Thickness-dependent stress effect in *p*-type metal–oxide–semiconductor structure investigated by substrate injection current

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The effects of oxide, Si wafer, and gate Al thicknesses on the substrate injection currents (J_{sub}) of *p*-type metal–oxide–semiconductor structures with ultrathin oxides are studied. J_{sub} is reported to be both trap-related (interface and Si bulk) and Si band gap-related (intrinsic carrier concentration). Both mechanisms have given rise to the stress near the Si/SiO₂ interface. Current–voltage and capacitance–voltage characterizations reveal that J_{sub} increases with oxide thickness, which is suggested to be dominated by the trap-related mechanism. A stronger dependence of J_{sub} on a change in oxide thickness is observed for a thicker Si wafer, which is proposed to be mainly caused by the band gap-related mechanism. Furthermore, a thicker gate Al introduces a higher J_{sub} , which is proposed to be due to both the trap-related and the band gap-related mechanisms. © 2003 American Institute of Physics. [DOI: 10.1063/1.1581004]

Stress-related problems have become pervasive in the complementary metal–oxide–semiconductor technology. Many device failures are caused by the stress that occurs during various processing stages.¹ Thermal oxidation of silicon requires volume expansion, and the oxidation rate depends strongly on the geometry² and external stress.³ Multiple overlaid films with different elastic and thermal properties introduce film stress,⁴ which is especially large at the edges of the films.⁵

Many electrical parameters of the metal–oxide–semiconductor (MOS) field-effect transistor (MOSFET) have been reported to be affected by the process-induced stress. For example, mechanical stress which is induced by the gate dielectrics⁶ influences the interface trap density, causing a threshold voltage shift,⁷ increasing the cumulative failure rate of time-dependent dielectric breakdown.⁸

Ma and co-workers studied the dependencies of radiation-induced⁹ and hot carrier-induced effects¹⁰ on the thickness of gate Al in MOS capacitors. However, the relationship between the substrate injection current (J_{sub}) and the thickness of gate Al of MOS capacitors is still unknown. J_{sub} of MOS capacitors has been stated to be useful in the Si-based photodetector.¹¹ Besides, the dependency of J_{sub} on the thicknesses of the oxide and the silicon wafer in an MOS structure is of interest. Thus, this work considers not only gate Al, but also the oxide and Si wafer thicknesses, with reference to the change in J_{sub} of MOS capacitors.

p-type 3 in. (100) Si wafers with a resistivity of 1–10 Ω cm were used. After standard Radio Corporation of America cleaning, several thick (500 μm) and thin (100 μm) silicon wafers were oxidized in a rapid thermal processor at 850 °C, 50 Torr of O₂, for various times to obtain oxides with different thicknesses. When comparing the effects of wafer thickness, the thickness of gate Al was fixed at 3000 Å. In the experiments on the effects of gate Al thickness, 500

μm thick wafers were used and the thickness of gate Al was set to 4000 Å, 6000 Å, and 8000 Å, on different chips. After gate Al deposition, MOS capacitors of size 150 μm by 150 μm were formed by conventional photolithography. Current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) curves were measured with an HP 4154 and an HP 4286, respectively. A 100 W halogen tube was employed as the light source to take *C*–*V* measurements under illumination.

Figure 1 shows the gate (J_g) and substrate injection current densities (J_{sub}) of MOS capacitors with various optical oxide thicknesses, with the wafer and gate Al thicknesses fixed at 500 μm and 3000 Å, respectively. Intuitively, J_g decreases with the oxide thickness. On the other hand, J_{sub} increased with the oxide thickness. The inset presents a typical *I*–*V* curve, showing that J_{sub} saturates when gate voltage >2 V under inversion region. J_{sub} is limited by the slow supply of minority carriers, electrons, in the depletion region, and the detailed mechanism will be discussed in the next paragraph. The current saturation phenomenon under inversion cannot be easily observed in MOSFETs and *n*-type MOS capacitors. In MOSFETs, the minority carrier can be

FIG. 1. J_{sub} and J_g of *p*-type MOS structures with oxides of various optical thicknesses. The inset shows a representative *I*–*V* curve of a device with 18 Å optical oxide thickness.

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FIG. 2. The J_{sub} vs C_{ext} of samples on the thick and thin silicon wafers. The inset shows J_g versus extracted capacitances for various samples in this work including different wafer, oxide, and gate Al thicknesses.

supplied via the source and drain regions.¹² In n -type MOS capacitors, the direct tunneling current of the majority electron carriers from the metal to the silicon is high under the inversion region, because the barrier height for electrons to tunnel through the oxide layer is lower.¹³ Accordingly, the limitation of the supply of minority hole carriers is unobservable in such a case.

Reportedly, J_{sub} of p -type MOS capacitors involve two major components; the depletion region generation current (J_{dg}), and the interface states generation current (J_{sg}).^{14–16} J_{dg} increases with Si bulk trap density, which relates to the minority carrier lifetime (τ_n). J_{sg} increases with the interface states density (D_{it}). The mechanism for which J_{sub} changes with τ_n and D_{it} , is called the trap-related effect in this letter. In addition, both J_{dg} and J_{sg} increase with Si intrinsic carrier concentration (n_i), which is governed by the band gap-related effect caused by the external stress. The Si band gap decreases (increases) when the Si lattice is under compressive (tensile) stress,¹⁷ increasing (decreasing) n_i and thus J_{sub} .

The mechanism for which J_{sub} increases with the oxide thickness in Fig. 1 is investigated as follows. The Si wafer undergoes tensile stress after oxidation due to volume expansion, and a thicker oxide may apply a larger tensile stress to the Si wafer, increasing the band gap, and decreasing n_i and thus J_{sub} . However, experimental data indicate that J_{sub} increases with the oxide thickness. Probably, the Si bondings near the Si/SiO₂ interface are broken after oxidation to create the Si interface and bulk traps, releasing some of the tensile stress, such that the band gap-related effect becomes small. However, a thicker oxide consumes a larger volume of Si, which may contribute to higher interface and bulk trap densities, increasing J_{sub} .¹⁸ So the trap-related effect dominates the J_{sub} behavior of devices for different oxide thicknesses.

Figure 2 shows the dependencies of J_{sub} and the extracted gate capacitance (C_{ext}) of the devices on the thick and thin wafers. C_{ext} is obtained from the two-frequency correction method developed by Hu.¹⁹ The purpose of converting the optical oxide thickness to C_{ext} is to more precisely determine the thickness of thin oxides. A larger C_{ext} under accumulation regions means a thinner oxide. The inset

FIG. 3. The normalized $C-V$ curves measured under illumination at various frequencies for samples on the thick and thin wafers, using for τ_n comparison. The inset shows dark $C-V$ curves in depletion region measured at two different frequencies, using for D_{it} comparison.

in Fig. 2 supports the claim that J_g increases with C_{ext} for the various samples used in this work, including those with different gate Al, oxide, and silicon wafer thicknesses. J_{sub} of the devices on both the thick and thin wafer falls as C_{ext} increases; that is, it increases with oxide thickness, consistent with Fig. 1. However, the slopes of the solid and hollow data point distributions clearly differ from each other. J_{sub} of devices on the thick wafer are more sensitive to the change in oxide thickness than that of those on the thin wafer.

$C-V$ measurements were made to determine the J_{sub} composition. The magnitude of inversion capacitance at a given frequency provides information on τ_n , and therefore, on the bulk trap density; a comparison of capacitance values at two different frequencies under the depletion region provides the information on the D_{it} .^{13,20}

Here, $C-V$ measurements were made on one device on the thick wafer and the other on the thin wafer in Fig. 2, whose C_{ext} at -3 V are both 2.6×10^{-10} F. Figure 3 shows the results. Illumination was made during the measurements of τ_n comparisons to increase the supply of minority carrier. Figure 2 clearly shows that devices on the thick wafer exhibit higher J_{sub} than those on the thin wafer at a -3 V C_{ext} value of about 2.6×10^{-10} F. However, the $C-V$ curves in Fig. 3 and its inset indicate that both τ_n and D_{it} differ little between the devices on the thick and thin wafers. Hence, the different sensitivities of J_{sub} to the change in C_{ext} (oxide thickness) between devices on the thick and thin wafers are not caused by the trap-related effect.

The ideal ratio of the stress sustained by silicon to that by oxide in an MOS structure is,²¹

$$\sigma_{\text{Si}}/d_{\text{oxide}} = 4\sigma_{\text{oxide}}/d_{\text{Si}},$$

where σ_{Si} and σ_{oxide} are the average stresses of Si and oxide, and d_{Si} and d_{oxide} are the thicknesses of the Si wafer and the oxide, respectively. Clearly, different Si wafer thicknesses induce different Si stress changes for a given particular change in the oxide thickness. As a result, the Si band gap, n_i , and then J_{sub} of devices on the thick and thin wafers have different sensitivities to the change in the oxide thickness.

FIG. 4. The J_{sub} of p -type MOS structures versus gate Al thicknesses for samples under two different C_{ext} .

The mechanism for which Si wafer thickness affect J_{sub} is supposed to be caused mainly by the band gap-related effect.

Figure 4 plots the effects of gate Al thickness on J_{sub} of devices with two similar C_{ext} values on a 500 μm Si wafer. For a given wafer thickness and similar C_{ext} (oxide thickness), a thicker gate Al thickness yields a higher J_{sub} . Again C - V analysis was employed and the results are shown in Fig. 5. First, the inset of Fig. 5 shows C - V curves under the depletion region, indicating little difference among the D_{it} values for all samples. Second, the magnitude of inversion capacitance at a certain frequency increases with gate Al thickness. Consequently, a thicker gate Al corresponds to a shorter τ_n and therefore, a higher the Si bulk trap density,

FIG. 5. The normalized C - V curves for samples with different gate Al thicknesses measured under illumination at various frequencies, using for τ_n comparison. The inset shows dark C - V curves in depletion region measured at two different frequencies, using for D_{it} comparison. The extra schematic diagram shows the stress effect of gate Al deposition on a MOS structure.

which in turn leads to a higher J_{dg} and thus J_{sub} , as observed in Fig. 4. The trap-related effects influence the J_{sub} behavior of devices for different gate Al thickness. On the other hand, the band gap-related effect may be also responsible for the increase in J_{sub} . For a certain oxide thickness, the Si wafer is generally under tensile stress. After the gate Al deposition, if the Al film is sufficiently thick, the chip curvature changes from convex to concave,⁹ as shown by the schematic diagram in Fig. 5, such that the silicon wafer is now under compressive stress. A thicker gate Al applies a larger compressive stress to Si, decreasing Si band gap, thereby increasing the n_i and J_{sub} of the devices.

In conclusion, J_{sub} of an MOS structure changes in three ways with the thickness of each component. (1) J_{sub} increases with the oxide thickness, the mechanism for which is suggested to be dominated by the trap-related effect. (2) J_{sub} of a device on a thick wafer is more sensitive to a change in the oxide thickness than that of a device on a thin wafer. The mechanism is suggested to be dominated by the band gap-related effect. (3) J_{sub} increases with the gate Al thickness. Both the trap-related and band gap-related effects are responsible for this observation. The substrate injection current is very sensitive to the thickness of oxide, Si wafer, and gate Al, and is useful for examining the effects of stress in p -type MOS structures.

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