DETERMINATION OF THE THICKNESS AND THE LATTICE DISTORTIONS IN $Al_{0.14}Ga_{0.86}N$ AND GaN LAYERS IN STRAINED-LAYER SUPERLATTICE CLADDING IN GaN-BASED VIOLET LASER DIODES. Miran Čeh(1), Sašo Šturm(1), Makoto Shiojiri(2), Jung-Tsung Hsu(3), Jer-Ren Yang(4) and Hiroshi Saijo(5). (1)Department for Nanostructured Materials, Jožef Stefan Institute, Ljubljana, Slovenia; (2)Kyoto Institute of Technology, Kyoto, Japan; (3)Opto-Electronics and Systems Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan 310, Republic of China; (4)Institute of Materials Science and Engineering, National Taiwan University, Taipei, Taiwan 106, Republic of China; (5)Department of Electronics and Information Science, Kyoto Institute of Technology, Kyoto 606-8585, Japan. Email: miran.ceh@ijs.si

The lifetime of violet laser diodes (LDs) containing multiple quantum wells (MQWs) InGaN/GaN has been improved to more than 10,000 h. This long lifetime was achieved by epitaxially lateral overgrowth of the GaN contact layer on the sapphire substrate [1] and the cladding of the AlGaN/GaN strained-layer superlattices (SLSs) [2]. There have been very few structural investigations of the AlGaN/GaN SLS cladding layers although their nanostructure greatly influences the final properties of the laser. High-resolution transmission electron microscopy (HRTEM) has proved to be an unsuitable analytical method to study the SLSs' structure since Al incorporation on Ga sites in GaN introduces only negligible structural changes. This is why in our study we applied HAADF-STEM imaging to resolve the different layers in the SLS's superstructure. The final aim of our work was to determine the thickness of the individual AlGaN and GaN layers comprising the SLS and to measure possible local distortions of the lattice structures.

A SLS cladding composed of 200 coupled layers of n-$Al_{0.14}Ga_{0.86}N$ and n-GaN was grown directly on an n-GaN:Si layer deposited on the (0001) sapphire substrate by metal-organic vapor-phase epitaxy. The nominal thickness of each layer was 3 nm. The cross-section samples for STEM were prepared by ion-milling. HAADF-STEM and HRTEM observations were performed in a JEM-2010F TEM/STEM. All the HAADF-STEM images were recorded with a 10-mrad semi-angle of the probe and an ADF detector range from 100 to 220 mrad. Figure 1 shows an experimental HAADF-STEM image of the whole n-type cladding region on the n-GaN:Si layer. Four hundred individual layers of the $Al_{0.14}Ga_{0.86}N$ and GaN are clearly resolved in the HAADF-STEM image. The $Al_{0.14}Ga_{0.86}N$ layers were identified as dark bands, while the GaN layers were identified as bright bands. Such a difference in the intensities between the $Al_{0.14}Ga_{0.86}N$ and GaN layers was also confirmed by HAADF-STEM image simulations. In order to determine the width of the $Al_{0.14}Ga_{0.86}N$ and GaN layers in the SLS we used an average filtering technique approach of high-magnification HAADF-STEM image of the SLS structure (Figure 2). First, a low-pass mask filter was applied to the fast Fourier transform (FFT) image of the original image (Figure 2a). The low-frequency intensity HAADF-STEM image (Figure 2b) was then obtained by an inverse FFT (IFFT) of the filtered image. The subtraction of a low-passed filtered image from the original raw HAADF-STEM image produced a normalized HAADF-STEM image without low spatial frequencies (Figure 2c). The real-space averaged image was finally obtained by adding up all the intensity line profiles perpendicular to the $Al_{0.14}Ga_{0.86}N$ and GaN layers, which were divided by the number of the intensity line profiles (Figure 2d). The full-width-at-half-maximum (FWHM) criterion was chosen to determine the width of the dark and bright layers. The average thickness of the $Al_{0.14}Ga_{0.86}N$ and GaN layers was determined to be 2.24 ± 0.09 nm and 2.34 ± 0.15 nm, respectively. Since the thickness of individual $Al_{0.14}Ga_{0.86}N$ and GaN layers is quite similar and the standard deviation of the thickness is small, it is reasonable to assume that the number of atom planes comprising each individual $Al_{0.14}Ga_{0.86}N$ and GaN layer in the [0001] direction is the same. A comparison of the measured $Al_{0.14}Ga_{0.86}N$ and GaN layer thickness with the lattice parameters of GaN indicates that each $Al_{0.14}Ga_{0.86}N$ and GaN layer is comprised of nine atom planes. The lattice distortions were measured from high-resolution experimental images (Figure 3). Accordingly, the real spacing between the (0002) $Al_{0.14}Ga_{0.86}N$ atom planes was

measured to be 0.249 nm (c= 0.498 nm) and the spacing between the (0002) GaN planes was measured to be 0.260 nm (c=0.520 nm). If we compare the measured c values with the c value for pure GaN (c= 0.519 nm) we can conclude that the lattice of the $Al_{0.14}Ga_{0.86}N$ crystal in the SLS shrinks by approximately 4 % along the c-axis, while the GaN lattice in the SLS layers undergoes no change along the c axis.

References

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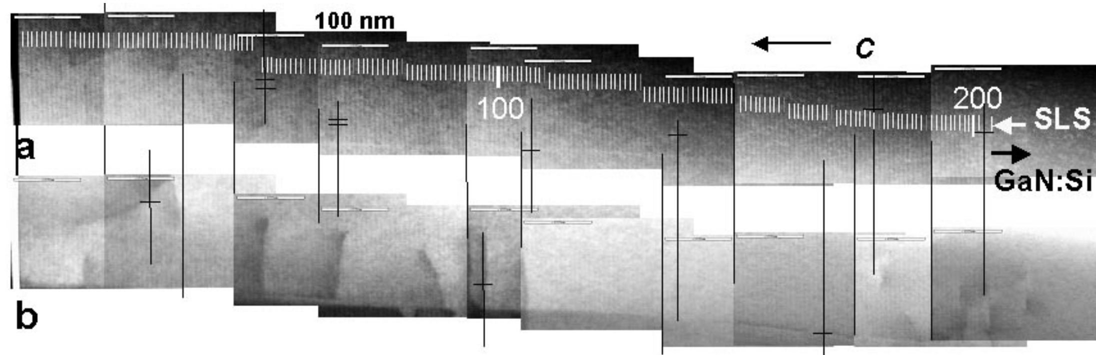

Figure 1. (a) Experimental HAADF-STEM image of the SLS cladding layer. About 200 couples of $Al_{0.14}Ga_{0.86}N$ (dark bands) and GaN layers (bright bands) are clearly resolved. (b) BF-STEM image of the same area. Dislocations are visible in strong diffraction contrast.

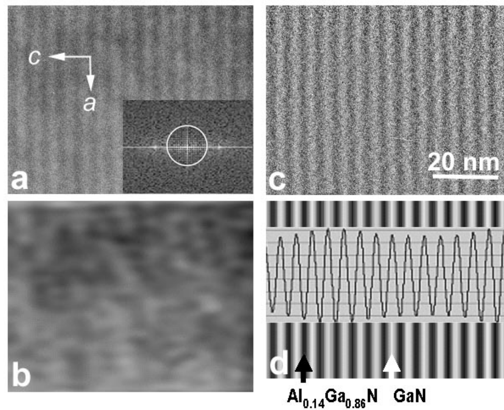

Figure 2. (a) Experimental HAADF-STEM image of the SLS cladding. The dark bands are $Al_{0.14}Ga_{0.86}N$ layers and the bright bands are GaN layers. Inset is the FFT image. (b) Low-frequency HAADF-STEM image reconstructed using the low-pass mask filter. (c) Normalized HAADF-STEM image by subtracting image b from image a. (d) Averaged, filtered, normalized HAADF-STEM image and the corresponding intensity line profile. The thickness of the layers was determined according to the FWHM criterion, from the line profile.

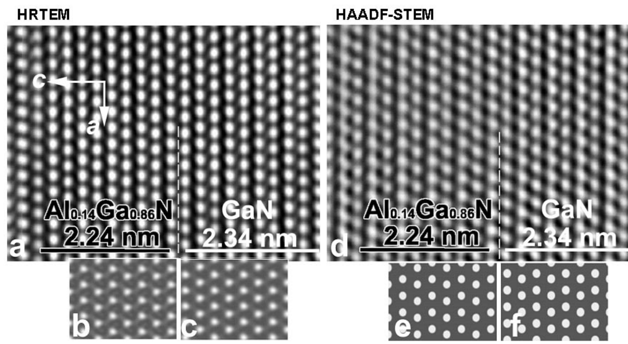

Figure 3. (a) Experimental HRTEM image, noise-filtering processed, of $Al_{0.14}Ga_{0.86}N$ and GaN layers in the SLS cladding. (b, c) Calculated images of $Al_{0.14}Ga_{0.86}N$ and GaN crystals 30 nm thick at Δf=-15 nm. (d) Experimental HAADF-STEM image, noise-filtering processed, of the $Al_{0.14}Ga_{0.86}N$ and GaN layers. (e, f) Calculated images of $Al_{0.14}Ga_{0.86}N$ and GaN crystals 30 nm thick at Δf=-20 nm, respectively. The dotted lines are the interface between the AlGaN and GaN.