron rest mass [5]. The time constant of tunneling from the oxide trap is given by $\tau = \hbar\cdot(2k_BT)^{-1} \pm \tau_1$ where k_B is Boltzmann constant and τ_1 the impurity vibrational period with its polarity depending on the impurities involved.

Thus, the trap density at x_{max}, i.e. $N_T(x_{max})$ can be obtained from measured I_{CPmax} as

$$N_{ot}[x_{\max}(T)] = \frac{dQ_{CP}(T)}{dx_{\max}(T)}\frac{1}{qA_G} \qquad (2)$$

with $Q_{CP} = I_{CPmax}/f$ denoting the recombination charge per cycle.

3. Experimental

For experiment three different nMOSFETs have been used in which only the gate oxide processing has been split, viz. NO oxide and two RPNO's with nitrogen concentration of 6% (RPNO1) and 9% (RPNO2), respectively. These devices had the same oxide thickness of 50Å, and aspect ratio of W/L = 20/0.25 um.

The vertical charge pumping was performed with fixed voltage amplitude of 2V. The test frequency is chosen higher than 90MHz to focus on the nitrogen diffusion into the channel in correlation with N_{ot} monitored near the interface [7].

4. Results and Discussion

Figs. 2-4 show I_{CP} measured at 90MHz from three MOSFETs with NO, RPNO1 and RPNO2 gate oxides. In all of these data, the trace of I_{CPmax} is shown to increase with T, suggesting thereby that (i) more traps near the interface participate in recombination via T-enhanced tunneling of electrons and (ii) the energy levels of these traps are slightly shifted from N_{it} at the surface.

Figs. 5-7 show the main result of the work, namely the corresponding Q_{CP} vs. 1000/T found at four different frequencies from each of these devices. Note in particular the conspicuous gap of Q_{CP} existing between 90MHz and 100MHz. Because Q_{CP} is proportional to N_{ot}, this suggests similar change in N_{ot} profile in corresponding x_{max} interval. This in turn is to be correlated with the diffusion of nitrogen into the channel.

This can be explicitly seen from Fig. 8, where N_{ot} profiles extracted from I_{CPmax} are plotted versus the tunneling distance x_{max}. Clearly, the effective interface layer from which the nitrogen diffuses into the channel is shown to be about 4.7Å. Also, MOSFETs having RPNO oxides, especially with 6% nitrogen concentration has N_{ot} of the order of 10^{13} cm^{-3} which is lower than its value in NO by an order of magnitude. These N_{ot} values tend to converge at about 5 Å from the interface. Finally, using the room

temperature data at 180MHz, the interface states are calculated to be 3.58×10^{9} cm^{-2}, 1.60×10^{9} cm^{-2} and 1.82×10^{9} cm^{-2} for thermal NO, RPNO1 and RPNO2, respectively.

5. Conclusions

The multi-T CP technique exploiting the temperature enhanced tunneling of electrons has been successfully used for near-surface N_{ot} profiling in differently processed gate oxides, viz. NO thermal oxide, RPNO with a 6% and 9% nitrogen concentration, respectively. The nitrogen diffused near the interface results in N_{ot} lower than the heavy nitrogen concentration region away from the interface by an order of magnitude. The RPNO with 6% nitrogen concentration appears to be optimal for reducing the N_{ot} in near-surface oxide regions.

Acknowledgements

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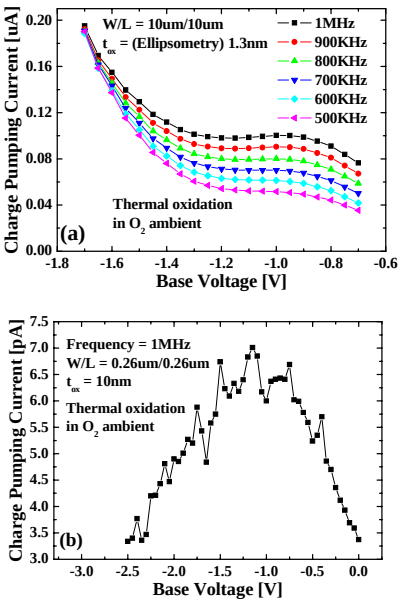

Fig. 1. I_{CP} vs. base voltage in thermally grown oxide in O_2 ambient; thin oxide, large cell size (a);thick oxide, small cell size (b).

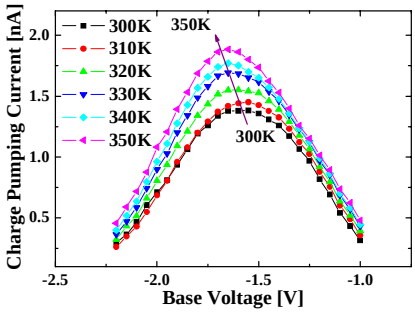

Fig. 2. I_{CP} vs. base voltage from MOSFET with NO thermal oxide.

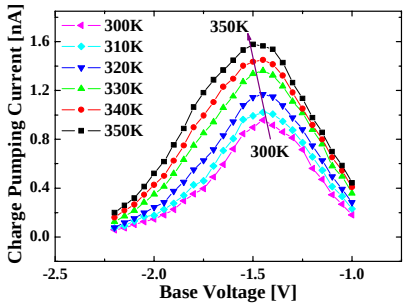

Fig. 3. I_{CP} vs. base voltage in MOSFET with RPNO of 6% nitrogen concentration.

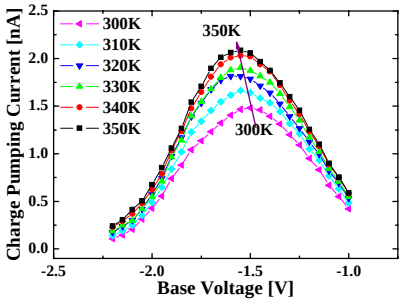

Fig. 4. I_{CP} vs. base voltage in MOSFET with RPNO of 9 % nitrogen concentration.

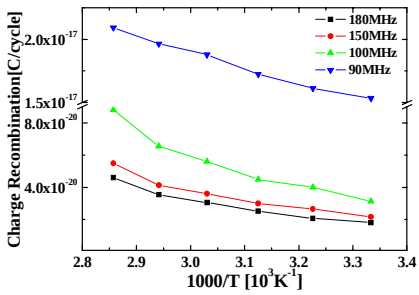

Fig. 5. Q_{CP} vs. 1000 / T for NO thermal oxide.

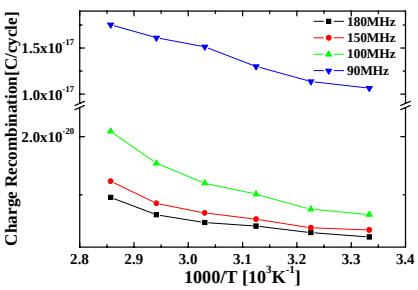

Fig. 6. Q_{CP} vs. 1000 / T for RPNO with 6% nitrogen concentration..

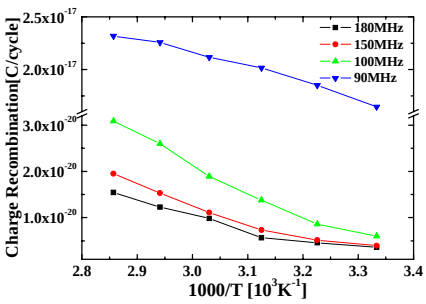

Fig. 7. Q_{CP} vs. 1000 / T^{-} for RPNO with 9% nitrogen concentration.

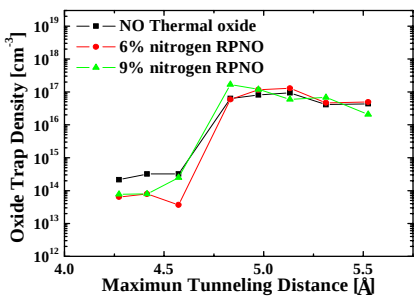

Fig. 8. N_{ot} vs. the maximum tunneling distance, x_{max} extracted from I_{CPmax} data by using (2).