Sub-nanometrically resolved chemical maps and their benefits for quantum cascade laser design and fabrication

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1. INTRODUCTION

Quantum cascade lasers (QCL) are devices with an unparalleled potential for laser emission with an emission energy fine-tuned down to the meV. These devices are, however, extremely complex to model and manufacture: they often comprise 30 or more stages, each stage itself containing about 20 wells and barriers, some of which are only a few Angstrom thick. Precisely controlling the composition and thickness of each individual well and barrier in every stage is crucial in attaining the desired emission in the final device. In this context, sub-nanometrically resolved chemical mappings are instrumental in the fabrication of a QCL. Such mappings provide both modelling and epitaxial teams the necessary feedback to identify deviations from a nominal structure, optimize both the design and the fabrication process, and, finally, demonstrate a QCL with the desired emission. However, even with the latest generation of transmission electron microscopes, equipped with state of the art EDX systems it is not possible to measure the composition of the finest wells. Thus, the quantification of the HAADF signal provides the only means to obtain chemical mappings with the desired resolution.

In the present contribution, the key role of chemical mappings is illustrated within the specific case of $In_{53}Ga_{47}As/In_{52}Al_{48}As$ QCL structures, grown on lattice-matched on InP using metal-organic chemical vapor deposition (MOCVD). In this specific case, the challenge lies in optimizing the switching between gallium and aluminum precursors in a way that enables one to obtain the targeted composition and thickness, while avoiding memory effects that mollify the interfaces between InGaAs and InAlAs and both broaden and shift the emission line.

2. RESULTATS

2.1 Experimental details

The $In_{53}Ga_{47}As/In_{52}Al_{48}As$ QCL structures studied here consist of 36 periods of InGaAs wells and InGaAs barriers. X'ray diffraction confirmed that the structure are lattice-matched on InP to within 1ppm. With such a small deviation from the lattice-matched case, the HAADF contrast reflects variations as aluminum (Z=13) replaces gallium (Z=31). It is therefore possible to detect deviations from the nominal compositions of the InGaAs wells and InAlAs barriers by quantifying the HAADF contrast to obtain a chemical mapping that reflects the aluminum content in the QCL structure using the following equation:

$$[Al]_{\%} = 48\frac{0.53Z_{In}^{1.7} + 0.47Z_{Ga}^{1.7} + Z_{As}^{1.7}}{0.47Z_{Al}^{1.7} - 0.01Z_{In}^{1.7} - 0.48Z_{Ga}^{1.7}}(R-1)$$

The quantification procedure was adapted from the one presented by the authors in References [1-2]. The scattering exponent here was found to be 1.7 by fitting the composition from this expression to EDX measurements in the thicker wells and barriers of the structure.

2.2 Chemical mappings of an non-optimized QCL structure

An HAADF image and the corresponding chemical mapping of on stage of a non-optimized QCL structure is shown in Fiugure 1. Both the image and the mapping reveal that the interfaces between InGaAs (bright) and InAlAs (dark) are fuzzy, a result of non-abrupt switching between the aluminum and gallium sources in original growth process. Furthermore, while the composition of the InGaAs wells is within 1at.% of the nominal 47at.%, the aluminum content in the InAlAs wells can deviate by as much as 25at.% from the nominal 48at.%. A QCL fabricated from this structure did not yield the desired emission.

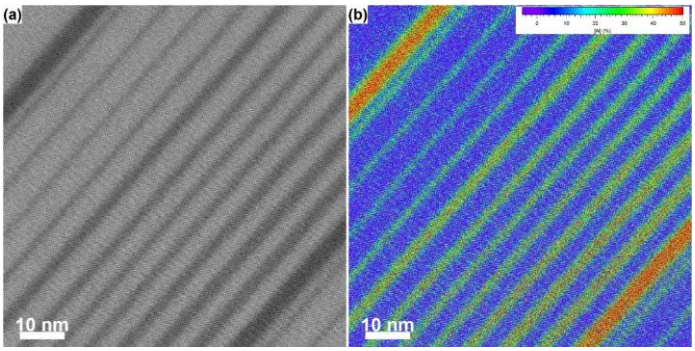

Figure 1. Image couleur (Times New Roman 9 centré)

2.3 Chemical mappings of the optimized structure

The MOCVD process was optimized by overshooting the aluminum precursor flow when switching to each InAlAs barrier. An HAADF image and the corresponding chemical mapping of one stage of the QCL are are shown in Figure 2. In this case the wells and barriers are well defined, indicating that the interfaces between InGaAs and InAlAs are abrupt. Furthermore, the chemical mapping reveals that all but the finest InAlAs well have the desired composition. A QCL fabricated from this structure emits at the desired wavelength with a low threshold. Both the threshold and wavelength are in excellent agreement with prediction from numerical structures that use the data from the chemical mapping.

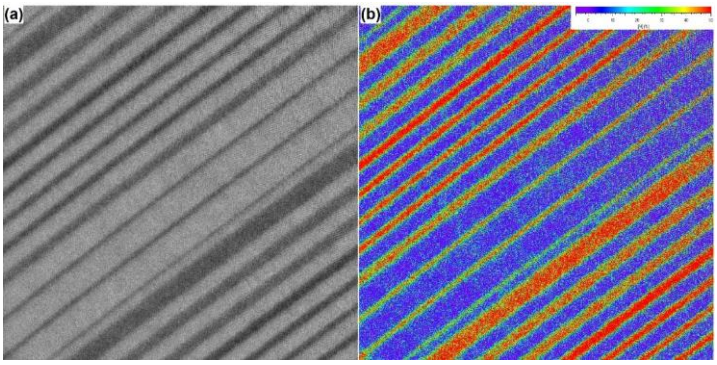

Figure 2. Image N/B

3. CONCLUSION

Sub-nanometrically resolved chemical mappings, obtained by quantifying the HAADF contrast, have been shown to be instrumental for the optimization of MOCVD-grown InGaAs/InAlAs QCL structures.

REFERENCES

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