Cathodoluminescence of rare earth implanted AlInN

Citation: Applied Physics Letters 89, 131912 (2006); doi: 10.1063/1.2357343
View online: http://dx.doi.org/10.1063/1.2357343
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Cathodoluminescence of rare earth implanted AlInN

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(Received 25 April 2006; accepted 6 August 2006; published online 27 September 2006)

AlInN layers implanted with europium and erbium ions are systematically studied and compared with similarly implanted GaN. Cathodoluminescence from four series of annealed samples shows that the Eu/Er emissions from AlInN are considerably broader than those from GaN, while the peak positions only change slightly. The rate of increase of cathodoluminescence intensity with annealing temperature, up to 1300 °C, is analyzed for all four series. For Eu the increase exceeds 10× in both hosts. Although some decomposition is observed for annealing at 1200 °C, well above the growth temperature, AlInN is shown to be a surprisingly robust host for rare earth ions. © 2006 American Institute of Physics. [DOI: 10.1063/1.2357343]

In recent years, rare earth (RE) doped III-nitride semiconductors have attracted considerable interest because of their potential application in light emitting devices. GaN has been widely used as a RE host.1-3 AlGaN, with its wider band gap, has been shown to offer further advantages for RE doping.4 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3 AlInN materials offer potential as alternative wide gap, has been shown to offer further advantages for RE doping.3
temperatures and attributed to different Eu sites. All the Eu emission lines appear at roughly the same spectral positions for the two different hosts, with the strongest line showing only a very slight redshift for AlInN:Eu, compared to GaN:Eu. The main difference between the spectra is in the width of the emission lines. The full width at half maximum of the main peak increases from 2 nm for GaN to 5 nm for AlInN. Moreover, it is found that this broadening of the emission lines does not change with the annealing temperature, indicating that the local environment is not changed by the annealing. Hence, we conclude that it is alloy disorder that increases the width of Eu emission lines from AlInN. The local environment around Eu ions in the ternary alloy is less homogeneous than in the GaN host.

Figure 2 compares normalized room temperature CL spectra of Er implanted AlInN (below) and GaN (above) after both samples were annealed at 1100 °C. The emission at about 537 nm is assigned to the Er intra 4f-shell transition \( ^2H_{15/2}-^4I_{15/2} \), and that at 558 nm is assigned to \( ^4S_{3/2}-^4I_{15/2} \). Both of these emission lines are again composites ascribed to different Eu sites in the host. The AlInN:Er emission peaks, at 535.5 and 556.5 nm, are slightly blueshifted with respect to GaN:Er. As was the case for Eu implanted material, the Er related emission lines are broader for the AlInN host. The relative intensity of the spectral lines is clearly different in the two hosts. In addition, a broad yellow band is observed in AlInN:Er samples annealed at 1000 °C and above. This yellow band was also observed in some Er:GaN samples annealed at 1200 °C and above.

The variation with annealing temperature of the integrated CL intensities of the main RE emission lines is shown in Fig. 3. Figure 3(a) shows that the integrated CL intensity (610–635 nm) of AlInN:Eu increases by one order of magnitude as the annealing temperature is increased from 800 to 1200 °C. It is noticeable that the integrated CL intensity of AlInN:Eu is several times stronger than that of GaN:Eu except for 1300 °C annealing, although it must be remembered that a smaller portion of RE ions will be excited in the GaN as described above. Moreover, some of our as-implanted AlInN:Eu samples emit red light whereas GaN:Eu does not show any emission at all prior to annealing. Below 1300 °C, the integrated CL intensity increases exponentially with the annealing temperature \[ I_{CL} = I_0 \exp(T/T_0) \] with a characteristic temperature \( T_0 \) of 175 K. The CL intensity drops, however, when the annealing temperature is increased to 1300 °C.

For GaN:Eu samples, the CL also increases by one order of magnitude with increasing annealing temperature from 1000 to 1300 °C as reported in Ref. 7. However, the increase from 1200 to 1300 °C is below the trend of the data. SEM images show that the sample annealed at 1300 °C has a more seriously damaged surface than that annealed at lower temperature. This shows that the polycrystalline AlN cap, used here for GaN:Eu, is not as robust as the monocrystalline AlN cap used in previous studies. 8

Figure 3(b) shows that the integrated CL intensity (510–580 nm) of AlInN:Er samples increased by a factor of about 5 in the annealing temperature range from 700 to 1200 °C. With the exception of the as-implanted and 1300 °C annealed, the integrated CL intensity again increases exponentially with a characteristic temperature of 330 K. The drop of the CL intensity for the sample annealed at 1300 °C is also due to decomposition of the ternary alloy, as mentioned above. It is worth mentioning again that the
as-implanted AlInN:Er was found to emit green light whereas GaN:Er did not show any emission before annealing. The integrated CL intensity of AlInN:Er is very close to that of GaN:Er annealed at the same temperatures.

By way of comparison, the optimized integrated CL intensity of Eu luminescence from both hosts is similar and one order of magnitude stronger than Er luminescence in the same hosts, as shown in Fig. 3.

The SEM images of AlInN:Eu in Fig. 4 give clues to the rapid reduction in CL intensity of the AlInN sample annealed at 1300 °C. Figure 4(a) shows that AlInN:Eu annealed at 1000 °C has a very clear and homogeneous background with some pits distributed across the surface, which are also seen in the as-grown samples. When the anneal temperature is increased to 1200 °C, the background of the SEM image in Fig. 4(b) shows a mixture of dark and relatively light regions. The pits are larger with more contrast around their edges than those in Fig. 4(a). This suggests that some decomposition of the AlInN has occurred. However, the CL intensity of Eu emission still increases in spite of this deterioration of the sample. In Fig. 4(c), the SEM image of AlInN:Eu annealed at 1300 °C shows some extra features and the CL intensity in this sample is much reduced.

Wavelength dispersive x-ray (WDX) measurements of the composition of AlInN:Er reveal that the InN fraction is constant at 17% when the annealing temperature is ≤1100 °C. A slight decrease, to 16% InN, is observed for the sample annealed at 1200 °C. Severe decomposition with significant In loss (measured InN fraction down to 10% accompanied by an increased Ga signal) was observed for samples annealed at 1300 °C. The measured Al and N fractions remain the same in all samples. Thus, surprisingly, AlInN is able to withstand annealing at up to 400 °C above the growth temperature. Further studies, including spatially mapped CL and WDX, are in progress and may clarify these effects.

In summary, CL from four series of Eu and Er implanted AlInN and GaN samples, annealed in a wide temperature range from 700 to 1300 °C, has been investigated. The Eu and Er emission lines for AlInN hosts are broadened compared to GaN host and the peak positions are slightly changed. Variation of the CL intensity of the four series of samples with the annealing at different temperatures has been demonstrated and compared. The integrated RE CL intensity increases exponentially with annealing temperature in both cases, but does so faster for AlInN:Eu whose characteristic temperature is about half of that for AlInN:Er. CL from the AlInN host survives annealing at temperatures up to 400 °C above the growth temperature.

The authors are grateful for the support by the European Research Training Network project RENiBEI (Contract No. HPRN-CT-2001-00297) and the ORS award scheme, and would like to thank S. Ruffenach and O. Briot for providing AlN capped GaN wafers for implantation.