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# Efficient lateral confinement by oxide aperture in mid-infrared GaSb-based vertical emitting light source

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## *Abstract*

The use of lateral oxidation for electrical and optical confinement on GaSb based mid-infrared vertical light emitting diode is demonstrated in this paper. The metamorphic growth of (Al)GaAs above a tunnel junction grown on GaSb-based resonant cavity light emitting diode, enables good structural quality of the As-based layers and the oxidation of AIAs embedded film. Oxide-confined devices with emission wavelength around 2.6  $\mu\text{m}$  are demonstrated, with no noticeable degradation from the oxidation thermal treatment. Such efficient oxide confinement scheme can be applied for the realization of high performance mid-infrared vertical cavity lasers.

Vertical cavity light emitting devices, epitaxially grown on GaSb, stand as a very attractive solution for a number of optical sensor applications in the mid-infrared range. The achievable emission band, with the lattice-matched alloys on this substrate, is extremely wide from the telecom wavelengths to atmosphere transparent windows relevant for gas spectroscopy. The 2-3  $\mu\text{m}$  range coverage enables the detection of a large variety of gases, relevant for the environmental pollution reduction and the control of industrial technological processes. Very recently, the GaSb-based vertical-cavity surface-emitting lasers (VCSEL) have been successfully fabricated above 2.3  $\mu\text{m}$ , with very promising electrical and optical properties [1,2].

GaSb based material system shows numerous advantages specifically in the design of vertical cavity lasers, since it affords to realize within a minimum lattice mismatch, high

reflectivity binary Bragg mirrors (AlSb/GaSb), associated with active regions offering a large variety of band diagram configurations accessing a wide spectral emission band.

The last unsolved design issue of GaSb-based VCSEL is the implementation of electrical and optical lateral confinement, for a good matching between the gain profile and the optical mode. This would improve efficiency, and thus allow shaping the optical properties of the emitted laser beam. Historically, confinement solutions for VCSELs, based on oxide confined designs, have been found in the AlGaAs material system, leading to high volume production and high reliability proofs. Unfortunately, oxidation of the equivalent antimonide alloy (AlSb) has not yielded encouraging results for its application as a confinement layer. The main reason comes from a large volume change occurring during the wet thermal oxidation, resulting in high internal stresses or even delamination [3]. The synthesis of antimony-based by-products during the oxidation process is responsible for these problems, which leads to inadequate insulating properties of the oxidized layer.

Other confinement schemes have been studied, with the disadvantages of poor optical guiding or adding complex steps such as epitaxial regrowth. Epitaxial regrowth technique has moreover been successfully applied on a patterned tunnel junction (TJ) both on InP and GaSb VCSELs. These results are the most efficient to date with the IR material systems, with which the selective oxidation of Al-rich layers cannot be used. Another solution, made possible by the variety of alloy compositions achievable on GaSb substrate, is the formation by lateral selective wet etching of an air gap aperture near the active region [4]. Finally, studies have been conducted on the reduction of scattering losses on VCSELs show that the oxide aperture confinement is the most flexible and suitable technique to shape accordingly the lateral index profile. Other techniques such as buried tunnel junction suffer from the

technological difficulty to finely adapt the refractive index profile of the lateral waveguide [5]. Hence the use of the mature oxidation technique developed for AlGaAs on a different platform than GaAs might be a simple and efficient solution for applying flexible confinement scheme.

lattice-mismatched growth of III-V materials on GaSb substrate, or antimonides on GaAs or Si substrates has been studied recently [6,7]. In particular it has been shown that growth can be achieved without defects, thanks to the faculty in that system to confine the propagation of dislocations (Lomer type) in the plane orthogonal to the direction of growth [8]. Hetero-epitaxial AlGaAs/GaSb structures can be then fabricated within a single-step monolithic growth. This opens access to the very large potentialities offered by the mature technology of AlGaAs system, particularly the flexibility and performances of the electrical and optical confinement through selective oxidation.

In this letter, we propose and demonstrate efficient electrical and optical confinements applicable for mid-infrared GaSb-based vertical cavity emitters such as VCSELs or resonant-cavity light-emitting diodes (RCLED), by accommodating AlGaAs epitaxial growth and its selective oxidation on GaSb active structure. The confinement apertures are then accessible down to a few micrometers, enabling single-mode emission for VCSELs, in the same manner and with the same technological reproducibility achieved with standard GaAs near IR VCSELs. The use of metamorphic GaAs–AlGaAs, as demonstrated for 1.55  $\mu\text{m}$  VCSEL on InP substrate [9], allows to use an oxide confinement layer and provides a wide stopband top DBR. Hanfoug et al [10] also used metamorphic AlAs on GaSb and its oxidation for lateral confinement in edge emitting diodes. In the latter report, only large oxide diaphragms were used, without detailed study on the impact of the metamorphic growth and the oxidation on the morphology of the vertical structure, nor on the confinement effect for small aperture

diameters. To date no similar demonstration with oxide confinement on GaSb substrate has been reported on surface emitting devices, and at wavelengths higher than 2.5  $\mu\text{m}$ .

A RCLED device emitting near 2.6  $\mu\text{m}$  including an oxide aperture has been fabricated, for a proof of concept. The vertical structure grown by molecular beam epitaxy and depicted in Fig. 1 includes a bottom AlAsSb/GaSb Te doped 6-period Bragg reflector, followed by an asymmetric  $3\lambda/4$  optical cavity embedding InGaAsSb/AlGaAsSb quantum wells. Above the cavity, placed in a node of the electromagnetic field standing wave, a thin GaSb p+ (15 nm at  $10^{19} \text{cm}^{-3}$ ) / InAs n+ (15 nm at  $10^{19} \text{cm}^{-3}$ ) tunnel junction is grown. Then, the n-type GaAs is grown directly on this last highly doped layer, to benefit from the low incidence of defect both with short scale impact within highly doped regions, and the position of the mismatched interface in the node of the field. As described by Mehta et al. [6], highly doped interface flattens the energy spikes present in the band structure, and hence improves the serial resistance of the heterostructure. A 50 nm thick AlAs layer dedicated for oxidation is also placed at the next node of the electric field to reduce optical losses introduced by the AlOx. This method differs from the one reported in [10], where thick AlAs (100 nm) have been used, grown on a superlattice to overcome the high lattice mismatch present at the hetero-interface. The antimonide Bragg mirror was grown at a temperature of 500°C. During the active region, the growth temperature was lowered at 420°C in order to improve the crystal quality of the QWs [11]. Moreover the arsenide topmost part of the structure was also grown at the same temperature to minimize the blue shift of the QWs emission induced by thermal annealing [12]. Due to the high lattice mismatch between InAs and GaAs layer (~7%), the strain is relaxed after only 1 ML. The doping of the TJ is done with ambipolar Si which is P-type for Sb based materials and N-type for As based materials, in addition with the advantage of avoiding

the dopant diffusion. The topmost GaAs-based epitaxial structure is simply formed by a basic stacking GaAs(350nm)/AlAs(50nm)/GaAs(570nm) enabling easy control of the lateral oxidation of the AlAs layer.

The surface of the grown structure was characterized by atomic force microscopy (AFM). An average surface roughness lower than 0.5 nm was measured, proving the good structural quality of the metamorphic (Al)GaAs layers. The figure 2 shows the high resolution x-ray diffraction (HRXRD) pattern of this structure together with its simulation pattern with original design thickness and composition values. The simulated diffractogram takes into account the full relaxation of the (Al)GaAs layers. Moreover, the position of the QWs corresponds to the aimed composition, and the satellite peaks related to the barrier/QWs periodicity match to the nominal thickness.

The reflectivity spectrum of the epitaxial structure is presented in Fig. 3 together with electroluminescence (EL) in pulsed mode (pulse width = 1  $\mu$ s, repetition frequency = 21 kHz) from a 6  $\mu$ m oxide-apertured device. The reflectivity spectra shows a stop-band centered near 2.6  $\mu$ m with a deep and broad cavity mode due to the absence of top mirror. The EL spectrum shows an emission enhanced by the resonant cavity with one peak corresponding to the single longitudinal mode. This demonstrates the correct matching between the optical cavity length, the stopband of Bragg mirrors, and the QWs emission. Regarding the impact of the misfit dislocations on the electro-optical properties, we did not observe any drastic reduction of the luminescence on the wafer with metamorphic layers in comparison to the lone 2.6  $\mu$ m QWs.

The top emitting RCLED is afterwards realized by contacting a AuGeNiAu contact on the backside, and an annular TiPtAu on the GaAs cap. Mesas are etched by inductively coupled reactive ion plasma (ICP-RIE) down into the GaSb layer below the cavity.

The thermal oxidation process is done with similar parameters as for AlGaAs/GaAs samples [13] (16 min at  $T_{\text{oxidation}}=420^{\circ}\text{C}$ ). An optical setup was used for the real time monitoring of the lateral oxidation, thanks to the transparency of the GaAs cap in the near-IR [14]. Oxide aperture could then be achieved with diameters in the range of 3-16  $\mu\text{m}$ , in order to show the effect of strong lateral confinement on both electrical and optical properties. The oxidation kinetics of the metamorphic GaAs/AlAs structure, as we observed, proceeded in every particular similar as lattice-matched layers on GaAs. During this thermal treatment, no delamination was observed either between GaAs and GaSb owing to small differences between thermal expansion coefficients, nor around the oxide layer, for which shrinkage below 10% is commonly observed without dramatic impact. In our case, very standard heterostructure has been used for the confinement aperture, even if tapered design, allowing significant reduction of the scattering losses, could be equally implemented. Also, the influence of residual absorption of the oxide in the mid infrared range should be considered in the design of the confinement aperture. Ravaro et al. observed an absorption peak, attributed to O-H ions in the oxide, in the 2.5-4.5  $\mu\text{m}$  wavelength range reaching  $1600\text{ cm}^{-1}$  around 3  $\mu\text{m}$  [15]. These substantial losses can be counterbalanced in the VCSEL structure with a sufficiently thin oxide layer well positioned at the field node. The mesas sidewalls are afterwards passivated by a 400 nm thick  $\text{SiO}_2$  layer by plasma enhanced chemical vapor deposition.

Figure 4 depicts the influence of the aperture size on the electrical characteristics of the

RCLED. Low turn-on voltages below 1 volt are observed for all except for the minimum 3  $\mu\text{m}$  apertures, thanks to the low voltage tunneling of the Esaki junction. The serial resistance increases linearly when the oxide diaphragm diameter decreases, showing more pronounced current crowding for narrow aperture sizes. Moreover, the observed resistance well below 100  $\Omega$ , demonstrates the good injection efficiency thanks to the lateral carrier spreading in the highly doped tunnel junction.

Optical characteristics have been measured on RCLED with different aperture sizes, as shown on fig. 4. First, the thermal treatment does not affect significantly the QW emission, since no important wavelength shift is observable between non-oxidized broad area and processed samples. Thus the stability, against important heat balance, of both the 2.6  $\mu\text{m}$  active region and the GaAs/GaSb stacking is particularly promising for application in laser devices. Also, significant light output powers was detected in pulsed electrical pumping (1  $\mu\text{s}$ , 21 kHz) on small aperture devices compared to broad area ones. The low quantum efficiency of the 2.6  $\mu\text{m}$  gain region could not allow us to demonstrate continuous wave characteristics. Maximum efficiencies have been measured for apertures of 5.5 and 8.3  $\mu\text{m}$ . Reduced efficiency for small apertures can be explain by a reduction of the active volume combined with stronger heating inherent to the current crowding. The fall of the efficiency for broader aperture is more surprising. One can infer it to a mismatch between the optical mode and the gain profile for these particular devices. Combined annular injection and localized thermal reduction of the gain could also produce such effect.

In conclusion, electrical and optical oxide confinement has been successfully applied on GaSb-based emitting devices. The metamorphic growth of arsenide alloys upon a GaSb/InAs tunnel junction enables good structural properties of AIAs and its wet thermal oxidation. Oxide



apertures as small as 3  $\mu\text{m}$  have been realized, and that in a very similar way than for GaAs lattice-matched stacks. The efficient lateral confinement has been demonstrated on a 2.6  $\mu\text{m}$  RCLED, and can be straightforwardly applied to mid infrared GaSb-based vertical cavity lasers.

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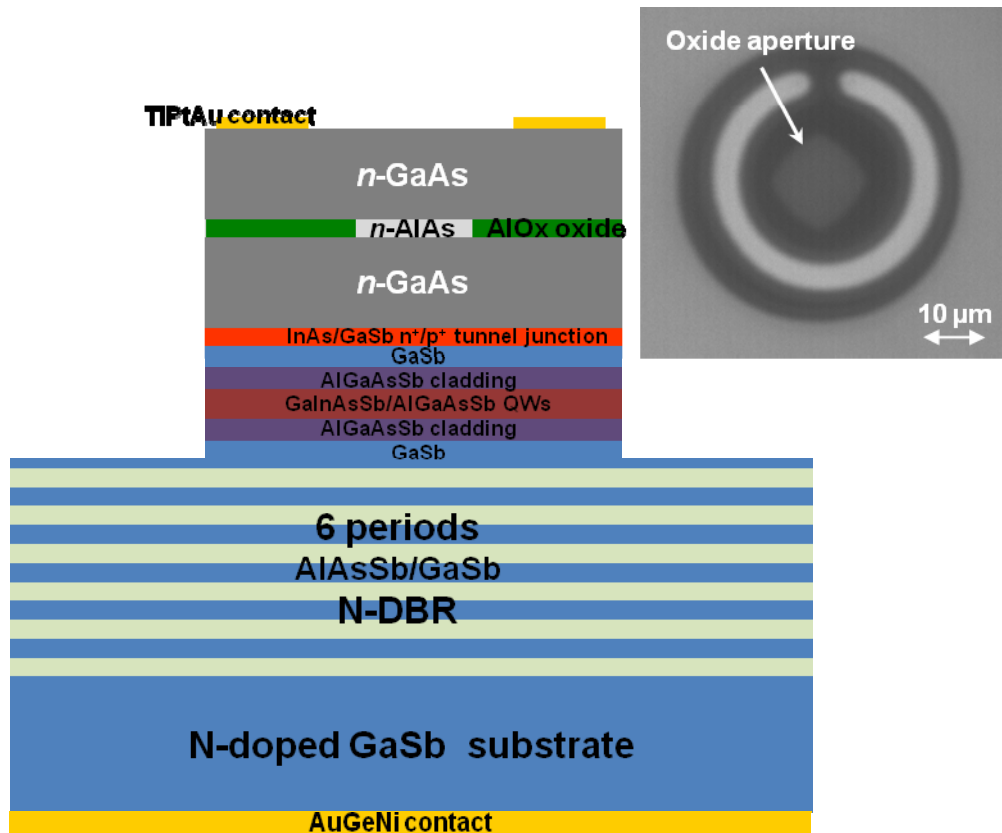


Figure 1: Schematic of the GaSb-based resonant cavity light emitting diode (RCLED) with AlOx confinement

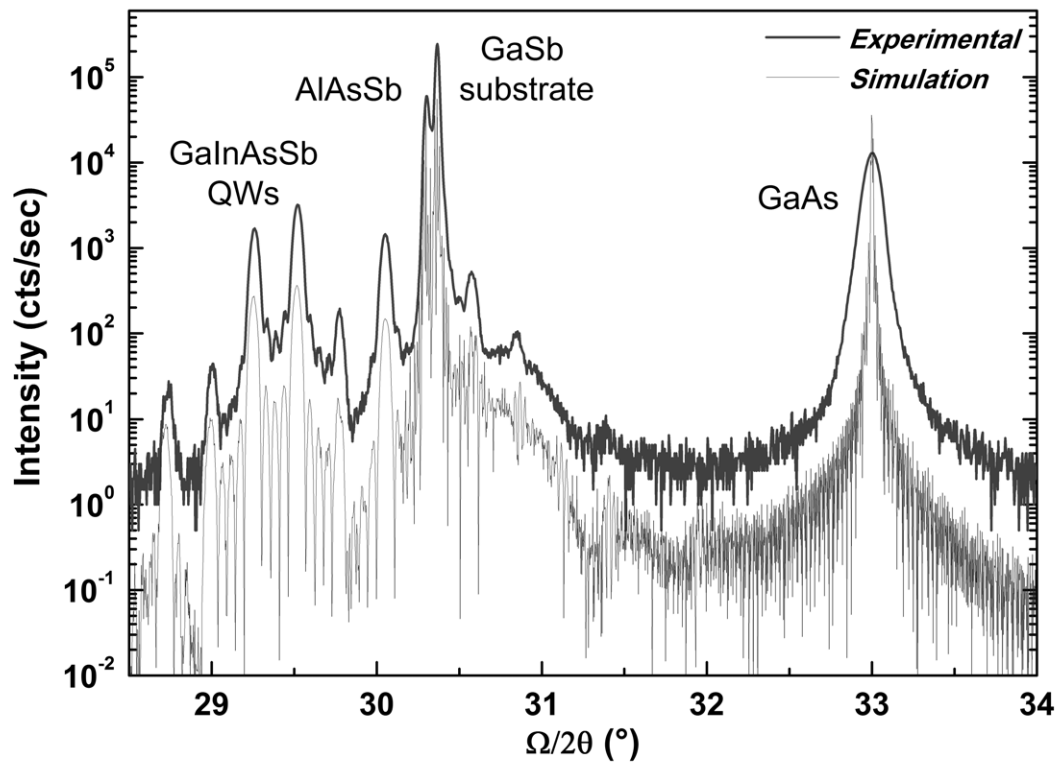


Figure 2: High resolution  $\Omega/2\theta$  x-ray diffractogram of the metamorphic RCLED structure grown on GaSb. The red curve represents the measured scan, and the blue one the simulation with expected compositions and thicknesses.

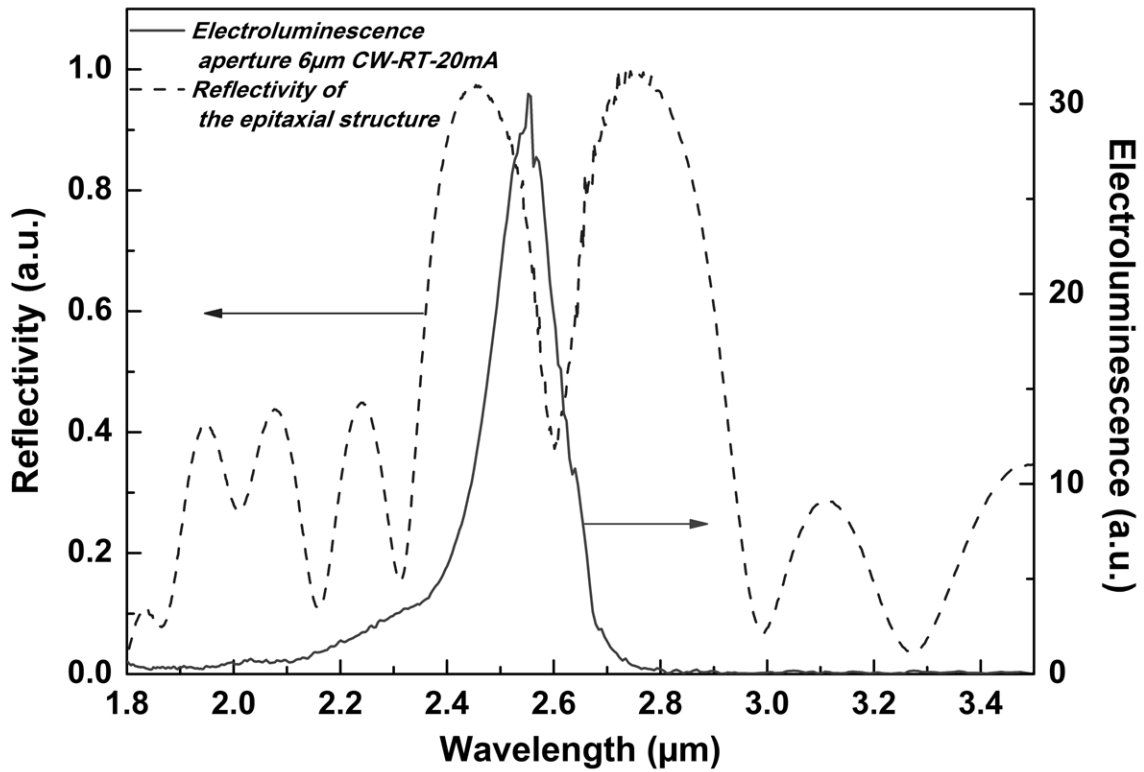


Figure 3: Reflectivity of the wafer after the growth and electroluminescence spectrum of a processed RCLED with an oxide aperture of 6 μm under 20 mA CW operation at RT.

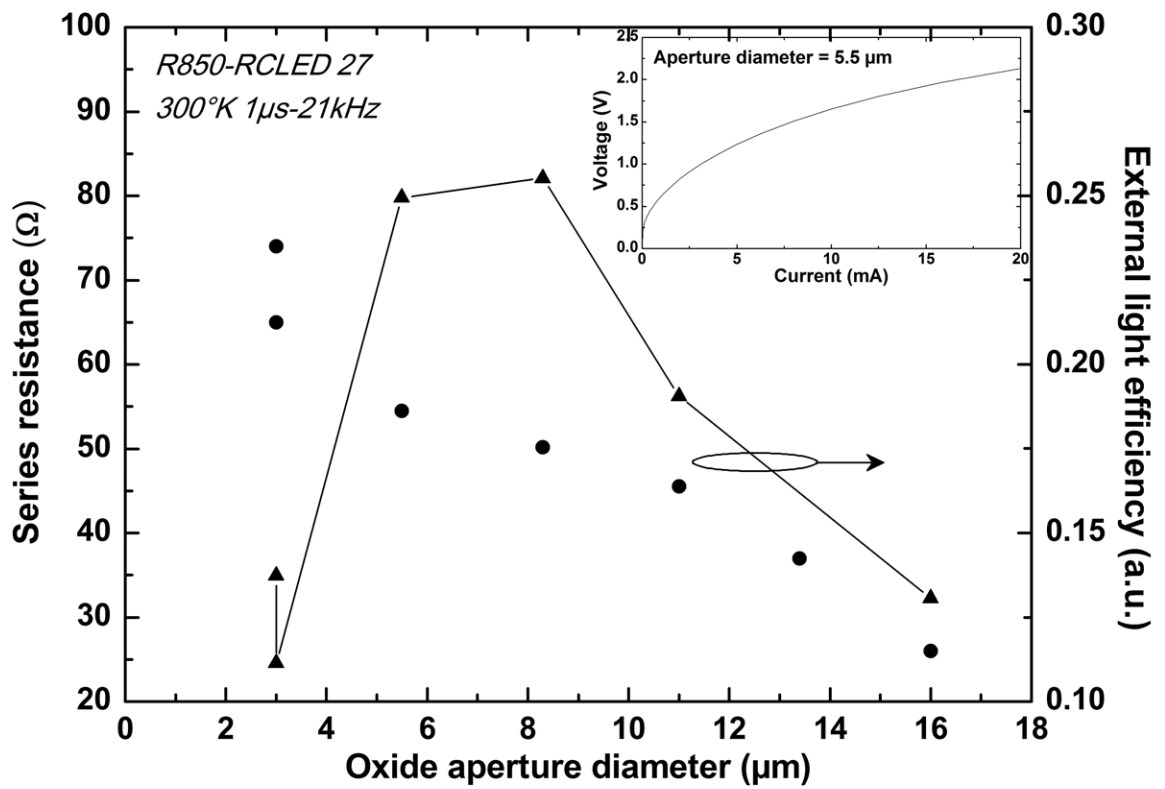


Figure 4: Evolutions of the serial resistance and of the LED efficiency as a function of the oxide aperture size.

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