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Hot Carrier Degradation Mechanism in Si nMOSFETs

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The gate oxide region affected by injected hot electrons and/or holes along the channel is experimentally determined. The oxide region varies with bias conditions, and the device degradation rate is correlated with the change in the hot-carrier injected region. Based on these results, the following degradation mechanism is proposed; (i) The degradations in transconductance, threshold voltage and subthreshold slope are caused mainly by trapped-electrons, but not generated interface-states. (ii) Enhanced degradations due to both hot-electron and hole injections are caused by electrons trapped in neutral centers produced by hot-hole injection.

I. INTRODUCTION

Device degradation caused by hot carrier injection into the gate oxide is a serious problem in submicron-channel MOSFET's. It has been known that the degradation is due to carrier trapping in the oxide and/or interface-states generation, and these are correlated with hot electron and/or hot hole injections.[1)-9)] However, it is still unknown what are the main roles of hot electrons and holes and which type of carrier has the main effects in the degradation. The degradations in transconductance and threshold voltage reflect the nature of the gate oxide at and/or near Si-SiO_2 interface above the channel portion. Therefore, in order to clear the degradation mechanism, it is most important to know which oxide portion hot electrons and/or hot holes are injected into.

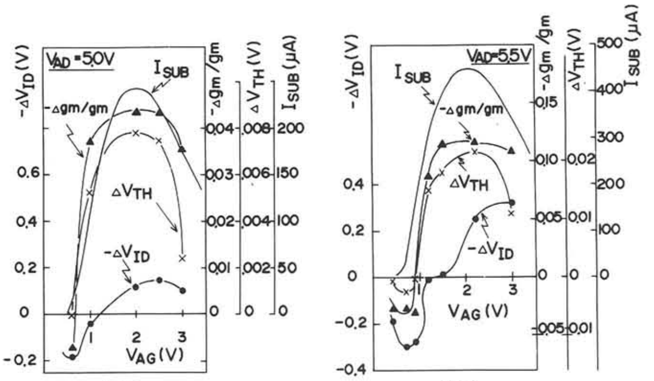
In this paper, the gate oxide region affected by injected hot electrons and/or holes along the channel is experimentally determined, and the oxide region is found to vary with bias conditions. From these results, the relationship between the degradation and hot carriers is clarified, and the degradation mechanism is proposed.

II. EXPERIMENT

Measured nMOSFET's were fabricated by poly-Si gate processes. Effective channel lengths were 0.5-1.1μm, source/drain junction depths were 0.25μm, and gate oxide thickness was 15nm. The final passivation layer was CVD phosphrous-doped SiO_2. Boron concentration of the p-type substrate was $3\times10^{15}cm^{-3}$. Surface boron concentration of the channel region was $7\times10^{16}cm^{-3}$. Device characteristics to evaluate the degradation were measured in reverse mode, that is, with the source and drain interchanged. Threshold voltage is defined at $0.1\times(W_{eff}/L_{eff})\mu A$ source current with drain voltage of 0.1V, where L_{eff} and W_{eff} are the effective channel length and width, respectively. The term g_m is the maximum transconductance at drain voltage of 0.1V.

III. OXIDE REGION AFFECTED BY INJECTED HOT ELECTRONS AND/OR HOT HOLES

The ratio of substrate current I_{SUB} to source current I_S is changed during stressing.[10)] I_{SUB}/I_S is strongly dependent upon the maximum lateral electric field E_{LMAX}, which is present in the drain depletion layer inside the drain layer. The I_{SUB}/I_S changes during stressing mean the changes in E_{LMAX} due to charges generated in the oxide above the drain depletion layer inside the drain layer.[10)] This oxide region will be called region I. From the I_{SUB}/I_S changes ($\Delta(I_{SUB}/I_S)/(I_{SUB}/I_S)$) after stressing and the relationship between I_{SUB}/I_S and gate voltage V_G obtained before stressing (I_{SUB}/I_S monotonically decreases with increasing V_G), equivalent V_G shifts (ΔV_{ID}) corresponding to the I_{SUB}/I_S changes are obtained. Generated charges Q_T in region I can be evaluated by ΔV_{ID}, because ΔV_{ID} is considered to be almost proportional to Q_T/C_{OX}(C_{OX}: gate oxide capacitance). Threshold voltage shifts ΔV_{TH} due to hot carriers in MOSFET operation reflect the nature of the oxide at and/or near Si-SiO_2 interface above the channel outside the drain. This oxide region will be called region II. Generated charges in region II can be evaluated by ΔV_{TH}. Positive (or negative) ΔV_{ID} and negative (or positive) ΔV_{TH} mean that positive (or



(a) (b)

Fig.1 Dependences of stress gate voltage V_{AG} on ΔV_{ID} and $\Delta g_m/g_m$. L_{eff}=0.7μm. (a), stress drain voltage V_{AD}=5.0V; (b), V_{AD}=5.5V. Stress time is 90min.

negative) charges are generated in regions I and II, respectively.[10)]

The relationship among stress gate voltage V_{AG}, ΔV_{TH}, $-\Delta V_{ID}$, $\Delta g_m/g_m$ and I_{SUB} in the saturation region are shown in Figs. 1(a) and (b). Stress drain voltage V_{AD} is 5.0V in Fig. 1(a) and 5.5V in Fig. 1(b). Stress time was 90min. From Fig. 1(a), it is found that (i) $-\Delta V_{ID}$ values are negative for V_{AG}<1.3V, and positive for V_{AG}>1.3V, and (ii) ΔV_{TH} values are positive in the whole V_{AG} region. Negative $-\Delta V_{ID}$ for V_{AG}<1.3V is associated with the trapping of holes in region I. The change in ΔV_{ID} with increasing V_{AG} can be explained by a decrease in the number of injected holes and an increase in the number of injected electrons into region I, mainly due to the exponential decrease of the hot-hole injection ratio and the exponential increase of the hot-electron injection ratio,[11)] as well as an increase in generated hot-electron and hole number. Thus in region I, hot-hole injection is remarkable for V_{AG}<1.3V and hot-electron injection becomes more significant than hot-hole injection as V_{AG} increases beyond 1.3V. The effect of V_{AG} on the injection ratios of hot holes and electrons is related to the changes in the effective barrier height for hot carriers with a distance from the interface, and the probability that hot carriers will lose energy by collision before they reach the interface[11)]. These are functions of the potential difference between the interface and the position where hot carriers are present, and the distance that hot carriers must travel before they reach the interface. With increasing V_{AG} in the saturation region, the electron current path becomes shallower and the hole current path becomes deeper due to a lower vertical electric field directed to the gate near the drain.[12)] Therefore, with increasing V_{AG}, the potential difference ϕ_{IC} and the distance X_{IC} for hot electrons near the drain should decrease as shown in Fig. 2. On the other hand, those for hot holes

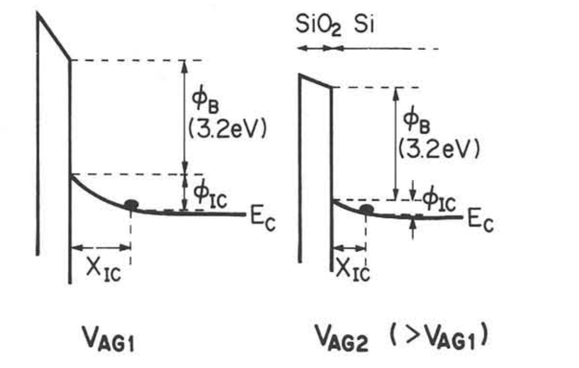


Fig.2 Effect of V_G on the potential defference ϕ_{IC} and the distance X_{IC} near the drain in the saturation region.

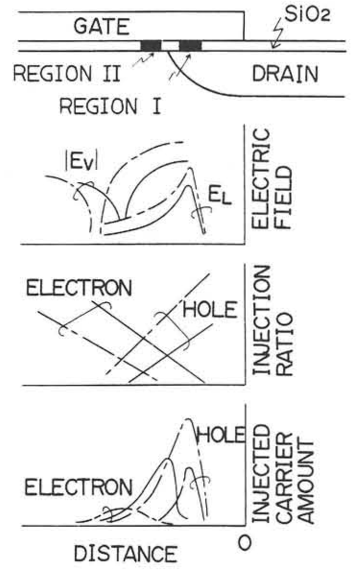


Fig.3 Schematic diagrams on electric fields, injection ratios of hot carriers and the amount of hot carriers injected into the interface, along the channel from the drain toward the source in the saturation region. —— corresponds to (a), —·— corresponds to (b) in Fig. 1.

should increase, conversely. As a result, with the increase of V_{AG} in the saturation region, the injection ratio of hot electrons increases and that of hot holes decreases. Both of these parameters change not only with V_{AG}, but also along the channel at a fixed V_{AG}. ϕ_{IC} and X_{IC} for hot electrons near the drain decrease along the channel from the drain toward the source even at a fixed V_{AG}, due to the decrease in the vertical electric field directed to the gate, and those of hot holes increase, conversely. These changes lead to an increase in hot-electron injection ratio and a decrease in the hot-hole injection ratio, along the channel from the drain toward the source with fixed V_{AG}. As a result, in region II, hot-electron injection is more important than hot-hole injection.

On the other hand, from Fig. 1(b), it is found that (i) negative $-\Delta V_{ID}$ values for V_{AG}<1.3V greatly decrease compared with those in Fig. 1(a), and (ii) negative ΔV_{TH} appears for V_{AG}<1.0V. These results indicate that at higher V_{AD}, hot holes are significantly injected into region II in addition to region I. The effect of bias conditions on the hot-carrier-injected oxide

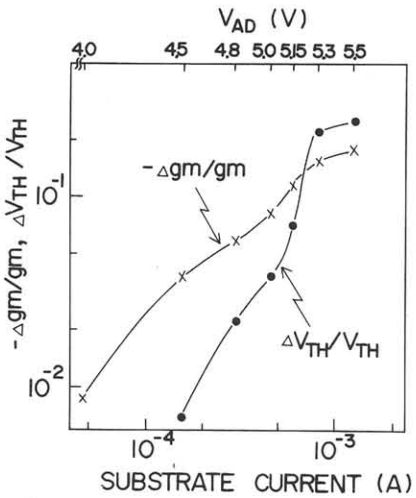


Fig.4 V_{TH} and g_m degradation ratios dependences upon the maximum substrate current for each stress drain voltage V_{AD}. L_{eff}=0.5μm. Stress time is 45min.

region can be qualitatively explained in the same way as the above, in terms of the changes in electric fields and injection ratios of hot electrons and holes near the drain as shown in Fig. 3. At higher V_{AD}, since the electron current path becomes deeper and the hole current path becomes shallower due to a higher vertical electric field directed to the gate near the drain[12], the injection ratio of hot electrons decreases, and that of hot holes increases. Thus, at V_{AD} higher than a critical value, hot holes are significantly injected into region II in addition to region I.

When both hot holes and electrons are remarkably injected into region II, device degradations are enhanced. In Fig. 4 are shown V_{TH} and g_m degradation ratios vs. the maximum I_{SUB} for each V_{AD}. As seen in Fig. 4, the degradation ratios are enhanced at V_{AD} higher than 5V as a critical value. The critical drain voltage is considered to depend upon device structure.

It is concluded that in the saturation region, (i) at V_{AD} lower than a critical value, region II is affected mainly by hot electrons, and hot holes are mainly injected into region I, therefore device degradations are mainly due to hot electrons injected into region II, and (ii) at V_{AD} higher than a critical value, hot holes are remarkably injected into region II in addition to region I, and device degradations are enhanced due to both hot electrons and holes injected into region II.

IV. DEGRADATION MECHANISM

In order to clear the hot electron effects on device degradation, a substrate-hot-electron injection method[13] was used. In this case, hot electrons are assumed to be uniformly injected into the oxide along the channel. The changes in

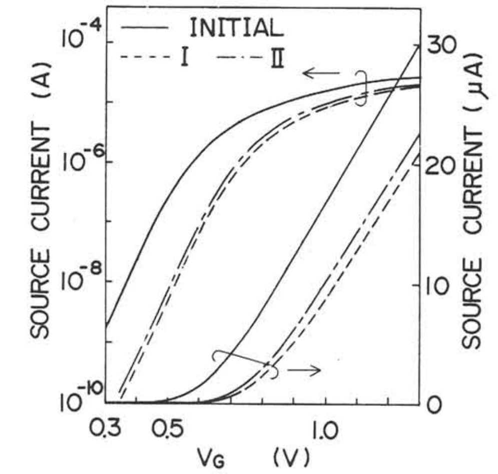


Fig.5 Changes in source current vs. gate voltage after substrate-hot-electron injection (I) and after subsequent release (II). L_{eff}=1.1μm. V_G, V_{SUB}, V_D and V_S are 6V, -4V, 0V, 0V during the injection, and -3V, 0V, 0V, 0V during the release. Each stress and subsequent release time is 60min.

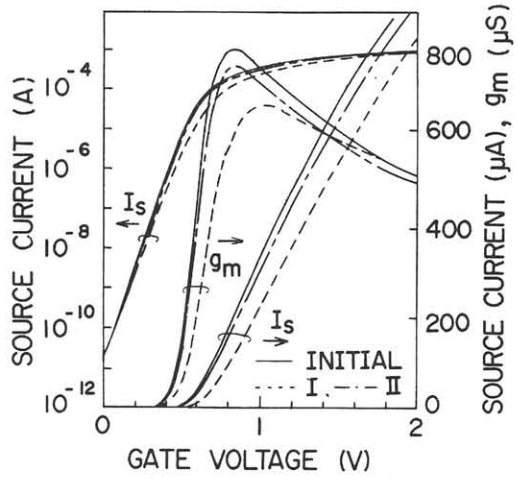


Fig.6 Changes in source current vs. gate voltage. L_{eff}=0.7μm. I, after hot-electron injection for 45min (V_{AG}=2.2V, V_{AD}=5.5V); II, after hot-hole injection for 45min (V_{AG}=0.6V, V_{AD}=5.5V) following the electron injection.

source current I_S vs. V_G after substrate-hot-electron injection (I) and after subsequent release (II) are shown in Fig. 5. V_G, V_{SUB}, V_D and V_S were 6V, -4V, 0V, 0V during the injection, and -3V, 0V, 0V, 0V during the release, respectively. Each stress and release time was 60min. From Fig. 5, it is seen that the change in subthreshold characteristics after the injection is almost a parallel shift along the V_G axis. This result indicates that the severest effect of the injected electrons is electron trapping, but not interface-states generation, which is supported by the following facts; (i) The degradation in V_{TH} was more remarkable than that in g_m ($\Delta V_{TH}/V_{TH}$=30%, $\Delta g_m/g_m$=8%), and (ii) although degraded g_m was not recovered at all, degraded V_{TH} was slightly recovered by the release (i.e., detrapping of trapped electrons).

On the other hand, for hot-electron injection in MOSFET operation in the saturation region,

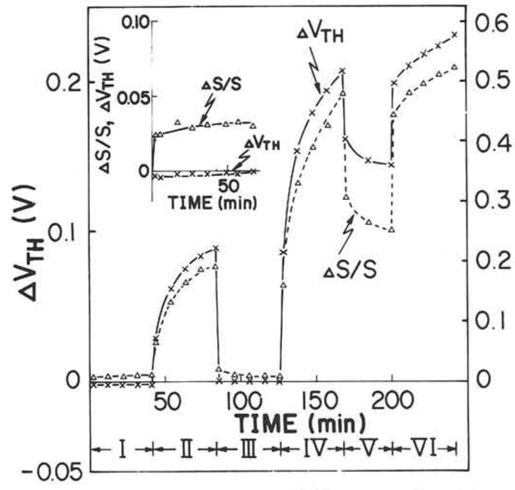


Fig.7 Changes in ΔV_{TH} and $\Delta S/S$ as a function of time. L_{eff}=0.7μm. I,III, hot-hole injection (V_{AG}=0.6V, V_{AD}=5.5V); II,IV,VI, hot-electron injection (V_{AG}=V_{AD}=5.5V); V, detrapping of electrons (V_{AG}=-3V, V_{AD}=0V). The insert of the figure is for only hot-electron injection.

subthreshold-slope S as well as V_{TH} and g_m is remarkably degraded as shown by curve (I) in Fig. 6. Moreover, hot-hole injection following the hot-electron injection (i.e., charge compensation of trapped electrons) causes such degraded characteristics to be almost recovered, as shown by curve (II) in Fig. 6. The degradations in S and g_m have been usually considered to be caused by generated interface-states. However, using a 2-D device simulator, it was confirmed that by introducing localized trapped electrons near the source (i.e., the reverse mode), the channel under the trapped electrons leaves the Si-SiO_2 interface, which leads to a decrease in the gate field effect to the channel. As a result, S and g_m are significantly degraded.

Therefore, it is concluded that the degradations in g_m, V_{TH} and S due to hot-electron injection in MOSFET operation are caused mainly by trapped-electrons near the drain, but not generated interface-states.

Next, hot-hole effects will be discussed. The changes in ΔV_{TH} and $\Delta S/S$ as a function of time are shown in Fig. 7. Hot holes are injected into region II during terms I and III, hot electrons are injected during terms II, IV and VI, and trapped electrons are detrapped during term V. The changes in ΔV_{TH} and $\Delta S/S$ as a function of time for only hot-electron injection are shown in the insert of the figure. From Fig. 7, it is found that (i) the degradations are significantly enhanced by electron injection following hole injection (I → II), compared with those for only electron injection shown in the insert, and (ii) the electron-injection-induced degradations are recovered by subsequent hole injection (II → III), and electron detrapping (IV → V). These results indicate that neutral electron-trap-centers are generated by hot-hole injection, and the enhanced degradation is due to an increase in the amount of trapped electrons. The contribution of interface-states to the enhanced degradation is extremely small.

It is concluded that the enhanced degradation due to both hot-hole and electron injections is caused by the increase in the amount of electrons trapped in neutral centers produced by hot-hole injection, but not enhanced interface-states generation.

V. SUMMARY

The gate oxide region affected by injected hot electrons and/or holes depends upon bias conditions. At drain voltages lower than a critical value, the oxide region above the channel outside the drain (region II) is affected mainly by hot electrons, and hot holes are injected into the oxide above the drain depletion layer inside the drain (region I). Significant hot-hole injection into region II occurs only under drain voltages higher than the critical value. The degradations in V_{TH}, g_m and subthreshold slope are caused mainly by localized trapped-electrons in region II, but not generated interface-states. Enhanced degradation appears when both hot-electrons and holes are injected into region II, and it is caused by electrons trapped in neutral trap centers produced by hot hole injection.

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REFERENCES

1) R.B. Fair and R.C. Sun, IEEE Trans. Electron Devices, vol.ED-28, pp.83-94, Jan. 1981.
2) H. Matsumoto, K. Sawada, S. Asai, M. Hirayama and K. Nagasawa, IEEE Trans. Electron Devices, vol.ED-28, pp. 923-928, Aug. 1981.
3) H. Gesch, J-P Leburton and G.E. Dorda, IEEE Trans. Electron Devices, vol.ED-29, pp.913-918, May 1982.
4) K.K. Ng and G.W. Taylor, IEEE Trans. Electron Devices, vol.ED-30, pp.871-876, Aug. 1983.
5) E. Takeda, A. Shimizu and T. Hagiwara, IEEE Electron Device Lett., vol.EDL-4,pp.329-331, Sep. 1983
6) M-S. Liang, C. Chang, W. Yang, C. Hu and R.W. Broderson, 1983 IEDM Tech. Dig., pp.186-189.
7) F-C. Hsu and S. Tam, IEEE Electron Device Lett., vol.EDL-5,pp.50-52, Feb. 1984.
8) T. Poorter and P. Zoestbergen, 1984 IEDM Tech. Dig., pp.100-103.
9) K.R. Hofman, W. Weber, C. Werner and G. Dorda, 1984 IEDM Tech. Dig., pp.104-107.
10) T. Tsuchiya and J. Frey, IEEE Electron Device Lett., vol.EDL-6, pp.8-11, Jan. 1985.
11) E. Takeda, Y. Nakagome, H. Kume and S. Asai, IEE Proc., vol.130, Pt I, no.3, pp.144-149, June 1983.
12) T. Tsuchiya and S. Nakajima, IEEE Trans. Electron Devices, vol.ED-32, pp.405-412, Feb. 1985.
13) B. Eitan, D.F.-Bentchkowsky, J. Shappir and M. Balog, Appl. Phys. Lett., 40(6), pp.523-525, Mar. 1982.