The Role of Boron Segregation and Transient Enhanced Diffusion on Reverse Short Channel Effect

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Abstract--This paper presents the results of an experiment that tests recent theories on the causes of reverse short channel effect (RSCE). In this experiment defect-free silicon films, uniformly doped with boron, were grown epitaxially. The samples were then subjected to the processing steps associated with channel profile formation. A gate oxide was grown, then silicon was implanted to simulate the damage due to a source/drain implant. Finally, a damage anneal was done. The resultant experimental dopant profiles as measured using SIMS reveal a different explanation for reverse short channel effect. Boron segregation during gate oxidation significantly reduces the boron concentration near the silicon-oxide interface. Subsequent diffusions show that in the presence of damage, the transient enhanced diffusion of boron refills the dopant lost during segregation. In the absence of damage, the profile remains as it was after gate oxidation.

I. Introduction

It is largely agreed that reverse short channel effect (RSCE), the enigmatic increase in threshold voltage as gate length is decreased, is the result of a laterally nonuniform dopant profile in the channel region. Many mechanisms have been suggested to obtain this sort of dopant profile, mostly focusing on transient enhanced diffusion near the source/drain regions coupled with a high recombination of interstitials at the silicon-oxide interface [1,2]. These theories propose that a high interstitial gradient near the surface is the primary factor in RSCE and can actually cause boron to diffuse uphill. To test this theory, we ran an experiment wherein uniformly doped boron epi layers were grown and subjected to the typical channel region formation process steps.

II. Experiment

We grew uniformly doped, defect free epi layers on four silicon wafers. The films were approximately 2.5μm thick with a uniform doping of $4x10^{18}$ atoms/ cm^3. Three of the wafers then underwent key process steps in the channel formation process. Table 1 shows the processing steps in order for each sample.

Setting sample 1 aside for use as a control, samples 2-4 underwent an 850°C gate oxidation. Sample 4 was then subjected to a blanket silicon implant at a dose of $1x10^{14}$ atoms/cm^3 and an energy of 40keV. This created damage to the lattice, but not enough to cause amorphization, and is meant to simulate the effects the source/drain implant damage has on the boron channel profile. Samples 3 and 4 then underwent an 850°C-20 minute furnace anneal in a nitrogen ambient, simulating a source/drain damage anneal.

Sample	1	2	3	4
2.5μm Boron Doped Epi Layer	✓	✓	✓	✓
60Å Gate Oxide		✓	✓	✓
Silicon Implant Dose=$1x10^{14}$ atoms/cm^2 Energy=40keV				✓
850°C/20min Furnace Anneal			✓	✓

Table 1: This table shows the experimental design, wherein four samples are used and the effect of the key channel formation process steps are observed on a uniformly doped epi film.

The resulting boron dopant profiles for all four samples were measured at Evans East using a PHI-6600 Quadrupole Secondary Ion Mass Spectrometer. The primary beam was O_2^+ with an energy of 3keV at an incident angle of 60°. The oxide layer was left on for samples 2-4 but in the following analysis, the first 60Å of data has been subtracted off. An oxygen leak was used in the chamber to eliminate the sputtering rate differences as one crosses the silicon-oxide interface.

III. Results

Figure 1 shows the experimental results. In the figure, 0Å refers to the silicon-oxide interface. A large spike in the boron profile is seen in the first 50Å for all samples. This is probably due to boron contamination from exposure to a cleanroom atmosphere[3] since the spike is present and nearly identical in all the samples, including sample 1, the control, which had no processing beyond epi formation. The surface is contaminated and when SIMS analysis is done, the boron knock-ons obscure the first ~130Å of the sample, 60Å of which is the gate oxide. We believe it is not a SIMS artifact because of the SIMS analysis technique used and the fact that the measured silicon sputter rate is constant to within 5Å of the surface of the sample. For these reasons, we do not believe the spike is related to the processing steps and does not significantly effect the results

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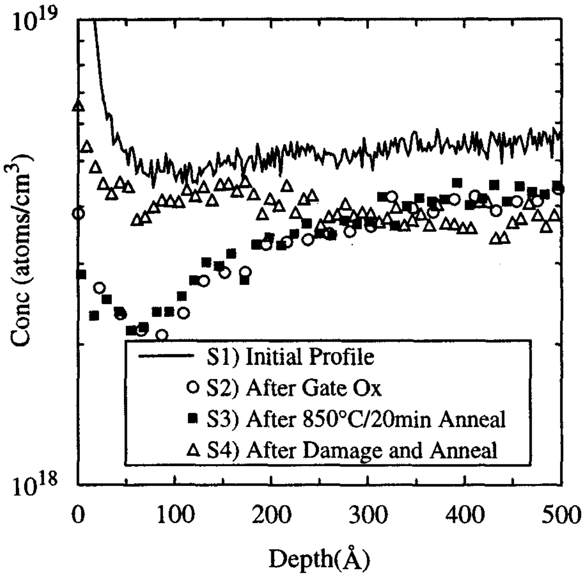

Fig 1: Dopant profiles obtained from SIMS analysis show a significant amount of boron is lost after gate oxidation near the silicon-oxide interface. Only after damage is introduced and an anneal done is the boron redistributed back into the surface region.

of the experiment, though it does make measuring of the profile within the first 60Å-100Å of the silicon-oxide interface impossible.

Ignoring the near surface spike, the data shows an initially uniform profile (sample 1). In sample 2 after gate oxidation, the concentration near the surface decreases from $4x10^{18}$ to $2x10^{18}$ atoms/cm^3 due to segregation of boron into the oxide. Sample 3 shows that an anneal in the absence of damage (equilibrium diffusion) has almost no effect on the profile. Sample 4, on the other hand, shows that after a non-amorphizing silicon implant, to create damage and simulate the channel profile near the source and drain, the boron diffuses back to an almost uniform profile. We also see that the boron is somewhat depleted at a depth of between 300Å and 500Å.

The resultant two dimensional channel profile for an actual NMOS device can be constructed from this data. During gate oxidation, the boron in the channel is uniformly depleted wherever the gate oxide is grown. The profile remains depleted until damage is introduced into the system, usually by means of the lightly doped drain (LDD) and source/drain implants. Then, near the source and drain where the excess interstitial concentration is high, the boron profile in the channel will undergo transient enhanced diffusion and refill the depleted boron layer near the surface. The final boron profile would then resemble that of sample 4, having a surface concentration of $4x10^{18}$ atoms/cm^3. In the center of the channel, away from the source drain, TED will be less due to surface recombination of interstitials. The profile in the center of the channel, farthest from the source and drain, will remain depleted and be more like sample 3 with a surface concentration of about $2x10^{18}$ atoms/cm^3. Our data shows no evidence of boron pile-up, but clearly shows boron depletion and then a subsequent refilling of the depleted zone only where TED occurs.

IV. Simulations

We simulated the experiment using a calibrated version of the fully coupled diffusion model in the TSUPREM4 process simulation program. The calibrated simulator is capable of accurately simulating transient enhanced diffusion over a wide range of processing conditions. The interstitial recombination length (D_I/Ksurf), a key factor in causing boron pile-up at the silicon-oxide interface, was 0.1μm at 850°C for these simulations. This is consistent with values used by Rafferty. The scale factor in the "+1" damage model was one. Figure 2 shows the results of the simulation compared with the experimental data. We see that using the "+1" damage model, no boron pile-up is observed in the simulation and the simulation agrees with the experiment within SIMS measurement error. If the damage scale factor is increased to ten[1] (ten interstitials created for each implanted ion), the simulation does show a

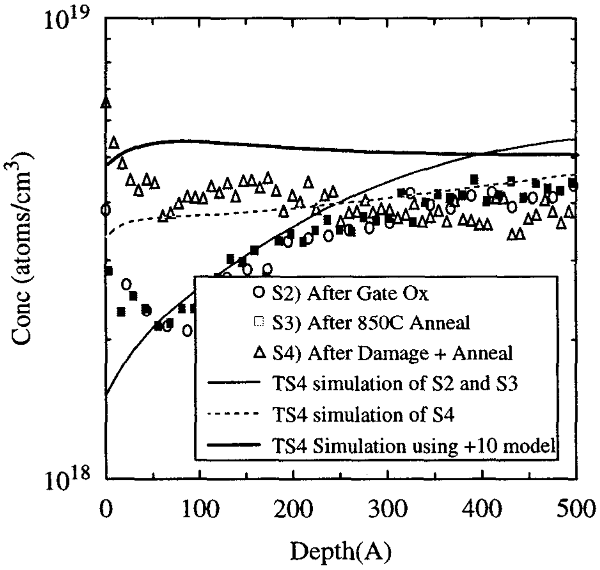

Fig 2: Simulations using a calibrated version of TSUPREM4 are able to accurately reproduced the experimental results, though no boron pile-up is observed in the simulation. When the damage scale factor is increased an order of magnitude, from 1 to 10, the a very small pile-up of boron is simulated.

very small pile-up of boron in the first 400Å of silicon, though it is nothing like that simulated by Rafferty.

V. Discussion

The results of this experiment suggest another method for creating a laterally nonuniform boron profile, the cause of reverse short channel effect, and implicate another process step, gate oxidation, for playing a key role in its creation. Lutze[4] looked at source/drain implant, channel implants, poly reoxidation, TEOS formation and silicide preclean as being involved in some manner with RSCE. He concluded the source/drain implant was the most important. It is, for it is the main contributor to lateral nonuniformity. But our data suggests the gate oxidation also plays a crucial role in RSCE creation for it sets the surface dopant concentration in the middle of the channel for long channel devices and also can create a dopant gradient near the surface where there was none.

RSCE can be attributed to a near surface boron depletion caused by segregation of boron into the growing gate oxide and then a subsequent refilling of the depleted region only where damage is present (i.e. near the source and drain regions). In order for TED to be nonuniform across the channel, the interstitial concentration must be nonuniform along the channel. Some nonuniformity occurs naturally because of the placement of the source/drain implants. We were unable to determine if this inherent nonuniformity in the interstitial profile was enough to explain RSCE, or whether another mechanism, such as a high surface recombination rate of interstitials[1] is also needed.

Our simulations used a low interstitial surface recombination length, consistent with the previous work, but no boron pile-up was seen when the "+1" model was used. The simulation was also in good agreement with the experiment. In order to simulate uphill diffusion of boron, we had to introduce a factor of ten more interstitials into the simulation and even then the uphill diffusion of boron was almost insignificant. This indicates that either the simulation is correct and boron does not pile-up at the surface, the simulation is incorrect or that a silicon dose of $1\text{x}10^{14}$ atoms/cm^2 does not create the needed damage to induce the large interstitial gradient necessary for boron to diffuse in a non-Fickian manner.

Since our data is suspect within the first 50Å, we cannot tell if boron pile-up, or uphill diffusion has occurred there. Integrating the dose from 50Å to 1000Å leads us to believe no pile-up of boron has occurred. The integrated dose for samples 2, 3 and 4 is identical, and is approximately 11% less than sample 1. If boron is piling up very near the surface during the damage anneal we should see a somewhat lower integrated dose for sample 4 compared to samples 2 and 3. Further experiments are underway, these using thicker oxides so the surface contamination spike doesn't obscure the boron profile at the silicon-oxide interface.

VI. Conclusions

We have designed and executed an experiment to test some theories on the causes of reverse short channel effect. We found no evidence of uphill diffusion of boron in the presence of damage, but were unable to measure the boron concentration in the first approximately 50Å of silicon due to surface contamination. The experimental results did, however, reveal another possible cause of RSCE. We observed a prominent surface depletion of boron, the result of the gate oxidation, and a subsequent refilling of the depleted region when an anneal, in the presence of damage, was done. When damage was not present, no refilling of the depleted region occurred. This can create lateral nonuniformity in the boron channel profile and thus contribute to reverse short channel effect.

Acknowledgments

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