# Electro-Optomechanical Transduction in Silicon Photonics through PZT Thin Film Integration

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*Promotors: Dries Van Thourhout (PRG) & Jeroen Beeckman (LCP)*

GHENT UNIVERSITY

imec
embracing a better life

# ELECTRO-OPTOMECHANICAL TRANSDUCTION

electricity

Optics

Mechanics

# OUTLINE


Introduction and motivation

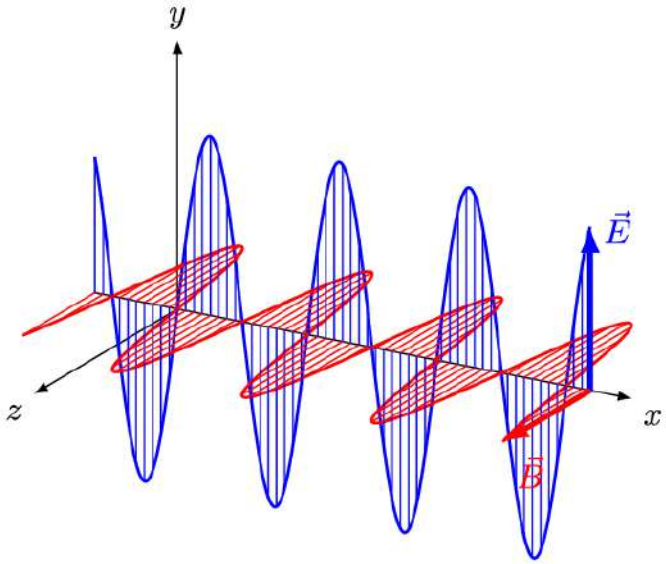
SAW actuation

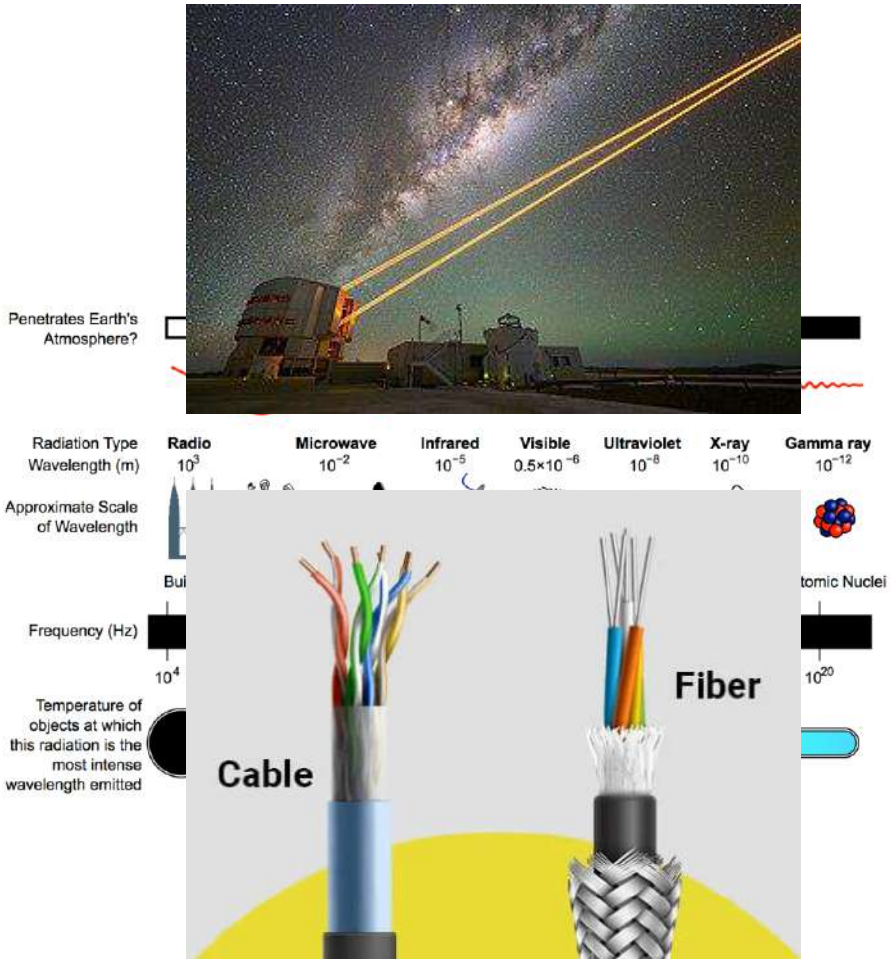
MEMS actuation

Photonic MEMS

Conclusion

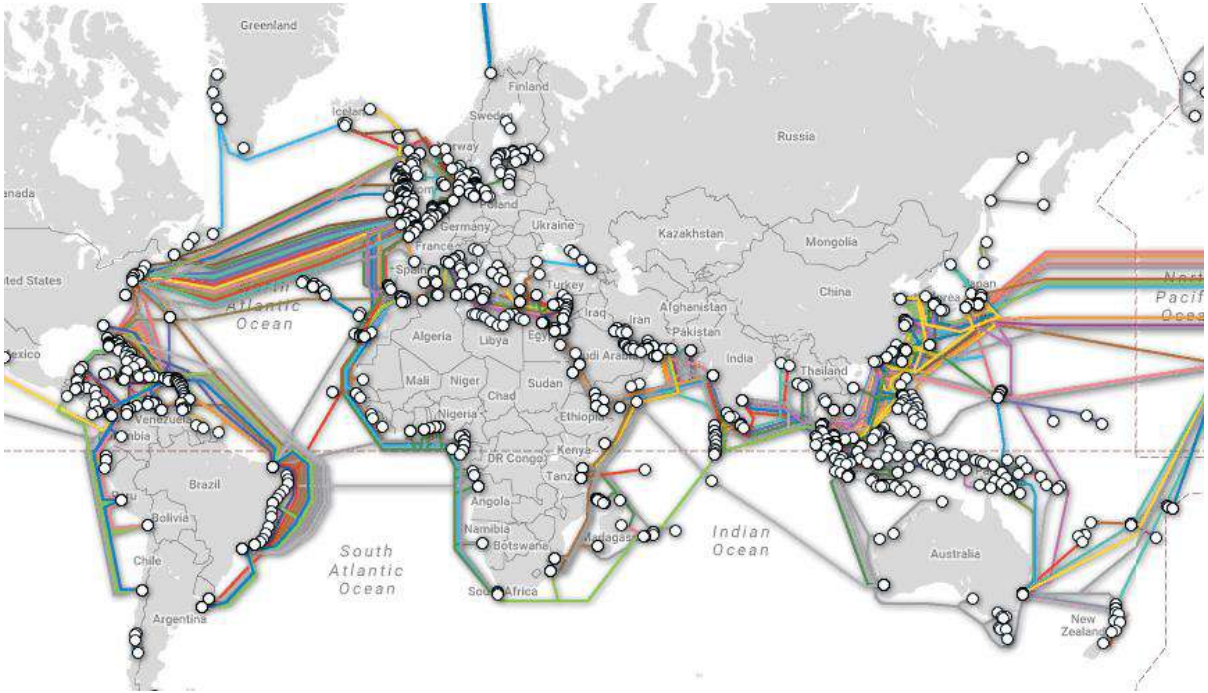
# LIGHT




*Wikipedia*

# GLOBAL NETWORK




more and more demand for internet speed, bandwidth

# DATA TRANSMISSION

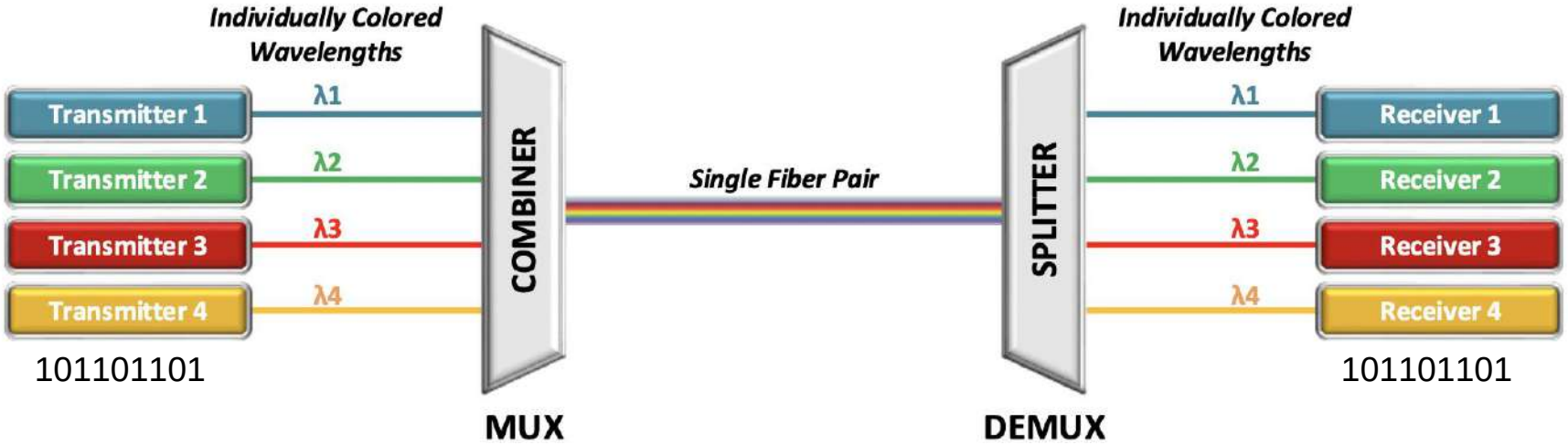
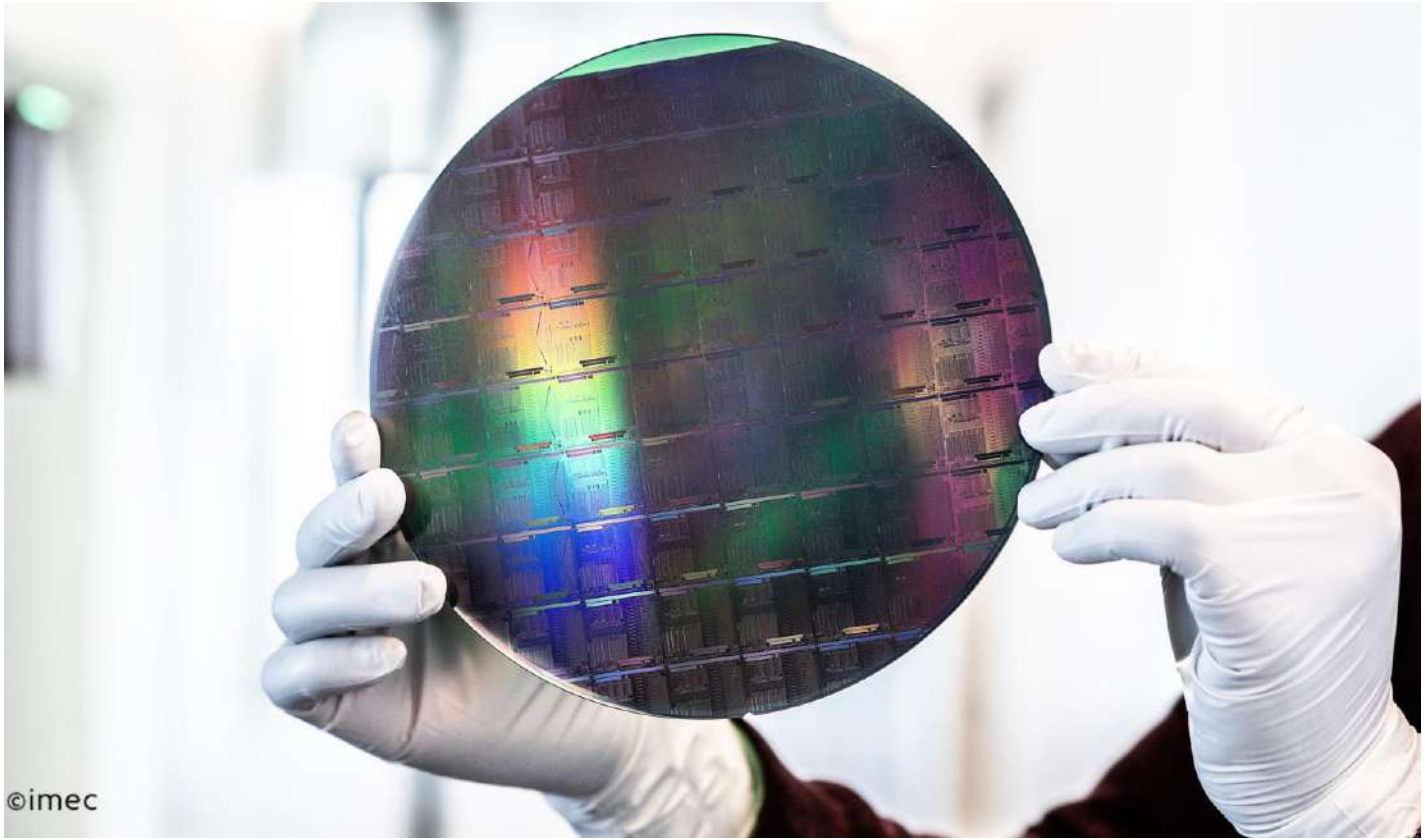
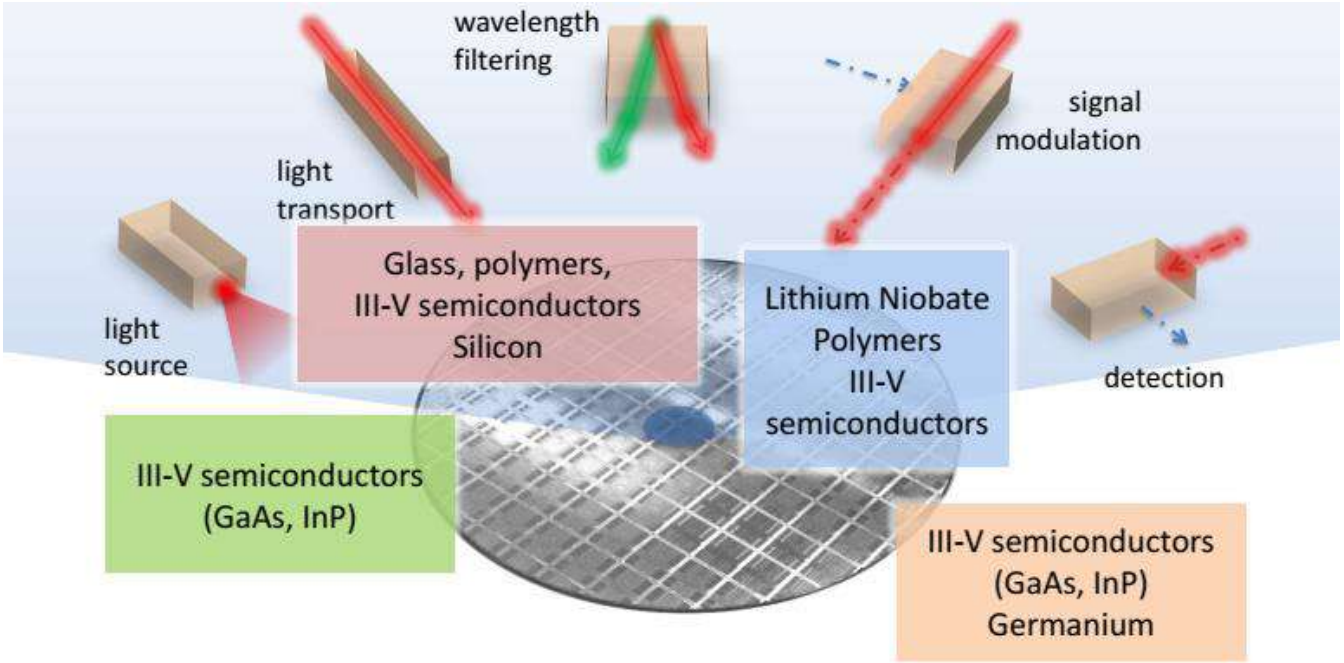



image: wwt

# PHOTONIC CHIP



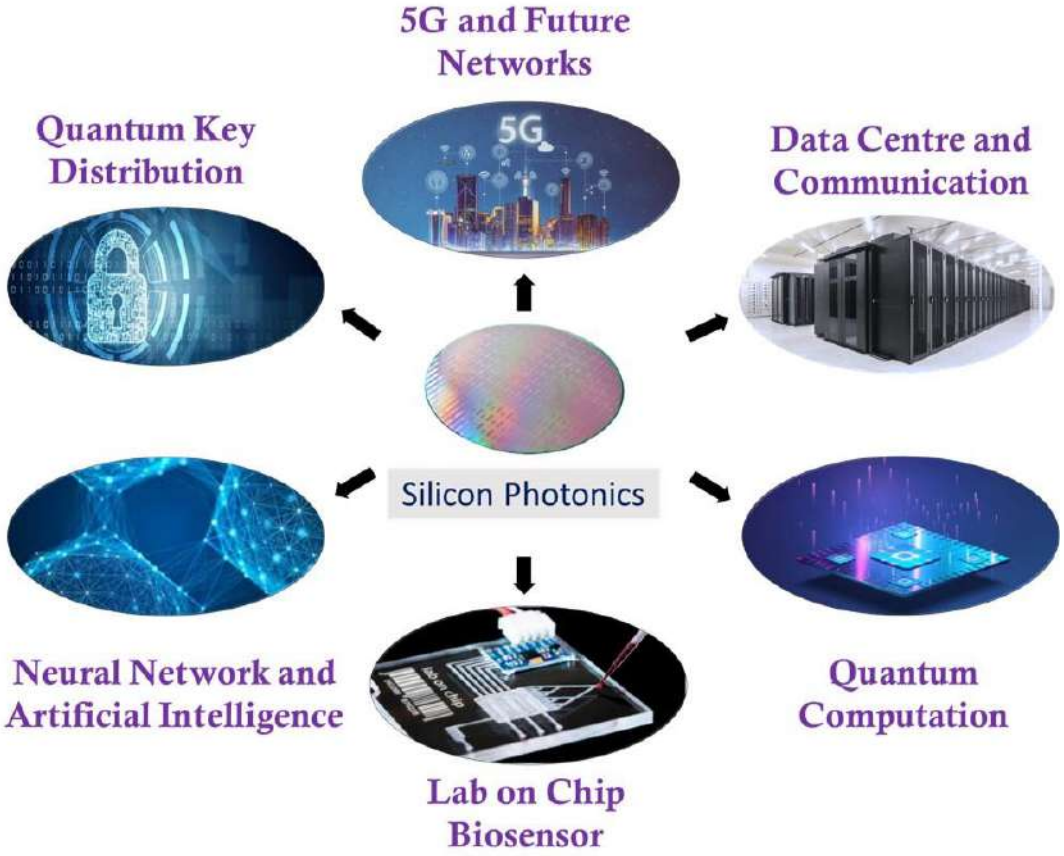
# Si PHOTONIC: MANY FUNCTIONS ON A CHIP




- Compact
- Scalable
- Cheap
- Mature

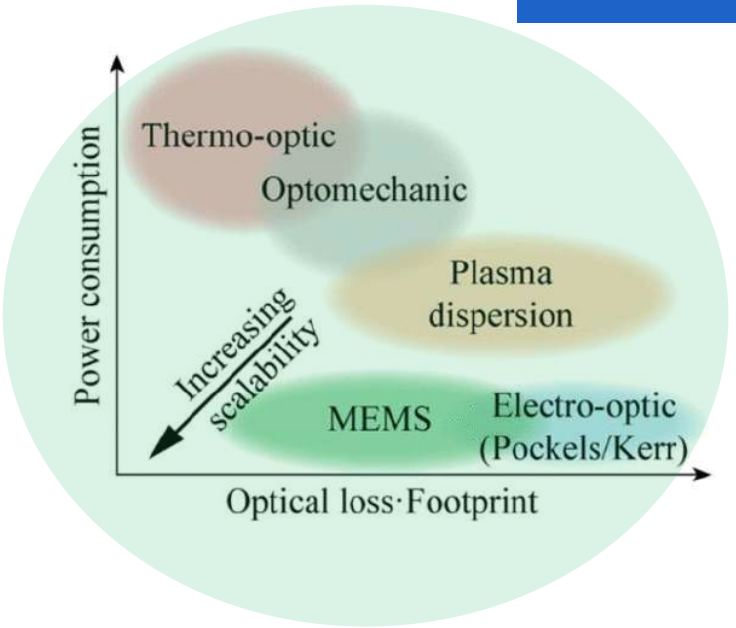
image: W. Bogaerts

# Si Photonics application

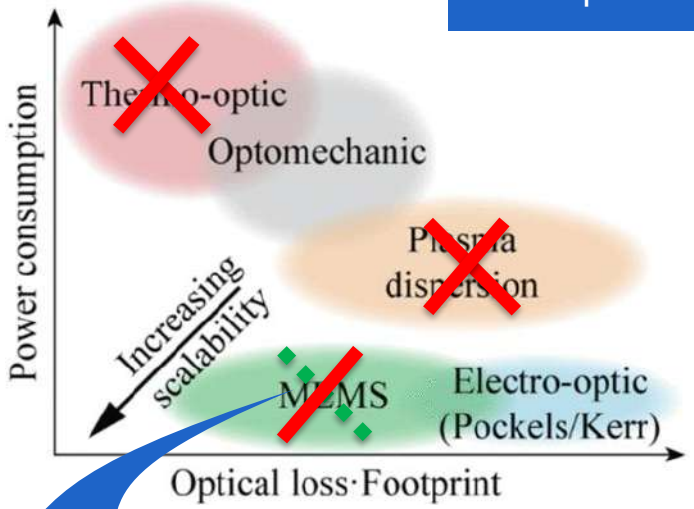


# TUNING MECHANISMS IN PHOTONICS

Si platform




SiN platform

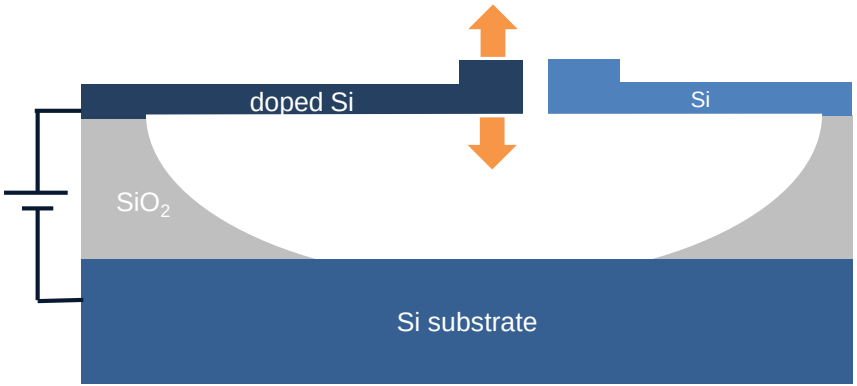



No electrostatic Actuation
=> try piezo-MEMS

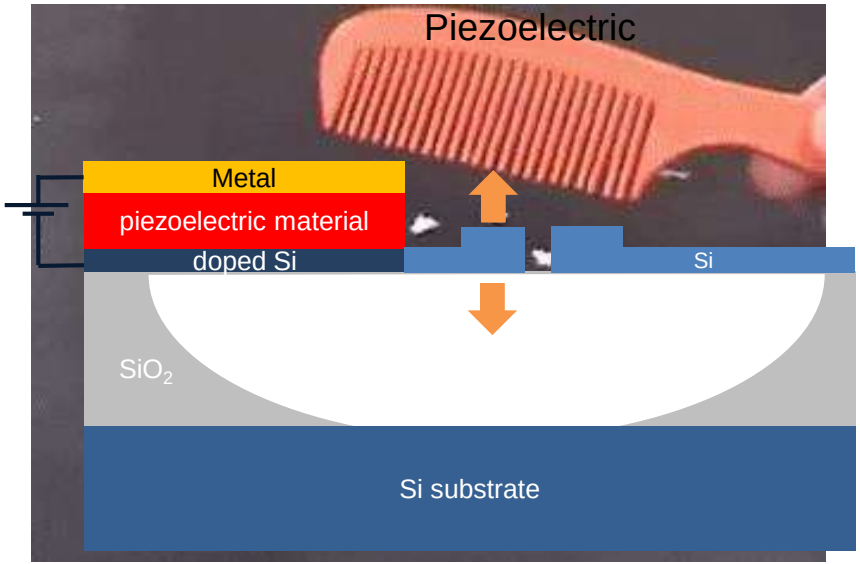
*N. Quack et al. 2020*

# ELECTROSTATIC VS PIEZOELECTRIC MEMS

Electrostatic



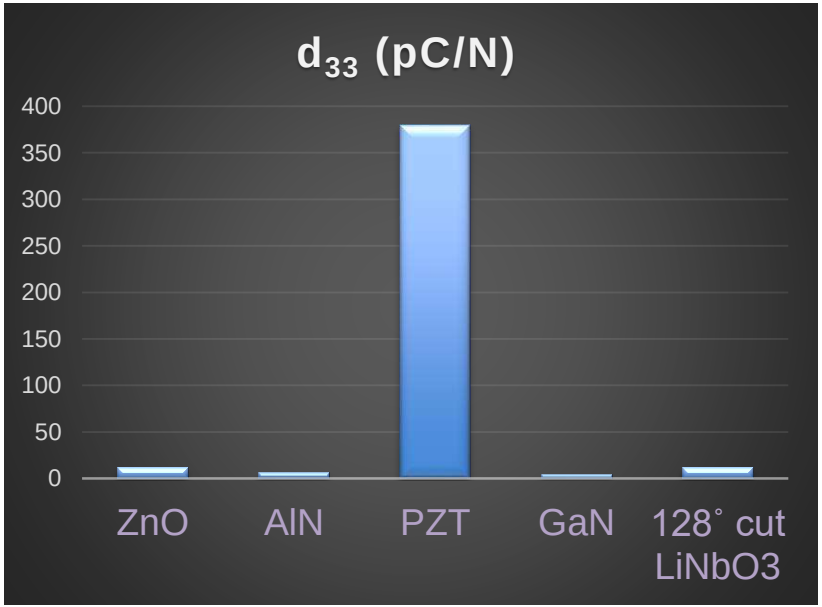

Piezoelectric

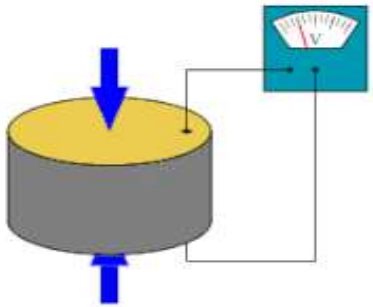


# PIEZOELECTRIC EFFECT

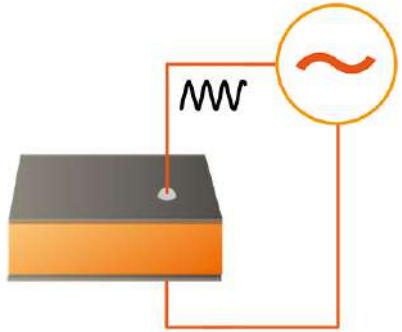
Non-inversion symmetry → polarization

→ piezoelectric effect



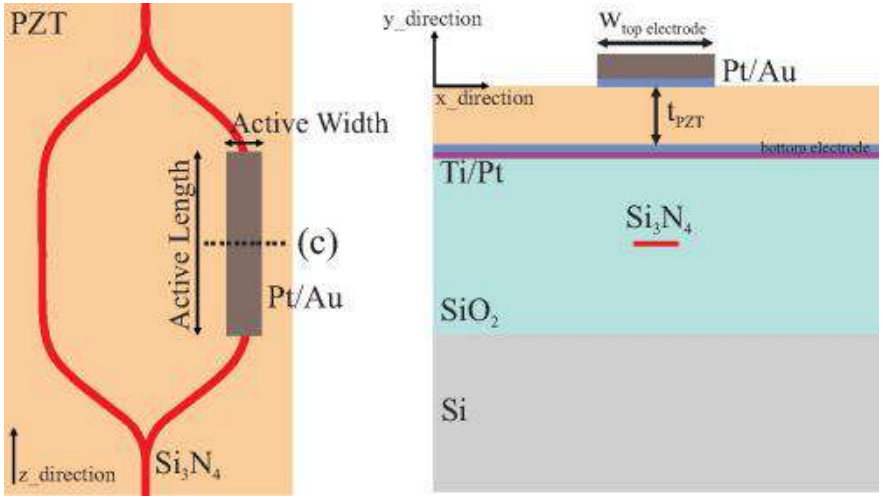



Direct piezoelectric

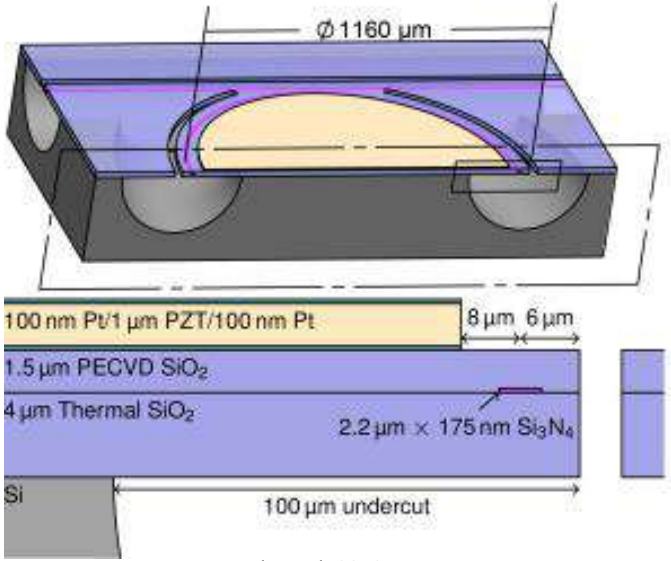


Indirect piezoelectric

# PZT FILM IN INTEGRATED PHOTONICS




Hosseini et al, 2015

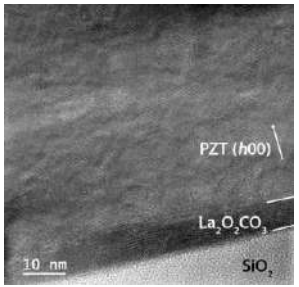


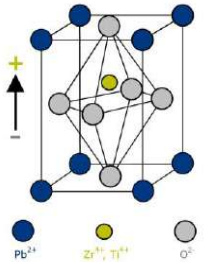

Jin et al, 2018

traditionally grown using Pt buffer layer → optically lossy

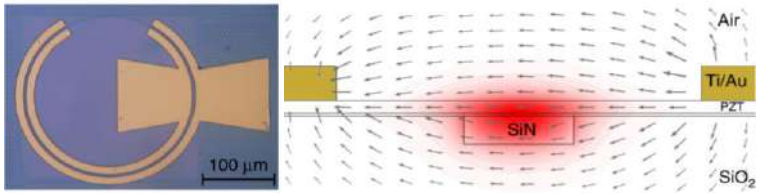
# NOVEL DEPOSITION OF PZT FILM FOR PHOTONICS

- Ultrathin Lanthanide buffer layer* → optically transparent
- Chemical solution deposition → cheaper
- strong electro-optic and non-linear effect → piezoelectric effect?



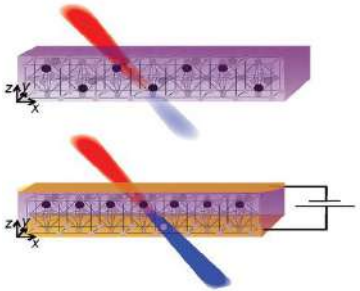




$T_C$ ~ 370°C




$V_\pi L$ ~ 3.2 V.cm

Alexander et al., (2018)




Effective $\chi^2_{zzz}$ ~ 128 pm $V^{-1}$

Feutmba et al., (2021)

*J. George et al. (2015)

# OUTLINE

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**SAW actuation**

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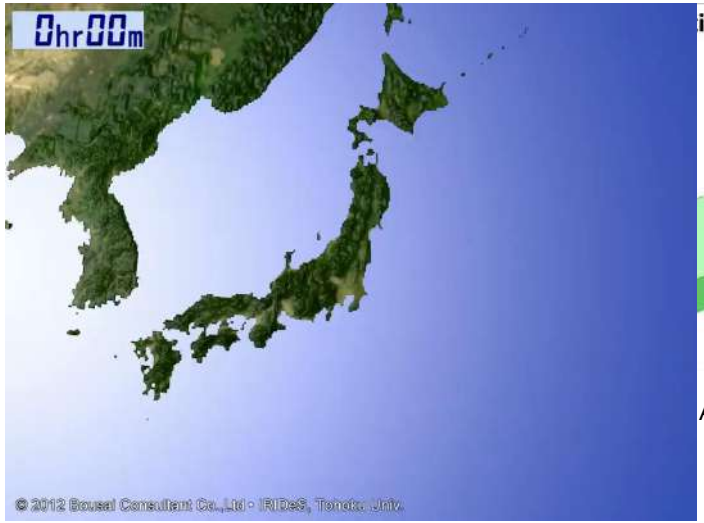
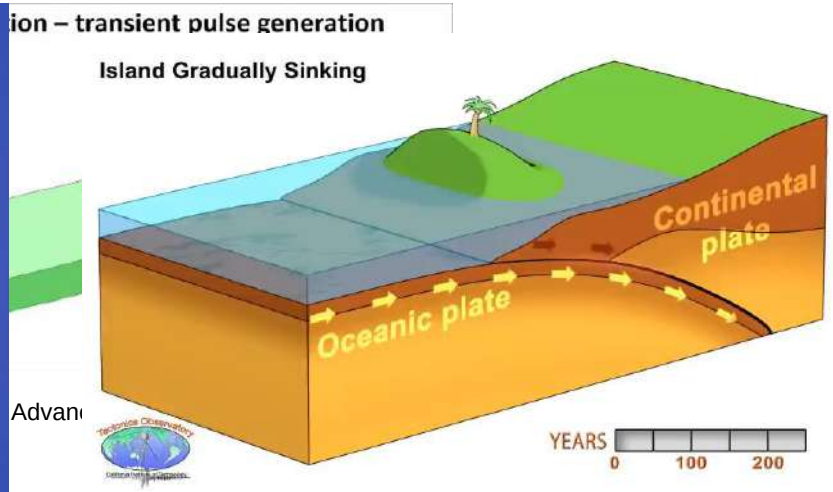
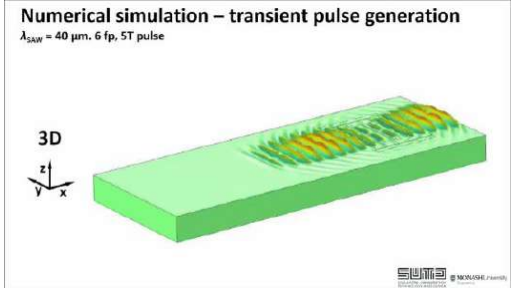
# SURFACE ACOUSTIC WAVES



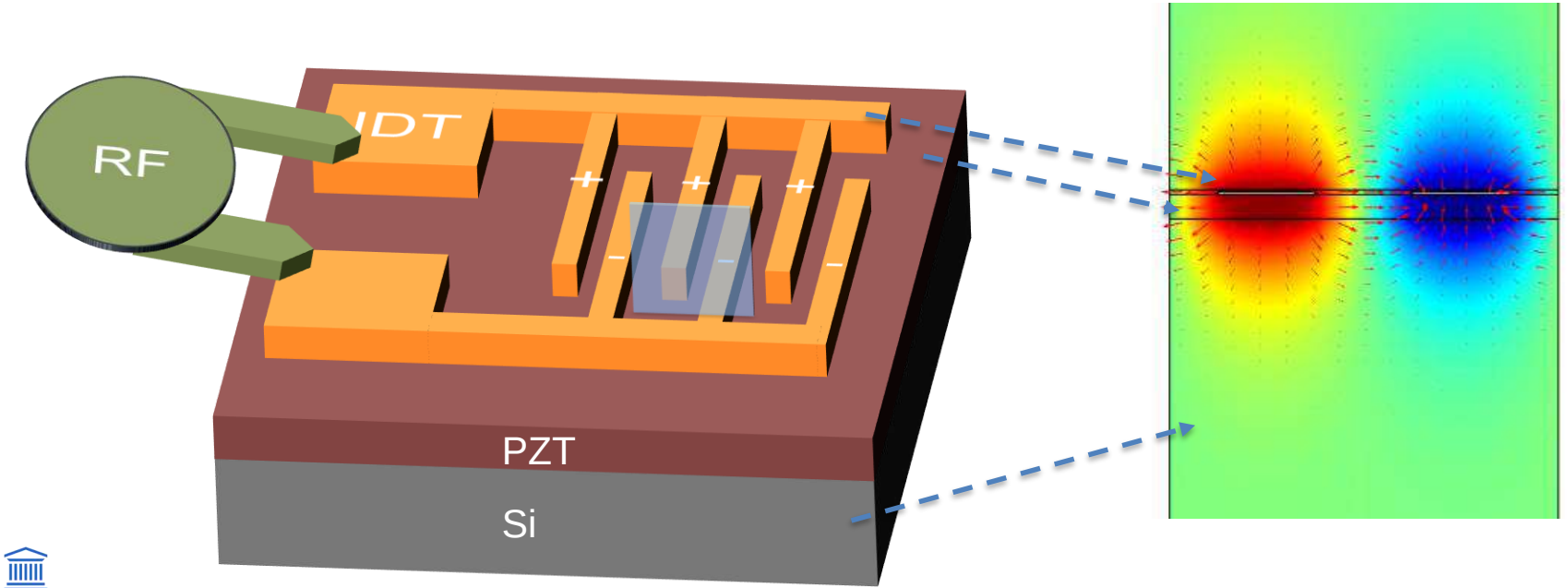



# SAW ACTUATION IN Si PIC

- Inter digital transducer (IDT): periodic E-field → periodic strain
- SAW $\lambda_0$= Period of IDT => SAW $f_0 = \frac{v_{acoustic}}{IDT\ period}$

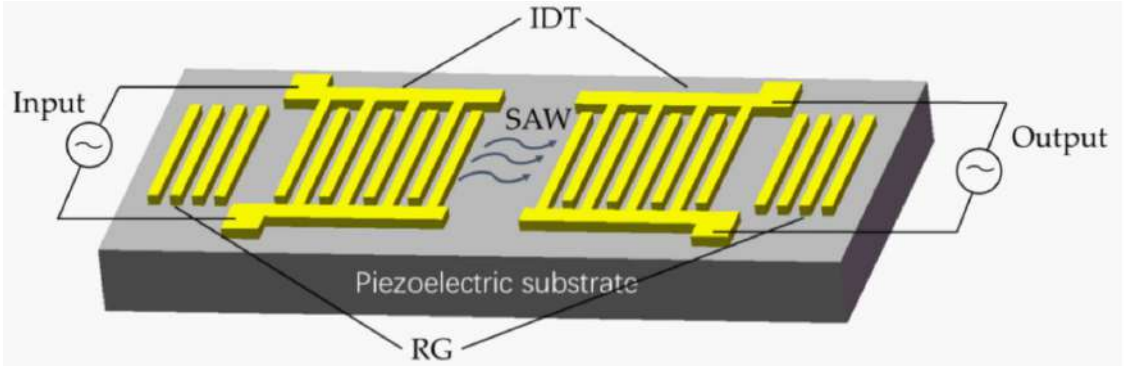


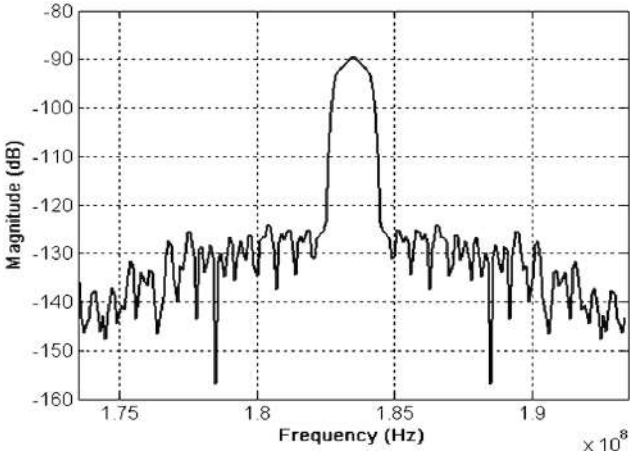

David et al. Science Advances (2016)




Cross section of one IDT period

# SAW FILTERS IN RF ELECTRONICS



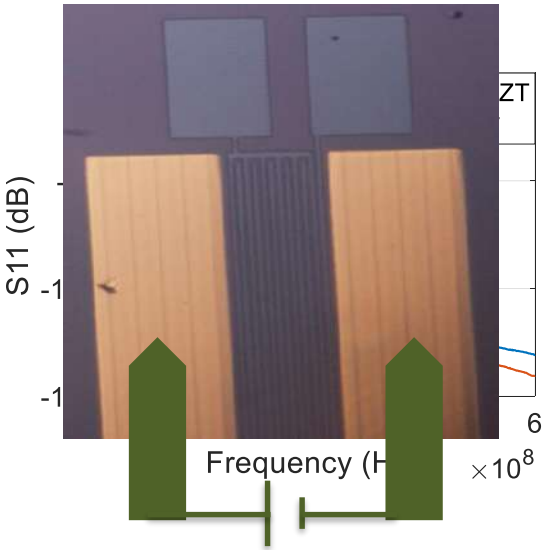





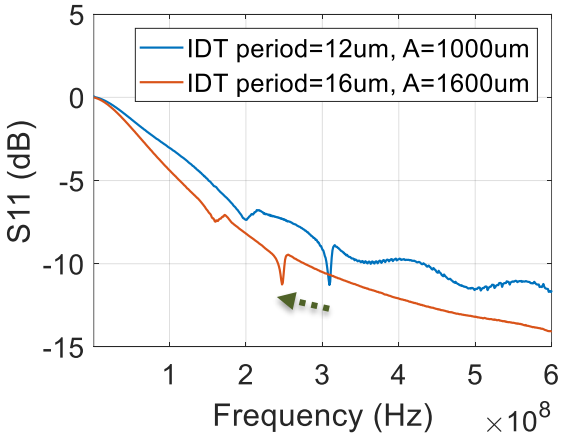

Liang et al. 2022, Priyanka et al. 2005

# ELECTRICAL CHARACTERIZATION OF SAW

$\lambda_{SAW}$ = IDT period

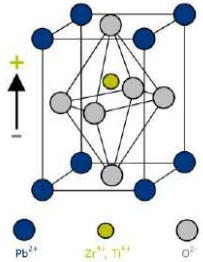



Uniform poling




IDT Period effect

# POLING PROCESS IN PZT

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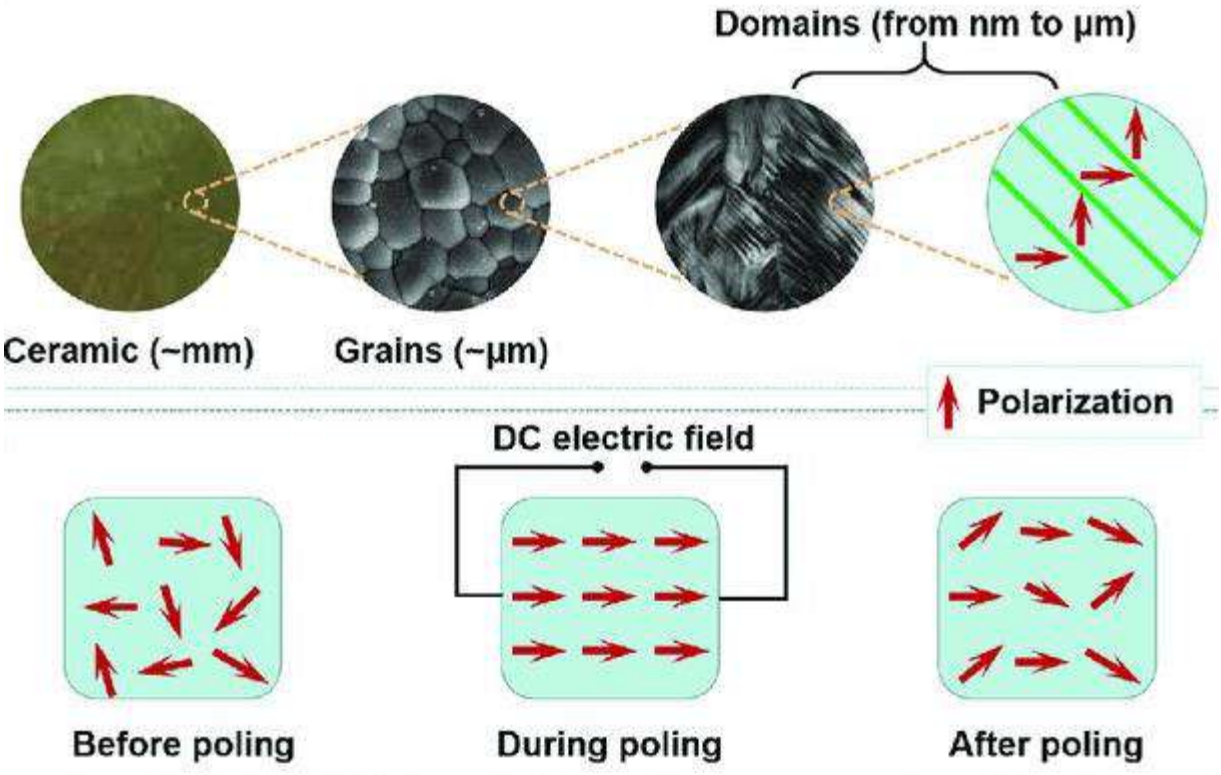
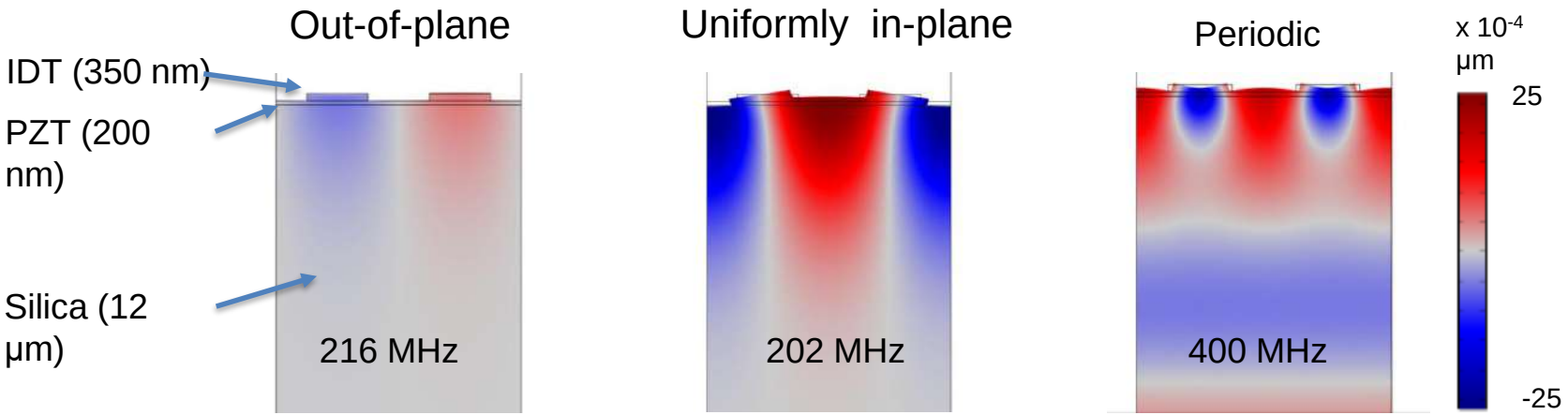
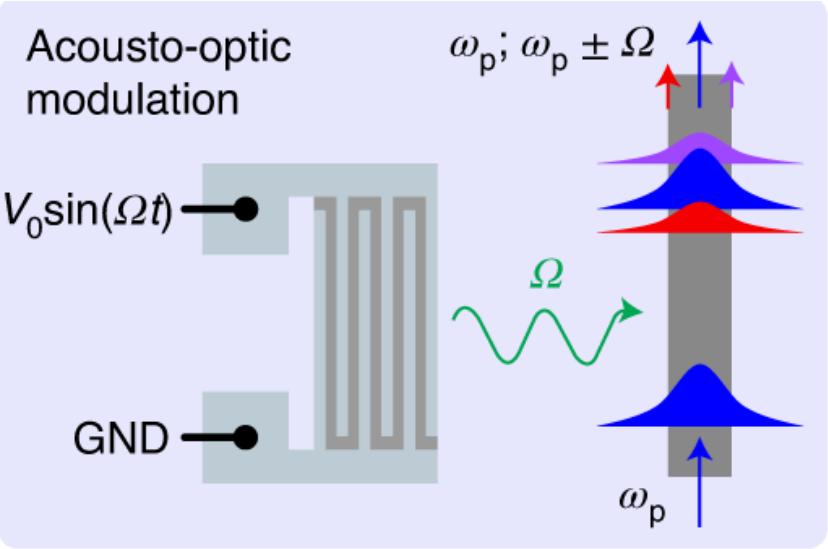


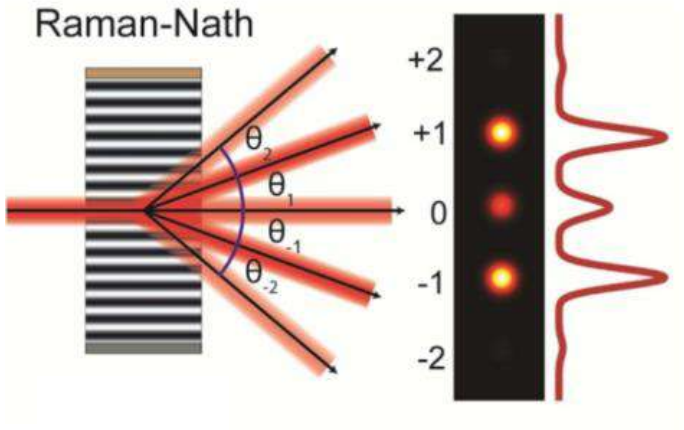
# PZT POLING DETERMINES TRANSDUCTION EFFICIENCY




Efficient SAW excitation when PZT domains along the applied electric field

# ACOUSTO-OPTIC MODULATION WITH SAW

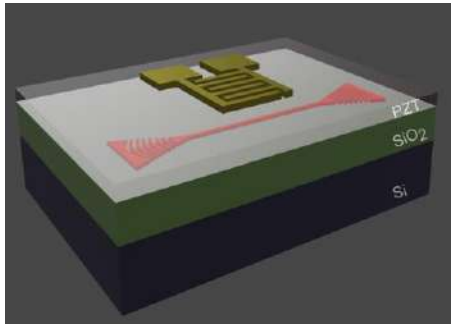


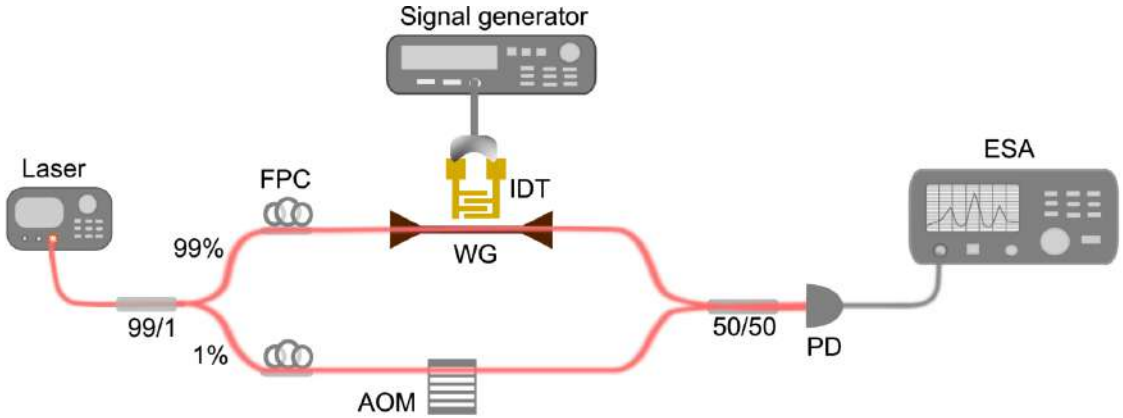




Kittlaus et al. 2020

# Optical characterization of SAW

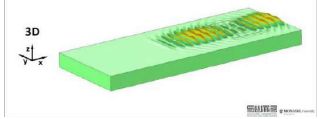
- Strain in the waveguide from SAW → $\Delta n_{eff}$ (photoelastic effect)
- Phase modulation $\Delta\phi = 2\pi\Delta n_{eff}/\lambda$ measured with a heterodyne setup (interferometer)



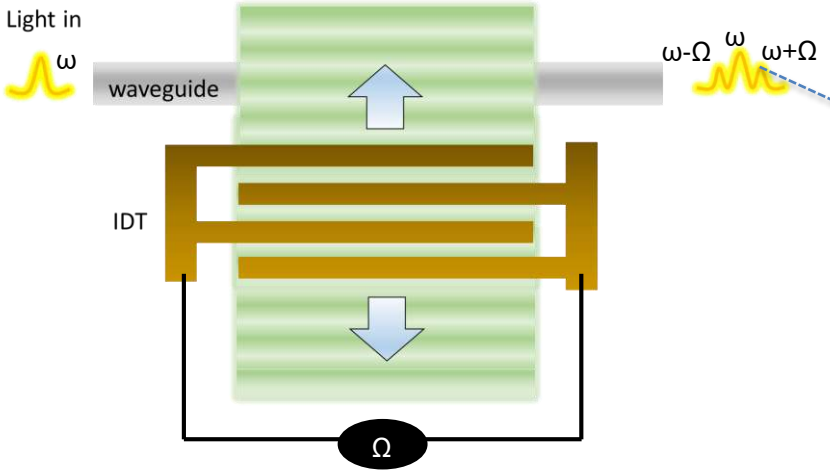

Schematic of a heterodyne Setup

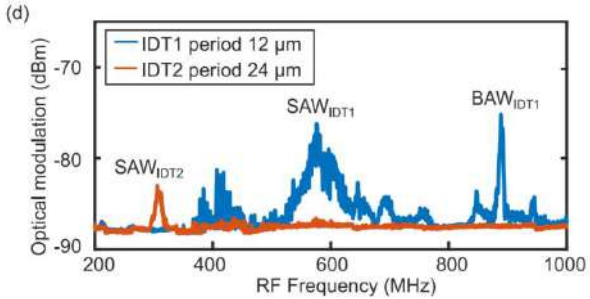
# ACOUSTO-OPTIC MODULATION RESULTS

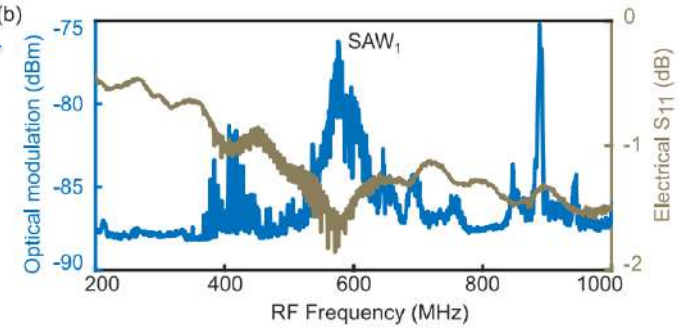



David et al. Science Advances (2016)

- IDT for periodic poling of the PZT film
- SAW creates a spatiotemporal strain profile in WG → phase modulation



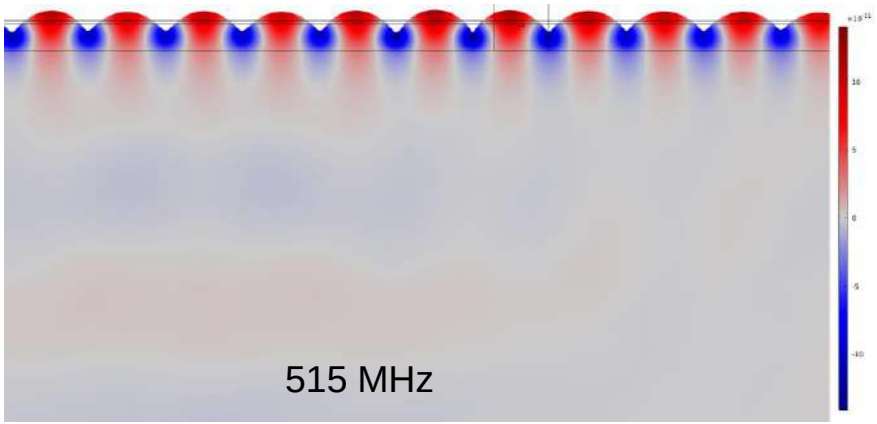




**$V_\pi L$ = 3.35 V cm**

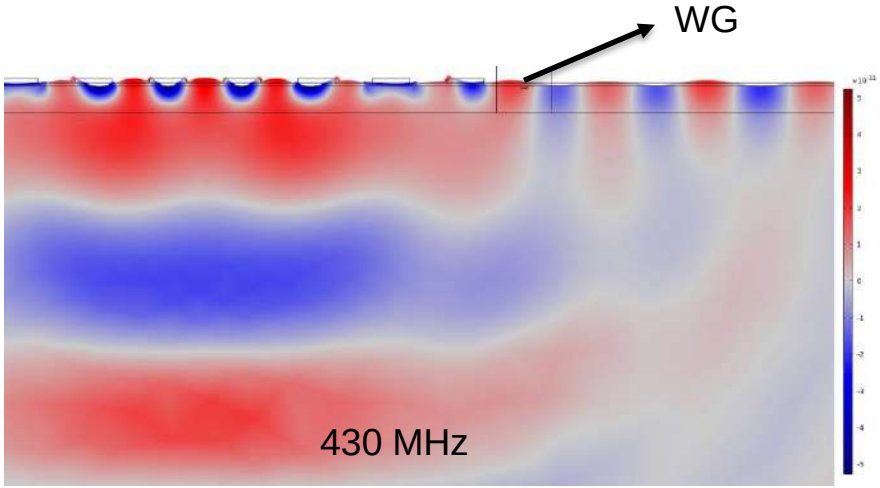
*I. Ansari et al., ACS Photonics (2022)

# SAW PROPAGATION FROM IDT OF 12UM PERIOD

20 nm thick Au IDT

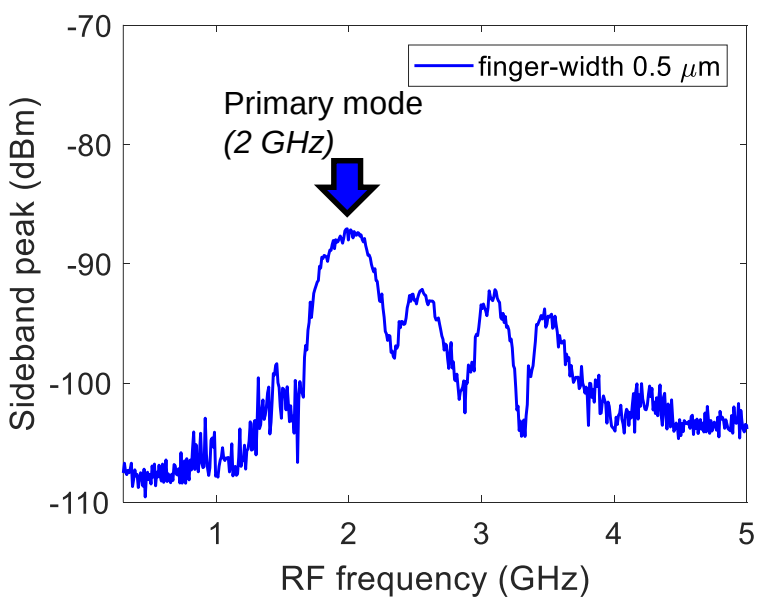


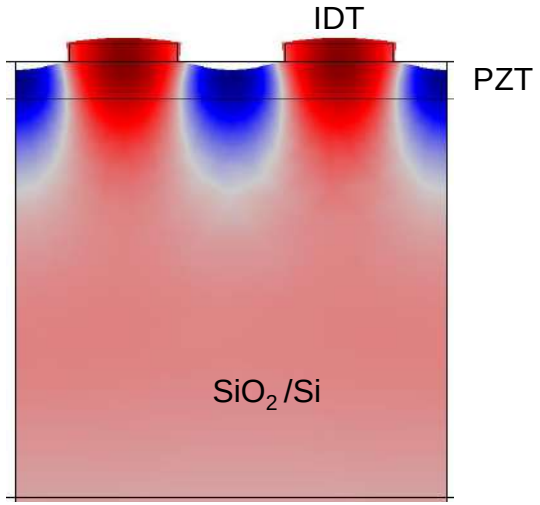

350 nm thick Au IDT




mass-loading and grating reflection from a thicker IDT disrupts the SAW propagation

# REDUCED MASS LOADING WITH AL ELECTRODES




Simulated Eigen-mode
(SAW)
*(2.2 GHz)*

$V_\pi L$ ~ 3.6 V.cm with 4 period IDT

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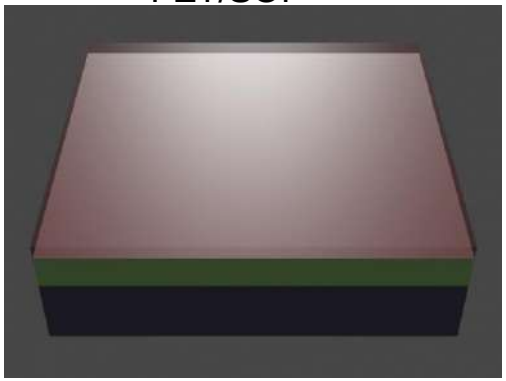
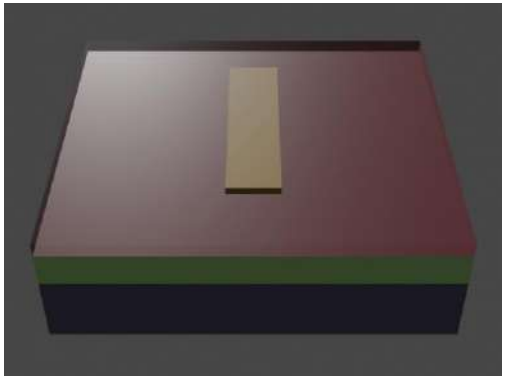
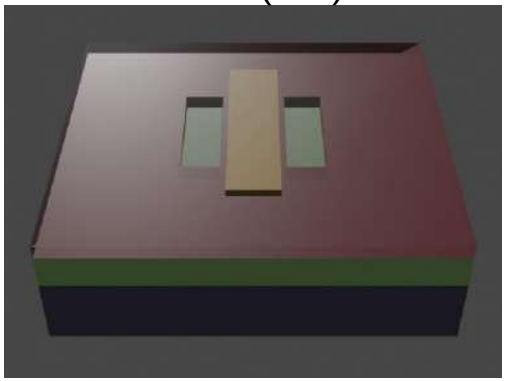
PZT/SOI



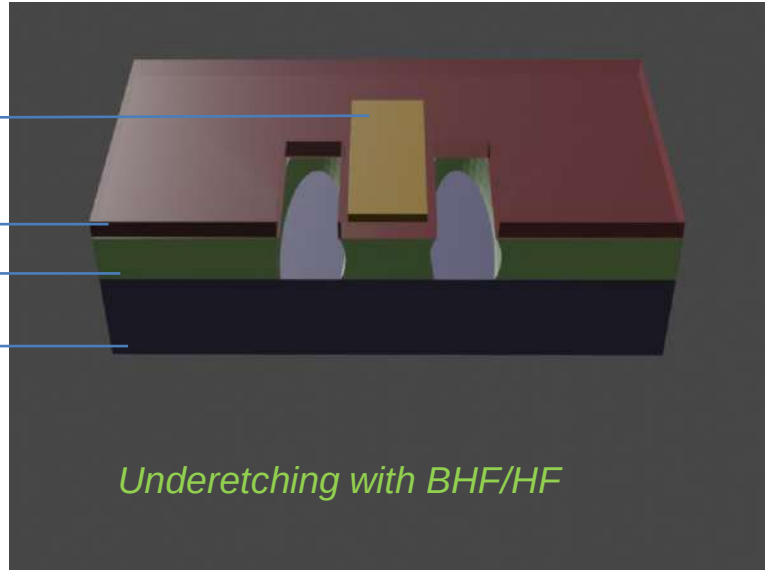
Patterned electrode/PZT/SOI



Etch window (RIE)



Under-etching in HF-VPE




Challenges:

- Under-etching without collapsing the suspended structures
- A mask to protect the sensitive device against the etchant (BHF or HF)

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# HYDROFLUORIC ACID (HF)


colorless, odorless,
acidic, highly corrosive

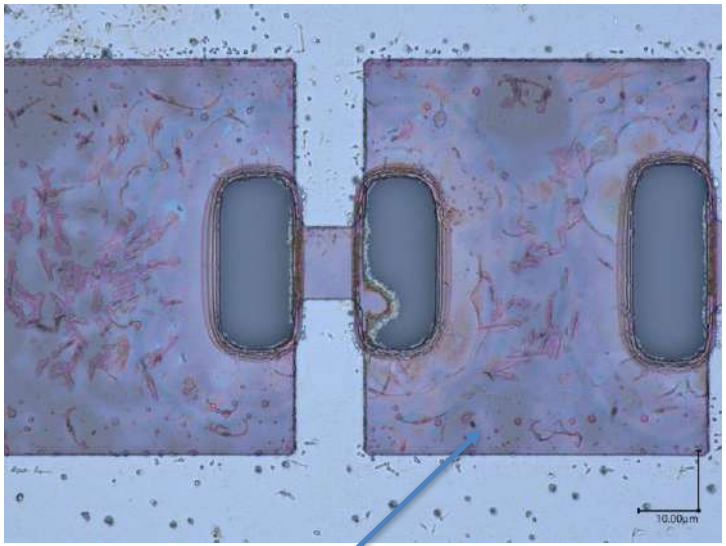
"*Hydrofluoric acid won't eat through plastic. It will, however, dissolve metal, rock, glass, ceramic. So there's that.*" – Walter White

# PPE

# UNDER-ETCHING WITH HF-VAPOR PHASE ETCHER

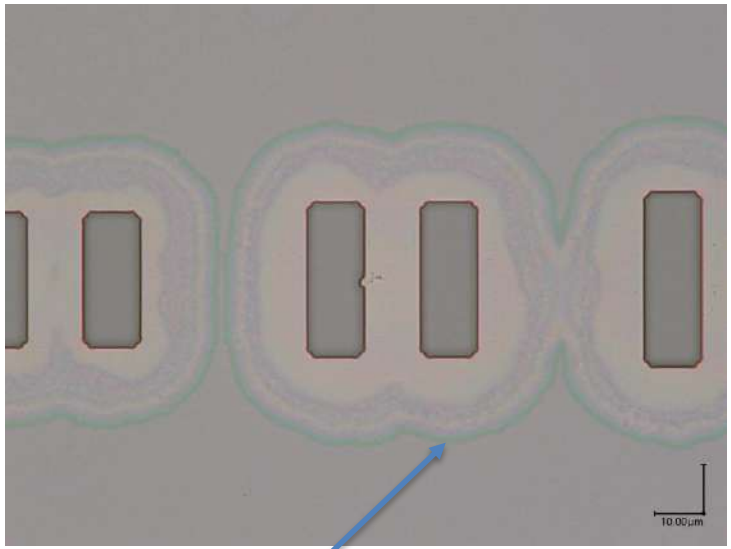
# MONITORING THE UNDER- ETCHING OF $SiO_2$

Poor visibility through PZT



PZT/SOI

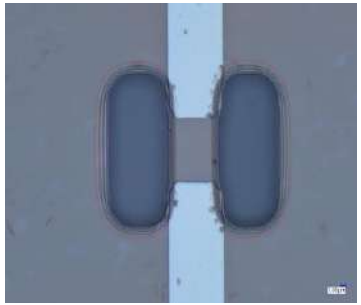
control SOI sample

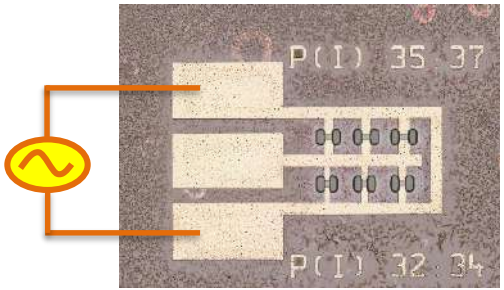


SOI

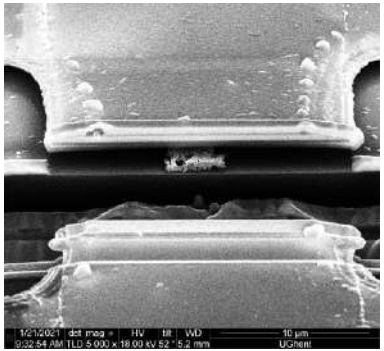
# SUSPENDED PZT/SI BEAMS WITH HF VAPOR ETCHING

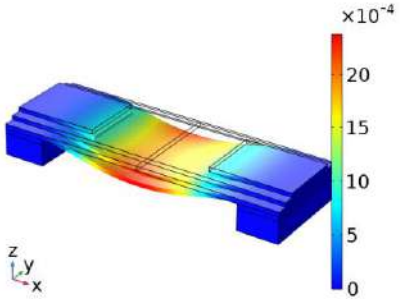
Al electrodes/PZT/SOI



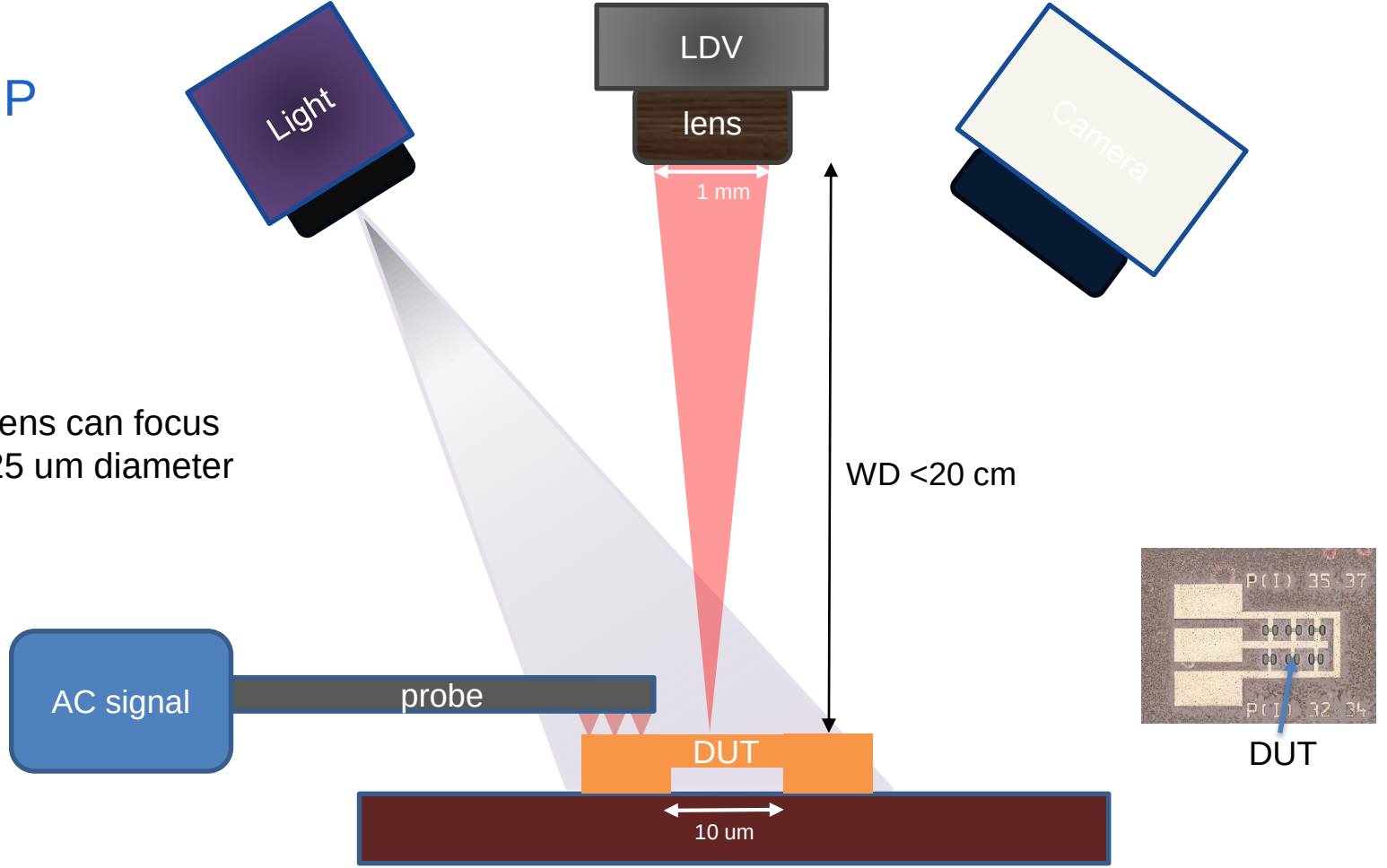



FIB* of a suspended beam





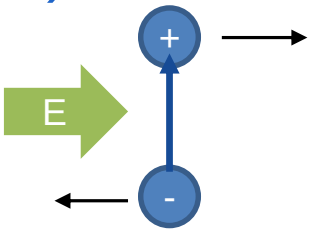
# LDV SETUP

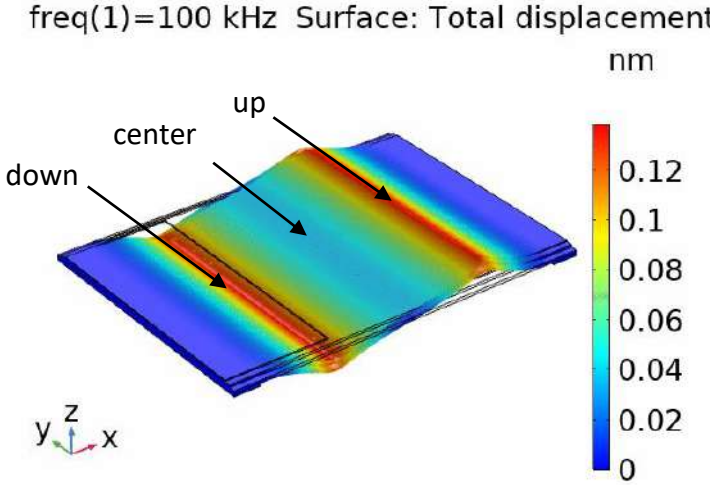


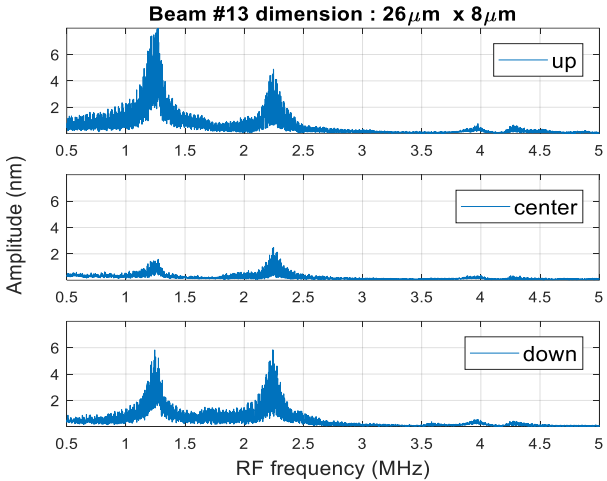

The integrated lens can focus beam down to 25 um diameter ($1/e^2$)

Setup automation with Matlab script

# AS-DEPOSITED PZT (DOMAINS OUT OF SUBSTRATE PLANE)

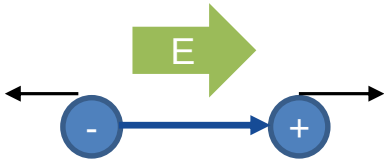


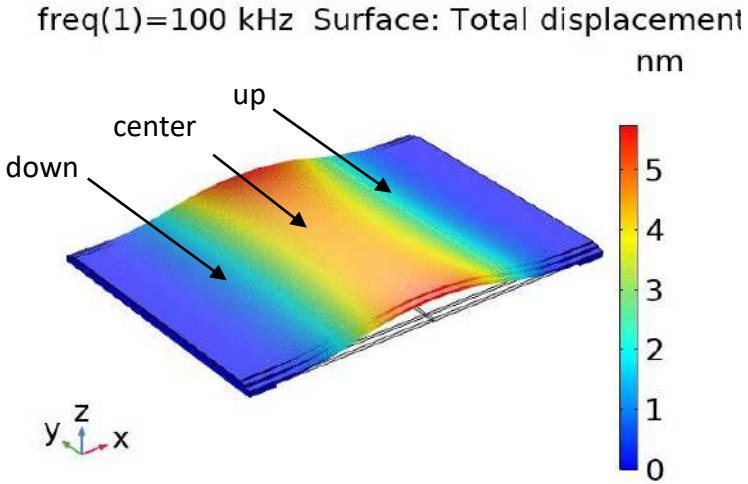



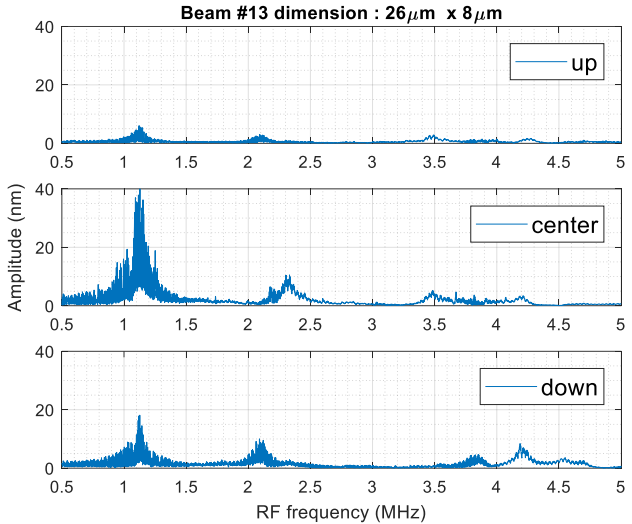




Applied electric field perpendicular to the PZT domain polarization => shear mode

# POLED PZT (DOMAINS ALONG E-FIELD IN-PLANE)




Applied electric field along the PZT domain polarization => longitudinal mode (efficient)

MEMS actuation confirmed

# OUTLINE

Introduction and motivation

SAW actuation

MEMS actuation

**Photonic MEMS**

Conclusion

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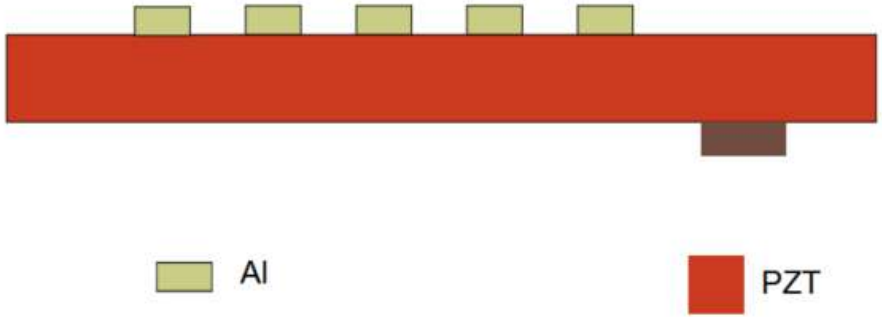
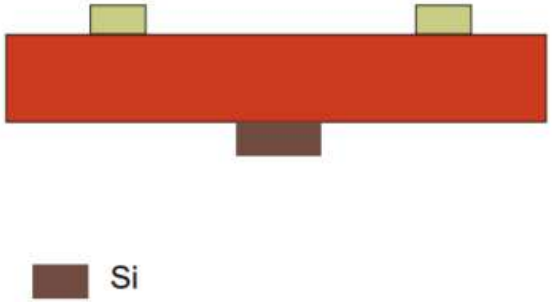
# TWO TYPES OF PHOTONIC MEMS DEVICES

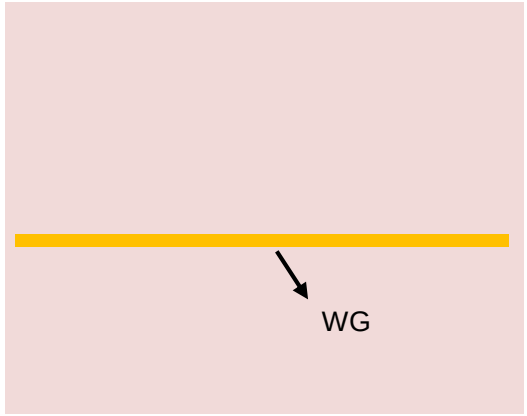
suspended IDT



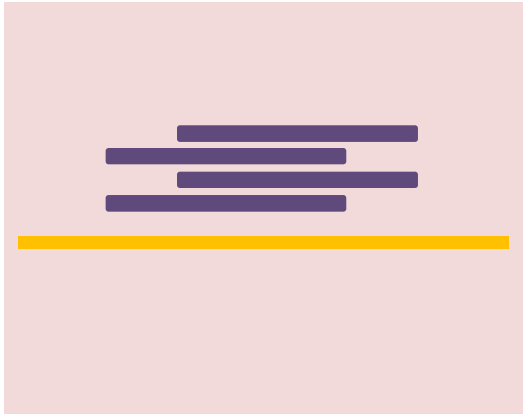

suspended EOMT



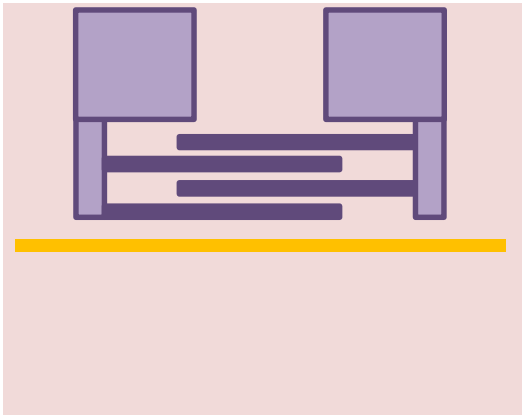

IDT→ inter-digital transducer
EOMT→ electro-optomechanical transducer



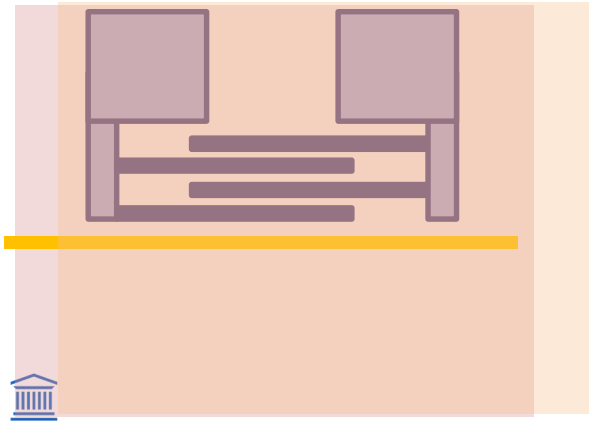

(a)



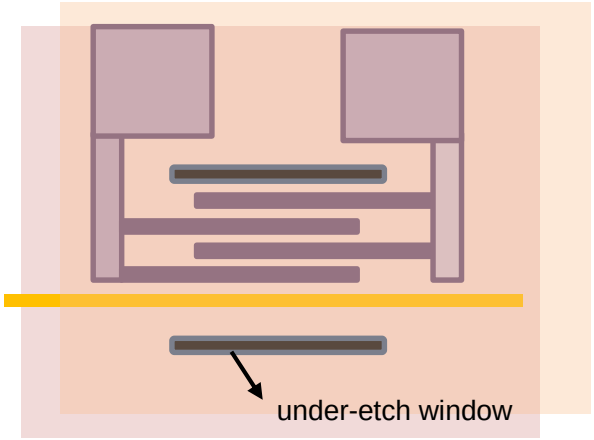
(b)



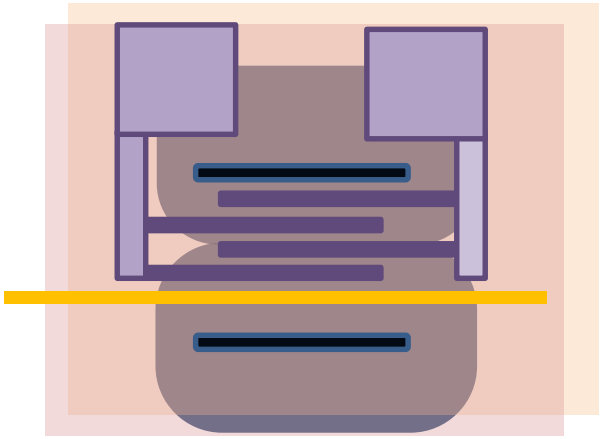
(c)



(d)

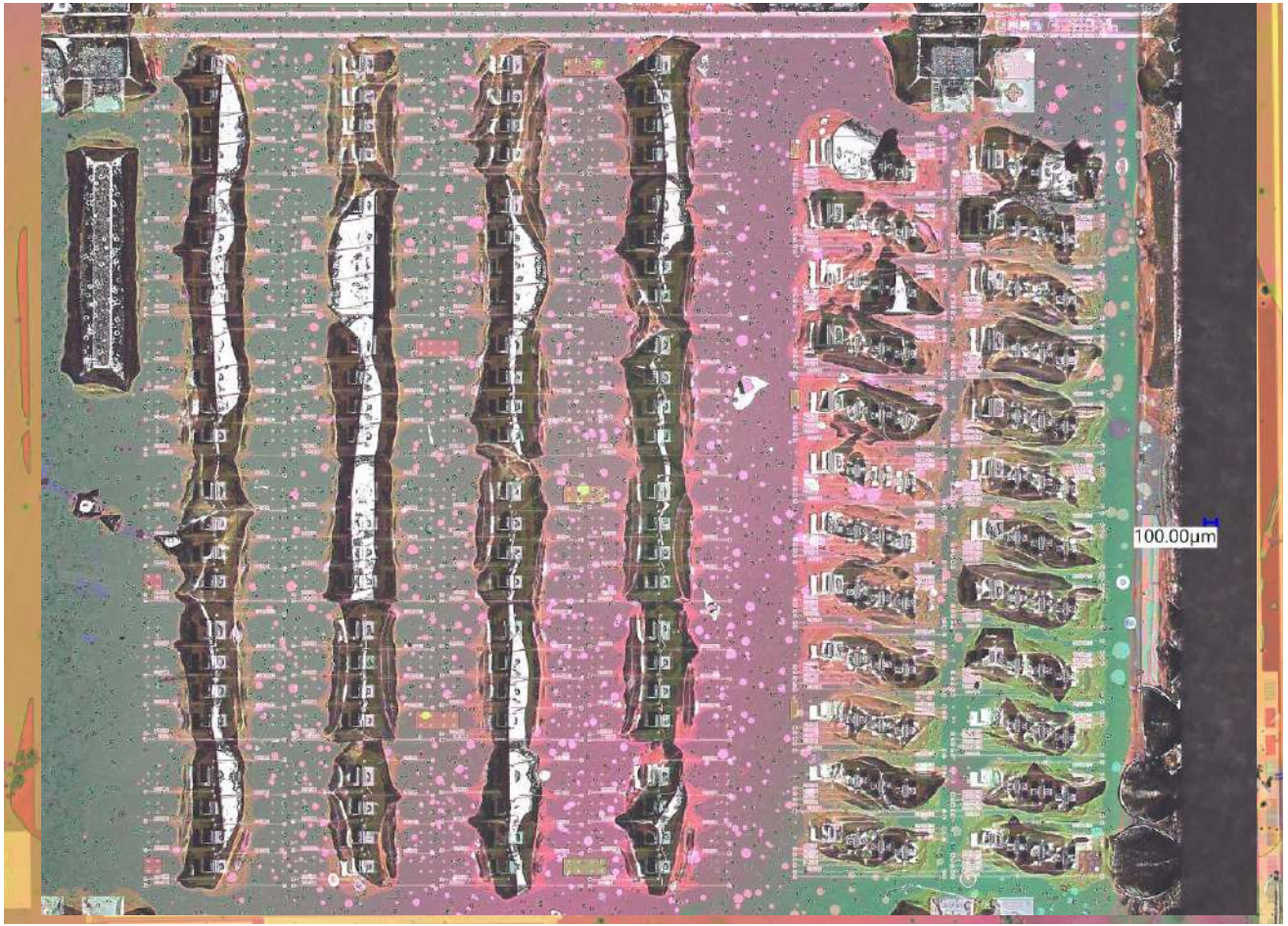



(e)



(f)

# FABRICATION- ATTEMPT 1

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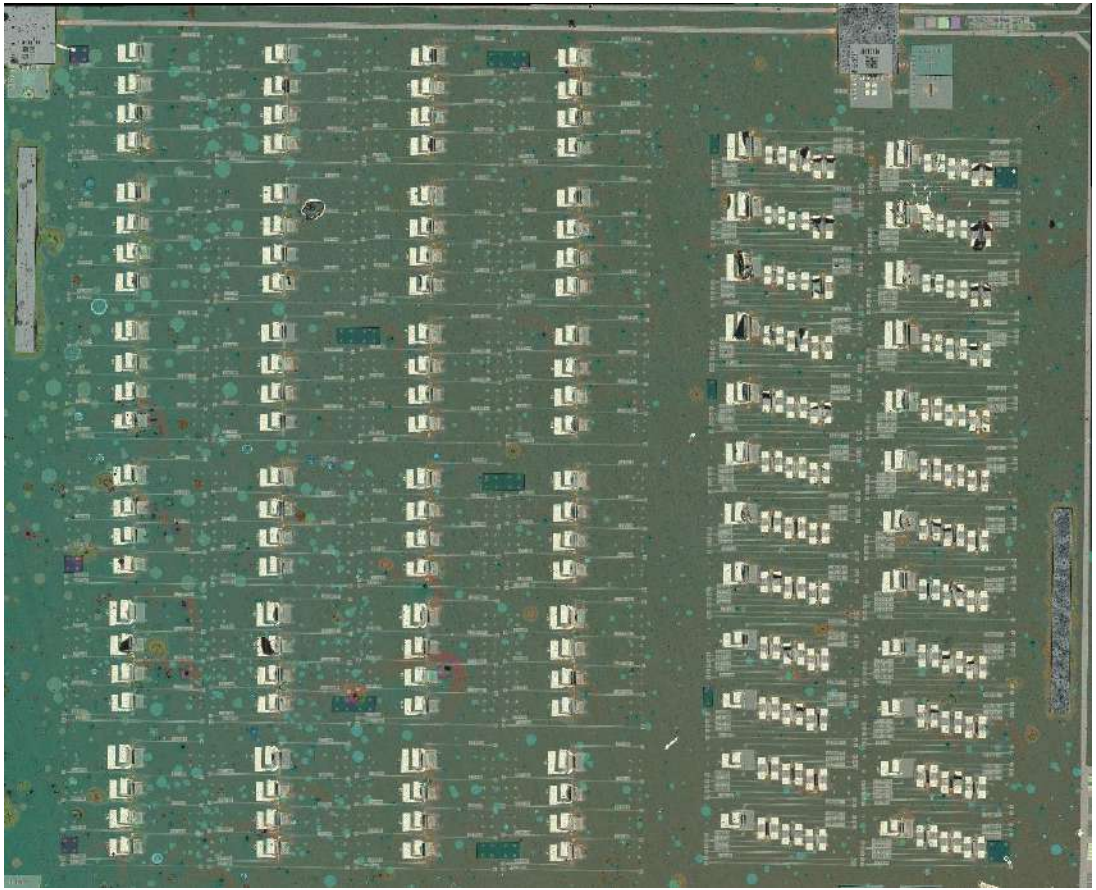
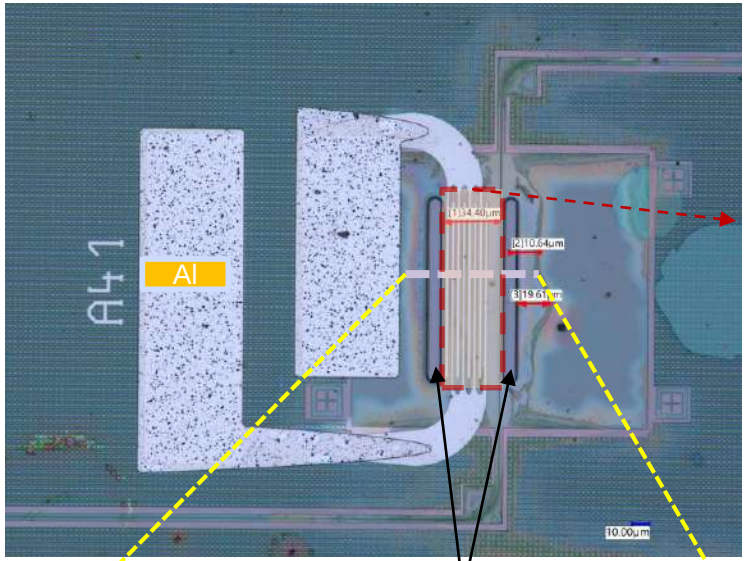
# FABRICATION- ATTEMPT 2

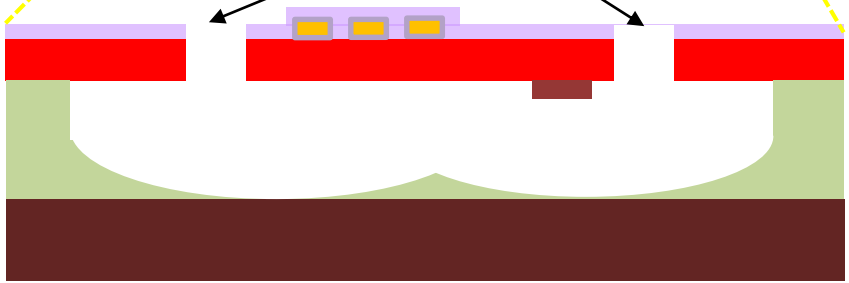


# SUSPENDED IDT




fully suspended region
(with some residual $SiO_2$
underneath)

underetch window



PZT (400 nm)

Si (220 nm)

$SiO_2$ (2 µm)

Si substrate

Al (100 nm)

$Al_2O_3$ (50 nm)

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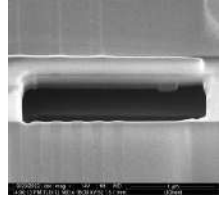
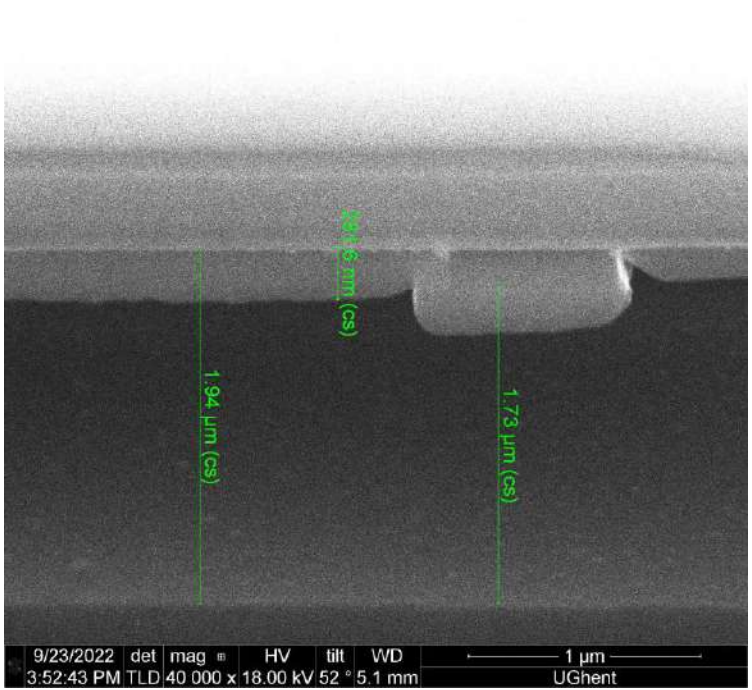
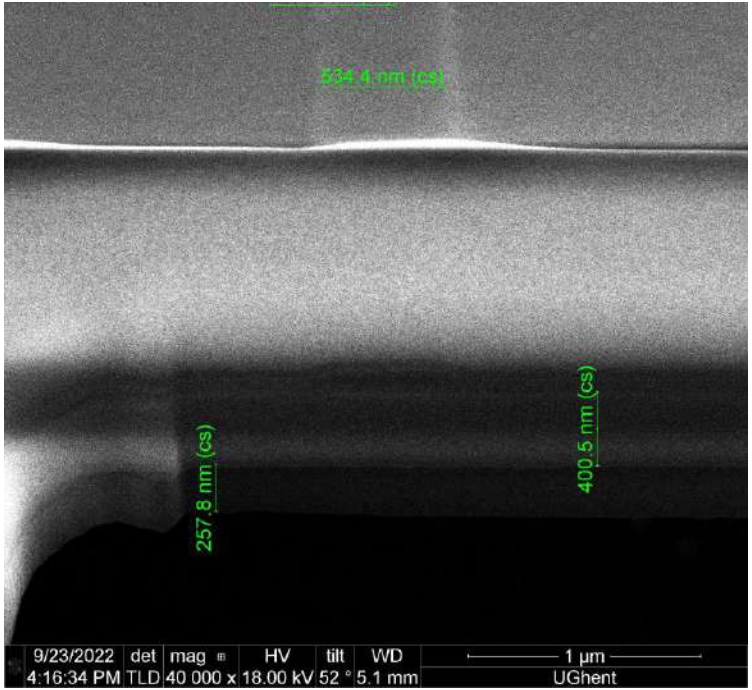
# CROSS-SECTION IMAGING WITH SEM

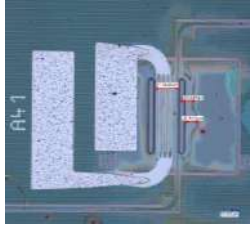


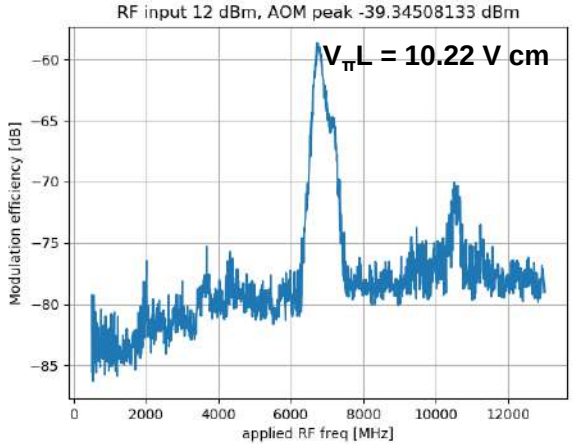


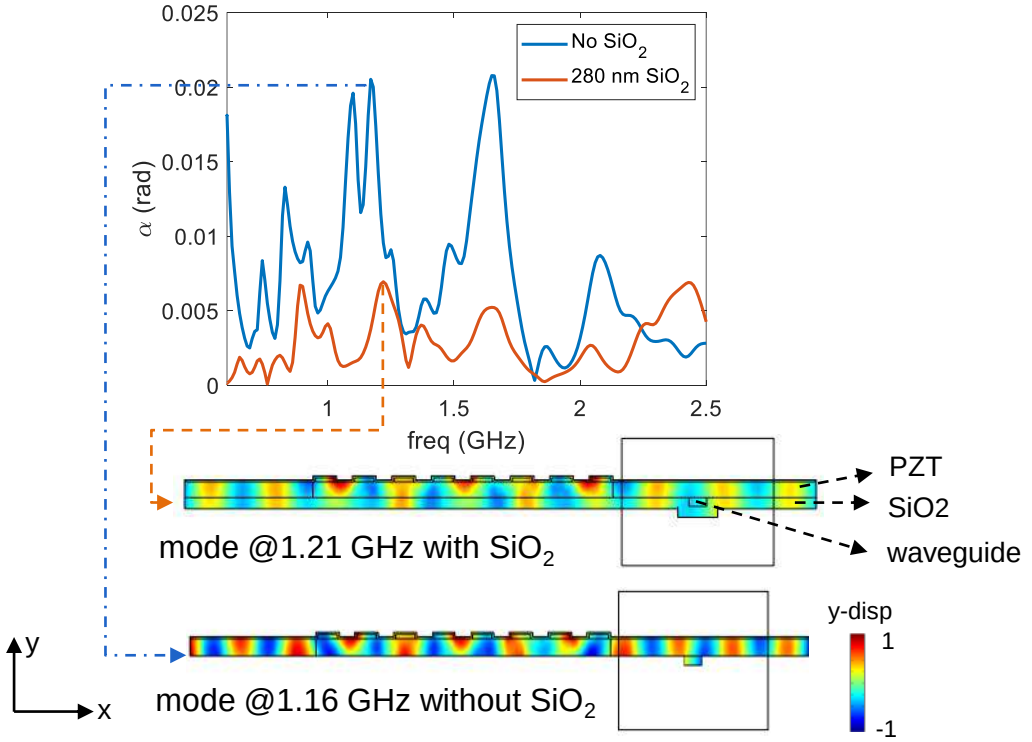




Residual $SiO_2$ persistent even after extra HF vapor exposure

# SUSPENDED IDT

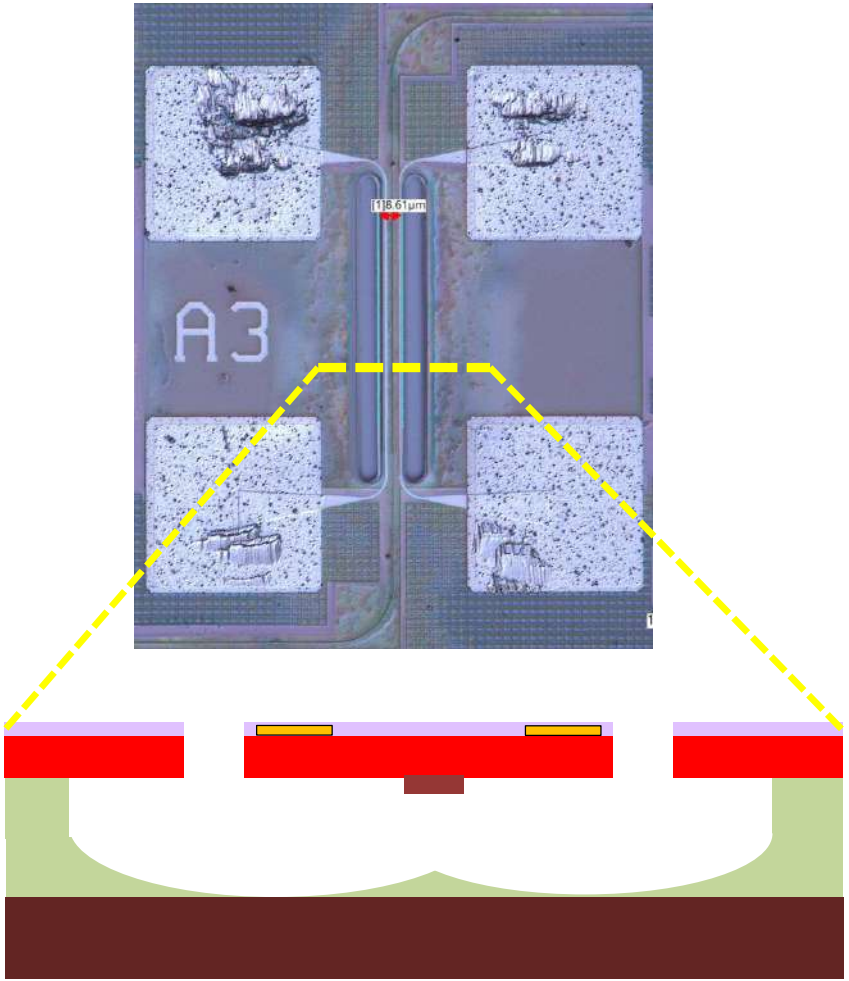





- No strong modulation at expected frequencies
- Residual oxide has a detrimental effect (acoustic leakage, un-uniform thickness creates asymmetry)

# SUSPENDED EOMT




PZT (400 nm)

Si (220 nm)

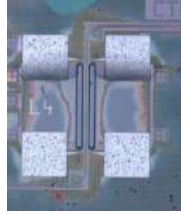
$SiO_2$ (2 µm)

Si substrate

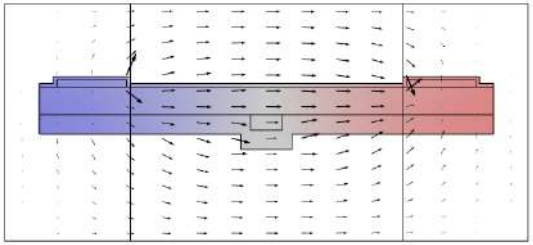
Al (100 nm)

$Al_2O_3$ (50 nm)

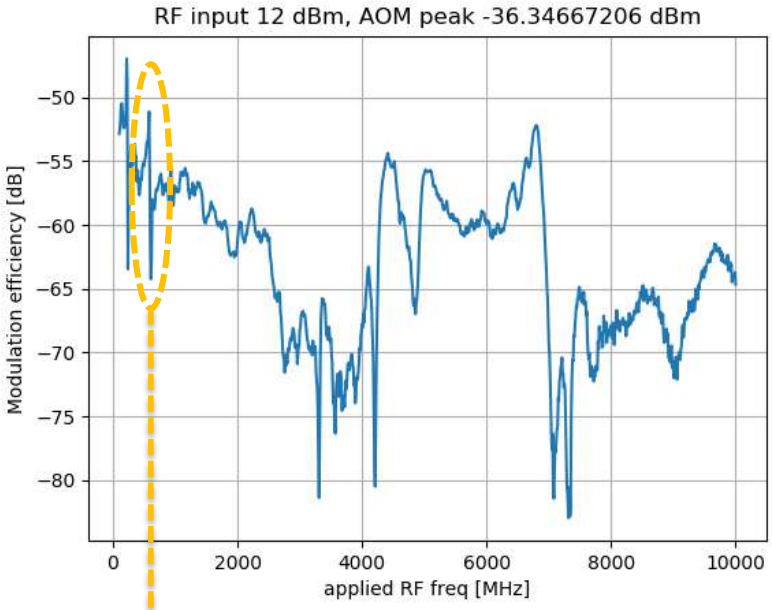
# SUSPENDED EOMT

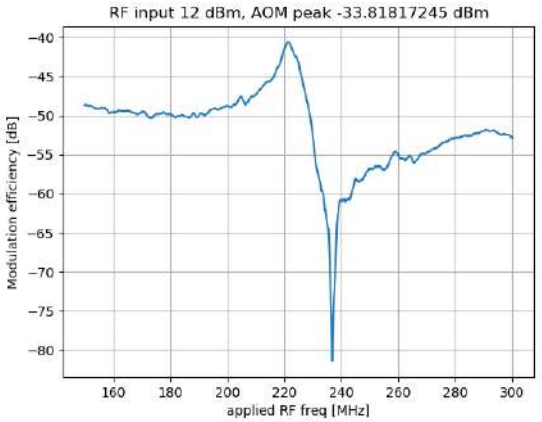


mode at 288 MHz



arrow→ electric field, color → x-disp




**$V_\pi L$ = 4.19 V cm**

**Manuscript under preparation*

# OUTLINE

Introduction and motivation

SAW actuation

MEMS actuation

Photonic MEMS

**Conclusion**

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# CONCLUSION

- SAW modulator with PZT seems promising. Further room for improvement (under-etching, SAW reflector), and repeatability analysis
- Poling is crucial in PZT
- MEMS actuation confirmed with LDV. Under-etching process with HF leaves some SiO2 residues
- PZT-based photonic MEMS devices show promising results but need improvement with the fabrication.
- Fano resonance for ultra-sensitive devices

# ACKNOWLEDGMENT


- Prof. Dries Van Thourhout, PRG
- Prof. Jeroen Beeckman, LCP
- Gilles, Ewout, Enes, Kobe, Hannes, Awanish, Tessa, John,..


Hybrid Optomechanical Technologies

Thank you!

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