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Effects of Plasma-Deposited Silicon Nitride Passivation on the Radiation Hardness of CMOS Integrated Circuits*

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Introduction

Silicon nitride films prepared by plasma-enhanced chemical vapor deposition (PECVD) have a variety of current applications and proposed uses including antireflection coatings for LEDs, LCDs, and solar cells; masks for III-V and II-VI device processing; and an interlevel dielectric for multilevel metallization. However, the most significant use of PECVD silicon nitride in the semiconductor industry is for final passivation of integrated circuits.

The plasma-enhanced deposition process is carried out at reduced pressures, usually less than 5 Torr. This low-pressure processing results in conformal films, that is, films with excellent step coverage. In addition, PECVD processing is done at low temperatures, typically 200-400°C, which makes it compatible with most metallization systems. These plasma-deposited silicon nitride films are scratch resistant and are an effective barrier against moisture and alkali ions.[1] These physical properties are superior to those of CVD SiO_2 or phosphosilicate glass (PSG) for final passivation applications.

The use of PECVD silicon nitride as a final passivation layer does have some disadvantages. These films tend to crack, particularly over aluminum steps, when subjected to thermal cycling. The cracking resistance is a complex function of several properties of the plasma-deposited silicon nitride film (determined by deposition conditions) and the substrate material.[2] Because most commercial plasma deposition machines process the wafers in a face-up, horizontal position, they are susceptible to contamination due to particulate precipitation. The growing acceptance of PECVD silicon nitride as a final passivation indicates that these have not proved to be serious drawbacks.

It is of the greatest importance, however, that neither the PECVD process nor the properties of the films produced by this deposition technique cause any undesirable effects on the electrical effects of the encapsulated devices. Recently it has been found that CMOS devices passivated with plasma-deposited silicon nitride exhibit large threshold voltage shifts when exposed to an ionizing radiation environment.[3,4] These postirradiation effects on the electrical characteristics of CMOS devices are not only important in the fabrication of radiation-hardened integrated circuits, but may also be of more general concern. Any of several mechanisms by which charge is injected into the gate oxide could possibly cause a similar degradation in the performance of MOS devices with PECVD silicon nitride final passivation. There is evidence to suggest a correlation between oxide charging produced by high field charge injection and that produced by exposure to ionizing radiation for oxides grown under a variety of conditions.[5]

The degradation in the radiation hardness of metalgate CMOS integrated circuits with PECVD silicon nitride passivation will be reviewed in this paper. The influence of processing variations on these degradation effects will be described. The properties of these films will be examined, and possible mechanisms which seem most likely to be responsible for the observed effects will be discussed.

Experimental

The test devices used in this investigation are metal-gate CMOS inverters. These circuits are fabricated using the optimized radiation hardened process sequence described by Derbenwick and Gregory.[6] The gate oxide is grown in dry oxygen at 1000°C to a thickness of 700 Å. No gate oxide anneal is used. The aluminum gates are evaporated from an induction-heated crucible. The aluminum was sintered at 450°C in nitrogen. All the circuits were processed identically through the sinter of the aluminum metallization. Baseline devices fabricated following our standard processing sequence have an 0.8 micron thick CVD phosphosilicate glass (PSG) layer deposited at 420°C as the final passivation. Other devices were passivated with PECVD silicon nitride films prepared under various conditions.

The PECVD silicon nitride films were deposited in a commercial planar, radial flow system* by reacting silane and ammonia in a nitrogen carrier at a reduced pressure.[7] All the deposition parameters were held constant except for the substrate temperature which

*Applied Materials Technology, Inc., Model Plasma I was varied from the normal 300°C down to room temperature. The RF power was held constant at 300 W at a frequency of 50 kHz, the reactor pressure was held at 0.2 Torr, and the gas flows held constant with an NH_3/SiH_4 ratio of 2.67.

Packaged devices were subjected to gamma irradiation from a ^{60}Co source at 2 Mrad/h. The postirradiation device characteristics were all measured within five minutes of each irradiation.

Results and Discussion

Properties of PECVD silicon nitride--Figure 1 shows several properties of the silicon nitride films deposited on (100) silicon wafers as a function of substrate temperature during deposition. The etch rate of these films in 7:1 buffered HF decreases nearly exponentially with increasing deposition temperature. The refractive index increases approximately linearly with increasing deposition temperature. The stress of these plasma-deposited silicon nitride films is compressive and increases monotonically with the deposition temperature. These PECVD silicon nitride films have no fixed stoichiometry, unlike CVD pyrolytic Si_3N_4. Ion backscattering analysis of films deposited under the same conditions as those deposited at 300°C in this study have shown these films to be silicon-rich with an Si/N atomic ratio near unity.[8] In addition, these plasma-deposited silicon nitride films contain significant amounts of hydrogen. Due to its uncertain chemical composition, PECVD silicon nitride has been described as a polysilazane, $Si_xH_yN_z$.[9] It has been shown that the hydrogen content of plasma-deposited silicon nitride increases at lower deposition temperatures.[10,11] The amount of hydrogen in the form of Si-H or N-H bonds was determined from infrared absorption measurements[8,9] for the films used in these experiments. The hydrogen content of these films decreases monotonically with increasing deposition temperatures from about 32 atomic percent hydrogen in films deposited on unheated substrates to about 20 atomic percent in films deposited at 300°C.[11]

Device characteristics after irradiation--Devices with PECVD silicon nitride passivation have the same preirradiation threshold voltages as the baseline

PSG-passivated devices. However, after irradiation, devices encapsulated with the plasma-deposited silicon nitride exhibit much larger threshold voltage shifts than the PSG-passivated devices. In Figure 2 and Figure 3, the radiation-induced threshold voltage shifts of n-channel and p-channel transistors on CMOS inverters with various passivation layers are plotted as a function of total gamma radiation dose. Baseline devices with PSG passivation are compared to devices with PECVD silicon nitride deposited at various substrate temperatures. The thickness of the silicon nitride films is between 0.96 and 1.02 micron in all cases.

In most cases, after irradiation the devices passivated with plasma-deposited silicon nitride show positive threshold voltage shifts for the n-channel transistors and negative shifts for the p-channel transistors. These shifts indicate a buildup of a net negative charge in the gate oxide for the n-channel devices and a net positive charge for the p-channel devices. Since the presence of a large negative-fixed oxide charge has not been observed in MOS structures, the net negative charge buildup in the n-channel devices is most likely due to the charging of interface states generated during irradiation. In addition, both the n-channel and p-channel transistors show a degradation in transconductance after irradiation. This further indicates that a significant increase in the interface state density is occurring. The net positive charge buildup in the p-channel devices, then, is also most likely caused by the charging of new interface states. Holes created during irradiation and trapped in the gate oxide will also contribute to the net positive charge buildup.

It is obvious from the data in Figures 2 and 3 that the substrate temperature during the deposition of the PECVD silicon nitride passivation is an important variable in determining the behavior of silicon nitride encapsulated devices under irradiation. The thickness of the passivating silicon nitride layer apparently has very little effect, however. Devices passivated with 500 Å and 9700 Å thick silicon nitride deposited at 300°C exhibited remarkably similar threshold voltage shifts after irradiation.

Discussion--The threshold voltage shifts produced in devices with PECVD silicon nitride passivation do not appear to be caused by exposure to the radiation environment of the plasma during deposition.[3] Therefore, this device degradation must be due to the properties of the silicon nitride films and/or due to chemical species present during the deposition. Of the major chemical components of PECVD silicon nitride, only hydrogen would be expected to have any effect on the electrical characteristics of the encapsulated device. Annealing in hydrogen at temperatures compatible with aluminum metallization (450°C or below) is known to reduce the preirradiation interface density.[12] There is also evidence which suggests that hydrogen annealing degrades the radiation hardness of metal-gate MOS devices.[6]

There is certainly hydrogen present in the PECVD reactor during the silicon nitride deposition process formed as a by-product of the decomposition of the reactant gases, SiH_4 and NH_3. It is not unreasonable to speculate that molecular hydrogen may be trapped in plasma-deposited silicon nitride during deposition, in addition to the chemically-bound hydrogen in the form of Si-H and N-H bonds. It would be extremely difficult to detect free hydrogen in these films; any molecular hydrogen which might be present would not be visible in the infrared spectrum. However, it is certain that there is a significant amount of hydrogen contained in PECVD silicon nitride some of which one may reasonably suspect is loosely bonded or trapped.

From Figures 2 and 3, one can see that the magnitude of the radiation-induced threshold voltage shifts for devices with plasma-deposited silicon nitride passivation decreases with increasing deposition temperature. The results for devices passivated with silicon nitride deposited on unheated substrates are exceptions to this trend and will be considered separately. This decrease in the size of the threshold voltage shifts corresponds to the decrease in the atomic percentage of hydrogen which is incorporated into these films as the deposition temperature increases. This correlation suggests that hydrogen is responsible for the degradation in radiation hardness. In order to observe an electrical effect due to hydrogen, however, diffusion to the Si/SiO_2

interface is required. The mechanics of hydrogen diffusion are not understood at this point. In addition, the influence of other factors including film properties and postdeposition annealing on hydrogen diffusion is not clear.

Devices passivated with PECVD silicon nitride deposited at $100^{\circ}C$ show a dramatic recovery in radiation hardness upon annealing to $400^{\circ}C$.[4] All the devices in this investigation were subjected to a $260^{\circ}C$ anneal for one hour as part of the packaging sequence. This annealing cycle quite probably is responsible for the of any significant degradation in the radiation hardness noted for devices with silicon nitride deposited on unheated substrates. It has been shown that hydrogen is evolved from plasma-deposited silicon nitride films upon high-temperature annealing.[8,10] As the deposition temperature is reduced, the amount of hydrogen which is released in the lower temperature anneals increases.[10] If the hydrogen contained in the silicon nitride passivation is responsible for the degradation in radiation hardness, the hardness recovery upon annealing for devices passivated with PECVD silicon nitride deposited at the lowest temperatures may be related to the loss of weakly bonded hydrogen.

Summary

The use of plasma-deposited silicon nitride as a final passivation over metal-gate CMOS integrated circuits degrades the radiation hardness of these devices. The hardness degradation is manifested by increased radiation-induced threshold voltage shifts caused principally by the charging of new interface states and, to a lesser extent, by the trapping of holes created upon exposure to ionizing radiation. The threshold voltage shifts are a strong function of the deposition temperature, and show very little dependence on thickness for films deposited at $300^{\circ}C$. There is some correlation between the threshold voltage shifts and the hydrogen content of the PECVD silicon nitride films used as the final passivation layer as a function of deposition temperature. The mechanism by which the hydrogen contained in these films may react with the Si/SiO_2 interface is not clear at this point.

Acknowledgments

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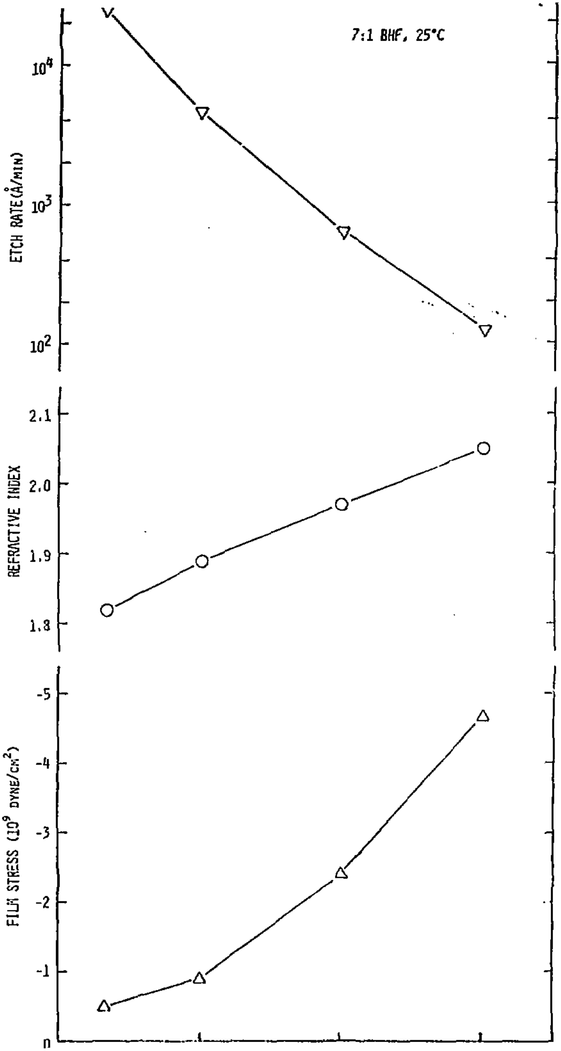
Figure Captions

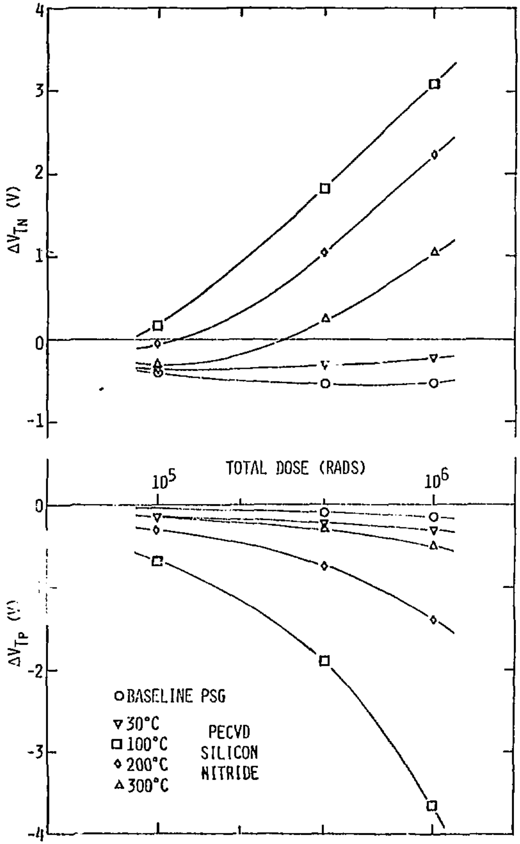
Figure 1. Properties of PECVD silicon nitride films as a function of deposition temperature. See text for deposition parameters.

Figure 2. Radiation-induced threshold voltage shifts versus gamma irradiation dose for n-channel and p-channel transistors on CMOS inverters with PSG and PECVD silicon nitride passivation. Inverter input held at 0 V during irradiation.

Figure 3. Radiation-induced threshold voltage shifts versus gamma irradiation dose for n-channel and p-channel transistors on CMOS inverters with PSG and PECVD silicon nitride passivation. Inverter input held at + 10 V during irradiation.



7:1 BHF, 25°C
ETCH RATE (Å/MIN)
10^4
10^3
10^2
REFRACTIVE INDEX
2.1
2.0
1.9
1.8
FILM STRESS (10^9 DYNE/CM^2)
-5
-4
-3
-2
-1
0



4
3
2
1
0
-1
ΔV_TN (V)
TOTAL DOSE (RADS)
10^5
10^6
0
-2
-3
-4
ΔV_TP (V)
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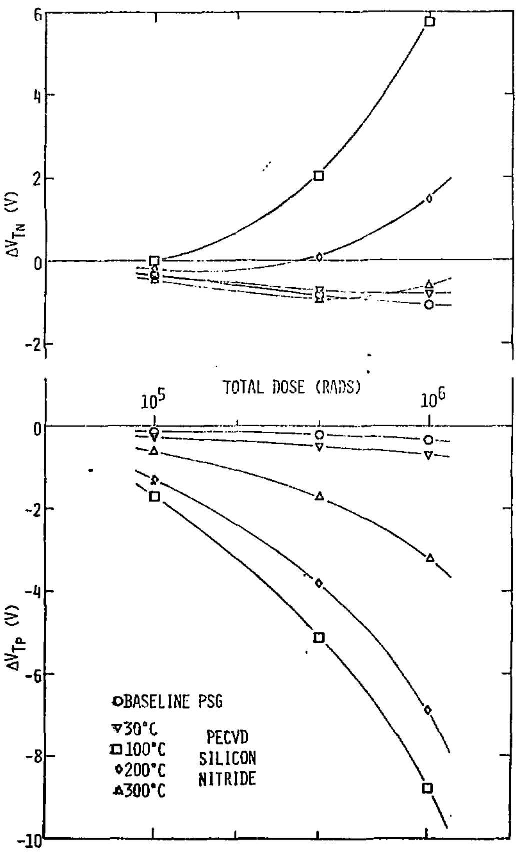
30°C
100°C
200°C
300°C
PECVD
SILICON
NITRIDE



6
4
2
0
-2
ΔV_TN (V)
TOTAL DOSE (RADS)
10^5
10^6
0
-2
-4
-6
-8
-10
ΔV_TP (V)
○BASELINE PSG
▽30°C
□100°C
◇200°C
△300°C
PECVD
SILICON
NITRIDE