Challenges of local electrical measurements on cross-sectional devices using Conductive Atomic Force Microscopy (C-AFM)

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The conductive tip atomic force microscopy (C-AFM) technique is now widely deployed for local electrical characterization of micro/nano materials and devices. It can be used to identify electrical defects that may be the origin of failures; it can be used to investigate electronic transport properties, with the possibility of correlating them with the material's topography. Finally, it can be used to characterize all the active layers of a device, and in particular the junctions that constitute it, through cross-sectional analysis.

Our study focuses on the latter approach, with emphasis on the experimental conditions and in particular on the electrical bias voltage applied between the tip and the sample. It will be illustrated by characterization and modelling of a cleaved p-AlGaAs:Be/n-GaInP:Si photovoltaic (PV) structure consisting of a stack of 8 layers with thicknesses ranging from 20 to 1900 nm.

The experimental C-AFM analysis with a positive bias voltage (+1 V) shows that the electrical measurement allows us to spatially resolve the different layers that compose the device, and notably to identify the highly doped regions (p and n), the p-type absorber and the space charge region. Despite the identification of these different regions, one important finding came out of this first analysis: the existence of a rectifying behaviour between the AFM tip and the sample, notably when the tip transits from a p+ to an n+ region. This rectifying effect is clearly observable when the same region is analysed with a negative bias voltage (-1V), where, for example, the p-type absorber, doped at 10^{17} cm^{-3}, appears two orders of magnitude more resistive than the measurement made under positive bias. A more detailed analysis of this rectification effect has been carried out on two GaAs multilayer structures with staircase n- or p-type doping, including the possibility of calibrating local n-type doping only under negative applied bias (-1 V) and p-type doping under positive bias (+ 1 V).

One of the key findings for the p-AlGaAs:Be/n-GaInP:Si cleaved structure is that measurements taken at +/- 1 V must be combined to reconstruct an electrical profile of the cross section that is more representative of the local resistivity by essentially highlighting the forward-biased polarization regime between the AFM tip and the region under study and getting rid of the current limitation by a potential barrier under reverse bias.

This methodology was explored by 2D finite-element electrical modelling including defect state distributions, solving the drift-diffusion and Poisson's equation. This was implemented in order to calculate the spatial distribution of free carriers along the structure, from which the local resistivity can be extracted. Electrical modelling shows that the experimental methodology under +/-1V is consistent with the expected resistivity profile. It also demonstrates the strong influence of surface states which can modulate the surface resistivity over several orders of magnitude. It should be noted that the impact of surface states is rarely taken into account in C-AFM analyses, and that their appearance here is to be expected as they are the result of the sample cleavage procedure for cross-sectional analysis.