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Non-Destructive Characterization of Electronic Properties of Pre- and Post-Processing Silicon Surfaces by UHV Contactless Capacitance-Voltage Method

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1. Introduction

To further advance the Si CMOS technology to its ultimate scaling limits as well as to develop new nano-devices such as Si-based single electron transistors, it becomes increasingly important to understand and to control delicate changes of Si surface properties due to nano-structure processing, since all the processing steps for semiconductor device fabrication are usually carried out on or through surfaces and electronically active defects introduced during processing can deteriorate performances of nano-devices.

Recently, surface science type techniques such as the scanning tunneling microscopy (STM), x-ray photoelectron spectroscopy (XPS), etc have made a great progress for characterization of microscopic structures and chemical compositions of surfaces. However, there has been no well-established non-destructive method for in-situ characterization of the electronic properties of semiconductor surfaces, before and after processing.

The purpose of this paper is to describe a novel UHV contactless capacitance-voltage (C-V) method which we have recently developed to overcome the above difficulty. The paper demonstrates that near-surface electronic properties such as the surface conduction type, surface doping density and surface and interface states density of Si wafers can be successfully determined before and after the processing in in-situ and non-destructive fashion in the UHV environments.

2. UHV Contactless C-V Method

The UHV contactless C-V measurement system developed in this study is schematically shown in **Fig. 1**. This system has made it possible to measure metal-insulator-semiconductor (MIS) C-V curves of "free" surfaces in UHV environments for the first time.

The essential part for C-V measurement is shown in the inset. A metal field plate is placed above the sample surface, keeping an ultrathin and constant "UHV-gap" (100-300nm) with the aid of a piezo-electric feedback of capacitance from three surrounding parallelism electrodes. The gap distance was determined by the optical method utilizing the Goos-Haenchen effect, i.e., change in reflectivity due to penetration of evanescent wave [1].

As shown in Fig. 1, measurements were done in a UHV C-V chamber which was placed on the pneumatic vibration isolator to avoid effects of vibrations. A vertical transfer mechanism was developed together with a special sample holder with plate-type springs. Furthermore, a movable sample stage with a stepping motor was developed to set the sample surface exactly under the probing sensor in the UHV environments. In principle, this system can be connected to any kinds of processing equipments such as those for dry etching, oxidation, CVD deposition and ion implantation by introducing a suitable sample transfer mechanism.

3. Application to Silicon Wafers

In order to investigate the capabilities of the novel system, UHV CV measurement were made on pre- and post-processing Si surfaces, using the UHV multi chamber system shown in **Fig. 2**.

Pre-Processing surfaces

Hydrogen (H)-terminated Si surfaces were chosen as a pre-processing surface because the surface is known to have well-defined atomic structure with flatness and high reproducibility. For H-termination, Si (111) surfaces were treated by Higashi's method [2] and Si (100) surfaces were dipped in HF:HCl=1:19 solution for 2min [3].

Figure 3 (a) shows typical UHV contactless C-V curve of H-terminated Si (100) surfaces measured in pulsed bias mode faster than the generation of minority carrier. In

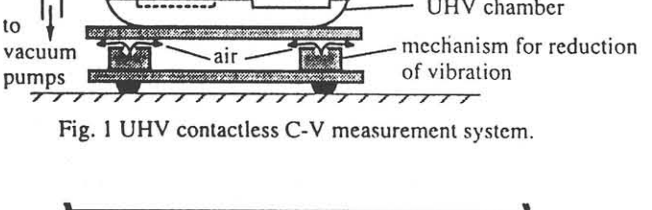

Fig. 1 UHV contactless C-V measurement system.

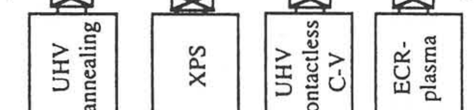

Fig. 2 UHV multi chamber system.

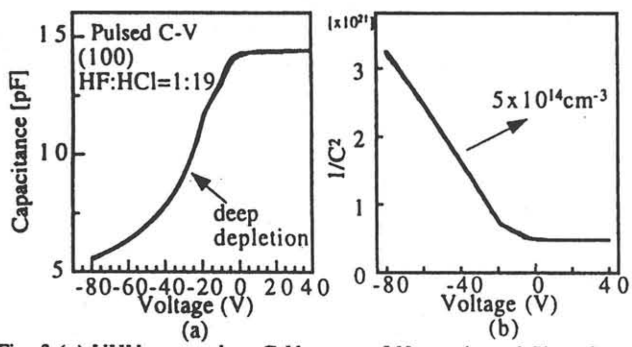

Fig. 3 (a) UHV contactless C-V curve of H-terminated Si surface measured in pulsed bias mode and (b) $1/C^2$ versus V plot.

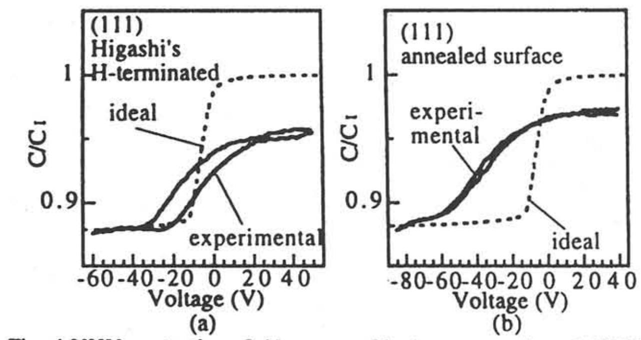

Fig. 4 UHV contactless C-V curves of hydrogen terminated (111) surface (a) before and (b) after annealing in UHV chamber.

this mode, deep depletion C-V behavior could be obtained. From the deep depletion curve appeared in the gate bias range less than -20V, the conduction type of this sample was n-type with a carrier concentration of $5.0\times10^{14}cm^{-3}$ calculated from the $1/C^2$ vs. V plots shown in Fig. 3 (b). These were in excellent agreements with the results of Hall measurements.

Figure 4 (a) shows the C-V curves measured in ramped bias mode just after hydrogen termination of (111) surface. Large hysteresis and limitation of capacitance change at the positive bias range were seen. After annealing of the sample at 300°C in UHV chamber, the hysteresis became much reduced and variation range of capacitance was increased, as shown in **Fig.4(b)**. This indicates that strong Fermi level pinning exist in UHV on hydrogen terminated surface due to surface traps in agreement with our previous measurement in nitrogen ambient at an atmospheric pressure [4].

Post-Processing Surfaces

As post-processing surfaces, Si surfaces with thick oxide and an ultrathin oxynitride layers were investigated.

Figure 5 shows the UHV contactless C-V curves of Si (100) surface covered with thick (100nm) SiO_2 layer which was formed by conventional high-temperature (1000°C) thermal oxidation using dry O_2 gas. The C-V curve obtained in a ramped bias mode shown in **Fig. 5 (a)** was found to be well in agreement with the calculated ideal one, showing the interface state density is extremely low.

The pulsed C-V curve and the corresponding $1/C^2$ vs. V are shown in **Fig.5(b)**. Deep depletion behavior was

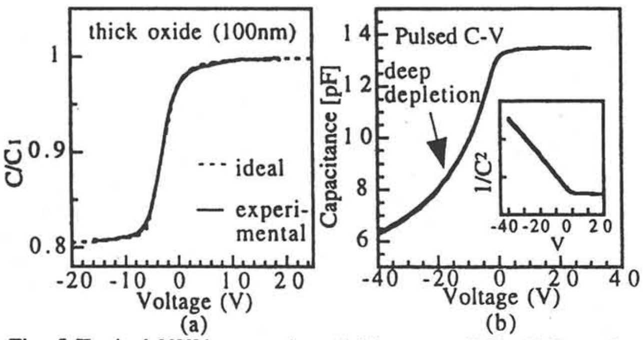

Fig. 5 Typical UHV contactless C-V curves of Si (100) surface with thick oxide. (a) ramped C-V curve and (b) pulsed C-V curve and resultant $1/C^2$ vs V plot in the inset.

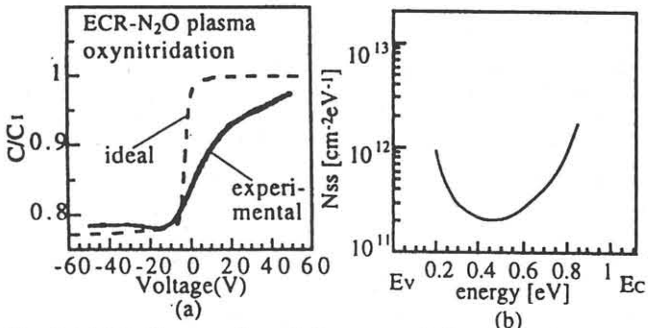

Fig. 6 (a) UHV contactless C-V curves of Si(100) surface after ECR-N_2O plasma oxynitridation and (b) distribution of interface state density.

clearly seen, and the calculated carrier concentration was also found to be the same with the value obtained from Hall measurements.

Figure 6 shows the UHV contactless C-V curve of the Si surface with 2-nm oxynitride layer formed by ECR-N_2O plasma oxynitridation at a low temperature of 400°C together with the calculated distribution of surface state density. Due to tunneling currents, it is impossible to measure electronic properties of such Si surfaces having ultrathin insulators by the standard C-V technique. By using the present UHV contactless C-V methods, direct characterization of electronic properties of such surfaces became possible for the first time. It is obviously useful for process development and optimization.

The present results clearly show that our UHV contactless C-V method is very powerful for in-situ characterization of electronic properties of "free" semiconductor surfaces without disturbing the status of the surface.

References

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