Substrate-patterning techniques for nitride growth

Sami Suikkonen, Muhammad Ali, Olli Svensk, Sakari Sintonen, Markku Sopanen, Harri Lipsanen, and Pekka T. Törnä

Enhanced control over substrate patterning leads to improvements in material quality and light extraction in nitride materials and LEDs.

Although gallium nitride (GaN) and its alloys are widely used in LEDs, there is still room for efficiency improvements. Because of the high cost of GaN substrates, foreign materials such as sapphire are commonly used in deposition of GaN films (epitaxy) onto LEDs. Several problems arise from this mismatch between the epitaxially grown GaN layer and the substrate.\textsuperscript{1,2} The mismatch in lattice constants and thermal-expansion coefficients creates strain and dislocations in the grown layer, while the refractive-index difference causes total internal reflection. These factors reduce the internal and light-extraction efficiencies of LEDs.

Several approaches have been successfully applied to reduce the dislocation density and improve the light-extraction efficiency of GaN films and LED structures, most importantly epitaxial lateral overgrowth,\textsuperscript{3} pendelo epitaxy,\textsuperscript{4} and patterned sapphire substrates (PSSs).\textsuperscript{5} Substrate-patterning methods have as an advantage that they cancel the effects of mismatch in lattice constant and refractive index between substrate and epitaxially grown film. It is, therefore, possible to improve both the material quality and the light-extraction efficiency using a single process. Two different methods are commonly used, i.e., patterning of either sapphire or sapphire/GaN templates. PSSs have the advantage of single epitaxial growth, while patterning of sapphire/GaN templates can be done using a larger range of techniques and offers more control in dislocation reduction and light-extraction engineering.

We have studied growth of GaN films on c-plane (the flat part of a sapphire crystal) PSSs and the effect of substrate patterning on LED performance.\textsuperscript{6,7} Patterning consists of hexagonal pit or pillar structures that are wet etched onto the sapphire surface: see Figure 1(a). When overgrown with GaN, the sapphire surface is completely covered with GaN: see Figure 1(b). However, the interface remains nonplanar and can be designed to scatter light efficiently. Both the pattern diameter and depth have a significant impact on the material quality and the efficiency of

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Figure 2. Normalized electroluminescence (E.L.) intensity (in arbitrary units, a.u.) of LEDs grown on patterned sapphire substrates.

Figure 3. Tilted view and cross-sectional SEM image of sapphire/gallium nitride (GaN) substrate with a 3μm-diameter hexagonal hole pattern.

overgrown LED structures (see Figure 2). We found that the efficiency improvement can be mainly attributed to increased light extraction, while improved material quality plays a minor role.

Sapphire patterning is fairly simple and easily scalable to production quantities. However, the degree of control over the shape and light-scattering properties of the substrate/layer interface is limited. Therefore, we have developed a process that consists of patterning sapphire/GaN substrates and subsequent overgrowth. We etch hexagonal holes on GaN films grown on c-plane sapphire (see Figure 3). The films are then overgrown with GaN and—with a correct choice of process parameters—voids are formed at the sapphire/GaN interface. The void shape and side-wall angle can be controlled by the aspect ratio of the original pattern (see Figure 4). If the aspect ratio is defined as the pattern diameter divided by its depth, the side-wall inclination angle decreases with increasing aspect ratio. This control of void shape opens up new possibilities in light-extraction engineering, which is especially important in chip geometries where light is extracted through the substrate, as in flip-chip designs.

We grew LED structures on these sapphire/GaN substrates and processed them into chips. LEDs grown on patterned sapphire/GaN substrates showed a 10% increase in light output for currents of 20–150mA. This increase is associated with improved light-extraction efficiency caused by the voids in the sapphire/GaN interface. Since the patterning technique offers full control over both void size and shape, we can expect more improvements once we have optimized the pattern geometry.

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Author Information

Sami Suihkonen, Muhammad Ali, Olli Svensk, Sakari Sintonen, Markku Sopanen, and Harri Lipsanen
Department of Micro- and Nano Sciences
School of Science and Technology
Aalto University
Espoo, Finland

Sami Suihkonen is a group leader. His research focuses on metal-organic vapor-phase epitaxy of group III nitrides (III-N) and processing of III-N light-emitting devices.

Pekka T. Törmä
OptoGaN GmbH
Dortmund, Germany

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