Growth of nitride-based light emitting diodes with a high-reflectivity distributed Bragg reflector on mesa-patterned silicon substrate

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(Ga,In)N/GaN multiple quantum well blue light emitting diodes (LEDs) grown on mesa-patterned silicon substrates with improved electro-optic characteristics are demonstrated. The active regions are grown on top of high-reflectivity AlN/(Al,Ga)N distributed Bragg reflectors (DBRs). Due to efficient stress relaxation at the mesa edges, crack formation during growth or upon the post-growth cool-down of the samples can be avoided. A large number of AlN/(Al,Ga)N bilayers in the DBR can be then included in the LED structures leading to strong enhancement of the LED device output power in spite of the presence of the absorbing silicon substrate at the LED emission wavelength.

1 Introduction

Silicon substrate presents several advantages over sapphire substrate for the growth of nitride materials, in terms of large surface availability, low cost and easy manufacturing. However, the growth of GaN on silicon substrate requires to develop complex buffer layers in order to avoid the apparition of cracks and to obtain high quality layers [1, 2]. Another way to achieve uncracked and high quality layers is to use mesa patterned Si substrates [3, 4]. In this case, strain in GaN layers is relaxed at mesa edges. In consequence, thicker GaN with improved structural quality can be grown without the formation of cracks. The use of mesa-patterned silicon substrates can also be advantageous for the growth of specific buffer layers such as distributed Bragg reflector (DBR) based on nitride multilayers. In these structures, a high reflectivity necessitates the growth of layers with a large contrast of optical index and then large lattice mismatch strain. Thanks to mesa patterns, such DBR can be grown with a strongly reduced risk of cracking [5]. Inserting a highly reflective DBR between the Si substrate and a nitride light emitting diode (LED) is particularly interesting because it can act as a reflector for the photons coming from the LED and thus enhance the total emitted optical power in the air. A few works regarding this subject have been reported in the literature, but were not totally satisfying both from the point of view of the GaN material quality [6] and the cracking issue [7]. In this paper, we demonstrate crack-free LED structures and devices on silicon with clearly enhanced crystal quality and performance.
2 Experimental

2.1 Substrate preparation 2 in. Si(111) substrates were used in this work. Photolithography and SF$_6$-based reactive ion etching (RIE) were used to define square mesas with different surfaces varying from $200 \times 200$ to $490 \times 490 \mu m^2$. The depth of the trenches in silicon is $5 \mu m$. The prepared substrates were then cleaned and chemically deoxidized just before their introduction in the growth reactor.

2.2 Epitaxial growth The growth technique used for the sample elaboration is the molecular beam epitaxy (MBE) in a RIBER reactor. Effusion cells are used for group-III (Al, Ga, and In) and dopant (Si and Mg) elements, whereas ammonia (NH$_3$) is the nitrogen source. The typical growth temperatures are 900, 800, and 550 °C for AlN, GaN, and InGaN, respectively.

The first nucleation steps on the Si substrate are described in Ref. [8]. The buffer layer is an AlN layer which is also the first layer of the DBR. The DBR consists of 30 AlN (49 nm)/Al$_{0.2}$Ga$_{0.8}$N (45 nm) bilayers. A 440 nm thick GaN layer is grown on top of the DBR. At this stage (dotted line in Fig. 1), the sample is cooled down and taken out of the growth chamber to evaluate the percentage of non-cracked mesas and to measure the reflectivity. Then, the sample is reintroduced in the MBE chamber for the growth of the active region of the LED, namely 1.5 μm thick GaN:Si, ten periods of (Ga,In)N/GaN multiple quantum well, 20 nm thick Al$_{0.1}$Ga$_{0.9}$N:Mg, and 200 nm thick GaN:Mg. As we use MBE, there is no need for thermal annealing to activate the acceptor behavior of Mg atoms [9, 10]. A cross-section of the full structure, obtained by scanning electron microscopy (SEM), is shown in Fig. 2.

2.3 Light emitting diode device process Standard UV lithography and reactive ion etching (Cl$_2$/Ar/CH$_4$) are used to define LED mesas. Then RIE is used to locally etch the p-type doped layers and the (Ga,In)N/GaN MQW to access to the n-type doped layer. The ohmic contacts are Ti/Al/Ni/Au (30/180/40/150 nm) on n-GaN and Ni/Au (5/5 nm) semi-transparent (ST) current spreading layer plus a Ni/Au (10/100 nm) contact as top electrode to p-GaN. An example of the obtained devices is shown in Fig. 3.

2.4 Characterizations The morphology of the samples is characterized by using an optical microscope and a SEM. The dislocation density is evaluated by counting on atomic force microscopy (AFM) images the depressions induced by the emergence of threading dislocations at the surface of the samples. Note that before the AFM analysis, the sample pieces are annealed under ammonia in a metal organic chemical vapor deposition growth chamber to obtain reliable data as explained in Ref. [11]. High resolution X-ray diffraction rocking curves on asymmetric reflections are used to evaluate the crystalline quality of the samples. The optical reflectivity is measured at room temperature.

Figure 1 Structure of the sample including a light emitting diode active region (2) and an AlGaN/AlN distributed Bragg reflector (1).

Figure 2 Cross-section scanning electron microscopy image of the full light emitting diode structure including the distributed Bragg reflector.

Figure 3 Nomarski top view of a processed light emitting diode and schematics of the same structure in side view.
temperature using a Xe white lamp. The spectra are normalized with a reference Al mirror. The electro-luminescence (EL) is measured at room temperature under continuous wave (CW) conditions.

3 Results and discussion

3.1 Cracking statistics

The cracking of the nitride layers has detrimental consequences on the device performance, such as current leakage, short-circuits, or current injection in a restricted area in fully processed LEDs. It is crucial to keep the largest number of uncracked mesas for a high process yield. We consider that as soon as a mesa is affected by one crack, it is not any more usable. An example of the resulting morphology obtained on the full LED+DBR structure is shown in Fig. 4.

Most of the mesas are uncracked due to the fact that stress relaxation occurs at mesa edges and thus reduces the overall stress in the nitride layers. It is important to point out that similar structures grown on planar Si substrates (without mesas) are affected by a large crack density. Note that the trenches between the mesas are cracked. This well illustrates the pertinence of substrate patterning to limit the crack formation on top of the mesas. To be more quantitative, we have counted the number of mesas which are uncracked. A total number between 100 and 500 different mesas have been analyzed depending on their area. This counting has been made two times: just after the growth of the DBR and the 440 nm thick GaN layer and on the complete LED+DBR structure. The results are shown in Fig. 5. The number of uncracked mesas progressively decreases from more than 95% for mesa side length of 200 \( \mu \text{m} \) to about 50% for mesa side length of 490 \( \mu \text{m} \). This effect is due to the inhomogeneous stress distribution of the nitride layers: from a relaxed stress state at the mesa edges to a tensile stress state at the mesa center. Actually the tensile stress at the mesa center increases with the mesa side length [3, 4]. This explains why large mesas are less efficient to avoid crack formation. Note that in the present case, the cracks mainly occur during the growth of the DBR because of the tensily stressed AlN on Al\(_{0.2}\)Ga\(_{0.8}\)N layers.

By carefully looking at the data of Fig. 5, we can distinguish a slight decrease of the percentage of the uncracked mesas for the full DBR+LED structure. This can be explained by the fact that the total thickness of this structure is larger and the sample has to sustain two thermal cycles from growth temperature to room temperature. The use of two separate growth runs to make the full DBR+LED structure is therefore not optimum. The number of cracked mesas could be probably reduced by using a single growth run.

3.2 Reflectivity

Thanks to the large number of AlGaN/AlN pairs, the expected reflectivity of the DBR (neglecting residual absorption) is very close to 100% (Fig. 6a). The measurements were performed on the structure constituted by the DBR plus a 440 nm thick GaN layer [see zone (1) in Fig. 1]. The presence of this GaN layer modifies the reflectivity spectrum as shown in the calculated spectrum in Fig. 6b. The measured reflectivity spectrum is reported in Fig. 6c. The maximum reflectivity of the experimental spectrum is 95% of the theoretical value. This attests to the good quality of the interfaces of the DBR.

3.3 LED optical characteristics

The reflectivity was measured again on the full LED+DBR structure (Fig. 7). Compared to the results shown in Fig. 6, the reflectivity signal is modified by the presence of the different layers of the LED and the semi-transparent NiAu electrode. It has been found in separate experiments that the transmission of this electrode is 0.4–0.5 and therefore can account for the reflectivity signal attenuation. The room temperature electroluminescence spectrum at 20 mA is maximum at a wavelength of \( \sim 425 \) nm. We can remark that the shape of the EL spectrum is significantly modified by the presence of the DBR. For a standard structure,
we generally observed an EL spectrum with a gaussian shape structured by interferences in the nitride layers, while in the present case we see an EL intensity enhancement at the maximum of reflectivity.

We have measured the output power as a function of the current by using a Si photodiode positioned 1 cm above the LEDs (Fig. 8). The LED intensity is compared to that of a LED without DBR grown on patterned Si substrate (the DBR is replaced by a simple 200 nm thick AlN buffer layer). The LED with the DBR delivers an output power ten times larger at 20 mA than the LED without DBR. This ratio cannot be explained only by the mirror effect of the DBR which avoids the light absorption by the silicon substrate (without DBR, the reflectivity at the interface between the Si substrate and the nitride layers would be ≈25%).

Figure 6 (a) Calculated room temperature reflectivity of the AlN/AlGaN distributed Bragg reflector. Room temperature reflectivity of the AlN/AlGaN distributed Bragg reflector capped with a 440 nm thick GaN layer: calculated (b) and measured (c).

Figure 7 Room-temperature reflectivity and electroluminescence spectrum at an injection current of 20 mA of a light emitting diode grown on a mesa patterned Si substrate including a high reflectivity distributed Bragg reflector.

We have then compared the crystalline quality of both structures. The full width at half-maximum of the GaN asymmetric (302) X-ray reflection is 0.38 and 0.68° for the LED sample with the DBR and without DBR, respectively. According to AFM microscopy experiments, the threading dislocation density is $2.3 \times 10^{10}$ and $2.6 \times 10^{10}$ cm$^{-2}$ for the LED with the DBR and without DBR, respectively. This
clearly indicates that the crystalline quality of the LED with the DBR is better. The DBR has therefore a filtering effect on the dislocations, improving the LED global efficiency and the total output power, as shown in Fig. 8. We have to point out that the output power increase between a LED with DBR and a standard LED on Si substrate with comparable dislocation densities should be much reduced compared to the results shown in Fig. 8.

4 Conclusions The use of mesa-patterned Si substrate is an attractive solution to develop highly strained structures, such as LEDs including DBRs with a large pair number, although these structures are impossible to grow without cracks on planar Si substrates. In addition, thanks to the numerous interfaces of the DBR, threading dislocations are efficiently filtered. However, the size of the mesas has to be below $350 \times 350 \mu \text{m}^2$ to ensure that more than 80% of the mesas are uncracked.

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