In-situ TEM Observation of Nickelide Contact Formation in InGaAs Nanowire Channels

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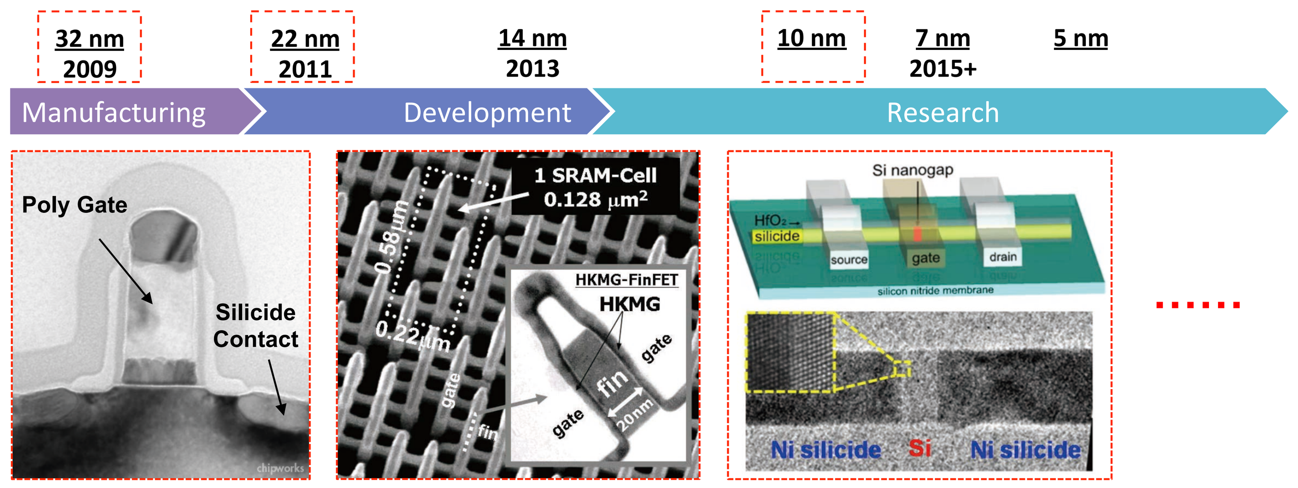
Motivation



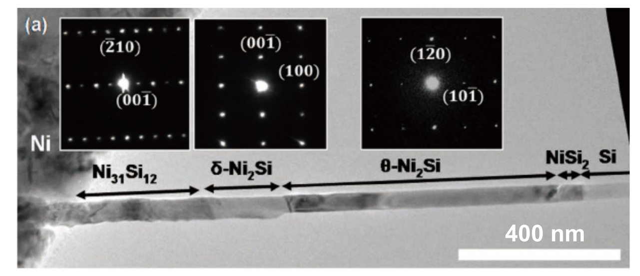
Contact requirements:

- Low resistivity, low processing T
- Clean and reproducible interface
- Self-aligned process
- Controllable channel length

Study of the metal-semiconductor reactions in sub-7nm channel materials is critical to continue scaling of semiconductor devices.

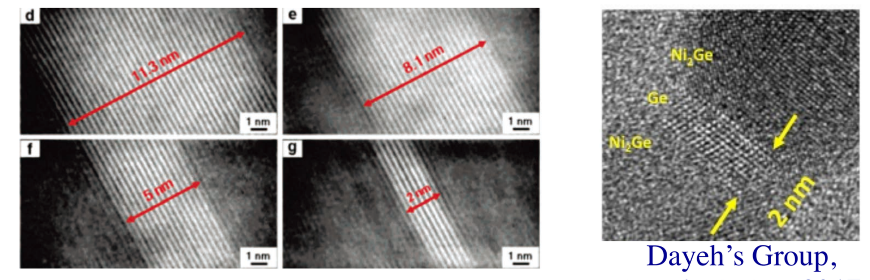
Objectives

1. Understand the differences of reaction thermodynamics in nanoscale channels than in their bulk counterparts.



Dayeh and Tu's Group, *Nano Letters*, 12, 3979, **2012**

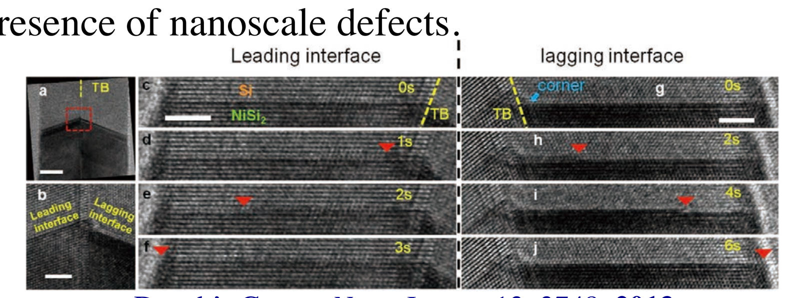
3. Achieve ultra-short channel lengths with well-controlled metal-semiconductor reactions.



Tu's Group, *Nano Letters*, 7, 2389, **2007**

Dayeh's Group, *in submission*, **2017**

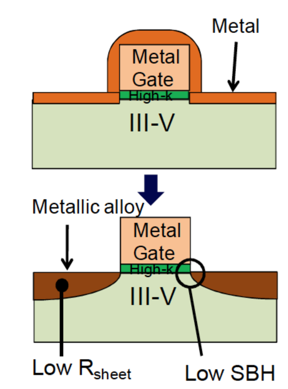
2. Explore the nucleation dynamics with the presence of nanoscale defects.



Dayeh's Group, *Nano Letters* 13, 3748, **2013**

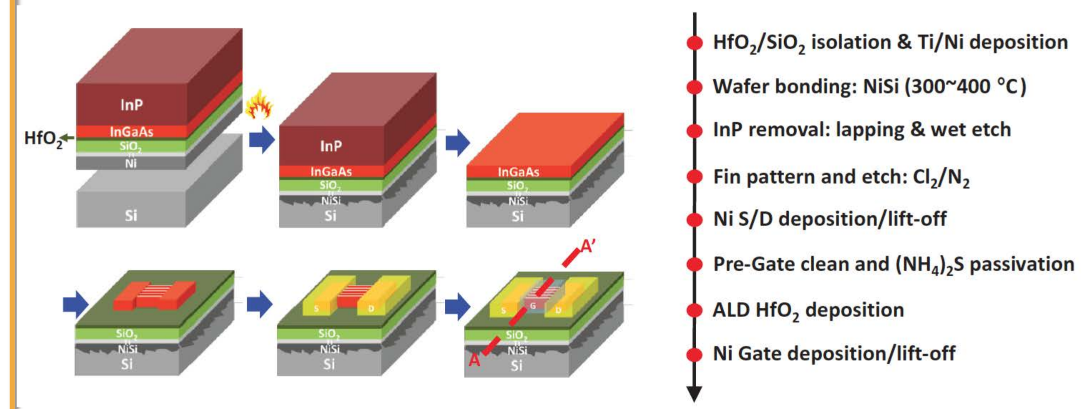
4. Contact reactions in nano-scale III-V channels have not been deeply investigated

Good examples of self-aligned contact formation to III-V planar devices on insulator on top of Si. ➔

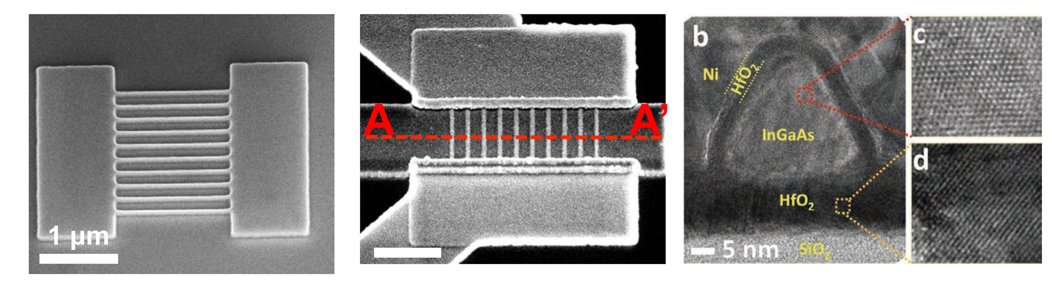


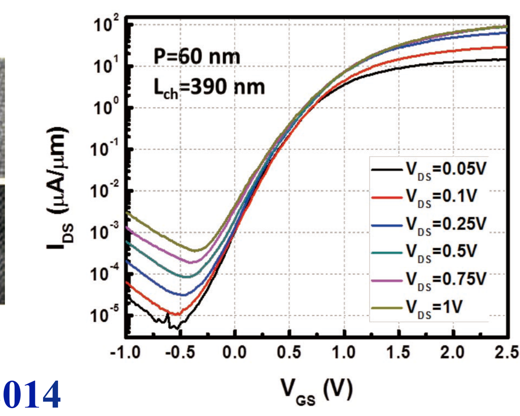
Kim et al., Electron Devices Meeting (IEDM), **2010**

Integration of III-V on Insulator on Si



The integration of III-V semiconductors on insulator on Si combines the advanced performance of III-V devices with well-developed fabrication procedure in silicon industry.

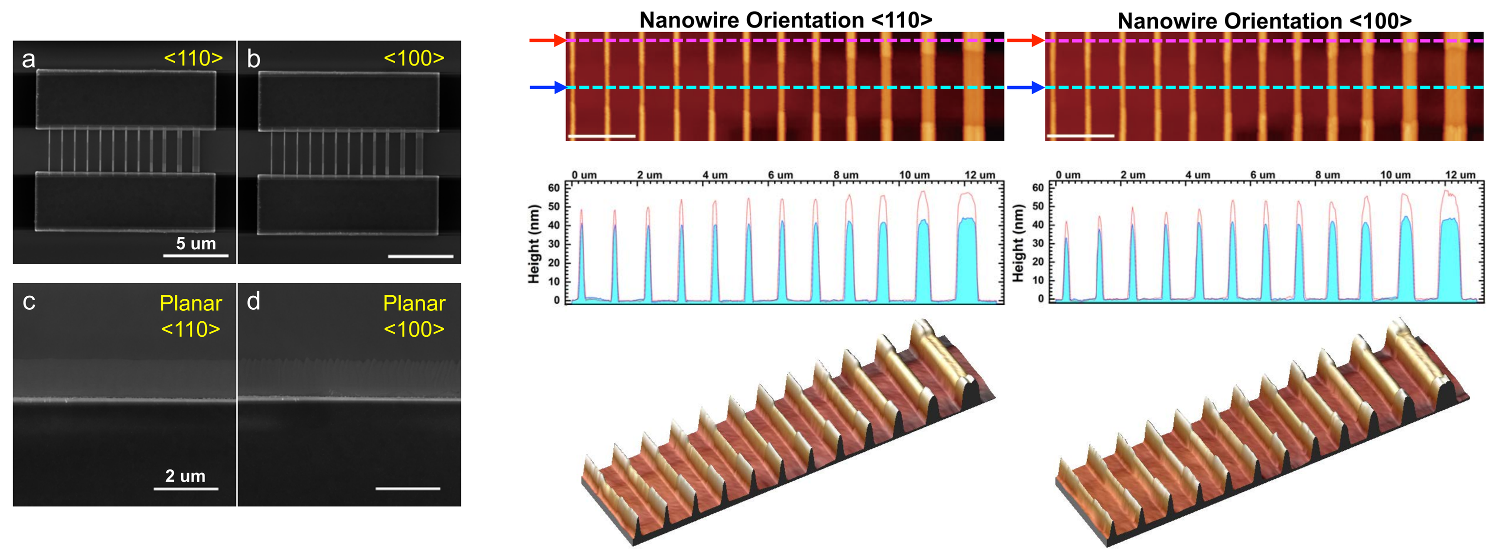




* This work was done by former group member, Dr. Xing Dai. Published in: *Advanced Functional Materials* 24, 4420-4426, **2014**

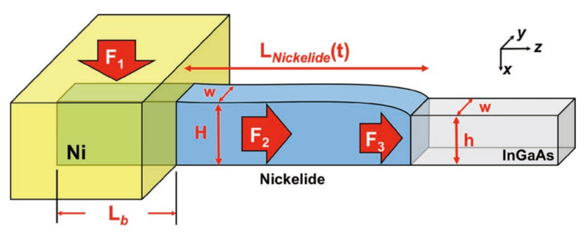
Morphologies and Kinetics

1. Orientation-dependent morphologies of Nickelide Contacts



- The nickelide phase has a flat interface with <110> oriented nanowires.
- Nanowires with smaller diameters have faster nickelide growth.
- Upon nickelide formation, the nanowire channel shows a 33% ± 5% height increase.

2. Surface-diffusion dominated process

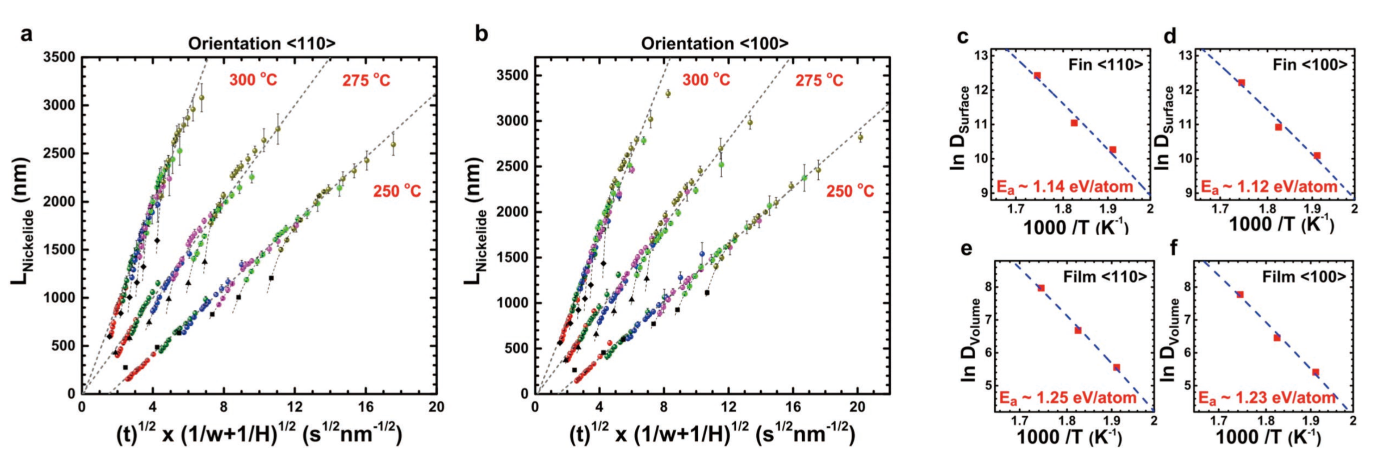


rate-limiting step	conditions	solution
Ni source supply limit	$k_{dissolve} \ll k_{growth}, D_{Ni}$	$L_{Nickelide}(t) = k_{dissolve}\left(\frac{1}{H}+\frac{2}{w}\right)L_b P t$
surface-diffusion limit $(X = 2(H+w)\delta)$	$D_{Ni} \ll k_{dissolve}, k_{growth}$	$L_{Nickelide}(t) = \sqrt{4PD_{Ni}\delta\left(\frac{1}{w}+\frac{1}{H}\right)}\cdot t^{1/2}$
volume-diffusion limit $(X = Hw)$	$D_{Ni} \ll k_{dissolve}, k_{growth}$	$L_{Nickelide}(t) = \sqrt{2PD_{Ni}}\cdot t^{1/2}$
interfacial reaction limit	$k_{growth} \ll k_{dissolve}, D_{Ni}$	$L_{Nickelide}(t) = k_{growth}\frac{h}{H}Pt$

*Here, $P = M_{Nickelide}(C^{eq}_{Ni/Nickelide} - C^{eq}_{Nickelide/InGaAs})/(N_A \rho_{Nickelide})$.

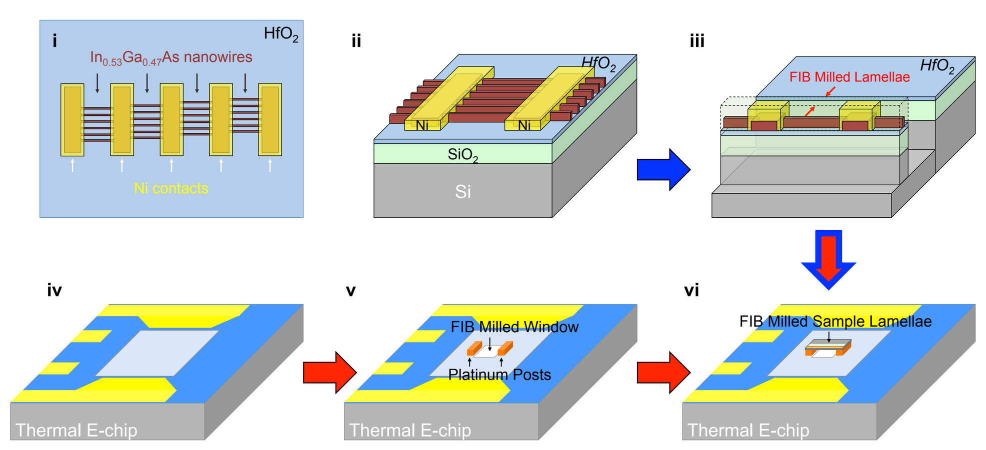
Three possible rate limiting steps:

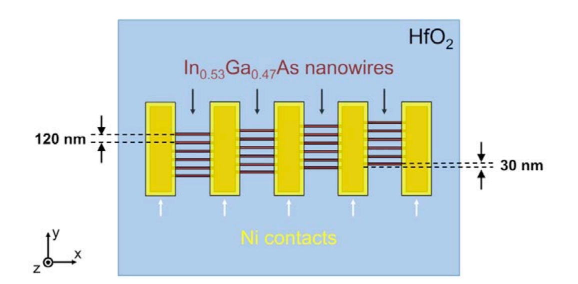
① Ni dissolution from contact
② Ni diffusion (surface or body)
③ Nickelide growth at the interface



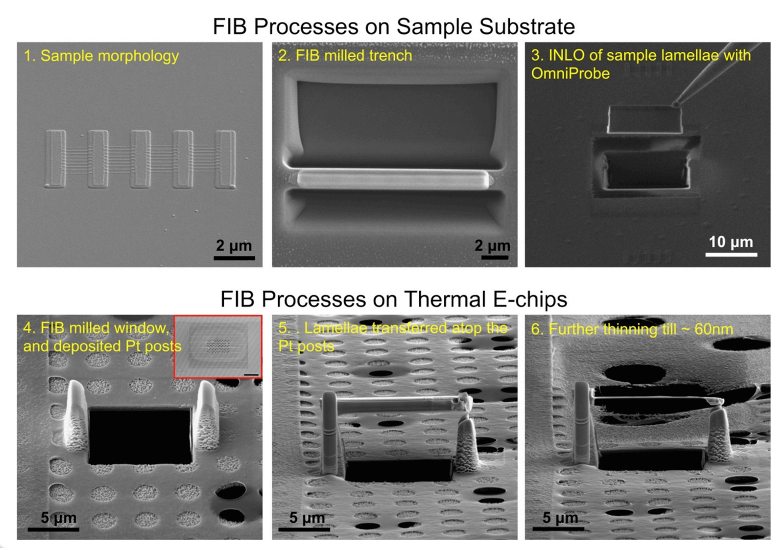
Chen, Renjie, and Shadi A. Dayeh. "Size and orientation effects on the kinetics and structure of nickelide contacts to InGaAs fin structures." *Nano letters* 15(6), 3770-3779, **2015**

in situ Heating TEM Platform

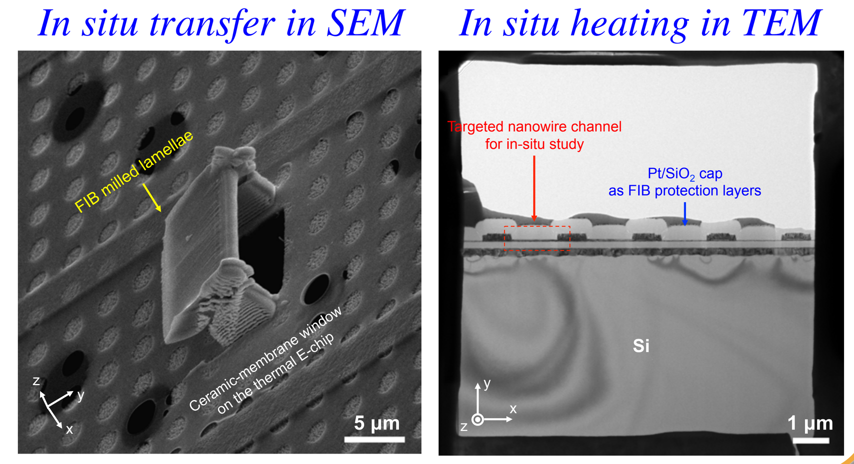




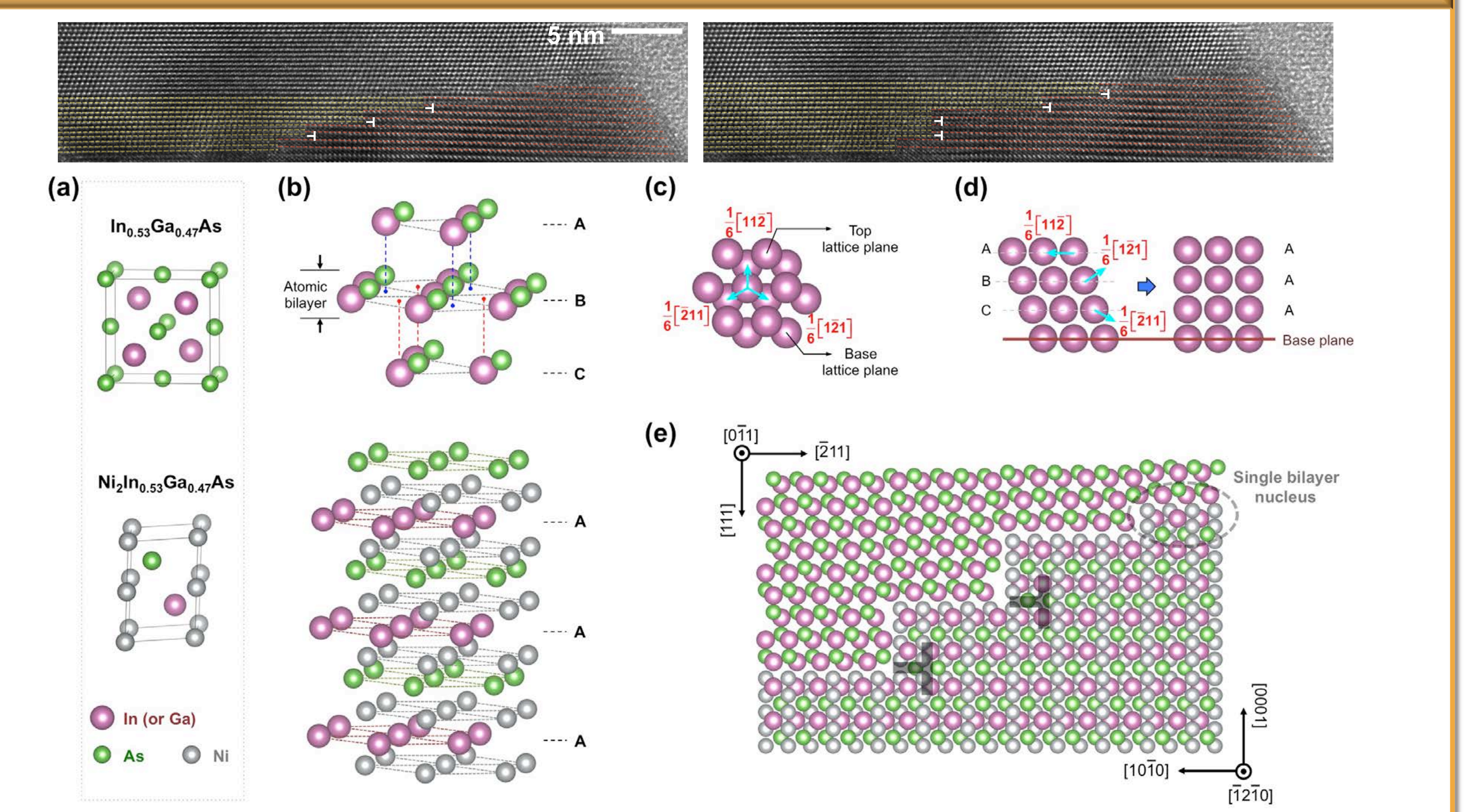
The nanowire arrangements are carefully designed in order to have at least one intact nanowire channel that is fully embedded in the SiO_2 layer after FIB milling.



In situ transfer in SEM *In situ heating in TEM*



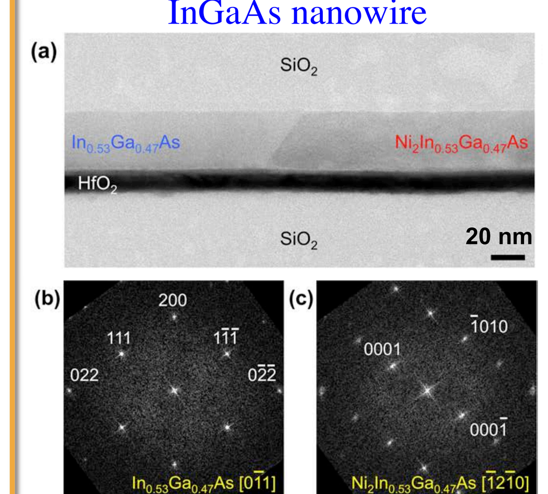
Interfacial Disconnections

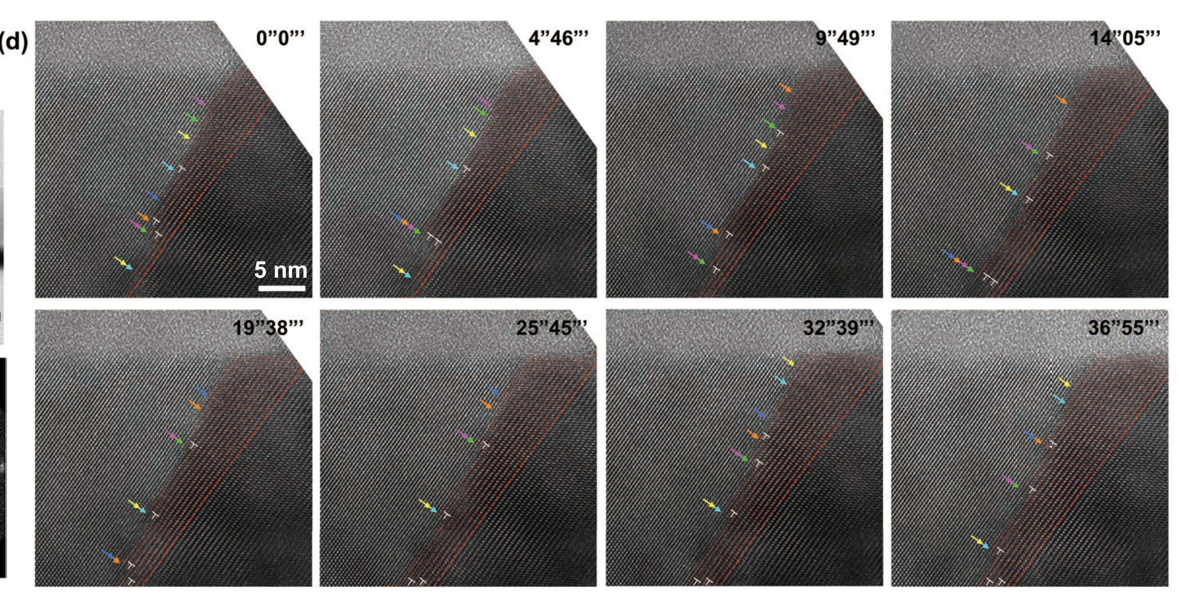


- The $In_{0.53}Ga_{0.47}As/Ni_2In_{0.53}Ga_{0.47}As$ phase transformation not only caused an unusual change in atomic stacking (A-B-C… type to A-A-A… type), but also introduced large elastic strain near the interfaces, resulting in interfacial disconnections (ledge + dislocation).

Ledge Nucleation and Propagation

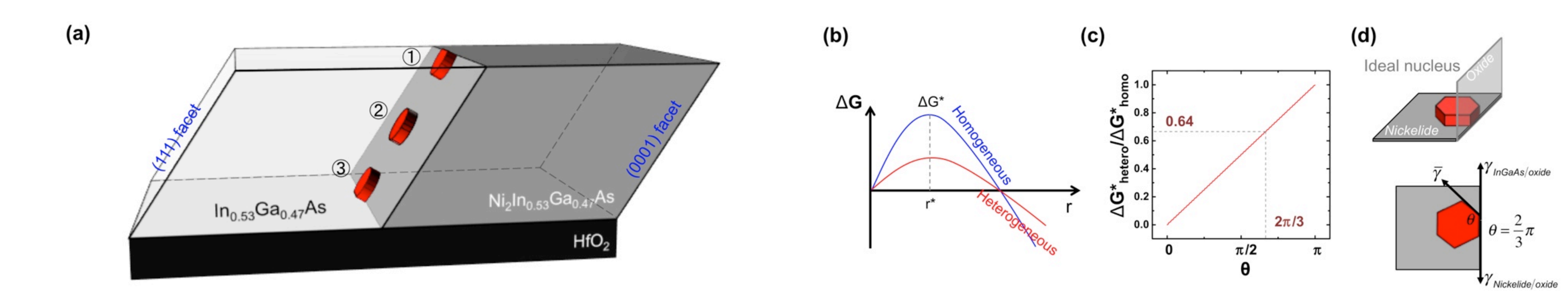
45nm-tall and 30nm-wide InGaAs nanowire





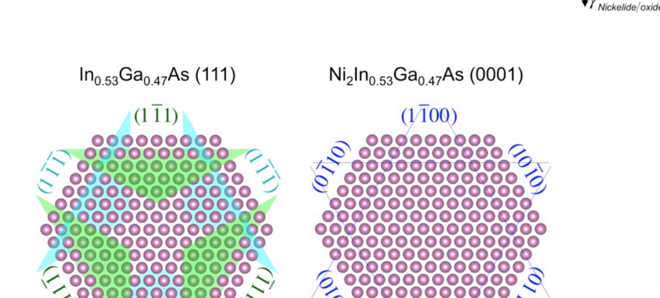
- The slanted interface follows the $In_{0.53}Ga_{0.47}As$ (111) || $Ni_2In_{0.53}Ga_{0.47}As$ (0001) atomic planes.
- Nickelide phase nucleates at the top surface of InGaAs channel and propagates downwards.

Modeling Nucleation



Three possible nucleation sites:

① heterogeneous: nanowire/SiO_2 interface
② homogeneous: inside nanowire channel
③ heterogeneous: nanowire/HfO_2 interface



Nucleation barriers:

$$\frac{\Delta G^*_{hetero}}{\Delta G^*_{homo}} = \frac{\theta - \sin\theta\cos\theta}{\pi}$$

Nucleation rates:

$$\frac{R_{hetero}}{R_{homo}} \approx 1.26\exp\left(\frac{\Delta G^*_{homo} - \Delta G^*_{hetero}}{kT}\right)$$

Renjie Chen, and Shadi A. Dayeh "Recordings and Analysis of Atomic Ledge and Dislocation Movements in InGaAs to Nickelide Nanowire Phase Transformation" *Small*, in revision, **2017**

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