Regrown Ohmic Contacts to $In_xGa_{1-x}As$ Approaching the Quantum Conductivity Limit

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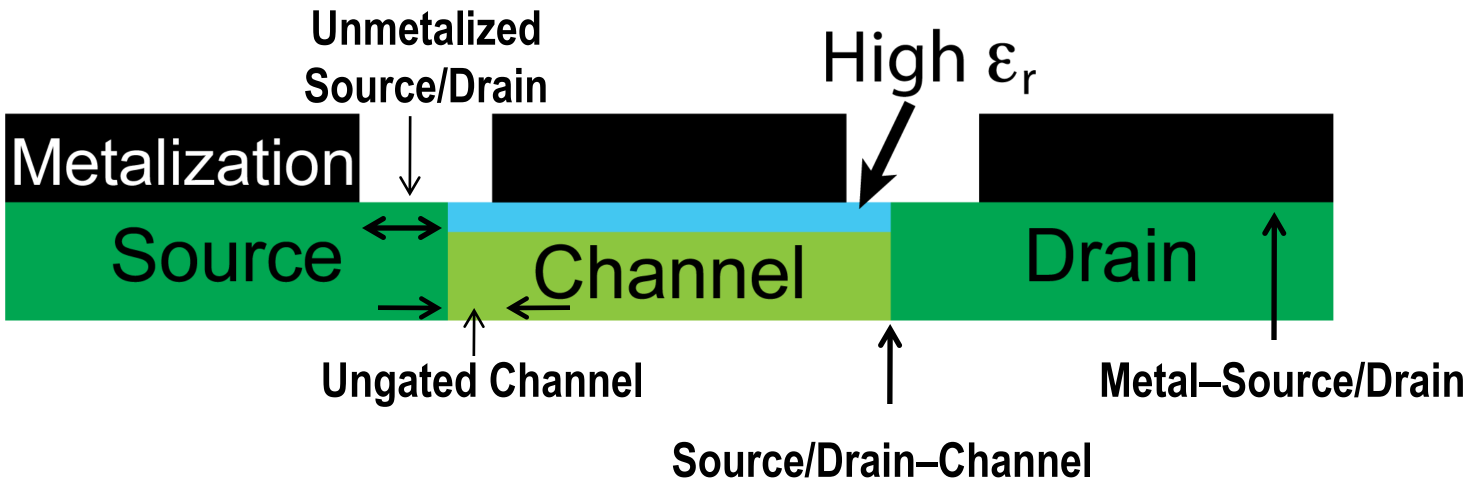
Outline

- Motivation
- Ballistic FET Current and TLM Quantum Conductance
- Process Flow
- Sample Structures
  - Regrowth TLM (RGTLM)
  - Transmission Line Measurement (TLM)
- Results
  - Metal-semiconductor (TLM)
  - Metal-semiconductor and semiconductor-channel (RGTLM)
- Theory Comparison
- Conclusion

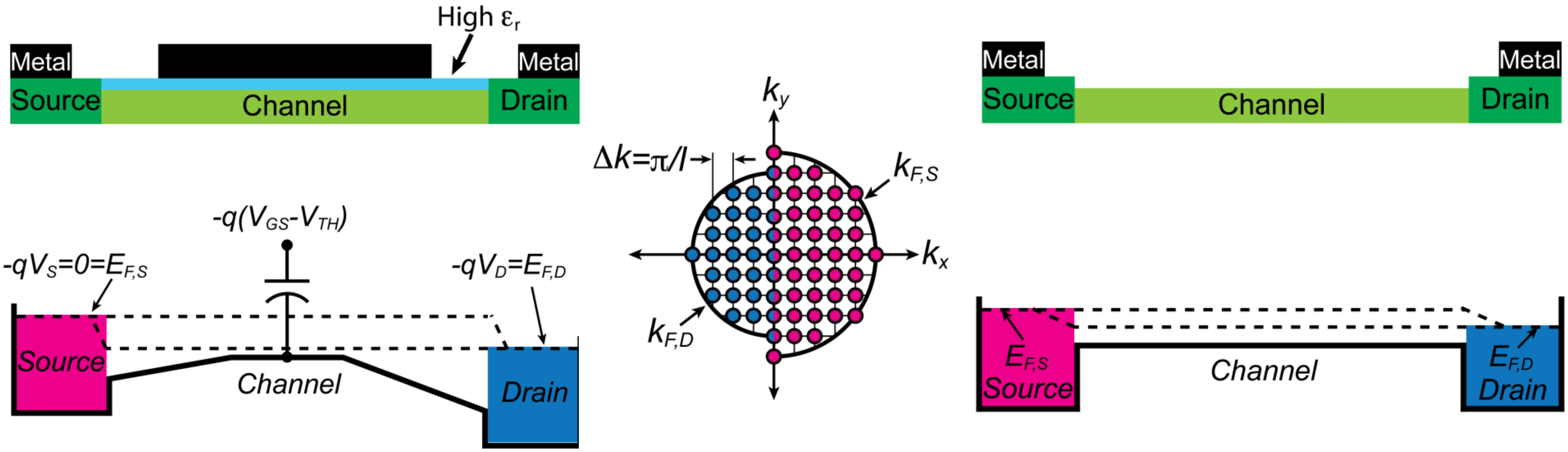
Motivation



- Two interfaces of interest
  - Metal–regrowth interface
  - Regrowth–channel interface
- Sheet resistance of regrowth
- Sheet resistance of ungated region
- Must ascertain contribution to overall access resistance from all of above

FET Ballistic Current = TLM Quantum Conductance

- Fundamental limits to contact resistance to a two-dimensional channel?
- Quantum limited contact resistance[1, 2] equivalent to ballistic transconductance



charge density $\mu \left(E_f - E_c\right)^1$

velocity $\mu \left(E_f - E_c\right)^{1/2}$

current $\mu \left(E_{f,s} - E_c\right)^{3/2} - \left(E_{f.d} - E_c\right)^{3/2}$

$$\mu \left(V_{gs} - V_{th}\right)^{3/2} - \left(V_{gd} - V_{th}\right)^{3/2}$$

current $\mu \left(E_{f,d} + qdV - E_c\right)^{3/2} - \left(E_{f,d} - E_c\right)^{3/2}$

$$\mu\ dV \times \left(E_{f,s} - E_c\right)^{1/2}$$

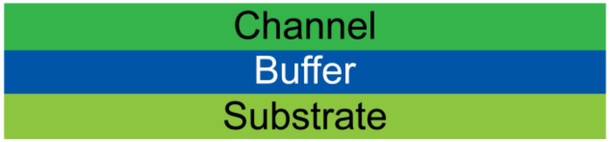
$$\mu\ dV \times \left(\text{carrier density}\right)^{1/2}$$

conductivity $\mu \left(\text{carrier density}\right)^{1/2}$

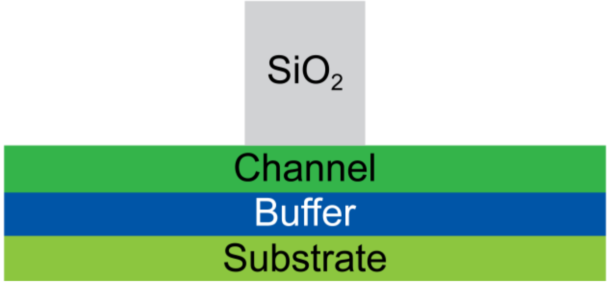
[1] P. M. Solomon *et al.*, IEDM Tech. Dig., 1989, p. 405; [2] J Guo *et al.*, IEEE Elec. Dev. Lett. **33**, 525 (2012).

Regrowth TLM (RGTLM) Process Flow

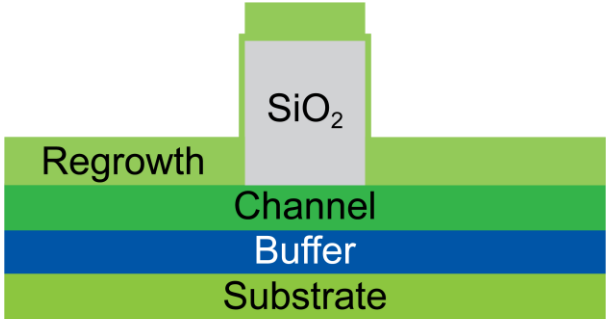
- Understand source (regrowth) to channel interface
- Rudimentary process flow
- Approximates FET structure and process flow
  - Independent of high-k properties
- Four-point Kelvin measurement



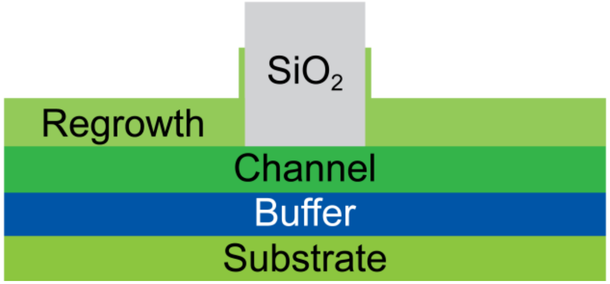
Epi growth



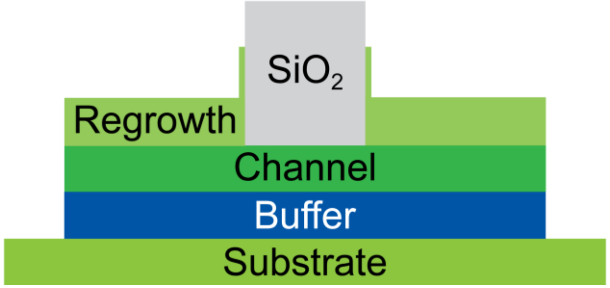
Dummy Pillar Definition



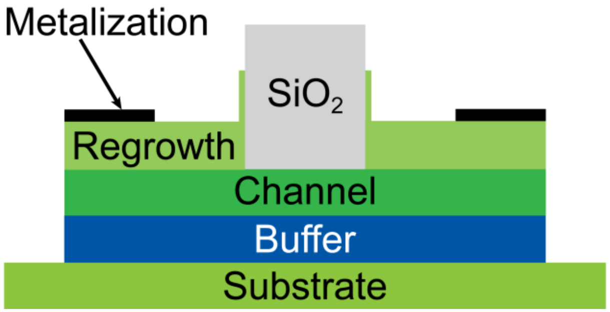
Regrowth



Planarization



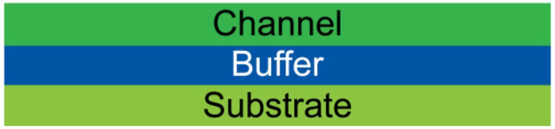
Isolation



S/D Metalization

TLM Process Flow

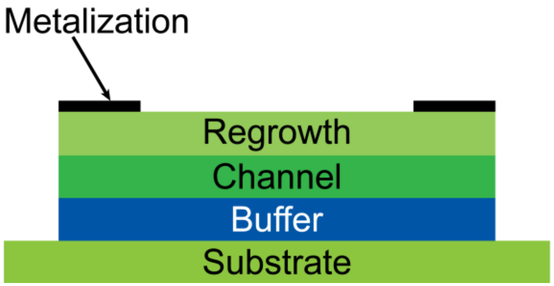
- Understand metal to source (regrowth) interface
- Rudimentary process flow
- Can be done on same die as RGTLM
- Four-point Kelvin measurement



Epi growth

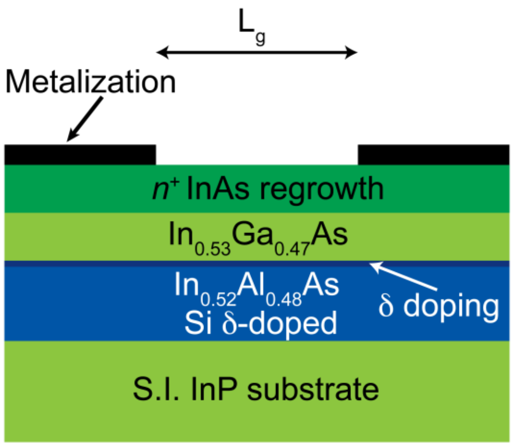
Regrowth

Isolation

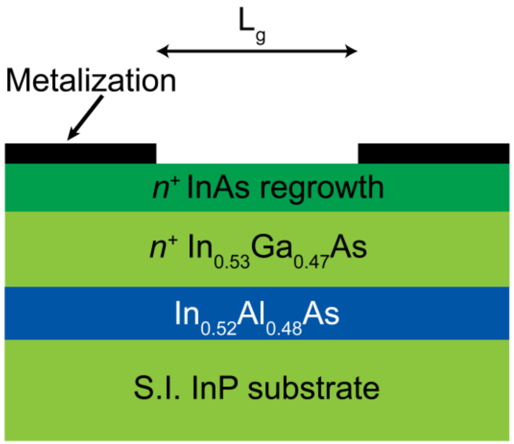


S/D Metalization

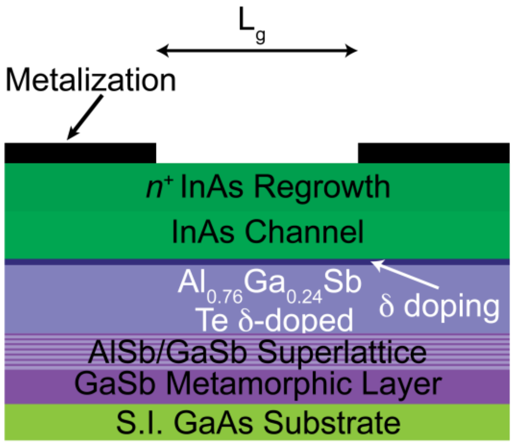
Sample Structures: TLM



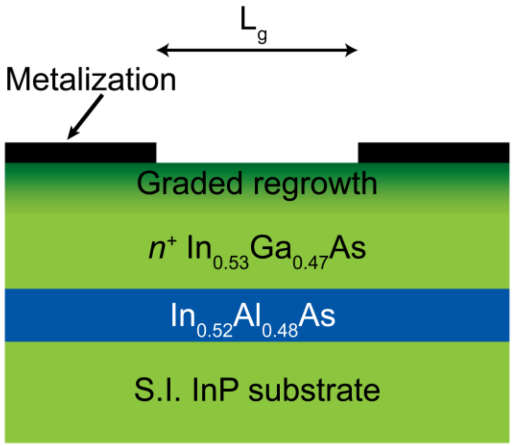
InAs RG on δ–doped 25 nm $In_{0.53}Ga_{0.47}As$ channel



InAs RG on 100 nm n^+ $In_{0.53}Ga_{0.47}As$ channel

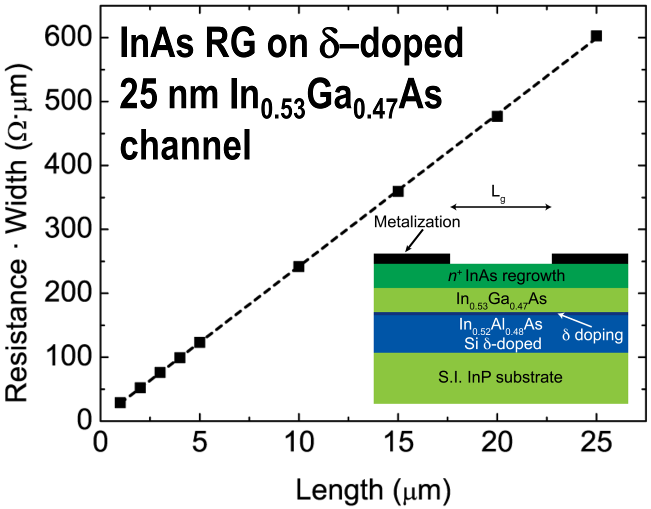


InAs RG on δ–doped 15 nm InAs channel

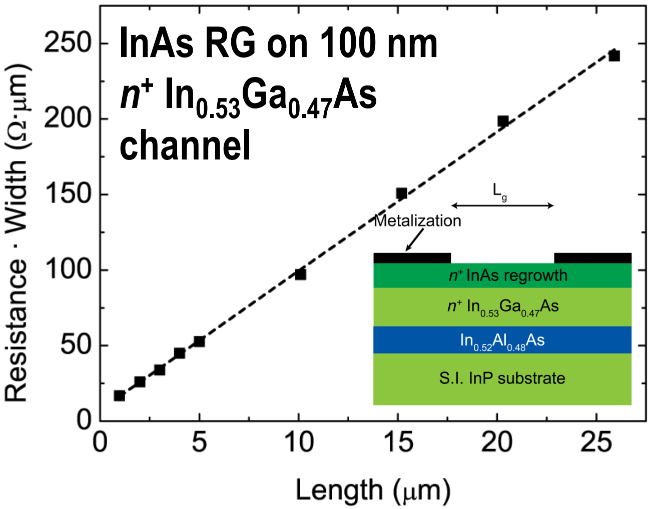


$In_{0.53}Ga_{0.47}As$ → InAs RG on 100 nm n^+ $In_{0.53}Ga_{0.47}As$ channel

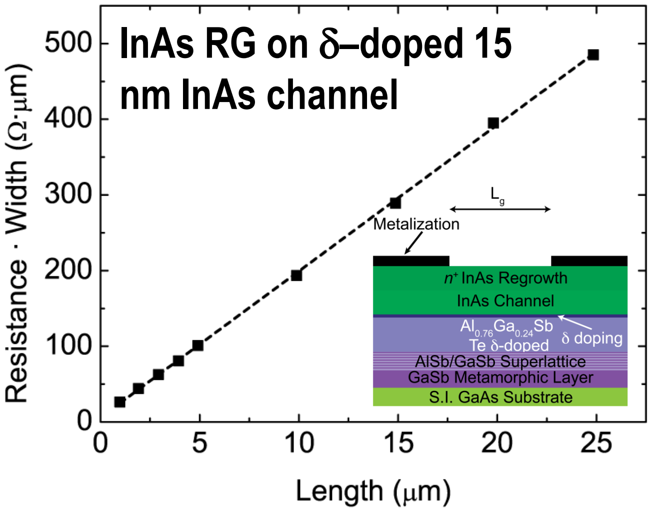
TLM Results



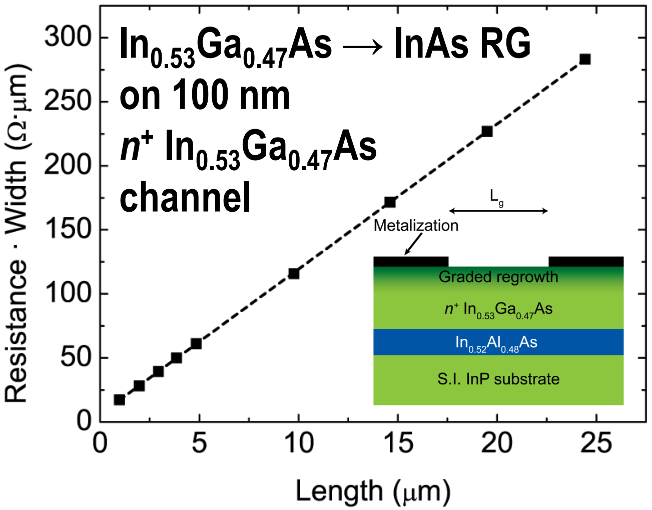
Slope: 23.8 Ω; Intercept/2: 2.1 Ω–μm



Slope: 7.4 Ω; Intercept/2: 4.6 Ω–μm

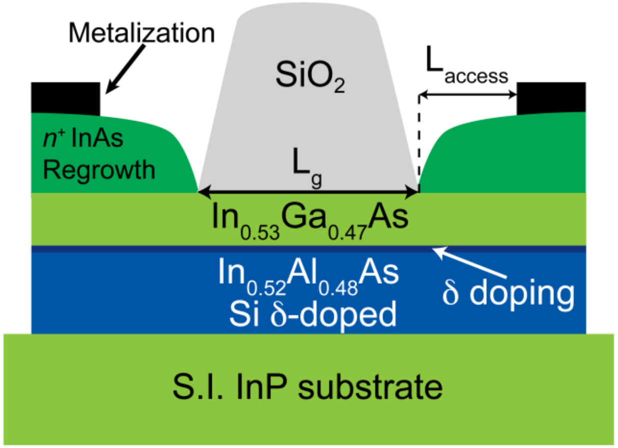


Slope: 19.3 Ω; Intercept/2: 3.0 Ω–μm

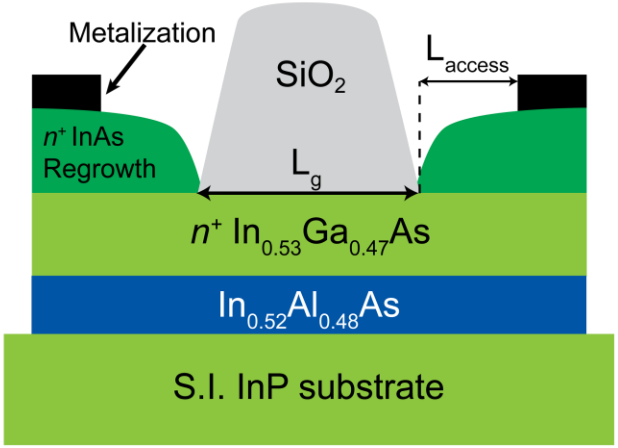


Slope: 11.3 Ω; Intercept/2: 3.0 Ω–μm

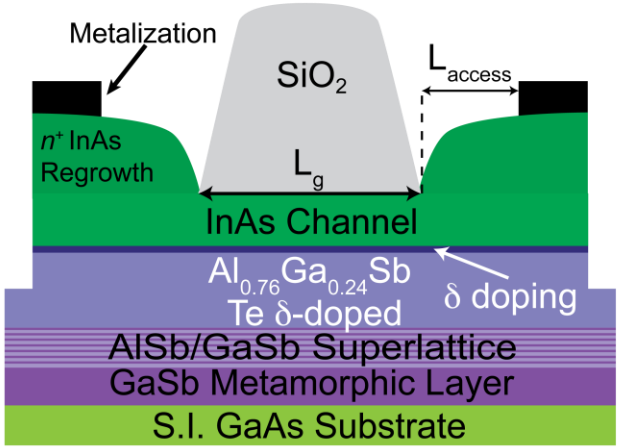
Sample Structures: RGTLM



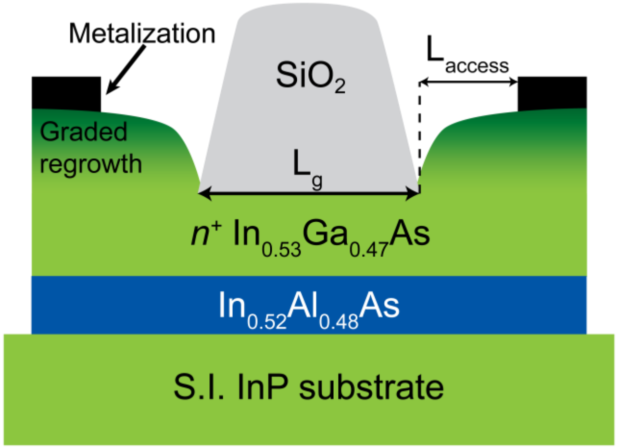
InAs RG on δ–doped 25 nm $In_{0.53}Ga_{0.47}As$ channel



InAs RG on 100 nm n^+ $In_{0.53}Ga_{0.47}As$ channel

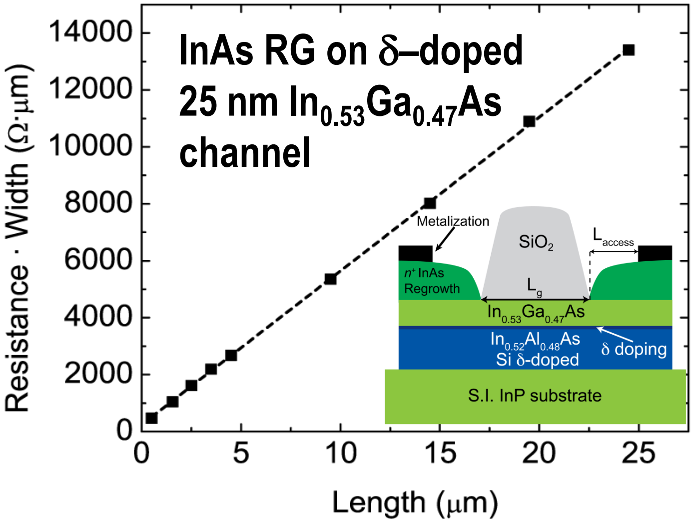


InAs RG on δ–doped 15 nm InAs channel

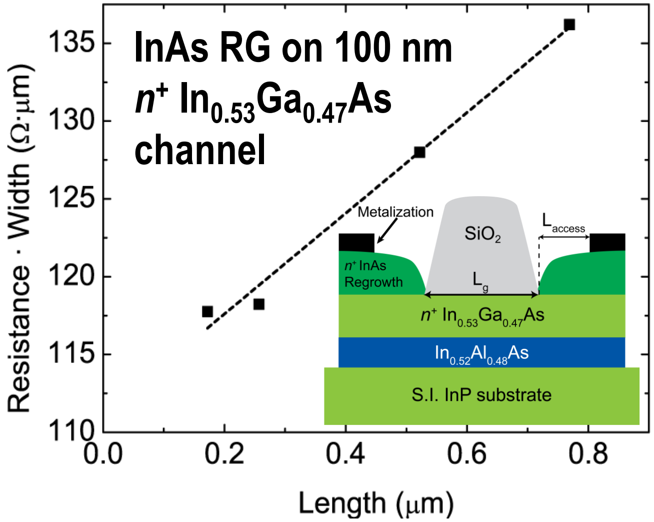


$In_{0.53}Ga_{0.47}As$ → InAs RG on 100 nm n^+ $In_{0.53}Ga_{0.47}As$ channel

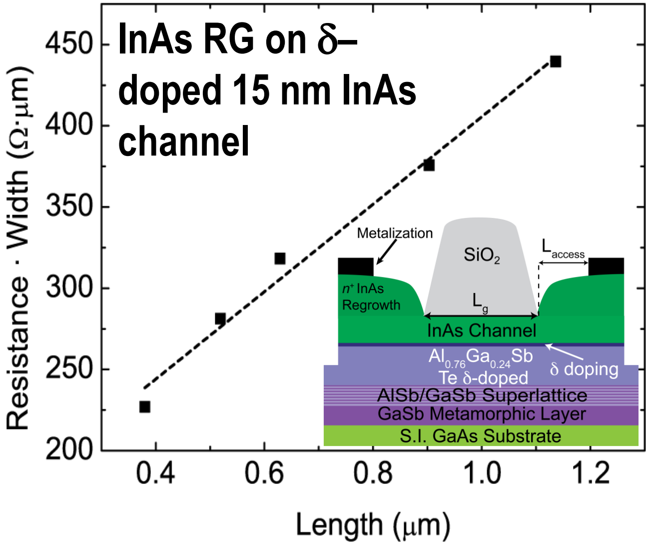
Regrowth TLM Results



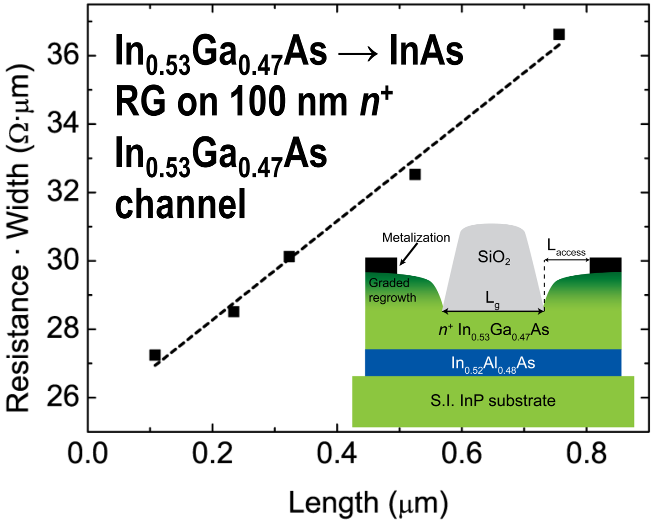
Slope: 540 Ω; Intercept/2: 120.8 Ω–μm



Slope: 32 Ω; Intercept/2: 55.6 Ω–μm



Slope: 269 Ω; Intercept/2: 68.2 Ω–μm



Slope: 15 Ω; Intercept/2: 12.7 Ω–μm

Results Summary

- **Contact resistance to thin channels (small n_s) limited by quantum conductance**
- **Low contact resistance of 12.7 Ω–μm (11.1 Ω–μm^2)**
- **Contact resistance low n_s channels 136.4 Ω–μm close to theoretical 80 Ω–μm**

N^+ Regrowth				
Composition	InAs	InAs	InAs	$In_{0.53}Ga_{0.47}As \rightarrow InAs$
Thickness	60 nm	60 nm	60 nm	60 nm
Doping	5-10×10^{19} cm^{-3}	5-10×10^{19} cm^{-3}	5-10×10^{19} cm^{-3}	5-10×10^{19} cm^{-3}
Sheet Resistivity	23.8 Ω	7.4 Ω	19.3 Ω	11.3 Ω
Channel				
Composition	$In_{0.53}Ga_{0.47}As$	$In_{0.53}Ga_{0.47}As$	InAs	$In_{0.53}Ga_{0.47}As$
Thickness	25 nm	100 nm	15 nm	100 nm
Doping	9×10^{12} cm^{-2}	3-5×10^{19} cm^{-3}	9×10^{12} cm^{-2}	3-5×10^{19} cm^{-3}
Sheet Resistivity	540 Ω	32 Ω	269 Ω	15 Ω
Access Resistivity	120.8 Ω–μm	55.6 Ω–μm	68.2 Ω–μm	12.7 Ω–μm
Metal/Regrowth Contact Resistivity	2.1 Ω–μm 0.2 Ω–μm^2	4.6 Ω–μm 1.5 Ω–μm^2	3.0 Ω–μm 0.4 Ω–μm^2	3.0 Ω–μm 0.8 Ω–μm^2

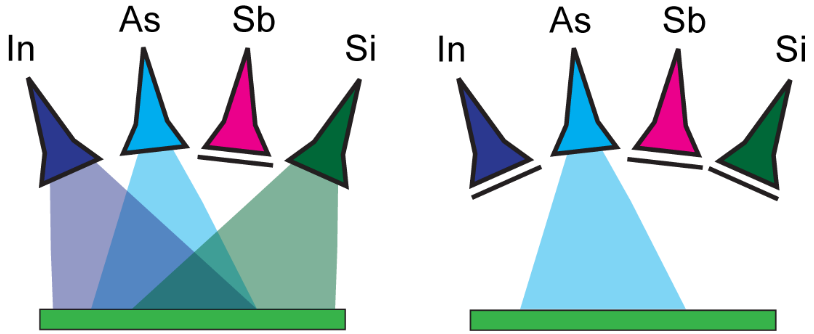
Conclusion

- Ballistic FET current equivalent to quantum conductance of TLM
- Should not add to FET contact resistance
- Material independent, i.e. true for all semiconductor materials
- Metal–regrowth contact resistance is small portion of overall R_c
    - ~ 3.0 Ω–μm (1.0 Ω–μm^2)
- Regrown ohmic contacts (136 Ω–μm) within a factor of 2 of theoretical 80 Ω–μm
- 12.7 Ω–μm (11.1 Ω–μm$^{2)}$ is true measure of interface properties
    - This includes regrowth to channel and metal to regrowth

Backup slides

MBE Regrowth by Migration Enhance Epitaxy (MEE)

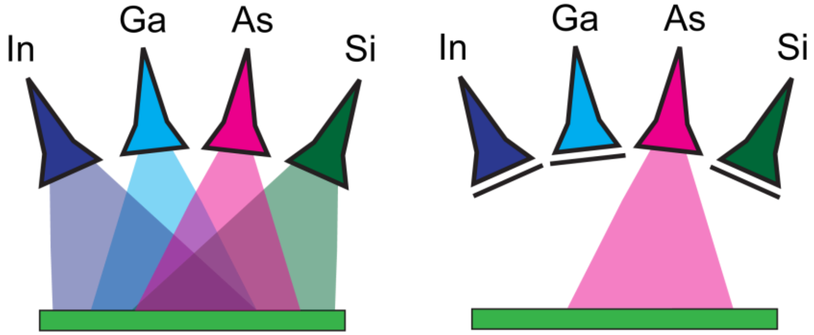
InAs Quasi MEE



In, As, and Si shutters open

As shutter open

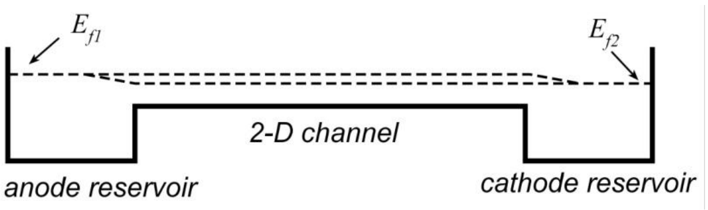
InGaAs Quasi MEE

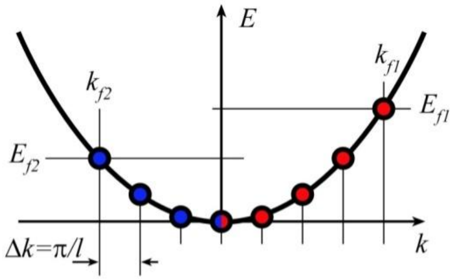


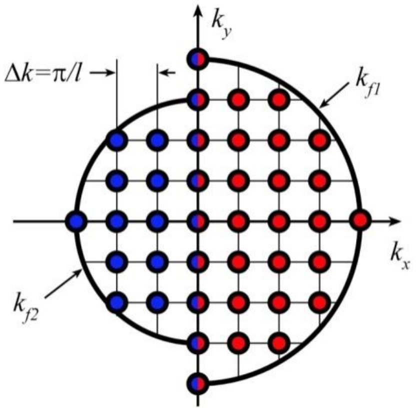
In, Ga, As, and Si shutters open

As shutter open

MBE Regrowth: Close to 2-D Quantum conductivity Limit:







Unidirectional 2D density of states: $c_{dos,1} = q^2 g m^* / 2\pi\hbar^2$

Charge density in left-moving states: $\rho_{s1} = c_{dos,1} V_{f1}$

Leftward-moving Fermi Velocity: $E_{f1} = qV_{f1} = m^* v_{f1}^2 / 2 \rightarrow v_{f1} = \sqrt{2qV_{f1} / m^*}$

Mean leftward electron velocity: $\bar{v}_1 = (4/3\pi) v_{f1} = (4/3\pi) \cdot \sqrt{2qV_{f1} / m^*}$

Leftward current: $J_1 = \rho_{s1}\,\bar{v}_1 = c_{dos,1} V_{f1} (4/3\pi) \cdot \sqrt{2qV_{f1} / m^*}$

Red States: charge moving in $+x$ direction; left to right

Blue States: charge moving in $-x$ direction; right to left

Energies taken relative to conduction band minimum in 2-D channel.

Total current: $J = c_{dos,1} \cdot \left(\frac{4}{3\pi}\right) \cdot \sqrt{\frac{2q}{m^*}} \cdot \left(V_{f1}^{3/2} - V_{f2}^{3/2}\right)$

Conductivity $G = \partial J / \partial V_f = c_{dos,1} \cdot \left(\frac{4}{3\pi}\right) \cdot \sqrt{\frac{2q}{m^*}} \cdot \frac{3}{2} \cdot V_f^{1/2}$

$G_{valley} = \frac{q^2}{\hbar} \cdot \frac{2^{1/2}}{\pi^{3/2}} \cdot n_{s,valley}^{1/2}$ including spin degeneracy.

Total conductivity found by summing over valleys and vertical eigenstates

UCSB regrowth resistance measurements are being limited by this effect