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Morphological investigation of double positioning growth of (1 1 1)-boron phosphide (BP) on the (0 0 0 1)-GaN

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Abstract

A BP layer was grown on a (0 0 0 1)-GaN by atmospheric-pressure metalorganic VPE procedure. The BP layer grew epitaxially on the GaN with relationship: (0 0 0 1), ⟨*a*-axes⟩-GaN//(1 1 1),⟨1 1 0⟩-BP. On the surface of (1 1 1)-BP layer, crystallites disposed with double positioning configuration were found. The presence of crystallite disposed with the double positioning indicated that the BP layer grew up on the GaN with the manner of ''degenerated epitaxy''. In the (1 1 1)-BP layer grown through ''degenerated epitaxy'' manner, crystalline imperfections, such as {1 1 1}-twins were involved.

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1. Introduction

Sphalerite type boron monophosphide (BP) is known as one of the indirect transition type III–V compound semiconductors [1]. Up to now, the sphalerite BP has been used to form a hetero-structure system with silicon (Si) for the fabrication of electronic devices, such as solar cell and hetero bipolar transistor [2].

In addition to the formation of BP/Si hetero-structure [3,4], the sphalerite BP layer has also been applied to form hetero-structure with wurtzite (0 0 0 1)-GaN [5]. By joining the BP layer on the GaN, dislocations in the GaN is reported to be annihilated to prolong at the hetero-interface between the BP and the GaN [5]. Convenience on the formation of a p-type conductive layer without intentional doping of impurities also makes BP possible as an

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alternative to impurity-doped group III nitrides, such as magnesium (Mg)-doped aluminum–gallium nitride (AlGaN), to form pn-junction with GaN for fabrication of a blue light-emitting-diode (LED) [6]. However, the hetero-epitaxial growth manner of the BP layer on the (0 0 0 1)-GaN has not been investigated in detail.

As one of the growth manners in hetero-epitaxial systems, ''degenerated epitaxy'' which can treat epitaxial growth of a layer on a substrate possessing a higher rotational symmetry is proposed [7,8]. The concept of ''degenerated epitaxy'' has been utilized so far to insight the growth manner of hetero-epitaxial system, for instance, growth system of three-fold rotational symmetric (1 1 1)-gold (Au) film on six-fold symmetric (0 0 0 1)-surface of a hexagonal crystal [7].

In this report, a BP layer is grown by metal organic vapor phase epitaxy (MOVPE) procedure on a (0 0 0 1)-GaN layer, and hetero-epitaxial growth manner of the BP on the (0 0 0 1)-GaN is investigated on the standpoint of the ''degenerated epitaxy''.

2. Experimental procedure

An undoped BP layer was grown on a 3000 nm thick MOVPE-grown (0 0 0 1)-GaN layer deposited on the (0 0 0 1)-sapphire substrate. The BP layer was grown at 850 °C by an atmospheric-pressure MOVPE procedure using triethylboran ($(C_2H_5)_3B$) (Rohm and Haas Electronic Materials, L.L.C.) and phosphine (PH_3) for boron (B) and phosphorus (P) source gases, respectively. The source gases were transported with hydrogen gas (H_2) to a MOVPE reactor. During the MOVPE growth of the BP layer, the input ratio of source gases to the reactor, i.e., $PH_3/(C_2H_5)_3B$ concentration ratio was maintained at approximately 600. The thickness of grown BP layer was measured utilizing a spectrometric reflectometer. Surface morphology of the BP layer was investigated using a Normarski interference contrast microscope. Stacking relationship of the BP layer grown on the (0 0 0 1)-GaN was evaluated by X-ray diffraction method using copper (Cu) Kα line with wavelength of 0.154 nm as incident X-ray beam. Crystalline structure of the BP layer was also evaluated by transmission electron diffraction (TED) and high-resolution transmission electron microscope (HRTEM) techniques. In the evaluation by TED, incident electron beam accelerated at 300 kV was introduced to be parallel to [1 −2 1 0]-direction of the (0 0 0 1)-GaN.

3. Results and discussion

Fig. 1 shows the X-ray diffraction pattern of 450 nm thick BP layer on the (0 0 0 1)-GaN. In addition to (0 0 0 2)-diffraction of the (0 0 0 1)-sapphire substrate for the GaN layer, diffraction peaks which can be related only to (1 1 1) of BP, i.e., (1 1 1)-BP and (2 2 2)-BP peaks, appeared with the (0 0 0 2) and the (0 0 0 4)-GaN diffraction peaks. The stacking relation of the BP layer on the (0 0 0 1)-GaN was therefore determined to be (0 0 0 1)-GaN//(1 1 1)-BP. From the diffraction angle ($2\theta = 34.5^\circ$) at which the (1 1 1)-BP diffraction peak appeared, lattice constant of the MOVPE-grown BP was calculated to be 0.454 nm. The calculated value agrees well with the lattice constant previously reported for sphalerite BP by other researchers [9,10].

On the surface of the (1 1 1)-BP layer, triangular shape crystallites were observed to dispose symmetrically with respect to the ⟨1 1 0⟩-direction of BP, as shown in Fig. 2. According to the concept of ''degenerated epitaxy'' [7], the (1 1 1)-BP which has three-fold rotational symmetry is permitted to dispose symmetrically with double positioning manner [11] on the six-fold rotational GaN. The presence of the crystallites disposed with double positioning on the (1 1 1)-BP layer therefore indicates that the ''degenerated epitaxy'' will occur in hetero-epitaxial growth of the (1 1 1)-BP on the (0 0 0 1)-GaN.

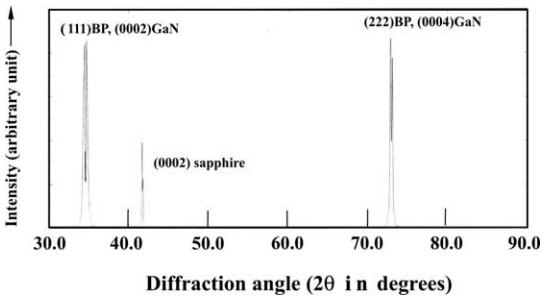

Fig. 1. X-ray diffraction pattern of MOVPE-grown BP layer on (0 0 0 1)-GaN.