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# MOVPE growth of long wavelength AlGaAsSb/InP Bragg mirrors

O. Ostinelli, G. Almuneau, M. Ebnoether, E. Gini, M. Haiml, W. Bächtold

Monolithic Distributed Bragg reflectors (DBRs) consisting of AlGaAsSb/InP quarter-wave multilayer were grown by Metal-Organic Vapor-Phase Epitaxy (MOVPE) on InP substrates. The quality of antimonide MOVPE grown material has been optimized to achieve highly reflective, defect-free, DBR stacks. With 21 AlGaAsSb/InP periods, reflectivity up to 97% at 1.59 $\mu\text{m}$  was measured.

*Introduction:* High speed, highly parallel, short distance, fiber optics links at the wavelength of 1.3-1.55 $\mu\text{m}$  are based on arrays of fast, current modulated laser diodes as light sources. Besides speeds of up to 20Gb/s, low operation voltage and low drive current for laser array structures, requirements for these lasers include cost effective fabrication techniques, possibility of simple on-wafer testing, and simple fiber coupling scheme. Vertical Cavity Surface Emitting Laser Diodes (VCSELs) are ideal candidates for this application. With the aim of fabricating monolithically 1.55 $\mu\text{m}$  VCSELs based on InP, the lattice-matched quaternary AlGaAsSb is used to form highly reflective DBRs, thanks to its large refractive index contrast within the 1.3-1.55 $\mu\text{m}$  wavelength band [1,2]. Previously, high performances VCSELs grown by Molecular Beam Epitaxy (MBE) have been demonstrated at both 1.3 and 1.55 $\mu\text{m}$  [3,4], but to date no report has been published concerning Sb-based DBRs using MOVPE. This letter proposes the implementation of a MOVPE, epitaxial growth technique, which is most widely used in the semiconductor industry, to fabricate AlGaAsSb-based DBRs. We present in this letter results obtained for DBRs composed of 10, 12 and 21 AlGaAsSb/InP pairs grown for the first time, to our knowledge, by MOVPE.

*Growth conditions:* All the structures were grown by MOVPE in a horizontal reactor heated by halogen lamps. The source precursors were trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminum (TMAI), phosphine (PH<sub>3</sub>), arsine (AsH<sub>3</sub>) and trimethylantimony (TMSb). Real-time *in-situ* reflectance anisotropy spectroscopy (RAS) was used to measure the growth rate in the reactor.

The epitaxial layers were grown on 2-inch (100) vicinal InP substrates, with 2° miscut angle towards [110], at a reactor pressure of 100mbar, under H<sub>2</sub> atmosphere. The substrate was placed on a graphite disc rotating on a graphite susceptor. For AlGaAsSb and InP the growth temperature was set to 565°C and 600°C respectively. The quaternary AlGaAsSb was grown with a ratio of group-V vs group-III precursors gas flows (V/III ratio) of 0.5. This low value is due to both the weak TMAI decomposition efficiency and the growth conditions with minimized V/III ratio on the growing surface.

*Experiments:* In order to study the growth properties of the antimony material system, GaAsSb and afterwards AlGaAsSb layers were grown. The formation of undesirable phases between In, Ga, Al, Sb, As and P at usual growth temperature (~600°C), and the wide miscibility gap of AlGaAsSb, makes the growth of these III-V compounds critical. These aspects affect directly the stability and the reproducibility of both the material quality and the composition. As a consequence, under non-optimized conditions, high defect density and crosshatching appear on the wafer surface. The gas switching sequences at the interfaces was carefully controlled, in order to avoid cross-diffusion of the atoms from the InP binary into the quaternary, and *vice-versa*. Additionally, parameters such as growth temperature, V/III ratio, reactor pressure, total flow, play a fundamental role in the growth process [5]. Each of these must be carefully tuned to achieve stable, homogeneous and reproducible growth of thick DBR multilayers. The

alloys composition was determined by correlating photoluminescence spectra (PL) and high-resolution x-ray diffraction (HRXRD) measurements.

The band gap energy of GaAsSb lattice-matched on InP is around 0.76eV. In order to shift the fundamental absorption edge far below 1.55 $\mu$ m, the addition of Al is required [1]. For this reason AlGaAsSb was grown with the TMAI precursor. However, the efficiency of the Al incorporation into the bulk is strongly limited by the low decomposition of the TMAI precursors below 600°C [6]. By reducing the TMGa flow, an Al concentration of 4-5% has nevertheless been achieved.

The required DBR reflectivity in a VCSEL exceeds 99% around the lasing wavelength, to ensure low threshold current, good wall-plug efficiency and low heat generation for the device. The calculated reflectivity of a 21 periods  $\text{Al}_{0.04}\text{Ga}_{0.96}\text{AsSb/InP}$  DBR, with the refractive indices taken in ref. [7] and neglecting the residual losses, is about 99.6% at 1.55 $\mu$ m.

Three DBR structures composed of 10, 12, 21 AlGaAsSb/InP quarter-wave pairs were grown. The stability of the surface during the bulk and the heterointerfaces growth was monitored by RAS. The measured thicknesses of AlGaAsSb and InP layers were 108nm and 120nm, respectively. For the 12 and 21 periods DBRs, the top layer consists of a  $\lambda/2$  InP layer to avoid Fabry-Pérot cavity deep in the center of the high reflectivity stop-band. The reflectivity of these two DBRs was measured with a spectrometer (Carry), calibrated with three dielectric DBRs to cover the range from 1 to 1.65 $\mu$ m. Residual losses caused by scattering and other mechanisms were accurately determined in the samples.

*Results:* In this section we essentially discuss the results obtained from the measurements of the 12 and 21 pairs DBR.

The growth rate for the quaternary and binary material was 0.9 and 1.6 $\mu\text{m}/\text{h}$ , respectively. These growth rates are essentially limited by the growth system and by the low decomposition at low temperature of the TMGa and TMAI precursors. The PL over the 2-inch wafer and the flatness of the interfaces revealed by transmission electron microscopy and HRXRD indicate the good quality of the epilayers. On the mirror-like surface, 40-50 defects per  $\text{cm}^2$  with a 50 $\mu\text{m}$ -elongated shape were observed under the optical microscope. Between the defects, large areas extend with good surface quality. The Secondary Ion Mass Spectrometry (SIMS) measurement of the antimony composition profile, represented in Fig. 1, shows that a variable amount of Sb is incorporated in the different InP layers. It shows also that the periodical growth of InP is not perfectly reproducible through the DBR. This was already observed by RAS measurement. The contamination of InP with Sb is a memory effect caused by the AlGaAsSb growth, which may lead to the relaxation of the epilayer, and hence surface crosshatch, for Sb concentrations above 3-4%. Elsewhere the concentrations of Al, Ga, As and Sb are more constant in the AlGaAsSb layers.

Fig. 2 shows the DBRs' absolute reflectivity spectra. The stop band is centered about 1.55 $\mu\text{m}$  and has a width greater than 170nm, due to the high refractive index contrast. The reflectivities at 1.55 $\mu\text{m}$  for the 12 and 21 pairs DBRs are 94 and 95%, respectively. The reflectivity of the thicker structure tends to increase with wavelength within the stop-band, up to the maximum of 97% at 1.59 $\mu\text{m}$ . However the reflectivity never reaches the theoretical 99% derived from calculation. The sloped stop band is not due to mismatched layer thicknesses, but is caused by the absorption of AlGaAsSb below the band gap (Urbach tail), extending towards shorter wavelengths. This is confirmed by transmission measurements, showed on Fig. 3, made on an AlGaAsSb bulk layer and on a DBR. A widespread absorption edge in the range 1.3-1.6 $\mu\text{m}$ , clearly suggests the lack of Al in the quaternary. This is not unforeseen, considering that the PL peak of AlGaAsSb is around

1.55 $\mu$ m (0.8eV). Losses due to surface scattering have also been quantified. At the wavelength 0.830 $\mu$ m, we found the percentage of scattering to be lower than 0.04%. At 1.55 $\mu$ m we do not expect a significant contribution of the scattering to the total reflectivity losses.

*Conclusions:* We demonstrate for the first time, to our knowledge, the feasibility of the monolithic growth by MOVPE of DBR structures with the material system AlGaAsSb/InP. DBRs composed of 10, 12, 21 mirror pairs were grown with a mirror like surface quality on 2" wafers. A maximum reflectivity of 97% at 1.59 $\mu$ m was achieved with a DBR consisting of 21 AlGaAsSb/InP pairs. For applications in the long wavelength VCSELs domain, however, this reflectivity will have to be increased. The main losses are probably caused by insufficient Al concentration in the quaternary material.

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**Figure captions:**

Fig. 1 SIMS measurement profile of Sb concentration in the 12 period DBR. AlGaAsSb and InP are indicated with distinct dashed areas.

Fig. 2 Absolute reflectivity measurement of DBRs composed of 12 (dashed) and 21 AlGaAsSb/InP periods (solid line).

Fig. 3 Transmission of one AlGaAsSb/InP period (solid line) and of 21 period DBR (dashed line).



Figure 1

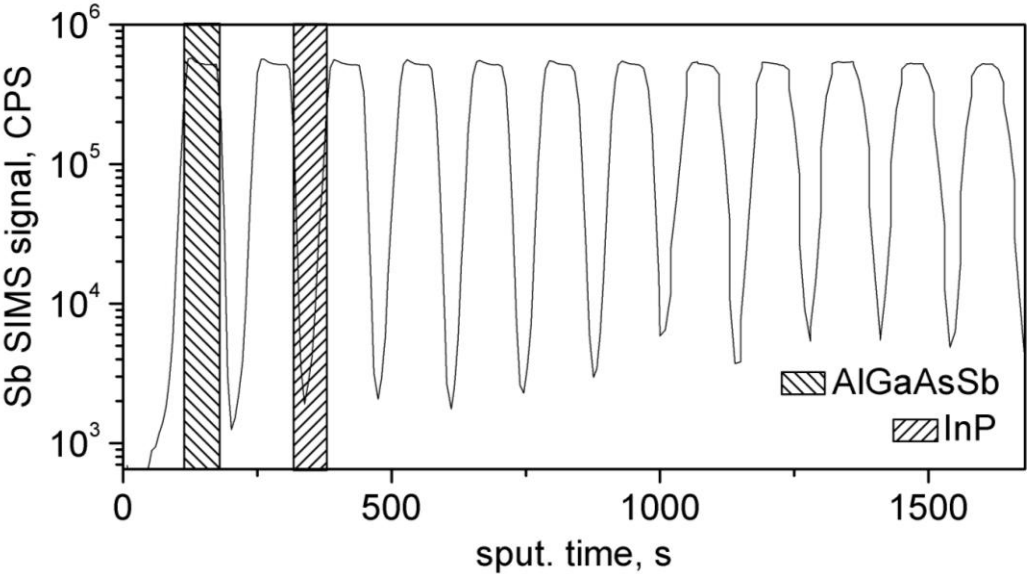


Figure 2

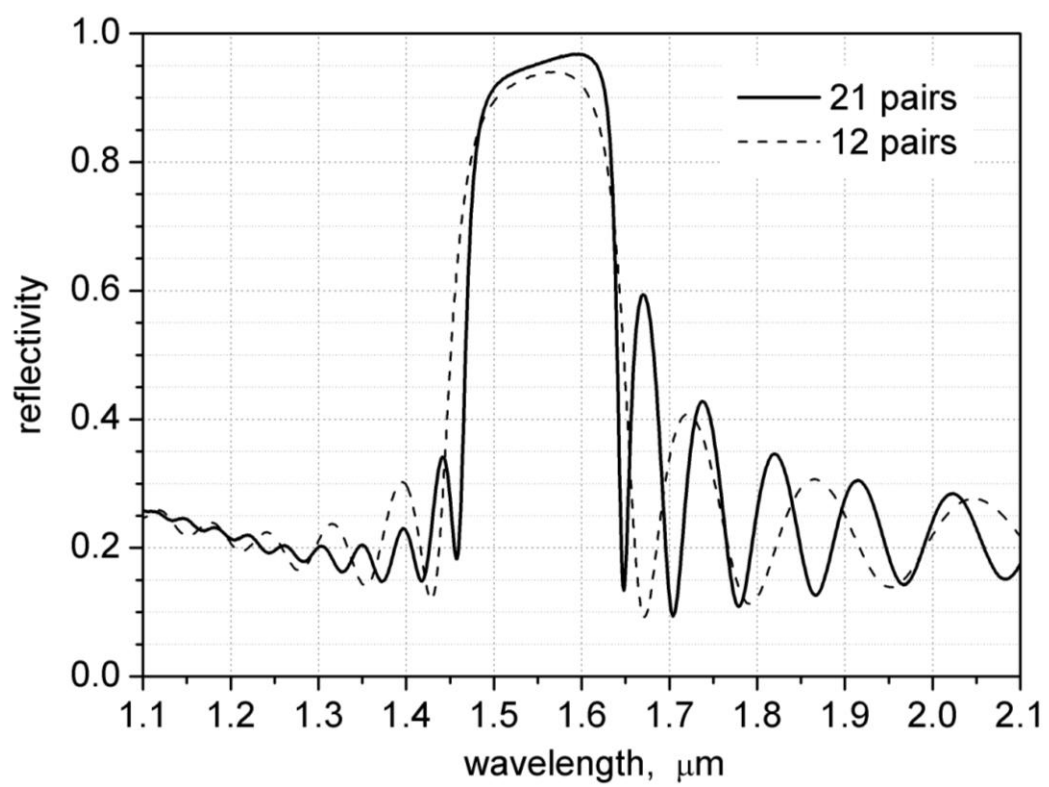


Figure 3

