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AndQC

Report on InAs/InGaAs/InAlAs planar 2DEGs down to 10nm from the surface with ballistic transport

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1. Introduction

This Deliverable is one of the starting elements of WP1, which is dedicated to the material synthesis of different superconductor-semiconductor platforms. In particular, it is part of the development process of *planar* hybrid systems, where the semiconductor part is constituted of two-dimensional electron gases (2DEGs) in InAs quantum wells (QWs), and the superconductor is constituted by aluminum deposited *in situ*. D1.2 concerns the optimization of the semiconductor building block of these systems, and stems on the activities of the related Task 1.2.

In order to allow for proximity-induced superconductivity, InAs 2DEGs must fulfill two conditions. First, they must be located close enough to the surface (down to about 10nm) to allow for sufficient wavefunction overlap at the surface. At the same time, low-temperature electron mobility should still be high enough (some 10^4 cm^2/Vs) to grant ballistic electronic transport. A compromise between these two requirements must be found, as surface scattering greatly limits electron mobility as the 2DEG is pushed towards it.

2. InAs/InGaAs/InAlAs planar 2DEGs

InAs planar 2DEGs were grown by solid source Molecular Beam Epitaxy (MBE) on GaAs (001) substrates at the Istituto Officina dei Materiali (Trieste, Italy) of the CNR node. Due to the large lattice mismatch to GaAs (around 7%), the achievement of virtually strain- and defect-free, metamorphic InAs QWs requires the insertion of engineered InAlAs buffer layers (BL) with increasing In composition x between the substrate and the active region [1]. We have adapted the growth structure and conditions starting from our previous experience in developing $In_{0.75}Ga_{0.25}As/In_{0.75}As_{0.25}As$ 2DEGs with low-T electron mobilities μ up to 3.2 X 10^5 cm^2/Vs with densities *n* around 3 X 10^{11} cm^{-2} in deep (>100nm) QWs [3]. Optimization proceeded in three phases:

1. Synthesis of 7nm-thick, deep InAs QWs, in order to reduce alloy and interface scattering, thus increasing electron mobility. To compensate for the higher strain, this required to increase the In content in the $In_xGa_{1-x}As/In_xAs_{1-x}As$ barriers form 0.75 to 0.81. Furthermore, the maximum x in the BL was increased to 0.84, since an overshooting of the In composition above that of the active region has proven to be beneficial in relaxing the lattice parameter of the latter [1]. A series of samples was grown in which the thickness *t* of the 0.84 region was varied from 50 to 400nm, in order to enhance progressively lattice relaxation (Fig. 1, left). Fig. 1 (middle) shows (004) X-ray diffraction rocking curves for 5 representative samples, obtained with a high-resolution diffractometer equipped with a four-crystal Ge (220) monochromator, using Cu Ka1 radiation. Peaks from the 0.81 and 0.84 regions can be identified (dashed lines). Their observed shift as *t* increases indicates a relaxation of the lattice parameter in the (001) direction due to a tetragonal distortion of the unit cell caused by the internal strain, which saturates for both regions at $t \approx 300$nm. Experiments with synchrotron radiation are under way, in order to evaluate the strain in the InAs QW through reciprocal space maps. Fig. 1 (right) shows the dependence of electron density and mobility on *t* in Van der Pauw samples measured at 4.2K. Thanks to strain reduction, μ increases up to $t \approx 300$nm at about μ = 7.1 X 10^5 cm^2/Vs, after which it saturates, consistently with the saturation of residual strain in the barriers.

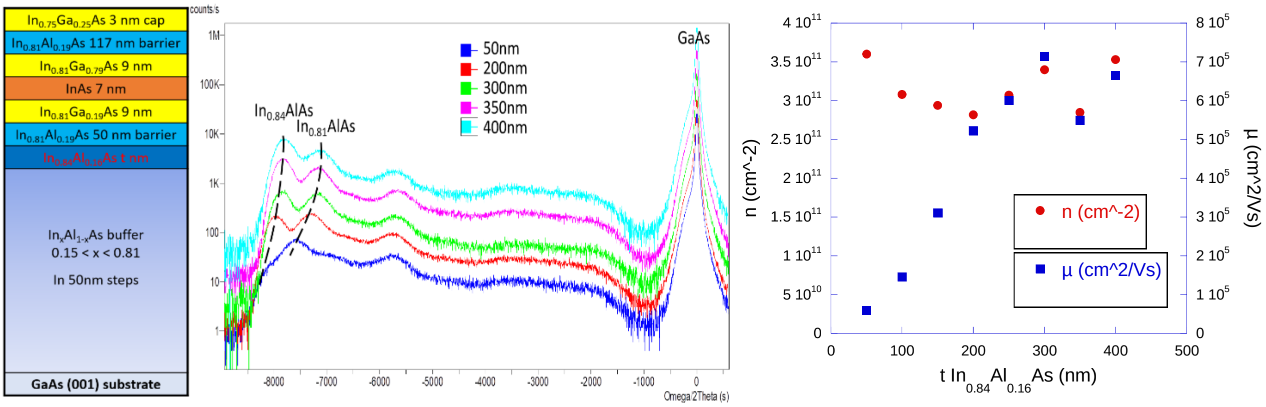

Fig. 1: left: schematics of the growth sequence to optimize growth of deep InAs 2DEGs. Middle: XRD scans for different thicknesses of the $In_{0.84}As_{0.16}As$ region *t*. Right: low-T electron density and mobility as a function of *t*.

2. Synthesis of shallow InAs QW (with distance to the surface *d* down to ≈ 10nm), in order to allow for proximity effects to a deposited superconducting layer (which will be the object of D1.6). We have grown a series of samples in which a 7nm InAs QW was separated to the surface by an $In_{0.81}Ga_{0.19}As$ barrier of different *d* (Fig. 2, left). As can be seen in Fig. 2 (right), µ is independent of *d* down to about 30nm (values around µ = 8 X 10^5 cm^2/Vs), and then decreases sharply to 3.6 X 10^4 cm^2/Vs at *d*=10nm, 1.2 X 10^4 cm^2/Vs at *d*=5nm and 6.1 X 10^2 cm^2/Vs at *d*=0nm (in the latter two samples most of the contacts were freezing upon cooldown, making them useless for application purposes). *n* is largely independent on *d* in the whole range, at values ≈ 3-4 X 10^{11} cm^{-2}.

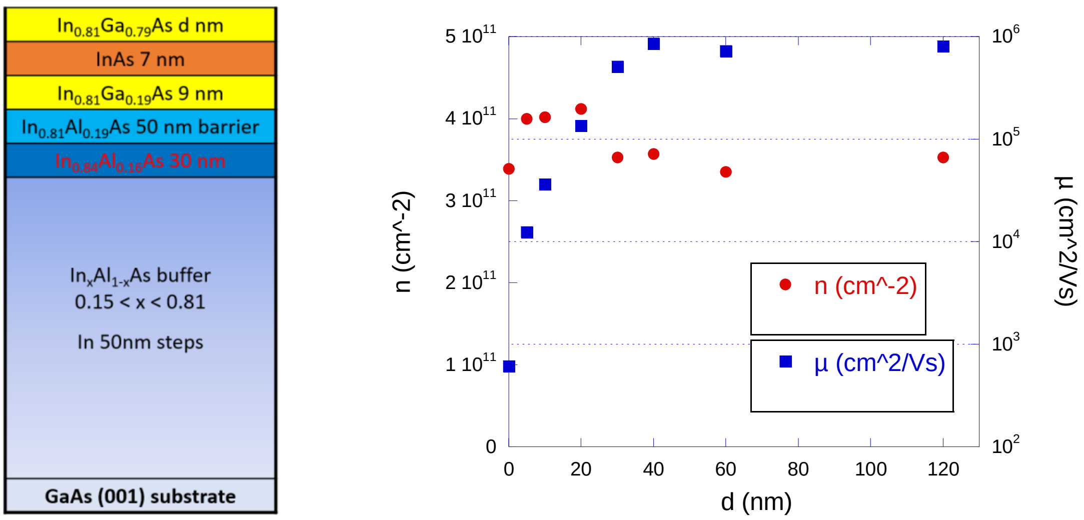

Fig. 2: left: schematics of the growth sequence for shallow InAs 2DEGs. Right: low-T electron density and mobility as a function of 2DEG depth.

3. Tuning of electron density in shallow (10nm) InAs 2DEGs. This was achieved through a Si δ doping layer in the InAlAs barrier at 7nm from the InGaAs/InAs QW (Fig 3, left). By changing the Si donor concentration *N,* we were able to tune *n* from 4 to 11 X 10^{11} cm^{-2}, with µ up to 5.5 X 10^4 as *n* increases (Fig. 3, right). Transport properties of such samples match the state-of-the-art reached on 10nm-deep InAs 2DEGs grown InP substrates [2], demonstrating the transferability of this approach to GaAs technology. For higher densities, the mobility drops sharply possibly due to parallel conduction in the Si δ doping channel, or population of the 2^{nd} subband. Further analysis through Shubnikov-de Haas oscillations and kp simulations is under way to investigate these hypotheses.

For a single *N*, an attempt to reduce the $In_{0.81}Ga_{0.19}As$ top barrier to 5nm resulted in a decrease of electron mobility to about 2.3 X 10^4 cm^2/Vs, which could provide an option in case 2DEGs shallower than 10nm should be explored.

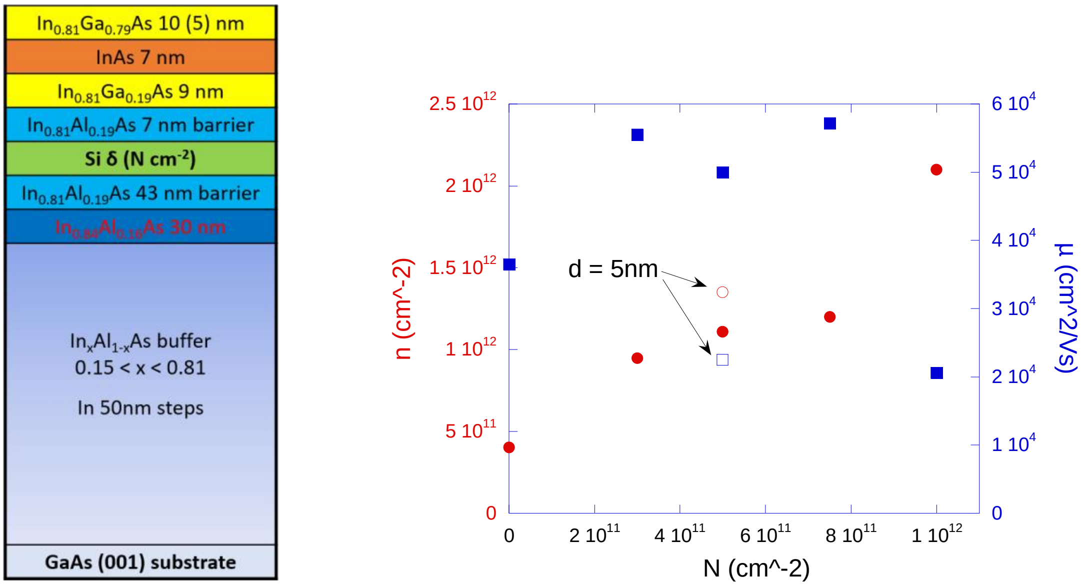

Fig. 3: left: schematics of the growth sequence for δ-doped, shallow InAs 2DEGs. Right: low-T electron density and mobility as a function of the 2D Si density *N*.

3. Conclusions

In the first year, deliverable D1.2 of the WP1 “Materials Developments” was successfully reached. Samples containing planar $InAs/In_{0.81}Ga_{0.19}As$ 2DEGs were synthesized on GaAs substrates at different QW depths and doping levels, and structural and transport characterization was performed. For all ranges of depth and doping, our samples proved to be competitive with state-of-the-art equivalent systems grown on InP substrates in terms of electron mobility. Optimised shallow InAs 2DEGs are being delivered to partner BME for Hall bar and QPC experiments, with the aim of assessing the strength of spin-orbit coupling through weak localization measurements.

4. References

[1] F. Capotondi, G. Biasiol, D. Ercolani and L. Sorba, Scattering mechanisms in undoped $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ Two-Dimensional Electron Gases, J. Crystal Growth 278, 538 (2005).

[2] J. S. Lee, B. Shojaei, M. Pendharkar, A. P. McFadden, Y. Kim, H. J. Suominen, M. Kjaergaard, F. Nichele, H. Zhang, C. M. Marcus, C. J. Palmstrøm, Transport Studies of Epi-Al/InAs Two-Dimensional Electron Gas Systems for Required Building-Blocks in Topological Superconductor Networks, Nano Lett. 19, 3083 (2019).