Combining Atom Probe Tomography with High-Resolution Scanning Transmission Electron Microscopy and Micro-Photoluminescence Spectroscopy for the study of semiconductor heterostructures

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1. INTRODUCTION

In the last few years, laser-assisted atom probe tomography (La-APT) has emerged as a powerful tool for the analysis of semiconductor heterostructures in 3D and at the nanoscale. The application of APT with transmission electron microscopy and optical spectroscopy techniques to the study of nanoscale objects may yield an extremely deep insight into the relationship between structural and optical properties when the obtained data are combined to yield a consistent and rich set of information. The methods of application may have increasing degrees of accuracy – and technical difficulty – which can be classified as (i) comparative approaches, in which different nanoscale parts of the same macroscopic sample are studied by the three techniques and (ii) correlative approaches, in which the same nanoscale object is subsequently studied with the three techniques. These approaches can be implemented in the study of heterostructure interface definition, presence of defects, carrier localization and optical emission in quantum confined systems, such as the AlGaInN and AlGaAs quantum well (QW) and quantum dot (QD) systems presented here. [1,2]. Furthermore, the use of complementary techniques may be extremely helpful for a correct interpretation of atom probe results, which are not always exempt of artefacts and biases [3,4].

2. RESULTS

2.1 Comparative approaches

An example of comparative approach is illustrated in fig. 1. Here, a set of multiple GaN-AlGaN asymmetric quantum wells is studied by µ-PL, HR-STEM is performed on lamellas and nanoscale tips, and finally tips are analyzed by APT. The set of data obtained by these three techniques allows not only for an extremely detailed comprehension of the structural factors determining the energies of the radiative transitions observed, but also for an unambiguous correction of a bias in the elemental composition measured by the atom probe.

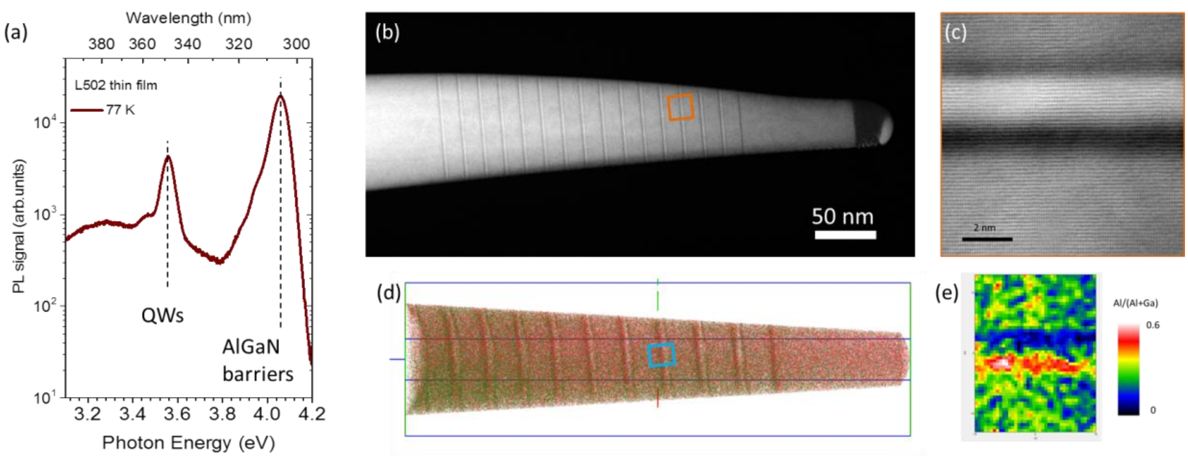

Figure 1. A comparative study on a GaN-AlGaN multi-QW set. (a) µ-PL exhibits spectral features which can be attributed to quantum well and barrier emission (b,c) HR-TEM performed on atom probe samples allow assessing the crystallography and yield first information about the interface definition; (d,e) finally, the 3D reconstruction obtained by APT

assesses the distribution of Ga and Al, which makes it possible to calculate the spectral properties of the system in the framework of a 3D effective mass approximation.

Another interesting example of comparative study has been performed on GaAs-AlGaAs core-shell nanowires. Here, APT was used to find evidence for the formation of quantum dots resulting from the fluctuations taking place within the AlGaAs shell. Such QDs would be extremely difficult to assess by TEM, and their calculated optical properties are in good agreement with the observed spectral signatures of the wires [2].

2.2 A correlative study on InGaN/GaN quantum wells

The correlative approach has been applied on a nano-object containing a portion of radial InGaN/GaN multi-quantum wells extracted from a core-multishell microwire. The photoluminescence spectra strongly suggest that the radiative recombination is due to excitons localizing in quantum dot-like regions within the quantum wells. HR-STEM not only provides information about the crystallography, the presence of extended defects and a 2D characterization of the quantum wells, but it also allows for the best possible APT reconstruction. It is then by APT that the access to the fully resolved 3D structure of the QWs becomes possible, with the evidence for In clustering forming quantum dot-like regions within the quantum wells. The size and composition of these regions well matches with the energy of the emission peaks previously recorded in µPL spectra..

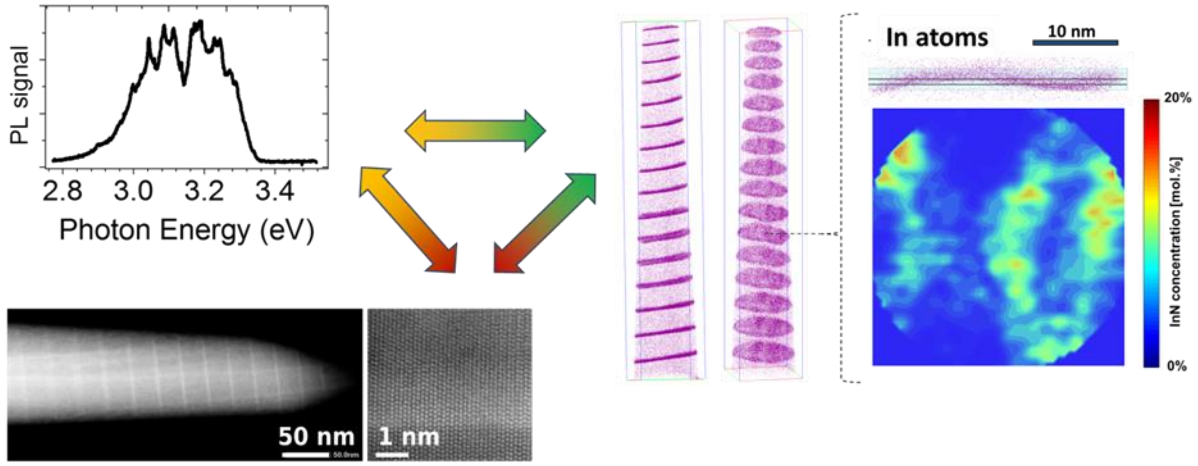

Figure 2. Scheme illustrating the correlative approach in which µ-PL spectroscopy, HR-TEM and APT are applied on a single nanoscale object containing a set of 20 InGaN/GaN quantum wells [1].

3. PERSPECTIVES

The combination of microscopy techniques with optical investigation tools should find more and more place in the next few years in the domain of nanosciences. Developments based on APT will be particularly focus on the correlative approach, through the elaboration of sample preparation protocols respectful of the optical properties of the nanoscale specimen. However, a further approach is also possible, based on the implementation of optical spectroscopic benches within an atom probe instrument itself [4].

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