## Limits on Gate Insulator Thickness for MISFET Operation in Pure-Oxide and Nitrided-Oxide Gate Cases

# T. Morimoto, H. S. Momose, M. Tsuchiaki, Y. Ozawa, K. Yamabe, and H. Iwai

ULSI Research Center, Toshiba Corporation

1, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, 210, Japan, Phone: 44-549-2183

Ultra-thin gate film MISFET operation was investigated in detail. When the gate film is extremely thin, significant gate leakage current, a result of tunneling, decreases the drain current and increases the source current, which results in anomalous transistor characteristics. Reoxidation of the "ON" film is a very effective way to suppress the leakage current without reducing drivability. It was found that the practical tunneling limit of the film thickness is around 2.5nm. Below this limit, drivability and transconductance fall significantly.

#### INTRODUCTION

The gate oxide thickness has continued to fall as MIS-FETs have been scaled down in size, though it is thought that there is an ultimate limit to thickness which is defined by the tunneling current [1]. This tunnellimited thickness is about 3nm. The defect density in an ultra-thin gate oxide will also limit MISFET operation. Recently, nitrided oxide films have been introduced as MIS gate insulators [2-6] because of their low defect density and high reliability in TDDB: In this paper, ultra-thin gate insulators, less than 2.5nm thick, were produced using both pure gate oxide and nitrided gate oxide films, and MISFET operation was compared with that of thicker films.

#### EXPERIMENTS AND RESULTS

 $N^+$  poly-gate n-MISFETs and  $p^+$  poly-gate p-MISFETs were produced by the CMIS process. Two kinds of gate insulator were used, pure oxide films and nitrided oxide films. The ultra-thin pure oxide was produced by rapid thermal oxidation. Nitrided-oxide films were produced by rapid thermal nitridation of oxide films.

Figure 1 shows the  $I_D-V_D$ ,  $I_S-V_D$ , and  $I_G-V_D$  characteristics of n-MISFETs with various ultra-thin gate insulators. Determining the thickness of these ultra-thin gate films is not easy, because calculations of thickness from C-V measurements is problematical due to the significant leakage component in the MOS capacitor. From C-V measurements and TEM observations (Fig.2) of thicker film samples, it was concluded that the above ultra-thin films are less than 2.5nm thick. In the "PO" film case (RTO) (Fig.1(a)), the leakage current through the gate film is very large. Short-circuit characteristics are observed between the gate and drain and the gate and source, however normal transistor operation is not observed. In the "N" gate film (RTN) (Fig.1(b)) and "ON" gate film (RTO + RTN) (Fig.1(c)) cases, some transistor

operation is observed, but the gate leakage current is still large. It should be noted that the unusual drain and source characteristics are the result of adding the gate leakage characteristics such as in Fig.1(a) to the normal transistor characteristics such as in Fig.1(d), and that the larger source current than drain current. In the "ONO" case (RTO + RTN + RTO) (Fig.1(d)), the gate leakage current is reduced significantly and transistor operation is almost complete. It should be noted that the drain current is the same in the "ON" and "ONO" samples. This means that reoxidation of the ultra thin "ON" film is a very important process to maintain normal transistor operation without reducing the drivability.

Figures 3 and 4 show the dependence of  $I_{DO}$  (drivability) and  $g_m$ , under high gate bias, on the gate film thickness for the "PO" and "ONO" gate n-MISFETs. It should be noted that  $I_{DO}$ , continues to increase as the gate insulator is reduced in thickness until it saturates and starts to decrease at around 2.5nm. The value of  $g_m$  also starts to decrease when the gate film is reduced in thickness to around 2.5nm. This  $g_m (g_m (D) \equiv \partial I_D / \partial V_G)$  reduction is caused by the large gate leakage current. Figure 5 shows  $g_m(D)$ ,  $g_m(S)$ , and  $g_G$  for the "ON" sample shown in Fig.1(c). The large gate leakage current results in small  $g_m(D)$  and large  $g_m(S)$ . Thus, prevention of the leakage current is very important.

Figure 6 shows the gate current dependence on gate bias for n- and p-MISFETs in the case of relatively thick films. It is interesting to note that the peak gate current in the nitrided oxide sample is larger than that in the pure oxide sample in the n-MISFET case, while it is smaller in the p-MISFET case [2,3,6]. This interesting effect can be explained by the presence of trapped electrons in the nitrided film as shown in Fig.7. Due to the change in the electric field caused by negative charges or trapped electrons in the film, holes are more easily injected into the gate insulator in the nitrided oxide n-MISFET case, and electrons are injected with more difficult in the nitrided oxide p-MISFET case. In the case of the ultra-thin film, however, these effects seem not to appear as a result of the tunneling gate current as shown in Fig.8.

### CONCLUSION

Ultra-thin gate film MISFET operation was investigated in detail. When the gate film is extremely thin, significant gate leakage current, a result of tunneling, decreases the drain current and increases the source current, which results in anomalous transistor characteristics. Reoxidation of the "ON" film is a very effective way to suppress the leakage current without reducing drivability.

It was found that the practical tunneling limit of the film thickness is around 2.5nm. Below this limit, drivability and transconductance fall significantly.

The gate current in nitrided oxide gate samples was larger than that in the pure oxide samples in the nMISFET case, and smaller in the p-MISFET case. This phenomenon can be explained by trapped electrons in the nitrided oxide gate films. However, this phenomenon was not clear in the ultra-thin gate film samples, due to the complicated tunneling current.

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Fig 1. Electrical characteristics (drain, source and gate currents versus drain bias) of ultra thin gate n-MISFETs. Gate bias is increased from 0 to 2.0V by 0.5V step.

- (a) "PO": pure gate oxide by RTO
- (b) "N": nitride film produced by RTN directly on Si.
  (c) "ON": nitride film produced by RTN on the "PO" (Fig.1(a)) film.
  (d) "ONO": reoxidized film on the "ON" (Fig.1(c)) film.

