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Short Communication

Study of the effect of local photon annealing on stress in silicon wafers

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Abstract

The effect of photon annealing on deformation in the crystal structure of boron doped Cz-Si wafers has been studied using triple crystal X-ray diffraction. Conventional annealing of the entire surface of double-side polished silicon wafers with halogen lamps (photon annealing mode) and rapid thermal annealing produce compression deformation. Annealing with special phototemplate providing for local annealing of multiple separated wafer areas (local photon annealing mode) at relatively low wafer temperatures (less than 55 °C) produces tensile deformation. This effect however is not observed if the reverse side of the annealed wafer contains a mechanical gettering layer. A mechanism explaining the experimental results has been suggested and can be used for the synthesis of charge pumps in photoelectric converter structures.

Keywords

photoelectric converters, local photon annealing, charge pumps, triple crystal X-ray diffraction, phototemplate

1. Introduction

Silicon wafer treatment in the so-called rapid thermal annealing **(RTA)** mode is becoming increasingly widely used due to the permanent increase in the size of wafers used for the fabrication of photoelectric converters. The process combines relatively low price, simplicity and high adaptability. It can be successfully used for the synthesis of shallow *p*-*n* junctions in photoelectric converter structures [1, 2]. On the other hand increasing the diffusion coefficient by almost one order of magnitude allowed implementing deep diffusion of lithium for the synthesis of local charge pump zones in preliminarily synthesized solar cell structures [3]. RTA is widely used for the production of metallic contacts to semiconductors [4]. RTA is also of great interest for researchers as a powerful tool in defect engineering. This primarily refers to annealing of radiation defects and impurity activation after ion implantation into silicon. Also of interest is annealing of thermal donor defects that are typical of heavily boron doped Cz-Si wafers [5]. Many studies have also dealt with the formation of defect oxygen containing regions in wafer bulk for internal gettering [6, 7]. Many works [8–14] have reported experiments for synthesis of hidden *n* conductivity regions in the bulk of *p* conductivity wafers using various methods. It has been suggested to use hidden *n* conductivity regions for the synthesis of charge pumps in base *p* conductivity regions of photoelectric converters [9–14]. Importantly the formation of thermal donors is sensitive to the presence of structural defects, gettering layers or inhomogeneities that produce stress fields in silicon. There is experimental evidence [15] that the formation of thermal donors and mechanical stress in silicon structures are interrelated. The aim of this work is to study and compare residual mechanical stresses generated by RTA in silicon wafers with surfaces treated using different methods in two annealing modes: photon annealing **(PA)** and local photon annealing **(LPA)**. This study will provide for a more efficient use of the process in the synthesis of photoelectric converter structures with charge pumps [10].

2. Experimental

Photon annealing was implemented on a RTA instrument with halogen lamps. The light power was 45 W/cm^2 and the heating rate to 1000 °C was 125 K/s [1]. LPA was implemented using a metallic mask (removable phototemplate) in the form of a 6 mm thick stainless steel plate having 1 × 1 mm^2 holes with 3 mm spaces between them over the entire plate area. The phototemplate was placed onto the silicon wafer surface and removed after treatment with light. The phototemplate also acted as a heat screen absorbing most of the heat energy released by LPA during light pulses which were 8 s in our experiment. Fast heat screen removal from the plate after the end of the light pulses reduced wafer heating. The temperature of the silicon wafer during heat treatment was within 45–55 °C as measured with a Term Pro-1200 pyrometer.

We used *p* conductivity Cz-Si wafers. The boron concentration was approx. 10^{15} cm^{-3} (ρ_v = 8–10 Ohm × cm), the oxygen concentration was (0.8–1.2) × 10^{18} cm^{-3} and the surface orientation was (100). The area of each wafer was 2.5 × 2.5 cm^2. Specimens 1 and 2 were cut from one wafer. Specimen 3 was cut from another wafer which was one-side polished and had a mechanically ground gettering layer on its reverse side. The parameters of the wafers are summarized in the Table 1.

The type of residual deformation (tension or compression) in the single crystal wafers was determined using triple crystal X-ray diffraction on a Bruker D8 DISCOVER diffractometer. X-ray radiation was monochromated with a Goebel mirror and a four-bounce Ge(400) monochromator. The analyzer was a double-reflecting Ge(400) single crystal. The instrumental error of this optical setup affects the measurement results but slightly. We obtained the required X-ray diffraction intensity maps in the θ–2θ coordinates for the untreated and as-treated silicon wafers. By way of a typical example the Figure 1 shows the intensity maps for Specimens 1 and 3 before and after different types of RTA.

A change in the interplane spacing Δ*d*/*d* leads to a change in the position of the X-ray diffraction intensity maximum along the 2θ coordinate on the maps. Wafer bending shows itself in peak broadening along the θ coordinate and a shift of the diffraction intensity maximum along this coordinate (see the Figure 1) [16]. Results of X-ray diffraction intensity map processing are summarized in the Table 1.

Table 1. Change of interplane space as a result of photon treatment of silicon wafers

Specimen #	Thickness, µm(specimen surface treatment)	Δd/d after treatment	
		PA	LPA
1	250 (double-side polishing)	–	+2.913 × 10^{-5}
2	250 (double-side polishing)	–0.887 × 10^{-5}	–
3	520 (gettering layer on reverse side)	–	–1.267 × 10^{-5}

3. Results and discussion

The effect of RTA on the residual stress in the wafers is illustrated in the Table 1. Analysis of these data shows that annealing of the similar Specimens 1 and 2 which were cut from one wafer and double-side polished generated different configurations of structural defects for conventional PA and the new suggested LPA methods.

After PA Specimen 2 had residual stress produced by compression deformation (negative Δ*d*/*d*). On the contrary LPA of Specimen 1 (Figure 1*b*) led to a positive Δ*d*/*d* suggesting tensile deformation of the lattice. However LPA of the thicker Specimen 3 (Figure 1*d*) with a mechanical gettering layer on the reverse side led to a negative Δ*d*/*d* which also testified to residual compression deformation in the wafer after LPA. Comparison of the halfwidths of the experimental rocking curves (X-ray diffraction intensity as a function of X-ray incidence angle on the specimen for a stable detector position) for Specimens 1 and 3 suggests that the heat treatment produced bending deformation in Specimen 1. Analysis of diffraction peak angular position as a function of linear coordinate on specimen surface using a method developed earlier [17] allowed us to calculate the bending radius which was 1.15 m. Specimen 3 did not undergo bending deformation as was indicated by a constant rocking curve halfwidth.

These experimental results primarily indicate a rearrangement of the defect and impurity structure in the wafers after RTA [4–8]. It is safe to conclude that the type of the defects generated by PA or LPA depends primarily on wafer temperature during heat treatment and the presence or absence of a gettering layer affecting defect redistribution in specimen bulk during heat treatment.

PA increases the wafer temperature to 1000 °C in 8 seconds. Generation and relaxation of defect-impurity complexes occur in the structure of the entire silicon wafer and lead to the formation of residual compression deformation (Specimen 2). The internal stress generated in Specimen 3 by the gettering layer and the rearrangement of the defect and impurity structure during LPA finally cause lattice compression. The residual compression deformation in Specimen 3 is approx. 40% higher than in Specimen 2 which had no gettering layer on the reverse side. However the thickness of Specimen 2 was approx. 2 times smaller than that of Specimen 3.

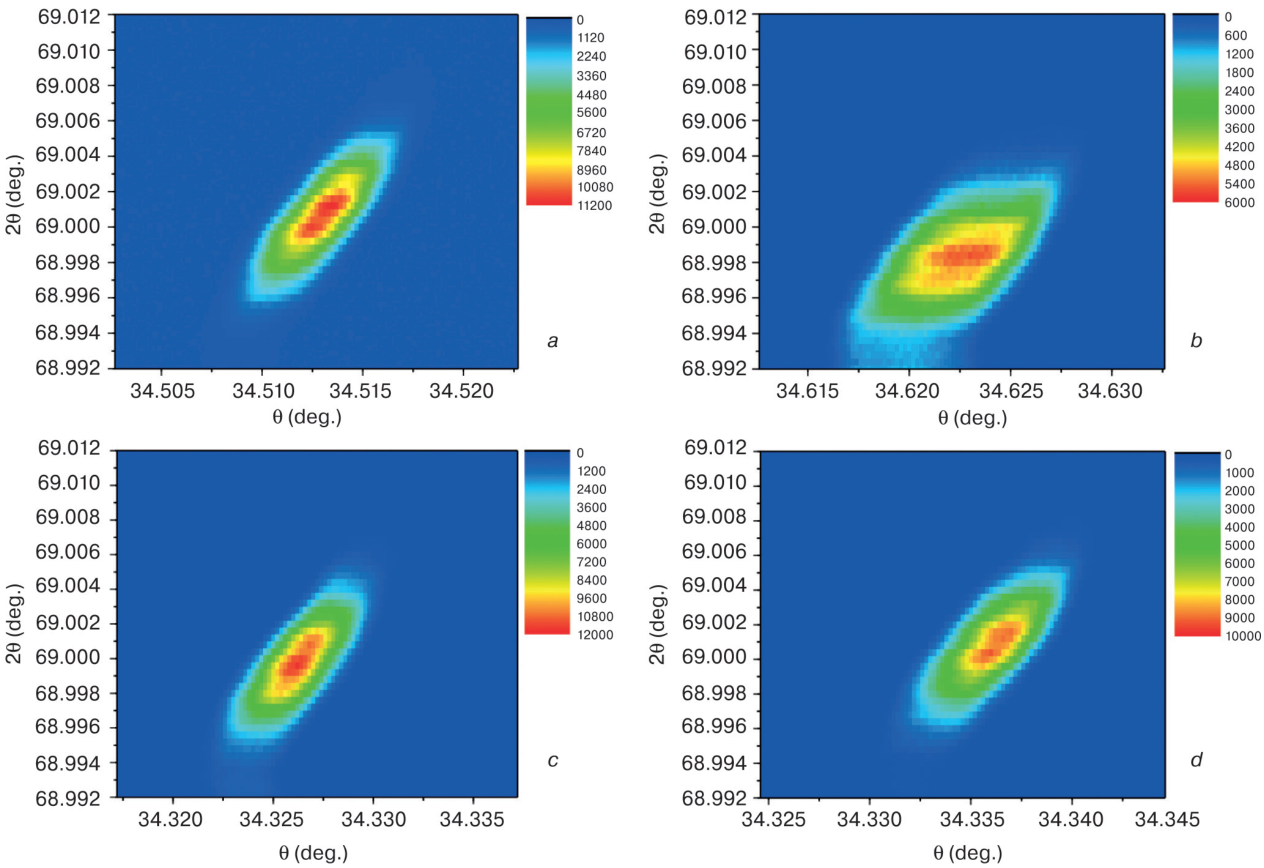

Figure 1. X-ray diffraction intensity maps near Si (400) site for Specimens (*a* and *b*) 1 and (*c* and *d*) 3: (a and c) before and (*b* and *d*) after treatmen

For LPA of the thinner wafer (Specimen 1) the surface temperature was within 55 °C. One can reasonably assume that the local photon impact generated a cloud-like defect and impurity structure containing discrete defect regions. The most probable mechanism causing residual tensile deformation in the lattice during LPA of Specimen 1 can be below-threshold generation of primary point defects, e.g. interstitial silicon atoms Si_i and V_{Si} vacancies as a result of the excitation of the crystal electron system by photogenerated electrons during Auger recombination (2.0–2.5 eV). The level of photon injection during LPA (45 W/cm^2) corresponds to an electron concentration of ~10^{18} cm^{-3}. Further association of point defects as a result of low-temperature migration mechanisms (including hopping migration of Si_i^+, photostimulated migration of Si_i and B_I and migration of vacancies and divacancies) leads to the formation of donor or acceptor defect clusters. In oxygen containing Cz-Si interstitial oxygen atoms O_i form high-mobility oxygen dimers O_{2i} which associate into clusters of low-temperature thermal donors TD-1 from $(SiO_n)^+$ complexes with $n < 10$ [18]. Simultaneously vacancy clusters form due to the generation of interstitial silicon atoms Si_i from thermal donor complexes [10, 11, 19]. Local spatial formation of clusters with a higher atomic density and the rearrangement of the defect and impurity structure in the excited volume (~6.0% of the surface area) lead to tensile deformation relative to the adjacent non-irradiated area where the initial lattice compression deformation is caused by the smaller atomic radii of impurity boron atoms. Our experimental data suggest that the presence of efficient gettering layers in the structure of silicon can completely offset the observed effect of LPA.

It should be noted that low-energy below-threshold generation of structural defects and complexes in boron doped Cz-Si wafers is a commonly known phenomenon that causes degradation and regeneration of solar cells [20]. One should however remember that the literary data on the origin of the defect-impurity complexes and their possible transformation as a result of RTA are controversial as can be concluded from the short list of works on the topic [4–8].

4. Conclusion

The experimental data showed that conventional heat treatment of the entire surface of double-side polished boron doped Cz-Si wafers in standard RTA mode with halogen lamps generates compression deformation. This was observed in double-side polished specimens and in one-side polished wafers with mechanically ground reverse side. In the latter case the effect was the strongest (typical compression stress was 40% higher than for double-side polished wafers).

LPA in the same RTA mode with phototemplate allowing multiple separated areas of wafer surface to be treated at relatively low wafer temperatures (below 55 °C) generated tensile deformation in double-side polished silicon wafers.

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