Ion implantation dose dependence of photocarrier radiometry for thermally annealed silicon wafers

Xianming Liu, Bincheng Li, and Qiuping Huang

1 Institute of Optics and Electronics, Chinese Academy of Sciences, P O Box 350, Shuangliu, Chengdu, Sichuan 610209, China
2 Graduate School of the Chinese Academy of Science, Beijing 100039, China

E-mail address: bcli@ioe.ac.cn

Abstract. Photocarrier radiometry (PCR) signal is a monotonic function of the implantation dose if the wafers are not annealed, because the signal is determined by the crystalline damage in the semiconductor induced by implantation. When the wafers are annealed at high temperature with most of the damages recovered, however, the PCR signal is no longer monotonic to the implantation dose. In this work, we obtained the PCR signals of the implanted and non-implanted regions from the same pieces of annealed sample. By subtracting the signals from the non-implanted regions, the influence of doped impurities on PCR signals is investigated. The different response at low implantation dose caused by B⁺ and P⁺ ions is analyzed.

1. Introduction
In the engineering of microelectronic fabrication, thermal annealing after implantation is an essential processing to reduce the implantation-induced crystalline structural damage and activate the implanted impurities [1, 2]. As to the implanted wafers without annealing, the optical and electrical properties of the implanted region will be altered during the thermal annealing process [3]. Photocarrier radiometry (PCR) signal of the implanted samples, which is sensitive to the properties of implanted region, is a monotonic function to the implantation dose for samples without annealing [4, 5], mainly due to the increasing defect density induced by increasing implantation dose. However, PCR signals of the annealed samples are seldom investigated previously. In this study, the PCR signals of the implanted and annealed samples were obtained. The influence of impurity density was extracted from the PCR signals and analyzed.

2. Experiment
Samples were prepared following the processing in microelectronic fabrication. Substrates used in this experiment were <100> oriented n-type polished silicon wafers, 525±20µm thickness, 7-10Ω·cm with phosphors as dopant. An oxide layer of 50nm was thermally grown on the surface before implantation to reduce implant channeling. In order to investigate the implantation-induced effects, only half of each wafer was ion implanted and the other half was left non-implanted. This was done by adding a semicircular mask on the surface to block the implanted ions. The wafers were implanted with 11B⁺ and 31P⁺ ions at different doses (10¹¹-10¹⁶cm⁻²) with the same energy of 100keV. After ion
implantation and cleaning the wafer surfaces, each wafer was then annealed for 30s at temperature of 1100°C in a rapid thermal processing system with inert nitrogen atmosphere.

The experimental apparatus has been described in detail elsewhere [6]. Briefly, a 110mW-power and 828nm-wavelength semiconductor laser with intensity periodically modulated by a function generator was used as the excitation source. The infrared emissions from the excited point were collected and focused through a pair of off-axis paraboloidal mirrors onto an InGaAs detector with a bandwidth of 0.8-1.8µm. For each sample, modulation frequency scans were performed from 2kHz to 600kHz on both the implanted and non-implanted regions, respectively.

3. Results and discussions

The resulting amplitudes at different modulation frequencies are presented as a function of implantation dose in Figs. 1 and 2 for B⁺ and P⁺ implanted wafers, respectively. Since the PCR signal is more sensitive to the surface at higher modulation frequency, only the signals in the kHz range are shown. The signal dependence on dose shows an irregular behavior in both figures. As the annealing process eliminated most of the implantation-induced defects, the PCR signals are mainly altered by implanted impurities and other wafer processing-induced variations. For example, the surface properties may be altered during the thermal oxidation, and the rapid annealing may induce new defects such as the dislocations due to the rapid temperature rise. These variations may be different among samples under different processing conditions, resulting in the irregular behaviour. In order to eliminate the influence induced by those nonuniform variations and the frequency response of the experiment system, the PCR signals of the non-implanted regions under the same experimental conditions were measured, which can be regarded as the equivalent system response. Then for each wafer the amplitude in the implanted region was divided by the non-implanted amplitude, with the ratios normalized by the values at low frequencies. The non-implanted phases were subtracted from that of the implanted regions. It is reasonable to do so as the non-implanted regions shared the same substrates with the implanted regions and the same thermal processing. The results are presented in Figs. 3 and 4 for B⁺ and P⁺ implanted wafers, respectively, which describe only the PCR signal changes resulted from the implanted impurities.

When the excitation source is modulated at frequency \( f \), the carrier-wave (CW) diffusion length can be determined by [7]

\[
L_{\text{cw}}(\omega) = \frac{D\tau}{\sqrt{1 + i \cdot 2\pi f \tau}}.
\]

where \( D \) is the ambipolar carrier diffusion coefficient and \( \tau \) is the lifetime of the carriers. At a higher frequency, the CW diffusion length becomes shorter. As a result, at the higher frequencies the
CW generated from the implanted layer on the surface is weighed more heavily in the PCR signal. From Figs. 3(a) and 4(a), we can see the amplitude ratios have greater divergences at high frequencies for heavily implanted samples. For implanted samples with dose lower than $10^{13}\text{cm}^{-2}$, especially for $P^+$ implanted wafers, the amplitude ratio values are approximately 1 covering the whole modulated frequency range, which indicates the PCR signals for both the implanted and non-implanted regions are the same after annealing. This also proves that the amplitude decreases for non-annealed samples in previous research are mainly due to the implantation-induced damages [4]. According to the PCR theory model, the phases are approximately zero at low frequencies and reach saturation ($-90^\circ$) at high frequencies. As shown in Figs. 3(b) and 4(b), therefore, the phase discrepancy values between the implanted and non-implanted regions come to maximum at approximately 20kHz and begin to decline at higher modulated frequencies. Taking both of the amplitude and phase into consideration, the most sensitive frequency range for PCR measurement on dose is in 10 - 100kHz.

In addition, Figs. 3 and 4 show that the amplitude ratios rise to more than 1 and the phase difference higher than zero at high frequencies for $B^+$ ion implanted wafers with implantation dose
lower than $10^{13}$ cm$^{-2}$, which cannot be found in P$^+$ ion implanted wafers. The different behaviours are attributed to the opposite doping type of the implanted ions. Considering the substrates are $n$-type with phosphors as donor atoms, implantation-added B$^+$ ions may act as acceptor impurities to compensate with donors in the substrates. At low implantation dose when the concentration of acceptors ($N_a$) is less than the donors ($N_d$), the implanted regions are still the $n$-type semiconductor, but the effective $N_d$ is less than that of substrates. The effective electric impurity concentrations decrease and result in the PCR signals increasing. If $N_a = N_d$, we have a completely compensated semiconductor that has the characteristics of an intrinsic material. The PCR signal comes to the maximum, corresponding to the dose of $5 \times 10^{11}$ cm$^{-2}$ in our experiments. With more doped acceptors of B$^+$ ions, a p-type compensated semiconductor occurs when $N_a > N_d$. PCR signals have significant decrease with increasing implantation dose just as the P$^+$ implanted samples. The decreases are attributed to the electrical property changes induced by high concentration doping such as the increasing surface recombination velocities and the decreasing diffusivities and lifetimes.

4. Conclusions
The presented experimental results indicate that the photocarrier radiometry measurement can be used for characterization of the annealed samples. Compare to the non-annealed samples, the carrier-waves are not caused by the implantation-induced damages but the doped impurities. For doping concentration testing, the best modulated frequency should be in an intermediate range of 10 - 100kHz.

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References
[1] Campbell S A 2001 The Science and Engineering of Microelectronic Fabrication, 2nd ed. (New York: Oxford University Press)
[2] Chason E, Pieraux S T, Poate J M, Borland J O, Current M I, Diaz, Eaglesham D J, Holland O W, Law M E, Magee C W, Mayer J W, Melngailis J, and Tasch A F 1997 J. Appl. Phys. 81 6513
[3] Pelaz L, Marqués L, and Barbolla J 2004 J. Appl. Phys. 96 5947
[4] Shaughnessy D, Li B, Mandelis A, and Batista J 2004 Appl. Phys. Lett. 84 5219
[5] Li B, Shaughnessy D, Mandelis A, Batista J, and Garcia J 2004 J. Appl. Phys. 95 7832
[6] Liu X, Li B and Zhang X 2008 J. Appl. Phys. 103 123706
[7] Tolev J, Mandelis A and Pawlak M 2007 J. Electrochem. Soc. 154 H983