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Deposition of a polycrystalline GaN layer on a porous Si/Si substrate by an electron beam evaporator with a successive ammonia annealing treatment

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ABSTRACT

This work begins with the deposition of a GaN layer on a porous Si/Si substrate using an electron beam evaporator. A few micrometres of porous Si were fabricated on the Si substrate for 10 and 30 min, and different porosities were obtained. For comparison, a GaN layer was also deposited directly on a Si substrate and a TiN buffer layer/Si substrate. The FESEM measurement revealed that the GaN layers turned into rough and distinguished hexagonal-facetted grains after the post-annealing treatment, especially the GaN layer on the 30 min-etched porous Si substrate. The XRD ω-scan revealed that the FWHM of the GaN peak was found to be the narrowest in the GaN layer on the 30 min-etched porous Si/Si substrate compared with those of the others. However, all of the samples exhibit very poor optical quality because no luminescence signal from GaN can be detected, as measured by photoluminescence (PL). The post-annealing treatment prompted the GaN layer to form a polycrystalline structure, as confirmed by the XRD measurement. Interestingly, the optical properties of the polycrystalline GaN greatly improved with a significant near band edge emission (NBE) and a GaN E_2 (high) peak at 3.42 eV and 568 cm^{-1}, respectively, as measured by PL and Raman measurements.

1. Introduction

Introducing a buffer layer of aluminium nitride (AlN) between a GaN layer and the Si substrate has become the common strategy to reduce threading dislocations and strains, which result from the large lattice mismatch between both materials [1–3]. Nonetheless, the use of a conductive buffer layer, such as TiN, is more preferable than AlN because it possesses electrical conductivity, which is beneficial to a device's development. Furthermore, TiN was reported to promote continuous growth and a flat surface of GaN [4]. However, threading dislocations inside the GaN layer remain high (~10^9-10^{10} cm^{-2}), which limits the material's potential in various device applications. Alternatively, the introduction of a porous Si layer on the Si substrate for GaN deposition would be a better solution to reduce the problem [5,6]. The void spaces of the porous Si could inhibit the threading dislocations from propagating into the GaN layer while releasing strains in the layer.

It is well-known that the interest in polycrystalline GaN layer is still low and has hardly been reported in the literature. Nonetheless, such a material is easier and cheaper to make and exhibits good optical behaviours with a strong PL emission. Polycrystalline GaN also contains a low electron affinity and a strong chemical and mechanical stability that makes it suitable for application as an electron field emitter [7]. Furthermore, its ferromagnetism at room temperature is preferred for diluted magnetic semiconductor memory devices [8]. It is predicted that a polycrystalline GaN layer with strong optical properties could be obtained by depositing the layer on a porous Si/Si because extended defects such as threading dislocations can be significantly reduced compared with depositing the layer on the Si substrate or a buffer layer/Si substrate.

To the best of our knowledge, the deposition of a GaN layer on a Si (100) substrate using e-beam evaporator only has been reported by Chaudhari et al. [9]. Their work, however, focused on the deposition of GaN directly on a Si (100) substrate using different deposition temperatures to enhance the crystallinity of the polycrystalline GaN layer. It is well known that the direct deposition of GaN on a Si (100) substrate is quite challenging as the layer commonly suffers from a high threading dislocation density and cracks because of the large difference between the lattice constants

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Table 1
Details of the GaN layer deposited on different surfaces using a Si substrate.

Sample	Type of surface for GaN deposition	Structure of sample
A	Si substrate	GaN/Si
B	TiN buffer layer/Si substrate	GaN/TiN/Si
C	10 min-etched porous Si/Si substrate	GaN/porous Si/Si
D	30 min-etched porous Si/Si substrate	GaN/porous Si/Si

of both materials and a high thermal expansion coefficient [10]. In recent years, porous Si has received substantial attention as the structure can 'sink-out' the defect dislocations tremendously from propagating into the subsequent layer. Therefore, depositing GaN onto a porous Si/Si substrate would minimize the problem related to the lattice mismatch. So far, the deposition of GaN on porous Si has never been demonstrated by e-beam evaporation, a simpler and inexpensive technique. To improve the deposited GaN layer by e-beam evaporator, a post-annealing treatment is proposed here.

It is important to realize that no work on the deposition of a GaN layer on a porous Si/Si using room temperature has been reported. In this work, we propose to deposit a GaN layer on a porous Si/Si substrate using a room-temperature e-beam evaporator. The porous Si was prepared with different porosities by changing the etching time from 10 to 30 min. Typically, the growth of GaN epitaxy on porous Si substrate is possible by using molecular beam epitaxy (MBE) [11] and metal organic chemical vapour deposition (MOCVD) [6,12]. This work offers an alternative way to expensive techniques, such as MBE and MOCVD. This technique also promotes a simpler and fast deposition rate of up to a few micrometres per minute, which benefited in depositing a thicker GaN layer in a shorter time. It should be noted that most of the polycrystalline growth is achieved by using an MBE system equipped with an ammonia source [8,13,14]. As a comparison, the GaN layer was also deposited on a Si substrate and a TiN buffer layer/Si substrate. Subsequently, the GaN layers were subjected to an annealing treatment in ammonia (NH_3) to improve the properties of the layers. Towards the end of this work, the best surface for GaN deposition is proposed.

1.1. Experimental procedure

In this work, n-type Si (100) substrates with a resistivity between 1 and 10 Ω cm and a thickness in the range of 300–360 nm were used. A few micrometres of Si substrate were fabricated into a porous structure using electrochemical etching with a hydrofluoric acid (HF) and *N,N* dimethylformamide (DMF) electrolyte solution at a ratio of 1:3 and an applied current density of ~10 mA cm^{-2}. This experiment was assisted by an external illumination using 100 W of incandescent light to promote the accumulation of holes on the Si surface for a more effective etching process. In this experiment, the porous Si/Si substrate was prepared with different etching times, 10 min and 30 min, which gives different porosities of Si. The images of the porous Si were observed through field-emission scanning electron microscopy (FESEM) using a Nova NanoSEM 450 model. In parallel, a 70 nm thick TiN buffer layer was deposited on a Si substrate using a radio-frequency (RF) sputtering system (model: Auto 500 RF sputter coater). The deposition of the TiN buffer layer had been optimized beforehand.

Next, a GaN layer was deposited onto the porous Si/Si substrate and the TiN buffer layer/Si substrate using an e-beam evaporator (model: T-T-6 Telemark). The deposition of the GaN layer directly on a Si substrate was also demonstrated. The source of the GaN was prepared by compressing a few grams of GaN powder, which was then placed into a copper (Cu) crucible in the e-beam evaporator system. The samples were attached to the substrate holder and placed directly above the Cu crucible. The system was first baked for 12 h at a temperature of 100 °C to remove moisture in the evaporator chamber. The current and pressure were kept constant at 50 mA and 10^{-5} Torr, respectively. The GaN layers were deposited at a thickness of ~1.80 μm. After that, all of the samples were annealed in an ammonia (NH_3) environment at 950 °C for 30 min with an ammonia flow rate of 4 standard litres per minutes (slm). The annealing process was conducted using a 3-zone furnace system.

In this work, the surface morphology of the GaN layers deposited on the porous Si/Si substrates, the TiN buffer layer/Si substrate and the Si substrate was observed by FESEM. The crystalline orientation and the structural quality of the GaN layers were determined by x-ray diffraction using a PANalytical X'pert PRO model. On the other hand, the optical properties of the GaN layers were investigated by a photoluminescence (PL) measurement with the use of a He-Cd laser source at the excitation wavelength of 325 nm. The Raman spectroscopy measurement was conducted with the use of an argon (Ar) ion laser source ($\lambda = 514.5$ nm) under the scattering configuration of $z(x, \text{unpolarised})\bar{z}$. Both measurements were carried-out at room temperature using a Jobin Yvon HR800 model. To facilitate convenient discussion with the readers, all of the samples are labelled and listed in Table 1.

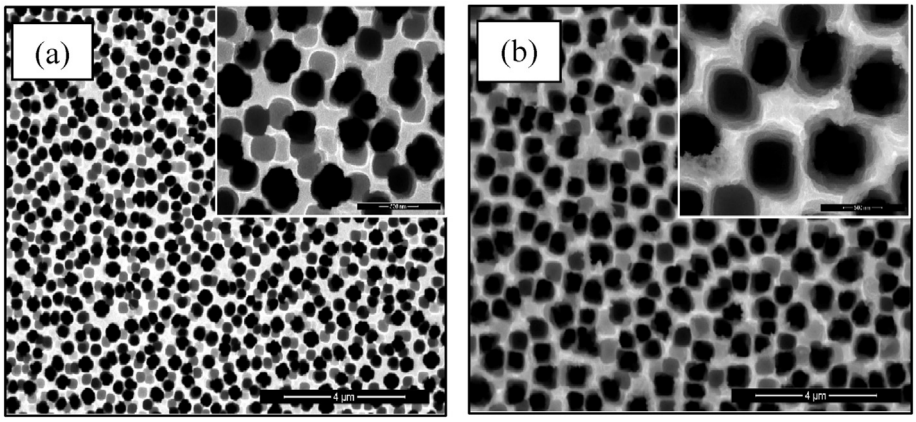

Fig. 1. Surface morphologies morphology of the porous Si on a Si substrate etched for at (a) 10 min and (b) 30 min with a constant current density of 10 mA cm-2. The inset figures show the porous Si surface at a higher magnification of 30 000 ×. Clearly, the size of the pores increases with etching time.