CORRELATION OF ROUGHNESS AND DEVICE PROPERTIES FOR HYDROGEN PLASMA CLEANING OF Si(100) PRIOR TO GATE OXIDATION

J.S. MONTGOMERY, J.P. BARNAK, C. SILVESTRE, J.R. HAUSER, AND R.J. NEMANICH
Center for Advanced Electronic Materials Processing
North Carolina State University, Raleigh, NC 27695

ABSTRACT

Hydrogen plasma treatment was used as a cleaning and conditioning step prior to gate oxide deposition in the fabrication of cluster-based MOS field effect transistors. Surface roughness was measured by atomic force microscopy and compared to current-voltage characteristics of the MOSFET devices. The MOSFET devices were evaluated on the basis of threshold voltage, peak mobility, interface scattering, and surface roughness coefficient. Following a 10 minute H-plasma exposure at a substrate temperature of 150°C the rms roughness increased from 1.1±0.3 Å to 17±9 Å. The rms roughness for samples treated for 10 minutes at 700°C was 4±1 Å. Analysis of the MOSFET devices treated in the low temperature range (200°C) show significant degradation due to the H-plasma interaction. Threshold voltage for the devices exposed to a 2 minute H-plasma at a temperature of 200°C was 0.72±0.02 V. In contrast the threshold voltage for the 600°C, 2 minute plasma exposure was 0.86±0.03 V. The peak mobility for those devices was 370 $cm^2/V \cdot s$. Further device analysis was accomplished from the current-voltage measurements to extract a value of interface scattering and surface roughness scattering for each device. Interface scattering and surface roughness scattering do not increase for H-plasma process temperatures of 450 - 700°C. An H-plasma treatment for 2 minutes at 500°C also resulted in no observable increase in rms roughness, a threshold voltage of 0.92±0.03 V, a peak mobility of 410 $cm^2/V \cdot s$, and no increase in interface scattering and surface roughness scattering.

INTRODUCTION

The preparation of silicon surfaces has emerged as one of the limiting factors in the production of reliable small-geometry electronic devices.[1-3] Preparation of silicon surfaces involves removing unwanted surface species, maintaining or creating an atomically flat surface, and providing a surface layer or termination consistent with the following steps of device fabrication. The incorporation of contaminants or an increase in surface roughness during cleaning steps prior to deposition of the gate oxide in MOSFET devices has been shown to degrade device properties such as threshold voltage, breakdown voltage, and peak mobility.[4, 5] Therefore, the pre-gate cleaning steps must be carefully controlled. Plasma cleaning appears to be a reasonable alternative to address these issues of surface preparation. *In situ* processing allows for multi-step processing without exposure to ambient contaminants.[6-9] Previous studies have demonstrated that H-plasma processing can remove surface carbon while reducing levels of residual oxygen.[10-13] The H-plasma treatment has also been shown to effectively terminate the silicon surface with hydrogen which can easily be displaced in subsequent processing steps. In addition, plasma cleaning uses significantly less chemicals than equivalent wet bench cleaning steps. Although much research has been performed in analyzing hydrogen/silicon surface interactions, the implications of these analyses in the operation of fully fabricated devices has yet to be completely realized. In this study rms roughness was compared to threshold voltage, peak

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mobility, interface scattering, and surface roughness scattering which were derived from the current-voltage drive characteristics of the fabricated MOSFET.

EXPERIMENTATION

The approach for this experiment was divided into device fabrication, surface analysis, and finally correlations between MOSFET performance and surface characterization. Two sets of wafers were subjected to identical conditions of *ex situ* wet chemistry and *in situ* plasma processing. Following plasma processing, one set of wafers underwent the subsequent steps for MOSFET production; the second set of wafers was analyzed to determine the rms roughness of the surface. The wafers used for the experiment were 100 mm dia., boron-doped, (100) silicon with a nominal resistivity of 0.05 - 0.10 Ω·cm. *Ex situ* wet cleaning consisted of an SC1/SC2/HF series of chemical baths which resulted in an hydrogen terminated surface prior to *in situ* processing. The SC1 solution consisted of H_20:NH_4OH:H_2O_2 (5:1:1). The SC2 solution consisted of H_20:HCl:H_2O_2 (5:1:1). Both SC1 and SC2 were held at 80°C. The "HF last" was a 0.5% solution of HF in H_20. The sequence of the *ex situ* preparation was *i*) SC1/10 minutes, *ii*) DI rinse/5 minutes, *iii*) HF dip/≈ 20 seconds, *iv*) DI dip-rinse, *v*) SC2/10 minutes, *vi*) DI rinse/5 minutes, *vii*) HF dip/≈ 10 seconds, *viii*) DI dip-rinse, *ix*) spin dry. The samples were then transferred (< 2 min.) to the processing chambers for *in situ* treatments.

In situ processing was performed in a proto-type cluster system.[8] This experiment utilized two of the available modules on the 3-station cluster which includes a remote plasma cleaning module (RPC) for cleaning and conditioning, a remote plasma enhanced chemical vapor deposition module (RPECVD) for deposition of a low temperature gate oxide, and a rapid thermal chemical vapor deposition module (RTP) for deposition of oxides and poly-silicon. In addition to the process modules there is an entry/exit station which can store up to 25 wafers.

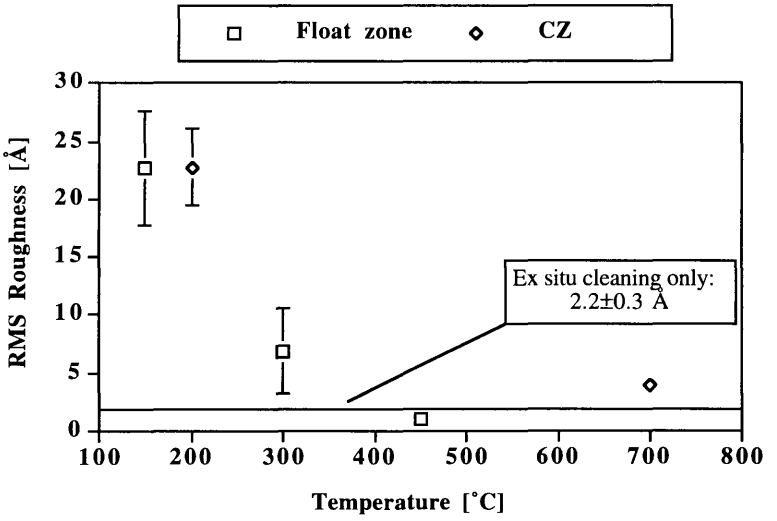

Figure 1.RMS roughness versus substrate temperature following H-plasma processing. Surface roughness prior to H-plasma treated is indicated by the horizontal line at 2.1 Å.

Samples designated for surface analysis were transferred to the cleaning module and subjected to an H-plasma exposure. Samples designated for MOSFET fabrication were subjected to an H-plasma exposure and then transferred to the RTP for a 100 Å gate oxide deposition and then a 1500 Å layer of poly-silicon. The RTP module operation and deposition have been described elsewhere.[14]

The RPC module is a stainless steel UHV system with a nominal base pressure of $5x10^{-9}$ Torr. During processing a single gas line directed hydrogen to a quartz tube coupled to the chamber. An RF power generator at 13.56 MHz was attached to a coil encircling the quartz tube. Molecular hydrogen dissociates into atomic hydrogen and affects the surface of the silicon wafer positioned ≈ 10 cm below the downstream end of the quartz tube. Samples were treated with combinations of temperature and exposure duration ranging from 200 - 700°C and 2 - 60 minutes, respectively. Process pressure was 15 mTorr with a hydrogen flow of 85 sccm and was maintained by a throttling valve/pressure transducer feed-back loop. The power used in generating the plasma was held constant at 20 W.

Evaluation of the effects of H-plasma cleaning on the surface morphology was accomplished with an ambient 10 μm AFM by Park Scientific, Inc. The cantilevers used in this experiment had silicon nitride pyramidal tips with an aspect ratio of 3:1 and a nominal tip radius of 100 Å. Scan sizes ranged from 1 - 5 μm at 512 points/trace. Scan rates ranged from 0.5 - 2 Hz. RMS values were obtained from no less than 3 separate scans per wafer. No determination was made of the force on the tip during scanning.

Final steps in the fabrication of the MOSFET devices was performed in separate facilities. The transistors evaluated in this experiment had gate areas of $(100\ \mu m)^2$, $(300\ \mu m)^2$, and $(500\ \mu m)^2$ with a gate width/length ratio of 1. Electrical characterization was conducted on a dedicated I-V test station which utilizes a computer controlling an array of Keithley Source

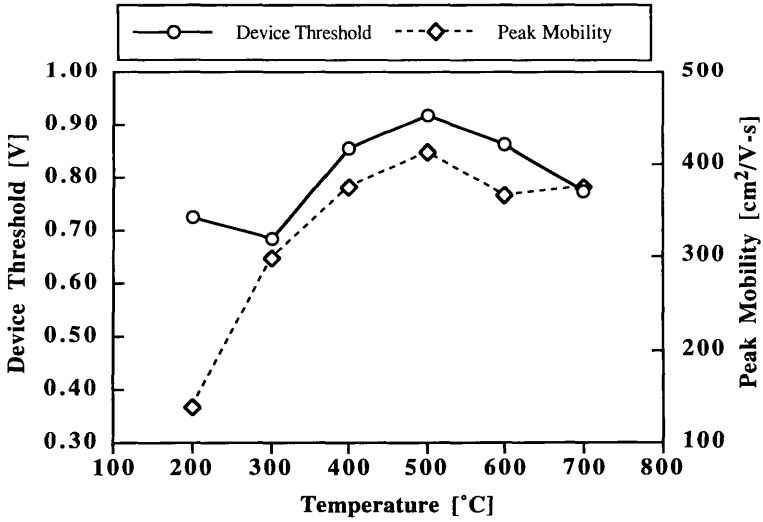

Figure 2.Device threshold and peak mobility of MOSFETs vs. substrate temperature during H-plasma processing. Plasma duration was 2 min. The theoretical threshold voltage for these devices was 0.85 V.

Measuring Units. For each wafer 5 transistors per 3 different chip locations were tested at a drain voltage (V_d) of 0.1 V. The semi-empirical mobility model put forth by Shin, et al.[15-17] was used to evaluate I-V data from the MOSFET devices. Using determined values for the gate oxide thickness and substrate doping, a non-linear least squares fit was obtained from the experimental current-voltage data. From the fitted curve, we then extract, for each device, values for threshold voltage, peak mobility, interface scattering, and roughness scattering coefficient.

RESULTS

The silicon substrates have been analyzed to determine rms roughness following exposure to an H-plasma. The control surface for these studies was only subjected to the standard *ex situ* wet cleaning described previously and was determined to have an rms roughness of 1.1±0.3 Å. The rms roughness as a function of the substrate temperature during a 10 minute plasma exposure is shown in Figure 1. Samples treated at 150°C show a significant increase in atomic scale roughness. The rms roughness for these samples was 23±5 Å. The samples processed with a substrate temperature of 450°C show no significant increase in the rms roughness as compared to the control surface prior to processing. The rms roughness obtained for these samples was 1.0±0.1 Å. In addition, for samples treated at substrate temperatures from 450 - 700°C, no significant increase in surface roughness was observed for processing durations up to 10 minutes.

Devices were analyzed based on threshold voltage, peak channel mobility, interface scattering, and the surface roughness coefficient using a previously published model for current-voltage drive characteristics of MOSFET devices[15]. Figure 2. shows the temperature dependence of threshold voltage and peak mobility for 2 minute exposures. Based on device dimensions and material properties, a theoretical threshold voltage of 0.85 V was determined for

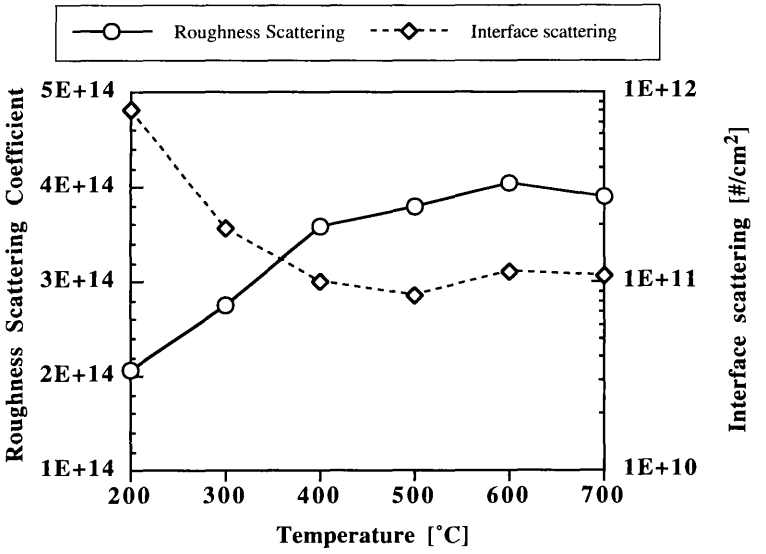

Figure 3. Roughness scattering coefficient and interface scattering vs. substrate temperature. The H-plasma exposure was 2 minutes in all cases.

these devices. The peak mobility also shows a similar trend (Figure 2.) with samples treated < 400°C suffering a significant drop in electron mobility. In Figure 3 values of interface scattering and the surface roughness coefficient are plotted as a function of substrate temperature. A reduction in the roughness scattering mechanisms is seen in the samples treated in the high temperature region (450 - 700°C). The MOSFET devices tested show consistent variations of threshold voltage, peak mobility, interface scattering, and surface roughness scattering as a function of substrate temperature during processing.

CONCLUDING REMARKS

The results display a consistent picture of the effect of the H-plasma treatment on silicon surfaces prior to device fabrication. In the low temperature region (≈ 200°C) the hydrogen is involved in an etching reaction which increases surface roughness, near surface damage, and surface defects. AFM measurements indicate an increase in surface roughness from 2.0±0.3Å before plasma processing to 23±3Å following the plasma exposure. These results along with other studies involving residual gas analysis and transmission electron microscopy suggests that the low temperature processing promotes an etching reaction.[18] In addition, studies conducted by this group and other researchers have shown an increase in the level of the interface roughness and the density of platelet defects following H-plasma cleaning at 150°C.[19, 20]

In the high temperature regime (450 - 700°C) the etching mechanism does not appear to be active. Samples treated with an H-plasma for 10 minutes at 700°C had an rms roughness of 4±1Å which is only a slight increase in roughness compared to the starting surface. To the limits of our AFM analysis, the samples treated with an H-plasma for both the 2 and 10 minute exposures exhibit no increase in surface roughness.

With an increase in interface roughness as observed by AFM, the threshold voltage, electron mobility, and scattering mechanisms in the inversion layer should also suffer. For samples treated with a 2 minute exposure at temperatures ≤ 300°C, the threshold voltage decreases by as much as 0.2 V; and the peak mobility drops to below 200 $cm^2/V\text{-}s$. In the high temperature regime, the threshold voltage is within experimental error of the theoretical value of 0.85 V; and the peak mobility reaches its maximum value of 200 $cm^2/V\text{-}s$. As seen in Figure 3. the interface scattering and roughness scattering also follow the temperature trend with no significant changes observed for samples treated at substrate temperatures ≥ 500°C. This compares well with the AFM observations at substrate temperatures ≥ 450°C which show very little increase in surface roughness.

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