Correlation between Hot Carrier Stress, Oxide Breakdown and Gate Leakage Current for Monitoring Plasma Processing Induced Damage on Gate Oxide

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Abstract— In this paper, we compare the HC stress and oxide breakdown results with the fast and commonly used gate leakage current measurement.

A clear correlation is found between low levels of gate leakage and both HC degradation and oxide breakdown. We, for the first time, demonstrate that the value of the gate leakage current is not only a failure indicator in the region about 1 nA but also a good indicator of the reliability of the devices in the region between 1 pA and 1 nA. Thus, from the value of gate leakage current, one can estimate the reliability of the devices, saving precious measurement time.

INTRODUCTION

For very-large-scale-integration (VLSI) manufacturing of integrated circuits (ICs), the use of high-density plasma enhanced deposition and anisotropic etching techniques is inevitable. However, since 1980s [1]-[3], degradation of gate oxides in MOS devices due to the electrical charging induced by plasma processing has been observed and reported. A lot of effort has been spent to understand the phenomena [4][5] and to find the method to monitor the charging damage [6]-[8]. The measurement techniques include gate leakage, threshold voltage shift, charge-to-breakdown and hot carrier stress. The charge-to-breakdown and the hot-carrier stress measurements are accurate measures of the gate oxide integrity [9]. However, they are not often used in monitoring damage because they are very time consuming [10].

In this paper, we compare the HC stress and oxide breakdown results with the simple and commonly used gate leakage current measurement [11]. The observed good correlation suggests that gate leakage current can be used to monitor device reliability under plasma stress, thereby saving a lot of measurement time.

EXPERIMENTAL

The test structures have been subjected to a 0.35 μ m CMOS backend-of-line process. The test structures are small transistors with $W \times L = 0.35\mu\text{m} \times 2\mu\text{m}$. The gate oxide thickness is 7.5nm. The charging tester consists of a MOS transistor with a finger-shaped metal antenna connected to the gate on the first or the second metal level. The antennas are patterned with a medium density plasma system. Oxide is deposited on top of the antennas with a high-density plasma (HDP) system. The antenna ratio (AR), which is defined as the ratio between the area of the antenna connected to the transistor and the active area of the latter are 1K, 10K, and 100K. To investigate the impact of the electron shading effect, comb shaped antennas with spacing of 0.6 μ and 5 μ are compared. The protection diode is connected to gate at subsequent level, in order to protect the gate oxide from damage produced by plasma process steps following the patterning antenna.

Gate leakage ($I_{g,leak}$) of the charging testers was measured by applying a gate voltage of $V_g = 3.6\text{V}$. A charging tester can be considered to fail when the $I_{g,leak}$ measured through its gate oxide exceeds 0.1nA, indicating that soft or hard breakdown occurred. The 0.1nA is selected as failure criterion based on the leak current distribution, as shown in figure 1. The devices with $I_{g,leak}$ higher than 0.1nA, diverge from the intrinsic slope, indicating extrinsic damage induced by plasma charging.

Special precautions in the measurement setup have to be taken to reach high enough accuracy with the low-level leakage measurements.

Figure 1. Distribution of gate leakage current. The devices with $I_{g,leak}$ higher than 0.1 nA, diverge from the intrinsic slope, indicating extrinsic damage induced by plasma charging.

Hot carrier (HC) stress was also performed on pMOSFETs. The pMOSFET was stressed at $V_d = -6.5V$, $V_g = -1.9V$. This V_g was chosen to maximize bulk current I_b . The HC lifetime, which is defined as the time the MOSFET takes for a 10 mV V_t shift, is compared with the initial $I_{g,leak}$ with $V_g = 3.6V$ measured on the same devices.

The oxide breakdown measurement was performed with a ramping voltage stress on more than one thousand devices. The gate oxide was stressed on 3.5V, corresponding with 4.7MV/cm for 1 second (step 1), 4.0V or 5.3MV/cm for 1 second (step 2), 4.5V or 6.0MV/cm for 1 second (step 3) and so on until 7.0V or 9.3 MV/cm for 1 second (step 8). In between each step gate leakage is measured. The results are plotted as a function of the initial $I_{g,leak}$ with $V_g = 3.6V$. This testing method was developed to reveal latent as well as actual damage, for a wide range of gate oxide thickness in a very fast way.

RESULTS

The HC lifetime of pMOSFETs are shown in figure 2 for devices with metal 1 antennas and 3 for device with metal 2 antennas. For failing devices with $I_{g,leak}$ above 0.1 nA, the HC lifetime is degraded very much. The devices with $I_{g,leak}$ in the range of 1 to 10 pA have longer lifetimes, while the others with $I_{g,leak}$ in the range of 10 pA to 0.1 nA value have clearly shorter lifetimes. A clear correlation is also observed with the size of the antenna connected to the gate of the transistor: increasing the antenna size by a decade, the $I_{g,leak}$ increases and the HC lifetime decreases by more

than a decade. No impact of the spacing between the fingers is observed: in this case, electron shading is not the major cause of the degradation.

Figure 2. HC lifetime as function of gate leakage current measured at 3.6V on the same devices with Metal 1 finger antenna. S is the spacing between two fingers.

Figure 3. HC lifetime as function of gate leakage current measured at 3.6V on the same devices with Metal 2 finger antenna. S is the spacing between two fingers.

The strong correlation with the antenna ratio is considered as a signature for plasma damage being the cause of the degradation [12][13]. In this case the plasma damage can be caused by the etching of the metal pattern or/and the oxide deposition by a high density plasma process. Plasma damage during metal etching is typically driven by electron shading and as such influenced by the spacing between the fingers of the antenna [14]-[17]. Since no impact is observed of the spacing between the fingers, it is more likely that the HC degradation is caused by the HDP oxide deposition. The mechanism and the required improvement on the HDP oxide deposition have been published before by the authors[18].

As well known, the HC mechanism of pMOSFET under I_b , max stress condition is the channel shortening effect due to electron trap near the drain region. This leads to increased drain current and reduced V_t . [19].

The almost 1:1 ratio between HC lifetime degradation and the antenna size is confirmed by other publications [20].

The results of breakdown measurement performed with a ramping voltage stress are compared with the gate leakage current on the same devices in figure 4 for devices with metal 1 antennas and 5 for devices with metal 2 antennas.

All the reference structures without extra antenna connected to the gate have an initial leakage current in the range from 10pA to 0.1nA and break down after stress at 8MV/cm. The antenna devices that are as good as reference devices and with low initial $I_{g,leak}$ value also have breakdown values after stress at 8MV/cm, as shown in the figures. For the antenna devices with higher initial $I_{g,leak}$ value, there is a clear linear trend between $I_{g,leak}$ and the breakdown field.

Figure 4. Breakdown field as function of initial gate leakage current measured on nMOSFETs with M1 finger antenna.

Figure 5. Breakdown field as function of initial gate leakage current measured on the same nMOSFETs with M2 finger antenna.

CONCLUSIONS

A clear correlation is found between low levels of gate leakage and both HC degradation and oxide breakdown. We, for the first time, demonstrate that the value of the gate leakage current is not only a failure indicator in the region about 1 nA but also a good indicator of the reliability of the devices in the region between 1 pA and 1 nA. Thus, from the value of gate leakage current, one can estimate the reliability of the devices, saving precious measurement time.

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