Mobility Enhancement of 2DHG in an $In_{0.24}Ga_{0.76}As$ Quantum Well by <110> Uniaxial Strain

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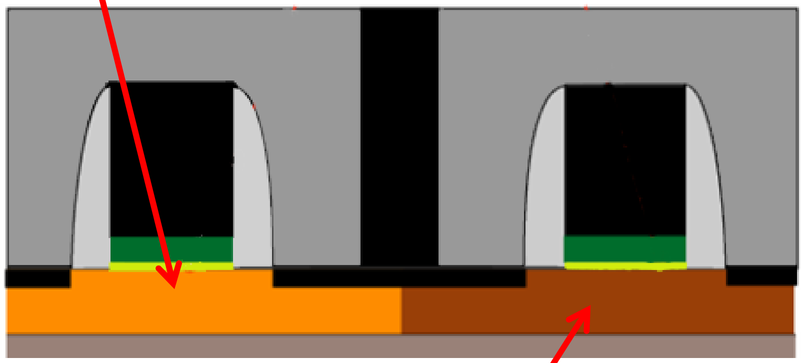
Motivation

- Improve p-channel InGaAs FETs for III-V CMOS
- Enhance μ : biaxial strain + uniaxial strain

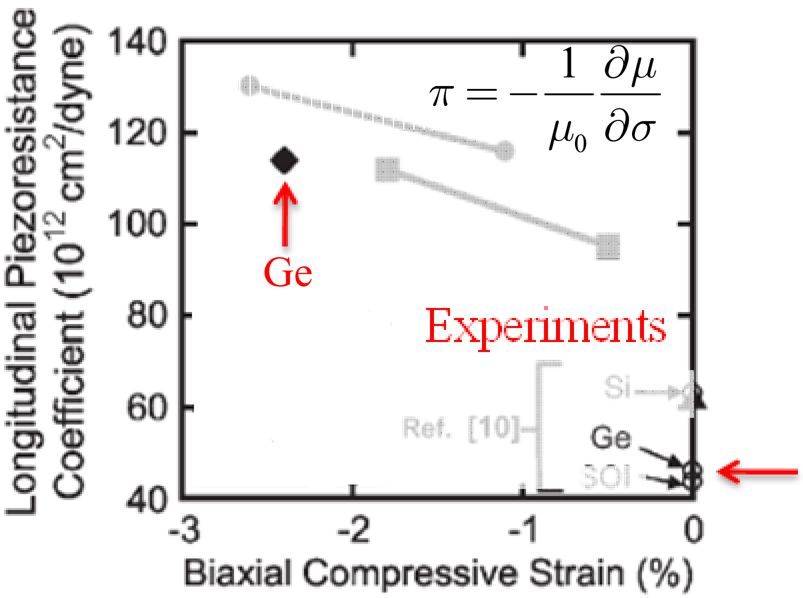
Demonstrated:
High-performance InGaAs nFET



Jesus del Alamo, *IEDM 2007*, short course

Wanted:
High-performance InGaAs pFET

Si_xGe_{1-x} pFET



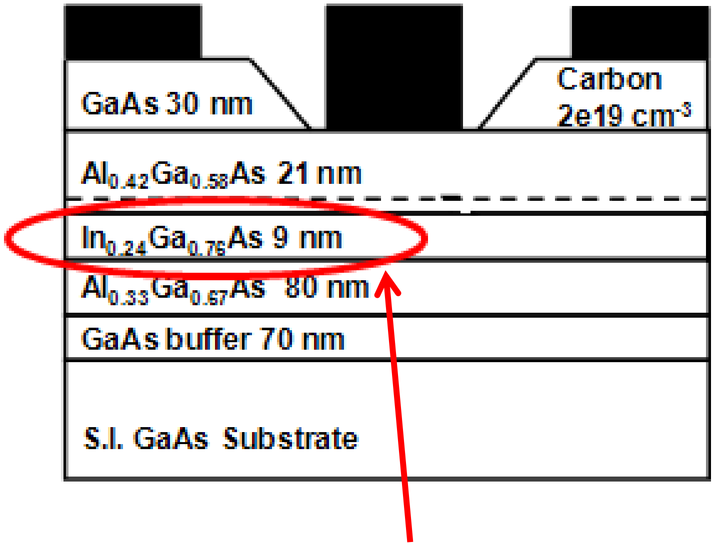
$$\pi = -\frac{1}{\mu_0}\frac{\partial \mu}{\partial \sigma}$$

$\pi_{L\_<110>}(\text{with } \sigma_{bi}) > \pi_{L\_<110>}(\text{without } \sigma_{bi})$

Leonardo Gomez, *EDL*, 2010

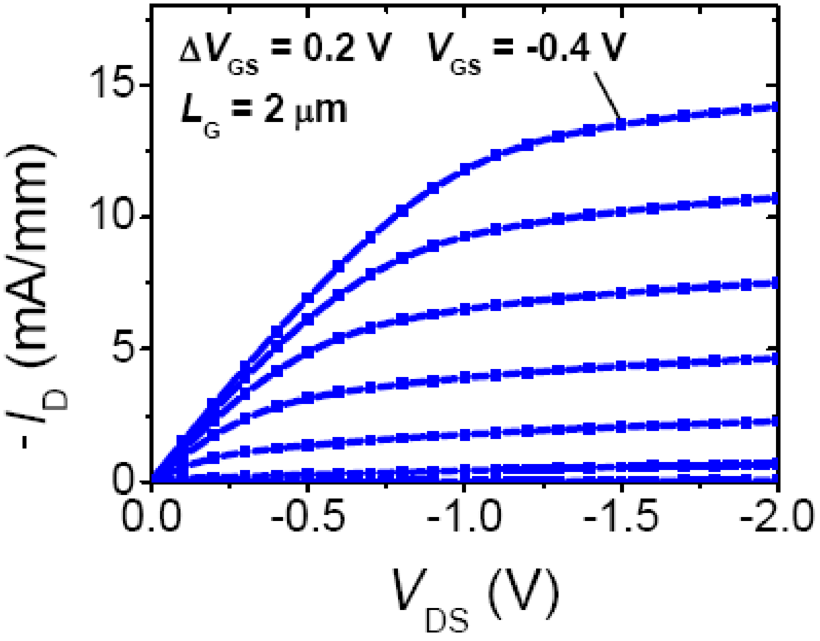
Experimental structure

- Biaxially strained p-channel $In_{0.24}Ga_{0.76}As$ QW:



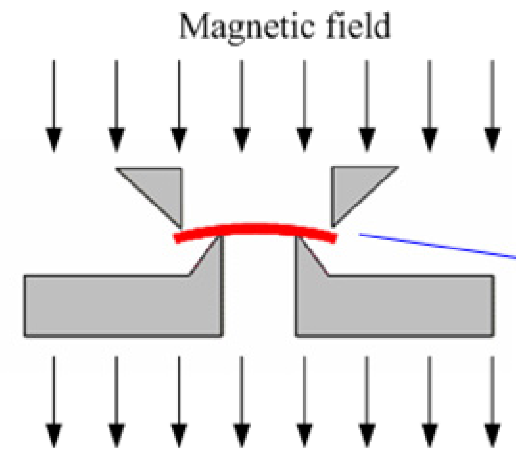
Channel strain :
1.7% biaxial compressive

- Typical output characteristics of fabricated QW-FET

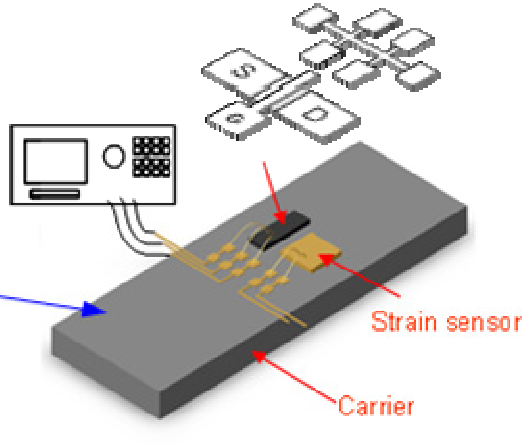


Experiment approach

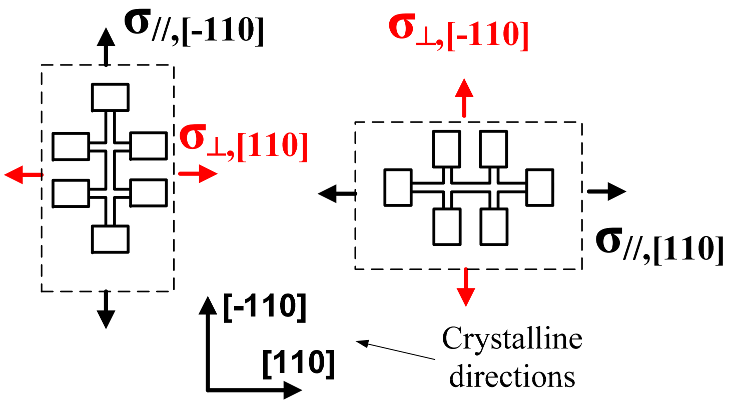
- Apply uniaxial stress to GaAs chips
- Measure response of ungated Hall bars
  - High I_G prevents accurate C-V to extract C_G and p_s



- Mechanism to bend GaAs chips
  - Can apply **tensile** or **compressive** stress

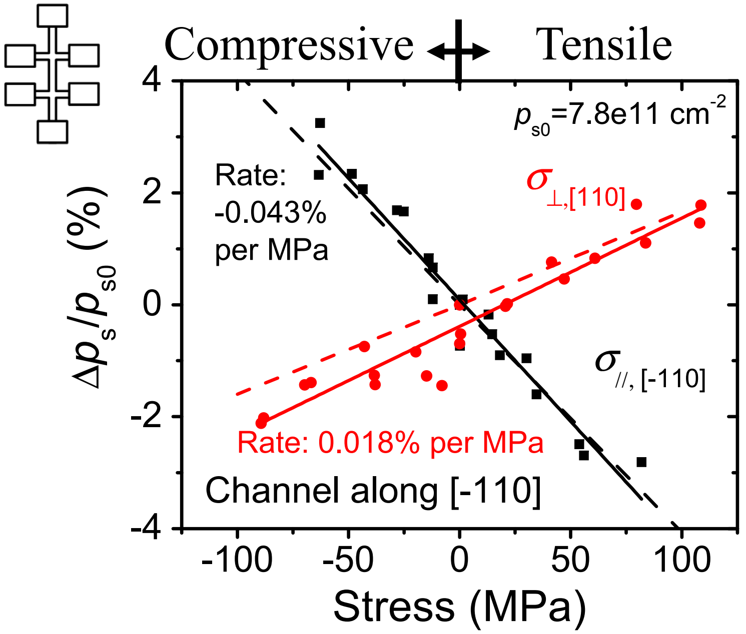


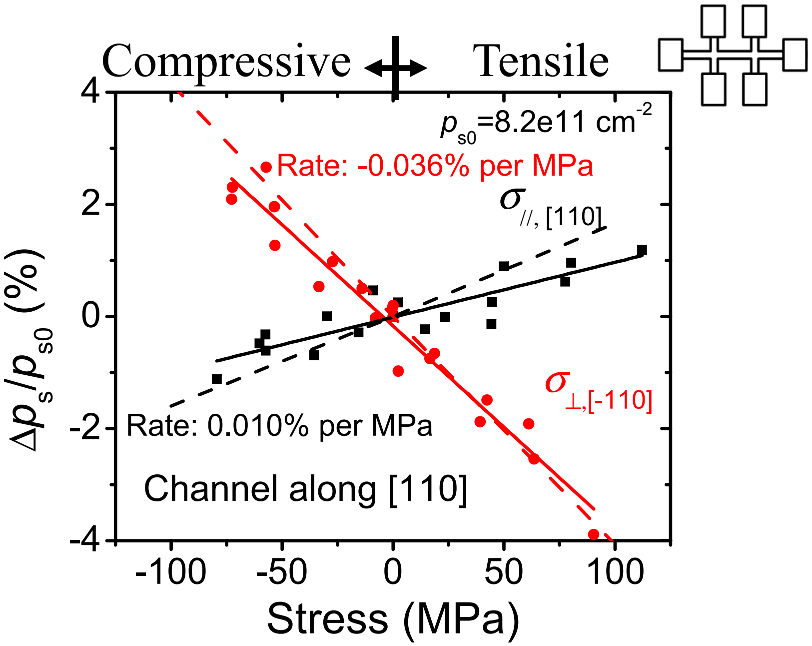
- Supporting mechanism and connections



- Stress and Hall bar orientations

Sheet hole density change

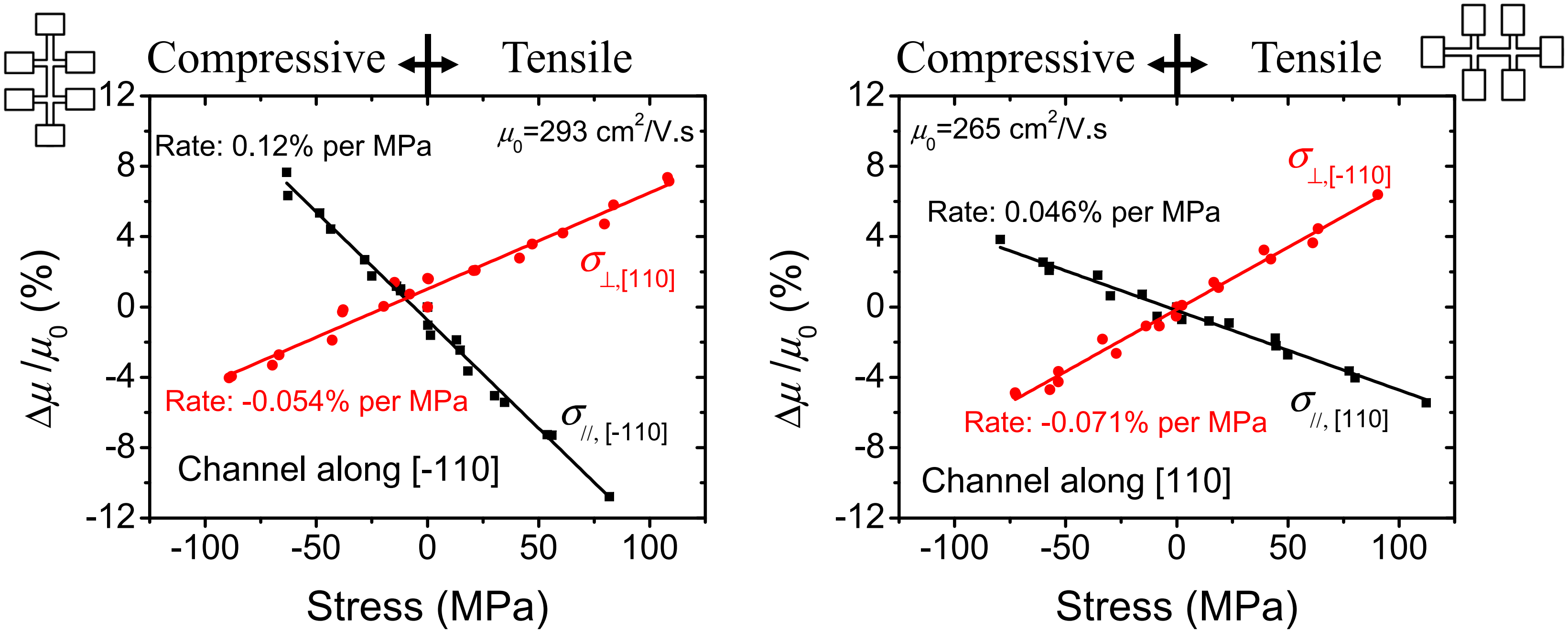




Solid lines: linear fittings to data
Dashed lines: 1D SP simulation with piezoelectric effect

- Almost identical patterns in Δp_s for Hall bars along [110] and [-110]
  - Δp_s determined by piezoelectric effect
  - Similar to our previous p-channel GaAs study. (L. Xia, to be published on *TED*)

Hole mobility change

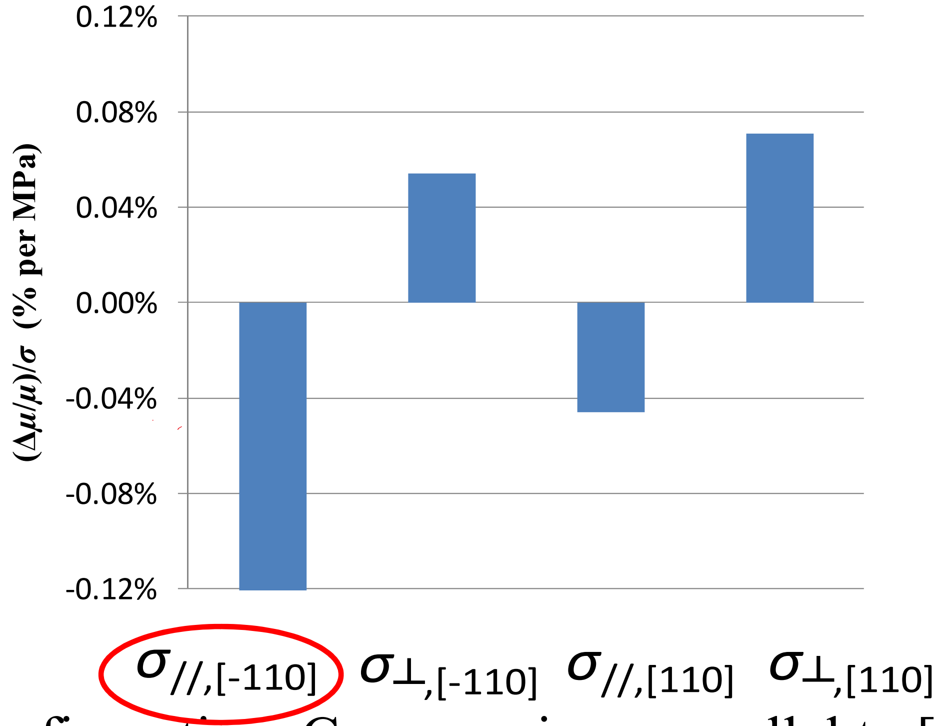


Solid lines: linear fitting to data

	$\mu_{//}$	$\mu_{\perp}$
Tensile	↓	↑
Compressive	↑	↓

- General trends of μ_h:
  - Dominant factor: relative orientation of stress and transport direction
  - Similar in Si and Ge

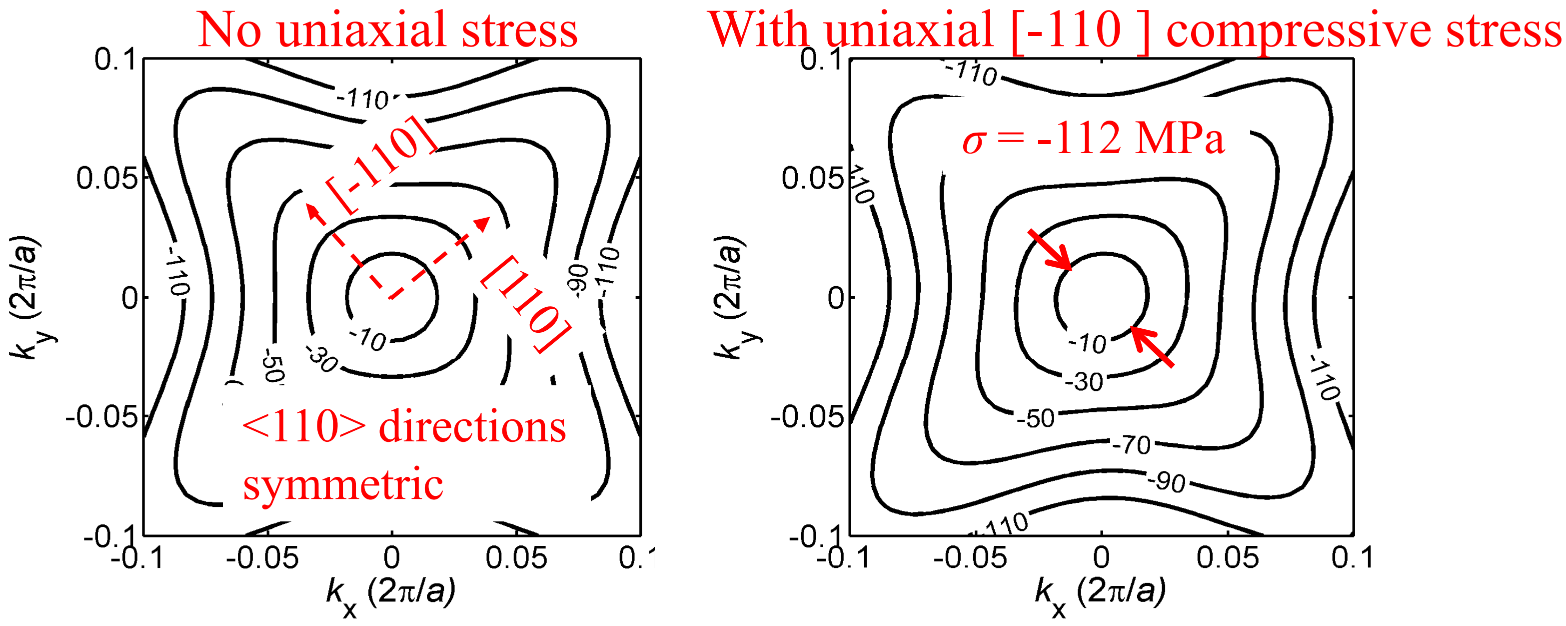
Sensitivities of μ_h to $\sigma_{<110>}$



- Preferred configuration: Compressive σ parallel to [-110] channel
- Questions:
  - Why $\pi_{//}$ different from $\pi_{\perp}$?
  - Why $|\pi_{//,[-110]}| \neq |\pi_{//,[110]}|$, and $|\pi_{\perp,[-110]}| \neq |\pi_{\perp,[110]}|$?

Anisotropy between $\pi_{//}$ and $\pi_{\perp}$

- Dominated by in-plane VB dispersion anisotropy
  - Simulation: 2D in-plane dispersion relation in QW by *k.p* method



No uniaxial stress

With uniaxial [-110] compressive stress

[-110]

[110]

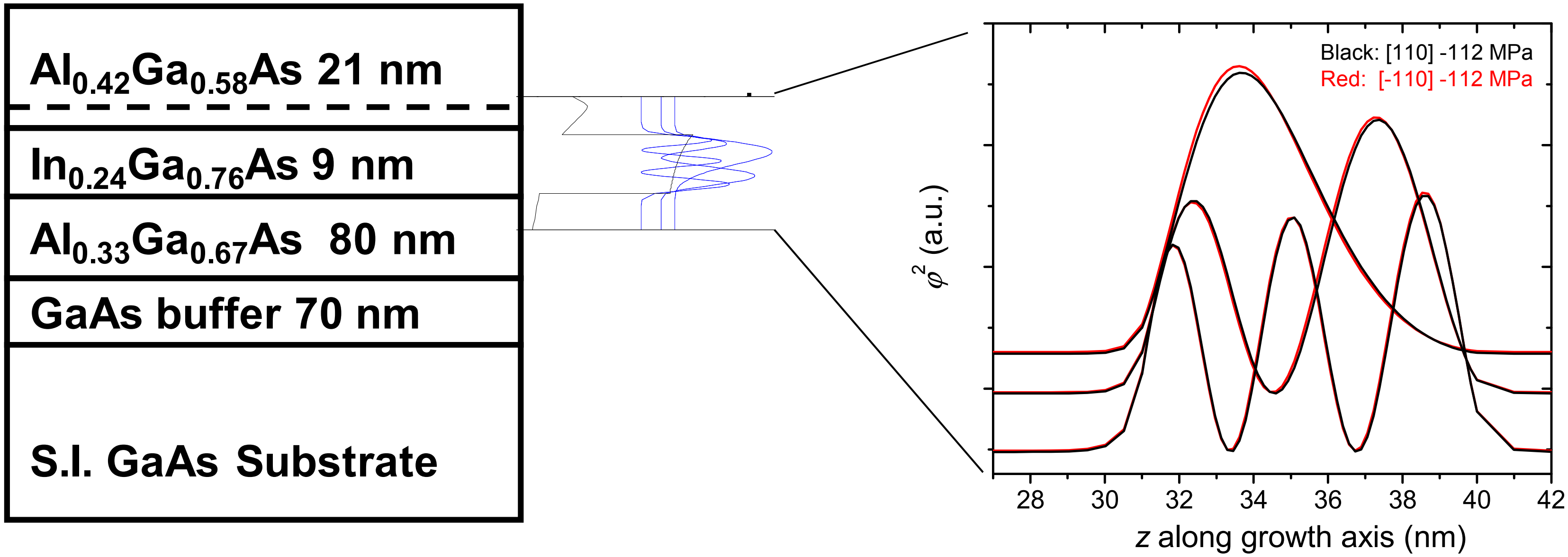
<110> directions symmetric

σ = -112 MPa

- Change of VB (m^*) // or ⊥ to σ are different → $\pi_{//}$ and $\pi_{\perp}$ different
  - Sign – opposite for $\Delta m^*_{//}$ and $\Delta m^*_{\perp}$
  - Magnitude – different (will show quantitatively later)
  - Similar in Si or Ge (S. Thompson, *IEDM*, 2004; O. Weber, *IEDM*, 2007)

Different π along the two <110> directions

- Counterintuitive:
  - $\Delta m^*_{//}$ (or $\Delta m^*_{\perp}$) should be the same for $\sigma_{[-110]}$ and $\sigma_{[110]}$
- 1st effect : p_s change due to piezoelectric effect ($p_s \uparrow \rightarrow \mu_h \downarrow$)
  - Partly explains $\pi_{\perp,[-110]}$ and $\pi_{\perp,[110]}$ difference
  - May have decreased $\pi_{//,[-110]}$ and increased $\pi_{//,[110]}$
- 2nd effect: polarization-field-induced quantization change



$Al_{0.42}Ga_{0.58}As$ 21 nm

$In_{0.24}Ga_{0.76}As$ 9 nm

$Al_{0.33}Ga_{0.67}As$ 80 nm

GaAs buffer 70 nm

S.I. GaAs Substrate

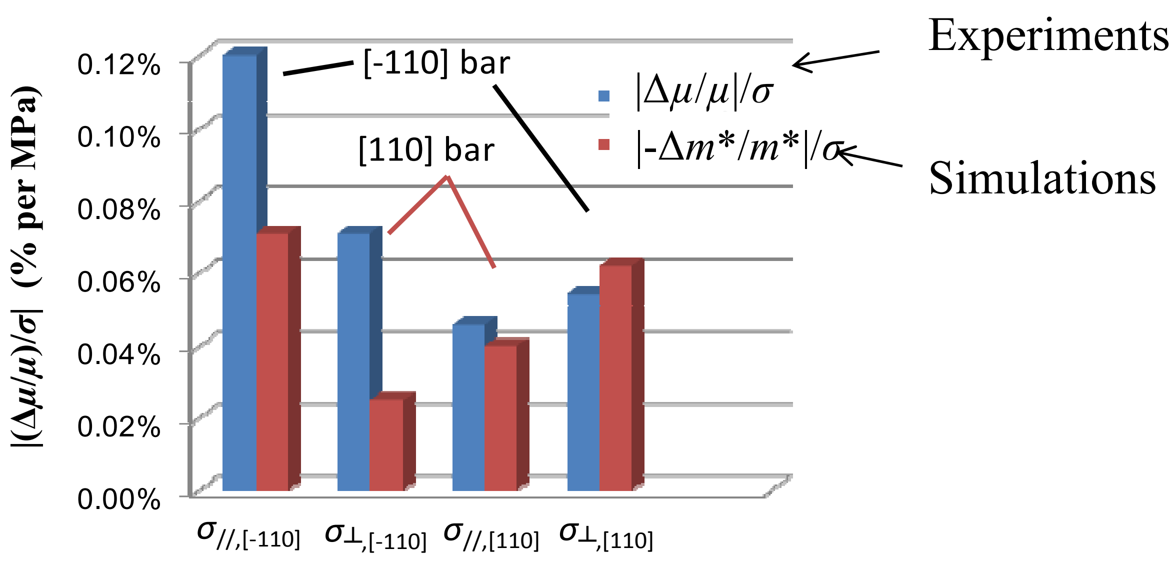
Comparison between experiments and simulations

- Extract average conductivity m^* by approximations:

(M. D. Michielis, *TED*, 2007)

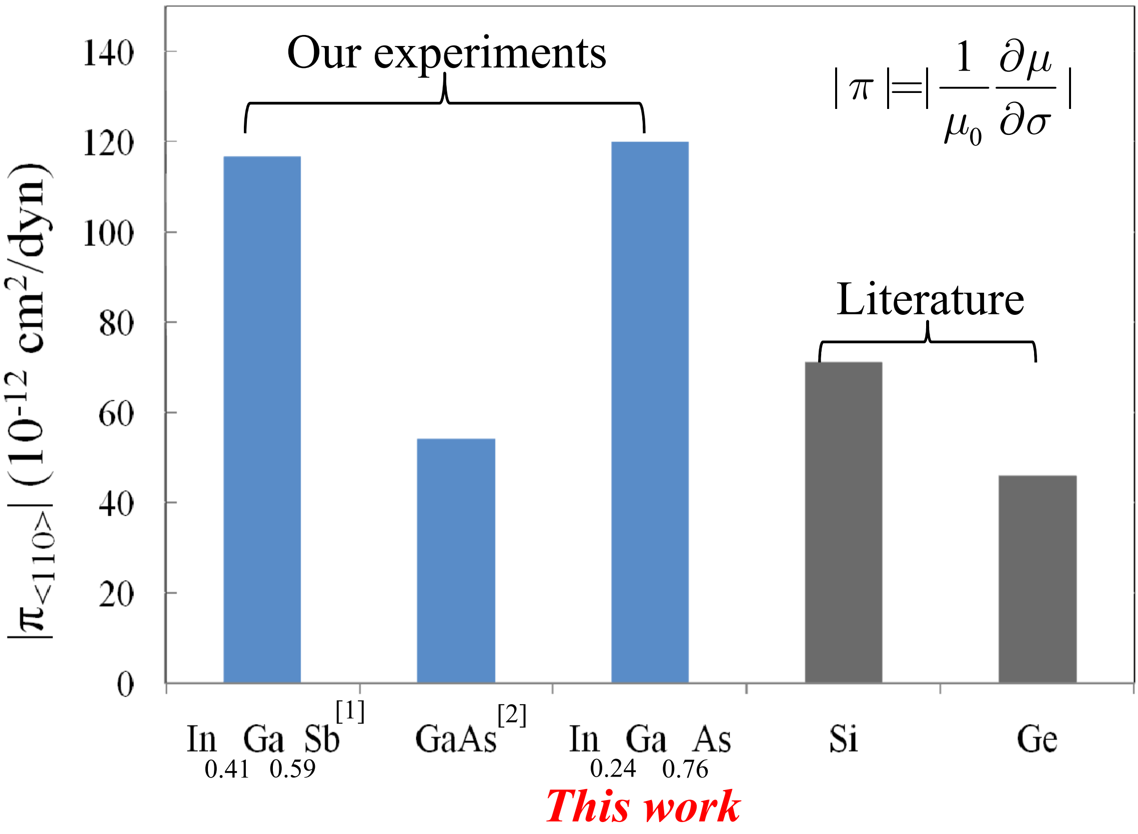
$$m_i^*(E) = \frac{\hbar^2 k_v^2}{2(E - E_v)}$$

$$m^* = \frac{\sum_i \int_{E_{vi}}^{\infty} m_i^*(E) f(E) g_i(E) dE}{\sum_i \int_{E_{vi}}^{\infty} f(E) g_i(E) dE}$$



- Other sources of anisotropy:
  - Anisotropic scattering (e.g. polar optical phonon scattering) $\tau_{//} \neq \tau_{\perp}$ when $m^*_{//} \neq m^*_{\perp}$ (J. J. Harris, *J. Phys. Chem. Solids*, 1973)
  - Lateral composition modulation along [110] (K. Y. Cheng, *Appl. Phys. Lett.*, 1992)
  - Strain relaxation along [110] (B. Bennett, *J. Electron. Mater.*, 1991)

Comparison with other materials



Measured from
2DHG or
inversion layers

$p_s = 6\sim8 \text{x} 10^{11}$ cm^{-2}
For Ge, $p_s = 2 \text{x} 10^{12}$ cm^{-2}

- Uniaxial strain is a viable path to enhance p-channel III-V FET performance
- Superposition of uniaxial strain on top of biaxial strain → large improvement in μ

[1] L. Xia, *APL*, 2011.
[2] L. Xia, to be published on *TED*