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Structural surface characteristics of aluminum-gallium nitride films on silicon carbide nanolayers on silicon

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Abstract. Experimental studies of the surface morphology of AlGaN films formed on nanometer-thick SiC layers synthesized on Si by atom substitution were performed. Structural characteristics of the surface of AlGaN/SiC/Si and AlGaN/AlN/SiC/Si heterostructures grown on Si with orientations (001), (011) and (111) were studied by atomic force microscopy. It is shown that the Si orientation has a significant influence on the surface morphology of AlGaN films. The surface roughness and characteristic dimensions of the AlGaN surface structure on nano-SiC/Si with and without an AlN buffer layer were measured. It is shown that the buffer AlN layer leads to a change in the surface structure dimensions of AlGaN layers.

Keywords: AFM, thin films, heterostructures, nano-SiC/Si, AlGaN

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Материалы конференции
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Структурные характеристики поверхности пленок нитрида алюминия-галлия на нанослоях карбида кремния на кремнии

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Аннотация. В работе проведены экспериментальные исследования морфологии поверхности пленок AlGaN, сформированных на слоях SiC нанометровой толщины, синтезированных на Si методом замещения атомов. Методом атомно-силовой микроскопии изучены структурные характеристики поверхности гетероструктур AlGaN/SiC/Si и AlGaN/AlN/SiC/Si, выращенных на Si с ориентациями (011) ,(001) и (111). Показано, что ориентация Si оказывает существенное влияние на морфологию поверхности пленок AlGaN. Измерена шероховатость поверхности и характерные размеры структуры поверхности AlGaN на нано-SiC/Si с буферным слоем AlN и без него. Показано, что буферный слой AlN приводит к изменению характерных размеров элементов структуры поверхности слоев AlGaN.

Ключевые слова: АСМ, тонкие пленки, гетероструктуры, нано-SiC/Si, AlGaN

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Introduction

Thin films of aluminum-gallium nitride (AlGaN) have unique physical and mechanical properties that make them an ideal material for creating high-performance electronic and optoelectronic devices such as LEDs, lasers, and transistors [1]. They have high thermal stability, high electrical conductivity, and a wide range of optical properties. Optimization of growth conditions and crystal direction can further improve the properties of these structures for various practical applications. Integration of AlGaN layers with silicon technologies is an important step in microelectronics development. It enables enhanced capabilities and performance of devices, creating high-performance LEDs, lasers, transistors, and other devices that are ideal for use in lighting, displays, and optical communications. Integrating AlGaN layers with silicon technologies also enables the creation of high-frequency transistors and other electronic devices with high performance and reliability, which reduces manufacturing costs and improves the cost-effectiveness of electronic device production. However, the growth of AlGaN layers on Si silicon crystals causes problems with mismatch of lattice parameters and thermal expansion coefficients between AlGaN and Si. This leads to the appearance of defects in the structure such as dislocations and disturbances in crystal orientation. In addition, the growth of AlGaN layers on Si wafers creates problems with controlling the composition and concentration of impurities in the structure, which can lead to changes in the optical and electrical properties of the material and reduce the performance of devices. High growth temperature of high quality AlGaN layers on Si crystals can also lead to structure degradation and device performance degradation. To solve these problems, various methods are used to compensate for inconsistencies in lattice parameters, in particular, various kinds of buffer layers are created on the silicon surface [2, 3].

To solve these problems, it is proposed to use Si substrates with a nanometer-thick silicon carbide layer (nano-SiC) synthesized by the atom substitution method [4] for the growth of AlGaN thin films. This nano-SiC/Si hybrid substrate configuration allows the growth of AlGaN layers on a SiC layer with a surface roughness of 0.5 nm, which is comparable to industrial SiC crystals. This solution avoids the appearance of defects in the structure and controls the composition and concentration of impurities in the structure. In this work AlGaN layers grown directly on nano-SiC/Si and on nano-SiC/Si with a buffer layer of aluminum nitride (AlN) are investigated. Studies of the surface morphology of AlGaN on nano-SiC thin films on Si with orientations (001), (011) and (111) is an important task for materials science.

Materials and Methods

Growth of AlGaN layers was performed on Si crystals with nanometer-thick SiC layers nano-SiC. The nano-SiC structures were synthesized using the atomic substitution method [5] on Si *p*-type conductivity substrates doped with boron with crystallographic directions (001), (011), and (111). The Si crystal with the (001) orientation was deflected from the base direction by 4° to the (111) direction. The SiC layers were synthesized in an atmosphere of carbon monoxide (CO) and silicon tetrahydride (SiH_4) for 10 minutes at 1100°C. The pressure inside the reactor during the synthesis was 0.5, 0.7, and 2.3 Torr for Si substrates with crystallographic orientations (001), (011), and (111), respectively. The thickness of the synthesized SiC layers was determined by analyzing spectra obtained by spectral ellipsometry on a Woollam M-2000D instrument. The surface roughness of the SiC films was measured by optical profilometry on a Zygo New View 6000. Thin films of AlGaN were grown by the HVPE method [6] on hybrid SiC/Si substrates with and without an AlN buffer layer. Layers of AlGaN were grown at 1020 °C in an ammonia and argon atmosphere with a total flux of 1 and 4 liters per minute, respectively. Aluminum and gallium atoms were delivered to the growth zone using a hydrogen chloride flow of 0.2 and 0.1 liter per minute, respectively. In the case of AlGaN films grown directly on hybrid SiC/Si substrates, the AlGaN layer thickness was 6-9 µm. Buffer layers of AlN thickness 2-3 µm were grown by the HVPE method immediately before the AlGaN films were formed. In the case of AlGaN/AlN/SiC/Si heterostructures, the thickness of AlGaN layers was 3-5 µm. The surface morphology of the AlGaN films was studied by atomic force microscopy AFM in contact mode on an Easy Scan Nanosurf microscope.

Results and Discussion

The study of nano-SiC/Si hybrid substrates by spectral ellipsometry showed that the thicknesses of all SiC layers synthesized on Si substrates are the same and equal to 3 nm. According to optical profilometry data, the surface roughness of all nano-SiC/Si hybrid substrates is 0.4—0.6 nm.

A study of the surface morphology of AlGaN thin films by AFM showed that the morphology of AlGaN layers is significantly different, depending on which orientation of the Si substrates these layers were grown on. This is not surprising since it was shown in [7] that when growing by the coordinated atom substitution method, a smooth SiC surface of orientation (111) is formed only on the Si substrate (111). In the case of SiC growth on the (001) and (011) Si faces, the SiC layer surface is covered by pyramids with inclined orientation faces (111). As a result, these surfaces resemble sawtooth structures. AlN, GaN and AlGaN films grow on these surfaces in the form of hexagonal c-axis blocks inclined with respect to the substrate plane, which will be directed perpendicular to the SiC(111) structure plane, that is, parallel to the SiC(111) plane will form (0001) planes of blocks consisting of $Al_xGa_{1-x}N$ with different composition. Such inclined hexagonal layers are called semi-polar layers [8]. Semipolar structures grow on SiC/Si hybrid substrates, both with and without an AlN buffer layer.

Morphology studies have shown that the characteristic geometric dimensions of the AlGaN layer surface structural elements on nano-SiC/Si substrates and on AlN/SiC/Si substrates are different (Fig. 1).

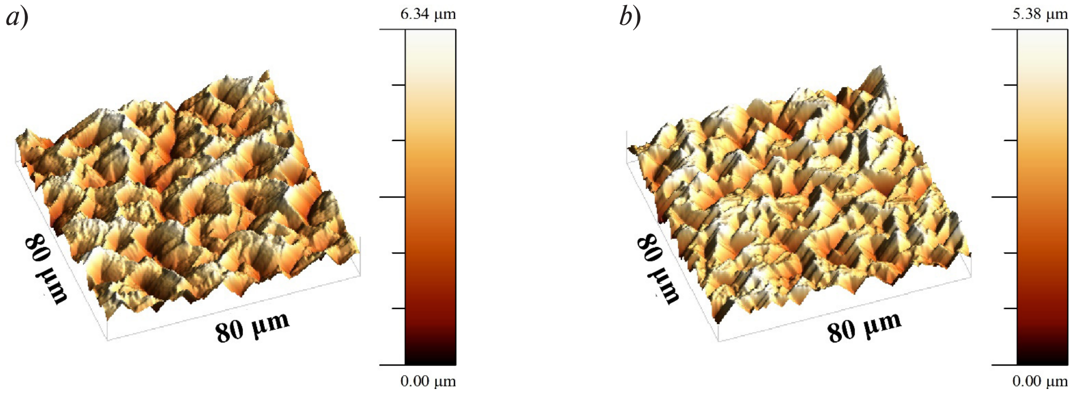

Fig. 1. AFM surface images of AlGaN/SiC/Si(001) (*a*) and AlGaN/AlN/SiC/Si(001) (*b*) heterostructures

Thus, the size of the sawtooth structures grown on the AlN/SiC/Si(001) substrate is smaller than the geometrical size of the structures grown on the nano-SiC/Si substrate. In the case of AlGaN films grown on Si substrates with (001) orientation, the surface has a sawtooth structure which consists of ridge-like clusters. The average surface roughness of the AlGaN/SiC/Si(001) and AlGaN/AlN/SiC/Si(001) heterostructures is 810 and 680 nm, respectively. The slope planes in the case of the AlGaN/SiC/Si(001) heterostructure are inclined 45±5° and 20±3° relative to the general plane of the sample surface, whereas they are inclined 40±5° and 25±2° for the AlGaN layer on AlN/SiC/Si(001). The height of the ridge-like clusters on the AlGaN surface on nano-SiC/Si(001) and AlN/SiC/Si(001) is 2—4 µm and 1—3 µm, respectively. Thus, in the case of growth of AlGaN films on nano-SiC/Si(001), the use of the AlN buffer layer leads to changes in the characteristic sizes and orientations of the crystal structural elements of the surface.

The surface of AlGaN films grown on Si substrates with orientation (011) has a mosaic structure with pronounced steps (Fig. 2). The surface structure of AlGaN films formed on hybrid nano-SiC/Si(011) substrate presents smooth terraces up to 20 µm2 with sharp slopes at the edges. The terraces occupy 70% and 55% of the total AFM image area of AlGaN/SiC/Si(011) and AlGaN/AlN/SiC/Si(011) heterostructures, respectively. The slope of the terraces and slopes relative to the general plane of the sample surface in the case of AlGaN on SiC/Si(011) is 5±1° and 25±5°, respectively. The height of the slopes of the AlGaN/SiC/Si(011) surface structure according to AFM data is 2.0±0.3 µm. The slope of the terraces and slopes relative to the general plane of the sample surface in the case of AlGaN on AlN/SiC/Si(011) is 5.3±0.2° and 28±5°, respectively. The height of the slopes of the AlGaN/AlN/SiC/Si(011) surface structure is 2–5 µm according to AFM data. According to AFM data, the RMS roughness of AlGaN films formed on SiC/Si(011) and AlN/SiC/Si(011) substrates is 480 and 700 nm, respectively, that is, in contrast to SiC/Si(001) and AlN/SiC/Si(001) substrates, pre-grown AlN layer resulted in increased roughness.

Analysis of AFM images (Fig. 3) of AlGaN layers grown on nano-SiC/Si(111) and AlN/SiC/Si(111) heterostructures showed that the surface was formed in the form of hills during growth. According to AFM data, the hills have a rounded shape. The surface of AlGaN film on nano-SiC/Si is covered by ridge-like clusters with base diameter of 10–30 µm and height of 200–400 nm. In the case of the AlGaN/AlN/SiC/Si heterostructure, the ridge-like structure has a base diameter of 20–50 µm and a height of 300–500 nm. The RMS surface roughness of AlGaN films in both cases is 60 nm. The slope of the side hillsides of the AlGaN layer surface on nano-SiC/Si relative to the general sample plane is 1.5±0.5°. The slope of lateral slopes of hilly structure of AlGaN on AlN/SiC/Si layers relative to the general plane of the sample is from 2.0±0.5°. In AlGaN films on nano-SiC/Si(111) growth defects in the form of growth pits (pit) were found, the formation of which is associated with the peculiarities of growth of AlGaN films on defective and not perfect in crystal quality, places of nano-SiC/Si hybrid substrates.

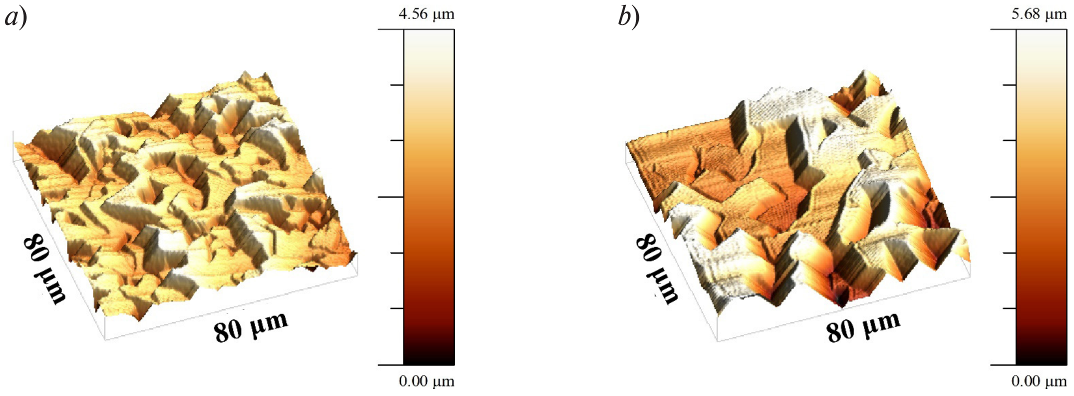

Fig. 2. AFM surface images of AlGaN/SiC/Si(011) (*a*) and AlGaN/AlN/SiC/Si(011) (*b*) heterostructures

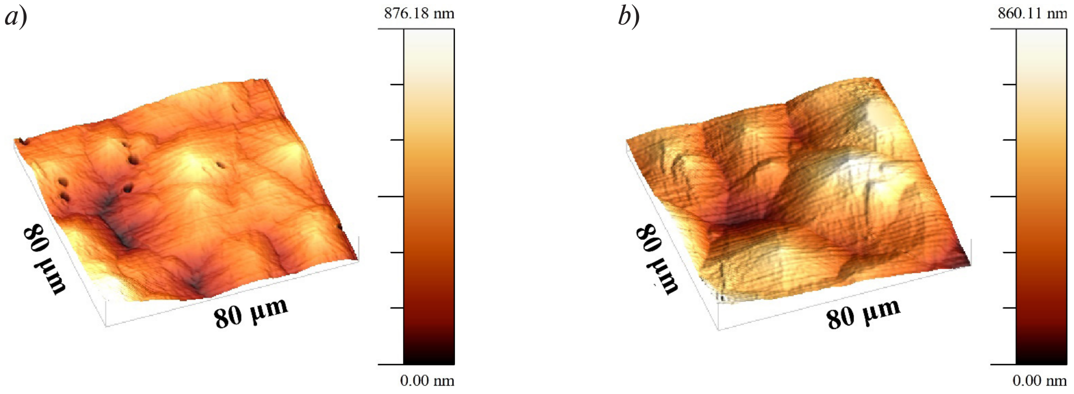

Fig. 3. AFM surface images of AlGaN/SiC/Si(111) (*a*) and AlGaN/AlN/SiC/Si(111) (*b*) heterostructures

Conclusion

Thus, in the present work the structural characteristics of AlGaN thin films formed by the HVPE method on nano-SiC/Si substrates with Si (001), (011) and (111) orientation was studied for the first time. The characteristic structural parameters of the surface of AlGaN layers on nano-SiC/Si have been determined by AFM method. It is shown that the surface structure of AlGaN layers grown on Si substrates with orientations (001), (011) and (111) is fundamentally different. As a result of studies, it was found that the buffer AlN layer grown on nano-SiC layers formed on Si substrates of orientation (001), leads to a decrease in the characteristic dimensions of the structural elements of the surface. When AlGaN films grow on nano-SiC layers formed on Si orientation (011) substrates, studies have shown that the opposite situation occurs, namely, the presence of a buffer AlN layer increases the characteristic sizes of crystal clusters on the surface. The buffer AlN layer grown on nano-SiC layers formed on Si orientation (111) substrates does not significantly affect the surface characteristics of AlGaN films.

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REFERENCES

1. **Alhassan A. I., Farrell R. M., Saifaddin B., Mughal A., Wu F., DenBaars S. P., Nakamura S., Speck J. S.**, High luminous efficacy green light-emitting diodes with AlGaN cap layer, Optics express. 24 (16) (2016) 17868–17873.
2. **Zhang Q., Yin X., Martel E., Zhao S.**, Molecular beam epitaxy growth and characterization of AlGaN epilayers in nitrogen-rich condition on Si substrate, Materials Science in Semiconductor Processing. 135 (2021) 106099.
3. **Arifin P., Sutanto H., Subagio A.**, Plasma-assisted MOCVD growth of non-polar GaN and AlGaN on Si(111) substrates utilizing GaN-AlN buffer layer, Coatings. 12 (1) (2022) 94.
4. **Kukushkin S.A., Osipov A.V.**, Theory and practice of SiC growth on Si and its applications to wide-gap semiconductor films, Journal of Physics D: Applied Physics. 47 (31) (2014) 313001.
5. **Grashchenko A.S., Kukushkin S.A., Osipov A.V.**, Coating of a nanostructured profiled Si surface with a SiC layer, Technical Physics Letters. 46 (2020) 1012–1015.
6. **Sharofidinov S.S., Kukushkin S.A., Red’kov A.V., Grashchenko A.S., Osipov A.V.**, Growing III–V semiconductor heterostructures on SiC/Si substrates, Technical Physics Letters. 45 (2019) 711–713.
7. **Kukushkin S.A., Osipov A.V., Soshnikov I.P.**, Growth of epitaxial SiC layer on Si (100) surface of n- and p-type of conductivity by the atoms substitution method, Reviews on Advanced Materials Science. 52 (2017) 29–42.
8. **Bessolov V.N., Konenkova E.V., Kukushkin S.A., Osipov A.V., Rodin S.N.**, Semipolar gallium nitride on silicon: technology and properties, Reviews on Advanced Materials Science. 38 (1) (2014) 75–93.

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