UNIVERSITY OF TWENTE.

MESA+ INSTITUTE FOR NANOTECHNOLOGY

# High-frequency surface acoustic waves for acousto-electronic transport

Wilfred G. van der Wiel

NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente

SPICE-Workshop Quantum Acoustics, May 18th 2016

SAWtrain network

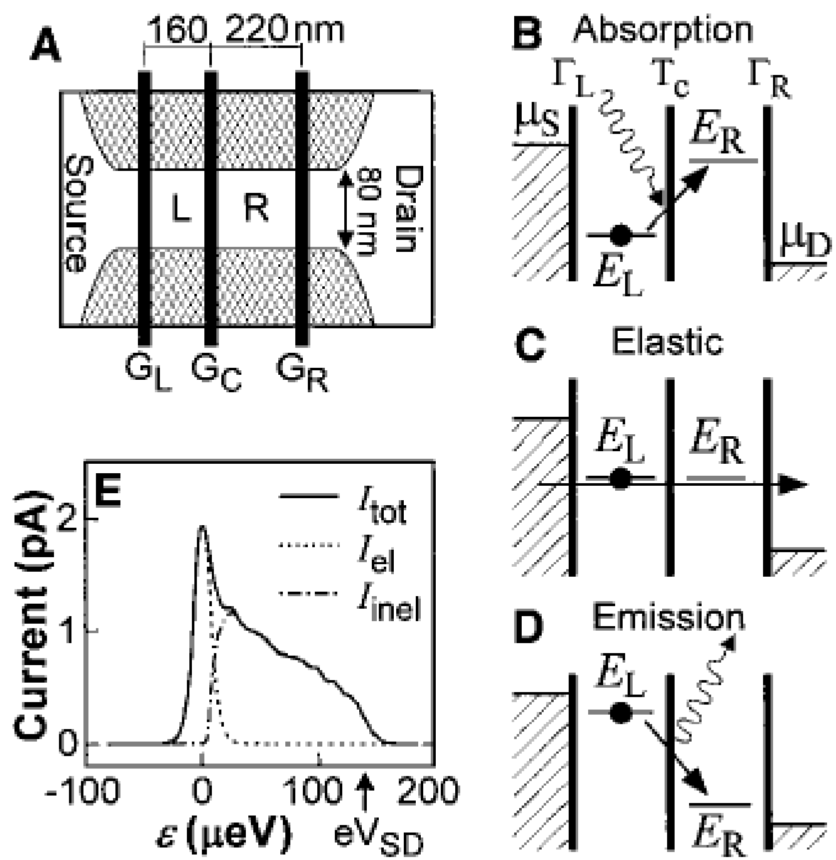
NanoElectronics.

30 OCTOBER 1998 VOL 282 SCIENCE

# Spontaneous Emission Spectrum in Double Quantum Dot Devices

Toshimasa Fujisawa, Tjerk H. Oosterkamp,
Wilfred G. van der Wiel, Benno W. Broer, Ramón Aguado,
Seigo Tarucha, Leo P. Kouwenhoven*

A double quantum dot device is a tunable two-level system for electronic energy states. A dc electron current was used to directly measure the rates for elastic and inelastic transitions between the two levels. For inelastic transitions, energy is exchanged with bosonic degrees of freedom in the environment. The inelastic transition rates are well described by the Einstein coefficients, relating absorption with stimulated and spontaneous emission. The most effectively coupled bosons in the specific environment of the semiconductor device used here were acoustic phonons. The experiments demonstrate the importance of vacuum fluctuations in the environment for quantum dot devices and potential design constraints for their use for preparing long-lived quantum states.

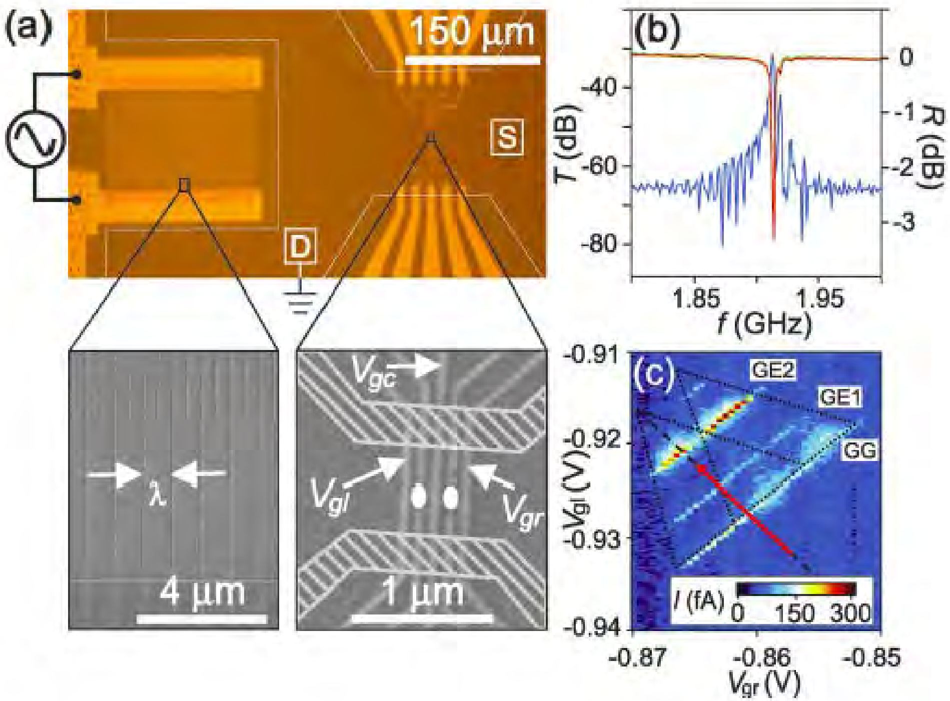


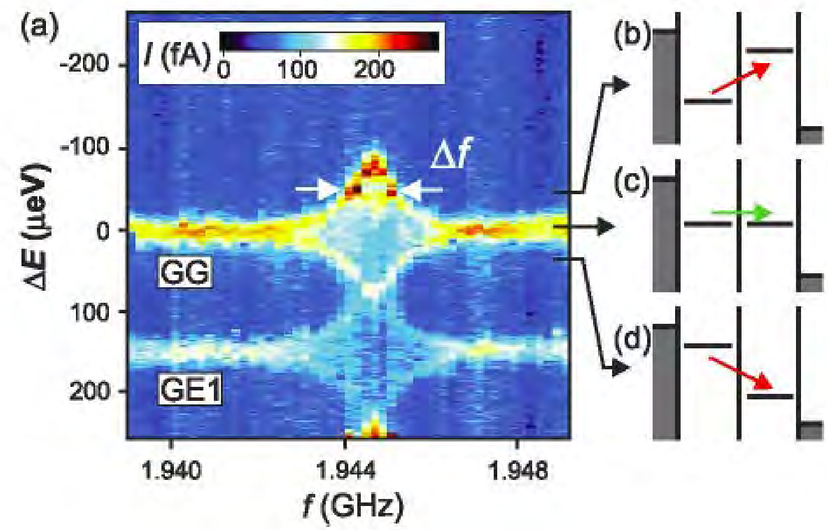
# Prologue

PRL **96,** 136807 (2006) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2006

## Surface-Acoustic-Wave-Induced Transport in a Double Quantum Dot

W. J. M. Naber,[1,2,3] T. Fujisawa,[2,4] H. W. Liu,[2,5] and W. G. van der Wiel[1,6]



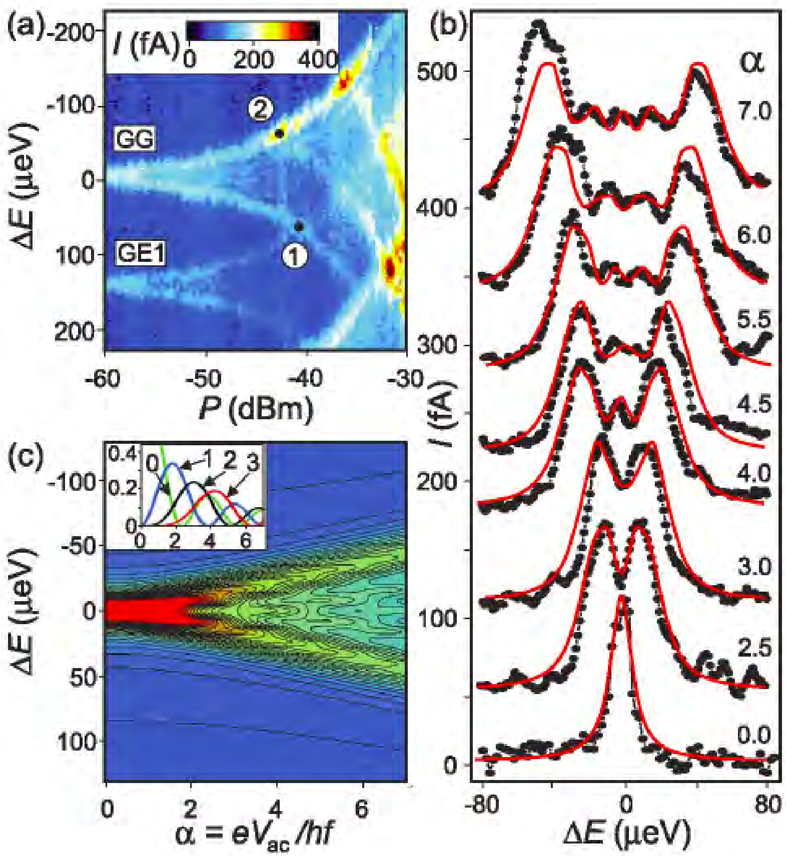



# Prologue

PRL **96,** 136807 (2006) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2006

**Surface-Acoustic-Wave-Induced Transport in a Double Quantum Dot**

W. J. M. Naber,[1,2,3] T. Fujisawa,[2,4] H. W. Liu,[2,5] and W. G. van der Wiel[1,6]




Resonance at 1.9446 GHz

$$hf_{\mathrm{SAW}} = 8\ \mu\mathrm{eV}$$

< GG line width (14 μev)

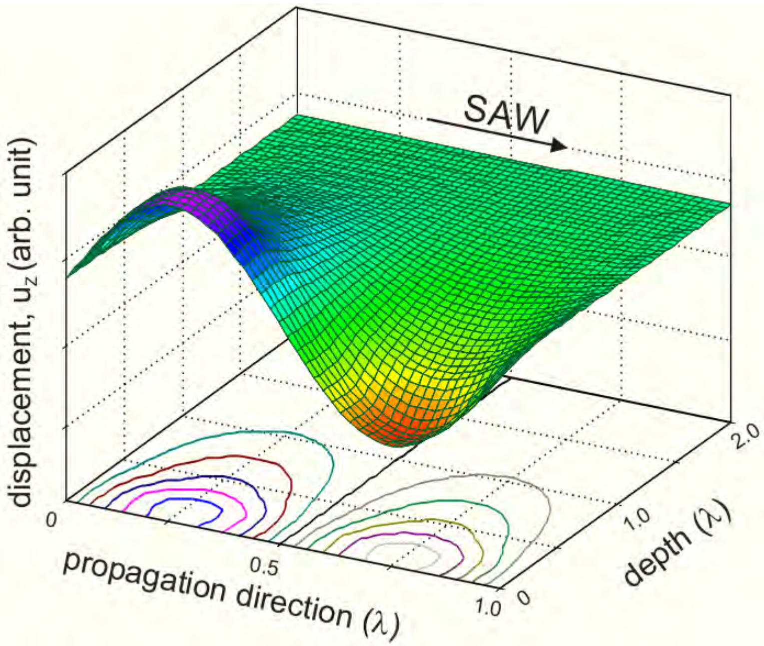
→ need for higher frequency

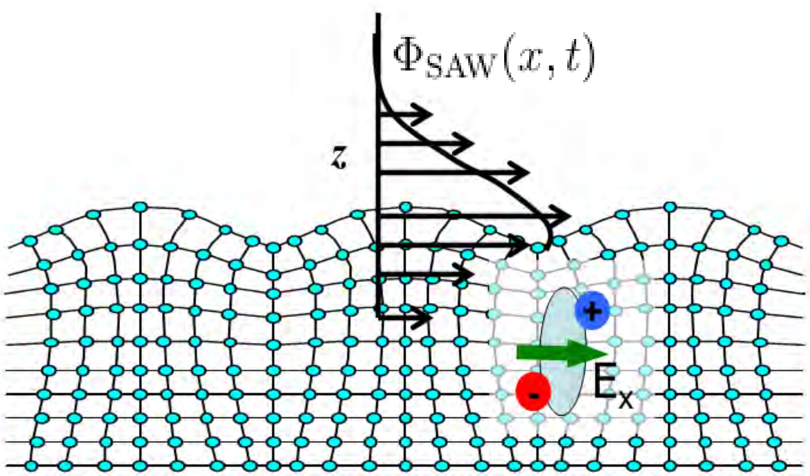
MESA+ INSTITUTE FOR NANOTECHNOLOGY

# Quantum Acoustics

$$hf_{\mathrm{SAW}} >> k_{\mathrm{B}}\,T$$

# Surface Acoustic Waves (SAWs)




- Mechanical Wave: Rayleigh Wave
  longitudinal and transverse motion

- Propagate in the surface with sound velocity
  energy concentrated in a thin layer (~ $\lambda$)

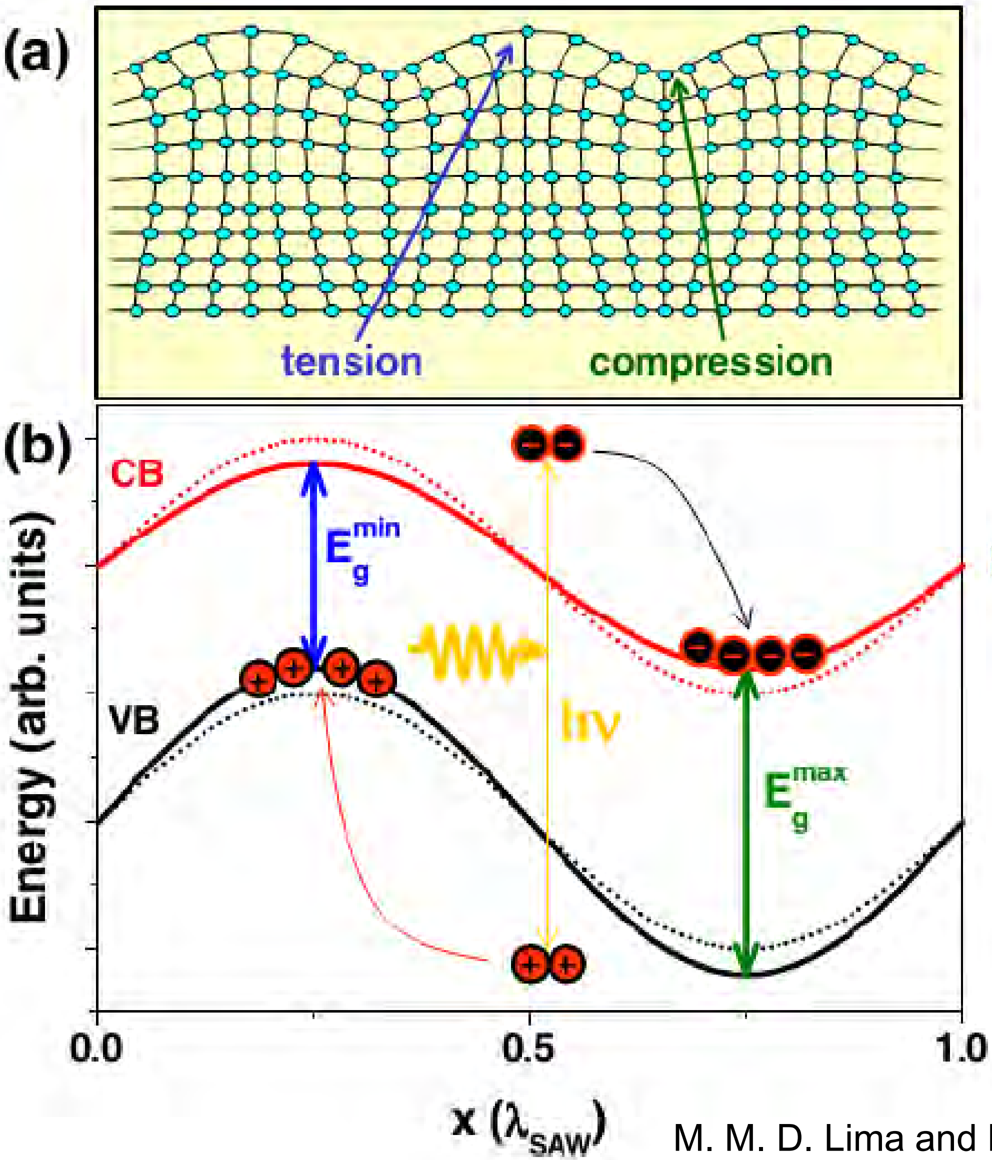
- Small amplitude
  less than 1 nm

- Much lower velocity than electromagnetic waves with a few km/s (EMW:SAW ~ 1:$10^5$)

- Sub-micron wave length

MESA+
INSTITUTE FOR NANOTECHNOLOGY

# Surface Acoustic Waves (SAWs)




Lattice displacement induced by Reyleigh wave

spatially- and time-dependent local strain

$$\tilde{\varepsilon}(\mathbf{r},t)$$

Band-gap modulation ~ meV

Piezo-field modulation ~ 100 meV

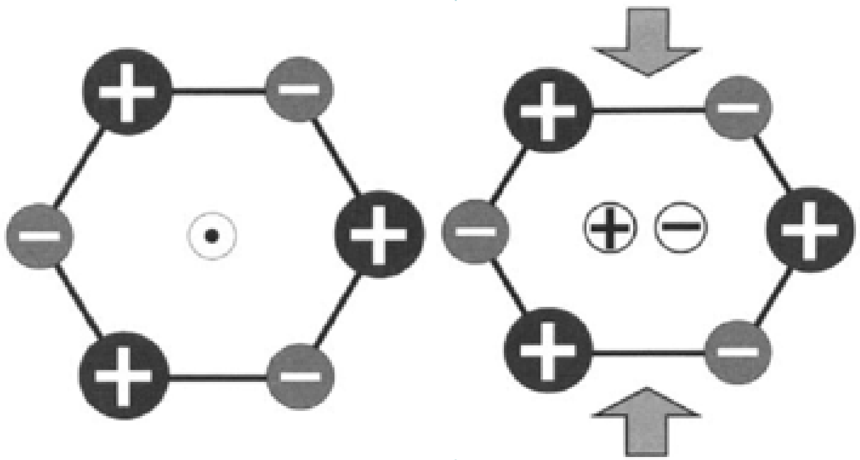



M. M. D. Lima and P. V. Santos, Rep. Prog. Phys. **68** 1639 (2005).

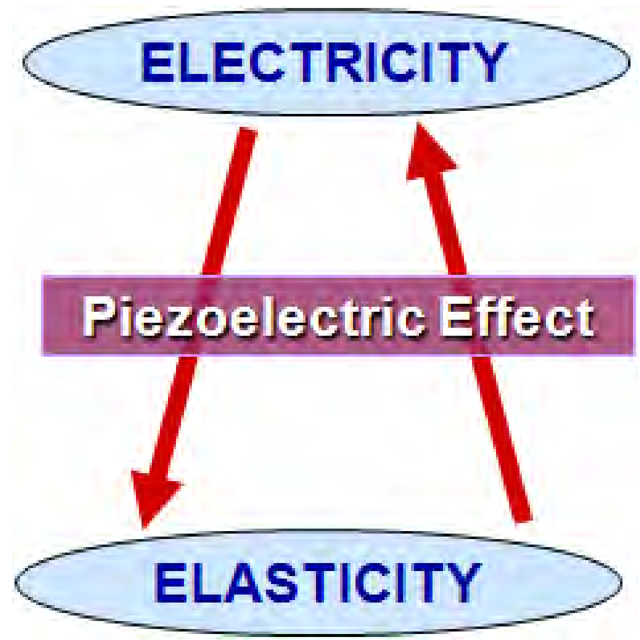
# SAWs: Piezoelectricity

**The direct piezoelectric effect** - the production of electricity when stress is applied

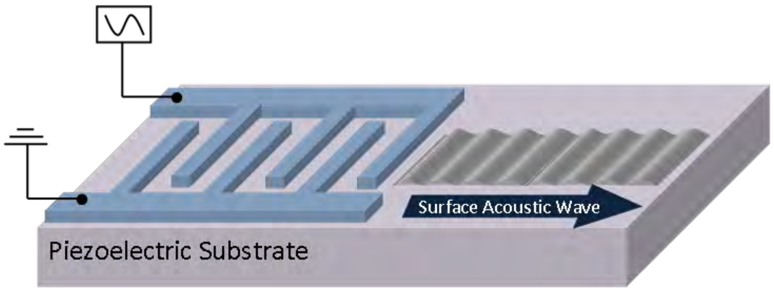
**The converse piezoelectric effect** - the production of stress and/or strain when an electric field is applied

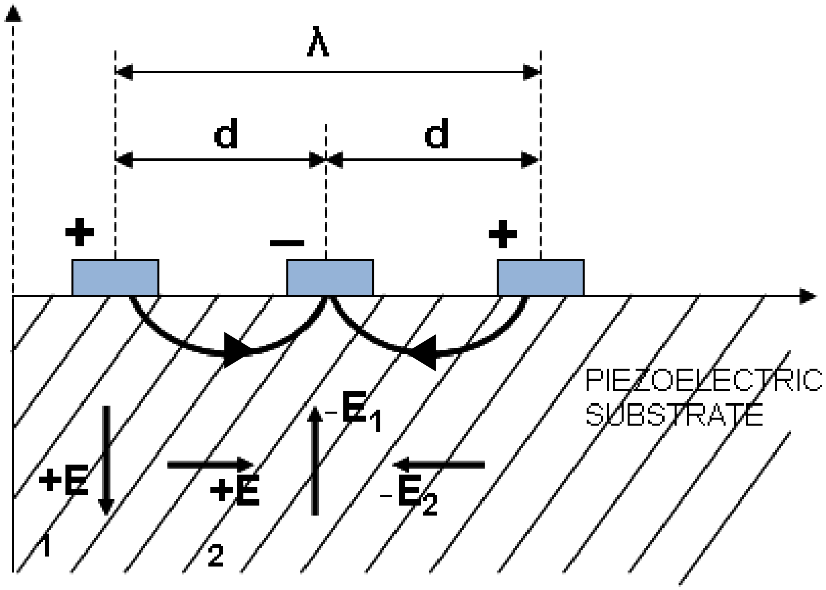


neutral    small dipole



# Interdigital Transducers (IDTs)

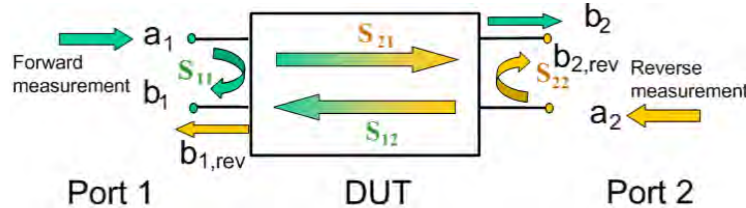


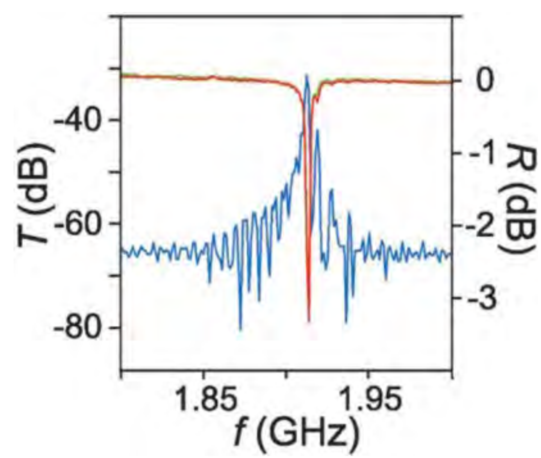

$$f_{SAW} = v_{SAW} / \lambda_{SAW}$$

**High frequency ≡ narrow fingers**

S-parameters describe how the DUT modifies a signal that is transmitted or reflected in forward or reverse direction




$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} * \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$




W. J. M. Naber et al. PRL **96,** 136807 (2006)

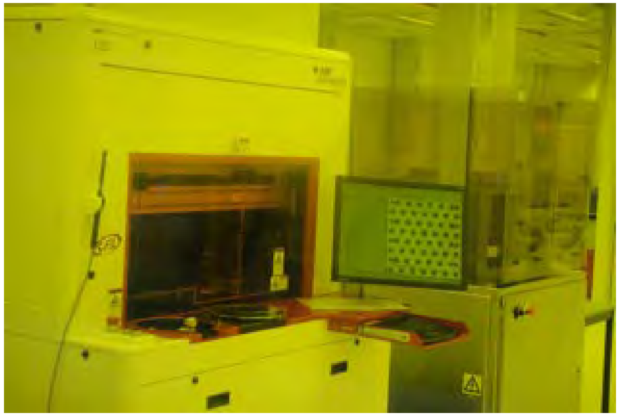
MESA+
INSTITUTE FOR NANOTECHNOLOGY

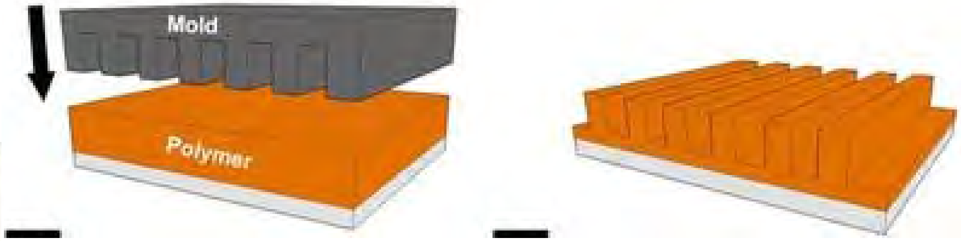
# Why printing?!

Johannes Gutenberg (1440)

Nanoimprint Lithography (NIL)

Stephen Chou (1996)





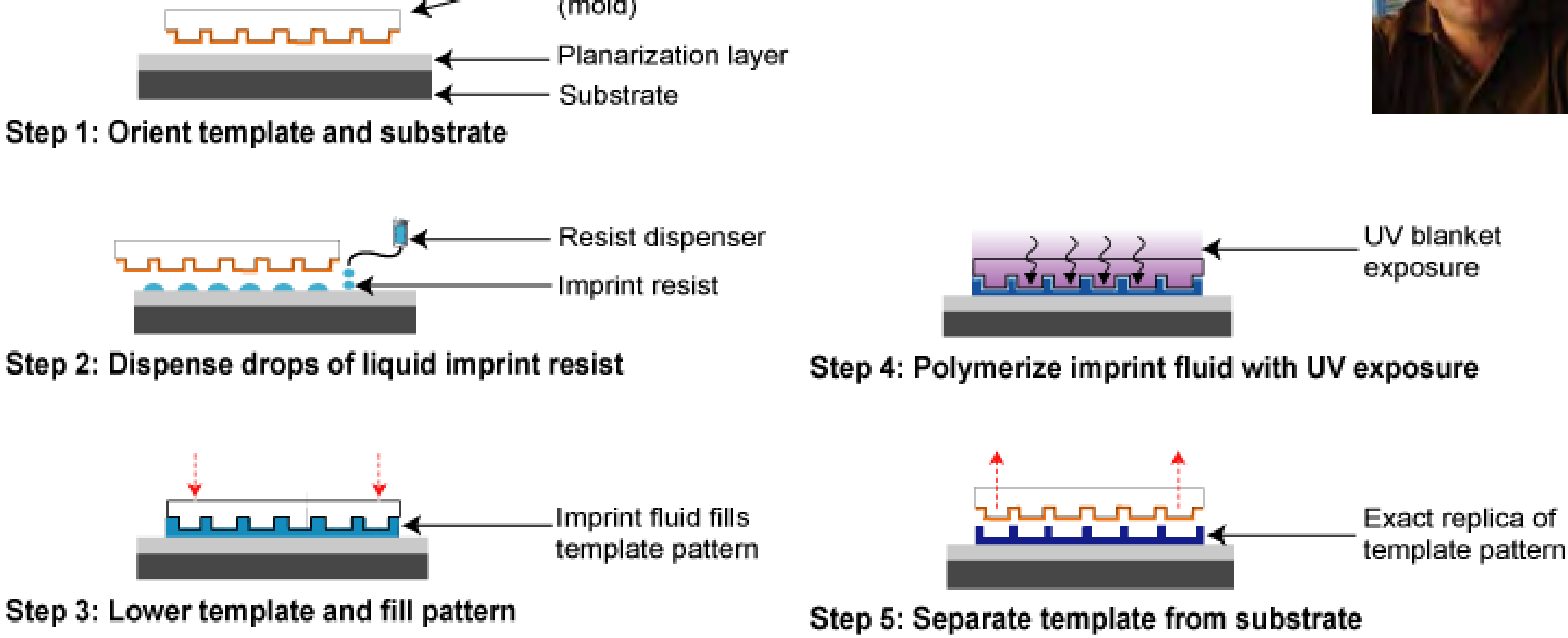

- Fast
- Economical
- Reproducible

MESA+
INSTITUTE FOR NANOTECHNOLOGY

# UV based Nanoimprint Lithography (UV-NIL)

NT&D
NANOTECHNOLOGY & DEVICES

Dr. Boris Vratzov

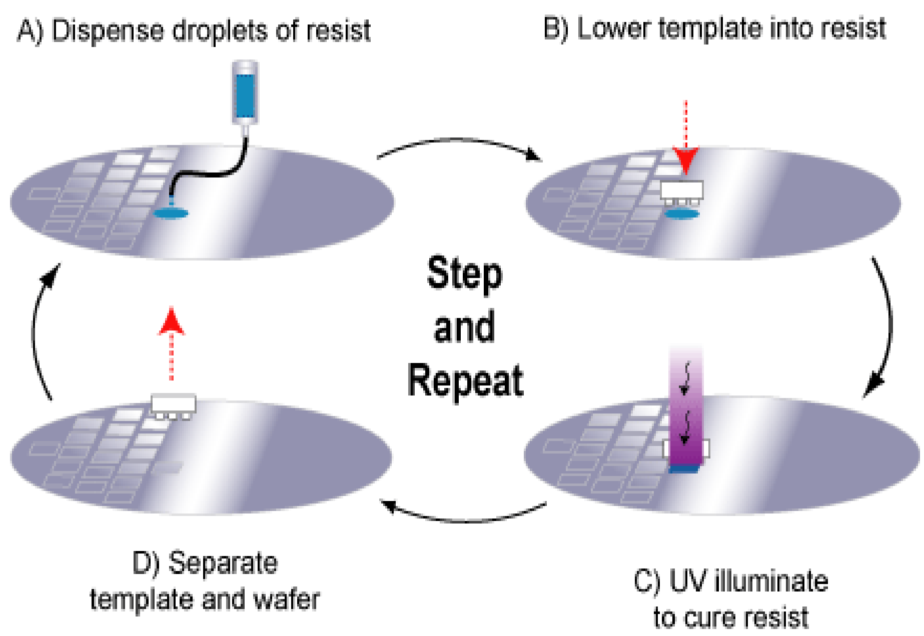


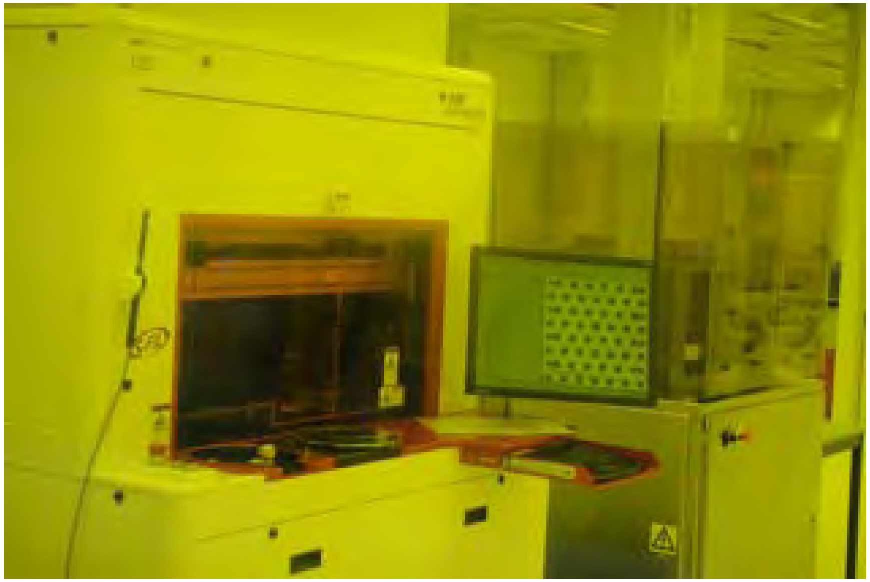

Molecular Imprints, Inc.

- Low force, room temperature process
- Precise 2D and 3D nano pattern definition
- Resist deposition by nano dispensing techniques
- Ultra high degree of uniformity and reproducibility
- Complete design definition
- Step & repeat on wafer scale

MESA+
INSTITUTE FOR NANOTECHNOLOGY

# UV based Nanoimprint Lithography (UV-NIL)



200mm wafer

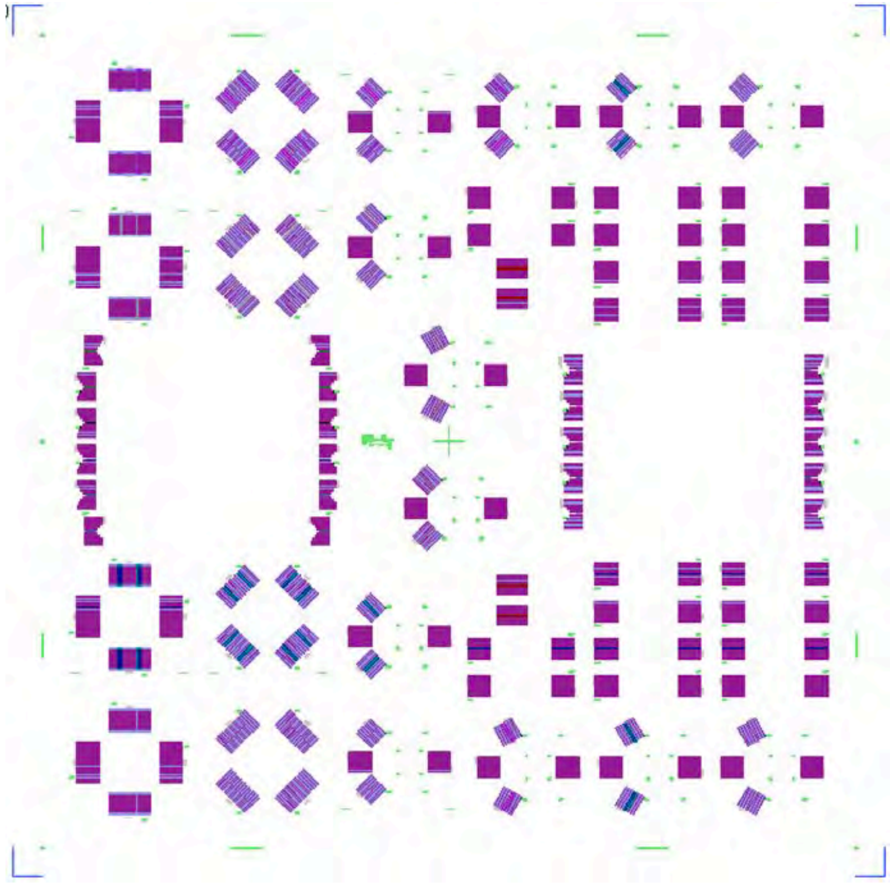
100mm wafer

# UV-NIL: IDT Templates

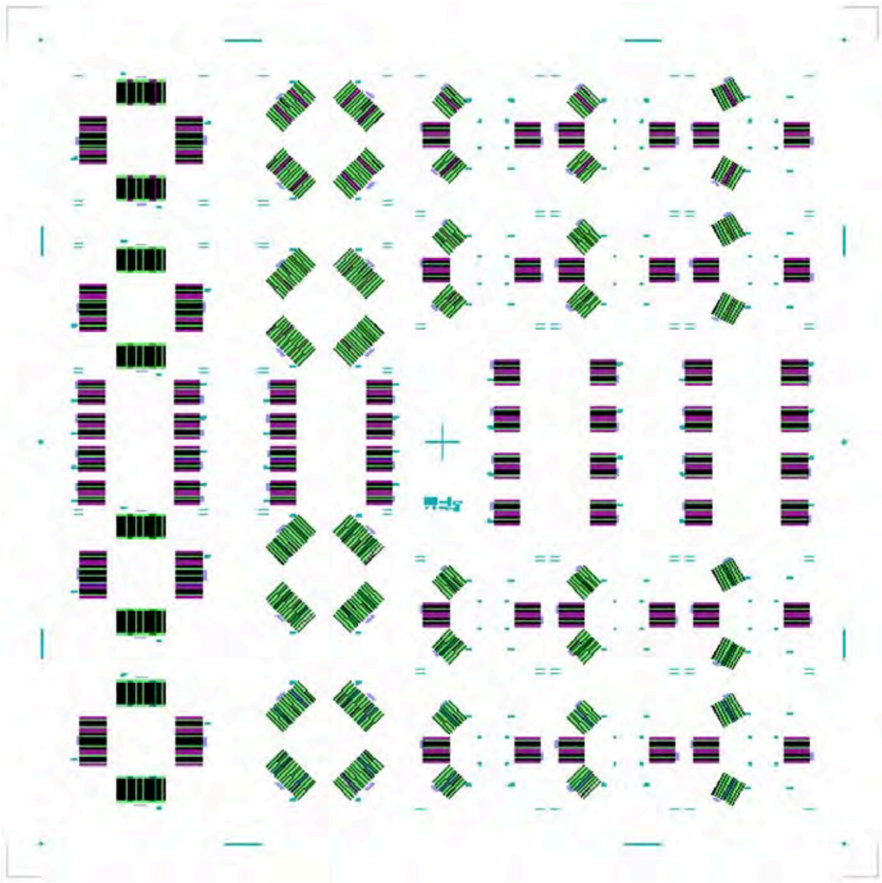
Design in collaboration with Paulo Santos (PDI)

Serkan Büyükköse

Single Finger Design
Chip size: 13 mm x 13 mm



Double Finger Design
Chip size: 13 mm x 13 mm

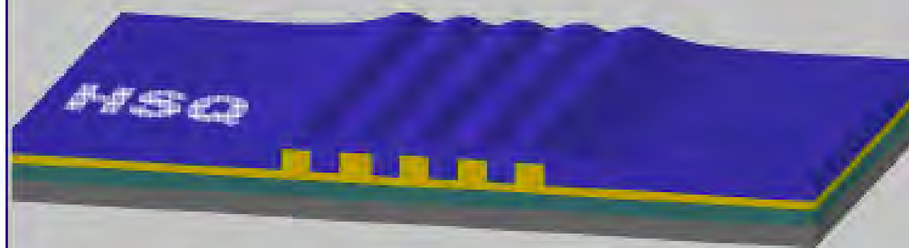


# NIL of Interdigitated transducers (SFIL-R)

**1 Pattern definition by SFIL method**


- organic imprint material

**2 HSQ application by Spin Coating**

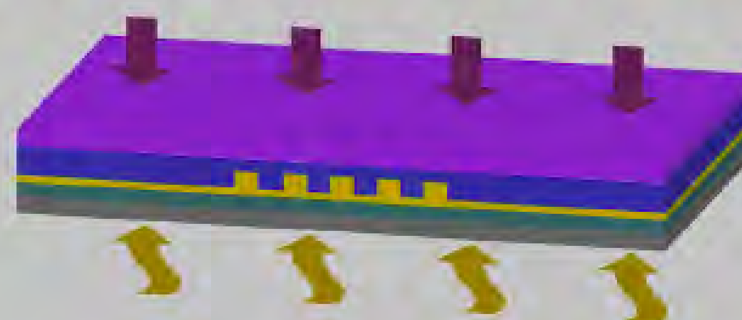



- shows deformation capability
- acts as etch mask under $O_2$ plasma

**3 Force application with flat stamp**


- anti-sticking layer coated DSP Si wafer

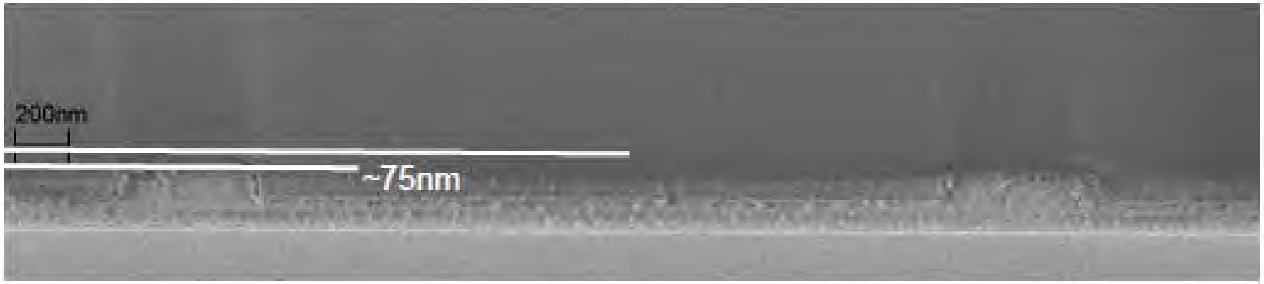
**4 Heating up HSQ under the pressure**

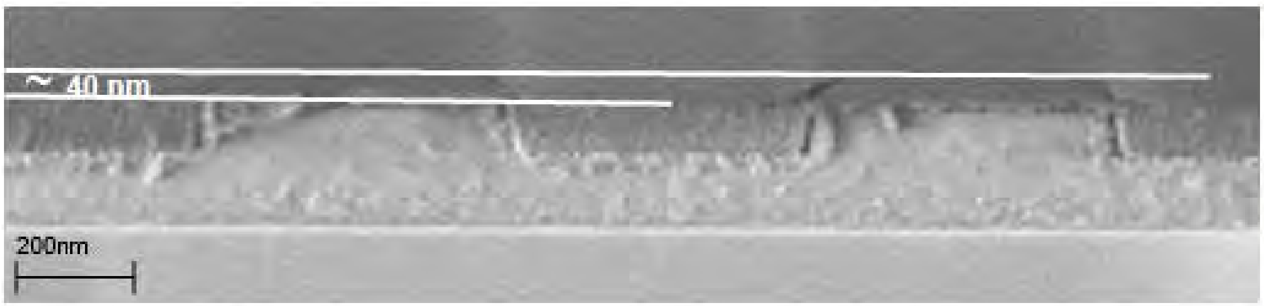


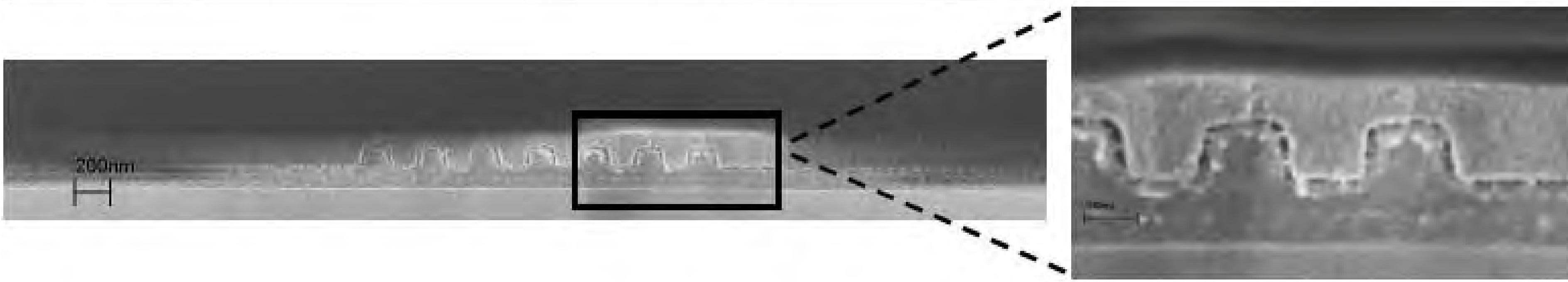
HSQ: hydrogen silsesquioxane

- to make HSQ harder

# NIL of Interdigitated transducers: HSQ planarization



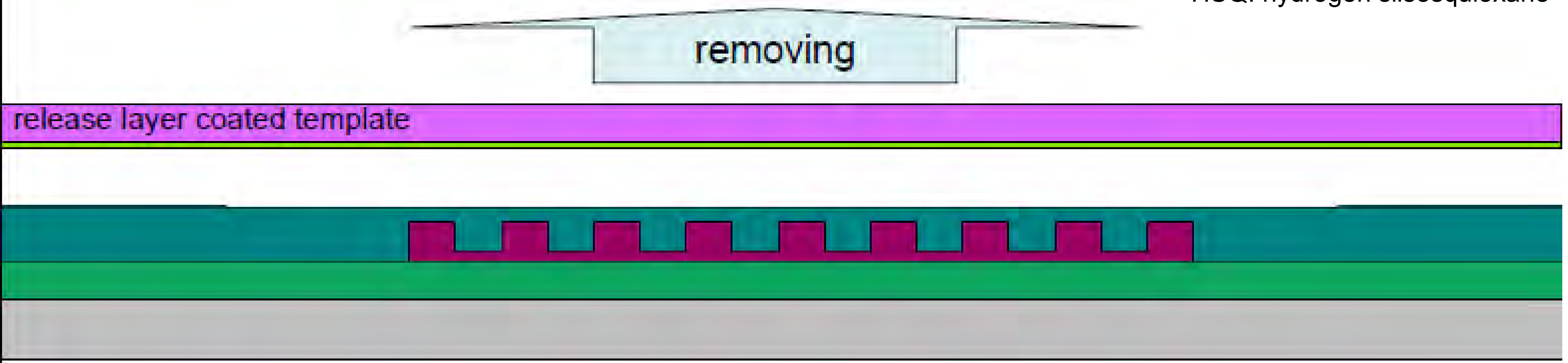



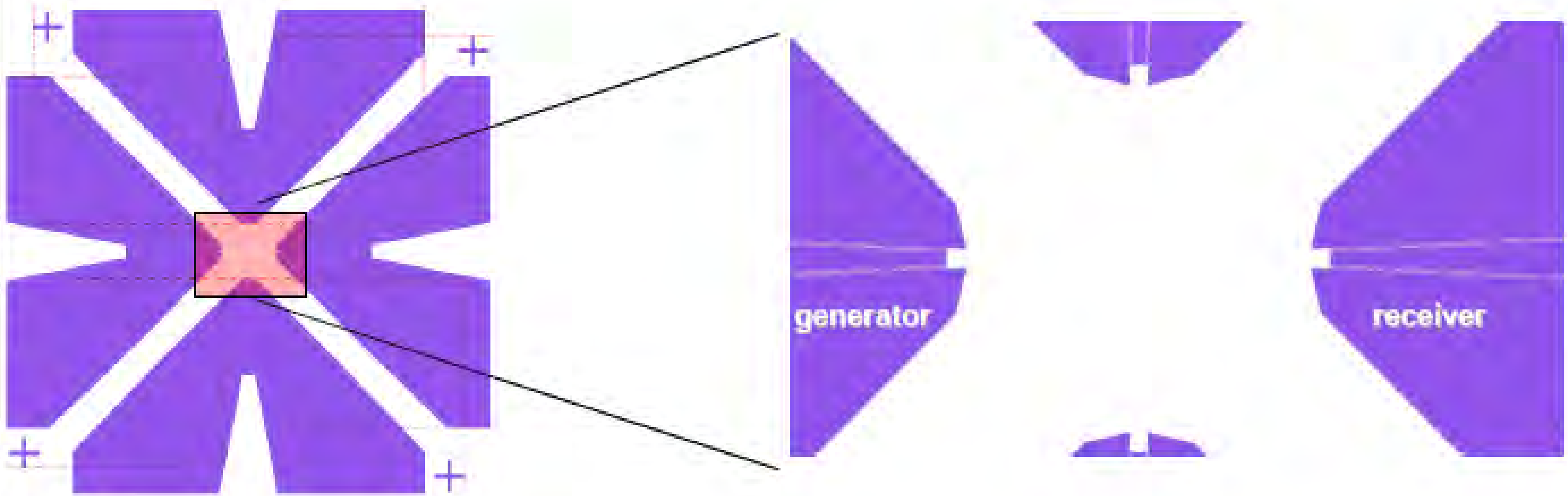

- Planarization quality decreases with feature size and spatial separation
- Appropriate planarization can **<u>not</u>** be achieved by applying simple “spin coating” method

S. Büyükköse, B. Vratzov and WGvdW, J. Vac. Sci. Technol. B **29**, 2 (2011).

# NIL of Interdigitated transducers: HSQ planarization

HSQ: hydrogen silsesquioxane

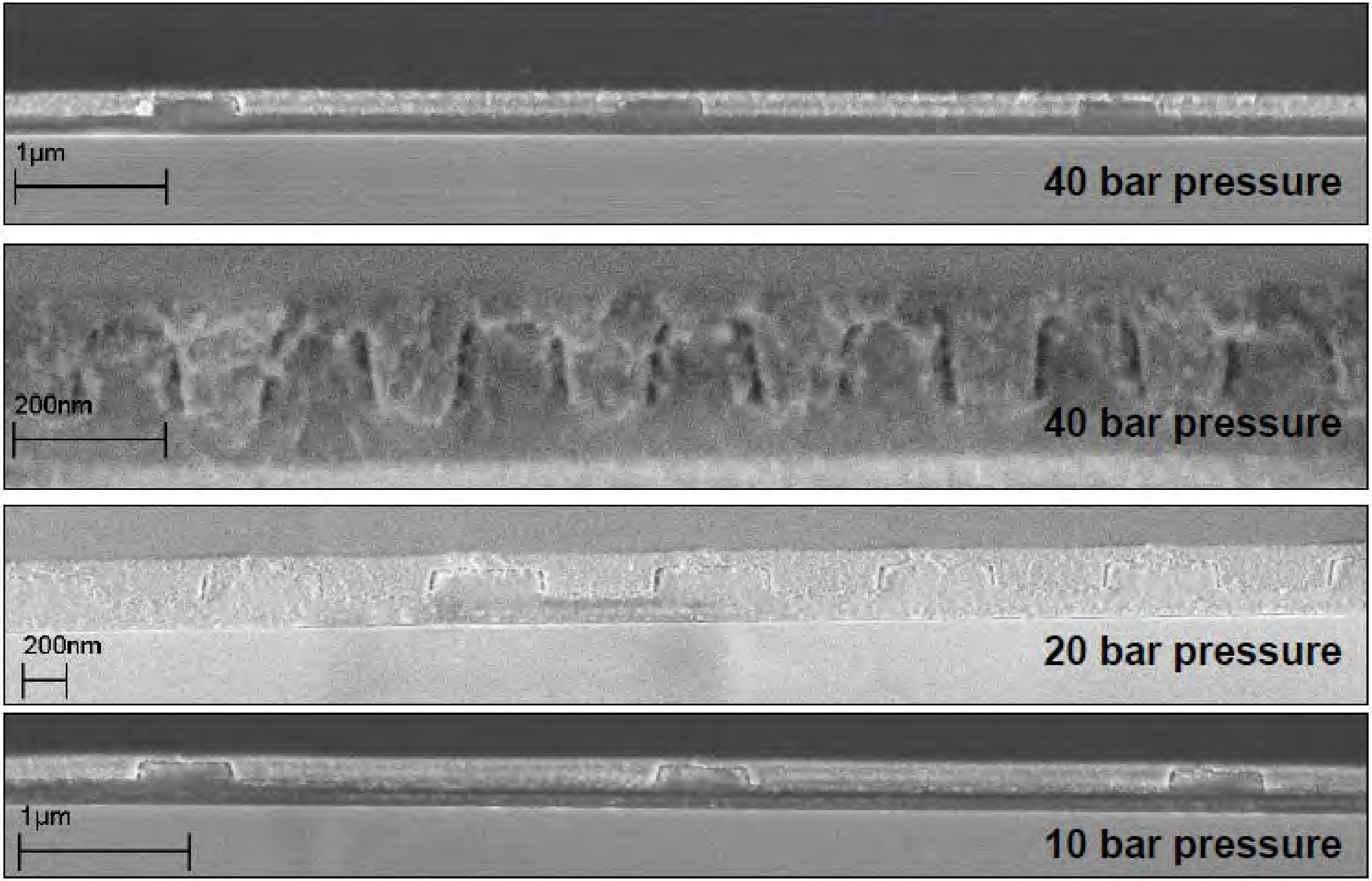



S. Büyükköse, B. Vratzov and WGvdW, J. Vac. Sci. Technol. B **29**, 2 (2011).

# NIL of Interdigitated transducers: HSQ planarization

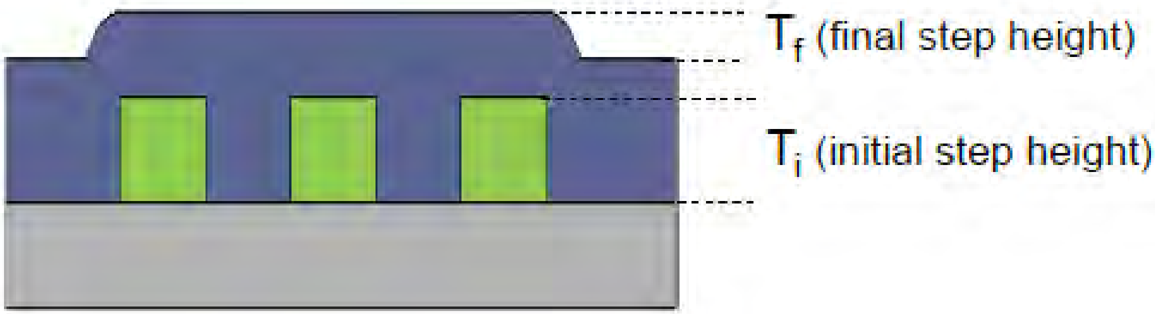
HSQ: hydrogen silsesquioxane




S. Büyükköse, B. Vratzov and WGvdW, J. Vac. Sci. Technol. B **29**, 2 (2011).

# NIL of Interdigitated transducers: HSQ planarization

HSQ: hydrogen silsesquioxane



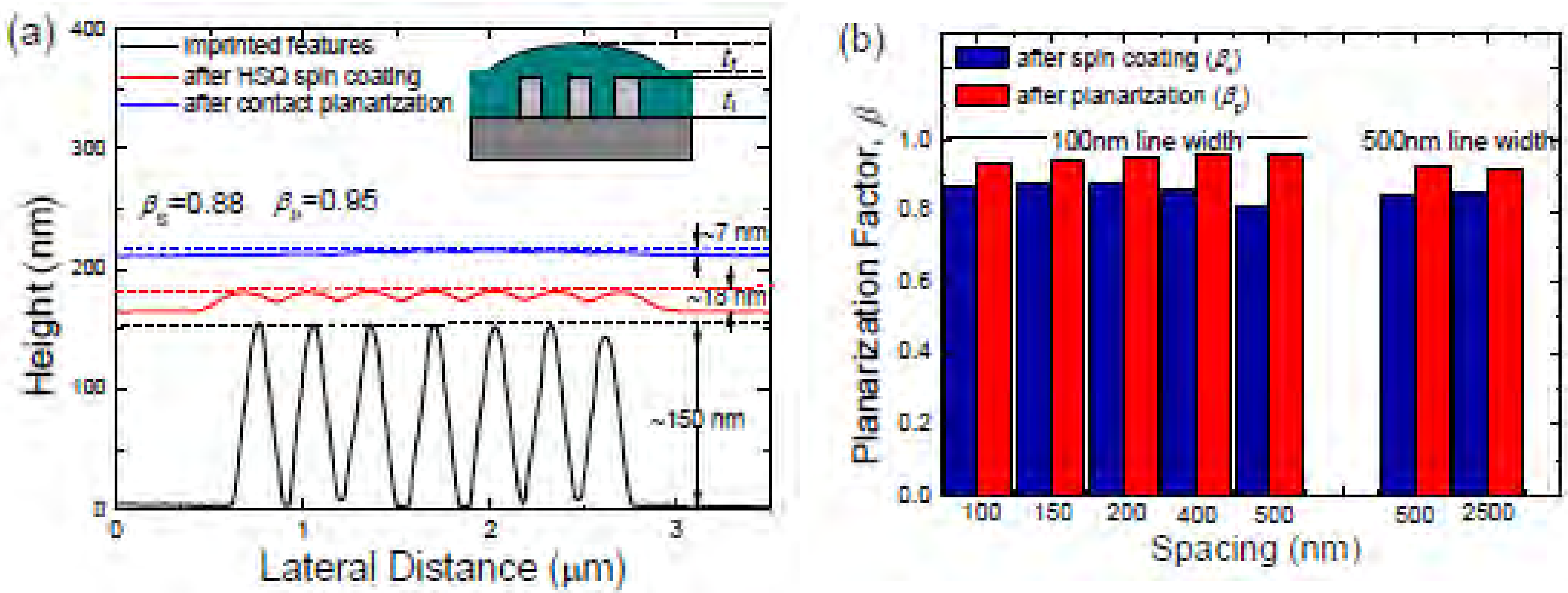

**_Planarization factor_**

$\beta$= (1- Tf/ Ti)

**or**

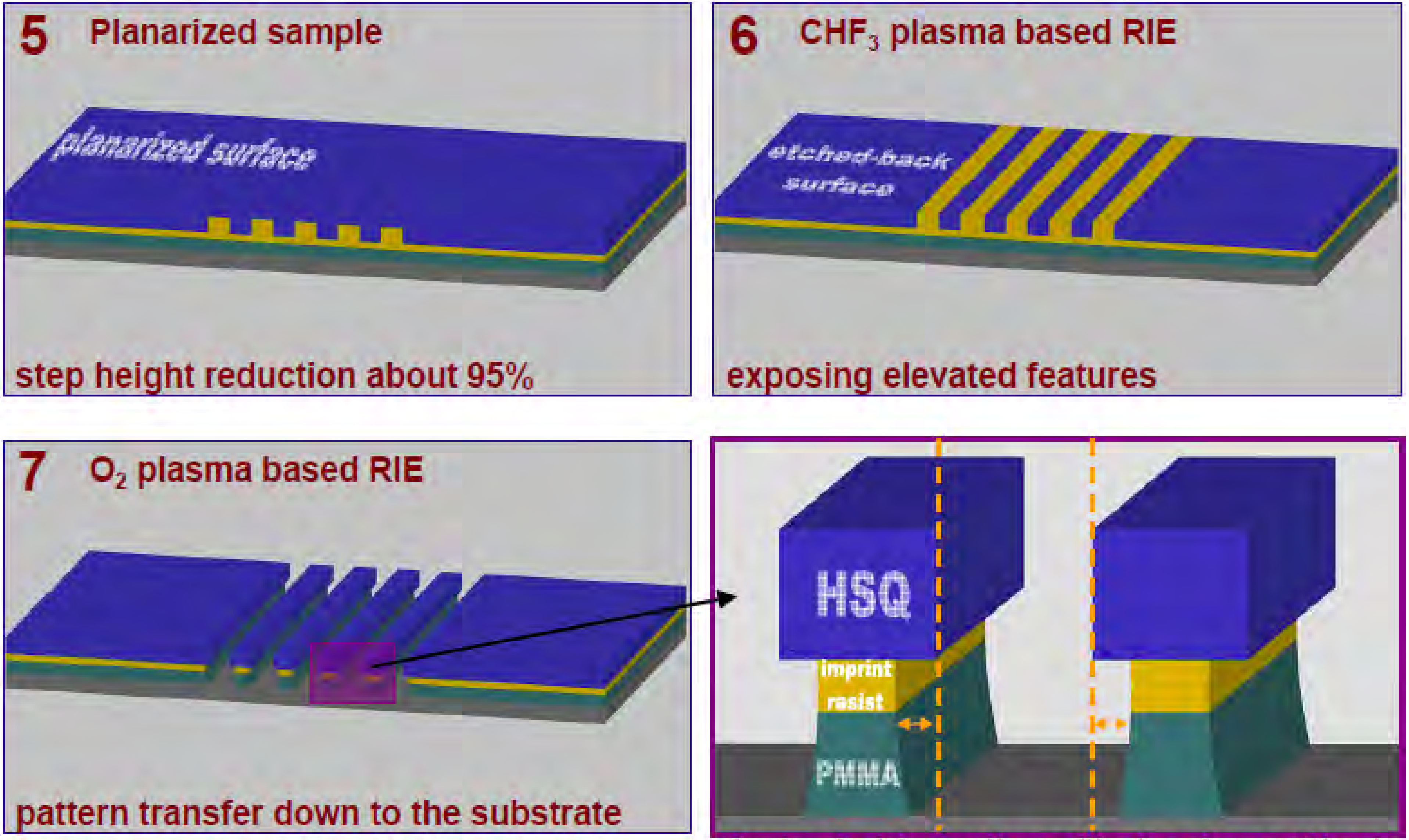
**_Degree of planarization_**

DOP(%)= 100x $\beta$



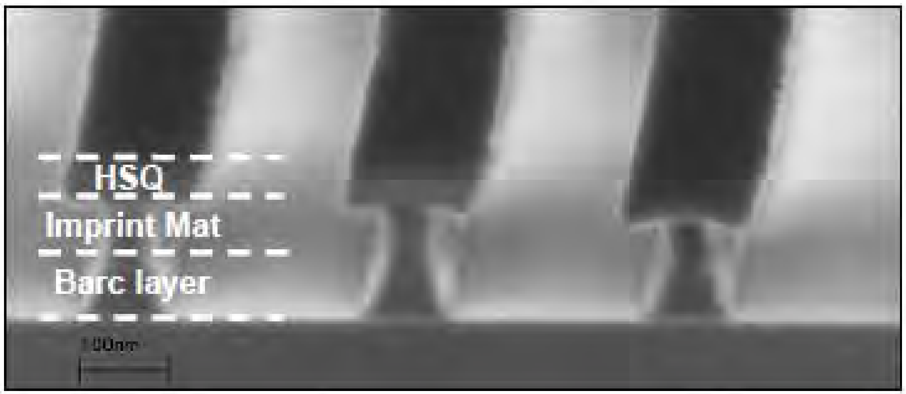

S. Büyükköse, B. Vratzov and WGvdW, J. Vac. Sci. Technol. B **29**, 2 (2011).

# NIL of Interdigitated transducers

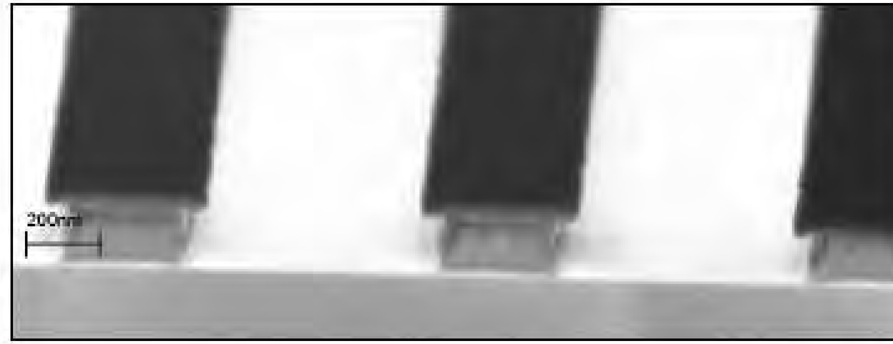


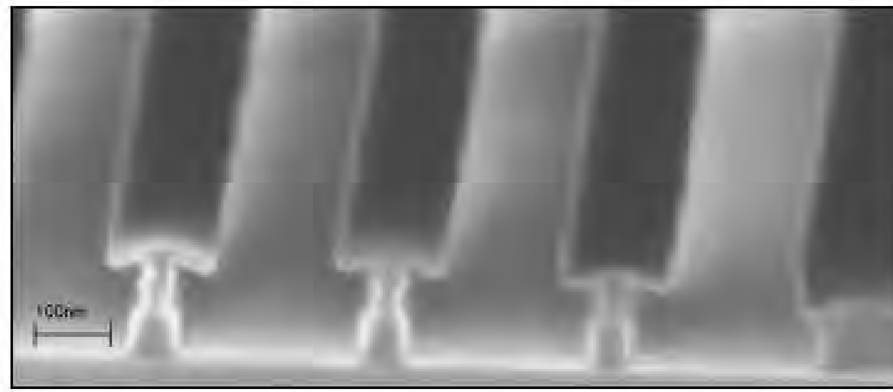

desired side-wall profile (under-cutting)

# NIL of Interdigitated transducers

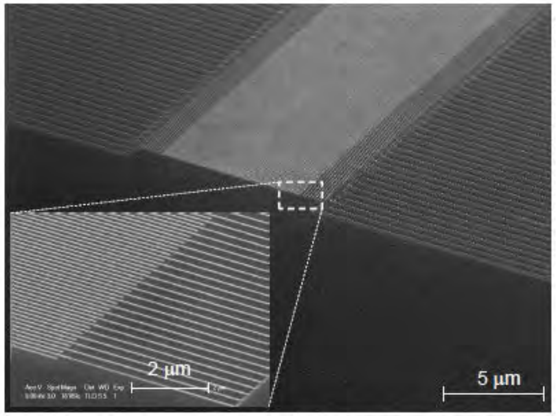

HSQ/OrganicImp.Mat/Barc layer coated samples etched under $CHF_3$ plasma for 4.2 min. and following $O_2$ plasma for 2 min.




HSQ/OrganicImp.Mat/Barc layer coated samples etched under $CHF_3$ plasma for 4.2 min. and following $O_2$ plasma for 3 min.

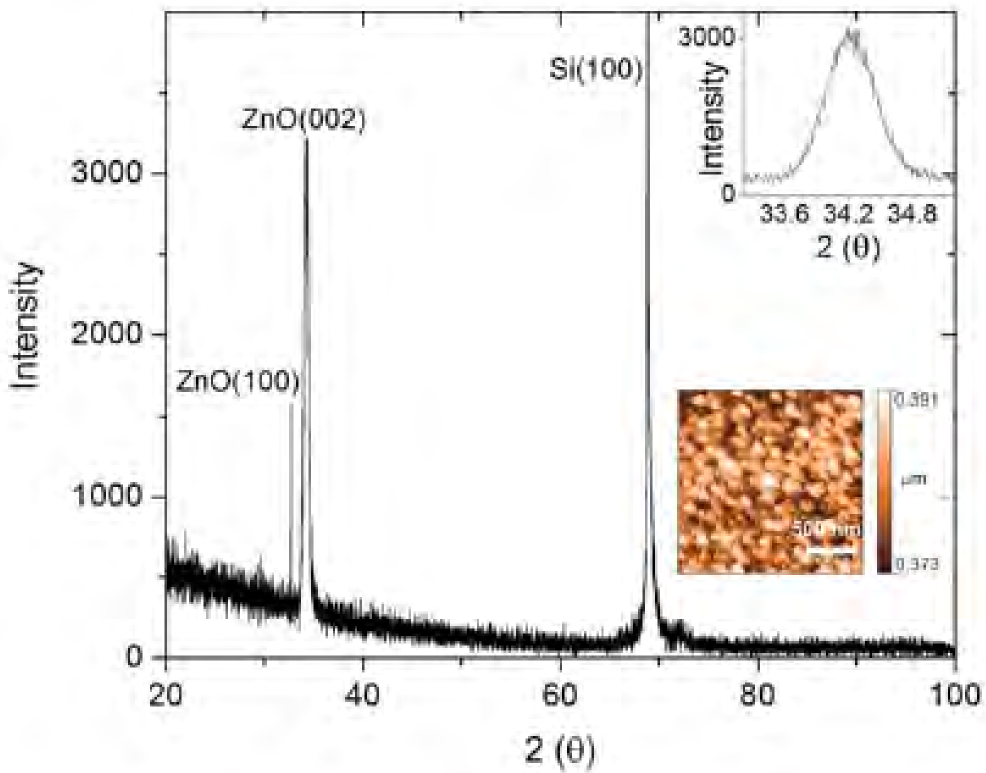
# IDTs on a $ZnO/SiO_2/Si$ multi-layer




- ZnO(230 nm)/$SiO_2$(100 nm)/Si multilayer
- $SiO_2$ buffer layer increases electromechanical coupling
- Sharply varying elastic properties → higher-order SAW modes
- ZnO: high electromechnanical coupling constant, easy to fabricate (sputter)
- Double-sided polished (low-resistive) p-type (100) Si substrate (5-10 Ωcm)

S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

# IDTs on a $ZnO/SiO_2/Si$ multi-layer



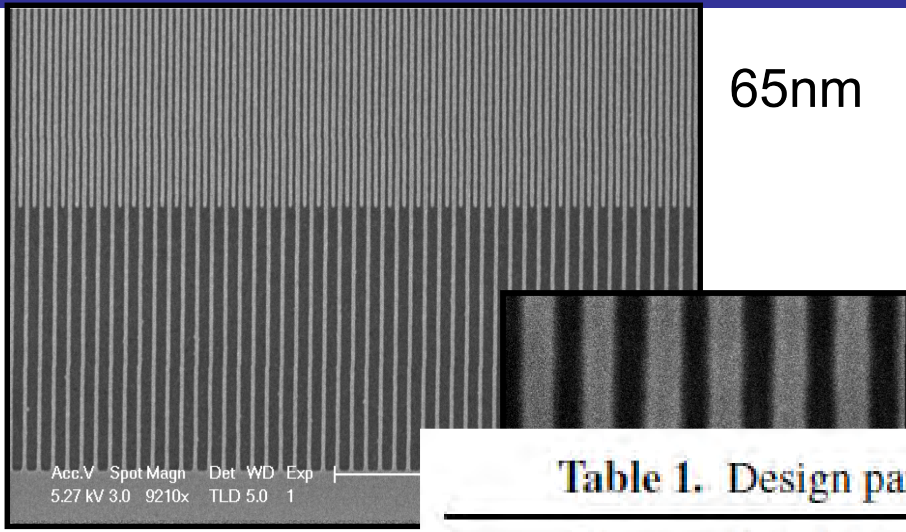

Collaboration with Dr. Yusuf Selamet Izmir Institute of Technology, Turkey

## ZnO

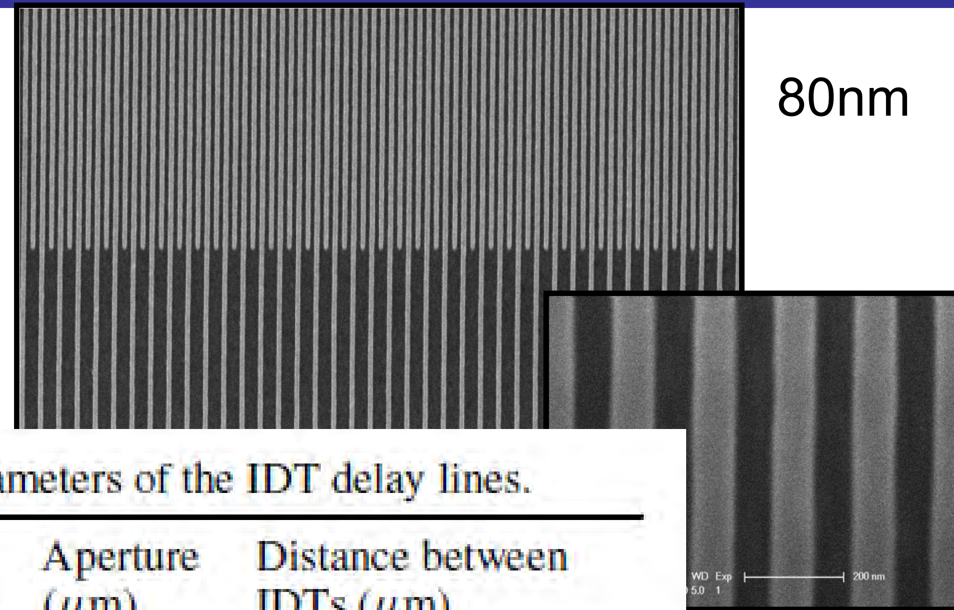
- RF sputtering
- Wurtzite symmetry with hexagonal unit cell
- (002) surface has the smallest surface energe → c-axis (002) perpendicular to surface
- Highly c-axis oriented ZnO gives highest piezoelectricity
- Polycrystalline, ~15 nm grain size
- RMS ~ 2.5 nm

S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

# IDTs on a $ZnO/SiO_2/Si$ multi-layer



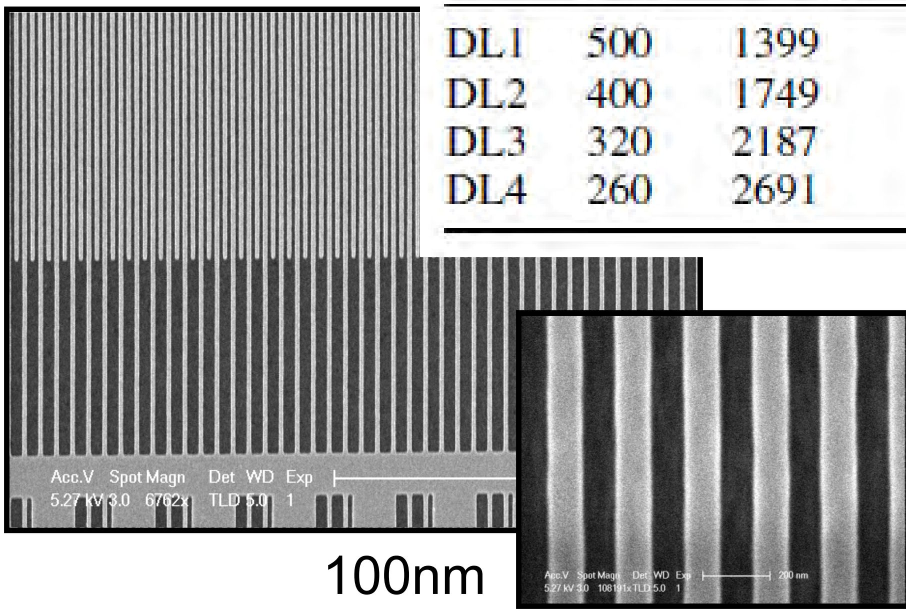

65nm



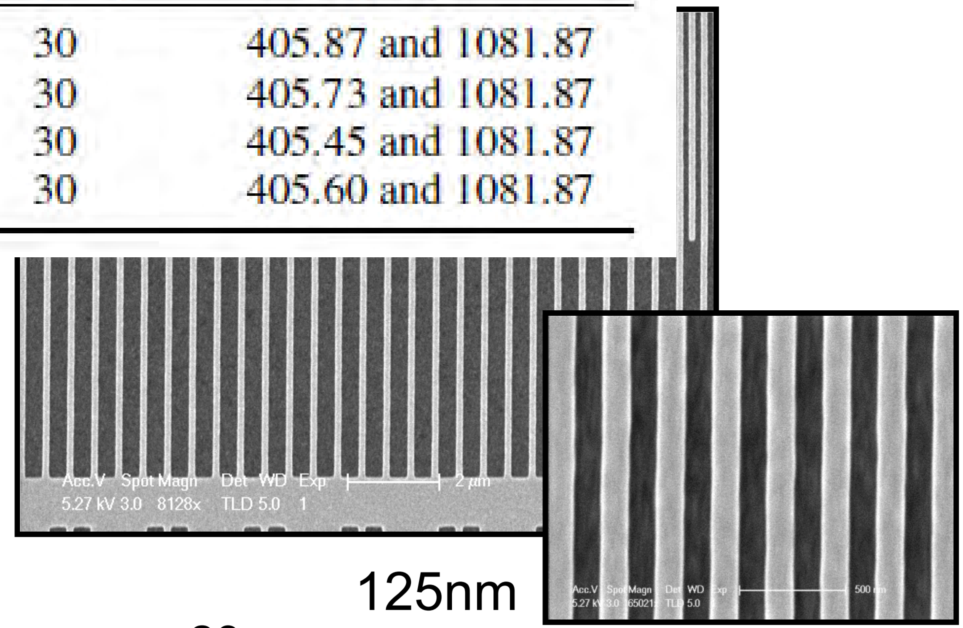

80nm

Table 1. Design parameters of the IDT delay lines.

| | λ (nm) | Number of fingers | Aperture (μm) | Distance between IDTs (μm) |
|---|---|---|---|---|
| DL1 | 500 | 1399 | 30 | 405.87 and 1081.87 |
| DL2 | 400 | 1749 | 30 | 405.73 and 1081.87 |
| DL3 | 320 | 2187 | 30 | 405.45 and 1081.87 |
| DL4 | 260 | 2691 | 30 | 405.60 and 1081.87 |

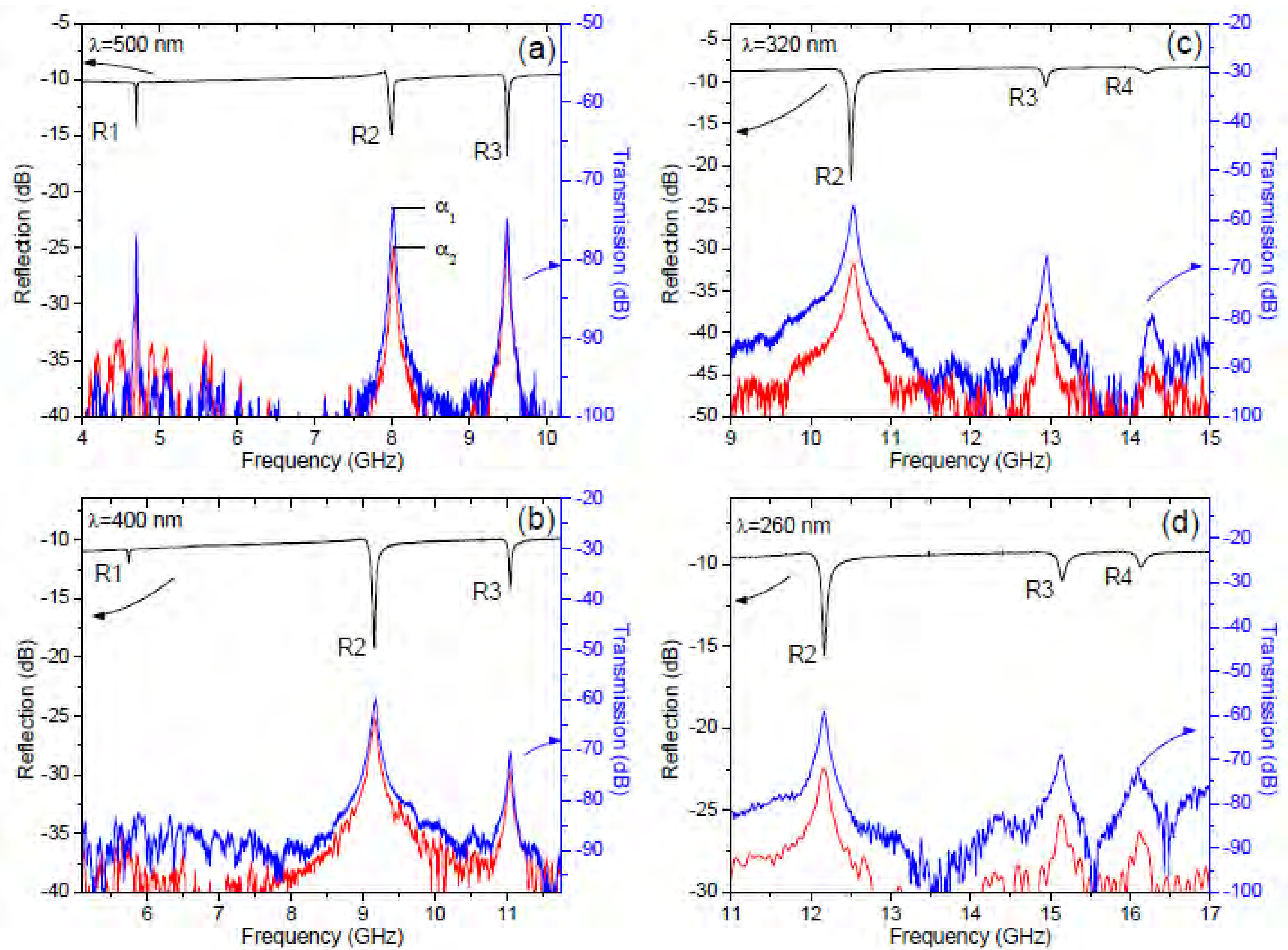



100nm




125nm

# IDTs on a $ZnO/SiO_2/Si$ multi-layer




Rn : n$^{th}$ Rayleigh mode

Blue: 405 um separation; Red: 1081 um separation

S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

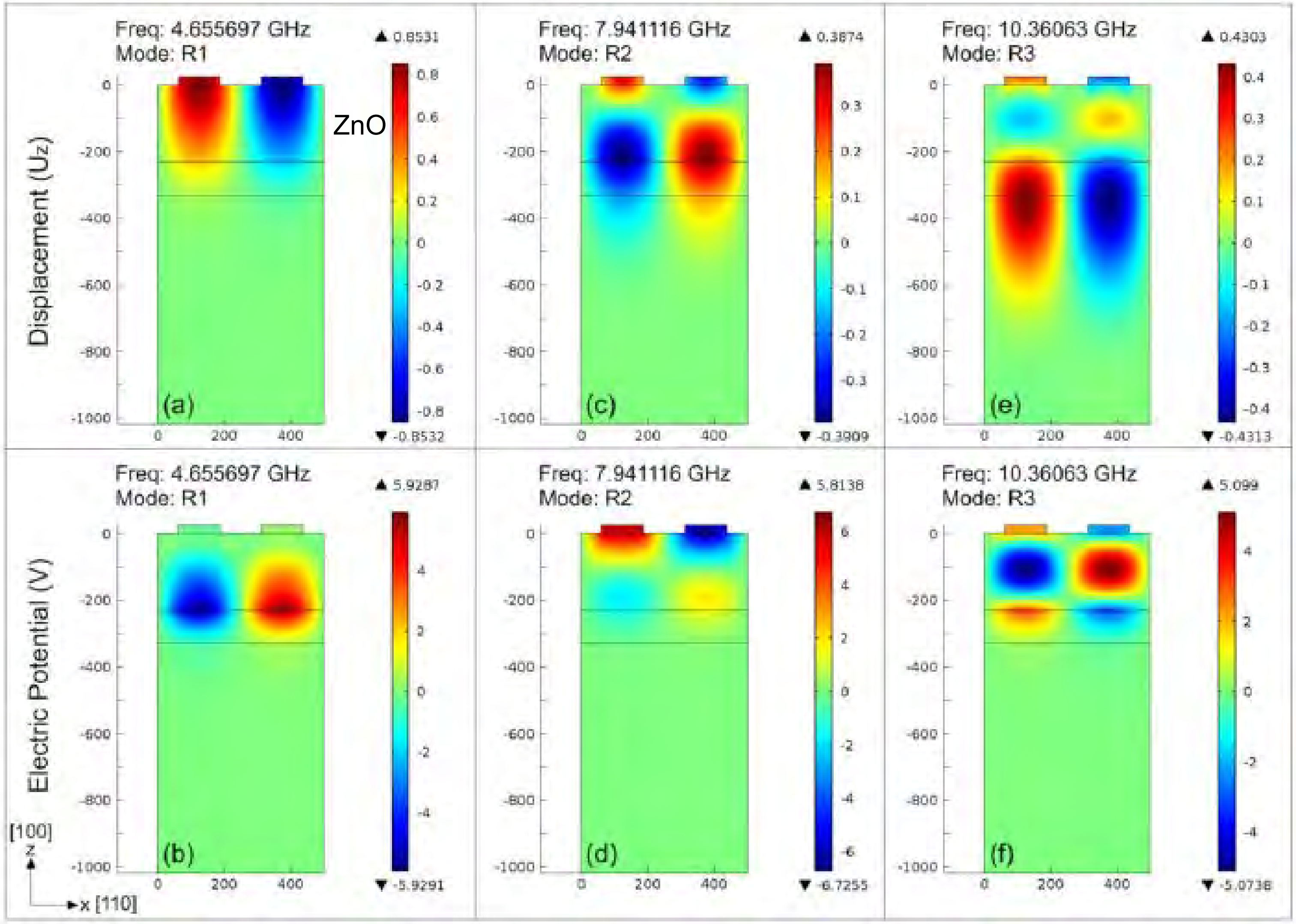
# Higher-order Rayleigh modes

- Appear when the acoustic velocity in the overlayer(s) is lower than in the substrate
- $v_{SAW,Si} > v_{SAW,SiO2}$ , $v_{SAW,ZnO}$
- Determined by the relative thickness of the film ($d_{ZnO}$ / $\lambda_{SAW}$)

**Table 2.** Experimental results of resonance frequency, velocity and electromechanical coupling coefficient for different excitation modes of DL1 ($\lambda = 500$ nm), DL2 ($\lambda = 400$ nm), DL3 ($\lambda = 320$ nm) and DL4 ($\lambda = 260$ nm) devices. R1, R2, R3 and R4 are first-order (fundamental), second-order, third-order and fourth-order Rayleigh modes, respectively.

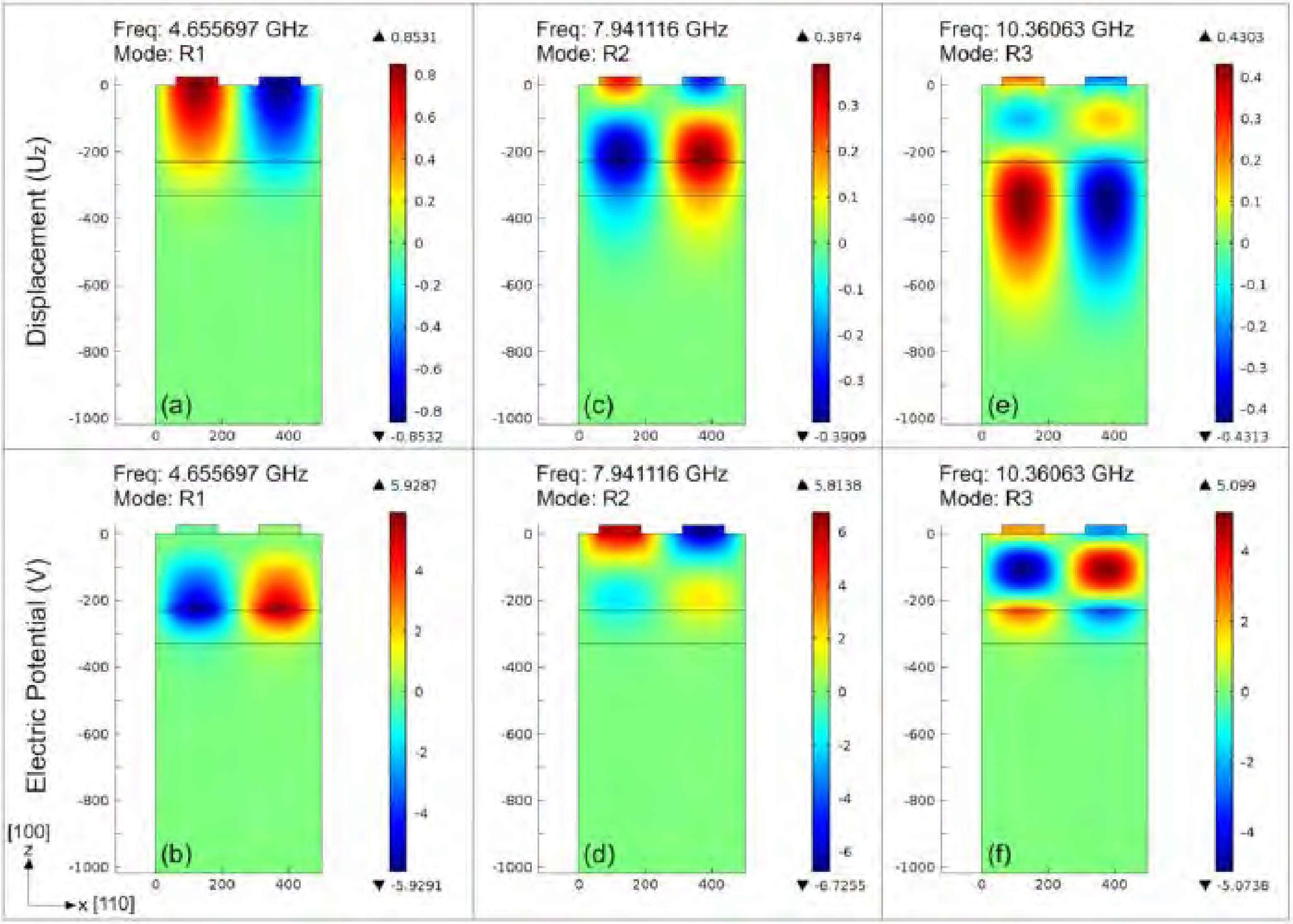
| | R1 | | | R2 | | | R3 | | | R4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DL | $f$ (GHz) | $v$ (m s$^{-1}$) | $k^2$ | $f$ (GHz) | $v$ (m s$^{-1}$) | $k^2$ | $f$ (GHz) | $v$ (m s$^{-1}$) | $k^2$ | $f$ (GHz) | $v$ (m s$^{-1}$) | $k^2$ |
| 1 | 4.697 | 2348 | 0.007 | 8.002 | 4001 | 0.030 | 9.495 | 4747 | 0.010 | — | — | — |
| 2 | 5.737 | 2295 | 0.012 | 9.137 | 3655 | 0.036 | 11.03 | 4412 | 0.014 | — | — | — |
| 3 | — | — | — | 10.54 | 3373 | 0.032 | 12.96 | 4147 | 0.013 | 14.26 | 4563 | 0.025 |
| 4 | — | — | — | 12.17 | 3164 | 0.033 | 15.14 | 3937 | 0.031 | 16.13 | 4194 | 0.028 |

# Higher-order Rayleigh modes (simulations), $\lambda$ = 500 nm



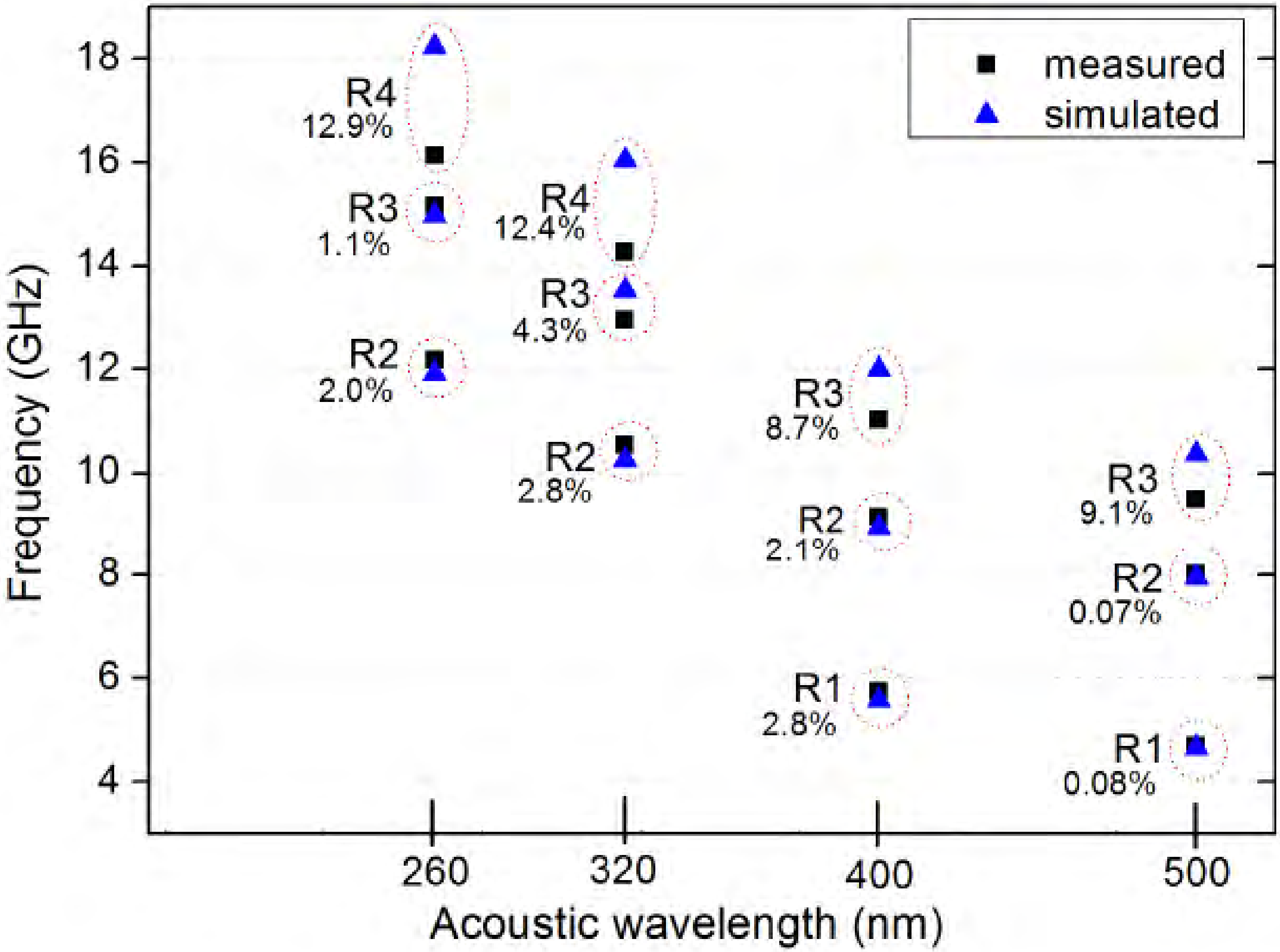

S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

# Higher-order Rayleigh modes (simulations), λ = 260 nm




S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

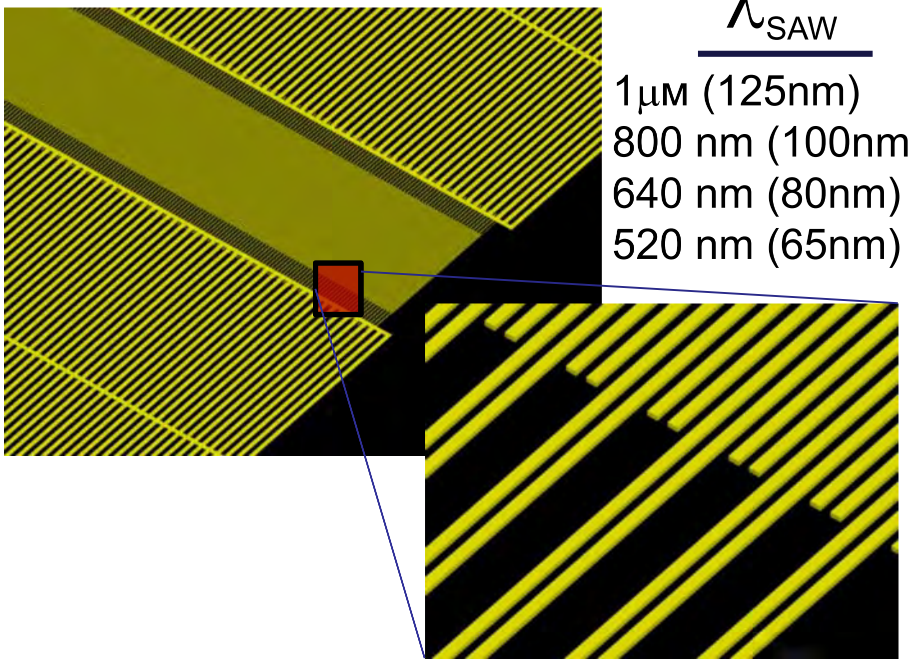
# Higher-order Rayleigh modes: comparison




S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

# IDTs on a $SiO_2$/ZnO/SiO2/Si multi-layer

Double Finger Design (ZnO=80 nm)



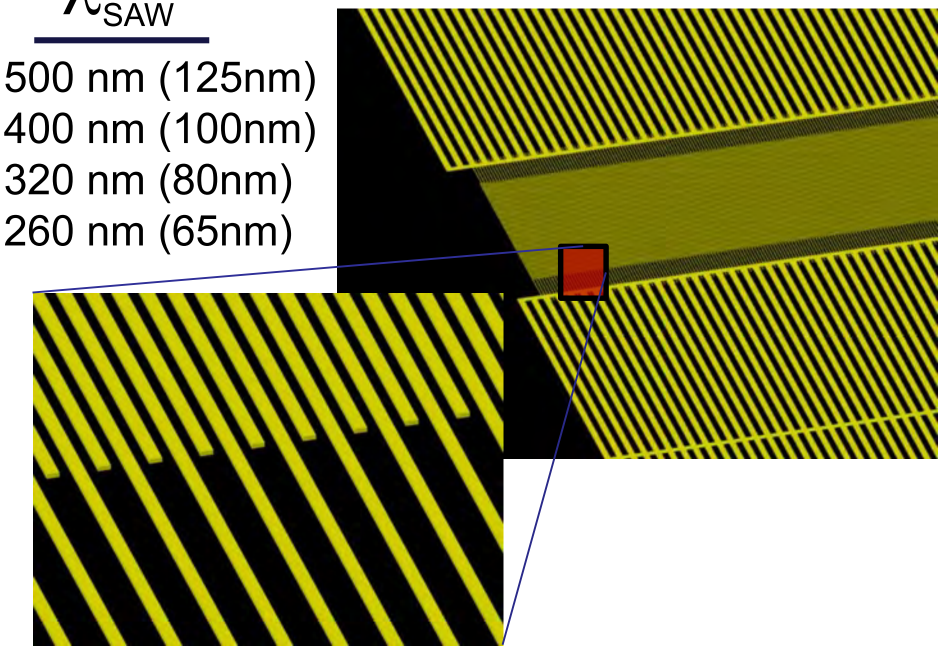
$\lambda_{SAW}$

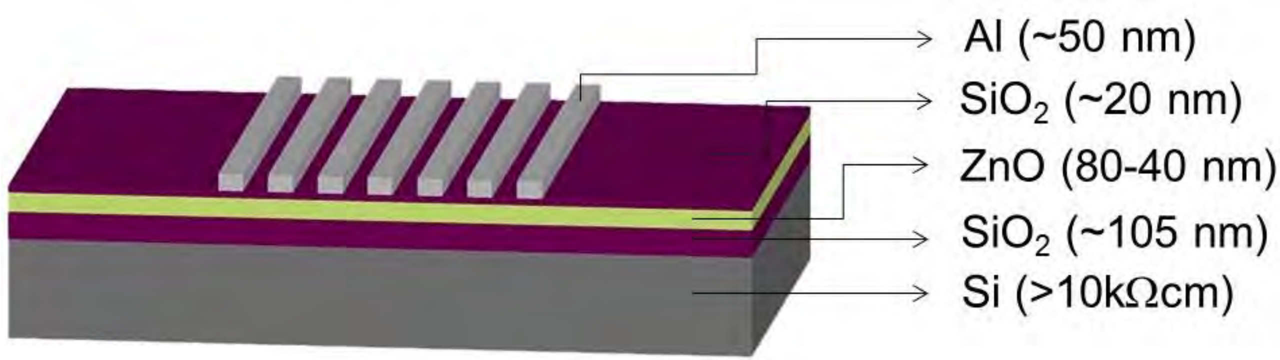
1μм (125nm)
800 nm (100nm)
640 nm (80nm)
520 nm (65nm)

Single Finger Design (ZnO=40 nm)

$\lambda_{SAW}$

500 nm (125nm)
400 nm (100nm)
320 nm (80nm)
260 nm (65nm)



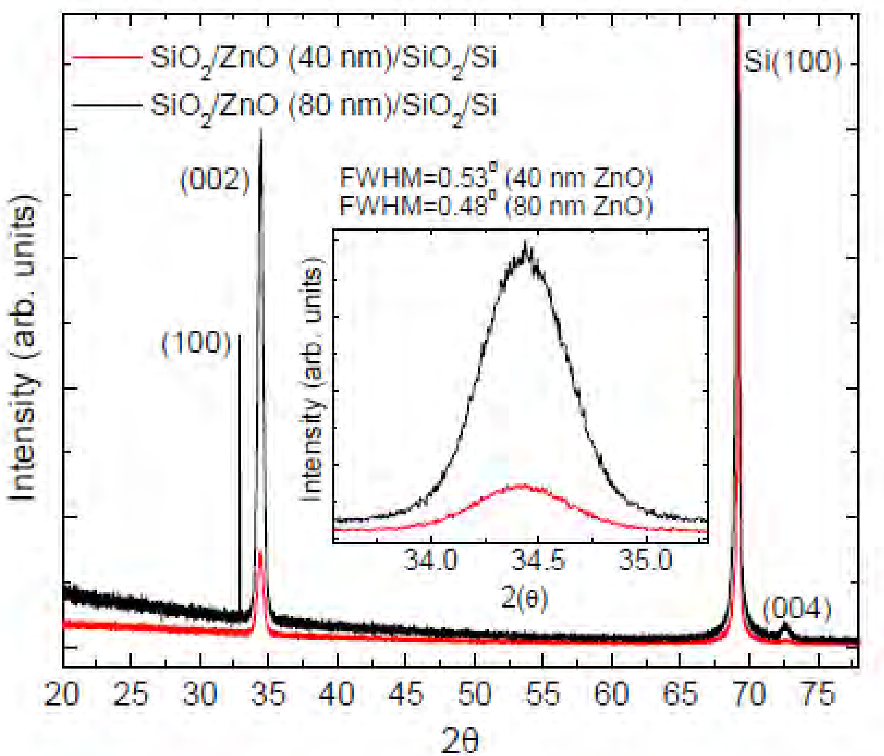


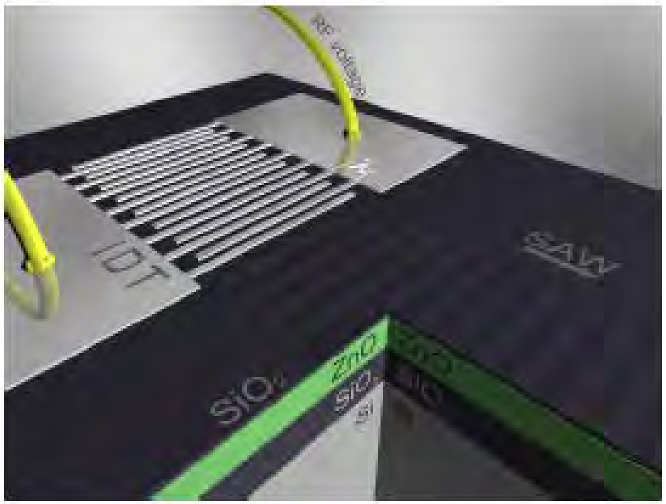



MESA+ INSTITUTE FOR NANOTECHNOLOGY

# IDTs on a $SiO_2/ZnO/SiO_2/Si$ multi-layer

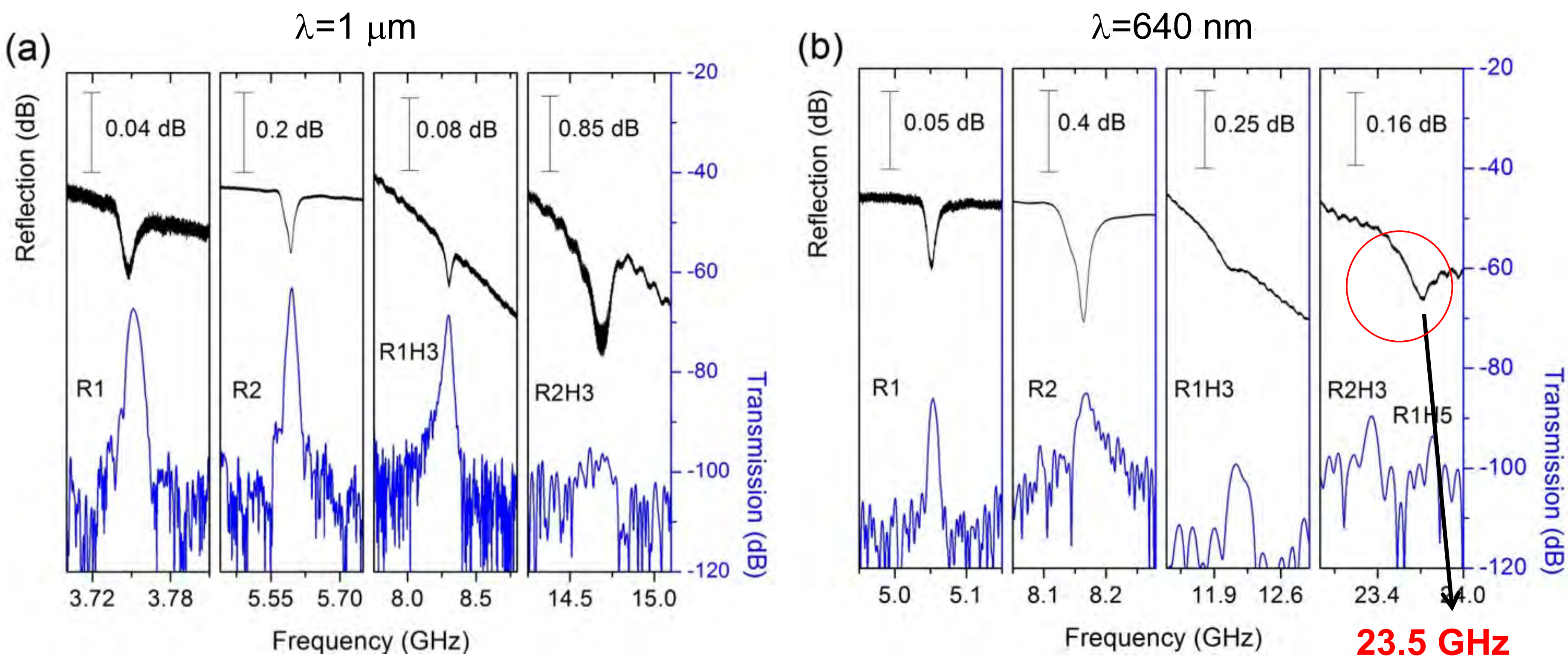
- $SiO_2$(20 nm)/ZnO(40,80 nm)/$SiO_2$(105 nm)/Si multilayer
- Unprotected ZnO is CMOS incompatible
- Substrate is a highly resistive Si (>10 kΩ)) wafer




S. Büyükköse, B. Vratzov, J. van der Veen, P. V. Santos and WGvdW
Appl. Phys. Lett. *102*, 013112 (2013).

# SAW Characterisation




Rn – nth Rayleigh mode
RnH3 – 3rd Harmonics

S. Büyükköse, B. Vratzov, J. van der Veen, P. V. Santos and WGvdW
Appl. Phys. Lett. **102**, 013112 (2013).

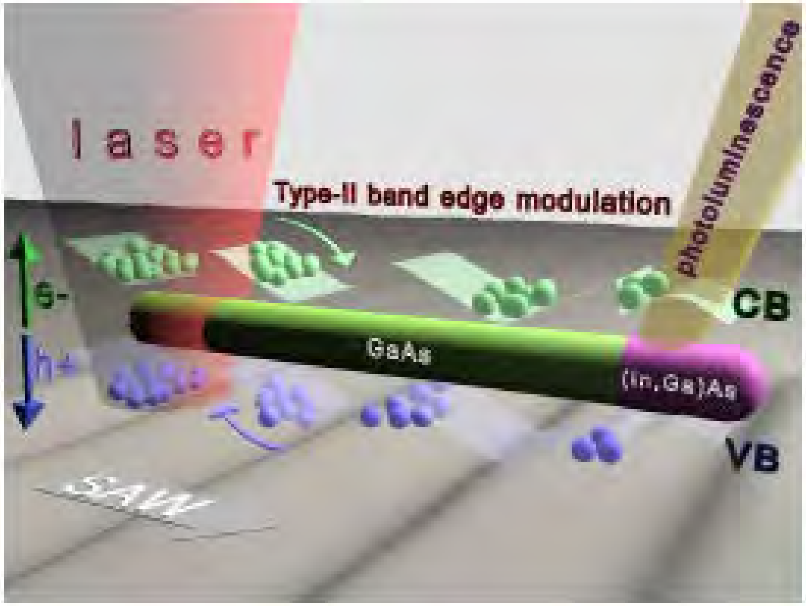
# High-frequency acoustic charge transport in GaAs nanowires

- Semiconductor nanowires (NWs) offer new possibilities for low-dimensional optoelectronic devices.
- The operation of such devices requires appropriate techniques for applying electrical control fields, which typically involve doping and contacting of nm-sized structures.
- An efficient carrier transport mechanism which eliminates electrical contact issue on nanostructures is important.

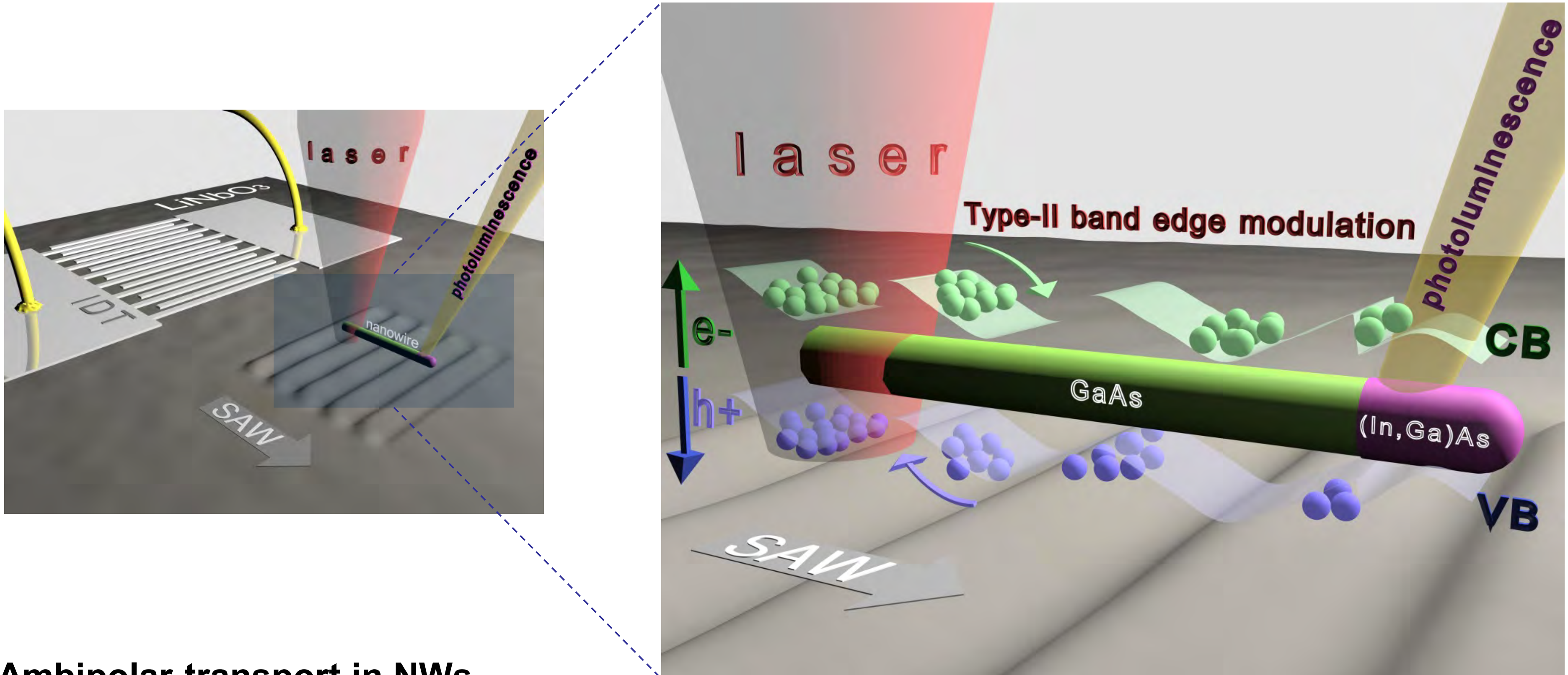
SAW enables contactless manipulation of carriers in semiconductors!

Paul-Drude-Institut für Festkörperelektronik

S Büyükköse, A Hernández-Mínguez, B Vratzov, C Somaschini, L Geelhaar, H Riechert, WGvdW and P V Santos, Nanotechnology **25**, 135204 (2014).



# Experimental details: Measurement setup I

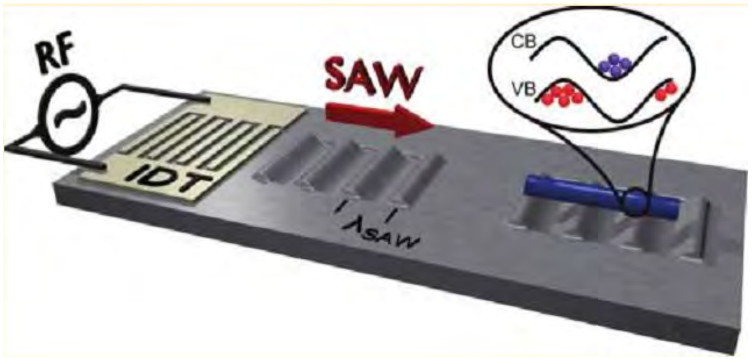



**Ambipolar transport in NWs**

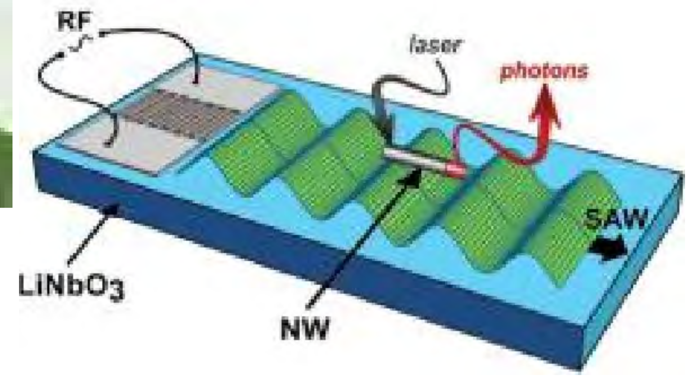
- SAW Induced type-II modulation of the band edges: $\lambda_{SAW} < L_{NW}$
- Excitation of electron-hole pairs by an incident laser pulse
- Spatial separation of e-h pairs due to the modulated conduction (CB) and valence band (VB)
- This prevents the recombination of the carriers and allows to transport the carriers at $v_{SAW}$.

# Previous works on SAW induced ambipolar CT in NWs

J. B. Kinzel et al. Nano Lett. **2011**, 11,1512




A. Hernández-Mínguez et al. Nano Lett. **2012**, 12, 252




SAW controlled modulation of the optical emission of single GaAs NWs.

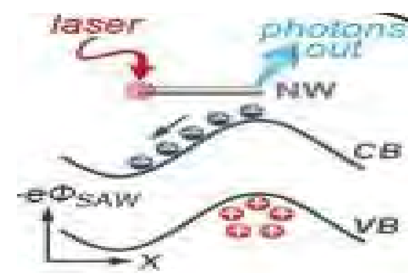
(no transport !)

$\lambda_{SAW}$ = 17.5 μm and 5.5 μm
Length of NW= 15 μm

SAW induced ambipolar transport in GaAs/AlGaAs core/shell NWs.

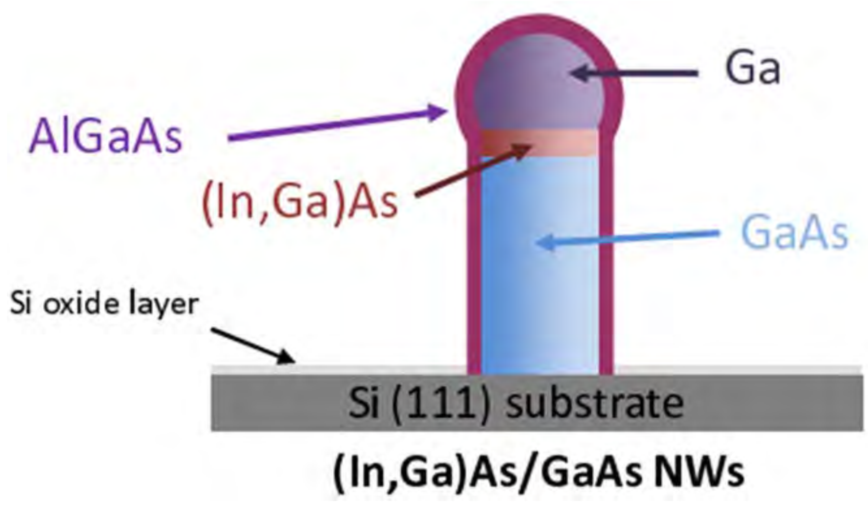
(max. transport efficiency ≅ 50 %)

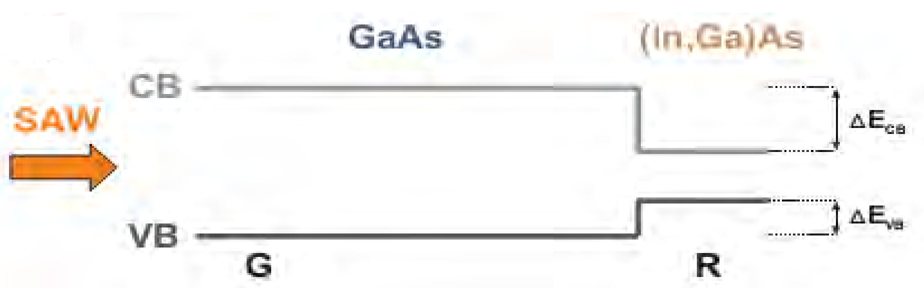
$\lambda_{SAW}$ = 17.5 μm
Length of NW= 8 μm




$$\Phi_{SAW}(x,t) = \Phi_{SAW_0} \sin[2\pi(x/\lambda_{SAW}) - (t/T_{SAW})]$$ , ($x<\lambda_{SAW}$)

# Experimental details: NW growth




Simple demonstration of band structure along growth direction

Breuer *et al.*, Nano Lett. **11**, 1276 (2011).

The GaAs NWs were grown by MBE using a self-assisted VLS method

A segment of approx. 300 nm length containing In inclusions at the top of the GaAs section.

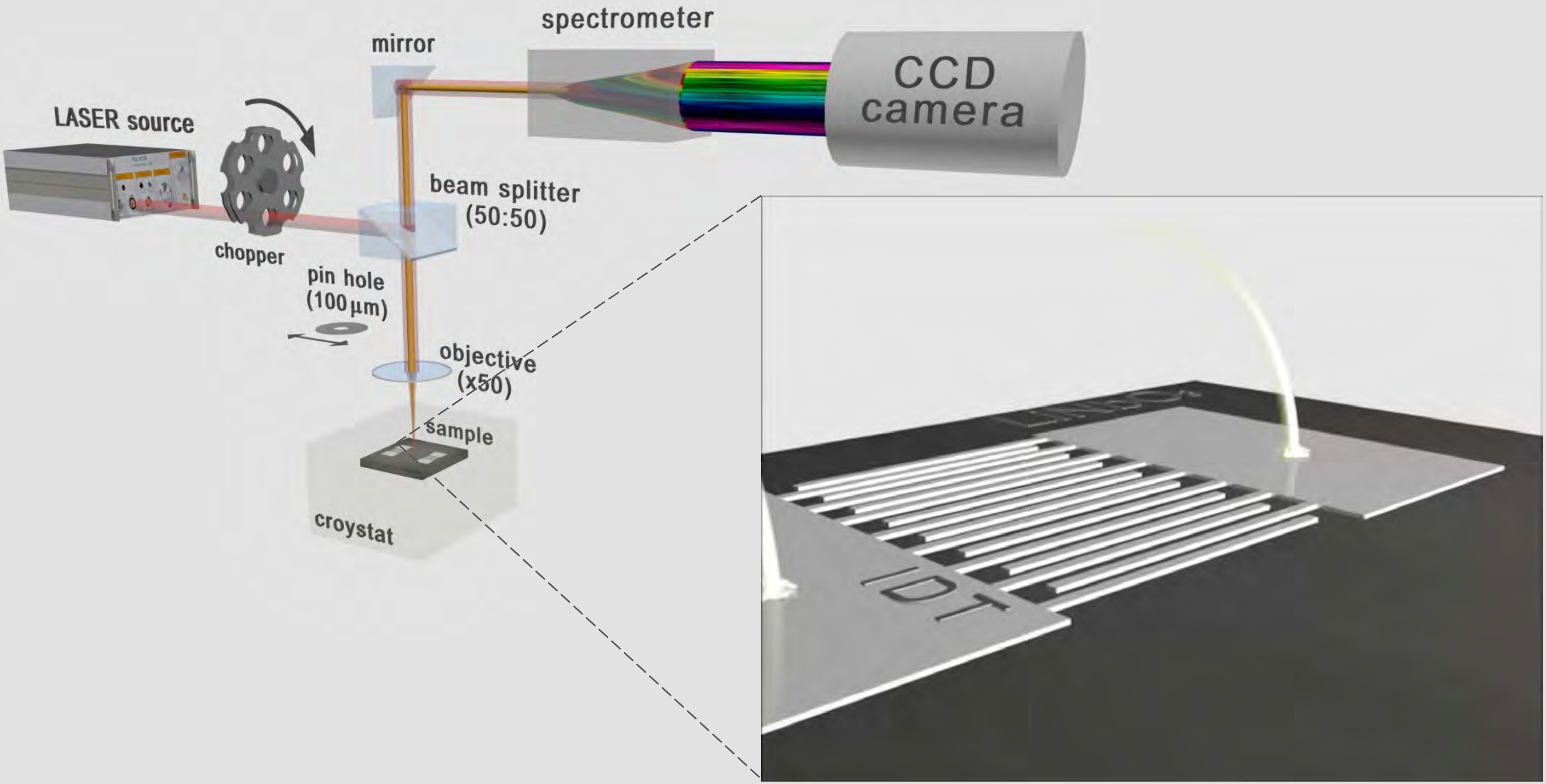
Alx Ga1−x As shell (x= 0.3) was incorporated to prevent non-radiative recombination at the free surfaces.

Average length of 7 μm and diameter of 150 nm.

NWs were removed from the substrate and mechanically dispersed on a 128° Y-cut $LiNbO_3$ substrate

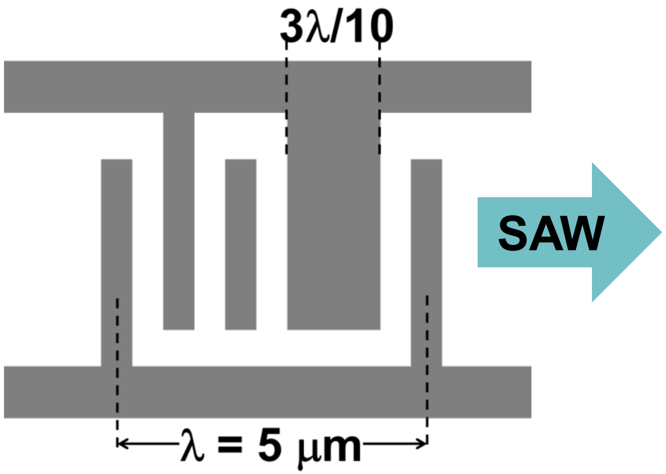
MESA+ INSTITUTE FOR NANOTECHNOLOGY

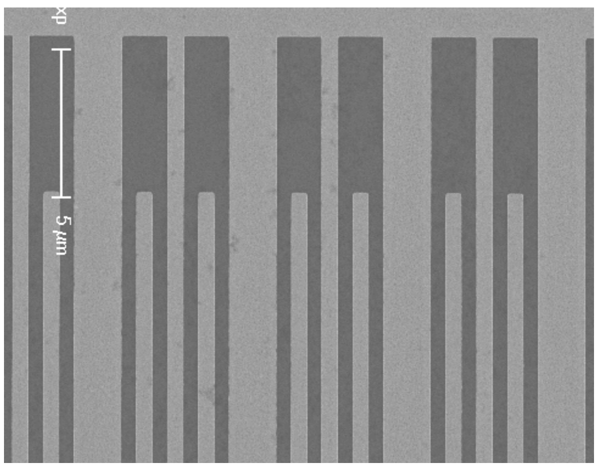
# Experimental details: Measurement setup I I

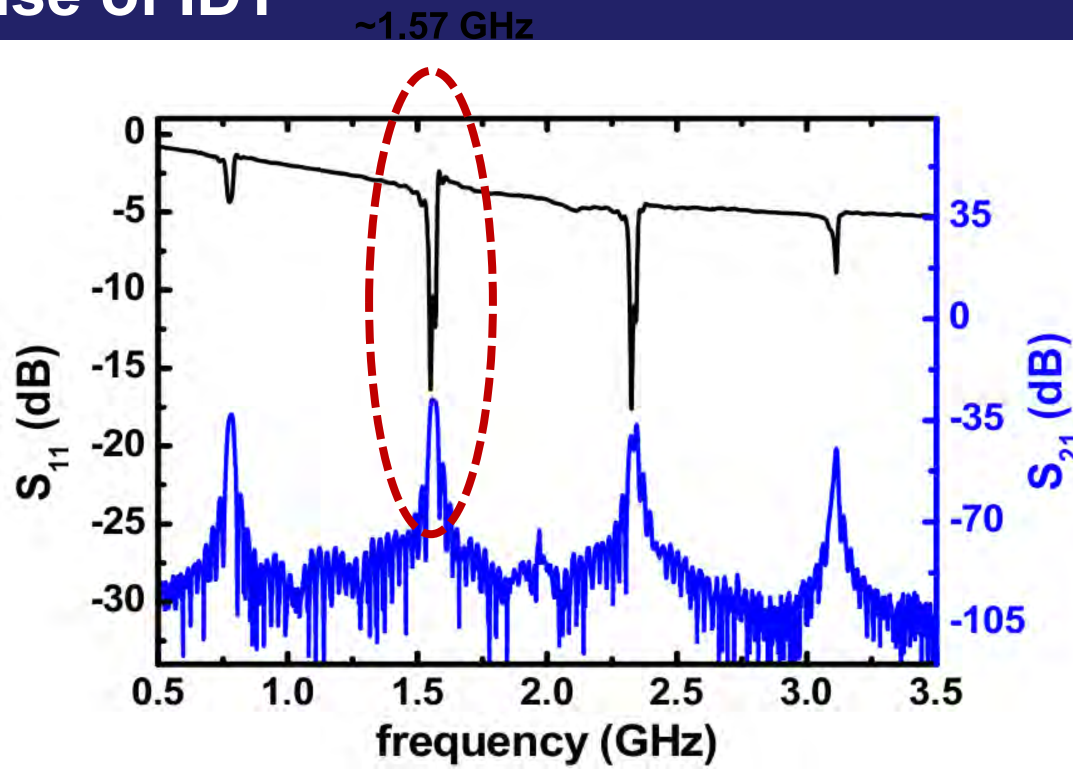



- Experiments performed a 20 K.
- A tightly focused (50X objective, spot diameter of 1.5 μm) laser beam of wavelength 756 nm.
- PL is collected by the same objective that focuses the laser beam and sent to the input of a spectrometer connected to a charge-coupled device (CCD) camera.

# Results: Frequency response of IDT






$\lambda_{SAW}$ = 2.57 um < $L_{NW}$ ~ 7 um

→ Simultaneous transport of electrons and holes in the **SAME** direction

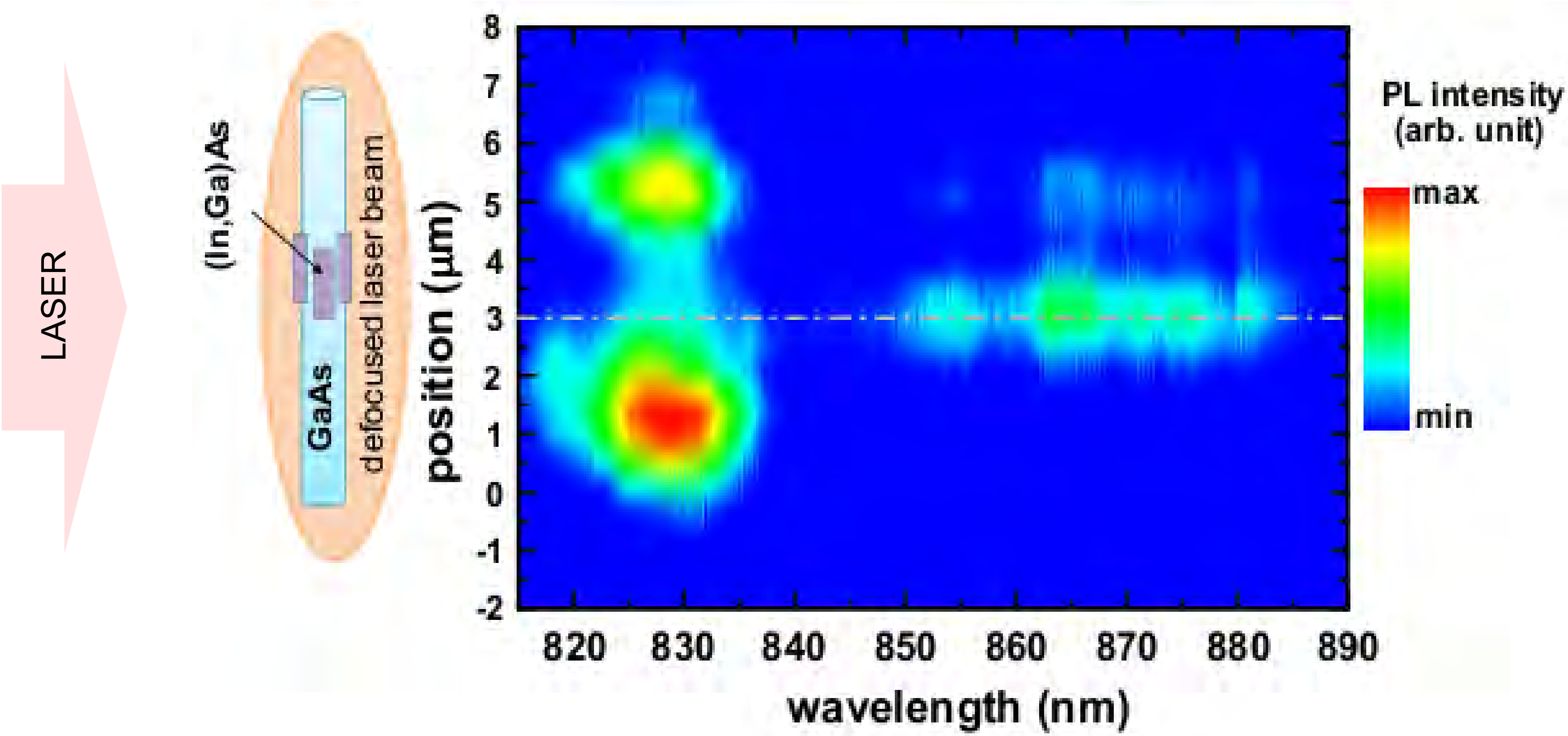
Floating-electrode unidirectional transducer (FEUDT) → higher SAW amplitudes

S Büyükköse, A Hernández-Mínguez, B Vratzov, C Somaschini, L Geelhaar, H Riechert, WGvdW and P V Santos, Nanotechnology **25**, 135204 (2014).

# Results: PL from NW under overall illumination

NW_1

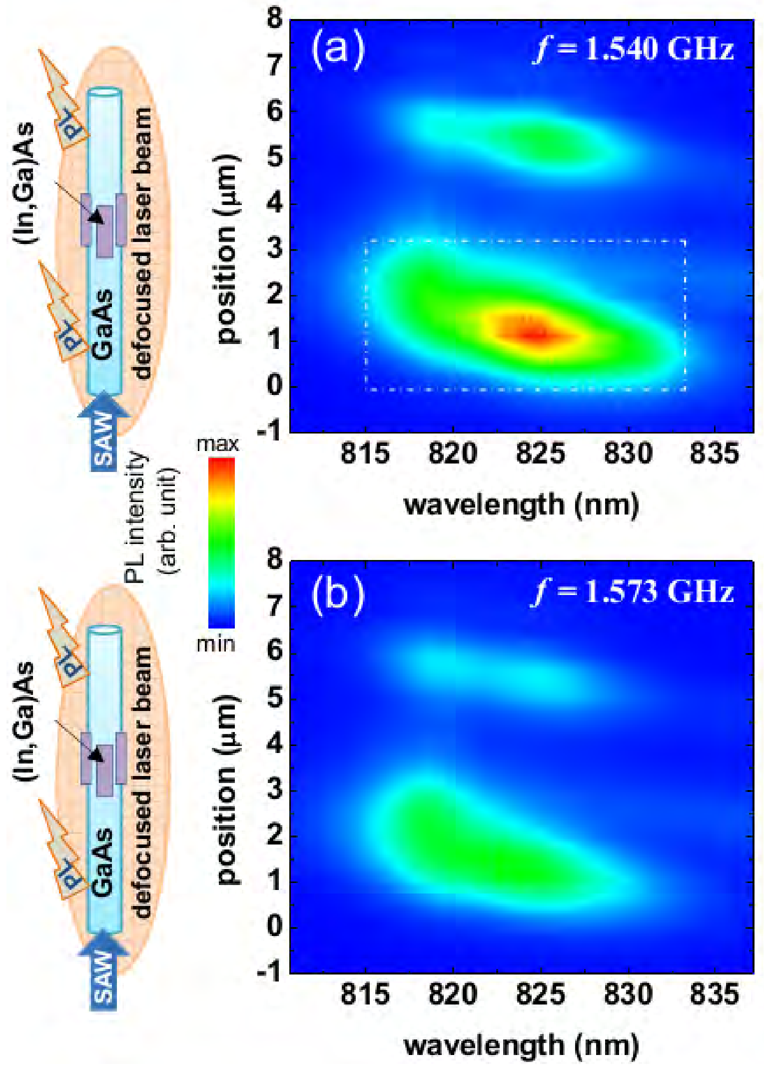
NO SAW




S Büyükköse, A Hernández-Mínguez, B Vratzov, C Somaschini, L Geelhaar, H Riechert, WGvdW and P V Santos, Nanotechnology **25**, 135204 (2014).

# Results: PL emission from GaAs segment

NW_1



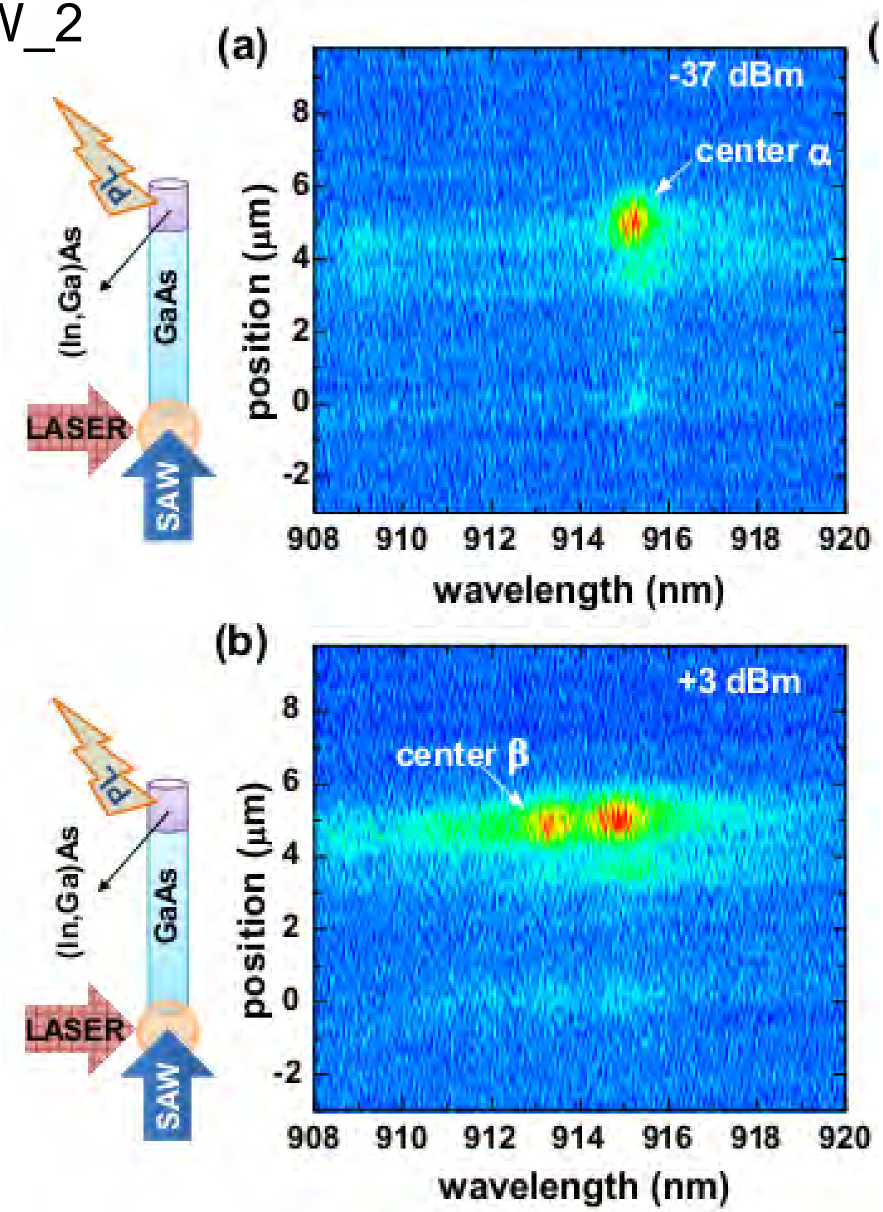

SAW off-resonance

SAW on-resonance
(40% suppression of PL)

S Büyükköse, A Hernández-Mínguez, B Vratzov, C Somaschini, L Geelhaar, H Riechert, WGvdW and P V Santos, Nanotechnology **25**, 135204 (2014).

# Results: PL emission from (In,Ga)As segment

NW_2

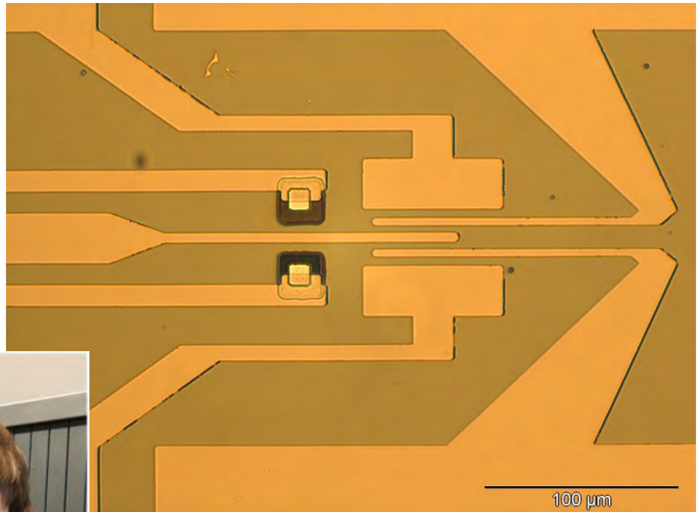



**PL images of two recombination centres at $x_r$= 5 μm for two RF powers**

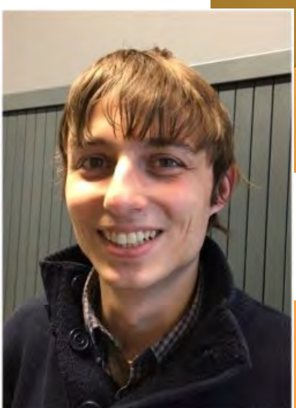
**(a)** $P_{RF}$ =  37 dBm, and **(b)** $P_{RF}$ = +3 dBm.

# Future Work: Measurements on Si-SAW devices

Photon detector

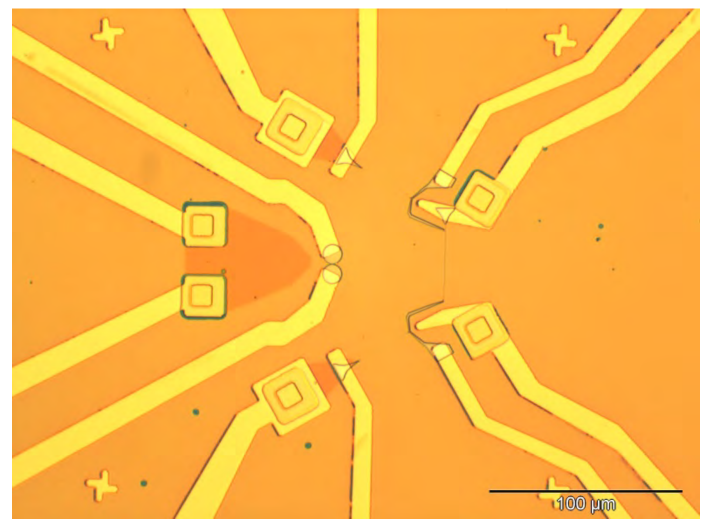



Acoustic switch

Single charge pumping

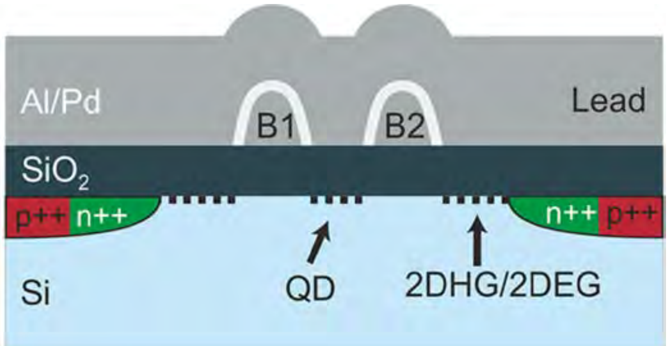

Single charge pumping (interfering SAW)



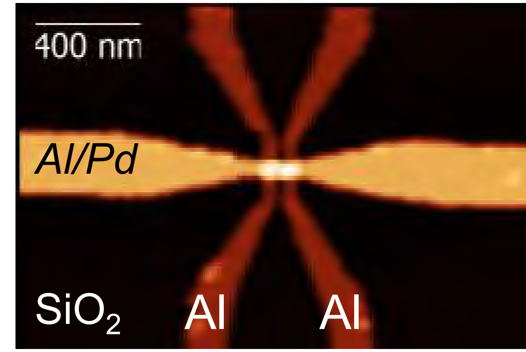

SAWtrain network

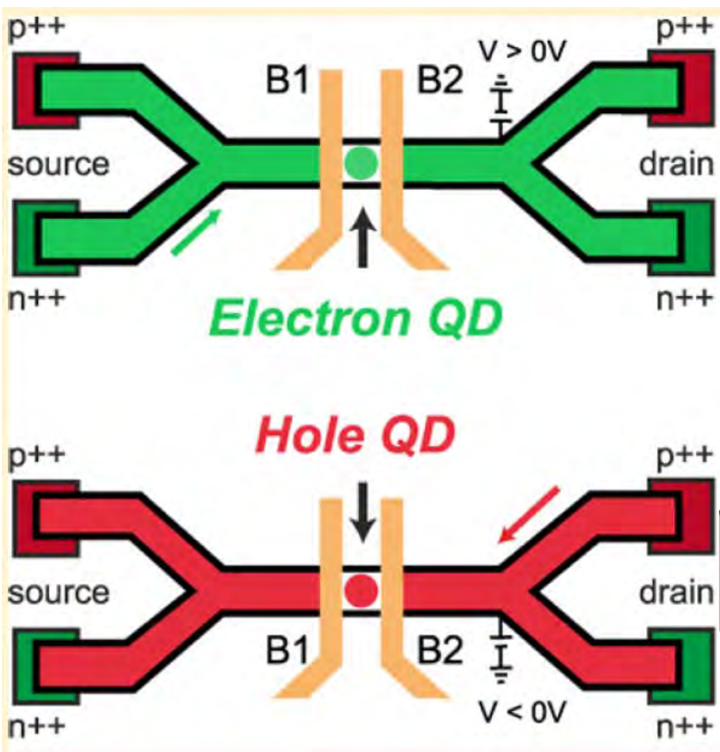

41

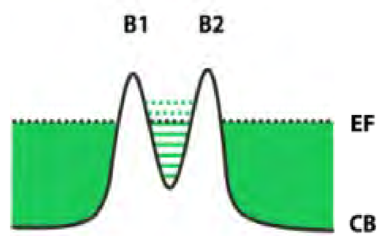
# AMBIPOLAR QUANTUM DOTS IN NANOMOSFETS

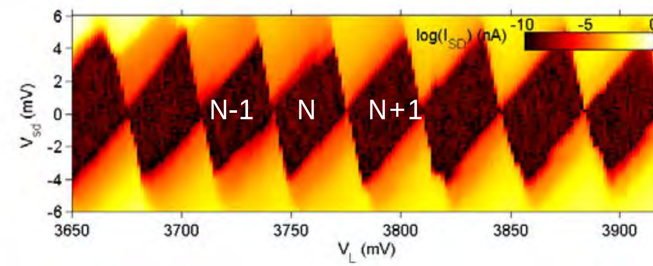



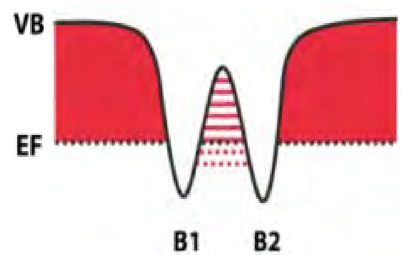

Compare single-hole tunneling with single-electron tunneling in one and the same device, i.e. with the same silicon, oxide, metal *and* impurities

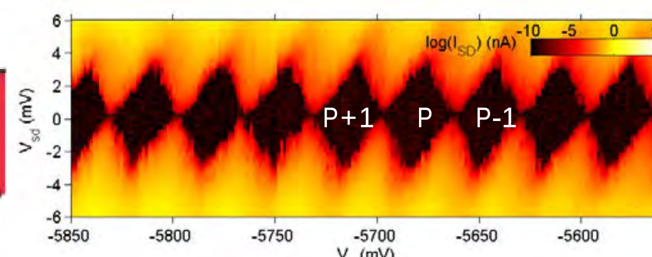


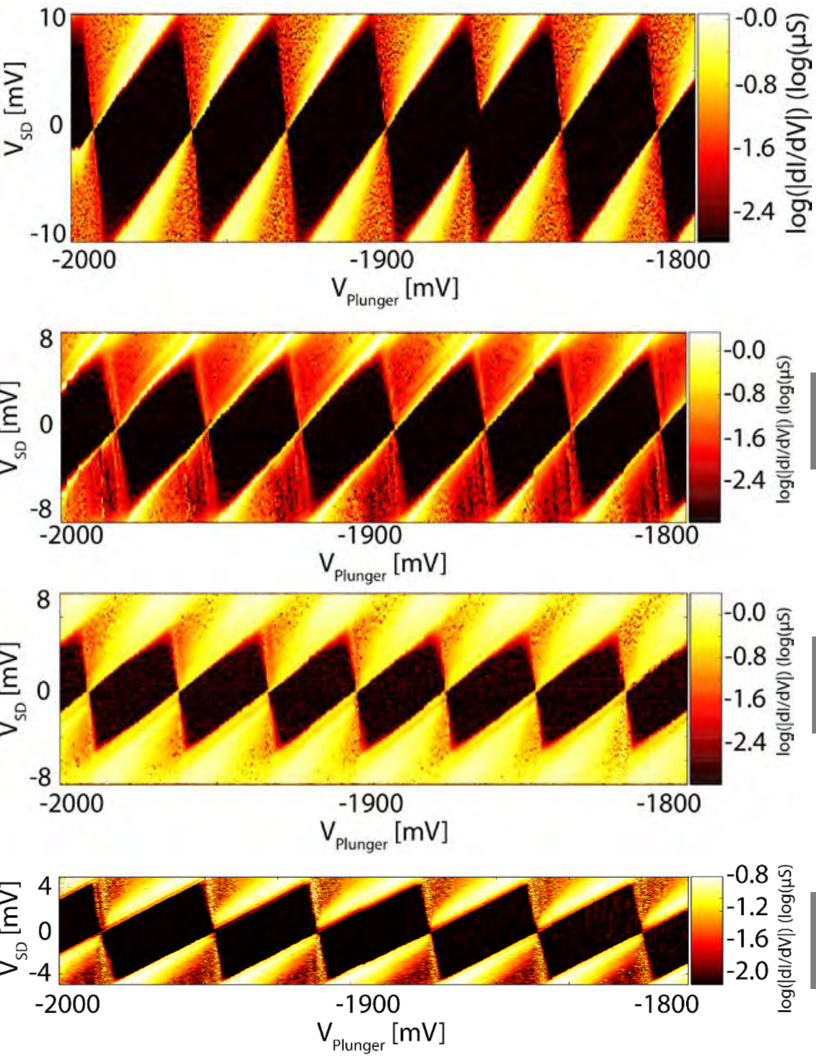



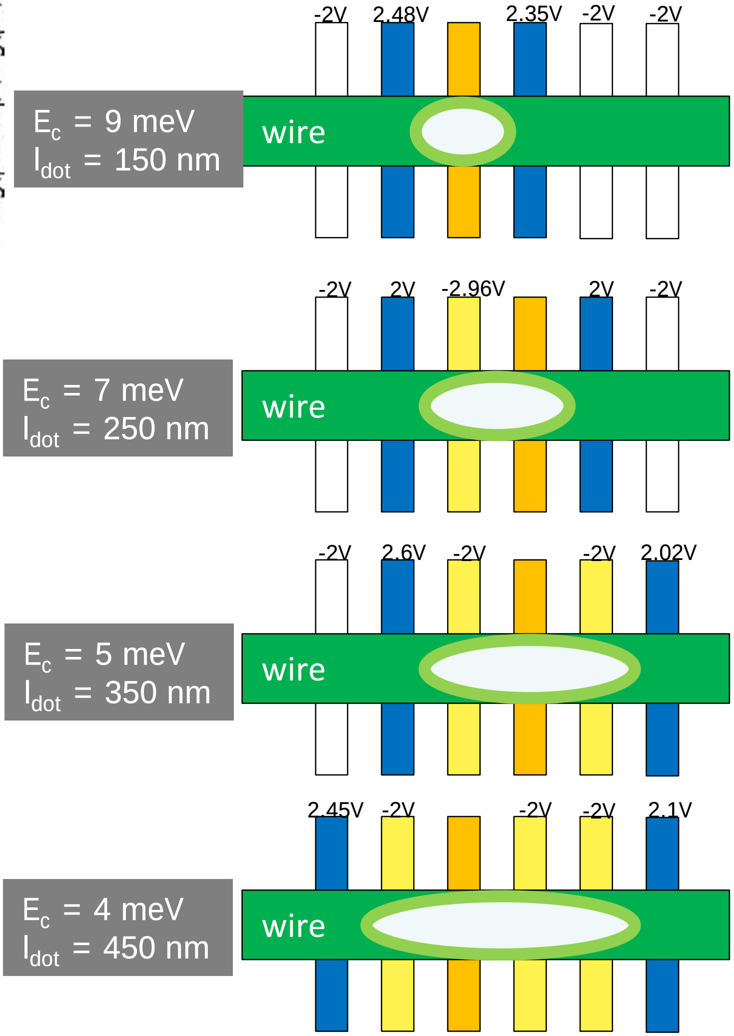



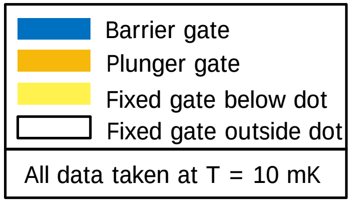



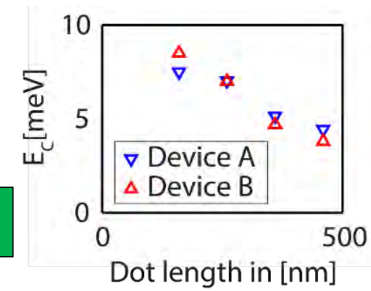

Müller et al, Nano Lett 2015, APL 2015

# GE/SI CORE/SHELL NANOWIRES



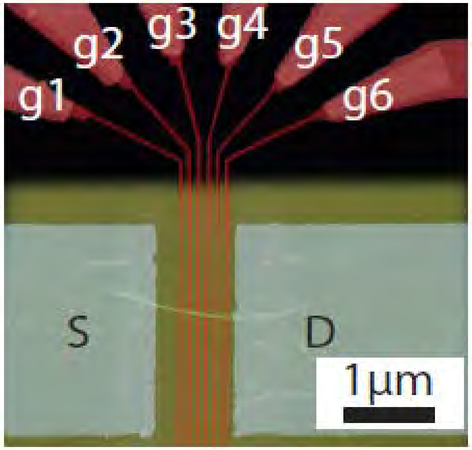



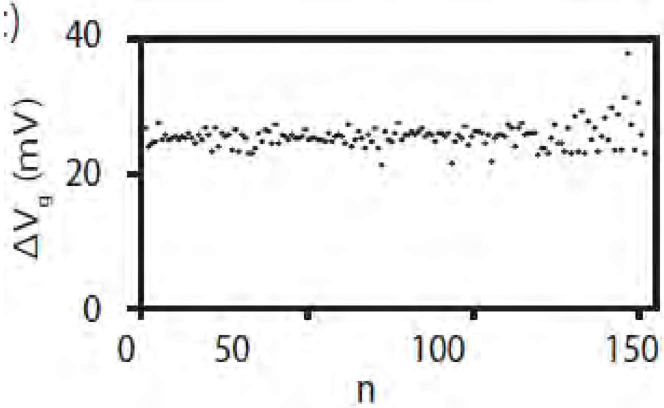

Braun et al, in prep

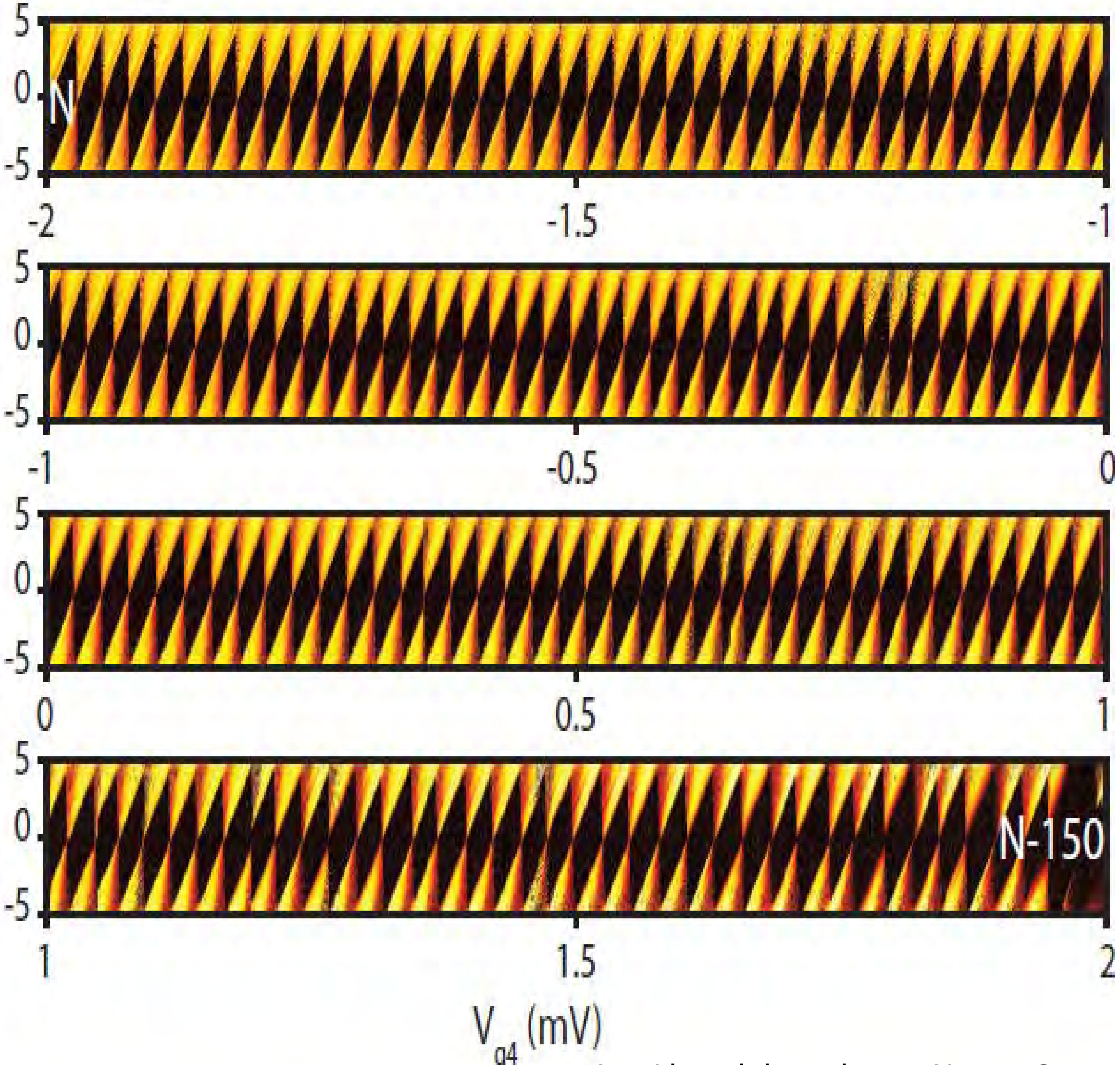
Braun et al, PRB Rap Comm 2016

# GE/SI CORE/SHELL NANOWIRES

- 0.5 micron long QD
- 30h measurement, few switches
- N ~ 160

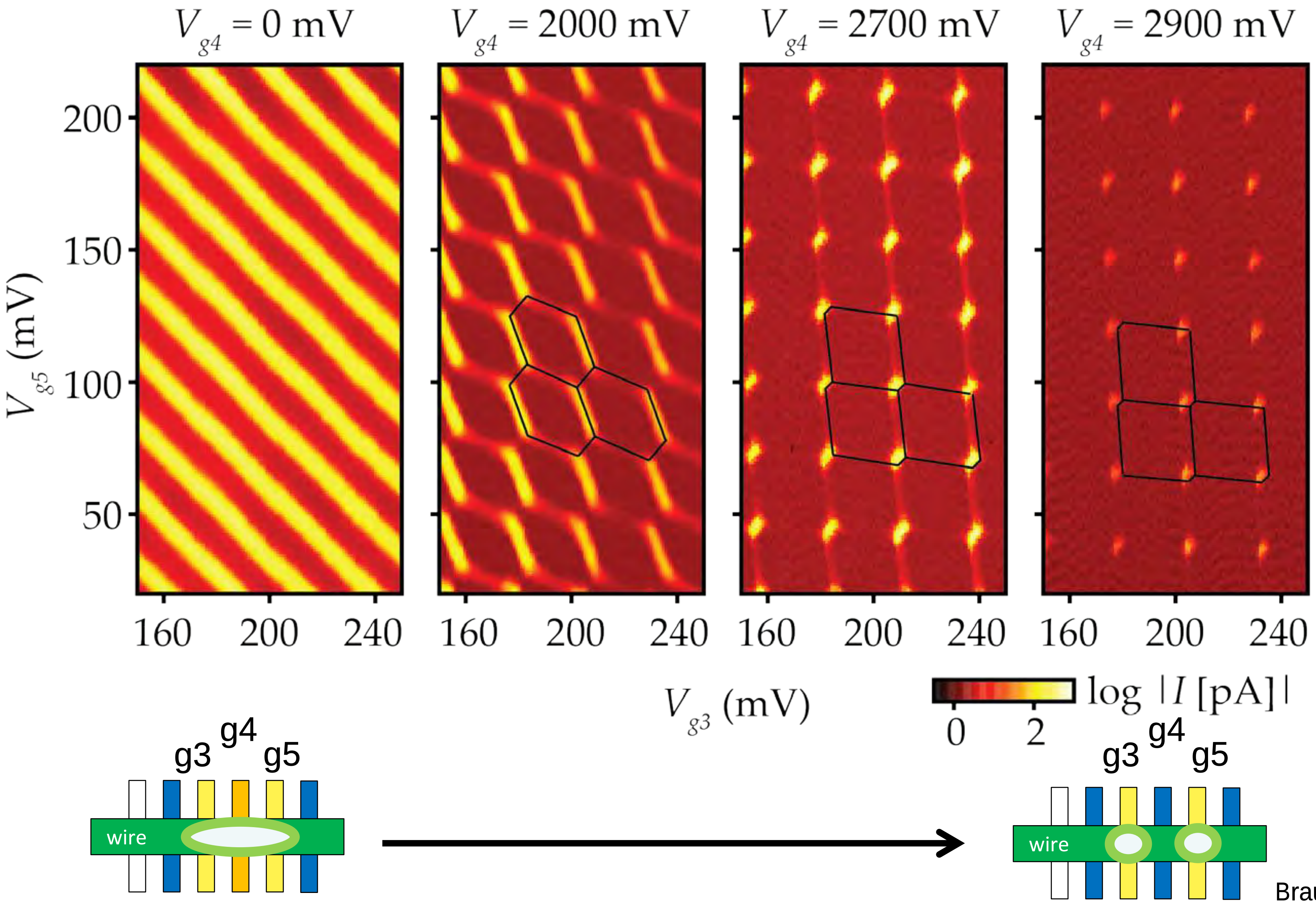


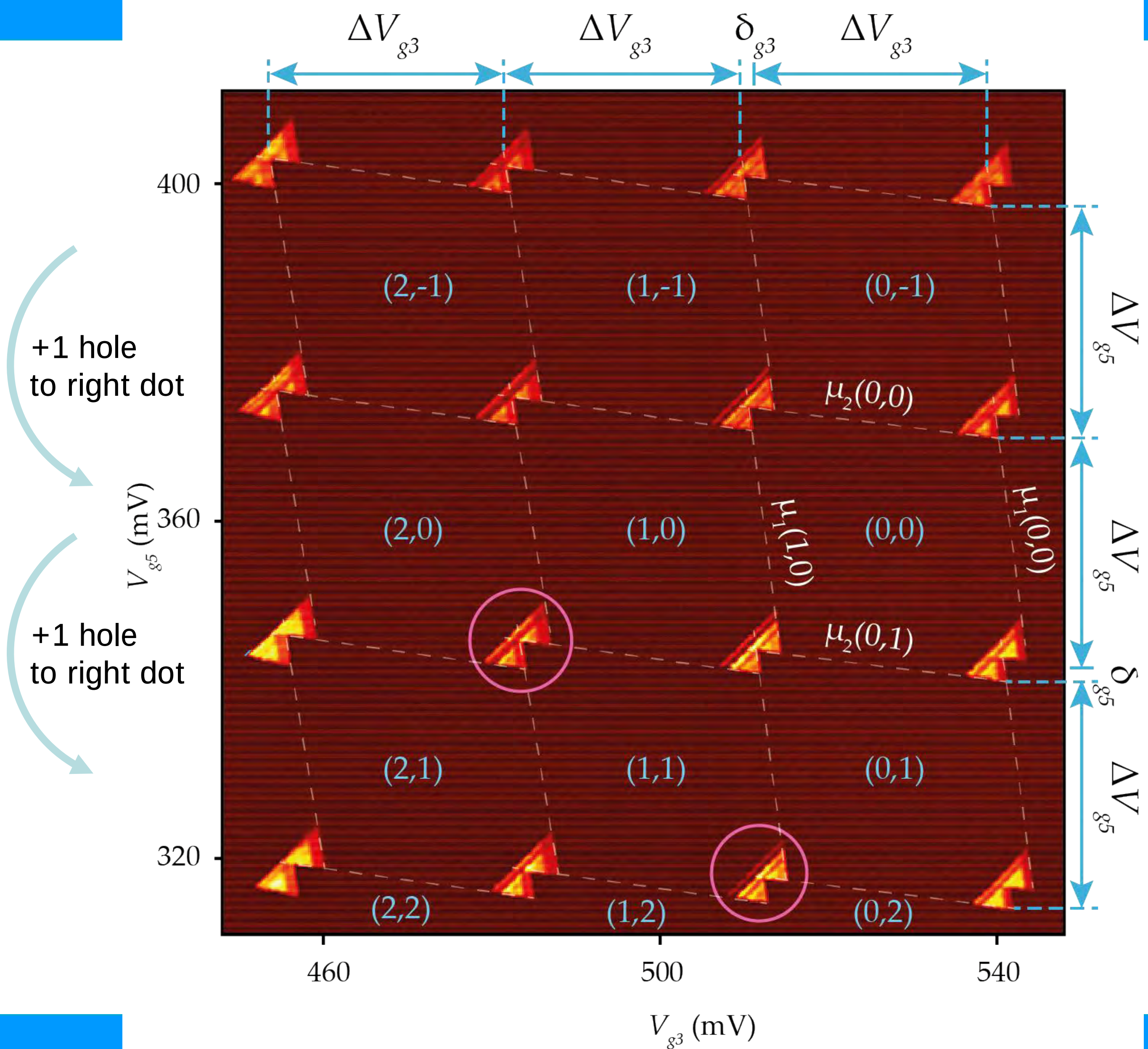

Ang Li et al, in review at Nature Comm

# GE/SI CORE/SHELL NANOWIRES




Brauns *et al*, in review

# GE/SI CORE/SHELL NANOWIRES



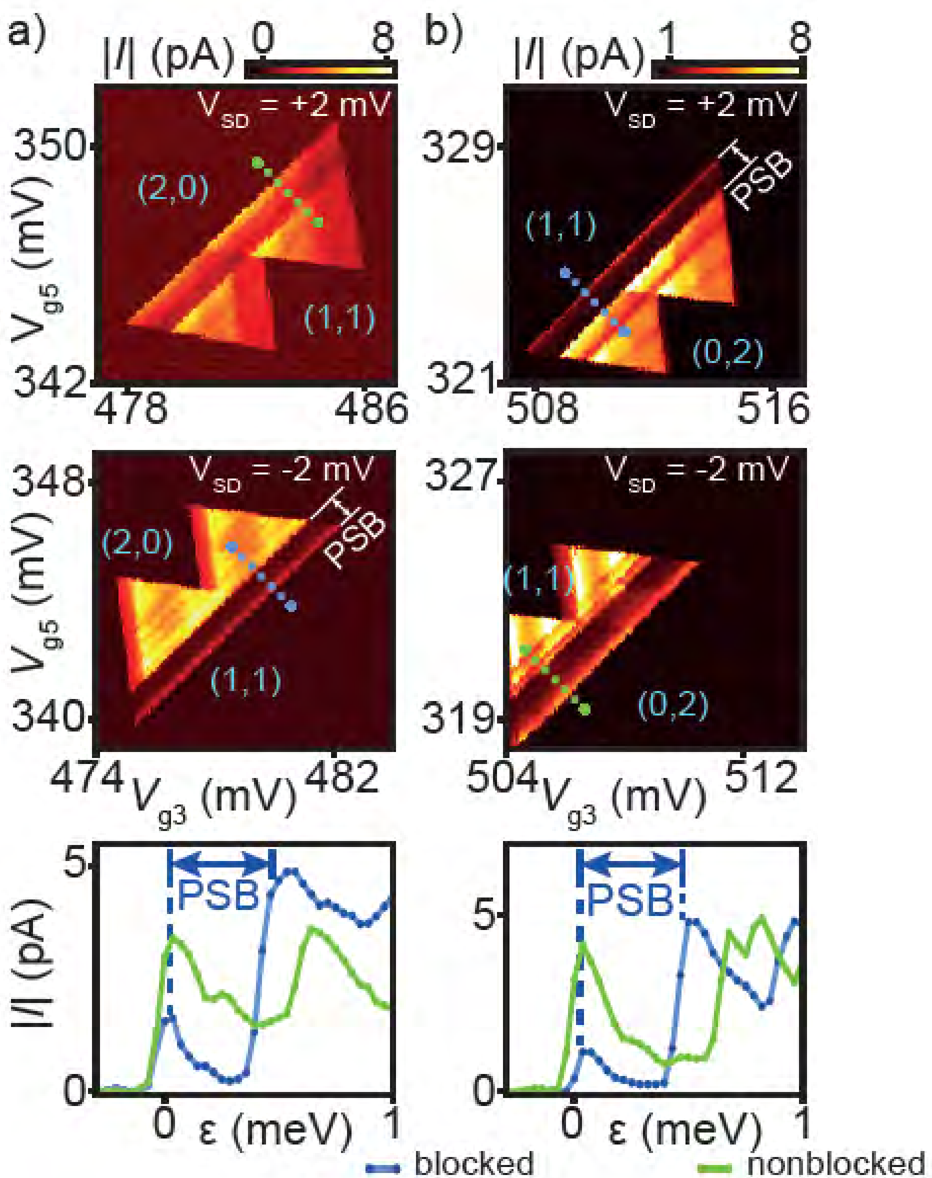

Shell filling in DQDs

(n,m)~(70,70)

$E_C$ ~10 meV
$E_{orb}$~0.6 meV

Braun s et al, in review

# GE/SI CORE/SHELL NANOWIRES



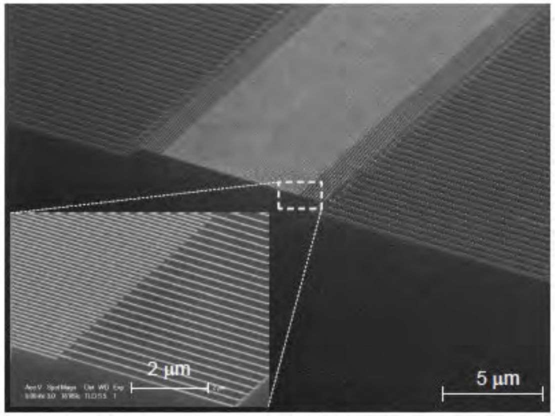

Pauli spin blockade

-at (1,1)-(0,2) at pos Vsd
-at (1,1)-(2,0) at neg Vsd

Hole spin blockade:

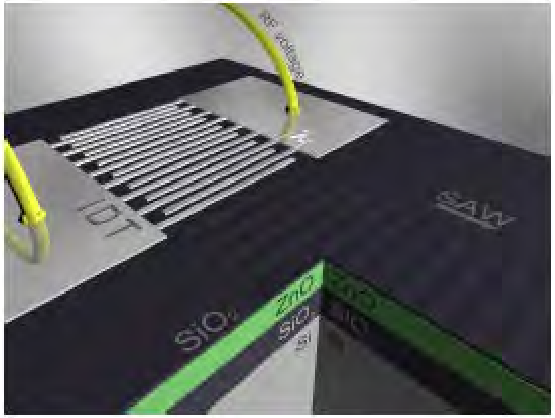
Pribiag et al., Nat nano 2013
Li et al., Nano Lett 2015
Brauns et al., in review

# Summary



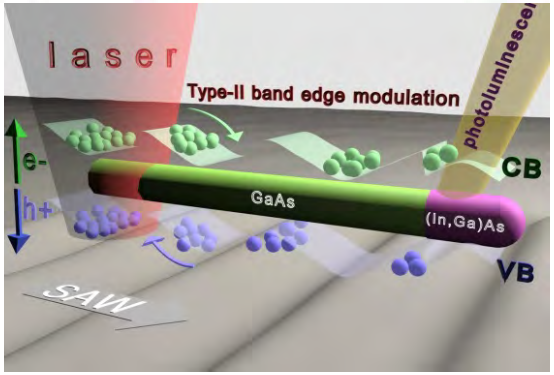

S. Büyükköse, B. Vratzov, D. Atac, J. van der Veen, P. V. Santos and WGvdW, Nanotechnology **23**, 315303 (2012).

$ZnO/SiO_2/Si$ multilayer: max. 16 GHz




S. Büyükköse, B. Vratzov, J. van der Veen, P. V. Santos and WGvdW
Appl. Phys. Lett. **102**, 013112 (2013).

$SiO_2/ZnO/SiO_2/Si$: 23 GHz




S Büyükköse, A Hernández-Mínguez, B Vratzov, C Somaschini, L Geelhaar, H Riechert, WGvdW and P V Santos, Nanotechnology **25**, 135204 (2014).