Mobility Enhancement of MOSFETs on p-Silicon (111) with In-situ HF-Vapor Pre-Gate Oxide Cleaning

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1. Introduction

Recently silicon (111) have been attracting much attention due to higher channel mobility of pMOSFET’s can be achieved than fabricated on conventional (100) substrates [1-2]. On the other hands, AlGaN/GaN HEMT’s has been reported grown on Si (111) [3]. This is very attractive because of silicon’s low cost, large size substrate available, good thermal conductivity. This success makes the integration of optical devices, high power and/or high-speed devices on silicon with advanced ULSI silicon technology possible. The requirements for gate oxide reliability becomes more and more stringent as the device size scales down to the deep-submicron era [4]. This is because the gate oxide thickness is fast approaching the physical limit imposed by the high leakage current due to direct tunneling. In general, the ultimate oxide thickness is believed to be around 1.5 nm. Beyond that, silicon dioxide would have to be replaced by high-k materials. However, we face the serious mobility degradation when depositing high-k directly on silicon. This degradation can be released if a buffered thin oxide exists before high-k deposition. But this buffered layer is not easy to scale down, consequently equivalent oxide thickness (EOT) is too thick to use for high-speed applications. Under this condition, the removal of the native oxide prior to gate oxidation becomes very critical for oxide thickness less than 2 nm. This is because the native oxide is in general poor in quality with low density [5]. This native oxide on the silicon surface is known to grow very quickly in the open air. Thickness can reach 0.5-1.0 nm within 10 minutes in the laboratory ambient. That makes the growth of ultra-thin oxide difficult. In this paper, we grow and characterize in detail native-oxide-free ultra-thin gate oxide on silicon (111) by an advance clustered vertical furnace with in-situ HF-vapor stripping of the native oxide. We found that the mobility of MOSFETs on silicon (111) can be significantly increased.

2. Experiments

The clustered vertical system consists of three modules, i.e., HF-vapor cleaning, oxidation, and in-situ n⁺-doped poly-Si deposition (Fig.1). Wafers, 6in p-type (111) of resistivity 36 Ω-cm, were processed through these three modules in sequence without exposure to the ambient, so as to obtain native-oxide-free poly-Si/SiO₂/Si MOS capacitors. To achieve this, the cabinet is filled with high purity nitrogen (with residual oxygen content of less than 4 ppm), to suppress any native oxide growth after the HF-vapor stripping of the original native oxide. Four kinds of samples, with oxide thickness of 3.2-3.5nm were obtained as follows: Wafers were split to receive either a conventional wet HF-dip or the in-situ dry HF-vapor (HFV) cleaning, and then wafers were further split to receive either a conventional O₂ or N₂O oxidation. The oxidation temperature was at 800°C. The oxide thickness was 3.5 and 3.2 nm for O₂ and N₂O respectively. Ununiformity of the gate oxide was found to be within ±1Å across the 6-in wafer.

3. Result and Discussion

Figure 2 shows the resultant SIMS-profile at the interface of poly-Si/Si samples which skip oxidation step in cluster system. The sample without any HF-treatment after conventional RCA cleaning was also shown, which shows the highest oxygen counts at the interface. It is seen that the oxygen is significantly reduced (about one order of magnitude) using the in-situ HFV treatment compared with the conventional HF-dip. This implies the native oxide can be precisely controlled. Fig.3 shows the drain current vs. drain voltage at V_G-V_TH=0.5, 1.0, 1.5, and 2.0 V for W/L= 100/1 μm. It can be seen that N₂O oxide (solid circles) with conventional HF-dip treatment is slightly larger than O₂ counterpart (solid triangle) at high field. This crossover phenomenon is similar to previous report on silicon [6]. For both O₂ and N₂O devices with HFV-treatment, the drain current is increased. Increase of mobility for O₂ oxide (22% increase at V_D=3.0 V, and V_G=2 V) is higher than that of N₂O counterpart (7% increase). No crossover phenomenon was found again for samples with HFV treatments. Since it is believed that degradation of current in the high field is due to surface roughness, this implies the surface roughness can be improved by using HFV treatment, this is consistent with our previous report [7] and in Ref. [5]. The transconductance times t_D and n_D at linear regime was plotted in Fig.4. Both O₂ and N₂O devices exhibit increased transconductance with HFV treatment. The transconductance of MOSFETs with N₂O-oxide decreases 7% with HFV-treatment compared with the conventional HF-dip one; while 17% increase was found for O₂-oxide. The significant increase of transconductance makes crossover phenomenon disappear for N₂O oxide vs. O₂ oxide. Since the interfacial trap density exhibits strong relation with the device’s mobility, as we’ve reported in Ref.7 and also in Chin et al. [5], the interface trap density can be reduced by HF-vapor treatment on silicon (100). From the result of
Fig. 4, we found that HFV also shows very effective mobility improvement on silicon (111) as that in silicon (100). Time-to-breakdown test were executed on MOS capacitors at constant $E_{ox} = 10 \text{ MV/cm}$, and result is shown in Fig. 5. It is clear that samples with HFV-treatment show an improved time-to-breakdown than counterparts for both O$_2$ and N$_2$O devices.

4. Conclusion

Using an in-situ HF-vapor stripping of the native oxide prior to gate oxidation has been demonstrated to improve the gate oxide integrity on silicon (111). This success makes the integration of optical devices, high power and/or high-speed devices on silicon (111) with advanced ULSI silicon technology possible.

References


Fig.1 Advanced cluster system: vertical furnace with in-situ HF-Vapor cleaning. Wafer can be processed through these modules in sequence without exposure to the air ambient, so as to obtain native-oxide-free poly-Si/oxide/Si MOS capacitor.

Fig.2 SIMS profiles for silicon without HF treatment. HF-dip, and clustered HF-vapor treatment. Samples skip the oxidation step and deposit poly-Si immediately.

Fig.3 The $I_D$ vs. $V_D$ curves under different $V_G-V_T=0.5$, 1.0, 1.5, and 2.0 V. The gate oxide was split four conditions, i.e., O$_2$ vs. N$_2$O oxide and with/without HF-vapor (HFV) treatment.

Fig.4 The transconductance times $T_{ox}$ for four split conditions at the linear regime.

Fig.5 The time-to-breakdown for samples with O$_2$ vs. N$_2$O oxide and with/without HF-vapor (HFV) treatment under constant $E_{ox} = 10 \text{ MV/cm}$. 

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