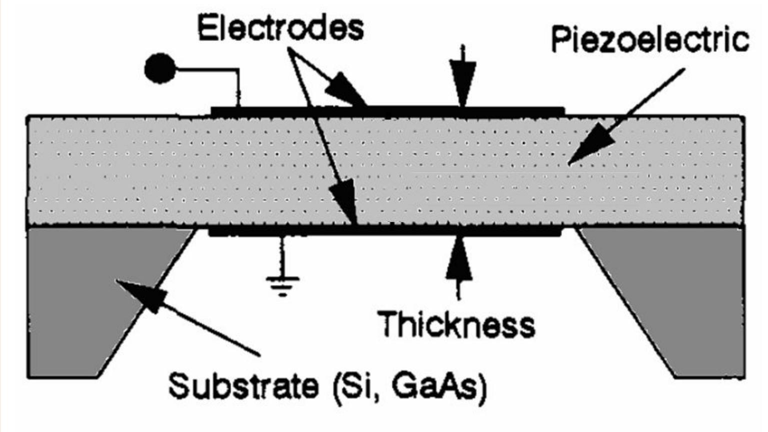
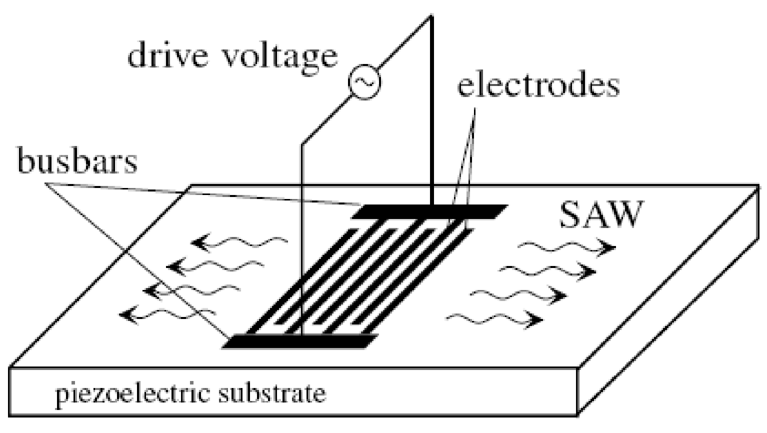
GHz SAW and FBAR devices manufactured using micromachining and nanoprocessing of wide band gap semiconductors

A.Müller*, D. Neculoiu*, A Dinescu*, C. Morosanu***, G. Konstantinidis**, D Vasilache*, M Dragoman* G. Sajin*

*IMT-Bucharest, Romania, alexandru.muller@imt.ro
** FORTH IESL Heraklion, Crete, Greece;,
*** National Institute of Material Physics (NIMP); Bucharest, Romania

FBAR/SAW





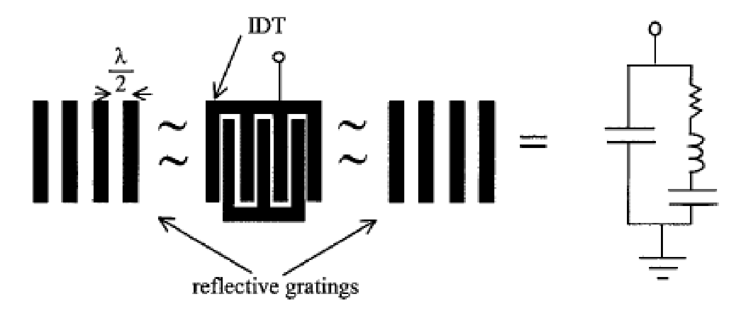


Fig. 17. SAW resonator.

d= membrane thickness

$d = \lambda/2 = v_s/2f_r$ (resonance)

$f_r = v_s/2d$

w=digit width= interdigit width

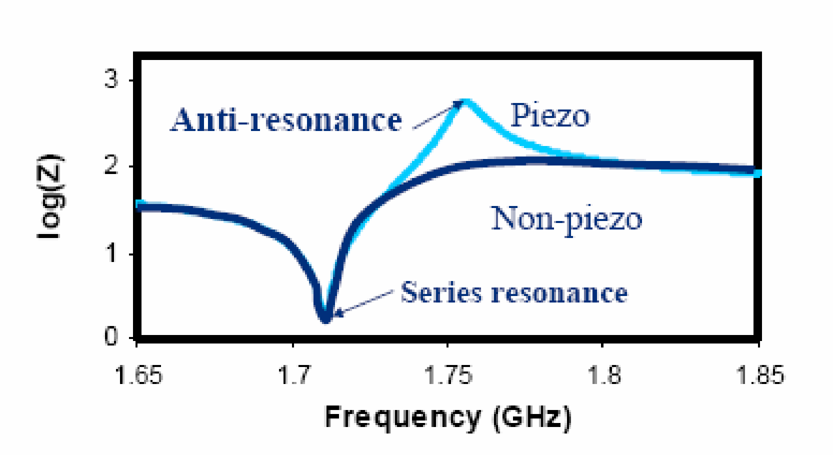
$2w = \lambda/2 = v_s/2f_r$

$f_r = v_s/4w$;

v_s~km/s; d~µm ; f_r~GHz

FBARs and SAWs resonate at their acoustic natural frequency (GHz range) not at their structural natural frequency (in the kHz range)

Expected frequency responses for piezo and non-piezo materials



- **All acoustic devices operate at resonance**
- ***Resonance* occurs when the input impedance is at a minimum and *anti-resonance* occurs when it is at a maximum**. The resonant frequency and the anti-resonant frequency are referred to as the **series frequency and the parallel frequency** respectively
- A series resonant circuit allows a maximum current flow at resonant frequency, whereas a parallel resonant circuit allows a minimum

. **At these frequencies the response is completely real and does not have an imaginary component.**

- The classical technologies for manufacturing SAW type resonators and filters based on non-semiconductor materials like quartz, lithium niobate or lithium tantalate, are restricted to frequencies below 1 GHz
- Most FBAR structures reported in the last years were manufactured on ZnO a semiconductor incompatible with monolithic integration

AlN and GaN technology create the possibily of manufacturing of GHz frequencies operating acoustic devices monolithic integrable with other circuit elements

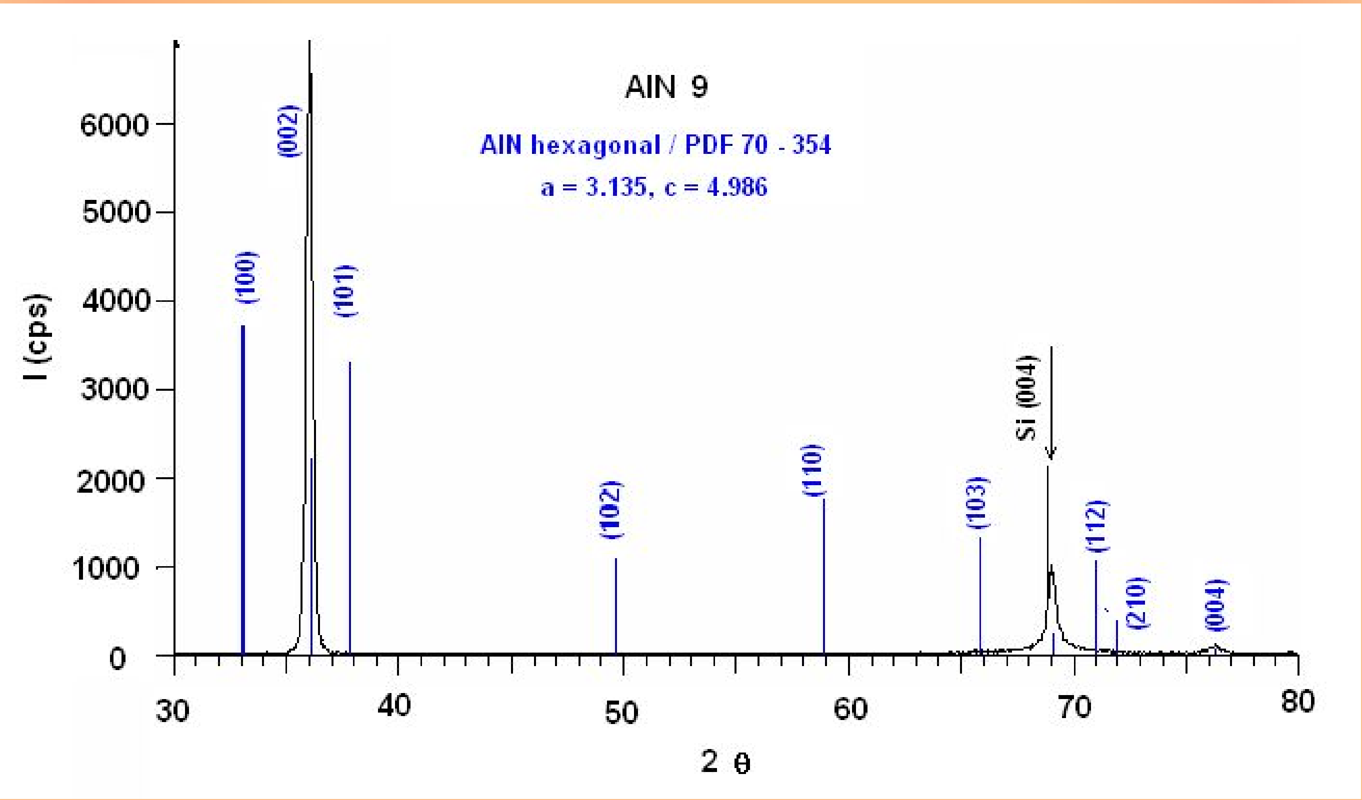
- In GHz SAW technology nanolithography for the IDT is necessary
- For FBAR structures it is necessary to develop very thin selfsustainable membranes

WHY TO INCREASE THE FREQUENCY?

- The cellular phone system is evolving from a third generation (3G) system to a fourth generation (4G) system. The radio frequency of 4G systems is expected to be within the high-frequency range from 3 GHz to 6 GHz.
- Sensors based on SAW and FBAR structures have a sensitivity: $S \alpha f^2$
- WBG semiconductor (AlN, GaN) technology opened the possibility to use micromachining and nanoprocessing and to increase SAW and FBAR operating frequency
- AlN and GaN create the possibility to integrate monolithic the SAW and FBAR resonators with other circuit elements

SAW structures manufactured using nanolithographic techniques

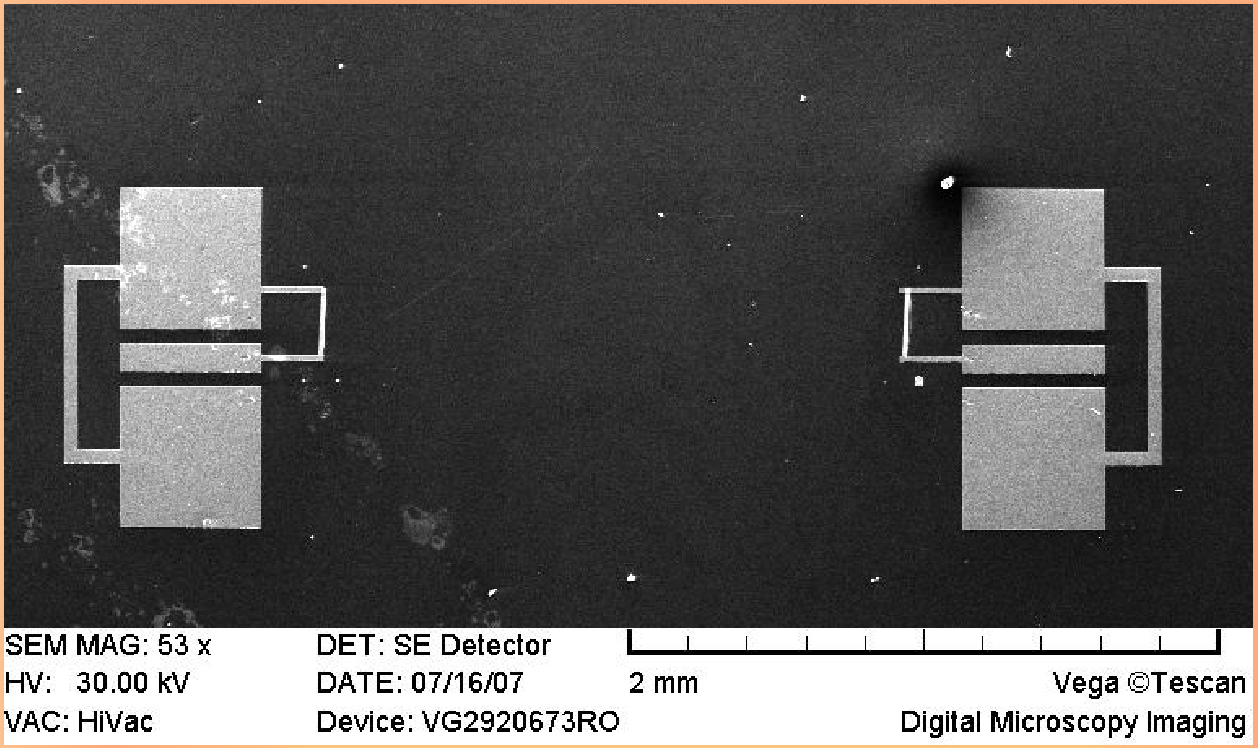
The structures were manufactured on AlN thin films deposited by magnetron sputtering on high resistivity silicon



XRD diffraction pattern for a high oriented AlN film sputtered onto a <100> oriented Si substrate

First run

The idea of the experiment

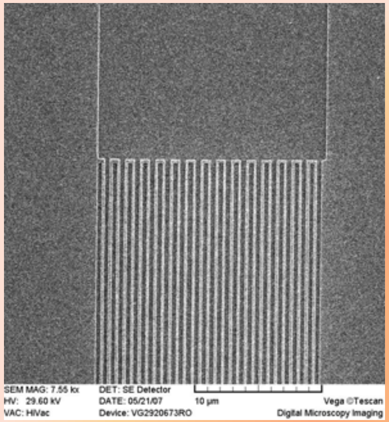


Each IDT structure has 30 digits and 29 inter-digits. The digits and inter-digits have a length of 200µm, and an equal width of 200 nm for one type of test structures and 300nm for the other type.

The first step in the SAW structure manufacturing was the measurement pads patterning and deposition. Conventional photolithography, e-beam metalization (Ti/Au 20nm/200nm) and lift-off technique was used (FORTH).

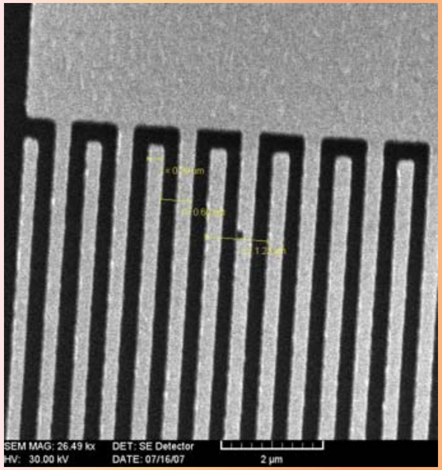
Due to the digits/interdigits dimensions, a direct writing process was used, for the IDT structure. The design transfer on the wafer was performed using a Scanning Electron Microscope (Vega from Tescan), equipped with an Electron Beam Lithography system (Elphy Plus from Raith) (IMT).

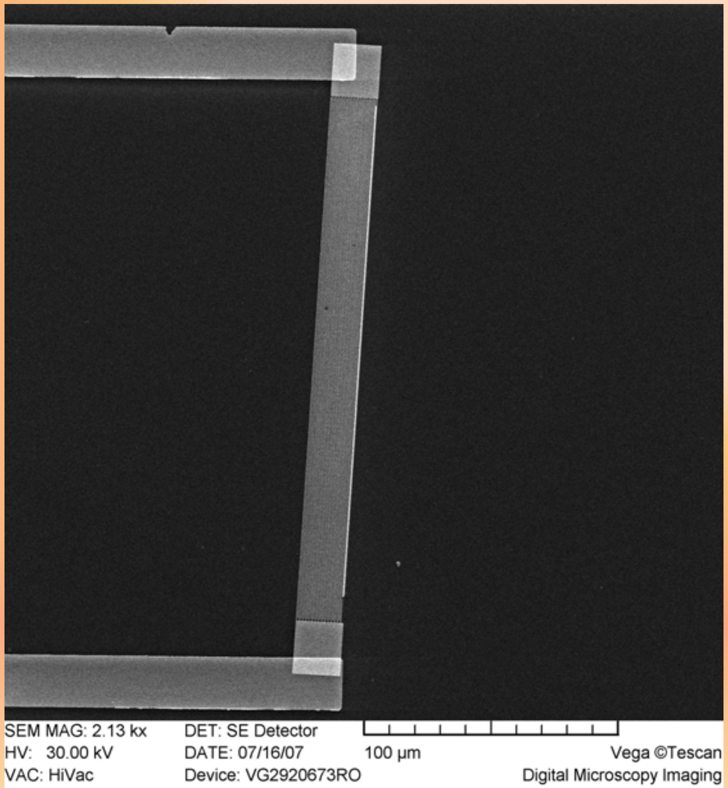
Finally, Ti/Au (20/nm/200nm) is deposited by e beam and a lift-off process, is used to remove the unwanted metal (FORTH).

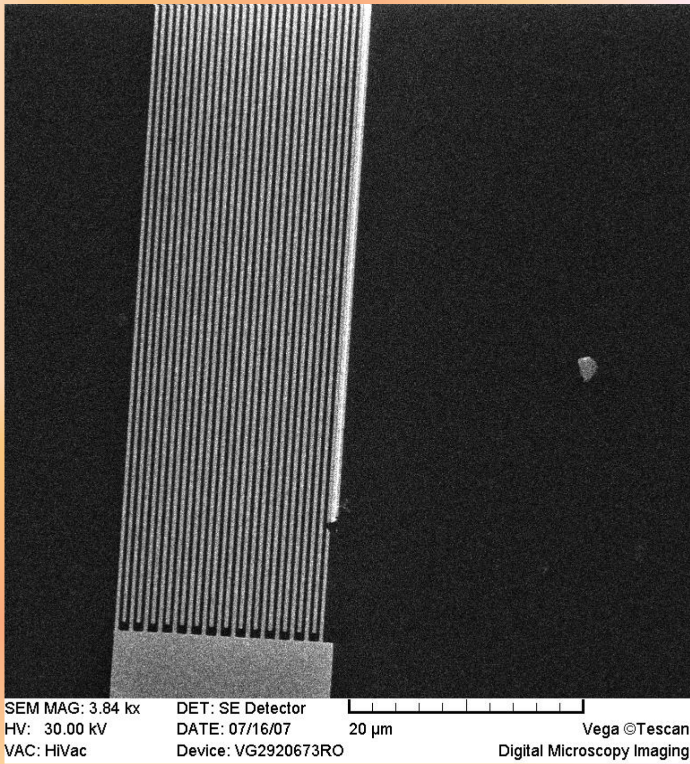


300nm lines in PMMA

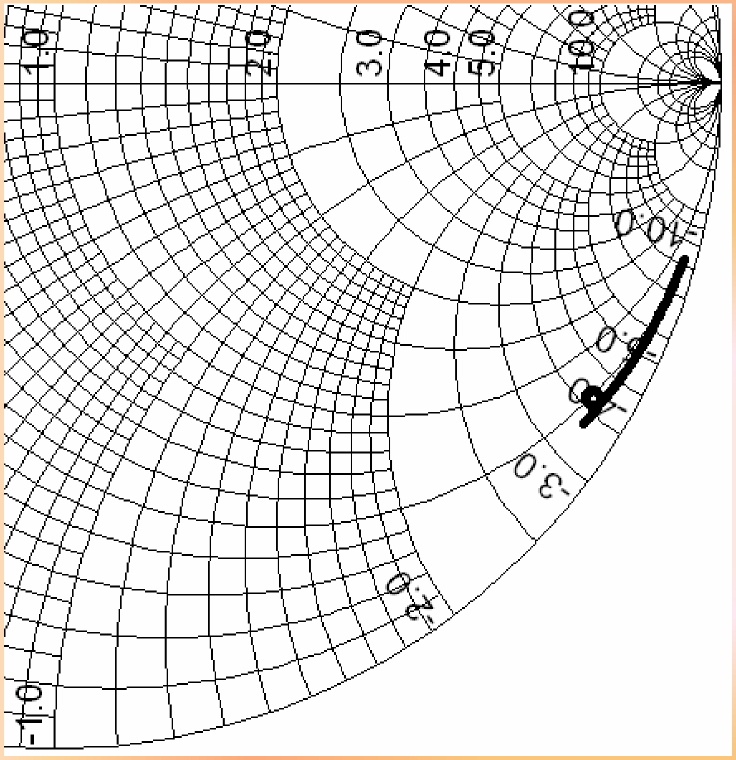
A SAW structure with an IDT having metalic fingers and pitches of 300nm



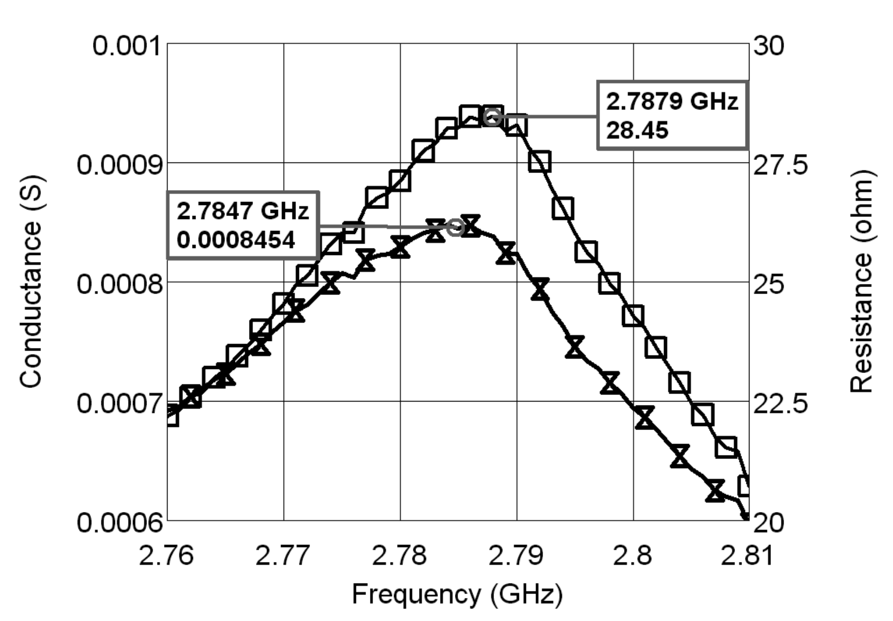




Measurement results



Smith chart representation of the SAW resonator input impedance (detail)



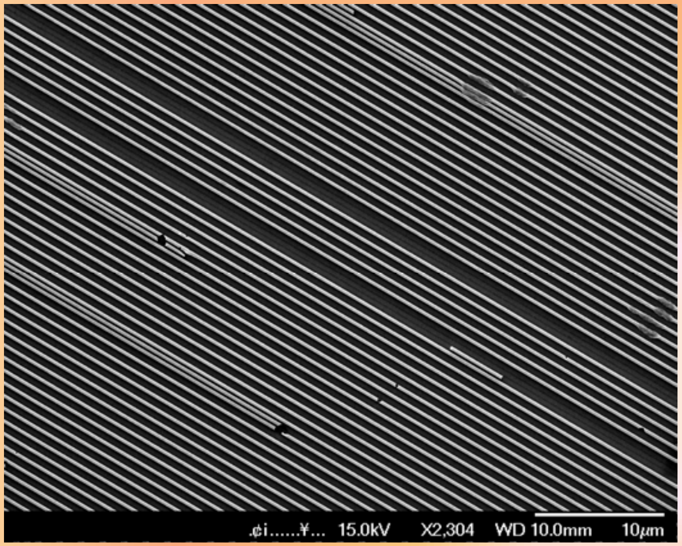
The resistance and the conductance of the SAW resonator

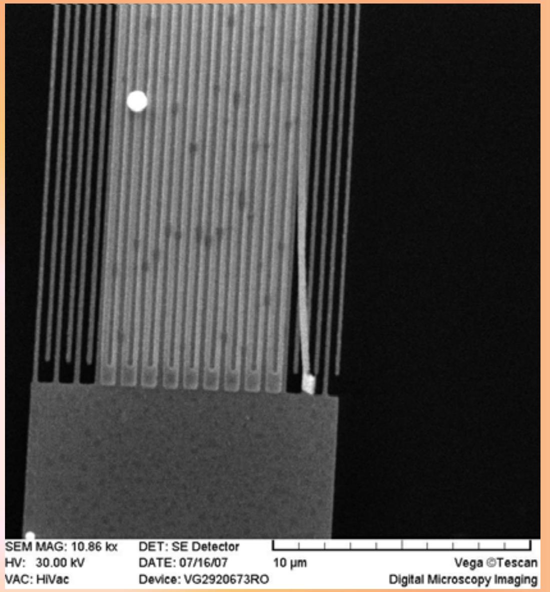
f_s = 2.7847 GHz and f_p = 2.7879 GHz. The resulting acoustic velocity of the surface waves of 3.336 ms^{-1} is lower than the values reported in the literature [8] because of the wave interaction with rather thick metallic electrode.

The effective coupling coefficient is defined as:

$$K_{eff}^2 = \frac{\pi^2}{4} \frac{f_s}{f_p} \frac{f_p - f_s}{f_p}$$

From (2), the effective coupling coefficient, K^2_{eff}, has a value of about 0.283 %. This value is closed to 0.25 % reported by other authors.

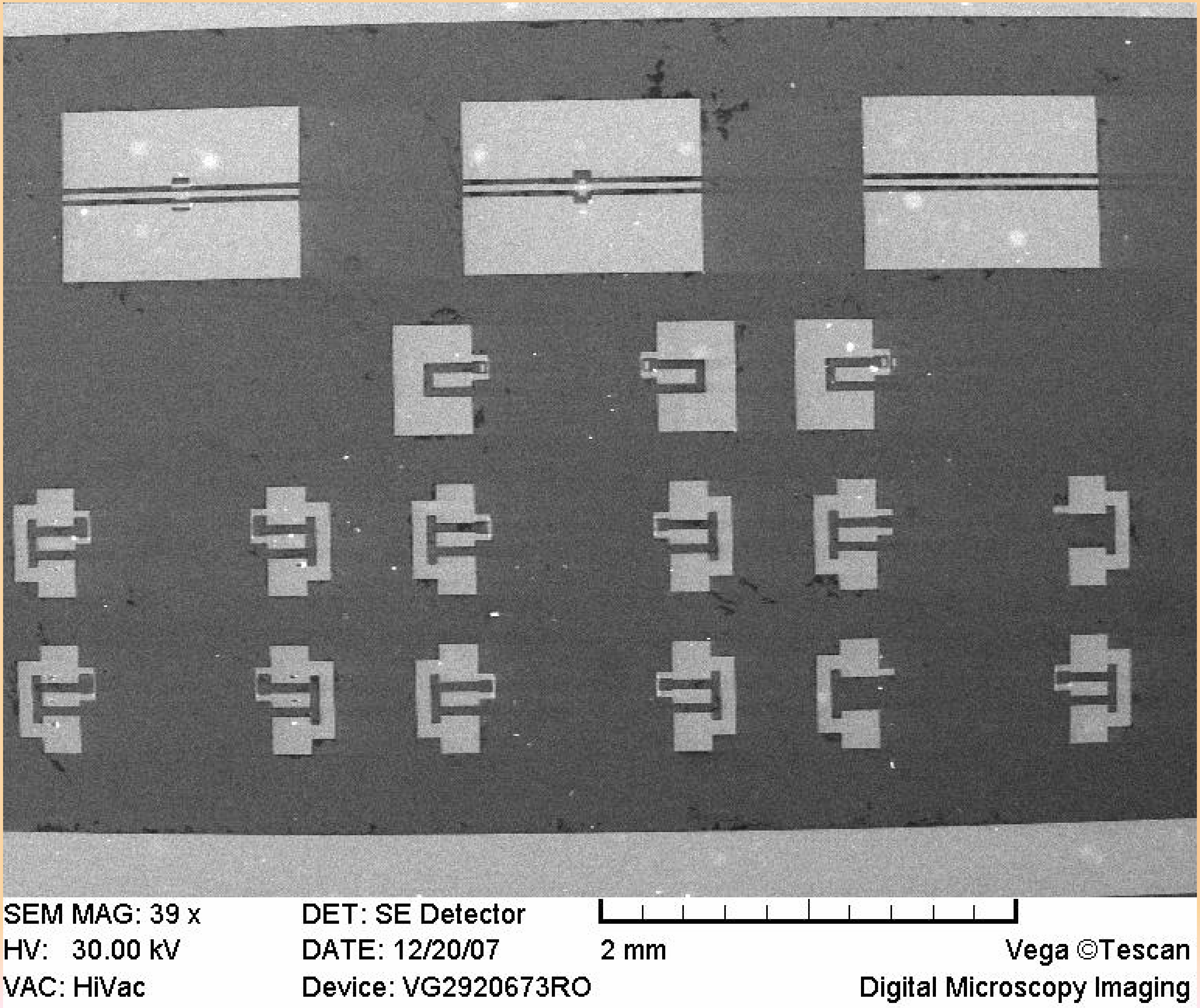


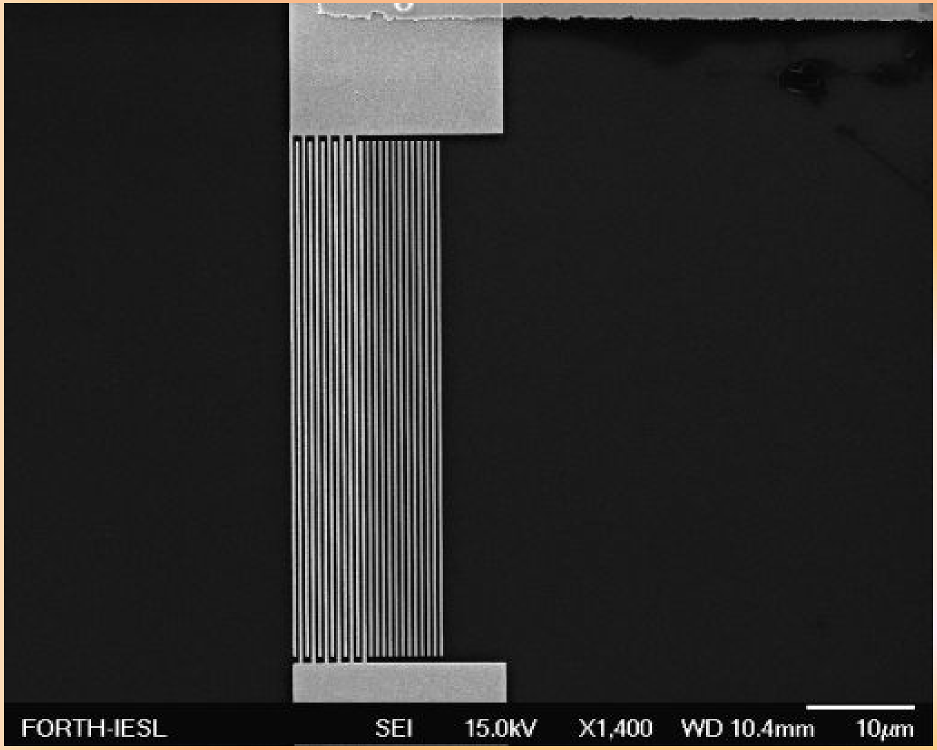


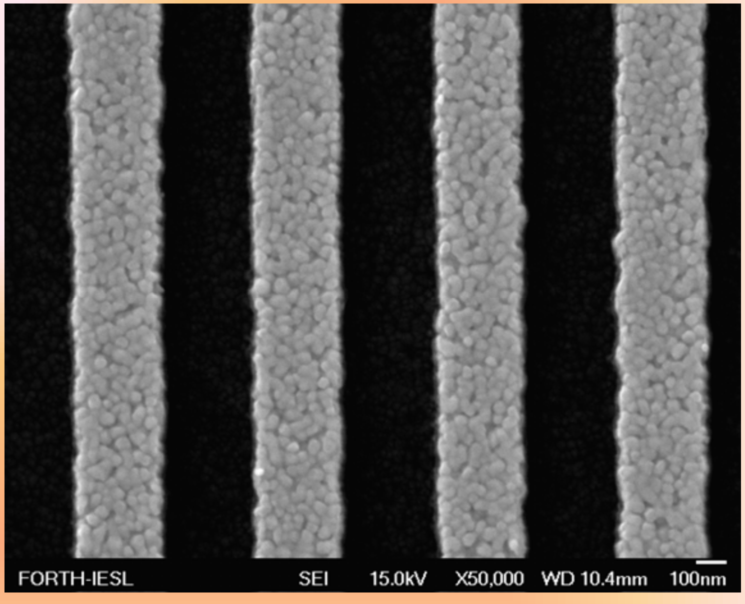
a b

Typical defects appeared in the 300 nm metallic lines of the IDT (a) disappearance of some lines and incomplete lift-off (b).

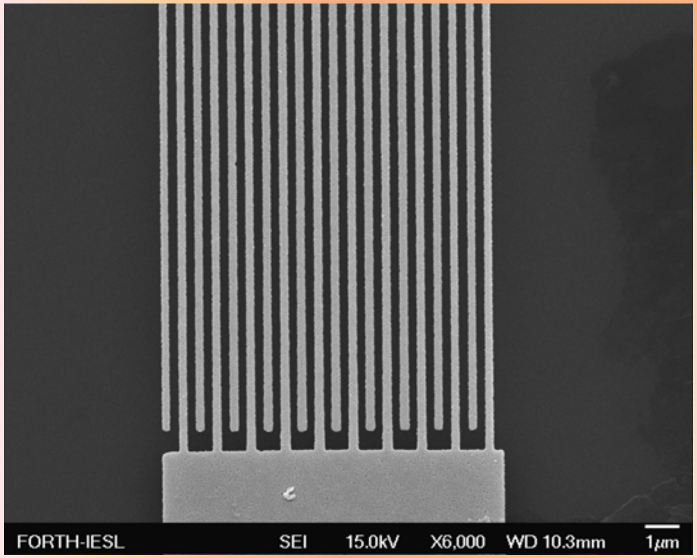
The second run

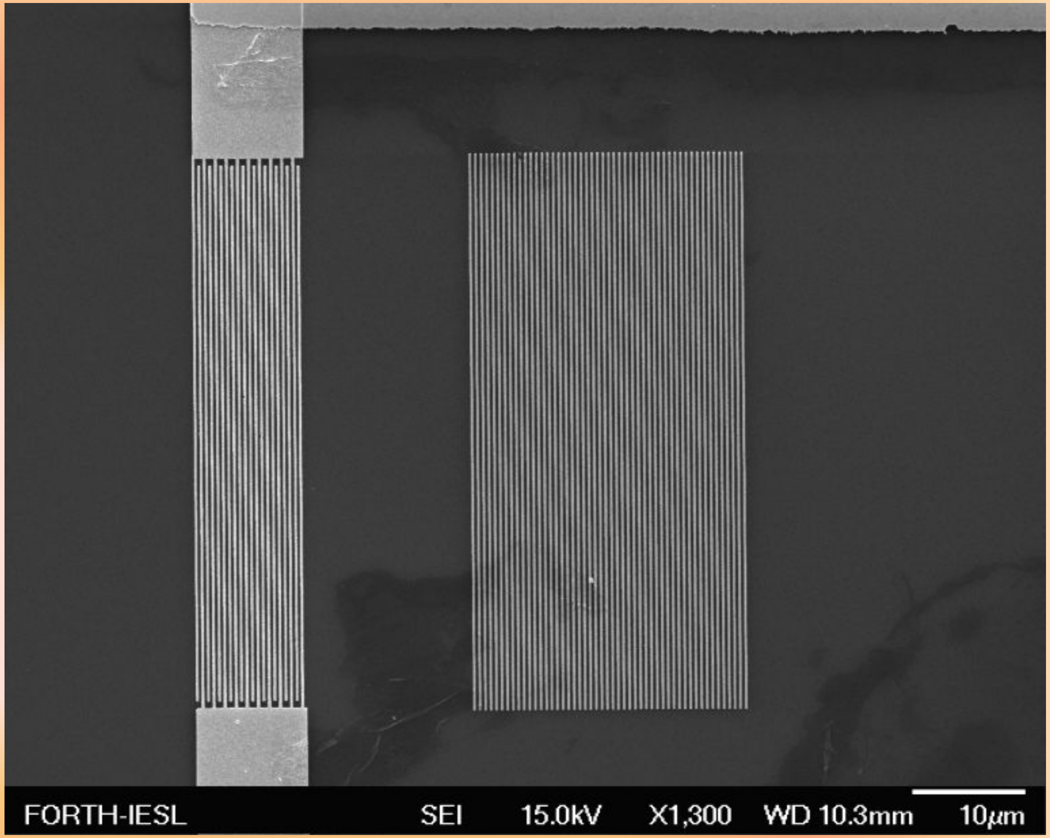




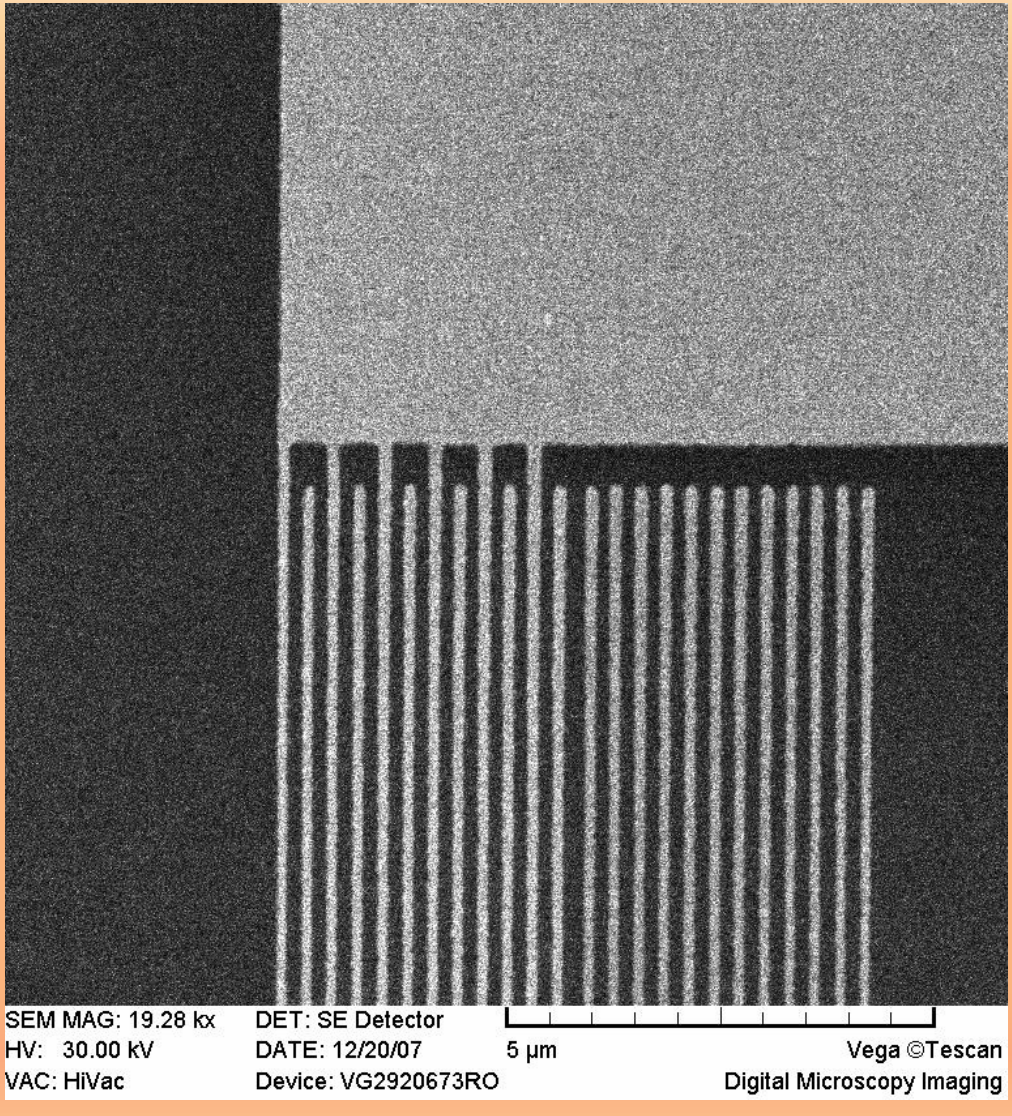


SAW structure (W=300nm)



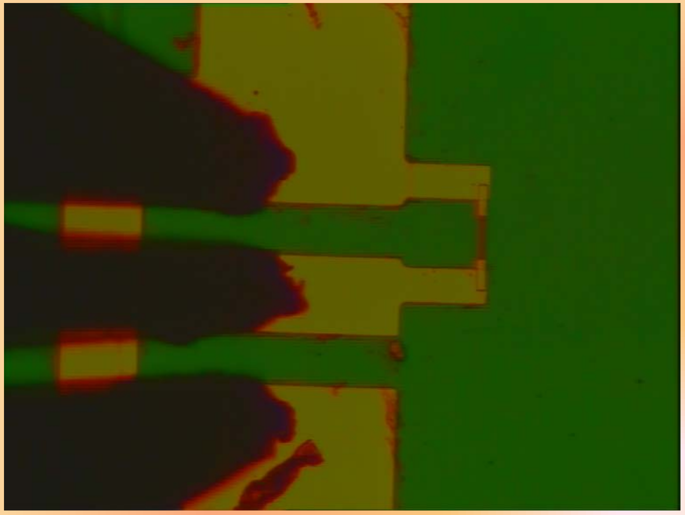


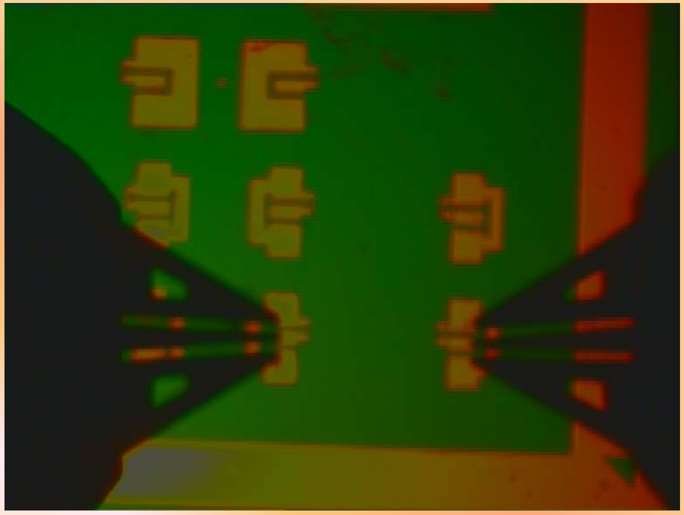
SAW structure (W=250nm)

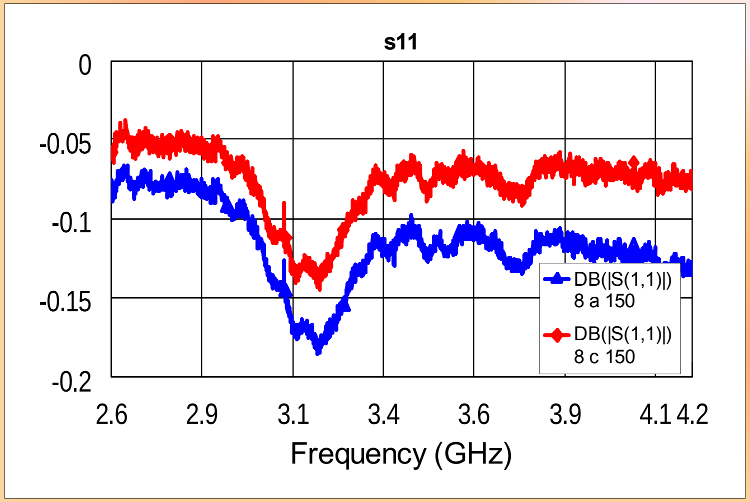


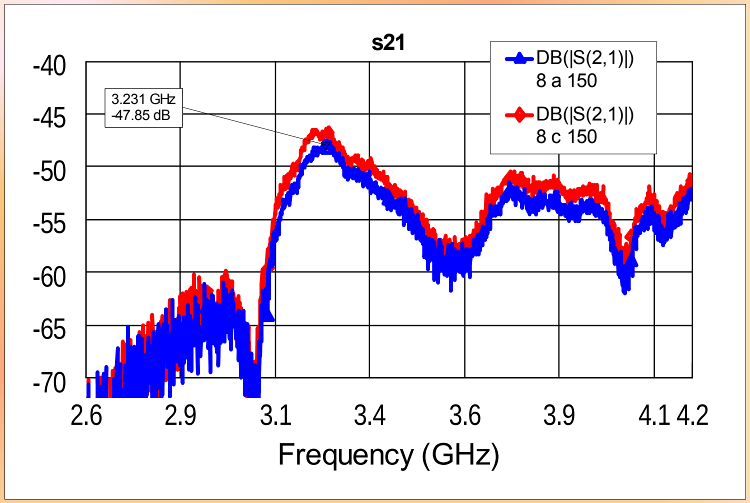
SAW structure detail (w=150nm)

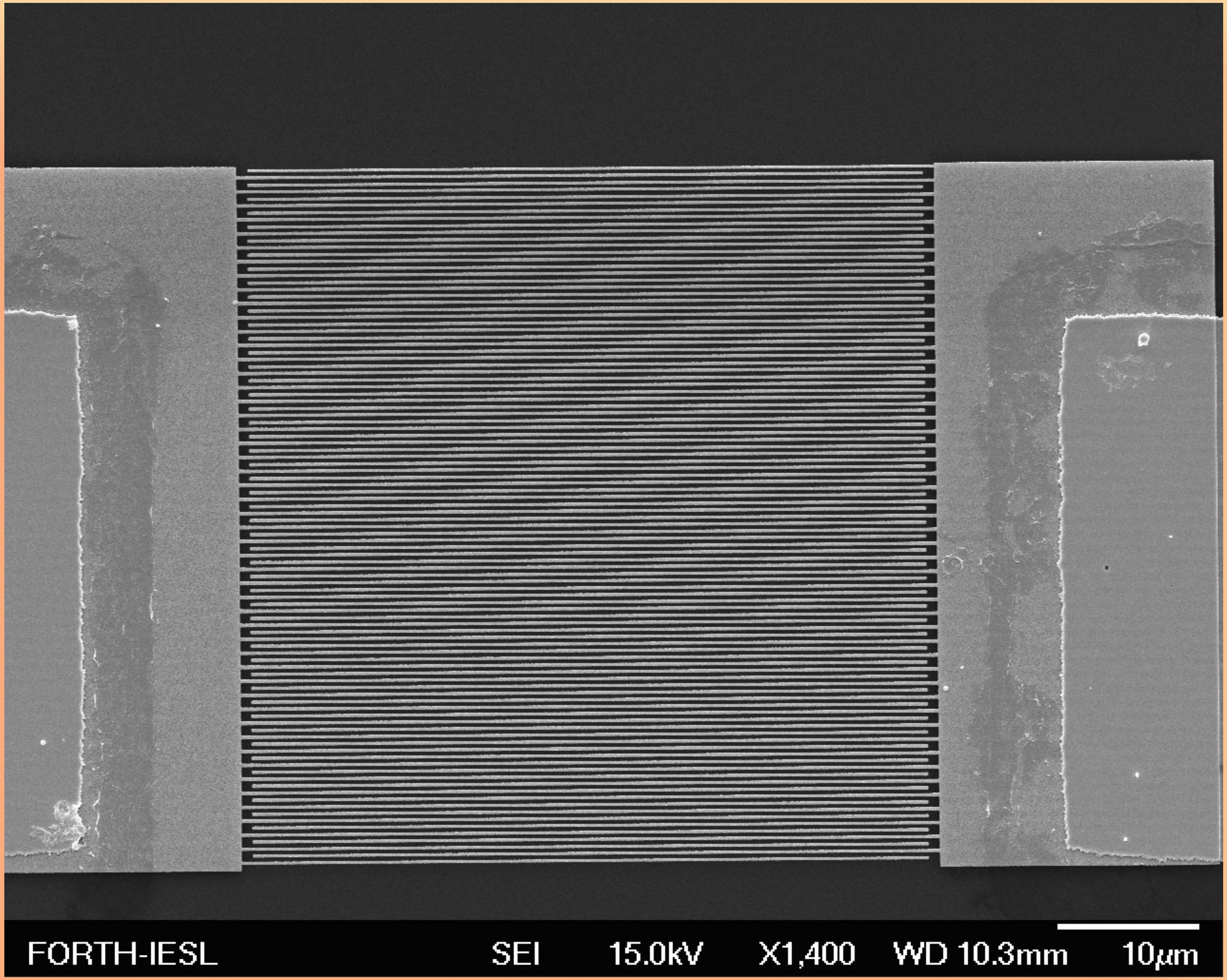
SAW - AlN 0.5 μm thick; 150 nm





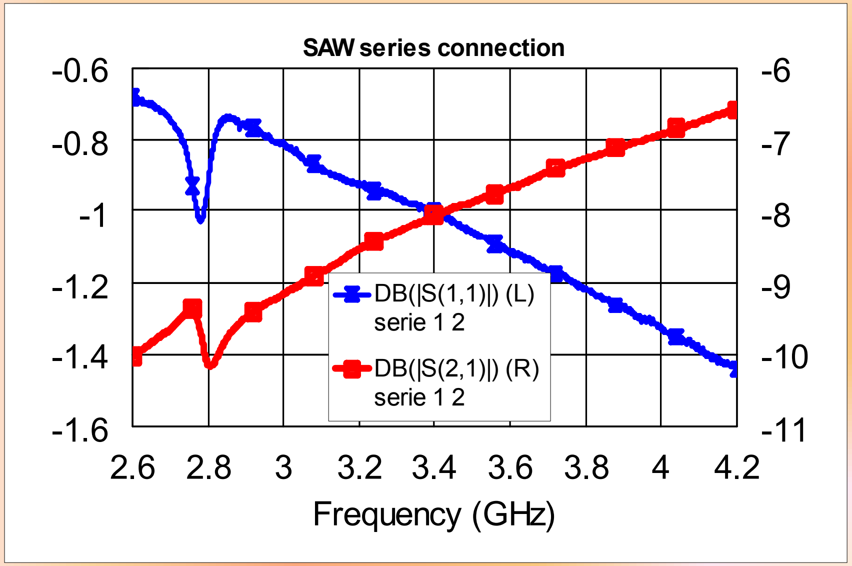


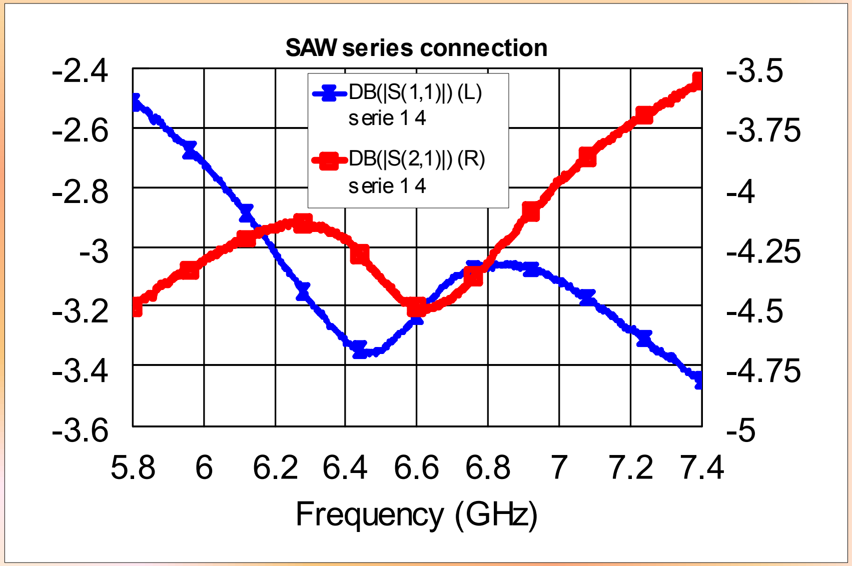


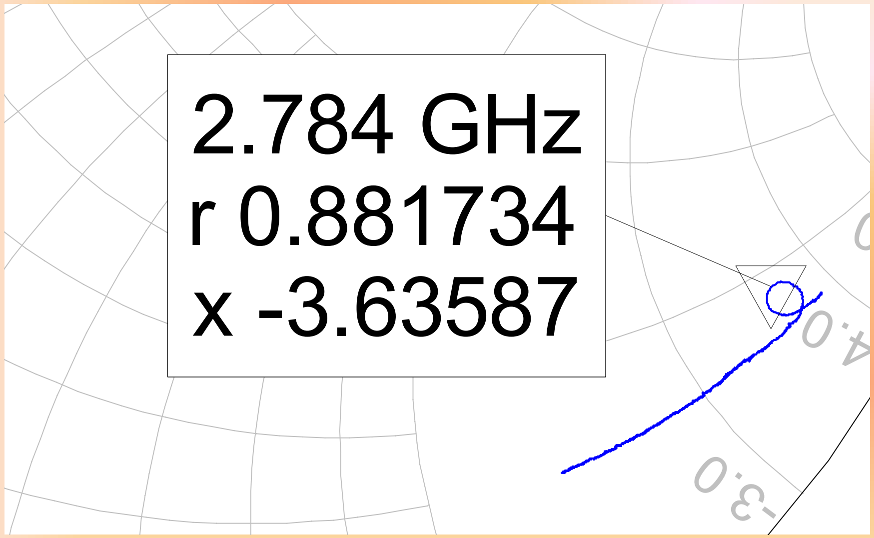


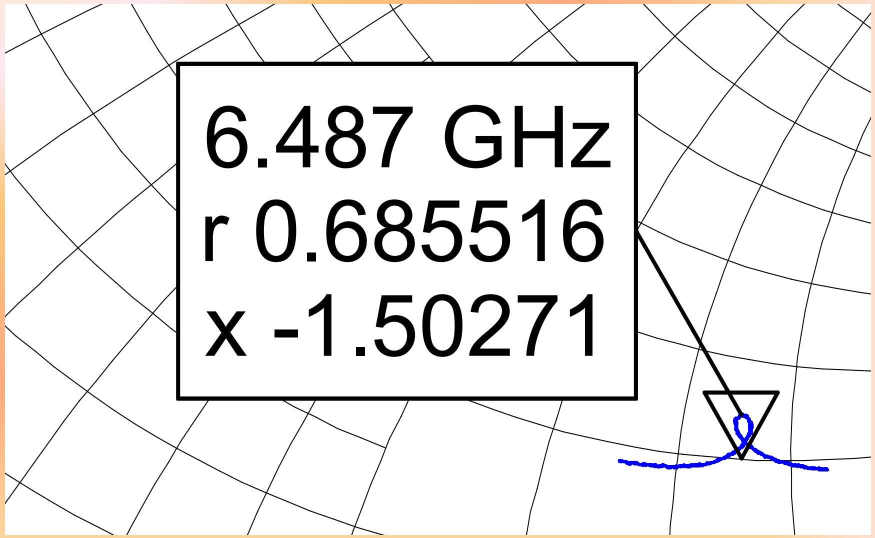
Series connection of SAWs (detail)
(w=300nm)

SAW - series connection (AlN 0.5 µm thick)





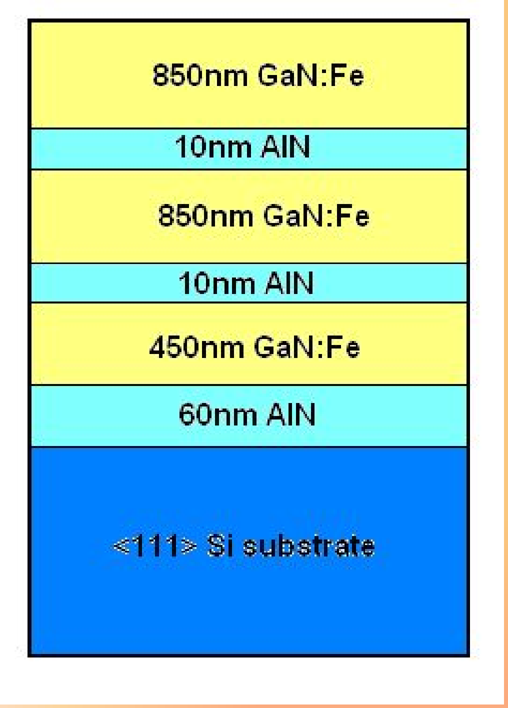




FBAR structurs

were fabricated on GaN and AlN

1.The GaN on silicon structure was grown by MOCVD

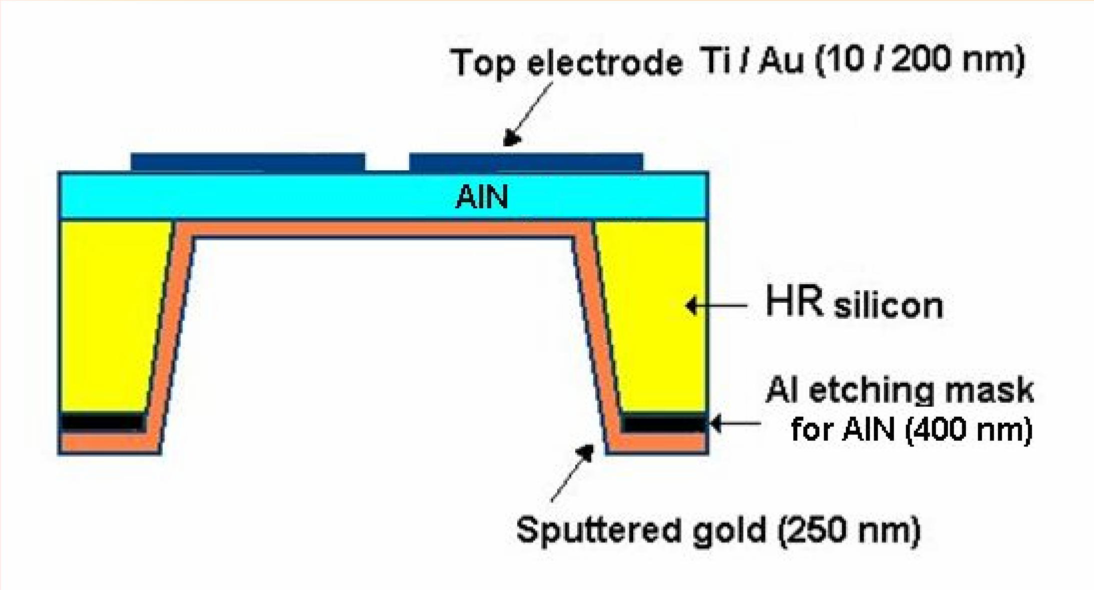


GaN membrane layer ~ 2.2μm

•**The first AlN layer has a buffer function**
•**The inter-layers (10 nm thick) are used in order to minimise the thermal stress and avoid the cracking of the GaN layers.**
•**The Fe doping allows to compensate the native doping in GaN layers**

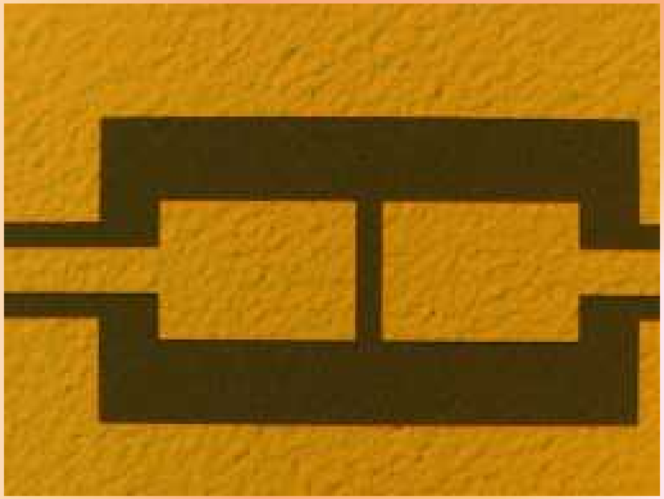
2. The AlN on silicon was deposited by magnetron sputtering The thickness was 2 μm and 0.357 μm

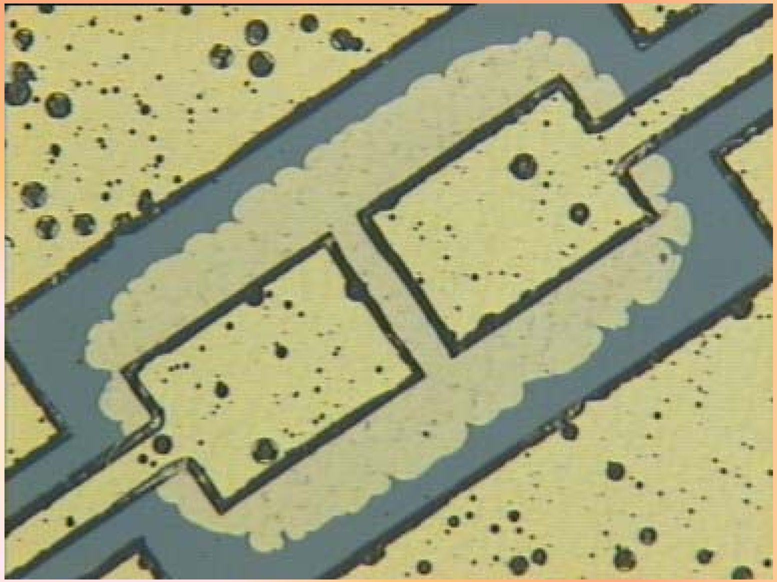
Main technological flow steps



Cross section of the FBAR structure with the evaporated Ti/Au for the top metallization and sputtered Au for the bottom contact. Sputtered Al is used as mask for the bulk-micromachining of the membrane

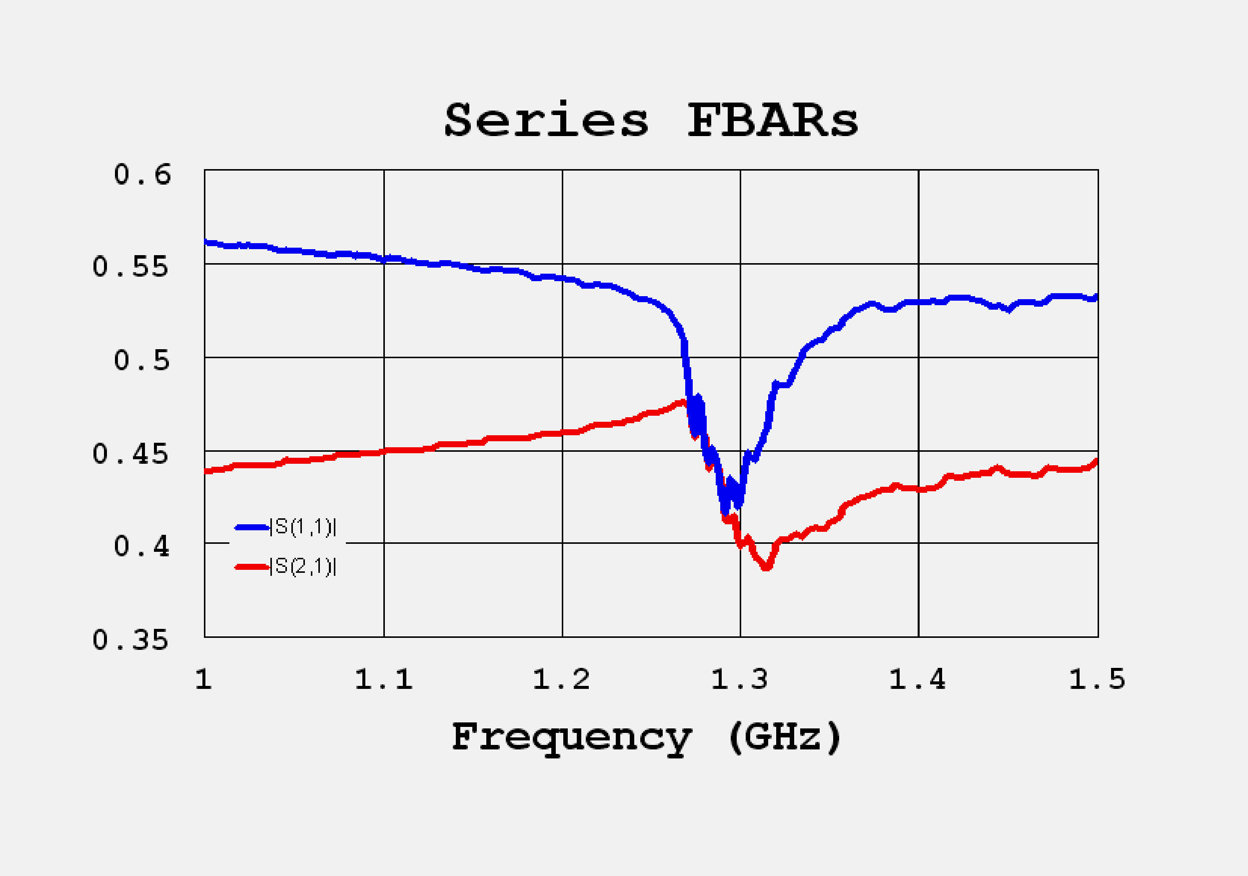
- **Conventional contact lithography, e-gun Ti/Au (10nm/200nm) evaporation (top).**
- **Lift-off techniques to define the FBAR structures on the top.**
- **Backside lapping of the wafer to a thickness of about 150µm.**
- **Al layer deposition (400nm) on the bottom (as mask during the RIE of silicon).**
- **Backside patterning for the membrane formation.**
- **Backside RIE of silicon down to the thin AlN layer using SF_6 plasma.**
- **Sputtering of 250 nm thin gold layer on the bottom of the wafer.**





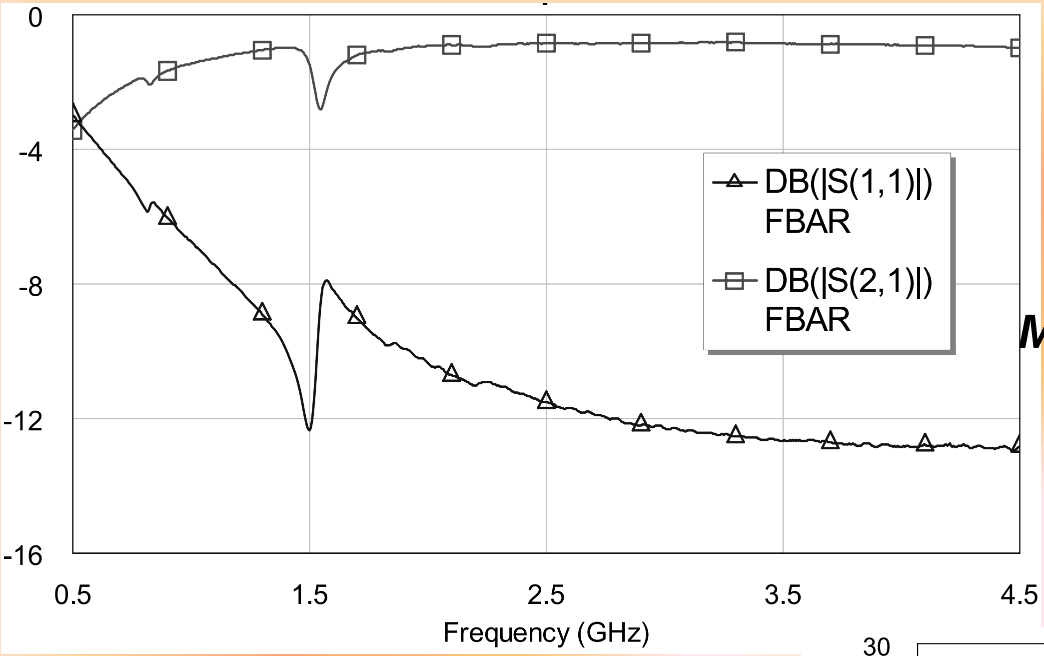
GaN membrane supported series connection of two FBAR structures (test structures)

GaN membrane FBAR
W=2.2μm

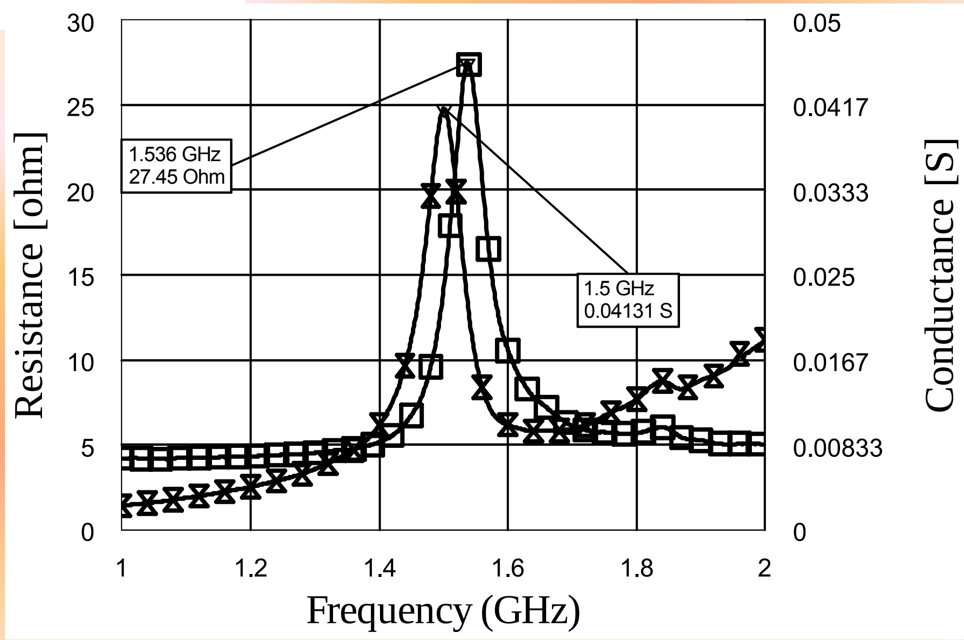


AlN membrane FBAR

(w=2μm)

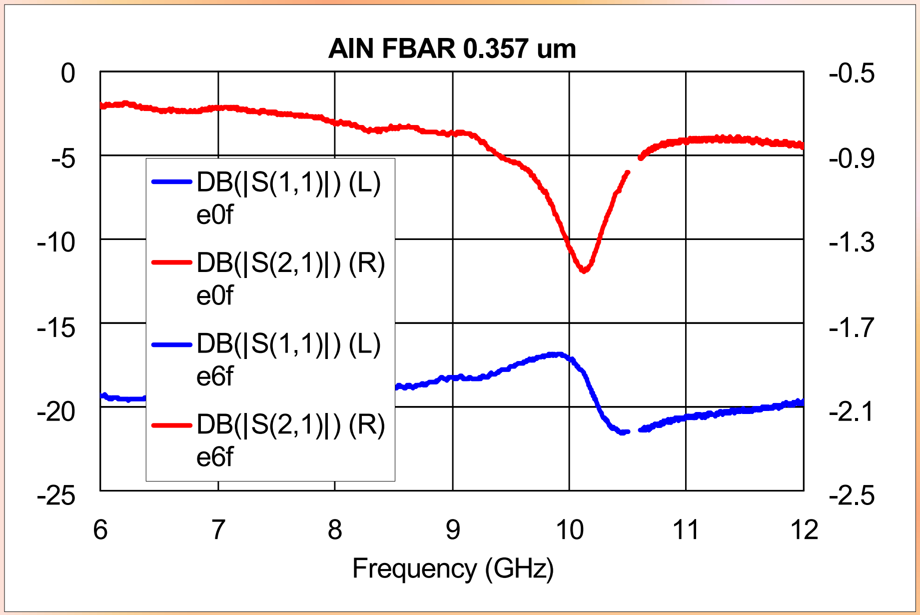


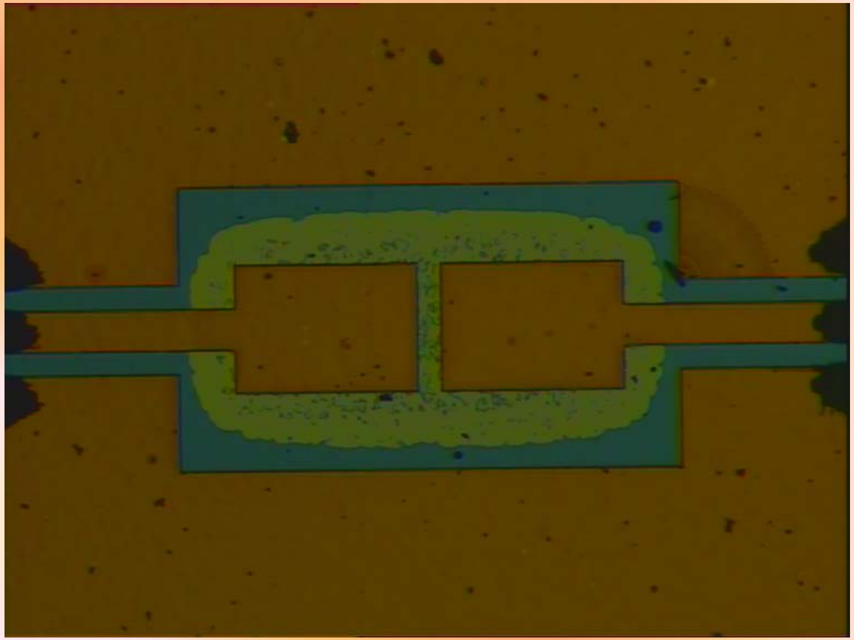
Magnitude of the measures S parameters of the AlN based FBAR 300 μm test structure



The resistance and the conductance of the two FBARs structures connected in series

FBAR series connection (AlN membrane W= 0.357 μm)



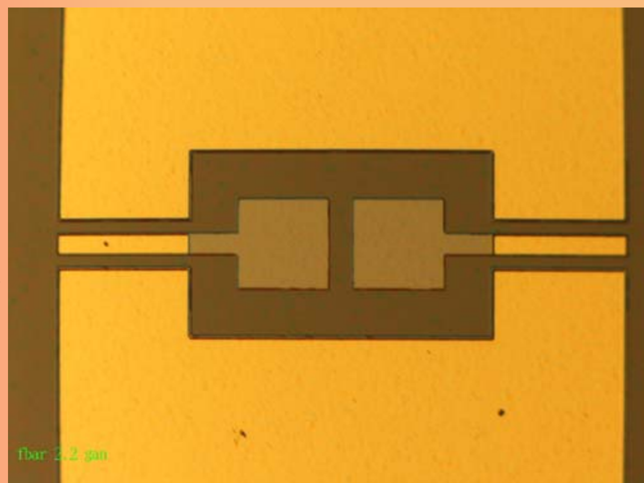


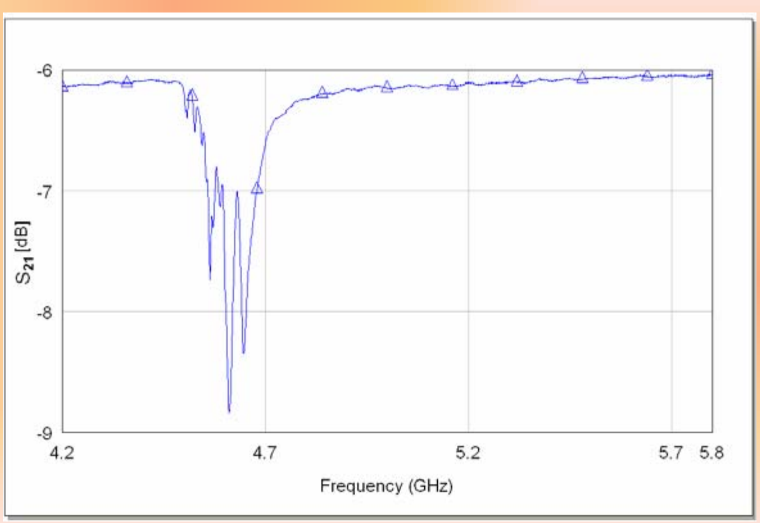
Work in progress:

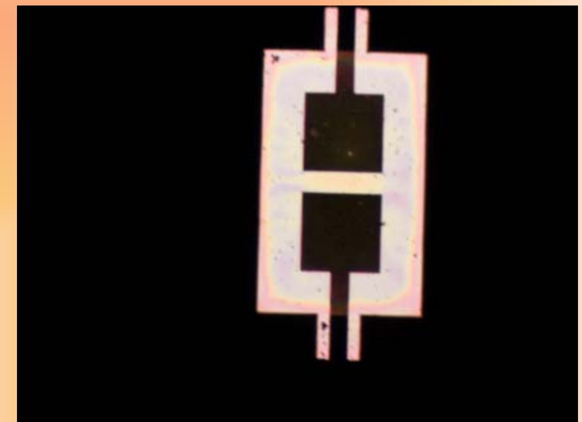
•700nm thin membrane supported FBAR structure based on GaN micromachining

•50nm thin Mo metallization

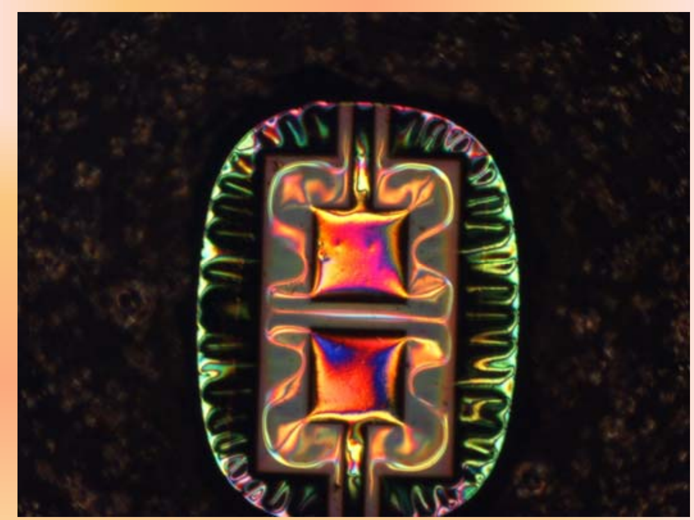
Before membrane manufacturing







Final structures

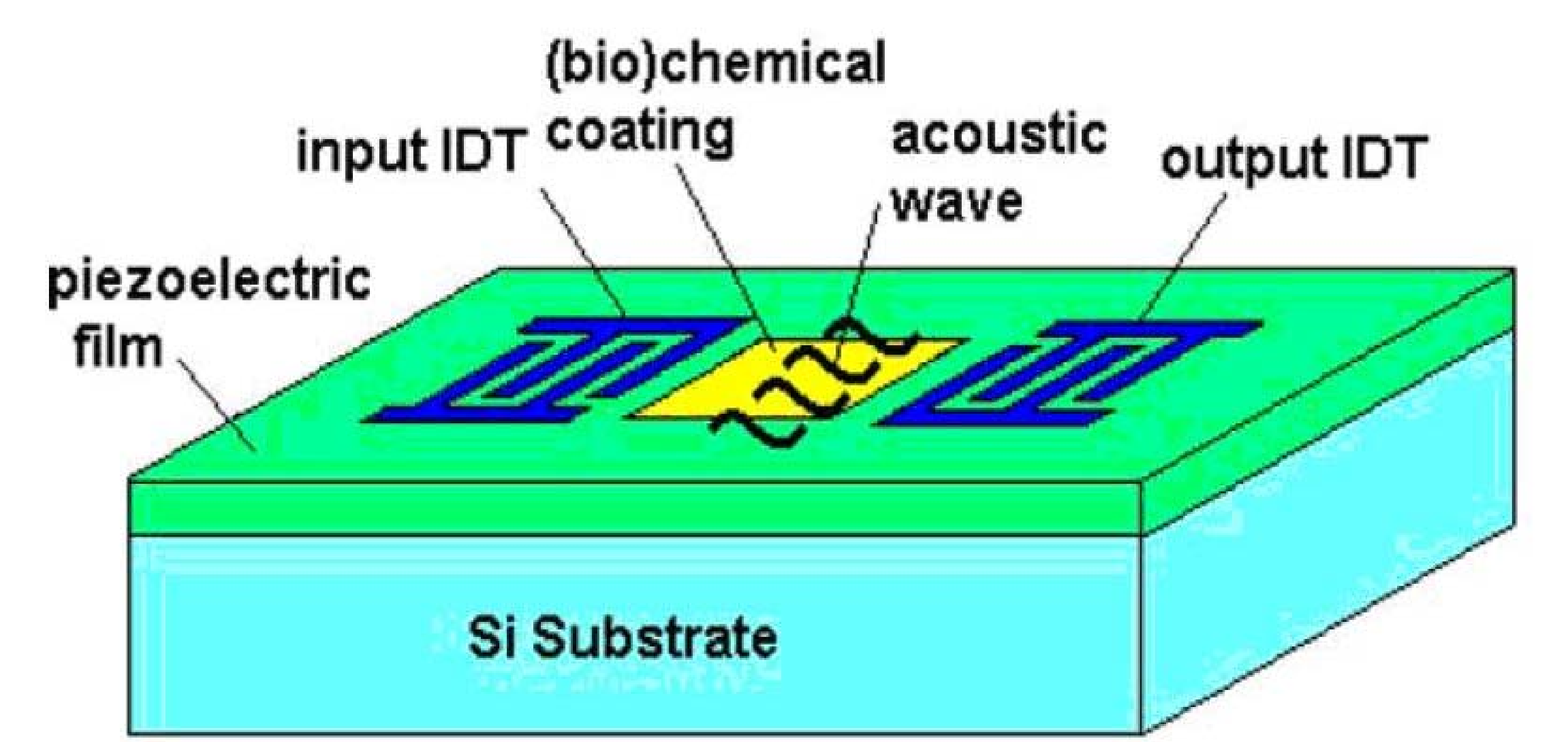


Best results obtained up to now

SAW device operating in the 5 GHz range, based on AlN/diamond, obtained with electronic lithography was reported [*P. Kirsch et all. Appl Phys. Lett.88, 223504, 2006*].

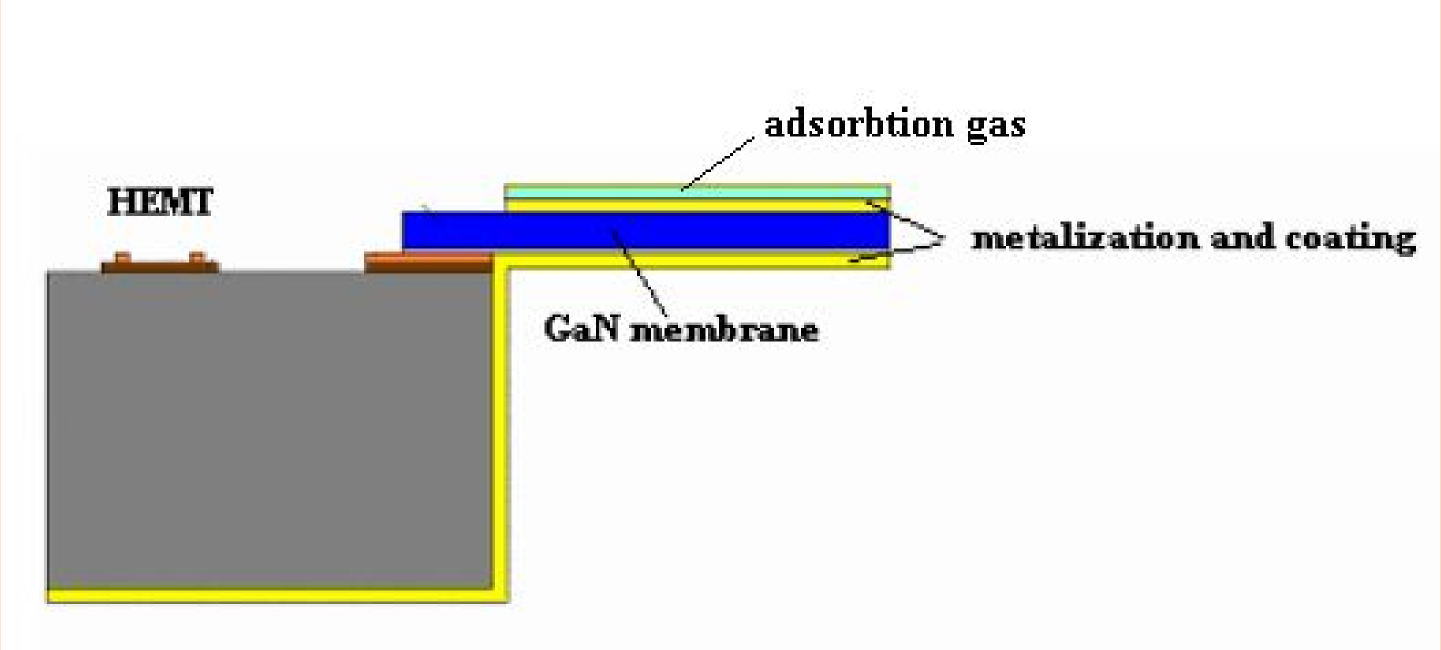
FBAR structure with operating frequency in the 5 GHz range, based on AlN, was reported *[K-W Tay et al, Japanese J. of Appl. Phys. No. 3, 2004, p. 1122].*

An emerging application of GaN FBARs - sensing of poison gases in harsh environmetal (1)

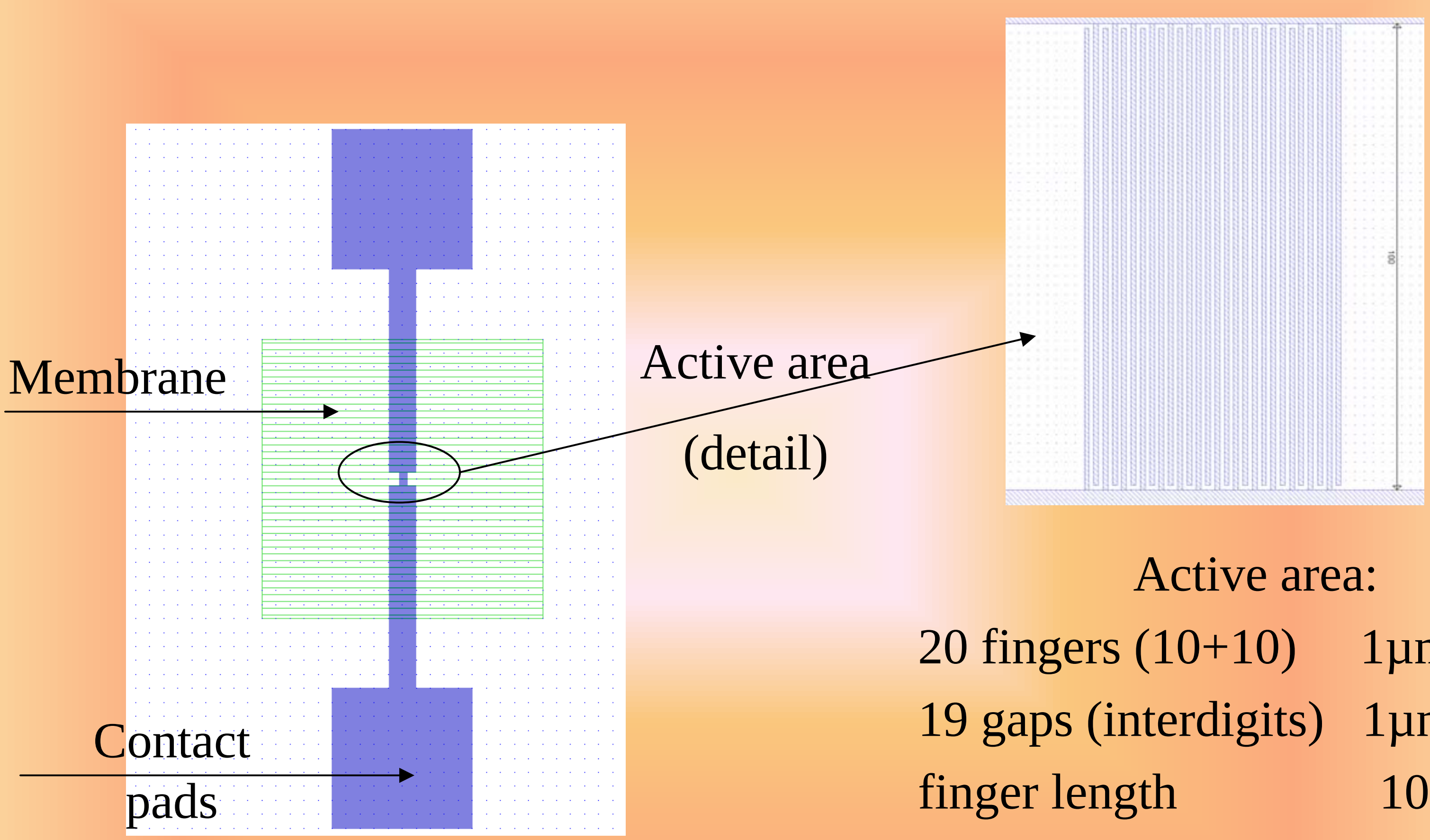


Sensitivity α f^2

An emerging application of GaN FBARs - sensing of poison gases in harsh environmetal (2) the device can be monolithic integrated with a HEMT on GaN



MSM GaN membrane structure for UV detection



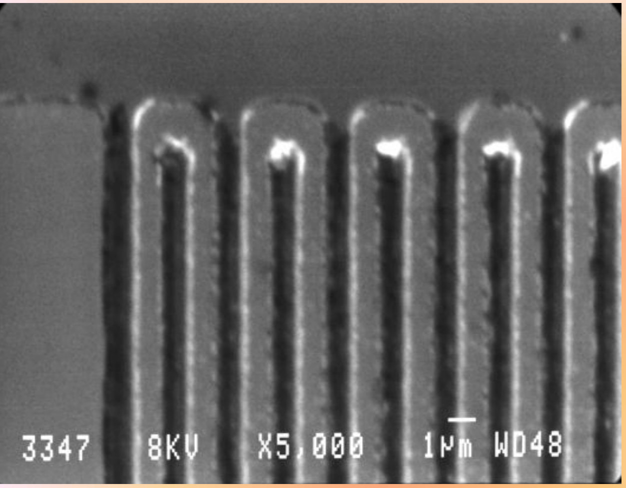
Active area:

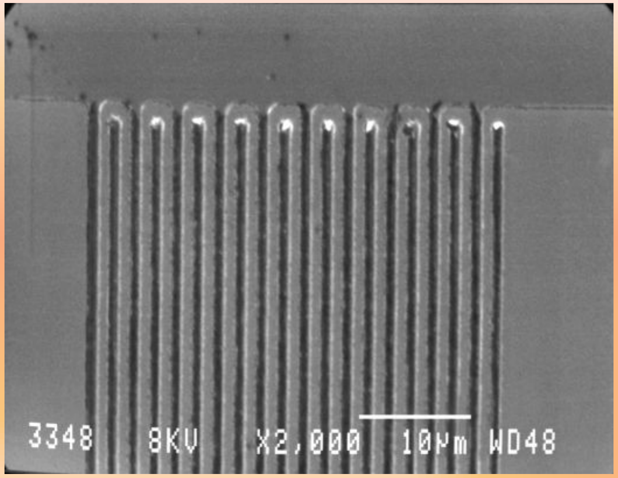
20 fingers (10+10) 1µm wide;

19 gaps (interdigits) 1µm wide;

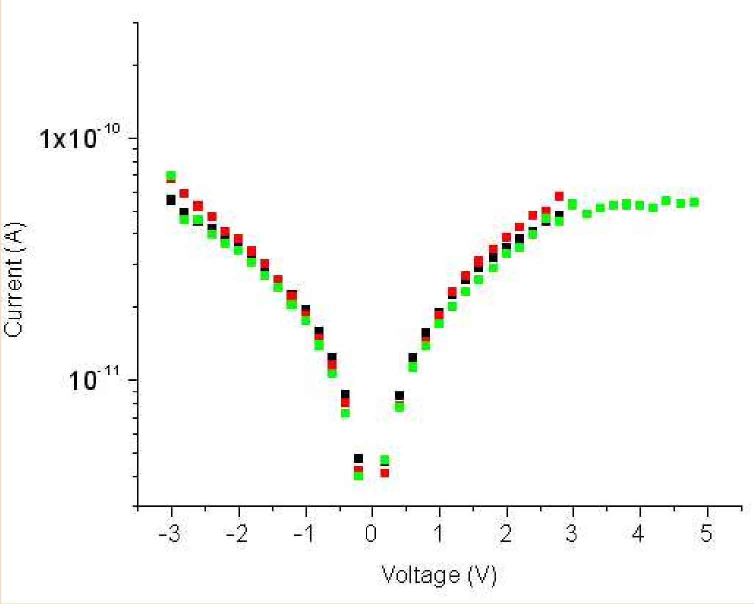
finger length 100 µm

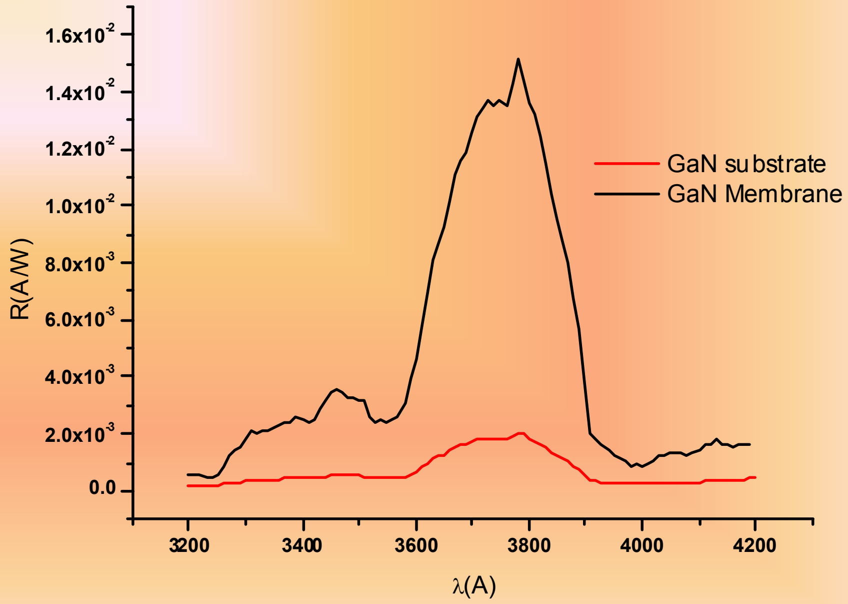
nontransparent metallization Ni/Au (20nm/100nm)

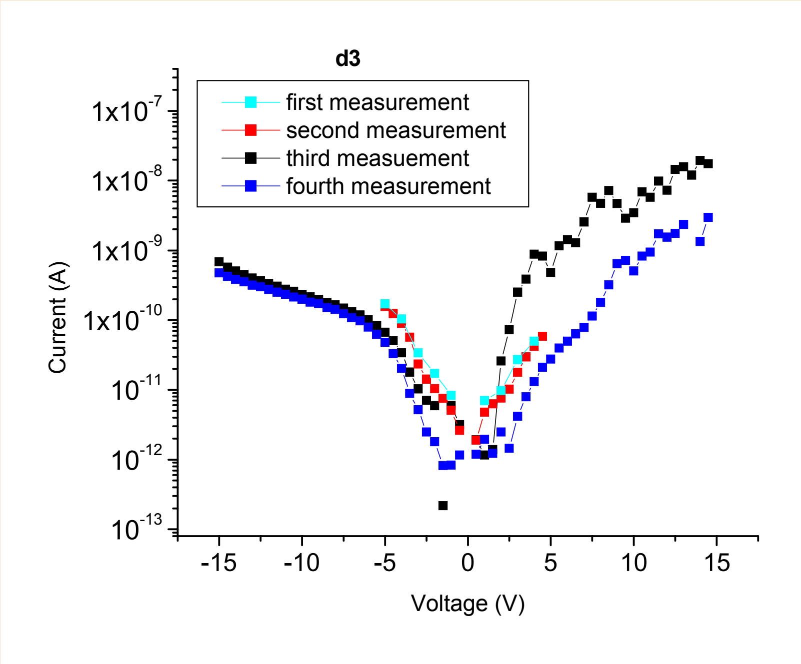


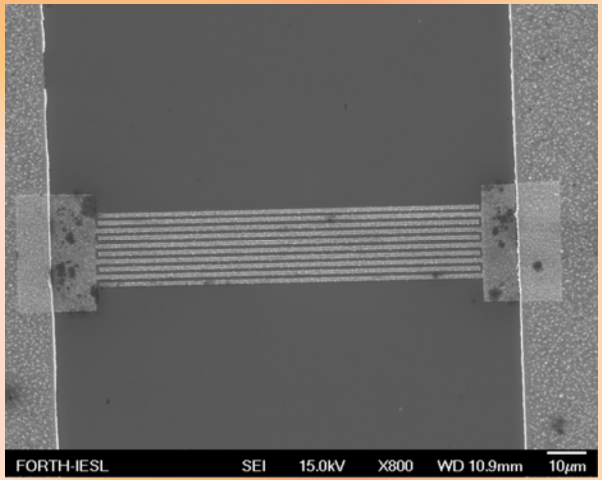


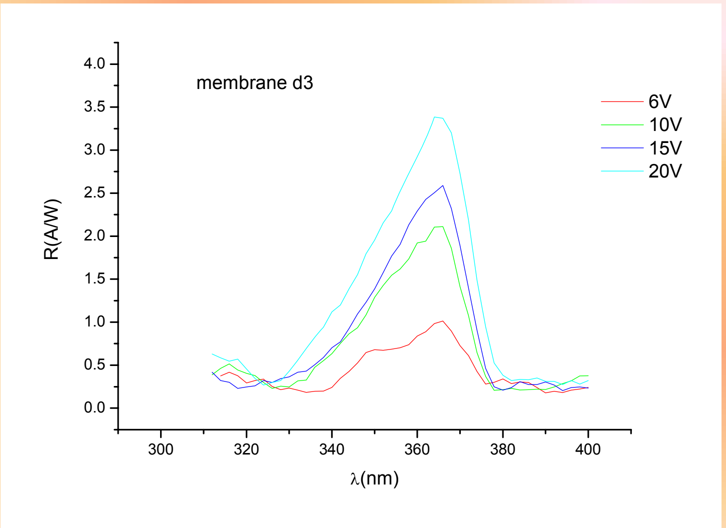
SEM photos of the 1 μm wide Ni/Au (20nm/100nm) lines The interdigit width was also about 1 μm

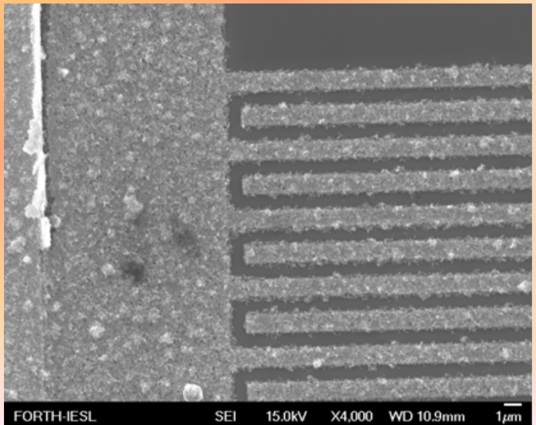




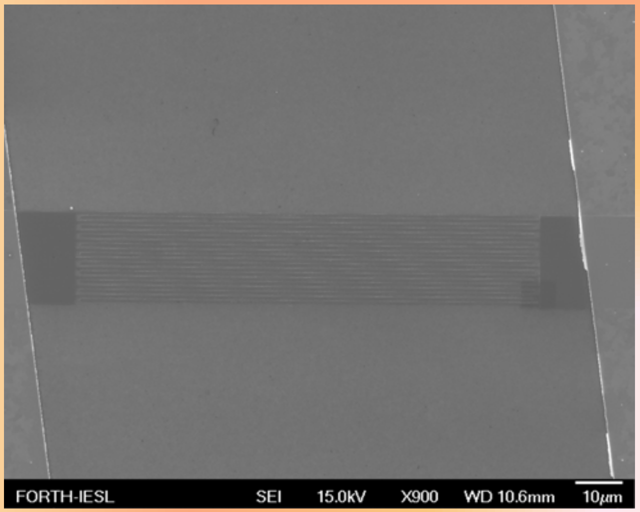

d3
first measurement
second measurement
third measurement
fourth measurement
Current (A)
Voltage (V)

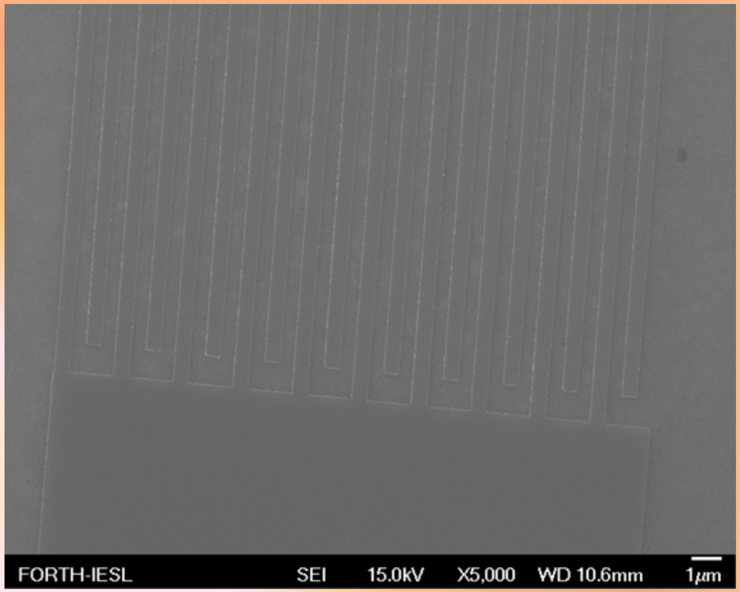

FORTH-IESL SEI 15.0kV X800 WD 10.9mm 10µm

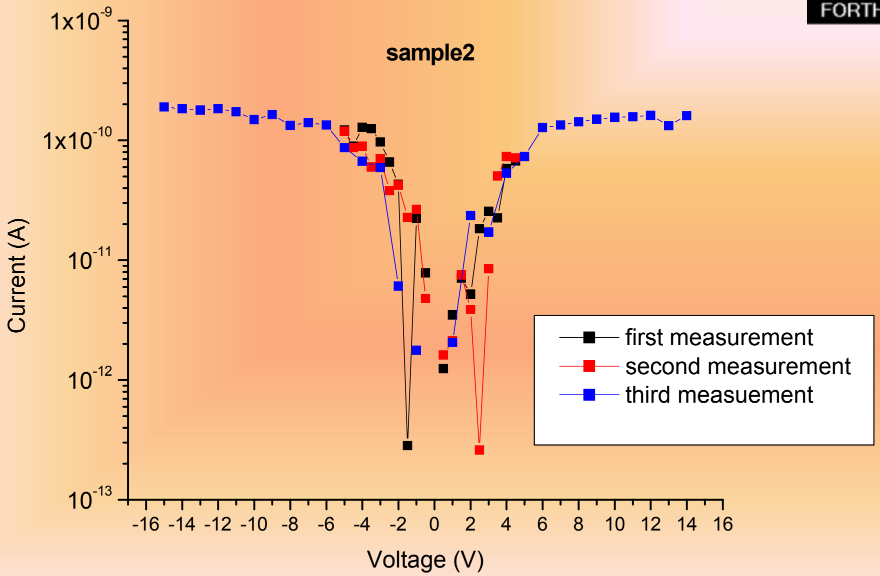

membrane d3
6V
10V
15V
20V
R(A/W)
λ(nm)


FORTH-IESL SEI 15.0kV X4,000 WD 10.9mm 1µm

0.45µm fingers and pitches GaN membrane MSM UV photodetector- work in progress







Conclusions

Micromachining and nanolithography can substantially improve:

- the frequency performances of acoustic devices on WBG semiconductors

-WBG SAW and FBAR based sensors performances

-performances of UV photodetectors

-