STRAIN-ENHANCED RASHBA SPIN-ORBIT INTERACTION IN CORE-SHELL NANOWIRES

InAs-InP core-shell nanowires

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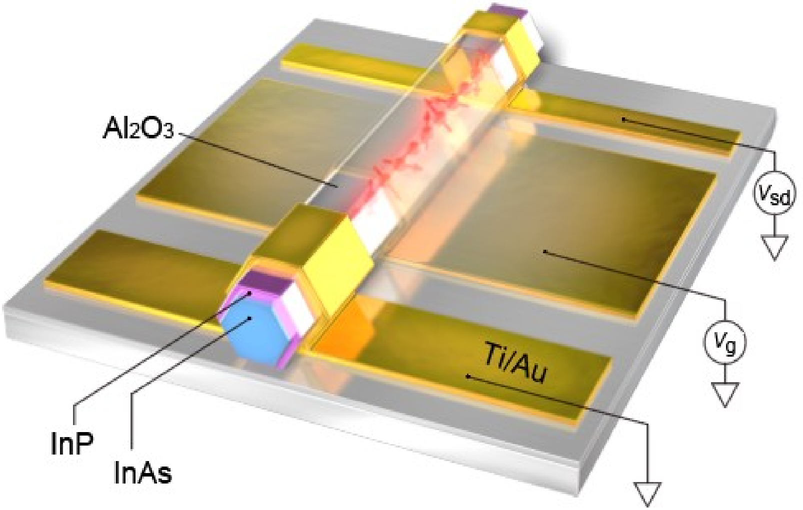
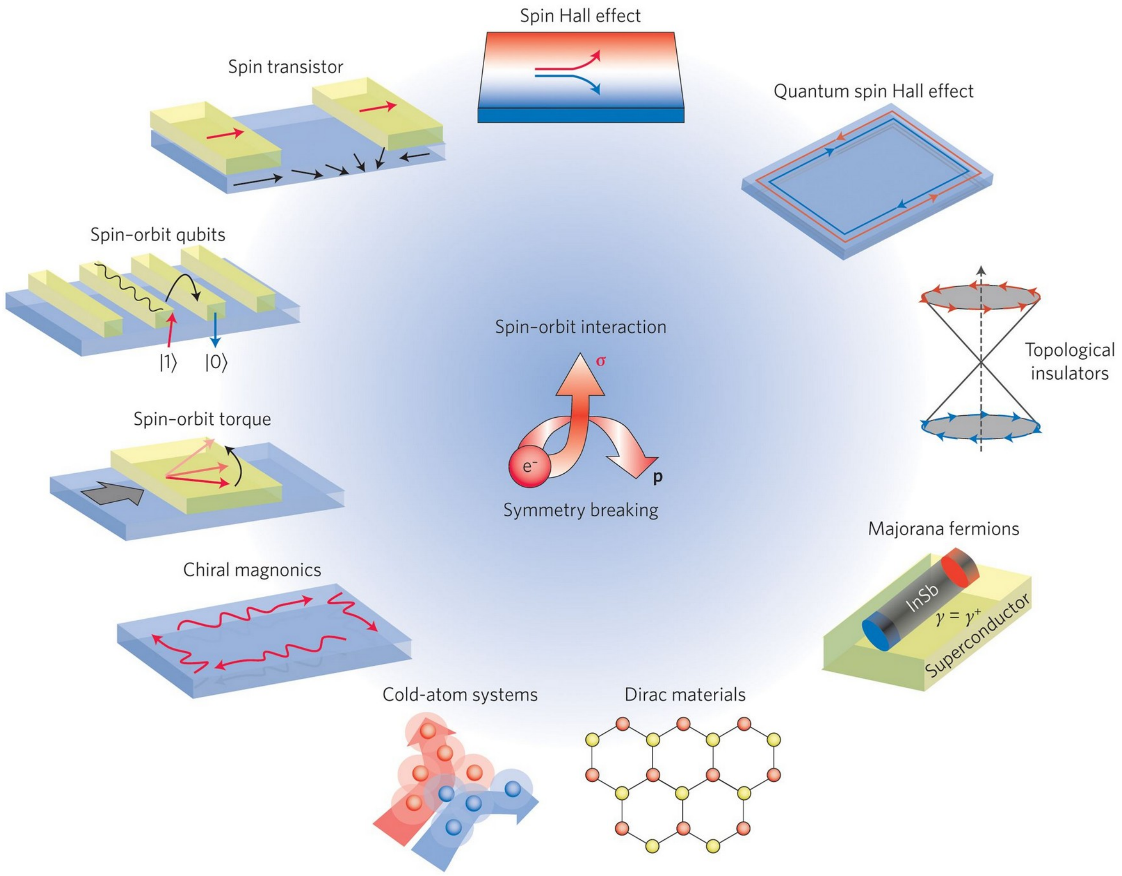


Motivation

The spin-orbit (SO) interaction is a relativistic effect that couples electron momentum and spin

$$H_{SO} = \vec{\alpha} \cdot \left(\vec{\sigma} \times \vec{k} \right)$$

Specially relevant in low-dimensional materials where motion is constrained



A. Manchon *et al.* Nat. Mat. **14**, 871 (2015).

Motivation

Among all the semiconductors (SMs), which are materials that allows for tunable conductance, III-V compound SMs present a large SO interaction

R. Winkler *et al.*, Spin-Orbit Coupling in Two-Dimensional Electron and Hole systems, Vol. 41 (Springer, 2003).

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$$
\mathrm{H}_{\mathrm{CB}} = \left(\vec{k} \frac{\hbar^2}{2m^*(\vec{r})} \vec{k} + E_F - e\phi(\vec{r}) \right) \sigma_0 \\
+ \underbrace{\frac{1}{2} \left(\vec{\alpha}_R(\vec{r}) \cdot \left(\vec{\sigma} \times \vec{k} \right) + \left(\vec{\sigma} \times \vec{k} \right) \times \vec{\alpha}_R(\vec{r}) \right)}_{\text{SO interaction}}
$$

The Hamiltonian is like the one of a free-electron with renormalized parameters

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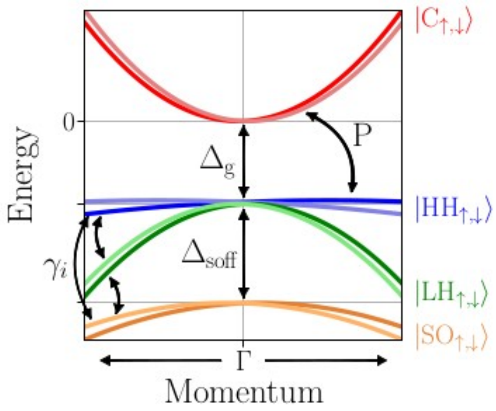
$$\mathrm{H}_{\mathrm{CB}} = \left(\vec{k}\frac{\hbar^2}{2m^*(\vec{r})}\vec{k} + E_F - e\phi(\vec{r})\right)\sigma_0$$

$$\underbrace{+\frac{1}{2}\left(\vec{\alpha}_R(\vec{r})\cdot\left(\vec{\sigma}\times\vec{k}\right)+\left(\vec{\sigma}\times\vec{k}\right)\times\vec{\alpha}_R(\vec{r})\right)}_{\text{SO interaction}}$$

The Hamiltonian is like the one of a free-electron with renormalized parameters

The SO coupling is Rashba type, origin as a result of the interaction with the hole bands



$$\vec{\alpha}_R(\vec{r}) = \frac{P^2}{3}\vec{\nabla}\left(\frac{1}{E_h - e\phi(\vec{r}) - E} - \frac{1}{E_{\mathrm{soff}} - e\phi(\vec{r}) - E}\right)$$

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Among all the semiconductors (SMs), which are materials that allows for tunable conductance, III-V compound SMs present

$$\mathrm{H}_{\mathrm{CB}} = \Bigg(\vec{k}\,\frac{\hbar}{2m}$$

$$\underbrace{+\,\tfrac{1}{2}\Big(\vec{\alpha}_R(\vec{r})\cdot\Big(\vec{\sigma}}_{\text{SO interaction}}$$

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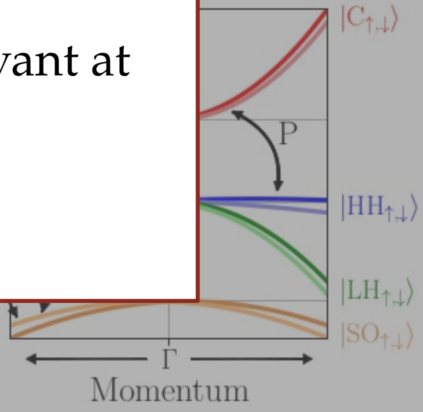
In low-dimensional materials, strain is relevant at the interface between materials

Effects of strain? New equation?



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Theory

We follow exactly the same derivation including a constant strain in the SM using the Bahder approximation

$$
\begin{aligned}
H_{\mathrm{CB,s}} &= \left(\vec{k} \frac{\hbar^2}{2\mathbf{m}_{\mathrm{eff,s}}} \vec{k}^t - q_{\mathrm{e}} \phi(\vec{r}) + a_{\mathrm{c}} \mathrm{tr}\left\{\mathbf{e}\right\} \right) \sigma_0 \\
&+ \left(\frac{1}{2} \mu_{\mathrm{B}} \vec{B} \mathbf{g}_{\mathrm{eff}} + \vec{\Omega}_{\mathrm{eff}}(\vec{k}, \vec{r}) \right) \vec{\sigma}^t
\end{aligned}
$$

With SO field

$$
\begin{aligned}
\vec{\Omega}_{\mathrm{eff}}(\vec{k}, \vec{r}) &= -\frac{P^2}{3} \left(\frac{\frac{1}{2}}{\left(E_{\mathrm{lh}}^{(0)}\right)^2} - \frac{\frac{3}{2}}{\left(E_{\mathrm{hh}}^{(0)}\right)^2} + \frac{1}{\left(E_{\mathrm{soff}}^{(0)}\right)^2} \right) \\
&\cdot \mathrm{adj}\left\{(\mathbf{1} - \mathbf{e})\right\} \left(\vec{\nabla}\phi(\vec{r}) \times \vec{k} + \vec{k} \times \vec{\nabla}\phi(\vec{r}) \right),
\end{aligned}
$$

Theory

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$$H_{\mathrm{CB,s}} = \left(\vec{k} \frac{\hbar^2}{2\mathbf{m}_{\mathrm{eff},\mathrm{s}}} \vec{k}^t - q_{\mathrm{e}} \phi(\vec{r}) + a_{\mathrm{c}} \mathrm{tr}\left\{\mathbf{e}\right\} \right) \sigma_0$$

$$+ \left(\frac{1}{2} \mu_{\mathrm{B}} \vec{B} \mathbf{g}_{\mathrm{eff}} + \vec{\Omega}_{\mathrm{eff}}(\vec{k}, \vec{r}) \right) \vec{\sigma}^t$$

With SO field

$$\vec{\Omega}_{\mathrm{eff}}(\vec{k}, \vec{r}) = -\frac{P^2}{3} \left(\frac{\frac{1}{2}}{\left(E_{\mathrm{lh}}^{(0)}\right)^2} - \frac{\frac{3}{2}}{\left(E_{\mathrm{hh}}^{(0)}\right)^2} + \frac{1}{\left(E_{\mathrm{soff}}^{(0)}\right)^2} \right)$$

$$\cdot \, \mathrm{adj}\left\{(\mathbf{1} - \mathbf{e})\right\} \left(\vec{\nabla}\phi(\vec{r}) \times \vec{k} + \vec{k} \times \vec{\nabla}\phi(\vec{r}) \right),$$

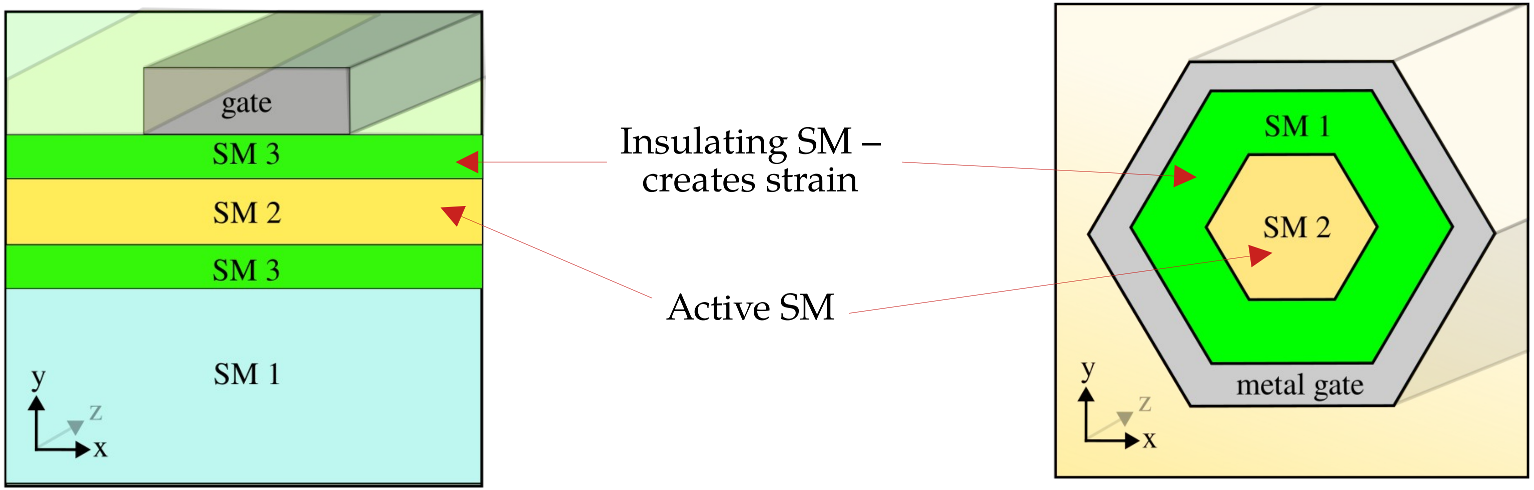
The Hamiltonian is very similar. Few remarks:

- SO interaction can no longer be written, in general, through a SO coupling.
- The effective-mass and the g-factor are now tensors with non-diagonal components.
- The strength of all these depend on the strength and type of the strain

Experiments

One way to control strain, is through a smart choice of the insulating substrates

Strain engineering



Insulating SM – creates strain

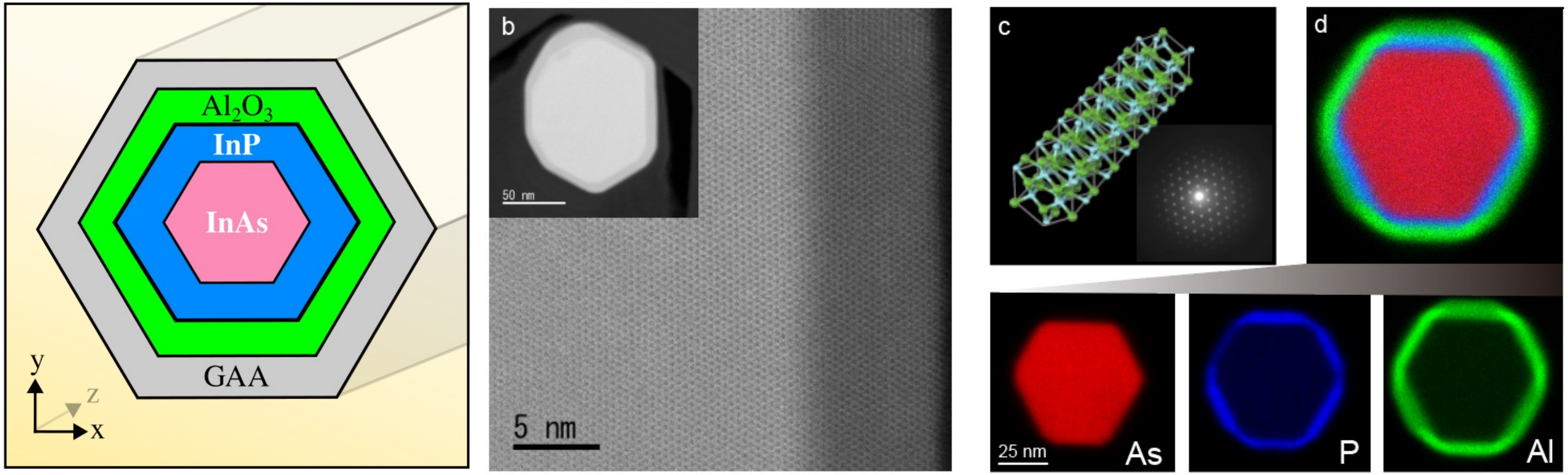
Active SM

In stacking planar heterostructures

In core-shell nanowires

Experiments

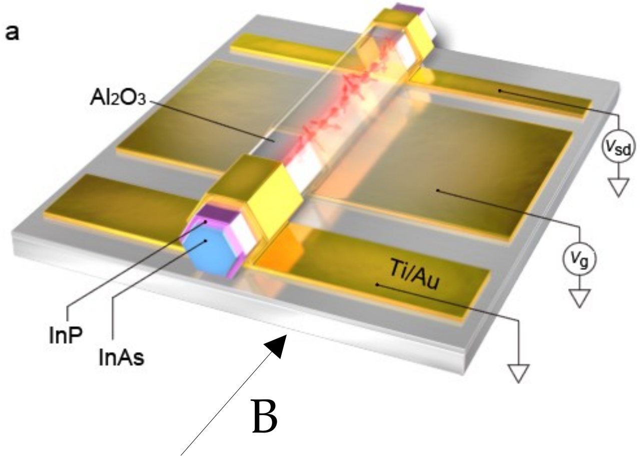
We explore experimentally InAs-InP core-shell SM NWs

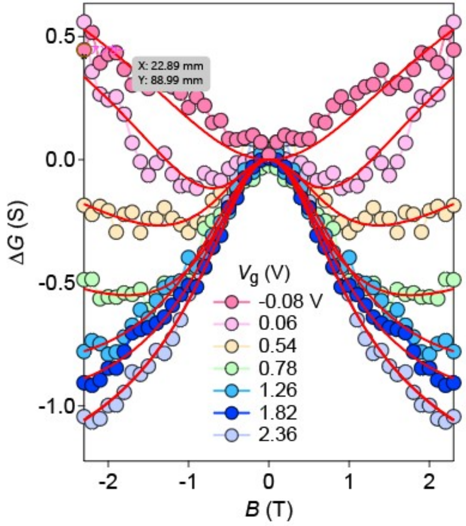


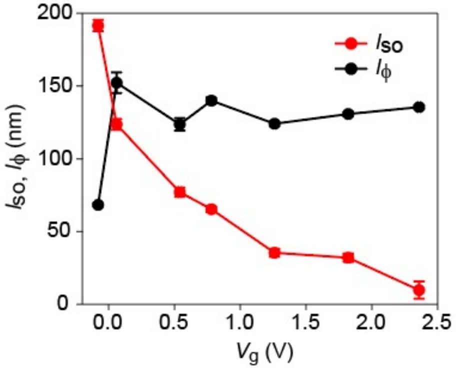
The strain near the interface is around 5%

Experiments

We perform magnetoconductance measurements to extract the SO coupling







Experiments

We compare the experimental results with our simulations, looking for the strain that fits the best

$$\alpha_{\mathrm{R}} \simeq -\frac{P^2}{3}(1-\varepsilon)\left[\frac{1}{\left(\Delta_{\mathrm{g}}+2\varepsilon\left(a_v-\frac{b}{2}\right)\right)^2} - \frac{1}{\left(\Delta_{\mathrm{g}}+\Delta_{\mathrm{soff}}+2\varepsilon a_v\right)^2}\right]E,$$

We perform self-consistent Schrödinger-Poisson simulations

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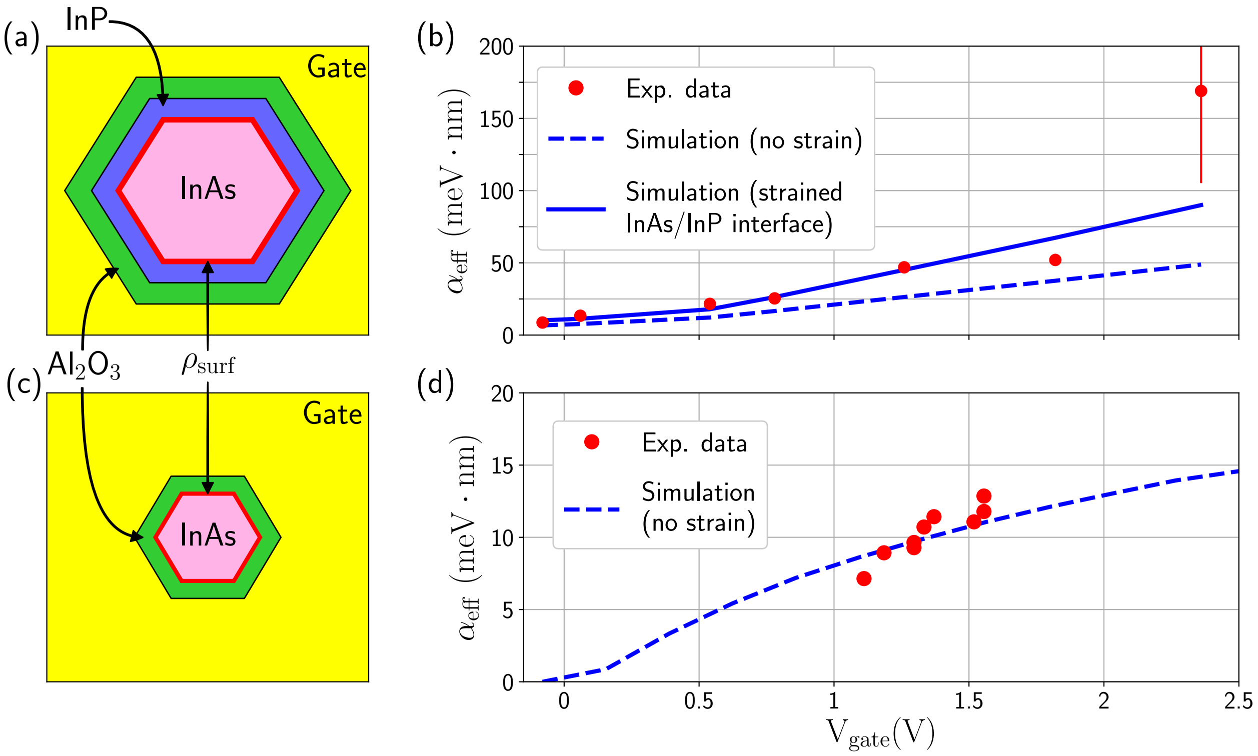
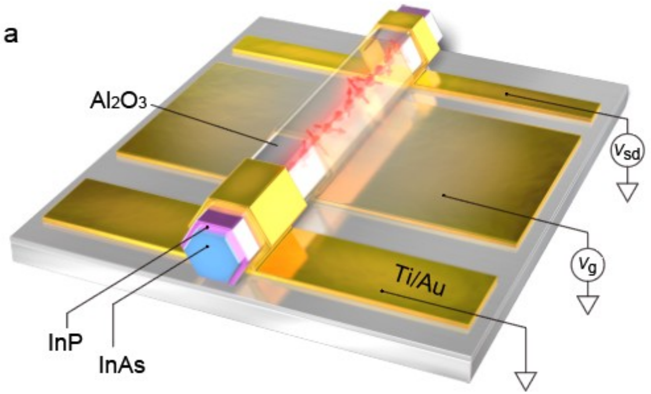


The results can only be explained once considered strain!
We obtain strain close to 5%

Take home message

- Strain-engineering of the SM material properties is viable.
- We prove SO coupling can be enhanced by proximitizing an insulating SM with different lattice mismatch.
- Our theory predicts intriguing phenomena!



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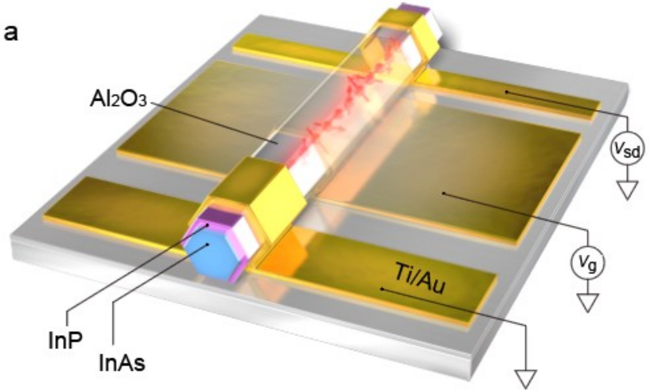

Thanks to my collaborators

Exp. (NTT lab)
Keiko Takase
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Kouta Tateno
Satoshi Sasaki

Theo.
Elsa Prada (ICMM-CSIC)
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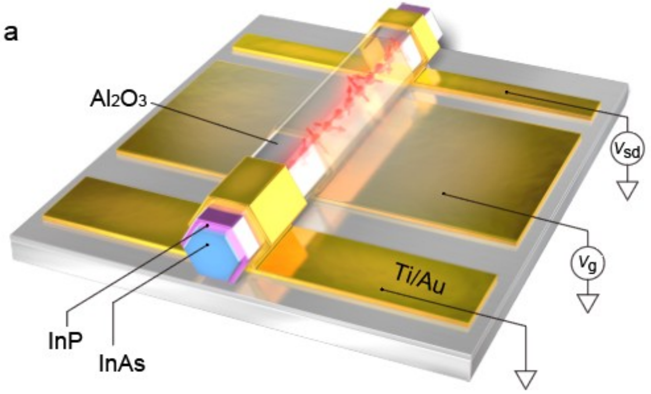

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And thank you for your attention!

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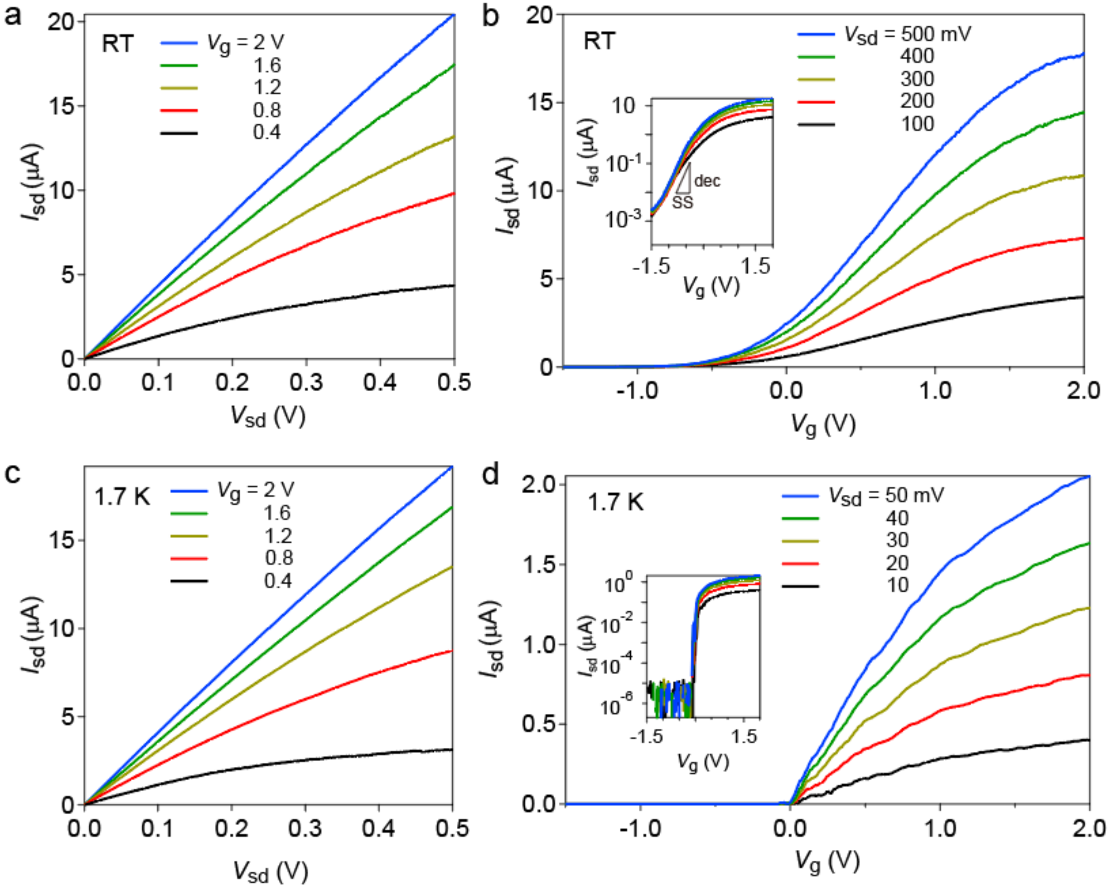
Supplemental material

Samuel D. Escribano

Supplemental material - exp

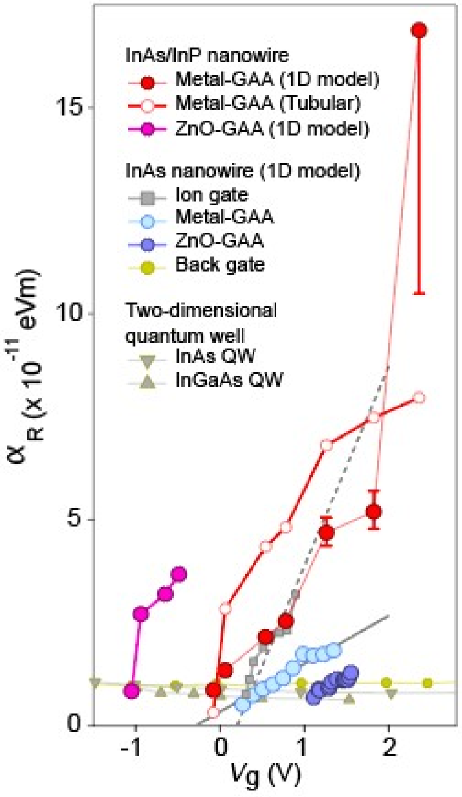
Characterization of its behaviour as a field effect transistor (FET), at room temperature (RT) and 1.7 K

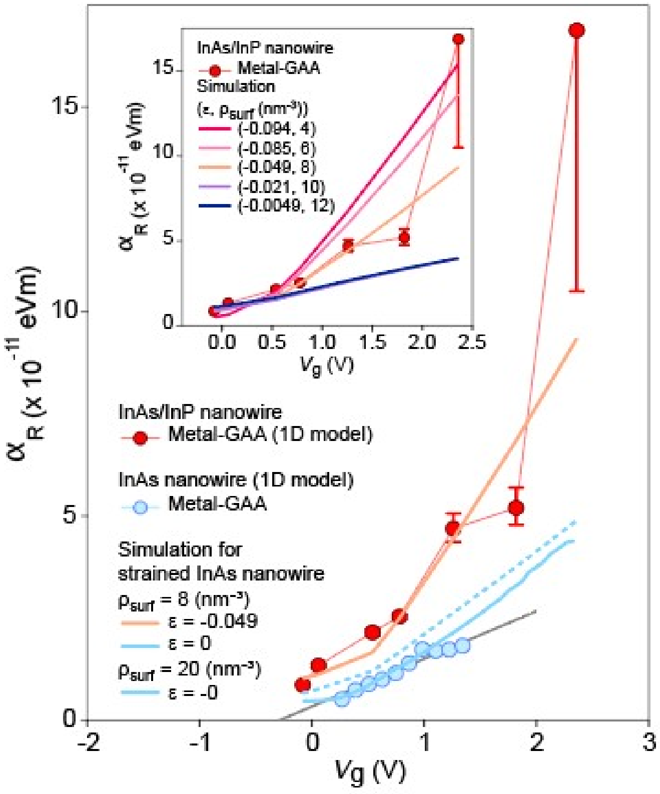
Behaves as expected



Supplemental material - exp

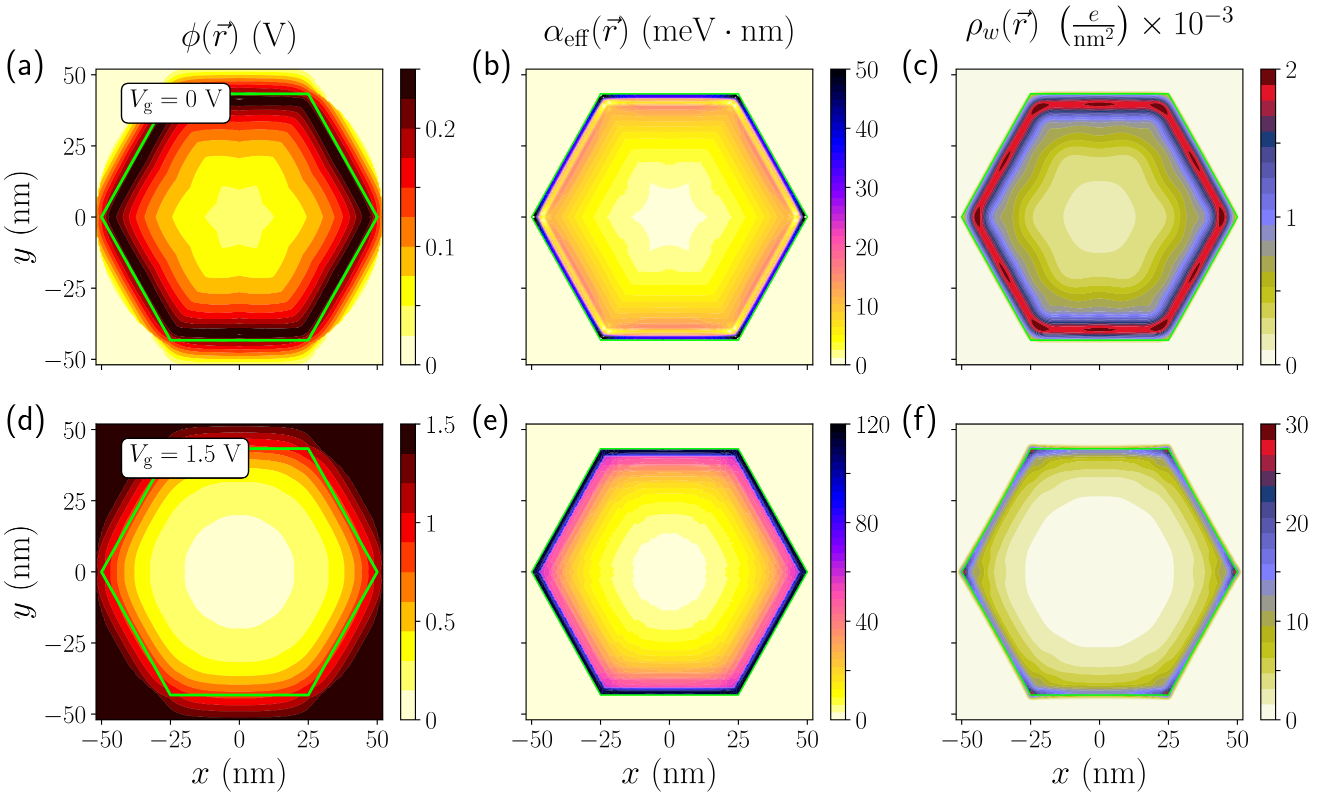
Comparison between the SO coupling in different platforms





Supplemental material - theo

Electric field, SO coupling and charge density of the wire, for two different gate potentials



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