Metamorphic InAs/InGaAs QWs with electron mobilities exceeding 7×10^5cm^2/Vs

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Why metamorphic InAs-based 2DEGs

- Potential platforms for a class of low-temperature applications
  - strong spin-orbit coupling
  - large g-factor
  - interface transparency to superconductors
- Near lattice-matched substrate:
  only GaSb → 24nm QWs, $\mu = 1.8\times10^{6}$ cm^{2}/Vs @ $n = 8\times10^{11}$ cm^{-2} a)
- InP, GaAs: need for metamorphic growth, strain-limited QW thickness (<10nm)
  - InP: 7nm QWs, $\mu \sim 10^{6}$cm^{2}/Vs @ $n = 6\times10^{11}$ cm^{-2} b) on gated Hall bars
  - GaAs: 4nm QWs, $\mu = 5\times10^{5}$ cm^{2}/Vs @ $n = 4.5\times10^{11}$ cm^{-2} c) on gated Hall bars

a) T. Tschirky et al., Phys. Rev. B 95, 115304 (2017)

b) A. T. Hatke et al., Appl. Phys. Lett. 111, 142106 (2017)

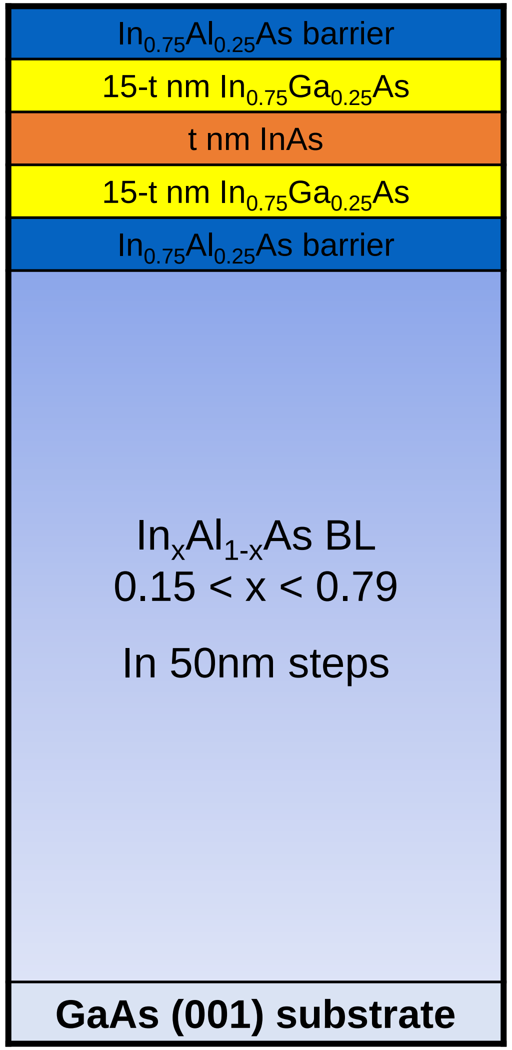
c) D. Ercolani et al., Phys. Rev. B 77, 235307 (2008)

Outline

- Goal: increase InAs QW thickness on GaAs substrates (smaller alloy + interface scattering → higher mobility)
- How: optimization of buffer layer (BL) to decrease strain in QW

- Growth protocol
- Structural and strain analysis (AFM, XRD, XTEM)
- Low-T transport characteristics
- Conclusions

Our starting point


$In_{0.75}Al_{0.25}As$ barrier

15-t nm $In_{0.75}Ga_{0.25}As$

t nm InAs

15-t nm $In_{0.75}Ga_{0.25}As$

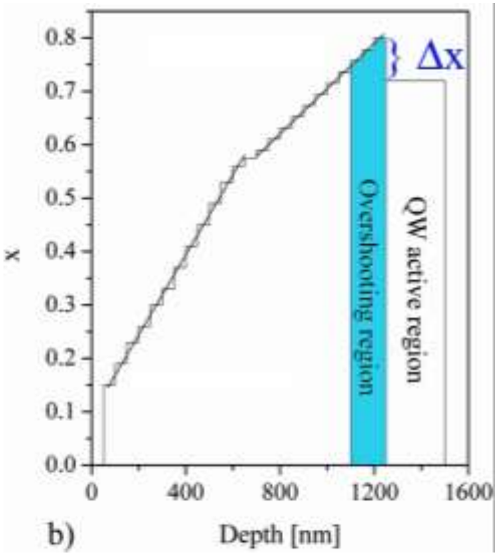
$In_{0.75}Al_{0.25}As$ barrier

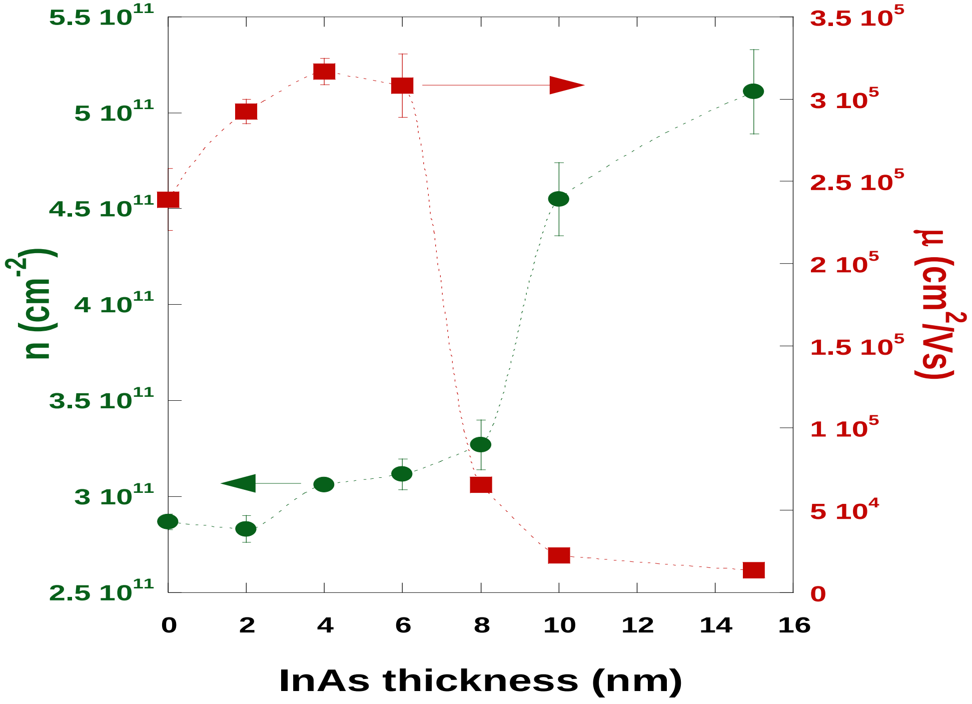
$In_xAl_{1-x}As$ BL

$0.15 < x < 0.79$

In 50nm steps

GaAs (001) substrate

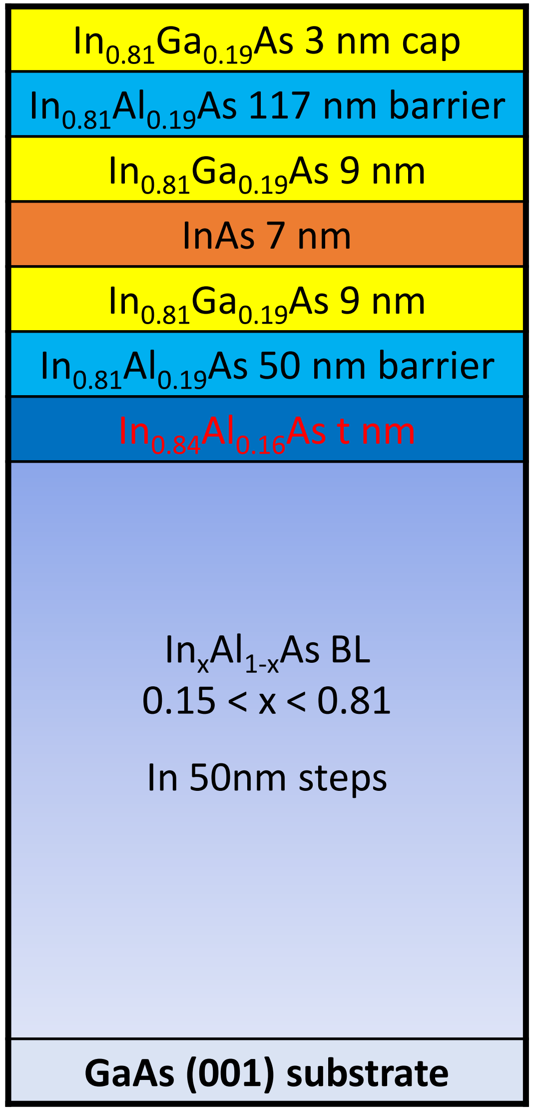




- Solid-source MBE on GaAs (001)
- Graded In_xAlAs BL, x up to 0.79 in 50nm steps @ 330C; gradual relaxation of lattice parameter
- InAs layer embedded in $In_{0.75}Ga_{0.25}As$ QW, no remote doping
- Up to 4-5nm InAs:
  - n roughly constant (~ 3×10^{11} cm^{-2})
  - μ up to 3.2×10^5 cm^2/Vs (5×10^5 under bias)
- Above 6nm InAs: misfit dislocations $\Rightarrow \mu$ degradation, increased n

J. Crystal Growth 278, 538 (2005).

Solutions to increase QW thickness



$In_{0.81}Ga_{0.19}As$ 3 nm cap

$In_{0.81}Al_{0.19}As$ 117 nm barrier

$In_{0.81}Ga_{0.19}As$ 9 nm

InAs 7 nm

$In_{0.81}Ga_{0.19}As$ 9 nm

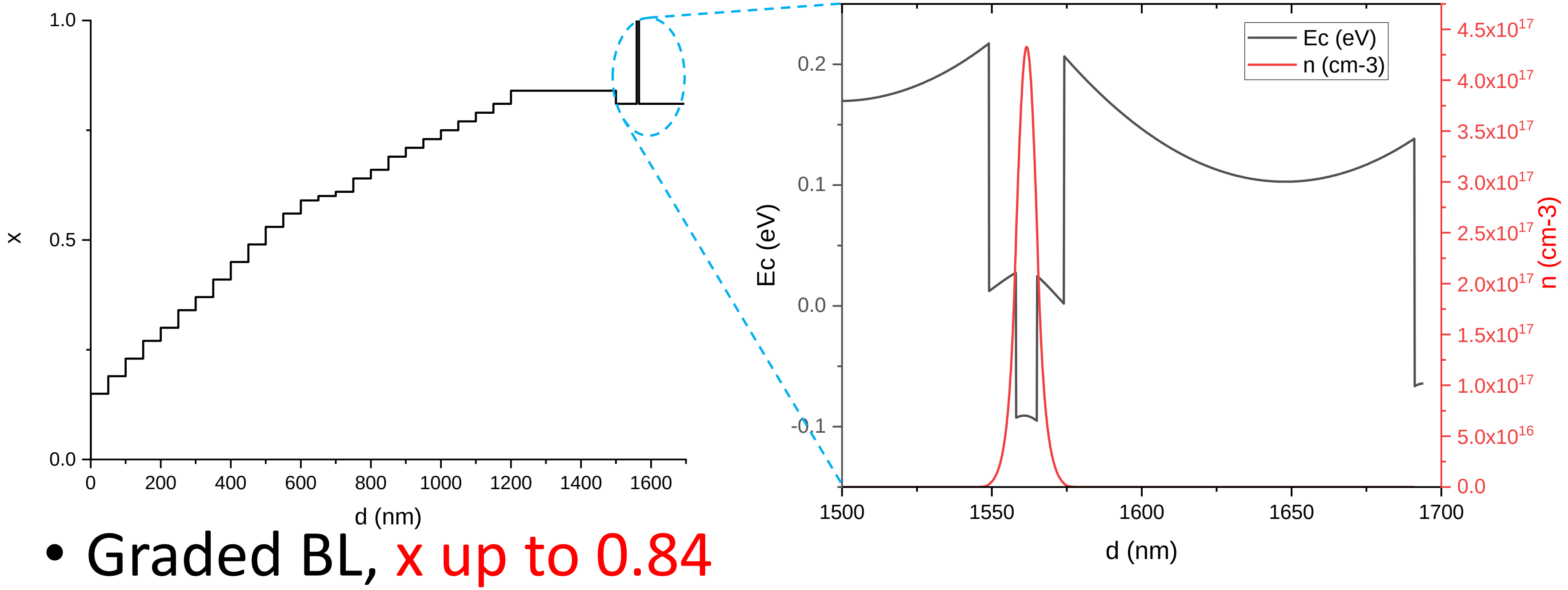
$In_{0.81}Al_{0.19}As$ 50 nm barrier

$In_{0.84}Al_{0.16}As$ t nm

$In_xAl_{1-x}As$ BL
0.15 < x < 0.81

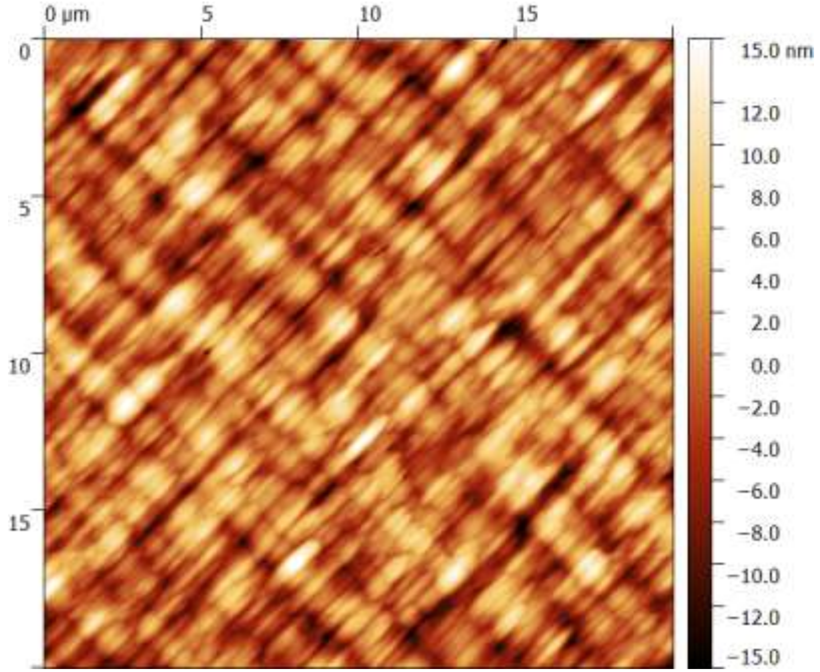
In 50nm steps

GaAs (001) substrate

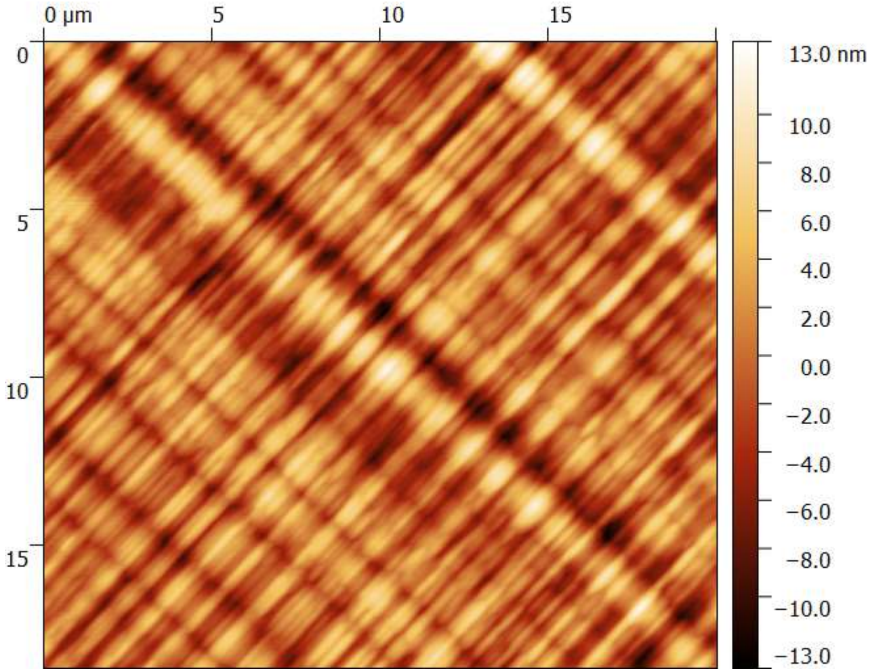


- Graded BL, x up to 0.84
- Last step: samples with varying $In_{0.84}Al_{0.16}As$ thickness *t* 50 ÷ 400nm ⇒ tuning of residual strain
- 120nm deep QW @ 470C
- 7nm InAs in 9nm $In_{0.81}Ga_{0.79}As$; $In_{0.81}Al_{0.19}As$ barriers

AFM images

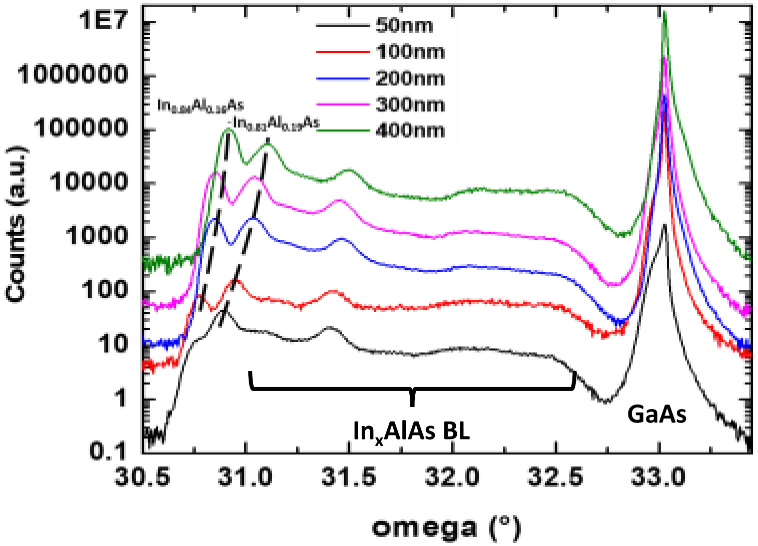


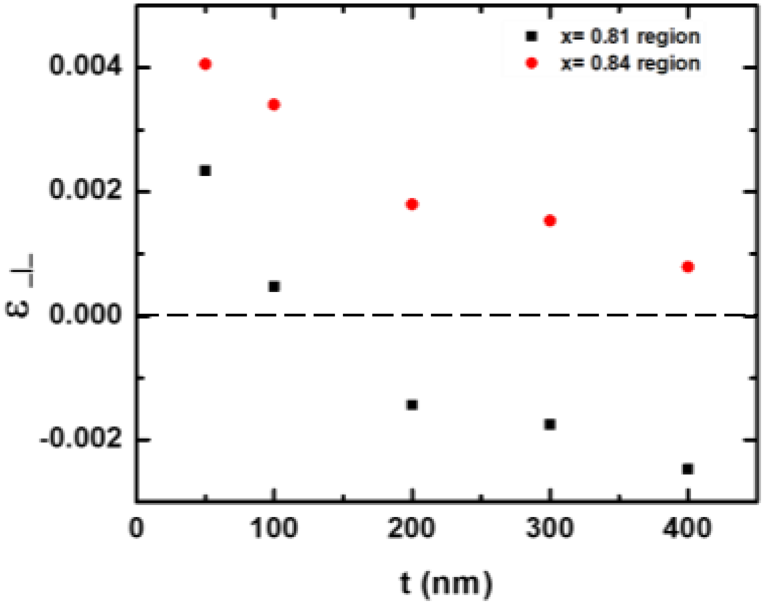
t = 50 nm
RMS roughness : 4.4nm



t = 300 nm
RMS roughness : 3.4nm

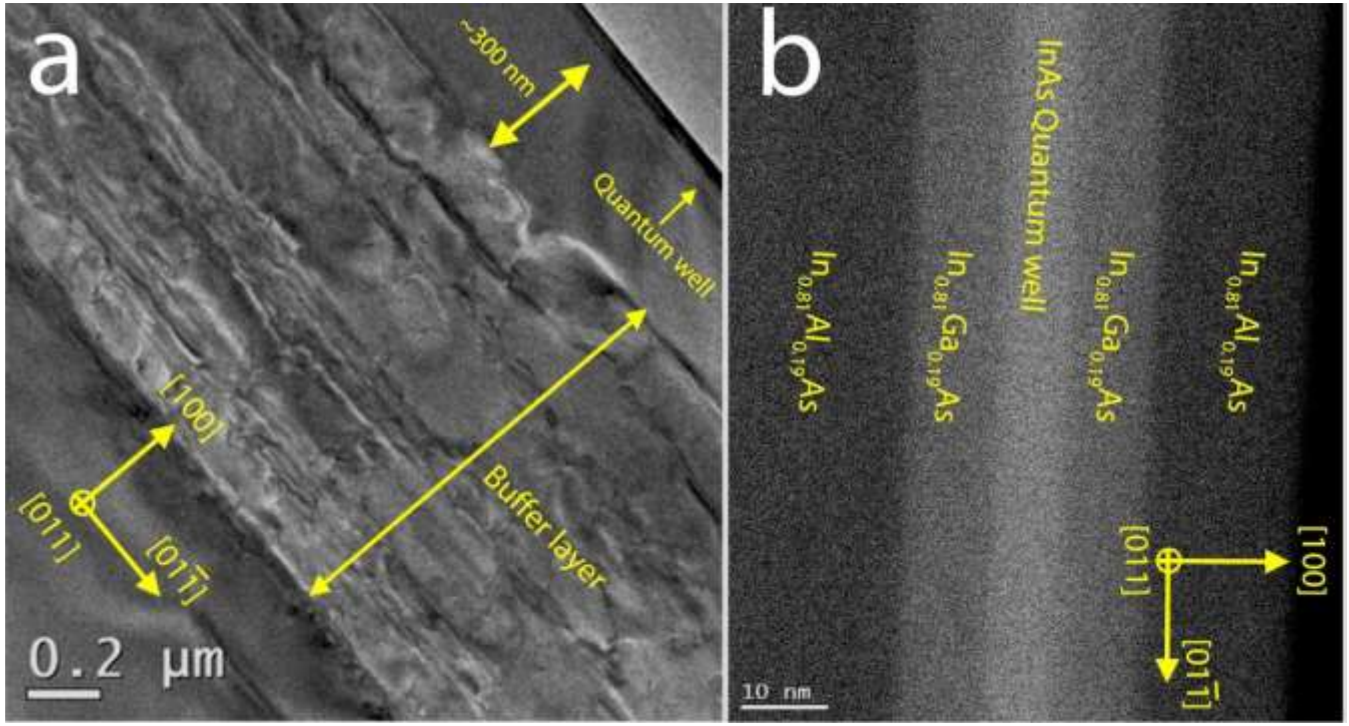
XRD analysis of strain





- Top: (004) XRD rocking curves showing GaAs and $In_xAl_{1-x}As$ Bragg peaks for different *t* (MCX beamline, Elettra, Trieste, 8keV photon energy)
- $In_{0.81}GaAs$ and $In_{0.84}GaAs$ peak shifts: strain reduction with increasing *t*
- Bottom: residual perpendicular strain in $In_{0.81}GaAs$ and $In_{0.84}GaAs$ vs *t* (*x* from (001) and (224) Bragg scans in bulk InGaAs)
- *t* ≥ 300nm: $In_{0.84}GaAs$ virtually strain-free, $In_{0.81}GaAs$ switches from compressive to tensile.

Cross-sectional TEM analysis

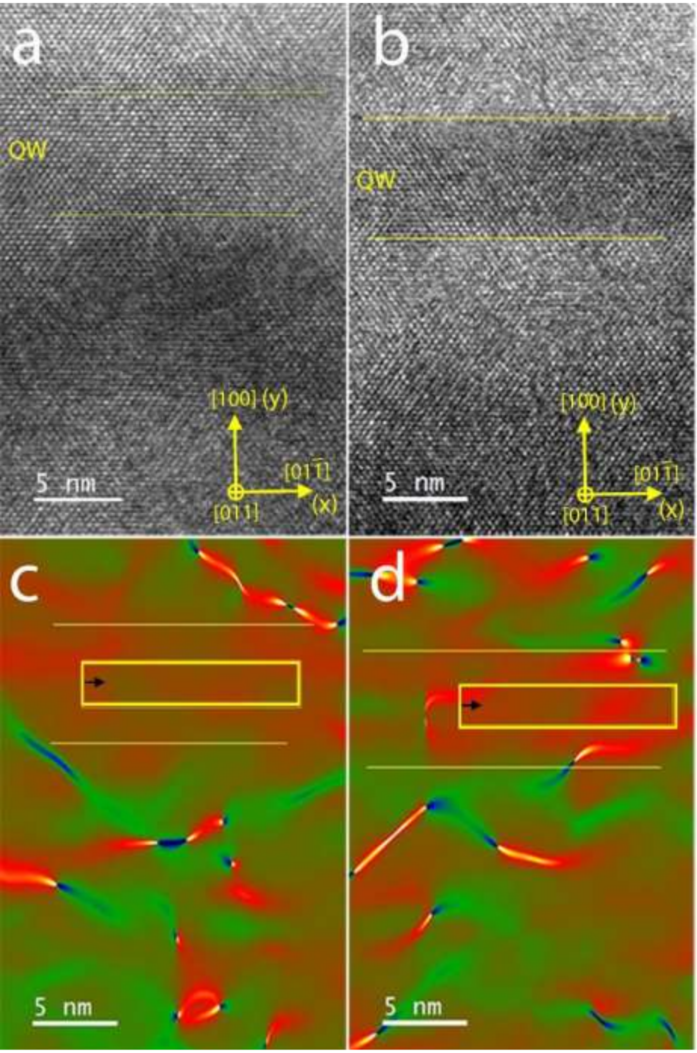


(a) Low-resolution [011] cross-sectional TEM overview of the heterostructure. Dislocations self-annihilate in the BL, dislocation-free QW region a)

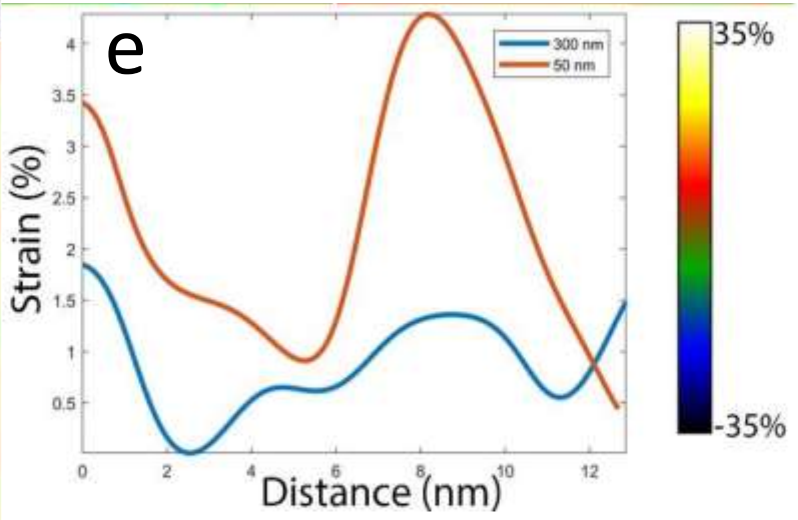
(b) Z-contrast HAADF STEM image of the QW region along the same zone axis

a) F. Capotondi, Thin Solid Films 484, 400 (2005)

TEM analysis of strain in InAs QW

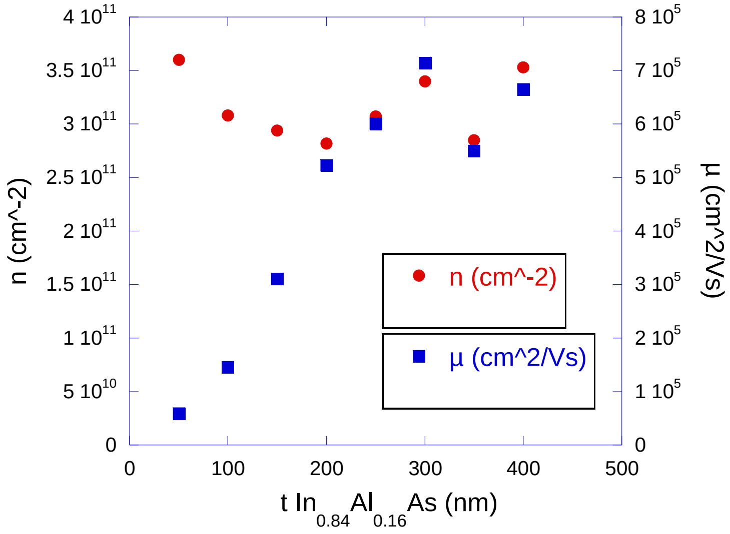


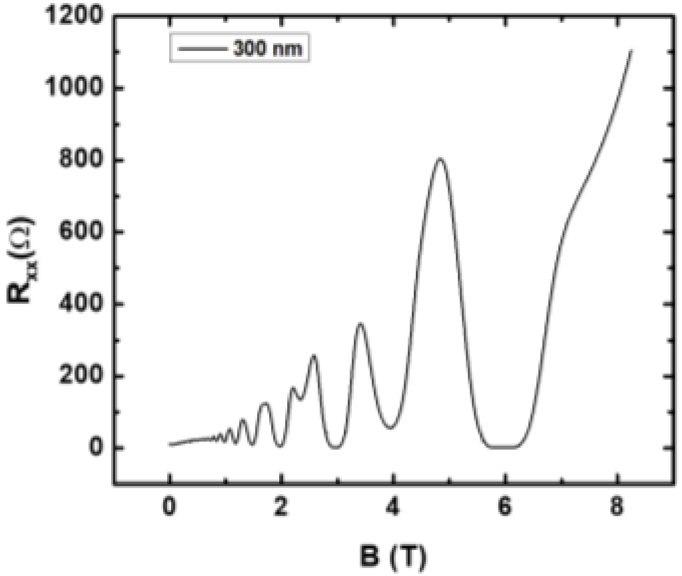
- High-resolution [011] cross-sectional TEM of InAs QWs for $t_{\text{In0.84GaAs}}$ of 300 nm (a) and 50 nm (b).
- Out-of-plane strain maps calculated using geometric phase analysis (GPA) with <111> reflections for heterostructure for $t_{\text{In0.84GaAs}}$ of 300 nm (c) and 50 nm (d)



- (e) strain profiles in yellow regions above. The mean strain values for $t_{\text{In0.84GaAs}}$ 300 nm and 50 nm is 0.9±0.5 % and 2.2±1.1 % respectively. Spatial resolution = 5 nm.

Low-T electron transport





- Low-temperature (T=4.2 K) electron charge density and mobility in InAs/In$_{0.81}$GaAs 2DEGs on Van der Pauw structures as a function of *t*.
- *μ* increases up to 7.1×10^5 cm^2/Vs at *t*=300nm, after which it saturates, consistently with the saturation of residual strain in the barriers. *n* ≈ 3-3.5×10^{11} cm^2/Vs, largely independent on *t*.
- Longitudinal resistance *Rxx* as a function of magnetic field B for *t* = 300nm: 2DEG without parasitic conduction channels, and onset of integer quantum Hall plateaus.

Conclusions

- Optimization of $In_xAl_{1-x}As$ buffer layer → strain reduction, thickness increase in metamorphic $InAs/In_{0.81}Ga_{0.79}As$ QWs on GaAs
- Thickness of last $In_{0.84}Al_{0.16}As$ step 50 to ≥ 300 nm:
  - Strain in $In_{0.81}Ga_{0.79}As/In_{0.81}Al_{0.79}As$ barriers compressive to tensile
  - Strain in InAs QWs from 2.2% to 0.9%
  - Low-T electron mobility from 6×10^4 cm^2/Vs 7.1×10^5 cm^2/Vs
- 2DEG quality:
  - substantially increased for growth on GaAs
    (μ = 3.5 X 10^5 @ n = 3.5×10^{11} cm^{-2}; 5×10^5 cm^2/Vs @ n = 4.5×10^{11} cm^{-2})
  - comparable with state-of-the-art on InP
    (μ = 8.3 X 10^5 @ n = 4×10^{11} cm^{-2}; $10^6 cm^2/Vs$ @ n = 6×10^{11} cm^{-2})

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