Optical and electrical properties of GaN-based light emitting diodes grown on micro and nano-scale patterned Si substrate

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Abstract:

We investigate the optical and electrical characteristics of the GaN-based light emitting diodes (LEDs) grown on Micro and Nano-scale Patterned silicon substrate (MPLEDs and NPLEDs). The transmission electron microscopy (TEM) images reveal the suppression of threading dislocation density in InGaN/GaN structure on nano-pattern substrate due to nanoscale epitaxial lateral overgrowth (NELOG). The plan-view and cross-section cathodoluminescence (CL) mappings show less defective and more homogeneous active quantum well region growth on nano-porous substrates. From temperature dependent photoluminescence (PL) and low temperature time-resolved photoluminescence (TRPL) measurement, NPLEDs has better carrier confinement and higher radiative recombination rate than MPLEDs. In terms of device performance, NPLEDs exhibits smaller electroluminescence (EL) peak wavelength blue shift, lower reverse leakage current and decreases efficiency droop compared with the MPLEDs. These results suggest the feasibility of using NPSi for the growth of high quality and power LEDs on Si substrates.

Introduction:

The wide band gap GaN-based semiconductors have received enormous attention for various applications, such as short-haul optical communication, traffic and signal lights, back lights for liquid-crystal displays, and indoor/outdoor lightings. Typically, GaN-based light emitting diodes (LEDs) were grown on sapphire or SiC substrate by heteroepitaxial techniques in a metal-organic chemical vapor deposition (MOCVD) system [1]-[3]. However, the low thermal and electrical conductivities make sapphire less perfect as a substrate for the GaN epilayers, meanwhile the high price and mechanical defects hinder SiC substrate's acceptability in the LED market. Silicon has been considered as an alternative substrate material due to its low manufacturing cost, availability of large size wafers, and good thermal and electrical conductivities. Thus, many efforts have been dedicated to the realization of GaN based LEDs on Si substrates. Even though good progress has been made, there are still several problems when using Si substrate for GaN epitaxial layers. The large lattice mismatch between GaN and Si (almost 17%) leads to high threading dislocation densities (TDDs) (around 10^{8}-10^{10} cm^{-2}) in the subsequent GaN epilayers. The other major problem is the thermal expansion coefficient difference (56%) between two materials, which induces a high tensile stress during the thermal cycling in MOCVD and often results in cracks and damages of epilayers. To reduce the density of cracks and threading dislocations of GaN grown on Si, a number of approaches have been reported, such as using AlN multilayer combined with graded AlGaN layer as buffer, epitaxial lateral overgrowth of GaN on micro-patterned Si, and nanoheteroepitaxial (NHE) lateral overgrowth of GaN on nanopore array Si, etc.. These methods effectively reduce the tensile stress and thus the crystal quality of GaN was greatly improved. Recently, our co-workers reported fabrication of GaN-based device structure on a nano-scale patterned silicon substrate [4] that shows significant improvement on reduction of TDDs, surface morphology and light emission. In the mean time, the optical and electrical properties of InGaN/GaN MQWs grown on these patterned silicon substrates have not been fully studied yet. In this paper, we examine various optical and electrical characteristics of GaN based LEDs grown on micro

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and nano-scale patterned Si substrates (MPLEDs and NPLEDs), and the experimental results can lead us to believe that NPLED is in general superior to its micro-scale counterpart.

Result and discussion:

First step to compare these two material growth methods is to check their material quality. In order to analyze the detailed epitaxial layer quality, we used TEM to compare the cross section between two types of devices in Fig. 1. A comparison of Fig. 1(a) and 1(b) shows that the dislocation density in the NPSi sample is reduced much more than that of MPSi's. The TDDs for MPSi is estimated to be 2.5×10^{10} cm^{-2} at the bottom of the n-GaN layer, and it decreases to 4.6×10^{9} cm^{-2} at the top of the n-GaN layer and 6.2×10^{8} cm^{-2} in the p-GaN region. On the other hand, for the epilayer grown on NPSi, fewer dislocations are observable within the range of view. As shown in Fig. 1(b), the TDDs at the bottom of the n-GaN layer is about 1.1×10^{10} cm^{-2}; however, the TDDs at the top of the n-GaN layer drop down to 5.7×10^{8} cm^{-2}, and it is only 8.8×10^{7} cm^{-2} in the p-GaN region. The reduction of TDDs NPSi over MPSi is about 10 times. Fig. 1(c) and 1(d) are TEM images are taken at the interface of epilayer/NPSi. As can be seen in Fig. 1(c), there are many dislocations bent and terminated in AlGaN layer or near the epilayer/NPSi interface. As a result, the density of TDDs in the subsequent quantum well region was much lower.

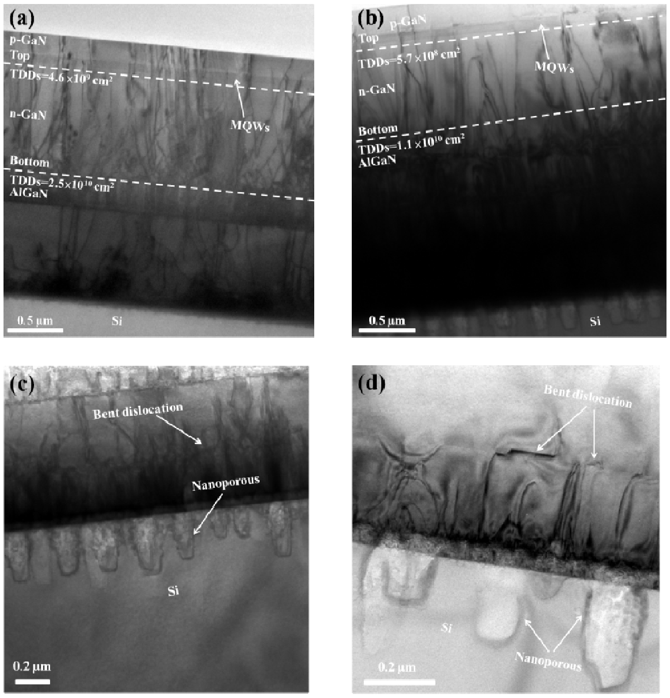

Fig. 1. TEM images of LEDs grown on (a)MPSi and (b)NPSi ; (c) and (d) region of between AlGaN layer and Si substrate for NPSi using g=(0002).

Potential variation affects how easy the carrier can be confined, and the combining rate can be regarded as how fast the carriers can recombined. The information about carrier recombination rate can be obtained from decaying behavior of photoluminescence. The low temperature TRPL decay for both samples was shown in Fig. 2. Because the measurement was carried out at 10K, the influence of the nonradiaive recombination process could be excluded. The TRPL results can be fitted by a biexponential decaying function: [5]

$$I(t) = I_1(0)\exp(-\frac{t}{\tau_1}) + I_2(0)\exp(-\frac{t}{\tau_2}). \qquad (1)$$

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, where I(t) is the PL intensity at time t ; τ_1 and τ_2 represent the characteristic lifetimes of the carriers. The fast decay time constant (τ_1) usually represents the radiative recombination of excitons and the relaxation of QW excitons from free or extended states toward localized states. Our fitting shows τ_1 =3.2 and 1 ns for MPLEDs and NPLEDs, respectively. The slow decay time (τ_2) accounts for communication between localized states and localized excitons. The fitting shows τ_2 =9.4 and 3.2 ns for MPLEDs and NPLEDs, respectively. In both fast and slow constants, NPLEDs' lifetime is generally shorter than MPLEDs' at low temperature. S. Chichibu, et. al. reported the electron-hole pairs in the potential minima of QWs can be referred to as localized excitons, and the emission efficiency can still be enhanced even though the wave function overlap is weakened. In the case of MPLEDs and NPLEDs, much higher radiative recombination rate observed in TRPL can be interpreted as direct evidence of stronger localized confinement in NPLEDs than MPLEDs, and also an indication of more efficient light-emitter.

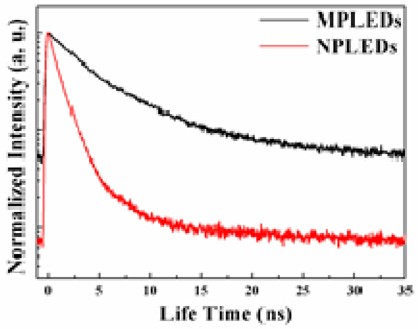

Fig. 2. The comparison of low-temperature TRPL between MPLEDs and NPLEDs.

The final trial of this nano-size template is to test the light emitting efficiency from the real device. LED devices with a chip size of $350\times350\ \mu m^2$ were fabricated on both MPLEDs and NPLEDs. Fig. 3 shows the light output intensity and normalized external quantum efficiency (EQE) as a function of forward current density for both samples. The light output-current curve of MPLEDs is linear under 20mA/cm^2. However, it rolls over beyond 20mA/cm^2 with a reduced EQE. The EQE is decreased to 62% of its maximum value when the current density at 100mA/cm^2. In contrast, the NPLEDs exhibits 20% efficiency droop with increasing the injection current density to 100 mA/cm^2. It can be attributed to reduced polarization field which also echoes to weaker QCSE under the circumstance of reduced strain in overgrown layers on NPSi template [6].

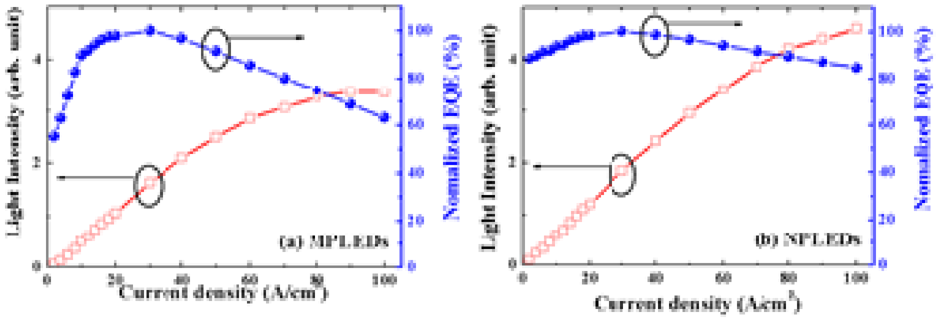

Fig. 3. Integrated EL intensity and normalized EQE as a function of forward current density for (a)MPLEDs and (b)NPLEDs, respectively.

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Conclusion:

In conclusion, the optical and electrical properties of LEDs grown on micro and nano-scale patterned Si substrate were investigated. We demonstrated a more homogeneous growth of InGaN/GaN active layers under this nano-scale template by plan-view and cross-section CL mapping. From temperature dependent PL and low temperature TRPL measurement, NPLEDs has better carrier confinement and higher radiative recombination rate than MPLEDs. On the actual device performance, NPLEDs exhibits smaller peak wavelength blue shift, lower reverse leakage current and decreases efficiency droop compared with the MPLEDs. The results suggest a weaker QCSE due to relaxation of strain in the epitaxial layers on nano-scale patterned substrate, which can be really useful for the next generation of large area, Si-based heteroepitaxy of GaN related optoelectronic devices.

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