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Recombination lifetime characterization and mapping of silicon wafers and detectors using the microwave photoconductivity decay (μPCD) technique

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Abstract

Recombination lifetime in oxidized high-resistivity silicon has been characterized by the microwave photoconductivity decay (μPCD) technique. In this technique, a silicon wafer is illuminated by a laser pulse that generates electron hole pairs. The transient of the decaying carrier concentration is monitored by using a microwave signal. The recombination lifetime is a measure of the material quality, i.e., defect/impurity concentration which affects the quality of the resulting detectors and their electrical properties. The μPCD technique is a non-contact and non-invasive technique that can map recombination lifetime of the entire wafer before it is selected for device/detector processing. The recombination lifetime mapping on a wafer is realized by a 2D color imaging code representing the range of the lifetime in μs. In general, the recombination lifetime is the smallest around the wafer edges (about 1000–2000 μs), and highest in the center of the wafer (5000–10,000 μs). The recombination lifetime has been measured under different injection levels and surface charge conditions. The results show that the lifetime in investigated n-type materials is almost independent of the injection level if the passivating SiO_2 film is corona charged.

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Keywords: Silicon; Lifetime; Particle detector

1. Introduction

Particle detectors made on high-resistivity silicon are widely used in high-energy physics (HEP) experiments. For example, in the future compact muon solenoid (CMS) experiment at CERN large hadron collider (LHC) accelerator, the central particle trajectory tracking system, i.e., tracker, will consist of approximately 80,000 silicon detectors with a total area of about 210 m^2 [1]. Segmented silicon detectors provide excellent spatial resolution while being cost effective due to well-established manufacturing technology.

The silicon particle detectors used in particle tracking systems are pin-diode structures designed

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to operate at full depletion mode provided by the reverse bias voltage. Furthermore, typically 300 μm thick sensors must be fully depleted at reasonably low operating voltages, typically less than 100 V. Therefore, the silicon sensors have traditionally been fabricated on wafers made by float zone crystal growth technique [2]. float zone technique ensures high-purity and sufficiently defect-free silicon crystals that are the basic requirements for producing high-resistivity silicon substrates for detector applications. On the other hand, float zone silicon (Fz–Si) has characteristically a low oxygen concentration because of the contact-less, crucible-free crystal growth technique. Low oxygen concentration in Fz–Si is, however, a drawback since oxygen has experimentally been found to improve the radiation hardness of silicon detectors [3].

Czochralski crystal growth method enables the production of silicon wafers with sufficiently high-resistivity and with well-controlled oxygen concentration [4]. Although the Czochralski silicon (Cz–Si) is the basic raw material for microelectronics industry, high-resistivity ($>1\,k\Omega\,cm$) Cz–Si wafers suitable for detector fabrication have become available only recently. This is likely due to the lack of commercial applications where both high-resistivity and tailored oxygen concentration would be required.

The detectors most important parameter is the signal-to-noise (S/N) ratio and it is directly affected by the leakage current of the device. Because the detector is a fully depleted volume device the generation current in the detectors 300 μm thick bulk is the dominant contributor to the total leakage current. The generation current is caused by the impurities and defects in the bulk. Thus, it depends on the quality of the silicon crystal and device processing. We have monitored the minority carrier lifetime in various detector substrates by the photoconductivity decay (μPCD) measurements. The interpretation of PCD measurement results is somewhat different in particle detector wafers than in substrates used for IC production. First, the thickness of detector wafers is usually 300 μm or less, i.e., thinner than standard wafers. Second, the bulk lifetimes in high-purity materials are very long. Production of high-quality detector elements require in practice minimum 2 ms lifetime in lowest lifetime area [5]. Because of these reasons, the suppression of the surface recombination is crucially important. Additionally, high lifetime excludes, e.g., surface photovoltage (SPV) as an option for characterizing the detector wafers. Third, the resistivity of the detector wafers is at least $1\,k\Omega\,cm$ corresponding doping concentration in n-type wafers less than $4\times10^{12}\,cm^{-3}$. This means that the injection level during the measurement effects the results. On the other hand, high injection level is known to reduce the surface recombination [6]. Thus, it is advantageous when measuring high-purity silicon samples.

2. Experimental

Typical particle detector fabrication processes contains 6–9 mask levels and consist of 2–3 ion implantations, 2–3 high-temperature oxidations and 3–4 low-temperature depositions of metals and insulators. Obviously, most potential risk of introducing the contamination into the silicon's bulk takes place during the high-temperature process steps, i.e., oxidations [7]. Thus, the cleanliness of the oxidation process and the pre-oxidation standard cleaning play an important role in successful detector process. The silicon materials used in this study are listed in Table 1. All wafers were passivated by the thermally grown silicon dioxide films prior the lifetime measurements.

The lifetime measurements were performed by a PCD measurement unit with a 902 nm pulsed laser operating at 200 ns cycles. The excitation level of minority carriers can be adjusted over three orders

Table 1
The materials investigated in this study

Crystal	Doping	Resistivity ($\Omega\,cm$)	Manufacturer	Orientation	Oxygen conc. (cm^{-3})	SiO_2 thickness (nm)	Average lifetime (μs)
Fz	P	7000	Wacker	<1 1 1>	N/A	300	2600–3800
Cz	P	1000	Okmetic	<1 0 0>	5×10^{17}	150	8200
Cz	B	2000	Okmetic	<1 0 0>	5×10^{17}	300	4500

of magnitude with this system. The transient of the decaying minority carrier concentration is monitored by using a microwave signal. The frequency of the microwave signal is between 10 and 11 GHz and it has been adjusted separately for each sample in order to get the highest possible reflected signal from decaying minority carriers [5]. The measurements were performed with and without Corona charging the SiO_2 film both front and back side of wafers. The purpose of the Corona charge deposition is to provide a surface potential opposite polarity of the minority carriers. This way an accumulation of minority carriers is created near the SiO_2/Si interface, which in turn reduces the probability that the light-excited minority carriers would recombine with the surface states. As a consequence, the measured effective lifetime increases and approaches the true bulk lifetime.

3. Results

The investigated wafers were lifetime scanned with constant injection level. Lifetime maps of several thousands of measurement point were plotted. The average lifetime values in different samples are listed in table. Typical circularly symmetric region of lower charge carrier lifetime is seen at the edge of the wafers, but overall values of lifetimes were very satisfactory in scope of particle detector production.

Selected wafers were later subjected to lifetime measurements with different injection levels. During these measurements, one point on the wafer was illuminated with different laser light intensities. The injection level measurements were repeated intentionally on low and high lifetime regions on the wafers and additionally with and without the surface charge deposition. The results of injection level measurements are shown in Figs. 1–3. Because of different values of lifetime in samples, the y-axis in the figures is scaled lifetime divided by maximum lifetime value in corresponding measurement point. The measurement points at very low injection levels (less than 10^{11} photons) are corrupted by the noise and are excluded from analysis. The noise in reflected microwave signal is very obvious when the density of excess carriers approaches the doping concentration of the sample.

It can be seen in Fig. 1 that the lifetime decreases in n-type Cz–Si with increasing injection level. When the sample is Corona charged the decrease

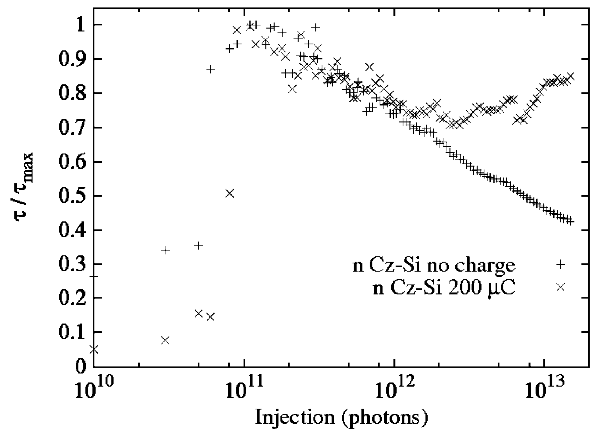

Fig. 1. The injection level dependence in n-type Cz–Si.

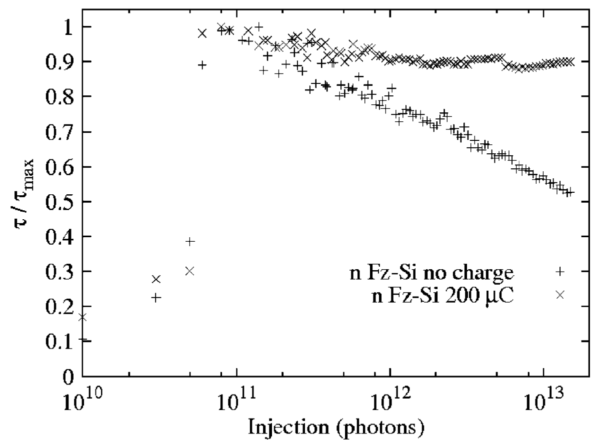

Fig. 2. The injection level dependence in n-type 7000 Ω cm Fz–Si.

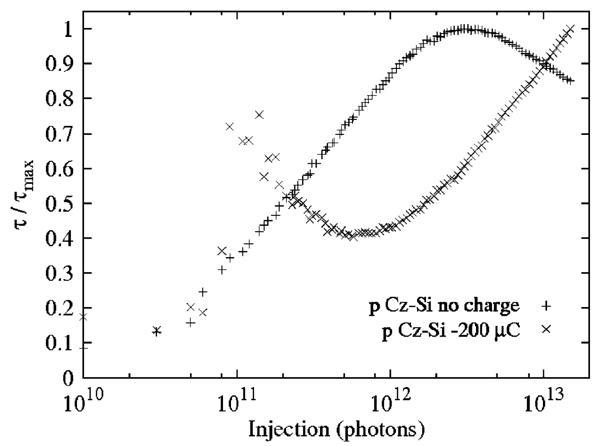

Fig. 3. The injection level dependence in p-type 2 kΩ cm Cz–Si. The both wafer surfaces were negatively charged during the measurement with deposited surface charge.

is less apparent and it almost vanishes. The injection level dependence in n-type high-resistivity Fz–Si is shown in Fig. 2.

Similar injection level behavior as in Cz–Si sample is observed in high-resistivity Fz–Si. The lifetime decrease over more than two orders of magnitude of injection level is about 10% and thus almost negligible.

4. Conclusions

We have characterized n- and p-type silicon particle detector substrates by μPCD technique. Our results indicate very high, more than 2000 μs, minority carrier recombination lifetimes in all investigated materials regardless of dry oxidation process. The lifetime maps revealing circularly symmetric regions of lower charge carrier lifetime is seen at the edge of the wafers. This edge contamination is apparently due to the impurities diffusing from the touching quartz parts into the silicon and further diffusion from this area towards the center of the wafer [7]. The lifetime values in the wafers center regions were, however, very satisfactory, in high-resistivity Cz–Si wafers even as high as 10 ms. Thus, it can be concluded that the initial material quality of Cz–Si detector wafers is not worse than traditionally used Fz–Si substrates in terms of lifetime. The slightly lower lifetime in investigated Fz–Si wafers is most likely due to the <1 1 1> orientated crystal exhibiting higher surface activity and thus limiting the maximum value of the measured effective lifetime.

The deposition of the corona charge was observed to greatly influence the injection level dependence of the lifetime. The charge opposite to the conduction type of the wafer provides an accumulation layer of the majority carriers near the wafer-oxidized surface, thus repulsing the minority carriers from the high surface recombination areas. When charging the wafer prior the PCD measurement, the lifetime was observed to be almost independent of the injection level. Without the charge, the lifetime decreased with increasing injection level in n-type Cz–Si and Fz–Si wafers. Similar behavior has been observed in Refs. [8,9] in iron-doped Cz–Si. The numerical calculations performed in Ref. [6], however, suggest that lifetime decrease with respect of injection level is a clue that the lifetime is dominated by the shallow levels.

The injection level dependence in p-type Cz–Si is in some extent peculiar. The injection level measurement without charge shows increase of lifetime with respect of injection level. This behavior has widely been accepted to be due to the breakage of iron boron pairs (Fe–B) into metastable interstitial iron (Fe_i) having lower recombination activity [10]. At high injection level, the lifetime however starts to decrease. This is possible if diffusing light generated minority carriers compensate the surface accumulation layer provided by negative corona charge.

To summarize, the μPCD lifetime measurement is a contactless, non-destructive, fast, and easily applicable method to characterize the process-induced contamination in silicon detectors. If the measurement is automated, then a large number of points on the detector surface can be mapped in a short time. The detector materials are high-resistivity silicon, thus the injection level during the measurement has to be taken into account. Our results show that the lifetime in investigated n-type materials is almost independent on the injection level if the SiO_2 film is corona charged on both sides of wafer surfaces.

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References

[1] The CMS Technical proposal CERN/LHCC 94-38.
[2] Lutz G. Semiconductor radiation detectors, device physics. New York: Springer; 2001. p. 260.
[3] Li Z, et al. Investigation of the oxygen-vacancy (A-center) defect complex profile in neutron irradiated high resistivity silicon junction particle detectors. IEEE Trans Nucl Sci 1992;39(6):1730–8.
[4] Savolainen V, et al. J Cryst Growth 2002;243(2):243.
[5] Härkönen J, Tuominen E, Lassila-Perini K, Palokangas M, Yli-Koski M, Heikkilä P, et al. Processing and recombination lifetime characterization of silicon microstrip detectors. Nucl Instrum Methods Phys Res 2002;A485(1–2):159–65.
[6] Schroder DK. In: Gupta DC, Bacher FR, Hughes WM, editors. Recombination lifetimes in silicon, recombination lifetime measurements in silicon. Philadelphia: American Society for Testing and Materials, ASTM STP 1340; 1998.

[7] Härkönen J, Tuominen E, Tuovinen E, Mehtälä P, Lassila-Perini K, Ovchinnikov V, et al. Processing of microstrip detectors on Czochralski grown high resistivity silicon substrates. Nucl Instrum Methods Phys Res 2003;A514:173–9.
[8] Watanabe K. Increase in effective carrier lifetime of silicon at low carrier injection levels. Semicond Sci Technol 1994; 9:370–2.
[9] Watanabe K. Dependence of effective carrier lifetime in iron-doped silicon crystals on carrier injection level. Semicond Sci Technol 1996;11:1713–7.
[10] MacDonald D, et al. Capture cross-sections of the acceptor level of iron–boron pairs in p-type silicon by injection-level dependent lifetime measurements. J Appl Phys 2001;89(12): 7932–9.