Differential Hall analysis of ultrashallow carrier profiles using X-ray photoelectron spectroscopy for nanometer depth resolution

Yu-Ting Ling,1,a) Wan-Ting Su,1 Tun-Wen Pi,2 and Ruey-Dar Chang1

1Chang Gung University, 259 Wen-Hwa 1st Road, Kwei-Shan Tao-Yuan 33302, Taiwan
2National Synchrotron Radiation Research Center, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, Taiwan

Abstract. In this study, differential Hall measurement (DHM) was developed to measure the carrier profiles in phosphorus doped ultrashallow junctions (USJs). Experiments using uniform phosphorus profiles in silicon on insulator (SOI) wafers demonstrated that the growth rate of the native oxide strongly depends on the phosphorus doping level. Therefore, the thickness of native oxide was monitored by X-ray photoelectron spectroscopy (XPS) to achieve nanometer depth resolution during DHM. The DHM method was applied to investigate the deactivation of phosphorus in laser annealed USJs. The DHM results indicate carrier profile redistribution near the surface due to uphill diffusion caused by phosphorus deactivation.

Keywords: Differential Hall measurement (DHM), X-ray photoelectron spectroscopy (XPS), ultrashallow junctions.

PACS: 61.72.uf, 61.72.sh, 72.20.My, 82.80.Pv

INTRODUCTION

The series resistance of metal-oxide-semiconductor field effect transistors (MOSFETs) is critical to the speed of integrated circuits. Therefore, heavily doped ultrashallow junctions (USJs) are required to achieve low resistance in source and drain regions [1]. Rapid annealing at high temperatures is used in dopant activation. However, dopant deactivation occurs during subsequent low-temperature processes. Influence of dopant deactivation on the carrier density needs to be characterized. Differential Hall measurement (DHM) has been used to measure active dopant profiles. A continuous anodic oxidation technique (CAOT) has been developed for DHM [2][3]. Hall measurement is performed after the removal of the anodic oxidized silicon. Carrier profiles are then calculated based on the residual carrier concentration obtained from each Hall measurement. Native oxide was also suggested for etching silicon layers [4]. However, an average oxidation rate is usually assumed for DHM. X-ray photoelectron spectroscopy (XPS) provides nanometer resolution in measuring the thickness of native oxide. In this study, we developed a DHM technique using XPS to achieve nanometer resolution for active dopant profiles. With the developed DHM technique, carrier redistribution due to the uphill diffusion caused by phosphorus deactivation was observed near the surface in ultrashallow junctions.

EXPERIMENTS

In order to examine the dependence of doping level on the growth rate of native oxide, (100) oriented p-type silicon-on-insulator (SOI) wafers were used. SOI wafers were first oxidized to form a screen oxide layer with a thickness of 15 nm. Then phosphorus doping was introduced by ion implantation with doses of 1.5×1015, 5×1015 and 1×1016 cm-2 at 50 keV. Samples were annealed at 1100 °C for 2 hr to obtain uniform profiles and eliminate implantation damages. Rapid thermal annealing (RTA) at 1100 °C for 10 s was used to activate the phosphorus. After the screen oxide was removed by dilute HF, samples were exposed to air from 1 hr to 21 days with a humidity of around 40 ± 5% to grow a native oxide layer. The thickness of the native oxide was determined by XPS with the light source from synchrotron radiation. Phosphorus concentration was analyzed by secondary ion mass spectroscopy (SIMS).

The experimental procedure for DHM analysis of phosphorus deactivation in USJs is illustrated in Fig. 1. (100) oriented p-type silicon wafers were preamorphized by germanium with a dose of 1×1015 cm-2 and at the energy of 20 keV. Phosphorus was then implanted into the amorphous layer at 2 keV with a dose of 1×1015 cm-2. Laser annealing was carried out for dopant activation. Subsequent furnace annealing at 500 °C for 640 min was performed to cause deactivation of phosphorus. Samples were first analyzed by Hall measurement. Then the thickness of...
native oxide was measured using XPS. After the native oxide was removed by dilute HF, samples were exposed to air for 24 hr to grow a new layer of native oxide. The process of measurement and oxidation repeated until the sheet resistance increased significantly. The phosphorus signal in XPS spectrums was also used to monitor the redistribution of phosphorus near the surface.

**RESULTS & DISCUSSION**

Figure 2 shows the thickness of native oxide measured by XPS for SOI samples that were exposed to the air at room temperature for different times. The phosphorus profiles in SOI wafers are uniformed and highly activated after annealing at 1100 °C. Based on the XPS signals of Si 2p, the oxide thickness \( t \) can be extracted as following:

\[
\frac{I_{sox}}{I_s} = \frac{n_{sox}}{n_s} \frac{\lambda_{sox}}{\lambda_s} \frac{1 - \exp\left[-t_{sox} / (\lambda_{sox} \cos \theta)\right]}{\exp\left[-t_s / (\lambda_s \cos \theta)\right]},
\]

where \( I_{sox} \) and \( I_s \) refer to the signals from the oxide layer and the silicon substrate. Parameters \( n_{sox} \) and \( n_s \) are densities of silicon dioxide and crystalline silicon. Inelastic mean free path (IMFP) of photoelectrons escaping from silicon dioxide and crystalline silicon is represented by \( \lambda_{sox} \) and \( \lambda_s \), respectively. The IMFP value is a function of kinetic energy. The XPS light source used for SOI samples was 400 eV obtained from synchrotron radiation. The IMFP values for silicon and silicon dioxide are 2.16 and 3.3 nm, respectively. The initial oxide thickness was thicker than that during DHM because wafers had been exposed to air for a long time. After deactivation at 500 °C, the initial oxide became thicker due to the additional annealing. However, the oxide thickness during DHM was less than that in samples before deactivation. This implies that the carrier density indeed affected the growth rate of native oxide on heavily phosphorus doped USJs. The oxide thickness was used to estimate the consumption of the silicon thickness after the growth of native oxide. The depth from the surface after each etching step during DHM was therefore obtained. The DHM results in Figure 4 show sheet resistance, sheet concentration and mobility as a function of the etching depth for USJ samples with and without deactivation annealing. The sheet carrier concentration decreased after deactivation annealing. This led to the increase of the Hall mobility due to the reduction of the ionized impurity scattering. When the sheet concentration of carriers decreased to \( 1 \times 10^{13} \) cm\(^{-2} \), the sheet resistance increased beginning of exposure. The growth rate of native oxide depends on the doping level. Higher doping level led to higher growth rate. After exposure to the air for more than one day, the oxide thickness almost saturated. The increase of the oxide thickness was less than 0.5 nm with more exposure time for 7 days. Because of the saturation of oxide thickness, the exposure time for the growth of native oxide was set to be 24 hr for DHM analysis.
significantly. The Hall mobility obtained from the last Hall measurement was contributed by the tail profile after high concentration phosphorus near surface was removed. Therefore, a high Hall mobility was observed. For Hall measurement, the correlation between sheet resistance $\rho_s$ and sheet Hall coefficient $R_s$ can be described as:

$$\frac{1}{\rho_s} = \frac{1}{\sigma_s} = \frac{1}{q \cdot N_s \cdot \mu},$$  \hspace{1cm} (2)

and

$$R_s = \frac{r}{q \cdot N_s}.$$ \hspace{1cm} (3)

where $\sigma_s$ is sheet conductivity and $N_s$ is sheet concentration. Parameters $q$ and $\mu$ refer to electronic charge and conductivity mobility, respectively. Effect of circulating currents can be described by the ratio $r = \mu_h / \mu_s$ where $\mu_h$ is Hall mobility. Based on two Hall measurements before and after the $i$th removed oxide layer, conductivity mobility $\mu_{si}$ and carrier concentration $n_i$ can be calculated by:

$$\mu_{si} = \left( \frac{1}{r} \right) \left[ \frac{\Delta (R_{si} \cdot \sigma_{si})}{\Delta \sigma_i} \right] \left[ \frac{\Delta (\sigma_i)}{\Delta \sigma_i} \right].$$  \hspace{1cm} (4)

and

$$n_i = \left( \frac{r}{q} \right) \left[ \frac{\Delta (\sigma_i)}{\Delta \sigma_i} \right] \left[ \frac{\Delta (R_{si} \cdot \sigma_{si})}{\Delta \sigma_i} \right].$$  \hspace{1cm} (5)

where $\Delta \sigma_i$ is the depth of silicon consumed by oxidation [5][6]. For USJs, assumption of an average etching depth was not suitable for such abrupt profile.

XPS provided an accurate depth resolution around 0.5 nm.

According to the DHM results using XPS for monitoring the oxide thickness, the carrier concentration as a function of the depth are shown in Fig. 5. An activation level around $1 \times 10^{14}$ cm$^{-3}$ was obtained after laser annealing near the surface of the phosphorus junction. After deactivation, the carrier concentration of the whole profile decayed. Carrier profiles before and after deactivation decreased sharply at 4.5 and 3.5 nm, respectively. The sharp decrease of the carrier profile is consistent with the projected range of phosphorus after implantation. However, the difference in the depth profile is around 1 nm between the carrier and chemical profiles after annealing. The shape of carrier profile remained
similar except for a dip near the surface. This suggests some profile redistribution near the surface during deactivation annealing at 500 °C.

![Figure 5](image1.png)

**FIGURE 5.** Carrier concentrations obtained by DHM using XPS analysis for samples before and after deactivation.

Figure 6 compares normalized XPS signals before and after deactivation. Similar background Si plasma signals were obtained for all profiles. Clear P 2p signals were only observed in samples with initial oxide. This indicates that most of the phosphorus is near the surface. Interestingly, evident increase of the intensity of the P 2p signal was observed after deactivation. The increase of the XPS signal suggests a high chemical concentration due to phosphorus uphill diffusion to the surface. This confirms evident profile redistribution as that observed in DHM results during deactivation annealing 500 °C. Point defect generation and enhanced tail diffusion during phosphorus deactivation was reported [7]. However, DHM and XPS results indicate that the redistribution of active and chemical profiles at the peak region cannot be ignored during phosphorus deactivation even at 500 °C.

![Figure 6](image2.png)

**FIGURE 6.** Comparison of normalized XPS signals for samples with and without deactivation with two oxide etching steps.

by uphill diffusion of phosphorus which resulted in the increase of surface phosphorus signals after deactivation.

**ACKNOWLEDGMENTS**

The XPS system used for analyzing SOI samples was supported by National Synchrotron Radiation Research Center (NSRRC), Taiwan.

**REFERENCES**