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Pendeo-epitaxy of stress-free AlN layer on a profiled SiC/Si substrate

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ABSTRACT

A new approach to the pendeo-epitaxy of elastically-unstrained AlN films is developed. The AlN films are grown using chloride-hydride vapor phase epitaxy (HVPE) on a silicon substrate with specially synthesized and shaped buffer layer of nano-SiC (NSiC). This NSiC epitaxial layer is grown using a new technique based on the substitution of a part of silicon atoms by carbon ones in a 100–110 nm thick subsurface layer of the silicon substrate. The 2D array of ~200 nm in diameter wells with the depth of ~70 nm that is less than the NSiC layer thickness is formed on the NSiC surface using electron beam lithography followed by reactive ion etching, the period of the array is of 400 nm. In a single HVPE process we grew ~20 μm thick AlN film both on the shaped and smooth regions of the prepared substrate. The AlN films are examined with reflection high energy electron diffraction, X-ray diffractometry, Raman spectroscopy and scanning electron microscopy. We use the results of these measurements to compare residual elastic stresses in the AlN film grown on the shaped and smooth regions of the substrate. The film on the shaped part of the substrate is elastically-unstrained contrary to the smooth part where elastic stresses result in the formation of a textured AlN layer. The model of the AlN growth on shaped SiC/Si substrates prepared using the atomic substitution technique is proposed.

1. Introduction

Semiconductors of III-nitrides group, in particular AlN epitaxial films, are widely used in powerful electronic, optoelectronic and high-frequency surface acoustic devices [1]. AlN epitaxial films are also used as buffer layers allowing to improve the structure of heteroepitaxial gallium nitride films grown on silicon substrates [2,3]. The main problem in obtaining high-quality AlN layers and, accordingly, perfect GaN films on silicon is the formation of a high density of misfit dislocations at the AlN/Si interface. Typically, the density of these dislocations is of the order of 10^{10} cm^{-2}. This is caused by a large difference in the lattice constants of aluminum nitride and silicon, resulting in essential elastic deformations. To reduce the density of the misfit dislocations various techniques can be applied. In particular, the techniques of epitaxial lateral overgrowth (ELO) method and pendeo-growth are in a wide use. To fabricate a GaN film using the ELO technique they first grow a GaN layer on a substrate, than deposit a dielectric mask and turn back to the growth of GaN [4]. In pendeo-epitaxy [5], the first step is also the growth of a GaN layer, which is followed by a shaping of this layer via the formation of pillars or etching wells. The next step is lateral overgrowth of the pillars of wells with GaN layer, which is being similar with a bridge over a river. Certainly, this growth technique provides drastic decrease in the number of the dislocations. Usually AlN layers on silicon are grown by MBE [6], MOCVD [7] or HVPE [8] methods in a combination with ELO technique [9], and in the case of GaN layers such methods are also in use [10–12].

By the present time the chloride-hydride vapor phase pendeo-epitaxy of AlN on Si substrate has not been reported. Moreover, in this work we present the first experiments on the pendeo-epitaxy of AlN on Si substrate with a buffer layer of nano-SiC (NSiC) synthesized by a new method of substitution of Si by SiC [13]. It should be noted that the simplicity and low cost of production of NSiC on silicon which exceeds the average cost of silicon substrate of the same diameter less than for two times (and ten times lower than with conventional technologies) reduce total cost of all grown thereon materials and structures. Therefore, the most expensive in proposed process are the last two stages: lithography (masking of the surface) and epitaxy of AlN which require complex technical equipment. In our work we used the method of electron-beam lithography, a relatively expensive and difficult process. However, the formation of the mask can be done using

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other significantly cheaper methods. For example, if one chooses the period of wells in the mask slightly larger, it becomes possible to use conventional optical lithography. Another option is to use the method proposed in [14]: sputtering of nanoparticles on the surface of silicon carbide for use as an mask during etching. After etching one can remove them and grow a layer of AlN. Thus, the technology in general and the final substrate obtained are relatively inexpensive, and the method proposed looks prospective.

2. Experimental details

For the growth of AlN we used precisely oriented (111) silicon substrates with a pre-deposited buffer layer of silicon carbide. The synthesis of SiC films was carried out in accordance with [13] on p-type silicon substrates of 1000 Ω·cm resistivity. The conditions of the SiC films synthesis were as follows: SiC films were grown in an atmosphere of carbon monoxide (CO) with 25% content of silane (SiH_4) at a total pressure of 2 Torr. We grew the films at 1250^0C during 20 min. The substrate heating and cooling rates in the vicinity of the growth temperature were 10-20^{o}C/min. The thickness of the SiC film was 100–110 nm according to ellipsometric data. One should note, that in [15] authors have studied the homogeneity of the samples obtained by the method [13]. In particular, by using an ellipsometer J.A. Woollam M-2000 authors have built a map of SiC film thickness on a 6-in. silicon substrate. It was shown that the maximum difference in the thickness is not more than 17% even on the scale of 6 in. Since growing conditions are well established and standardized, all grown thin films have similar characteristics, including the difference in the thickness of the film in the periphery and in the center of Si substrate. Thus, it can be assumed that the SiC film, grown in our experiment, has the same relative variation in thickness.

Than a thin layer of chromium was deposited on the SiC film by means of electron-ion sputtering that is the bombardment of the metal target with a beam of charged particles. After this we covered the sample with the positive electron resist ZEP 7000–22 (Zeon Corporation) and used electron beam lithography and Cl/O2 plasma etching of the chromium film through the mask formed in the electron resist layer [16]. This allowed us to obtain a chromium mask presenting 2D array of 200·200 nm^2 squares with the periodicity of 400 nm (Fig. 1). The next stage was the etching of wells in the SiC layer. We used SF_6/Ar/O_2 plasma reactive ion etching through this chromium mask. The diameter of the formed wells was ~200 nm. We etched the wells to the depth less than the thickness of the SiC layer to prevent the "baring" of silicon under the SiC layer. After the processing the rest of the mask was removed from the SiC surface by a liquid etchant.

Than in a single process of chloride-hydride vapor phase epitaxy (HVPE) we grew aluminum nitride layers on the both shaped with the wells and remained smooth regions of the prepared SiC structure. The parameters of the HVPE growth were especially designed to grow AlN film on the silicon surface covered with NSiC layer [8]. Epitaxy of AlN was performed at a temperature of 1080C, the ratio of V/III was equal to 50, and flow ratio of H_2/NH_3 was 5:1. Growth rate of AlN film was about 0.2 μm/min and the total thickness of the grown AlN layer was 20 μm.

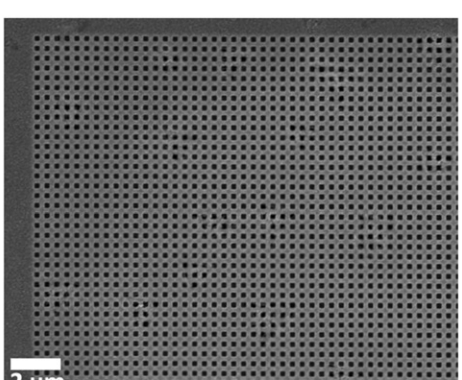

Fig. 1. SEM image of the shaped SiC-Si(111) surface after electron beam lithography.

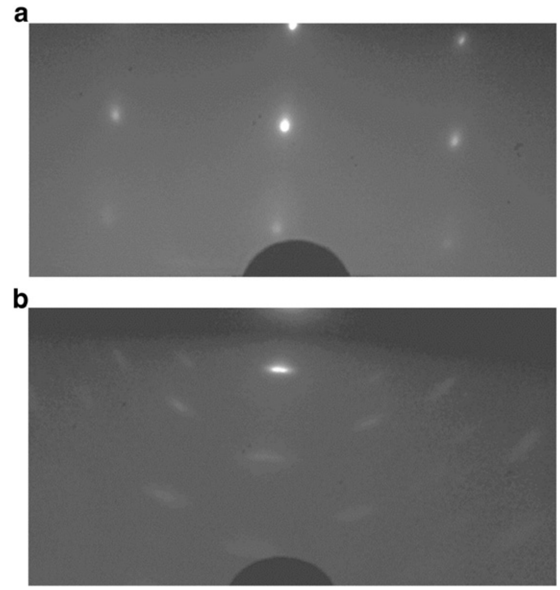

Fig. 2. Reflection high energy electron diffraction patterns from AlN grown on the structured (a) and on the smooth SiC/Si(111) surface (b). The reflections from the epitaxial layer (a) and the semi-ring reflections indicating the texture (b) are clearly visible.

3. Results

The AlN films grown on the wells-structured surface of the SiC/Si as well as on the smooth surface were examined by reflection high energy electron diffraction (RHEED), X-ray diffractometry, Raman spectroscopy and scanning electron microscopy (SEM). All obtained data clearly indicate the quality of the AlN layer synthesized on the shaped

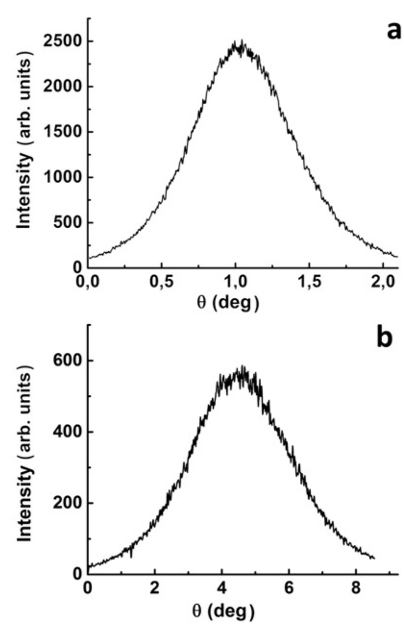

Fig. 3. The rocking curves of AlN within a masked region (a) and within the unmasked one(b).