EFFECT OF NEUTRON-TRANSMUTATION DOPING ON THE NANOSCALE SURFACE MORPHOLOGY OF N-SI (111) SINGLE CRYSTALS

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Abstract. In this work, the nanoscale surface morphology of n-Si silicon single crystals with a (111) crystallographic orientation was investigated using atomic force microscopy. A comparative analysis was carried out for as-grown and neutron-transmutation-doped n-Si samples. The AFM images reveal that the as-grown n-Si (111) surface is characterized by a non-uniform nanoscale relief with local peaks, valleys, and island-like formations within a height range of approximately 0–12 nm. These morphological features may be related to growth-induced surface imperfections, oxygen-associated structural formations, and local microstructural inhomogeneities. After neutron-transmutation doping, the surface morphology becomes noticeably modified, showing a relatively more uniform and compact nanoscale relief. The obtained results indicate that neutron-transmutation doping affects not only the electrophysical properties of silicon single crystals but also their surface state and nanoscale topography. These findings are important for evaluating surface quality, defect distribution, and doping-induced structural changes in n-Si-based microelectronic and nanoelectronic devices.

Keywords: n-Si, silicon single crystal, (111) surface, neutron-transmutation doping, AFM, surface morphology, nanoscale relief.

Introduction. Monocrystalline silicon remains one of the most important semiconductor materials for modern microelectronics, optoelectronics, sensor technology, and nanoelectronic devices. Its wide technological use is related to the high structural perfection of silicon single crystals, the possibility of controlled doping, good mechanical stability, and well-developed crystal growth and wafer processing technologies. Among different crystallographic orientations, the Si (111) surface is of particular interest because its atomic arrangement, surface energy, and defect-sensitive regions can significantly influence the formation of near-surface structural inhomogeneities. The surface state of silicon single crystals plays an important role in determining the performance and reliability of semiconductor devices. Even small nanoscale changes in surface morphology may affect carrier transport, recombination processes, oxide formation, contact properties, and the stability of device structures. Therefore, the investigation of surface topography and nanoscale relief is important for understanding the relationship between crystal growth conditions, impurity distribution, and the functional properties of silicon-based materials. One of the key factors affecting the structural state of Czochralski-grown silicon is the presence of background impurities, especially oxygen. Oxygen atoms can be incorporated into the silicon lattice during crystal growth and may exist in different forms, including interstitial oxygen, oxygen-related complexes, and silicon dioxide precipitates. These oxygen-associated formations can create local elastic strains and contribute to the development of nanoscale surface features. As a result, the morphology of the Si (111) surface may reflect not only the crystal growth history but also the distribution of oxygen-related defects in the near-surface region. Neutron-transmutation doping is an effective method for modifying the electrical properties of silicon with high spatial uniformity. During this process, nuclear reactions induced by neutron irradiation lead to the formation of dopant atoms inside the silicon lattice. Although this method is mainly used to control the electrophysical parameters of silicon, neutron exposure and subsequent structural relaxation can also influence defect distribution, local lattice disorder, and surface morphology. Therefore, it is important to analyze how neutron-transmutation doping affects the nanoscale surface structure of n-Si single crystals. Atomic force microscopy is a powerful technique for studying semiconductor surfaces at the nanoscale level. It allows direct visualization of surface relief, local peaks, valleys, island-like formations, and roughness variations without causing significant damage to the sample. In the present work, AFM analysis was used to compare the surface morphology of as-grown and neutron-transmutation-doped n-Si (111) single crystals. Special attention was given to changes in nanoscale relief, surface uniformity, and the possible influence of oxygen-related structural formations on the observed topography. The aim of this study is to investigate the effect of neutron-transmutation doping on the nanoscale surface morphology of n-Si (111) silicon single crystals. By comparing AFM images of the as-grown and neutron-transmutation-doped samples, the work reveals how doping-induced structural changes affect the surface relief and near-surface state of silicon. The obtained results can be useful for evaluating the surface quality of silicon single crystals and for improving the technological control of silicon-based microelectronic and nanoelectronic devices.

Materials and Methods.

In this study, n-type silicon single crystals with a (111) crystallographic surface orientation were used as the investigated material. Two types of samples were analyzed: as-grown n-Si single crystals and neutron-transmutation-doped n-Si single crystals. The as-grown silicon samples were obtained by the Czochralski growth method and were characterized by a specific electrical resistivity in the range of approximately 3–10 Ω·cm. The initial samples had a low dislocation density and contained background oxygen impurities, which are typical for Czochralski-grown silicon single crystals. Neutron-transmutation-doped n-Si samples were selected for comparison in order to evaluate the influence of transmutation doping on the nanoscale surface morphology. The initial structural and electrophysical characteristics of these samples were close to those of the as-grown silicon crystals. This made it possible to compare the surface state of the two sample groups and to determine the morphological changes associated mainly with neutron-transmutation doping. The working surface of all samples corresponded to the (111) crystallographic plane. Before surface analysis, the samples were prepared in a form suitable for atomic force microscopy measurements. Special attention was paid to the near-surface region, since nanoscale relief, local peaks, valleys, and island-like formations can provide important information about growth-related defects, oxygen-associated structural formations, and doping-induced changes. The surface morphology of the samples was investigated by atomic force microscopy. AFM measurements were carried out using a Solver-NEXT atomic force microscope. This method allows direct three-dimensional visualization of the surface relief at the nanoscale level. The AFM technique was used to obtain topographic images of both as-grown and neutron-transmutation-doped n-Si (111) samples. The obtained AFM images were analyzed by comparing the height distribution, surface uniformity, local microprotrusions, island-like formations, and nanoscale roughness features. The height scale of the investigated surface region was within the nanometer range, which made it possible to identify small morphological changes caused by neutron-transmutation doping. The comparison between the two sample states was used to determine how doping affects the surface nanorelief and near-surface structural condition of n-Si single crystals. The analysis was focused on the qualitative and comparative evaluation of the AFM topography. The as-grown sample was considered as the reference state, while the neutron-transmutation-doped sample was used to reveal doping-induced surface modification. This approach provides a basis for understanding the relationship between neutron-transmutation doping and nanoscale surface morphology in n-Si (111) silicon single crystals.

Results and Discussion

The nanoscale surface morphology of the as-grown and neutron-transmutation-doped n-Si (111) single crystals was investigated by atomic force microscopy. The obtained AFM images make it possible to compare the initial surface state of the silicon single crystal with the surface modified after neutron-transmutation doping.

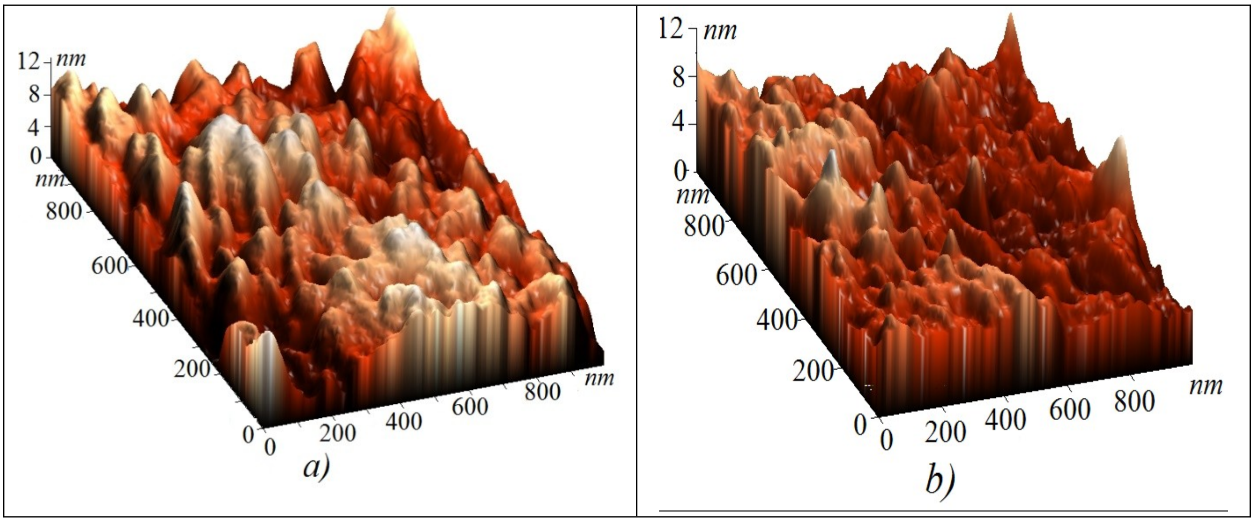

Fig. 1. AFM images of the (111) surface of n-Si silicon single crystals: (a) as-grown; (b) neutron-transmutation-doped.

As shown in Fig. 1a, the surface of the as-grown n-Si (111) single crystal has a clearly expressed nanoscale relief. The AFM image shows randomly distributed local peaks, valleys, and island-like formations over the surface. The height variation is observed within the nanometer range, reaching approximately 10–12 nm in some regions. Such a surface morphology indicates that the initial silicon single crystal is not ideally flat at the nanoscale level. The observed surface irregularities may be related to growth-induced imperfections, oxygen-associated structural formations, and local inhomogeneities formed during the crystallization process. The as-grown n-Si surface contains separate island-like features with different lateral dimensions. Some of these formations have a relatively sharp profile, while others are wider and smoother. This indicates that the surface relief is formed by non-uniform nanoscale structural regions. The presence of such features can be associated with oxygen-related precipitates or silicon dioxide formations in the near-surface region. Since Czochralski-grown silicon usually contains background oxygen impurities, the formation of oxide-related structural fragments on or near the surface is possible. These features can influence surface roughness, local strain distribution, and the electronic behavior of the near-surface layer. After neutron-transmutation doping, the surface morphology changes noticeably, as shown in Fig. 1b. Compared with the as-grown sample, the neutron-transmutation-doped n-Si surface demonstrates a more uniform and compact nanoscale relief. The high and irregular island-like formations become less pronounced, and the surface appears more evenly distributed over the scanned area.

This suggests that neutron-transmutation doping affects the near-surface structural state of the silicon single crystal. The observed modification of the surface relief may be explained by doping-induced changes in the distribution of defects and impurity-related structural formations. Neutron-transmutation doping is mainly used to obtain a more homogeneous distribution of electrically active dopants in silicon. However, the AFM results show that this process can also influence the nanoscale morphology of the surface. The more uniform relief observed in the doped sample may be related to structural relaxation, redistribution of point defects, and changes in oxygen-associated formations in the near-surface region. A comparison of Fig. 1a and Fig. 1b shows that the main effect of neutron-transmutation doping is not the formation of a completely new surface structure, but the modification and partial smoothing of the existing nanoscale relief. In the as-grown sample, the surface is characterized by more distinct peaks and island-like formations. In contrast, the neutron-transmutation-doped sample exhibits a more regular topographic distribution. This indicates that the doping process can reduce the degree of morphological non-uniformity on the n-Si (111) surface. The obtained AFM results are important for understanding the relationship between neutron-transmutation doping and the surface state of silicon single crystals. Since the surface morphology of silicon affects carrier recombination, oxide formation, contact properties, and device stability, the observed changes may have practical importance for microelectronic and nanoelectronic applications. In particular, the relatively smoother and more homogeneous surface of the neutron-transmutation-doped sample may be beneficial for improving the reproducibility of silicon-based device structures. Thus, the AFM analysis confirms that neutron-transmutation doping influences not only the electrophysical properties of n-Si single crystals but also their nanoscale surface morphology. The transition from a more irregular as-grown surface to a more uniform doped surface indicates that neutron-transmutation treatment can modify the near-surface structural state of n-Si (111). These results provide useful information for evaluating the surface quality of silicon single crystals intended for electronic and radiation-related applications.

Conclusion. In this study, the nanoscale surface morphology of as-grown and neutron-transmutation-doped n-Si (111) silicon single crystals was investigated using atomic force microscopy. The comparative AFM analysis revealed that the surface state of n-Si single crystals is noticeably affected by neutron-transmutation doping. The as-grown n-Si (111) sample exhibited a relatively non-uniform surface relief with randomly distributed peaks, valleys, and island-like formations. These morphological features indicate that the initial surface of the silicon single crystal contains growth-related inhomogeneities and local structural irregularities in the near-surface region. The AFM image of the as-grown sample showed that the surface relief varies within the nanometer range, with local protrusions reaching approximately 10–12 nm. The observed island-like structures may be associated with oxygen-related formations, silicon dioxide precipitates, and local elastic distortions formed during the crystal growth and cooling processes. Such nanoscale surface features are important because they may influence the electrical behavior of the near-surface layer, surface recombination processes, oxide formation, and contact quality in silicon-based devices. After neutron-transmutation doping, the morphology of the n-Si (111) surface changed noticeably. The doped sample demonstrated a more uniform and compact nanorelief compared with the as-grown sample. The sharpness and irregularity of the island-like formations decreased, and the surface became more evenly distributed over the investigated area. This suggests that neutron-transmutation doping can modify the near-surface structural state of silicon and promote partial smoothing or redistribution of nanoscale surface features. The comparison of the two AFM images confirms that neutron-transmutation doping affects not only the electrophysical properties of silicon single crystals but also their surface morphology at the nanoscale level. The transition from a more heterogeneous as-grown surface to a relatively smoother doped surface may be related to defect redistribution, structural relaxation, and changes in oxygen-associated formations in the near-surface region. Therefore, AFM analysis provides useful information for evaluating the relationship between doping processes and surface quality in n-Si (111) single crystals. The obtained results are important for the technological control of silicon materials used in microelectronics, nanoelectronics, sensors, and radiation-related applications. A more uniform surface morphology after neutron-transmutation doping may contribute to improved reproducibility and stability of silicon-based device structures. Thus, the present study demonstrates that neutron-transmutation doping is not only an effective method for modifying the electrical properties of silicon but also a factor influencing its nanoscale surface topography.

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