

Alternating Be and C doping for strain compensated GaAs/AlAs distributed Bragg reflectors

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We demonstrate a new type of strain compensated, p-type distributed Bragg reflector (DBR) using alternating doping of Be in GaAs and C in AlAs with carbon concentrations as high as $2 \times 10^{20} \text{ cm}^{-3}$. These DBRs exhibit simultaneously a high crystalline quality, an excellent surface morphology, and no misfit dislocations, which cannot be achieved in undoped or Be-doped DBRs. The absolute optical reflectivity is as high as in the undoped DBR. The differential resistance of these structures is comparable to best reported values in Be-doped DBRs. © 1997 American Institute of Physics. [S0003-6951(97)04116-8]

Distributed Bragg reflectors (DBRs) are an essential part of complex optoelectronic devices such as vertical cavity surface emitting lasers (VCSEL). In order to achieve high optical reflectivity, the total thickness of the DBR amounts to several μm , which, altogether with the lattice mismatch, results in a relaxation of the lattice by the formation of misfit dislocations degrading the structure.¹ In order to reduce the electrical resistance, the DBR is heavily doped, although this may result in a reduction of the optical reflectivity due to free carrier absorption. A balance between the optimum structural, electrical, and optical properties is thus desirable. For GaAs/AlAs p-type DBRs the most commonly used dopant is Be, although it is well known that the out-diffusion of Be in AlAs layers represents a serious drawback of this dopant-host material combination.² In this letter, we demonstrate that the alternating doping of the DBRs with Be in the GaAs layers and with C in the AlAs layers produces high quality, strain compensated p-type DBRs with excellent structural, optical, and electrical characteristics.

Highly doped GaAs/AlAs DBRs were grown by solid source molecular beam epitaxy (MBE) on (001) GaAs substrates. The DBRs consist of 20 pairs of 82.7 nm AlAs and 69.6 nm GaAs for an operation wavelength of 980 nm. For the alternating doping the C concentration in AlAs is $2 \times 10^{20} \text{ cm}^{-3}$, while the Be concentration in GaAs is $2 \times 10^{18} \text{ cm}^{-3}$. The substrate temperature was adjusted to 505 °C and the beam equivalent pressure (BEP) ratio of As₄ to Ga for GaAs to 15. The growth rate was 1 $\mu\text{m}/\text{h}$ for GaAs and 0.2 $\mu\text{m}/\text{h}$ for AlAs. We used a resistively heated graphite filament as the carbon source. It was operated near its maximum power of about 600 W. The x-ray diffraction (XRD) measurements were performed with a double- and a triple-crystal diffractometer (BEDE D3) using Cu K α_1 radiation. The x-ray topographs were obtained with a double-crystal camera equipped with a curvable Si monochromator.³ The surface morphology was studied by atomic force microscopy (AFM) in the constant force contact mode recorded over areas of $3 \times 3 \mu\text{m}^2$ and $10 \times 10 \mu\text{m}^2$. The wavelength dependence of the optical reflectivity was detected in a conventional setup, the absolute reflectivity was determined by ellipsometry. The differential resistance was measured on 67 and 20 μm diam mesas structured by reactive ion etching.

In previous publications we showed that very high carbon doping can be used to obtain strain compensated, p-type GaAs/AlAs DBRs.^{4,5} The strain compensation resulted in a large increase of the critical thickness⁶ of the DBR with respect to the undoped or Be-doped case.⁷ The high carbon doping also results in a low differential resistance. However, at the same time it induces a certain degradation of the surface morphology of the bulk structural quality and, consequently, of the absolute reflectivity compared to undoped DBRs. We also observed a much higher defect density in GaAs:C than in AlAs:C. Therefore, we propose the synthesis of strain compensated, highly p-doped DBRs by doping GaAs with Be and AlAs with carbon. In this way we take advantage of the strain compensation produced by the high C doping of AlAs. At the same time the problems associated with both the out-diffusion of Be in AlAs and the degradation of the quality produced by the high carbon doping of GaAs are avoided. In contrast to Be, carbon has a negligible diffusivity in GaAs and AlAs layers.^{8,9} No structural degradation associated with the Be doping of GaAs was observed at typical concentrations. We compare this new type of DBR with GaAs:C/AlAs:C DBRs of the same thickness.

After growth, both types of DBRs were characterized by XRD. Diffraction curves near the (004) GaAs substrate reflection are shown in Fig. 1. The upper curve corresponds to the GaAs:C/AlAs:C DBR. Due to the contraction of the lattice produced by the carbon doping,¹⁰ the zeroth order peak of the DBR overlaps with the GaAs substrate peak, which implies that strain compensation has been achieved (the perpendicular strain is less than 1×10^{-4}). In this case the carbon concentration on lattice sites is $1.6 \times 10^{19} \text{ cm}^{-3}$ in GaAs and $1.6 \times 10^{20} \text{ cm}^{-3}$ in AlAs. Therefore, 90% of the strain compensation is produced by the doping of the AlAs layers, while only the remaining 10% is obtained by the doping of the GaAs layers. Other ratios of carbon concentrations in GaAs and AlAs were also tested, but usually resulted in a reduced quality. In single layers we had previously found that the concentration of carbon in the AlAs lattice can be as high as $5 \times 10^{20} \text{ cm}^{-3}$ without any observable structural degradation of the layers.¹¹ This concentration is more than a factor of 2 higher than the concentration required to compensate the strain of AlAs on GaAs. However, the carbon concentration on lattice sites, which can be achieved in GaAs without degradation of the structural quality, is about a factor

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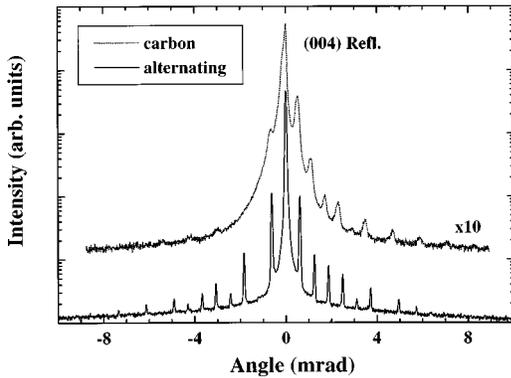


FIG. 1. Experimental diffraction curves of a 20 pair GaAs:C/AlAs:C DBR and a 20 pair GaAs:Be/AlAs:C DBR measured near the GaAs (004) reflection. The 0th-order peak of the DBR overlaps perfectly with the GaAs substrate peak indicating a complete strain compensation. The upper curve has been multiplied by a factor of 10.

of 10 smaller. Therefore, the strain compensation can be more effectively obtained by increasing the carbon concentration in AlAs rather than in GaAs.

In the case of doping by C alone and for the carbon concentration required to obtain the strain compensation, a pronounced broadening of all superstructure peaks was repeatedly observed with a full width at half maximum (FWHM) of the satellite peaks of $190 \mu\text{rad}$ (39 arcsec). This broadening can be produced by several factors, among them the strain variation along the growth direction caused, e.g., by oscillations of the carbon cell power during the growth. Another possible reason for this broadening is a structural degradation of the layers. In the lower part of Fig. 1 the diffraction curve for a GaAs:Be/AlAs:C DBR is shown. In this case, an even better overlap of the DBR's zeroth order with the substrate peak is obtained. This implies that the average strain of the DBR with respect to the GaAs substrate lattice is negligible. Much sharper satellite peaks with a FWHM of $60 \mu\text{rad}$ (12 arcsec) are also evident. Moreover, these satellites are observed up to the 10th order. This means that the GaAs:Be/AlAs:C DBR is of a very high structural quality. The comparison between the two curves in Fig. 1 leads to the conclusion that the degradation of the structural quality is due to the high carbon doping in GaAs.

In order to prove this conclusion, we performed reciprocal space mapping of both DBRs. These area scans are measured near the reciprocal lattice point $\mathbf{G}=(004)$ in the diffraction plane perpendicular to the sample surface. The vector \mathbf{q} is the difference between the scattering vector \mathbf{Q} and the reciprocal lattice vector \mathbf{G} . The terms (q_x, q_z) are the components of \mathbf{q} parallel and perpendicular to the surface. These area scans are plotted in Fig. 2. The rocking curves shown in Fig. 1 correspond to a scan along q_z integrated over a certain range of q_x . The diffuse scattering visible in a large area around $\mathbf{G}=(004)$ in Fig. 2(a) indicates that there is a degradation of the structural quality in the GaAs:C/AlAs:C DBR. The broadening in the q_x as well as the q_z direction is probably caused by microdefects due to carbon precipitation. For a variation of the strain along the growth direction (parallel to q_z) without such structural degradation, there would be no broadening in the q_x direction. This is actually found for the GaAs:Be/AlAs:C DBR shown in Fig. 2(b), where a

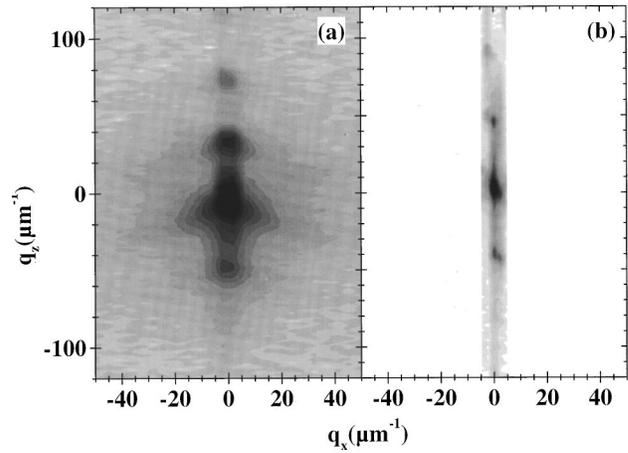


FIG. 2. Reciprocal space mapping of the GaAs:C/AlAs:C DBR (a) and of the GaAs:Be/AlAs:C DBR (b) shown in Fig. 1. A broadening of the peaks is clearly observed in (a), both in the q_x and q_z directions, thus indicating a structural degradation due to the high carbon doping of GaAs.

limited area scan with a higher angular resolution is shown in order to resolve the sharp superstructure peaks. A low resolution scan over the same area as in Fig. 2(a) verified that the scattering intensity in Fig. 2(b) for $|q_x| > 5$ is lower than the noise level. In order to prove the absence of any misfit dislocations, x-ray topographs have been recorded. Neither of the two investigated structures showed any signature of the presence of misfit dislocations.

The surface morphology as detected by AFM images is shown in Fig. 3 for the C-doped DBR in (a) and the alternately doped DBR in (b). The peak to valley values of the surface roughness are 25 nm for the carbon doped DBR in Fig. 3(a) and 6 nm for the alternately doped DBR in Fig. 3(b), while the root mean square (rms) values are 3 and 1 nm, respectively. There is a very good agreement between the AFM and the XRD measurements in the sense that the alternating Be and C doping preserves the excellent surface morphology, interface perfection, and bulk structural quality.

The optical reflectivity was measured in a standard configuration in order to determine the stop band position, which was repeatedly in good agreement with the intended position, i.e., centered at 980 nm. The absolute reflectivity was measured by ellipsometry. The absolute reflectivity for the carbon doped DBR is 98%, while for the alternately doped DBR it is 99%. We attribute this increase of the absolute reflectivity to the higher structural quality of the alternately doped DBR as shown by XRD and AFM. Furthermore, its reflectivity is identical to the absolute reflectivity in undoped DBRs of the same thickness. This demonstrates that even at this high level of doping ($2 \times 10^{20} \text{ cm}^{-3}$) intraband absorption of free carriers does not reduce the reflectivity.

In order to determine the resistance, 67 and 20 μm diam mesas have been produced by reactive ion etching. The contacts were made of Ti/Pt/Au for the DBR and AuGe/Ni/Au(Ge) for the substrate. For 67 μm diam mesas of the GaAs:C/AlAs:C DBR and for 20 μm diam mesas of the GaAs:Be/AlAs:C DBR the differential resistance determined in the range of the I - V characteristic with ohmic behavior is 3 and 14 Ω , respectively. Normalizing the resistance to the area of the mesa, we obtain values of 1.1×10^{-4} and 4.4

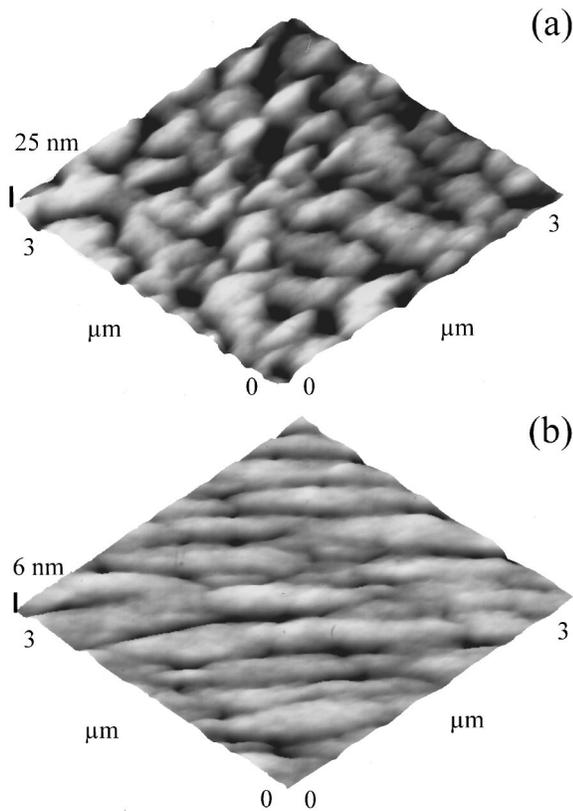


FIG. 3. AFM images of the GaAs:C/AlAs:C DBR (a) and of the GaAs:Be/AlAs:C DBR (b) of Fig. 1. The gray scale covers the peak to valley value of 25 nm for (a) and 6 nm for (b). Each image corresponds to an area of $3 \times 3 \mu\text{m}^2$.

$\times 10^{-5} \Omega \text{ cm}^2$, which clearly show an improvement of the alternately doped DBR with respect to the C-doped DBR. These values are in the range of the best data reported in the literature.¹²⁻¹⁴

In summary, strain compensated GaAs/AlAs DBRs are realized with C doping and alternating doping of Be and C using solid source MBE with a graphite filament as the car-

bon source. X-ray investigations demonstrate that alternating doping of the DBR results in a much higher structural quality than C doping alone. AFM measurements show the improvement of the surface morphology of the alternately doped DBR with respect to the C-doped DBR. The absolute reflectivity of the GaAs:Be/AlAs:C DBR is found to be as high as in the undoped DBR. The differential resistance is comparable to best values found in the literature.

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