Development of Thin Gate Oxides for Advanced CMOS Applications

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Abstract— **A study has been performed to investigate oxynitrides as thin gate dielectrics. The method of nitridation was a two step process involving variations of nitrous oxide and oxygen thermal soak times. The investigation of oxynitride gate dielectric was carried out through the fabrication of MOS capacitors. Thickness measurements were obtained using VASE ellipsometry and CV analysis was performed to test the electrical integrity of the dielectric. The CV analysis resulted in high frequency curves that displayed a low frequency response due to minority charge.**

Index Terms—**Oxynitride, thin oxide, nitrous oxide, CV analysis, breakdown, VASE**

I. INTRODUCTION

THERMALLY grown films of silicon dioxide serve various key roles in the fabrication and operation of integrated circuits. The most critical role of silicon dioxide is its use as a MOSFET gate dielectric. The gate dielectric for a MOSFET must satisfy a number of demands to be successful and silicon dioxide has been successfully used since the early 1970's. One demand is that the oxide thickness must be controlled to the desired thickness that matches the design specifications of the MOSFET. This thickness must be sufficiently uniform across the wafer, wafer to wafer, and from run to run. Another requirement is an electrically stable interface for the oxide film and the silicon surface including minimal values of charge in the oxide and at the interface. The oxide film must also exhibit a dielectric breakdown strength in the 8-10 MV/cm range implying a pinhole free film that contains a negligible number of defects that would cause breakdown at lower than expected electric fields. The dielectric must be chemically, electrically and thermally stable under the processes for fabricating integrated circuits and compatible with other materials used during manufacturing. The oxide must also exhibit sufficient levels of leakage-current to meet the off-state current leakage requirements of the integrated circuit. Furthermore, the oxide needs to exhibit high resistance to hot-carrier damage and the oxide needs to be resistant to boron penetration or out-diffusion during subsequent processing temperatures. Lastly, the most important requirement of a gate dielectric is its ability to be scaled in thickness with the scaling of transistor channel lengths.

As CMOS integrated circuit technology advances, the main focus of scaling the MOSFET is with respect to scaling the gate length. The advantages of scaling the gate length include an increase in the drain current, a decrease in gate area of the minimum sized transistor, both of which lead to improved circuit speed, and thirdly an increase in the density of devices per chip. However, scaling of the gate length in deep sub-micron devices can lead to unwanted short channel effects such as drain-induced barrier lowering (DIBL). DIBL is an increase in the subthreshold (off-state) drain current, I_{Dst}, as the gate length is reduced. The subthreshold drain current is one component of the total off-state leakage current.

Two measures to reduce this effect are shallow source/drain extension regions and reducing the depth of the channel depletion region. The second measure is achieved by increasing the dose of the threshold adjust implant to increase the doping in the channel. However, if the gate oxide thickness remains constant, the threshold voltage is increased as the doping concentration near the surface is increased. Since the threshold voltage is held constant or is slightly decreased as MOSFETs are scaled, the increased threshold voltage due to increased channel doping must be offset. This can only be done by decreasing the gate oxide thickness. In summary, this means to continue to scale the gate length of transistors, the gate oxide thickness must be decreased by approximately the same scaling factor as the gate length.

II. THEORY

One modification to the basic silicon dioxide gate material that has been examined is the incorporation of nitrogen into the oxide (oxynitrides). Oxynitrides have been studied as replacement gate dielectrics for thicknesses below 4.0nm. There are four main advantages of oxynitrides over silicon dioxide as the gate dielectric. The first and most important being improved suppression of boron penetration which can lead to shifts of the threshold voltage. Boron has a preference to outdiffuse from the poly gate and reside in the oxide. The incorporation of nitrogen into the gate dielectric prevents this

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mainly due to an increased lattice density which prevents diffusion. The second advante being improved hot electron immunity. This results in larger electric fields being allowed with the same level of hot electron reliability. The third advantage being improved breakdown characteristics and reliability. The incorporation of nitrogen into the dielectric improves the integrity and breakdown characteristics depending on the concentration of nitrogen, however too high a concentration will reduce the benefits and even lead to large flatband voltage shifts. The fourth and final benefit being increased high-field electron channel mobility.

Nitridation of oxides is considered a variation of silicon oxidation. Such films are formed through the nitridation of silicon dioxide by the oxidation of silicon in a nitrogen containing ambient (NH_3, N_2O, NO), or thermal growth of nitrogen-implanted silicon. Figure 1 below depicts the multiple methods used to incorporate nitrogen which include thermal and physical and chemical vapor deposition methods.

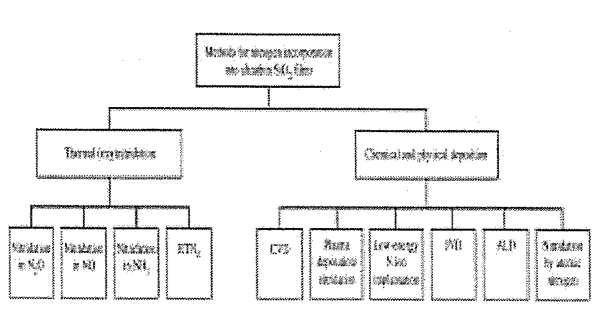

Figure 1: Methods of Nitridation

Exposing silicon dioxide films to pure ammonia (NH_3) or nitrous oxide (N_2O) at high temperatures and atmospheric pressures will cause thermal nitridation of silicon dioxide. This technique will result in a mostly silicon dioxide film with nitridation occurring at the silicon surface and the silicon-dielectric surface.

The reactions that lead to the nitridation of the dielectric are shown in figure 2. The introduction of nitrous oxide into the furnace tube will rapidly decompose it into N_2 and atomic oxygen. The atomic oxygen will then initiate a series of reactions to form nitric oxide. This is the key step of the reactions as nitric oxide is the main nitriding agent. The nitric oxide will then diffuse through the SiO_xN_y layer and react with silicon at the surface to incorporate nitrogen. However, nitrogen is also removed due to the atomic oxygen and the concentration of nitrogen is dependant on the amount incorporated and the amount removed by the atomic oxygen.

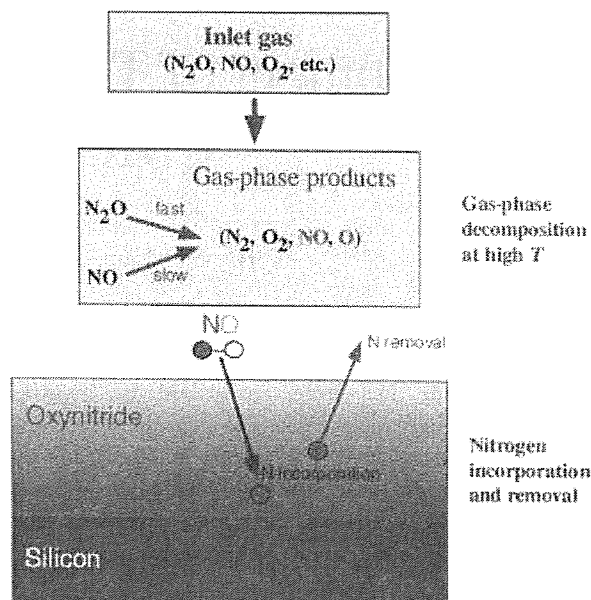

Figure 2: Reactions to form nitride layer in the dielectric

However, the use of a hydrogen containing ambient results in a higher fixed charge density (Q_f) and a large number of electron traps (Q_{ot}) in the dielectric film. These charges and traps will shift the threshold voltage and reduce stability under hot carrier stressing. To alleviate this issue, the NH_3 ambient can be replaced with N_2O to avoid hydrogen incorporation. This is usually performed as a two-step oxidation with an oxide grown in dry O_2 followed by a nitridation step or a post-oxidation anneal in the N_2O ambient.

The placement of the nitrogen peak can be engineered based on the application. To aid in the suppression of boron penetration from a P+ doped poly gate the peak would be desired away from the surface and below the gate. However, this profile would not serve as a good barrier for hot carrier immunity. For that application a nitrogen peak near the surface would be preferred to prevent hot carrier injection. The engineering of the nitrogen profile results from the ambient the oxynitride is grown in and the order of the oxidation and nitridation steps in a two-step recipe.

A uniform nitrogen profile can be achieved by growing the dielectric layer in a nitric oxide (NO) ambient. Dielectrics grown in a nitrous oxide (N_2O) ambient will have a peak near the dielectric-substrate interface. This profile can be attributed to some of the nitrogen being removed from atomic oxygen.

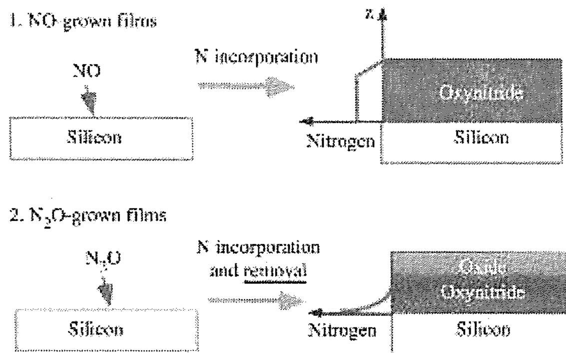

Figure 3: Nitrogen peak location for NO and N_2O grown films

A peak near the interface may also be achieved by annealing a previously grown oxide in a nitric oxide or nitrous oxide ambient. The peak near the interface may also be attributed to the removal of nitrogen near the surface by atomic oxygen. A reoxidation of a previously grown oxynitride layer in an O_2 ambient will push the nitrogen peak away from the interface and towards the poly gate.

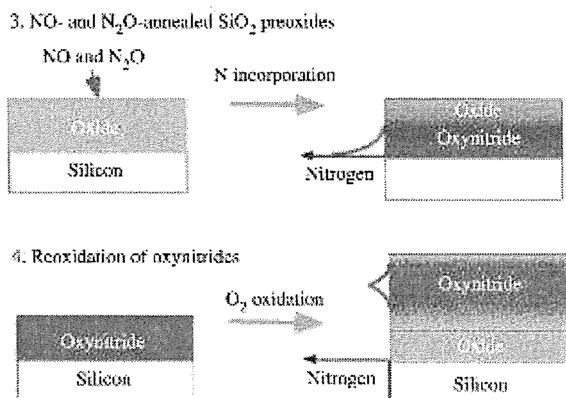

Figure 4: Nitrogen peak location for NO, N_2O and Reoxidized grown films

III. EXPERIMENT

To investigate the properties of the nitrided oxide, capacitors were manufactured using two different recipes for the formation of the oxynitride layer.

The wafers were cleaned in a standard RCA clean and followed by a final HF dip to ensure there was no moisture on the surface of the wafers. A TransLC chlorine clean was performed on the thermal furnace tube to reduce sodium ion contamination of the furnace tube and quartzware. The oxynitride was grown at 900 C with a 30 minute soak in nitrous oxide. This was followed by two splits of the oxygen soak, a 20 minute soak and a 10 minute soak. Next inline measurements of surface charge analysis on the SCA and oxynitride thickness measurements using the VASE ellipsometry. Aluminum was then evaporated instead of sputtered to eliminate unnecessary plasma damage. The aluminum was then patterned using a g-line stepper with the standard capacitor mask and NMOS active mask. The aluminum was then etched in a wet bath and the resist removed in wet baths instead of being ashed to eliminate plasma damage.

The manufactured capacitors were then tested using the Keithley 82 test setup. High frequency capacitance voltage measurements were performed on the capacitors. The voltage was swept from -4 to 2 volts in 20mV steps with a 70ms delay between steps.

IV. Results and Discussion

The VASE measurements carried out inline yielded the thickness measurements of the nitrided oxide. The thickness for the thirty minute O_2 soak was 149Å. The thickness for the twenty minute O_2 soak was 92 Å. Following the above described testing procedure, capacitance voltage analysis of the capacitors was also performed. The two different splits were measured with varying size gate areas. The plots for the two different splits are shown below in figures 5 and 6.

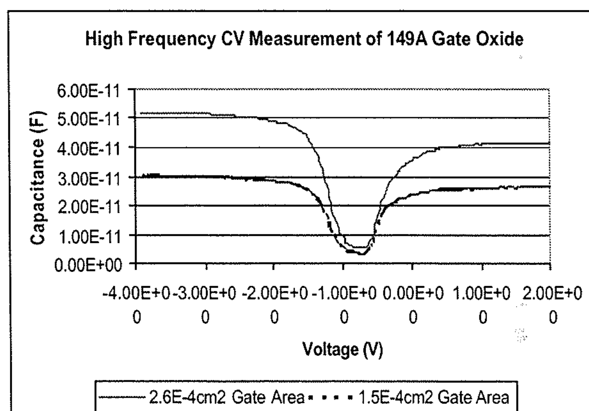

Figure 5: 149A Gate Oxide High Frequency CV Measurement

The capacitance voltage curves are high frequency measurements. However, both curves display a low frequency characteristic by the inversion portion of the curve rising towards the accumulation section as happens during low frequency sweeps. This low frequency response can be attributed to minority charge being available at the field regions of the dielectric surrounding the gate. This minority charge does not allow the gate to fully invert the region underneath it and this results in the low frequency response.

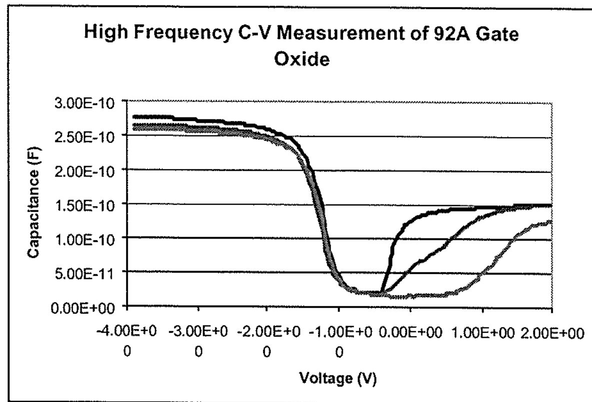

Figure 6: 92A High Frequency CV Measurement of 100Kum^w Gate Area

The capacitance voltage curves in figure 6 display the same low frequency response as the curves in figure 5. However, the three curves are from different areas of the wafer and the response in the inversion portion is different for each curve. The shift in the response between the three curves could be attributed to different charge levels across the wafer which would result in different levels of minority charge. However, more investigation would need to be done to further examine the reasoning.

V. CONCLUSION

This study investigated the methods of nitriding an oxide dielectric and employed a two step oxynitridation recipe. The two splits on soak times yielded different gate dielectric thicknesses showing the ability to scale the oxynitride. MOS capacitors were successfully fabricated to demonstrate electrical use of the oxynitride dielectric. The expected trend of oxide capacitance dependency on gate area was still obtained However, the high frequency CV measurements demonstrated a low frequency response and further work to investigate this issue should be carried out.

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