V-shaped defects connected to inversion domains in AlGaN layers

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Thick AlGaN layers and AlGaN/GaN superlattices have been grown on GaN using metalorganic chemical vapor deposition. Cross-sectional transmission electron microscopy has been used to show that V-shaped surface pits on these samples differ from similar features observed in the InGaN system. Inversion domains and segregated Al are found in the middle of each V pit, and superlattice layers are observed to follow the pit sidewalls.
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Superlattices and thick layers of AlGaN/GaN and InGaN are of interest for high power and optoelectronic applications. For example, AlGaN/GaN superlattices may be used in high electron mobility transistors in high temperature, high power devices.[1] Previous studies have shown that V-shaped surface defects (also known as inverted hexagonal pyramids) form on InGaN when the In concentration is high.[2,3] These defects contain excess In on their sidewalls[3] and are always connected to dislocations in the InGaN.[4] Recently, InGaN layers have been shown to end abruptly at such defects.[5] Although similar pits have been observed in AlGaN,[6,7] they have not been studied in detail. Here, we describe the formation of regular V-shaped defects in both thick AlGaN layers and AlGaN/GaN superlattices. Differences are noted between the InGaN and AlGaN systems, and inversion domains are shown to play an important role in defect formation in AlGaN. Such inversion domains are often found in GaN layers grown on sapphire, in addition to other defects such as dislocations and stacking faults.[8–11] The polarity of the GaN is reversed at the domains,[12] which are usually narrow and traverse from the GaN/sapphire interface to the top surface of the sample. Similar domains have been shown to play a fundamental role in the formation of large pyramids that grow from the surface of GaN.[13]

Thick AlGaN layers and superlattices of AlGaN/GaN were grown on thick layers of GaN at 1150 °C by metalorganic chemical vapor deposition. (0001) oriented sapphire was always used as the substrate. Nitridation of the sapphire was not used. Initially, a thin GaN buffer layer was deposited at 500 °C, followed by a thick GaN layer grown at elevated temperature using a two-step growth method.[14,15] Layers were grown with 6 and 8 at. % Al, and the AlGaN/GaN superlattices had periodicities of 9, 20, and 30 nm. The microstructure of the layers was investigated by transmission electron microscopy (TEM). Cross sections were prepared by embedding small pieces of the samples face to face in a 3 mm diameter Ti grid,[16] followed by grinding to a thickness of 50 μm and Ar^+ ion milling until perforation. Conventional microscopy was carried out in a Philips CM20 TEM at 200 kV, high-resolution images were taken on a JEOL JEM-4000EX TEM at 400 kV, and chemical maps were obtained on a JEOL JEM-3000F at 300 kV.

Thick (1.2 μm) AlGaN layers showed pits at the sample surface that were superficially similar to those observed in

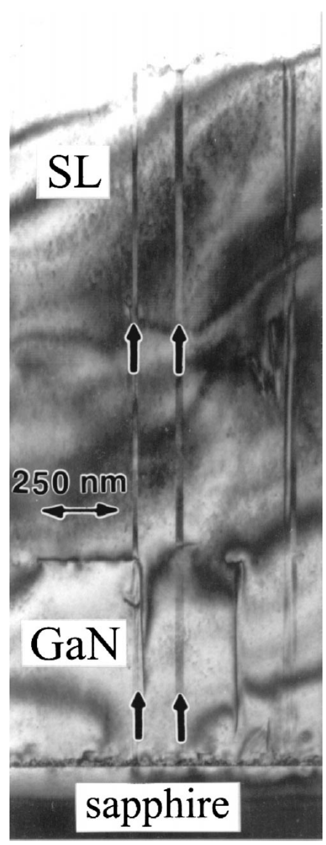

FIG. 1. Cross section of the sample with a superlattice in the top region. Arrows mark two inversion domains which originate in the GaN buffer layer and traverse through the whole layer to the top surface.

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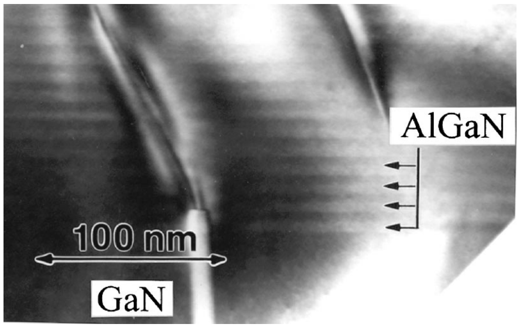

FIG. 2. High magnification image of AlGaN/GaN superlattice grown on GaN.

InGaN.[2,3] The layer surface was flat between the pits,[17] in good agreement with the results of Mazur *et al.*,[7] who found that V-shaped pits in thin AlGaN layers grown on GaN were associated with threading dislocations. Contrary to their findings for AlGaN, as well as to those for InGaN, the pits examined here are connected to inversion domains.[17]

Figure 1 shows an image of a cross-sectional sample of an AlGaN/GaN superlattice (SL) that has a periodicity of 9 nm, a total thickness of $\sim 1\ \mu$m, and an Al content in the AlGaN layers of 6 at. %. V-shaped pits are present on the surface. Arrows mark two inversion domains (Fig. 1) which originate in the GaN buffer layer and traverse through the whole layer to the top surface. Figure 2 shows the SL layers at high magnification, with the AlGaN marked by arrows. Dislocations are present in the SL region, and one of the threading dislocations (visible on the left side of Fig. 2) has traversed into the SL from the thick GaN. The AlGaN/GaN interfaces are sharp and parallel to the surface. High-resolution images (e.g., Fig. 3) show that the pits are connected to inversion domains. (Figure 3 shows two overlapping pits instead of the more common discrete pits.) This configuration was observed in many pits and also in the thick layers. Both energy-selected imaging and energy dispersive x-ray mapping (Fig. 4) confirmed the presence of segregated

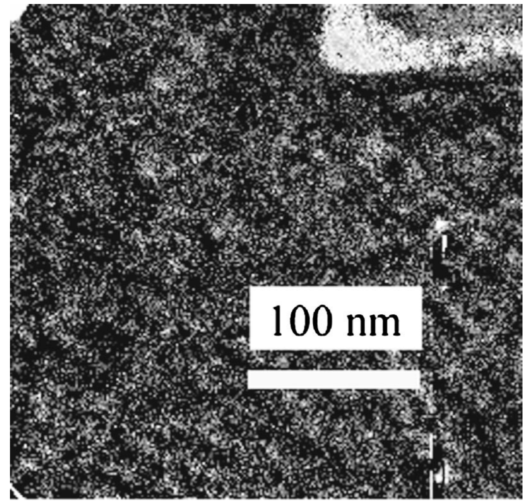

FIG. 4. Chemical map showing Al at a pit on the surface of an AlGaN/GaN superlattice.

Al within each pit. Bright field images (Fig. 5) show that the superlattice layers follow the sidewall of each pit, in contrast to the InGaN system in which equivalent layers end sharply.[5] The pits are most likely to result from the slower growth rate of the layers above each inversion domain than above the matrix, and this slower growth rate may in turn result from the fact that the layers form below the segregated Al (Fig. 4). In contrast, inversion domains in GaN can grow faster than the GaN matrix around them, to form pyramids on the sample surface.[9,11,13] Inverted pyramids are never observed in GaN.

The present study has shown that in the AlGaN/GaN system inversion domains originate from the low temperature GaN buffer layer (adjacent to the sapphire) and traverse the SL to emerge at the top surface of the sample in the

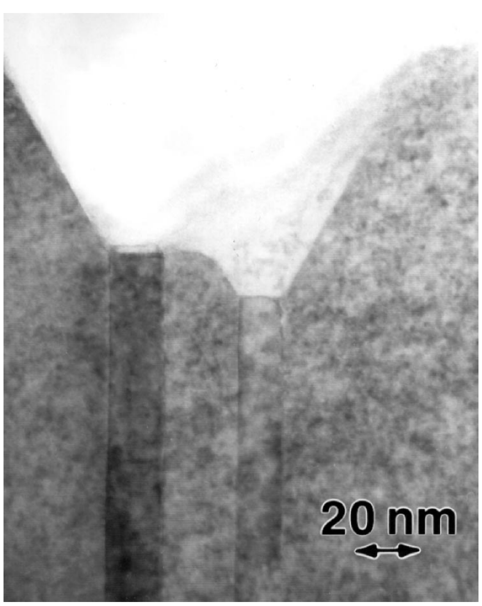

FIG. 3. High-resolution image of a pit formed on the surface of an AlGaN/GaN superlattice.

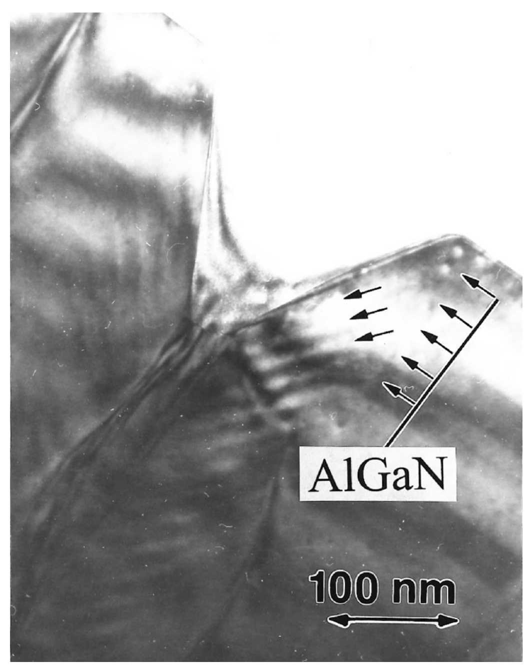

FIG. 5. AlGaN/GaN superlattice (with a periodicity of 30 nm) bent around a V pit. The image is taken at two beam condition to show the bent layers clearly, while the walls of the inversion domain are not sharp at this tilt.

middle of a V pit (see the two inversion domains marked by arrows in Fig. 1). The results highlight the fact that the suppression of inversion domains in the GaN layer must be addressed in order to decrease the defect density in the overlying layers. Further work is needed to investigate systematically the pit formation in the thick layers and in the superlattices taking into account the built-in strain as well.

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[1] M. S. Shur and M. A. Khan, MRS Bull. **22**, 44 (1997).
[2] P. Li, S.-j. Chua, M. Hao, W. Wang, X. Zhang, T. Sugahara, and S. Sakai, MRS Internet J. Nitride Semicond. Res. **5S1**, W11.31 (2000).
[3] J. E. Northrup, L. T. Romano, and J. Neugebauer, Appl. Phys. Lett. **74**, 2319 (1999).
[4] X. H. Wu, C. R. Elsass, A. Abare, M. Mack, S. Keller, P. M. Petroff, S. P. DenBaars, J. S. Speck, and S. J. Rosner, Appl. Phys. Lett. **72**, 692 (1998).
[5] N. Sharma, P. Thomas, D. Tricker, and C. Humphreys, Appl. Phys. Lett. **77**, 1274 (2000).
[6] M. D. Bremser, W. G. Perry, T. Zheleva, N. V. Edwards, Q. H. Ham, N. Parikh, D. E. Aspens, and R. F. Davis, MRS Internet J. Nitride Semicond. Res. **1**, 8 (1996).
[7] J. H. Mazur, M. Benamara, Z. Liliental-Weber, W. Swider, J. Washburn, C. J. Eiting, and R. D. Dupuis, MRS Internet J. Nitride Semicond. Res. **5S1**, W3.77 (2000).
[8] L. T. Romano and J. E. Northrup, Mater. Res. Soc. Symp. Proc. **449**, 423 (1997).
[9] B. Pécz, M. A. di Forte-Poisson, F. Huet, G. Radnóczi, L. Tóth, V. Papaioannou, and J. Stoemenos, J. Appl. Phys. **86**, 6059 (1999).
[10] W. Qian, M. Skowronski, and G. S. Rohrer, Mater. Res. Soc. Symp. Proc. **423**, 475 (1996).
[11] J-L. Rouviére, M. Arlery, A. Bourret, R. Niebuhr, and K. Bachem, Inst. Phys. Conf. Ser. **146**, 285 (1995).
[12] K. Dovidenko, S. Oktyabrsky, J. Narayan, and M. Razeghi, MRS Internet J. Nitride Semicond. Res. **4S1**, G6.46 (1999).
[13] J. L. Weyher, P. D. Brown, ARA. Zauner, S. Müller, C. B. Boothroyd, D. T. Foord, P. R. Hageman, C. J. Humphreys, P. K. Larsen, I. Grzegory, and S. Porowski, J. Cryst. Growth **204**, 419 (1999).
[14] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, Appl. Phys. Lett. **48**, 353 (1986).
[15] S. Nakamura, Jpn. J. Appl. Phys., Part 2 **30**, L1705 (1991).
[16] Á. Barna, G. Radnóczi, and B. Pécz, in *Handbook of Microscopy*, edited by S. Amelinckx, D. van Dyck, J. van Landuyt, and G. van Tendelo (VCH, 1997), Vol. 3, Chap. II/3, p. 751.
[17] Zs. Makkai, B. Pécz, M. A. di Forte-Poisson, and F. Huet, Mater. Sci. Forum **353–356**, 803 (2000).