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Growth of SiC, AlN, and GaN films on silicon parts of arbitrary geometry for microelectromechanical applications

© *T.T. Kondratenko*[1], *A.S. Grashchenko*[2,3], *A.V. Osipov*[3], *A.V. Redkov*[2,3], *E.V. Ubyivovk*[3], *Sh.Sh. Sharofidinov*[4], *S.A. Kukushkin*[2,3]

[1] Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
[2] Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
[3] St. Petersburg State University, St. Petersburg, Russia
[4] Ioffe Institute, St. Petersburg, Russia
E-mail: sergey.a.kukushkin@gmail.com

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A technique is proposed for the formation of epitaxial films of silicon carbide, gallium nitride and aluminum nitride on the surfaces of non-planar silicon parts. Using this technique, a GaN/AlN/SiC/Si heterostructure was grown on the surface of a silicon ring. The samples were studied by scanning electron microscopy, as well as by Raman and energy-dispersive spectroscopy. It is shown that the preliminary deposition of a SiC layer on silicon by the atom-substitution method in which (111) facets are inevitably being formed regardless of the local crystallographic orientation of the substrate surface makes it possible to efficiently grow on silicon parts subsequent layers of III-nitrides of both the wurtzite and sphalerite types.

Keywords: GaN, AlN, SiC, silicon, atom substitution, MEMS.

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In works [1–3] there was developed a technique for forming non-planar epitaxial silicon structures with a uniform distribution of electrophysical and design parameters (layer thickness, specific resistance, charge carrier lifetime, and dislocation density) in different crystallographic directions. Being used in high-voltage power rectifier diodes, non-planar cylindrical $p-n$ structures ensure reduction in the device forward voltage drop by 15-20%, leakage current decrease by $2-3$ times, and reduction in the cooling system size by $3-5$ times; in addition, they provide a significant decrease in the heat resistance of the device housing structure as compared with that of planar analogues. To create such $p-n$ structures, the authors of [1–3] used as substrates hollow thin-wall cylindrical samples cut from single-crystal silicon grown by the Czochralski method. Silicon was deposited on the substrate surfaces by vapor-phase epitaxy in a specially designed reactor [1–3]; the silicon dislocation density ranged from 10^2 to $10^4\,\mathrm{cm}^{-2}$ [1,3]. All this shows a great promise of this approach.

In connection with these investigations, the following reasonable question arises: whether it is possible to create on such a profiled cylindrical substrate non-planar layers of wide-bandgap semiconductors, namely, of such compounds as silicon carbide (SiC), gallium nitride (GaN), aluminum nitride (AlN) and solid solution AlGaN. This task is incomparably more complicated than that of growing planar epitaxial films of those substances on a (111) silicon substrate. In this case, the growth of epitaxial structures is hindered by not only a great $(19-20\%)$ difference between lattice parameters of the Si substrate and mentioned semiconductor compounds, but also by a significant difference in their symmetries, especially of the silicon cylinder lateral surface formed by sections of atomic planes of different crystallographic orientations $\{hkl\}$. This task seems to be unsolvable in principle, since face (111) is obligatory needed for the epitaxial growth of AlN and GaN films. Even when it is necessary to grow semipolar layers of AlN and GaN on the Si (100) surface, the surface is pre-etched so as to form facets (111) arranged at a certain angle to plane (100) [4]. However, this problem can be solved (though not immediately), if the SiC epitaxial layer is initially formed on the surface of the profiled cylindrical Si substrate not by the method of chemical vapor deposition [5] but by the consistent atom-substitution method [6]. Papers [6–8] have shown that, independently of the initial silicon substrate orientation, plane (111) inevitably gets formed among other planes during the SiC growth. For instance, during the SiC growth on plane (111), Si gets completely converted into the SiC plane (111) in the process of substitution. During the conversion, the Si face (100) transforms into a SiC face consisting of a great number of facets looking like saw-tooth structures whose lateral faces are covered by planes (111). The angle between the orientations of face (100) and faces (111) is $54^\circ 44'$. Initially, the smooth Si (110) surface turns to the SiC surface covered by prism-like growth figures each having face (111) as one side and face $(11\bar{1})$ as another side. Therewith, the angle between the SiC face (111) and initial Si face (110) is $35^\circ 26'$. Detailed description of morphology of these faces may be found in [6–8]. Another key feature of the consistent atom-substitution method is formation in the near-surface region (between the SiC and Si layers) of a porous sublayer [9] that enables damping the elastic stresses

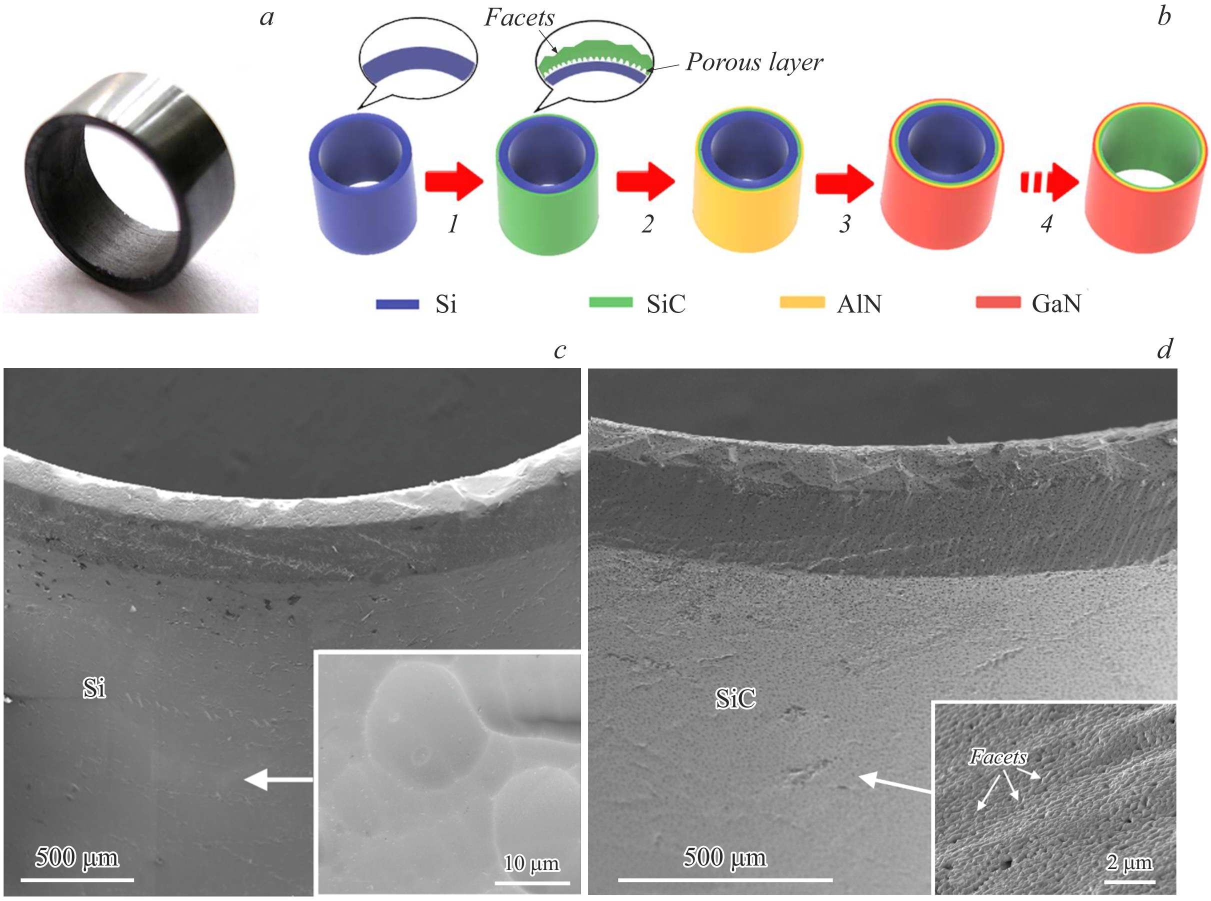

Figure 1. *a* — a photo of the used cylindrical silicon substrate (KEF $\langle 111 \rangle$). *b* — schematic procedure for depositing the heterostructure on the substrate: *1* — growth of the SiC buffer layer by the atom-substitution method with formation of (111) facets, *2*, *3* — deposition of the AlN and GaN layers by the HVPE method, *4* — optional removal of the silicon layer by chemical etching for obtaining a freestanding ring heterostructure GaN/AlN/SiC (the colored figure is given in the electronic version of the paper). *c*, *d* — SEM images of the surface of the initial silicon ring and SiC layer deposited by the atom-substitution method, respectively. The insets (panels *c*, *d*) illustrate the surface microstructure and emerging facets.

Conditions for synthesis of the AlN and GaN layers

Layer	Flow of Ar, ml/min	Flow of NH_3, ml/min	Flow of HCl, ml/min		Growth temperature, °C	Growth time, min	Layer thickness estimate, μm (as per SEM data)
			through Al	through Ga			
AlN	4	1.5	200	0	1050	1	~ 3.5
GaN			0	100		2	~ 9

induced by the mismatch of lattices and thermal expansion coefficients.

To our opinion, these two features may allow growing on a profiled Si surface the AlN and GaN heterostructures and a number of other crystals having either the wurtzite or sphalerite lattices. Indeed, the symmetry of prisms confined by the (111) facets is characteristic of both the cubic-symmetry and hexagonal-symmetry crystals, i. e. their symmetry is non-degenerate. This means that on the considered surfaces there can grow crystals of both the cubic and hexagonal symmetry. The type of symmetry will depend on thermodynamic conditions, i. e. on the growth temperature and incident flows of the growing layer components. This opens radically new promises for growing hexagonal semipolar crystals; just this was expected to be clarified in this investigation.

In this connection, the main goal of this work was experimental verification of the in-principle possibility of

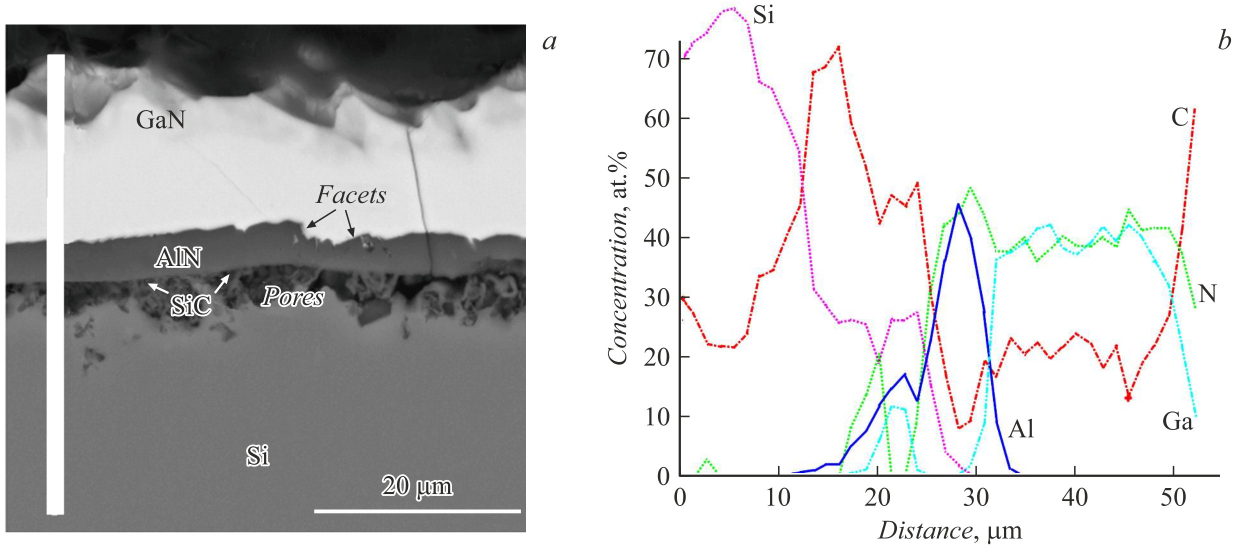

Figure 2. *a* — SEM image of the cleaved sample and grown GaN/AlN/SiC/Si layers (formation of facets in the AlN and GaN layers is visible). *b* — estimated sample composition measured by energy-dispersive spectroscopy along the line marked in the SEM image.

implementing such an approach to synthesize SiC films and films of the AlN and GaN compounds on the surface of a single-crystal Si item of an intricate (non-planar) shape.

As an item to be studied, a hollow silicon ring 7 mm in diameter and 10 mm in length (Fig. 1, *a*) was chosen; the sample was grown from *n*-type silicon KEF-0.02 (phosphorus-doped silicon) according to the procedure described in detail in patent [2]. The ring was subject to abrasive polishing with diamond paste and, subsequently, to chemical-dynamic polishing in a mixture of hydrofluoric acid (HF) and nitric acid (HNO_3). Notice that, due to the annular geometry, the sample surface exhibited almost all possible crystallographic orientations. After that, in the ring near-surface region a silicon carbide layer 110 nm thick (Fig. 1, *b*) was formed by the atom-substitution method [6–8]. SiC was synthesized at the temperature of 1290°C, pressure of 2.3 Torr, and total flow of the CO and SiH_4 gases of 12 SLM. In the process, the ratio between the CO and SiH_4 gases was 1:0.12. Then the layers of aluminum nitride and gallium nitride (Fig. 2, *a*) were grown on the formed SiC layer by the method of chloride–hydride epitaxy (HVPE) which ensures a high growth rate. The conditions under which the layers were grown by HVPE, as well as estimates of thicknesses of the obtained layers (according to the scanning electron microscopy (SEM) data), are listed in the Table.

The images presented in Figs. 1, *c*, *d*) demonstrate the structure and morphology of the surfaces of the initial silicon and deposited SiC layer. The Fig. 1, *d* inset demonstrates well-distinguishable facets formed after the SiC growth; the facets are typical of the atom-substitution method [6–8]. Fig. 2, *a* presents a SEM image of the cleaved sample surface after synthesizing the layers of aluminum and gallium nitrides; this image also demonstrates the facets formed in both the AlN and GaN layers. Fig. 2, *b* presents the results of estimating the composition by energy-dispersive spectroscopy, which confirm the layers elemental compositions. Notice that the elevated content of carbon in the near-surface region may be a consequence of the sample preprocessing for SEM. The Raman spectra measured with spectrometer Witec Alpha 300R manifest the presence of the main lines of silicon ($521\,cm^{-1}$), silicon carbide ($796\,cm^{-1}$), aluminum nitride ($657\,cm^{-1}$) and gallium nitride ($567\,cm^{-1}$), and also confirm the structure and composition of the successively deposited layers.

Thus, in this work there was proposed and successfully implemented in practice a technique for covering three-dimensional intricate-geometry silicon parts with layers of GaN, AlN and SiC. A positive effect of facets formed on the SiC (111) surface in the process of synthesis by the atom-substitution method was shown. Notice that, in addition to being used as a substrate for synthesizing III-N layers, the deposited SiC layer can play also an independent role of either a membrane, or a component of microelectromechanical systems (MEMS), or protective coating for silicon (which is significantly softer). In addition, after all the layers are grown, the initial blank sample of silicon may be, if necessary, etched away [11]; this allows obtaining a freestanding GaN/AlN/SiC heterostructure or membrane of a preset 3D geometry. The obtained results open new possilities for creating MEMS devices based on wide-bandgap semiconductors and making them compatible with the silicon technology.

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Conflict of interests

The authors declare that they have no conflict of interests.

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