Feasibility of Low-Cost Micro-LED Manufacturing with Sputtering

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ABSTRACT

Feasibility of low-cost micro-LED manufacturing has been investigated using a newly developed epitaxial growth technique named PSD (pulsed sputtering deposition). We have fabricated RGB InGaN LEDs on various low-cost substrates such as glass or metal foils. We have also developed a cascaded LED structure which allows to simplify the fabrication process of the multi-color LED array.

1 Introduction

Conventional fabrication process of visible LEDs includes crystal growth of IIIV semiconductors such as InGaN by MOCVD (Metalorganic vapor phase epitaxy). However, MOCVD suffers from high growth temperature and low throughput. Recently, we have developed a new low temperature epitaxial growth technique called PSD (pulsed sputtering deposition) for fabrication of large area group III nitride devices. [1-3] It is known that pulsed supply of raw materials of IIIV semiconductors enhances surface migration of atoms on the growth surface and the use of it leads to dramatic reduction in growth temperatures, which is known as migration enhanced epitaxy (MEE). An additional advantage in the use of low temperature PSD nitride growth is suppression of interfacial reaction between nitrides and substrates. If we utilize low temperature epitaxial growth process such as PLD, we can possibly fabricate RGB LEDs on chemically vulnerable low-cost substrates such as metal foils, glass, or polymers. In this presentation, We will show advantages in the use of low temperature sputtering process for preparation of micro-LED displays.

2 Experimental Details

For the demonstration of sputtering preparation of micro-LEDs, nitride LED structures were grown by PSD in substrate temperatures range form room temperature (RT) to 700 °C. The basic properties of PSD-GaN were investigated with samples grown on sapphire or bulk GaN substrates. We have also developed fabrication process of cascaded device structures based on n^+/p^+ GaN tunneling contacts. Low-cost substrates such as Hf foils, amorphous SiO_2 plates, or polymer films were employed for demonstration of large area nitride devices.

3 Results and Discussion

We have grown lightly Si-doped GaN with [Si] of 2×10^{16} cm^{-3} and found that its RT electron mobility is as high as 1240 cm^2 V^{-1}s^{-1}, which was dominantly limited by polar optical phonon scattering. [4-7] We have also found that the doping efficiency of PSD n-type GaN is close to unity at electron concentrations up to 5.1×10^{20} cm^{-3} based on comparison of the results from SIMS and Hall effect measurements. In fact, a record low resistivity for n-type GaN of 0.16 mΩcm was achieved with an electron mobility of 100 cm^{2}V^{-1}s^{-1} at a carrier concentration of 3.9×10^{20} cm^{-3}. This experimental result shows that n-GaN can be used as a transparent conductive film with higher electron mobility compared to that for ITO (Indium Tin Oxide). This unusually high electron mobility of PSD heavily doped n-type GaN can be explained within a framework of conventional scattering theory by modifying a parameter related to nonparabolicity of the conduction band. Ge atoms also work as donor up to 1 x 10^{21} cm^{-3} in the GaN films, although they show slightly lower electron mobility at the same carrier concentrations compared with Si-doped GaN. These excellent electrical properties clearly show the remarkable advantage of growing high-quality n-type GaN by the low-temperature PSD method. In particular, high quality heavy-doped n-type GaN prepared by PSD helps to realize tunnel junctions and facilitates the fabrication process of micro-LED displays.

Growth of Mg-doped GaN films with low residual hydrogen concentration using a low-temperature PSD process is also an important technology for fabrication cascaded LEDs with tunneling contacts. [8] Our PSD growth system is inherently hydrogen-free, allowing us to obtain high-purity Mg-doped GaN films with residual hydrogen concentrations below 5×10^{16} cm^{-3} and to prepare tunneling contacts without high temperature annealing. In the SIMS depth profile for Mg atoms, no memory effect or serious dopant diffusion was seen. The as-deposited Mg-doped GaN films showed clear p-type conductivity without thermal activation. The GaN film doped with a low concentration of Mg (7.9×10^{17} cm^{-3}) grown by PSD has shown hole mobilities of 34 cm^2 V^{-1}s^{-1} at RT, which are among the highest values reported so far. These good results suggest that the irradiation of high energy particles and strong UV light from plasma may be helping for formation of GaN with less compensating defects. In fact, we have succeeded in operating electronic and optical devices such as HEMTs and LEDs using this PSD-GaN.

We have also found that PSD low temperature process is quite compatible with growth of high In concentration InGaN, which is necessary for fabrication long wavelength light emitting devices such as red LEDs. We have successfully fabricated RGB full color LEDs at maximum process temperature of 480 °C, which is important for fabrication of micro-LED displays. The reduction in process temperature with PSD allows us to utilize various large area low-cost substrates such as metal foils, flat glass, graphite films, and polymer films that have never been used for growth of nitride semiconductors so far due to their chemical vulnerability. These substrates are chemically and/or thermally vulnerable, which makes epitaxial growth of nitride devices on them with conventional MOCVD process at high temperatures quite difficult. One serious problem with the use of glass or polymer substrates lies in their amorphous nature. It is well known that growth of crystalline materials on the amorphous materials usually results in formation of low quality small grain poly materials. To solve this problem, we have tried to insert buffer layers such as multilayer graphene or AlN between GaN and substrates. We have found that the use of two-dimensional multi-layer graphene buffers dramatically improves the film quality of GaN on glass substrates and, in fact, we have succeeded in fabrication of RGB full color LEDs on glass substrate. [9] Since metal foils and polymer films are quite flexible, we can expect fabrication of low-cost flexible GaN devices on them. We have demonstrated operation of RGB LEDs on flexible metal foils. [10] We have also found that this kind of low temperature process is quite useful even for fabrication of nitride FETs, which can be used for switching devices for LEDs. We have demonstrated successful operation of nitride thin film transistors on various substrates such as polymer films. [11] We have also developed fabrication process for cascaded device structure with tunneling connections which allows to simplify the fabrication process of the multi-color LED array. [12] We found that the use of tunnel junctions work well and help to fabricate RGB-LEDs which operate separately for each color, in a single epitaxial growth process.

4 Conclusion

Feasibility of low-cost micro-LED manufacturing with sputtering process was investigated. All the experimental data indicate that the use of low temperature PSD process allows to fabricate nitride devices such as RGB LEDs and TFTs on various low-cost substrates, opening a new avenue for the low-cost realization of large-area integrated nitride micro-LED displays.

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