SECONDARY ION MASS SPECTROMETRY SIMS XII

Proceedings of the Twelfth International Conference on Secondary Ion Mass Spectrometry (SIMS XII), Université Catholique de Louvain, Brussels, Belgium, September 5-10, 1999

Editors

A. BENNINGHOVEN, P. BERTRAND, H-N. MIGEON
and **H.W. WERNER**

2000

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Amsterdam - Lausanne - New York - Oxford - Shannon - Singapore - Tokyo

A. Benninghoven, P. Bertrand, H.-N. Migeon and H.W. Werner (Editors).
Proceedings of the 12th International Conference on Secondary Ion Mass Spectrometry,
Brussels, Belgium, 5-11 September 1999

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DETERMINATION OF SURFACE HYDROGEN IN PLASMA IMMERSION IMPLANTED SILICON

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1. Introduction

Silicon-on-insulator (SOI) is a desirable substrate to fabricate low power, low voltage microelectronics devices [1,2]. Bruel, et al. recently demonstrated that SOI wafers could be produced using a layer transfer technique encompassing hydrogen implantation, wafer bonding, and cleavage [3], and this process has attracted much attention [4,5]. Plasma immersion ion implantation (PIII) has been proposed to be an alternative to conventional beam-line ion implantation in this ion-cut process, especially for thin SOI substrates used in fully depleted CMOS (complementary metal oxide semiconductor) devices [6-10].

In hydrogen PIII, the entire silicon wafer is immersed in a plasma and biased to a pulsing negative high voltage to attain ion implantation. Our previous studies have shown that the amount and distribution of the adsorbed hydrogen affects the yield of the ion-cut method [11-12]. The surface hydrogen can deteriorate the bonding strength, cracked surface uniformity, as well as interfacial quality. If the surface hydrogen concentration is high, it can also impede wafer bonding thereby leaving patches of voids on the SOI or acceptor wafer. Hence, it is important to understand the mechanism of surface hydrogen incorporation. As the entire wafer is immersed in a hydrogen plasma during PIII, hydrogen can adsorb onto the wafer surface during the "off-cycle" of the voltage pulse and subsequently diffuse or can be knocked into the substrate by ion mixing. Another origin of surface hydrogen is the plasma sheath expansion at the beginning of each pulse. When a negative pulse is applied to the wafer, electrons are repelled on the time scale of 10^{-10} s and a plasma sheath is formed. The sheath continues to expand and ions are brought in motion on the time scale of 10^{-7} s. The time to achieve a static Child law sheath state is on the order of 10 μs or longer. Because the sheath propagation is much slower than the ion movement, this period can be described by quasi-static Child law [13]. Although the ions in the quasi-static Child law sheath are implanted at a voltage almost equal to the applied voltage, the ions in the matrix sheath are implanted with lower energy. The lowest energy can be near zero if the initial position of the hydrogen ion is just above the wafer at the beginning of the pulse.

Thus, it is important that this surface hydrogen component be determined accurately to match modeling results. As the concentration of surface hydrogen is quite large (higher than 1×10^{22} atoms/cm^3), the sputtering rate in the surface region will likely be different that that in the bulk of the silicon wafer. In this work, we performed a systematic study on the variation on the sputtering rate in this hydrogen-rich region using high resolution SIMS and crater depth measurement. The correlation between surface hydrogen and the blistering efficiency is also discussed.

2. Experimental

The PIII experiments were conducted in a custom designed PIII machine [14,15] employing five different pulse durations ranging from 5μs to 100μs. P-type, 100-mm, 10-20 Ω-cm, <100> silicon wafers were implanted. The implantation voltage was 20kV. In order to keep the amount of adsorbed hydrogen constant, the implantation time was the same for all samples (1 hour). The pulsing frequency for each run was adjusted to maintain the same integrated current or dose for all samples. The implantation dose was 5×10^{16} atoms/cm^2. After implantation, the samples were annealed at 600°C for 5 minutes. The samples were measured for surface hydrogen by high depth resolution SIMS using a cesium ion beam and a CAMECA IMS-4F. The beam current was 5nA and it was rastered to 70μm. In order to calculate the exact sputtering rates, profiles were conducted to a certain time and the craters were measured by high resolution stylus profilometry and atomic force microscopy.

3. Results and discussion

Our model predicts that a longer pulse width decreases the surface hydrogen to implanted hydrogen ratio [12]. As a proof, we performed a blistering experiment on five wafers implanted using pulsing durations from 5μs to 100μs. When the wafer is heated, the implanted hydrogen coalesce into bubbles or microcavities along the projected range [11]. In the absence of a surface stiffener such as a bonded wafer, the internal pressure build-up causes the surface to blister. The bubble density and size give a quick, albeit indirect, measure of the implanted hydrogen distribution as our previous experiments indicate that a more mono-energetic implant (i.e. more compact) distribution gives rise to denser and bigger bubbles at the same implantation dose. Our results indeed show that blistering is more efficient when the pulse width is longer [12]. The experimental observation is consistent with the cracking temperature observed for the bonded structures. The samples implanted employing 30μs and 60μs pulses were bonded to a silicon wafer with a pre-grown 150nm thermal oxide layer. The bonded structures were then annealed to achieve layer transfer. The cracking temperature could be identified by a clear sound when the structure cleaves. The cracking temperature was 600°C and 500°C for the 30μs and 60μs samples, respectively. The lower cracking temperature of the 60μs sample confirms its more mono-energetic hydrogen distribution.

In order to fit the experimental results to our model, we need to determine the accurate in-depth distribution of this surface hydrogen component. We chose the 60μs sample for this detailed study. Craters were created for different sputtering time and measured. The exact sputtering rate of each region is determined empirically by difference. Table 1 displays the sputtering time of each crater, the measured crater depth, and the sputtering rate of the region (for example, the sputtering rate for 32s represents that between 25s and 32s). To minimize statistical error due to the shallowness of the craters, each crater was measured 8 to 10 times to generate an average.

Table 1: Sputtering rates at different depths in the hydrogen PIII sample

Sputtering Time (s)	Measured Crater Depth (A)	Sputtering Rate (A/s)
15	57	3.7
18	78	4.3
18	74	4.1
24	99	4.1
24	94	3.9
32	166	5.2
40	197	4.9
40	201	5.0
48	242	5.0
56	268	4.8
60	306	5.1
64	328	5.1
72	390	5.2
80	402	5.1
100	553	5.5
100	547	5.5
120	640	5.3
140	767	5.5
150	797	5.3
160	872	5.5
180	980	5.5
200	1095	5.5

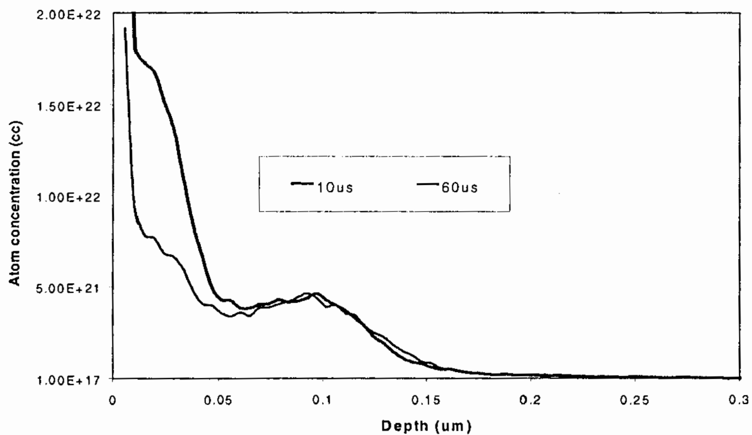

Fig. 1: SIMS depth profiles of the10μs and 60μs pulse width samples.

The calculated sputtering rate is observed to be slower in the near surface region when the hydrogen concentration is highest. Using the empirical results, the depth scale of the SIMS profile can be adjusted. Fig. 1 depicts the adjusted depth profiles of the 10μs and 60μs samples. The results unequivocally illustrate that a higher surface hydrogen component is unfavorable to the ion-cut technique.

4. Conclusion

The sputtering rate in the presence of a large concentration of implanted hydrogen is slower. Our empirical results can be used to calibrate the exact depth scale of the SIMS depth profile. The correction is needed for accurate modeling of the hydrogen plasma immersion ion implantation and ion-cut method.

Acknowledgments

The work was supported by City University of Hong Kong Strategic Research Grants 7000964 and Hong Kong Research Grants Council Earmarked Grants 9040332 and 9040344.

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