Nanoprocessing and micromachining technologies of GaN/Si for sensors and filters operating at frequencies above 5 GHz

A. Müller, S. Iordanescu, A. Dinescu, A. Stefanescu, I. Giangu,
G. Konstantinidis, A. Stavrinidis, G. Stavrinidis, T. Kostopulous

IMT Bucharest, Bucharest, Romania
FORTH-IESL-MRG, Heraklion Crete, Greece

Outline

Introduction

Temperature GaN based GHz operating SAW sensors

- **Sensitivity vs. resonance frequency analysis**

Pressure GaN based GHz operating SAW sensors

- **Sensitivity vs. resonance frequency analysis**

GaN based GHz operating SAW filters

Conclusions

Introduction

WBG semiconductors for acoustic devices

- Most acoustic devices (SAWs and FBARs) used in communication applications and sensors (including T and P sensors) are based on classical non-semiconductor piezoelectric materials (quartz, $LiNbO_3$, langasite, etc). The operation frequency of these devices is limited to values below 2.5 GHz.
- Progress in deposition/growing of high quality piezoelectric WBG semiconductors like AlN and GaN on sapphire, diamond, SiC and Si substrates has initiated an intensive research in the development of acoustic devices on WBG semiconductors.
- Developments in micromachining and nanolithographic techniques on these semiconductor materials make possible the increase of the operating frequency of FBAR and SAW devices up to 10 GHz; the area application of SAW based filters at frequencies higher than 5 GHz is very large.
- The development of acoustic devices on WBG semiconductors was mainly focused on communication applications.

Introduction

WBG semiconductors for acoustic devices

- The high resonance frequency which can be obtained using GaN SAW resonators is an advantage for sensors, because of the higher sensitivity that can be achieved (hundreds of KHz/ºC). This simplifies signal processing electronics.

- Microwave integrated circuits based on GaN are able to work at high temperatures because of the wide bandgap of this semiconductor material.

- In contrast with silicon based circuits, where a pn junction, placed close to the hot areas of the IC, can be easily used for precise temperature determinations, different techniques must be used for T measurements in GaN based MMICs.

- Monolithic integration of a GaN SAW based T/P sensors in the GaN MMICs can be a reliable solution; also hybrid integration can be used.

Temperature GaN based GHz operating SAW sensors

A SAW based T sensor is fully compatible with wireless data reading (often necessary because of the high temperatures and harsh environmental conditions); battery-less operation is possible.

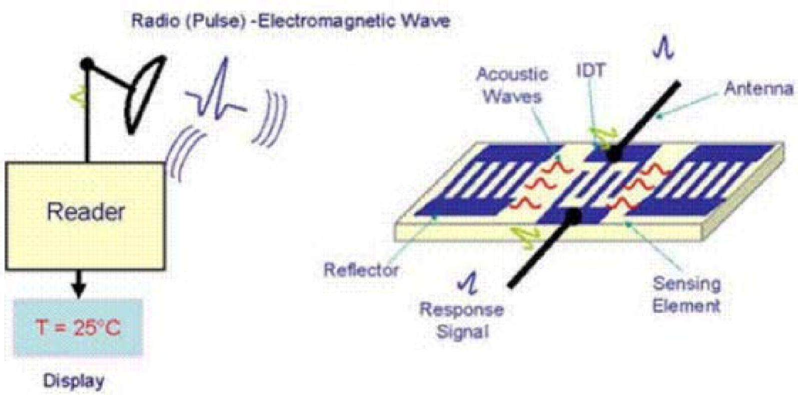
***s = df/dT**;* a higher resonance frequency means an increased sensitivity;

S = 1/fx (df/dT) = TCF is - in a first approximation - frequency independent.

$$S = TCF = \frac{1}{f}\frac{df}{dT} = \frac{1}{v}\frac{dv}{dT} - \frac{1}{L}\frac{dL}{dT}$$

v – the sound velocity
L – lengths of the propagation region

A wireless SAW based sensor system consists of a reader unit emitting radio waves and a SAW transponder as sensor element



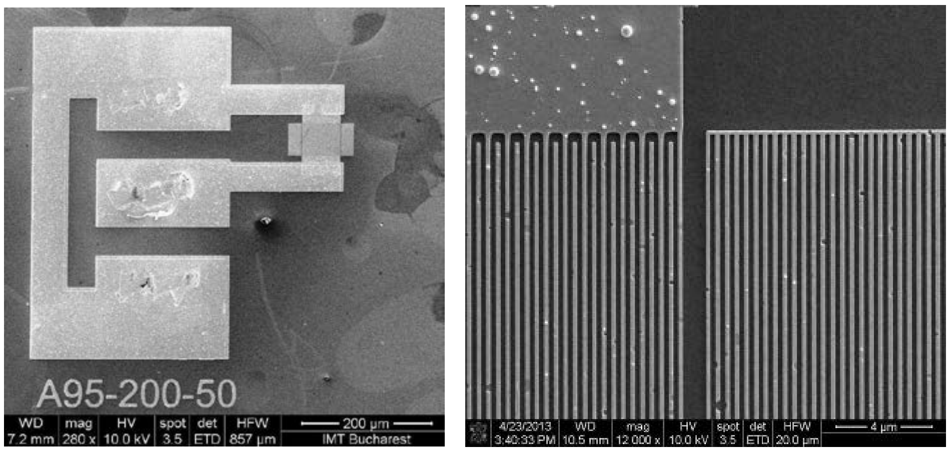
[D. S. Stevens, et al, Fourth International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, Chiba University, Japan, 2010]

There is a reported value of **S = 43 ppm/ºC** on GaN [1]

[1] F. Calle, et. al., Phys. Stat. Sol. (c) 2 (3) 976–983 (2005)

Temperature GaN based GHz operating SAW sensors

Four different SAW test structures were fabricated



(a) *(b)*

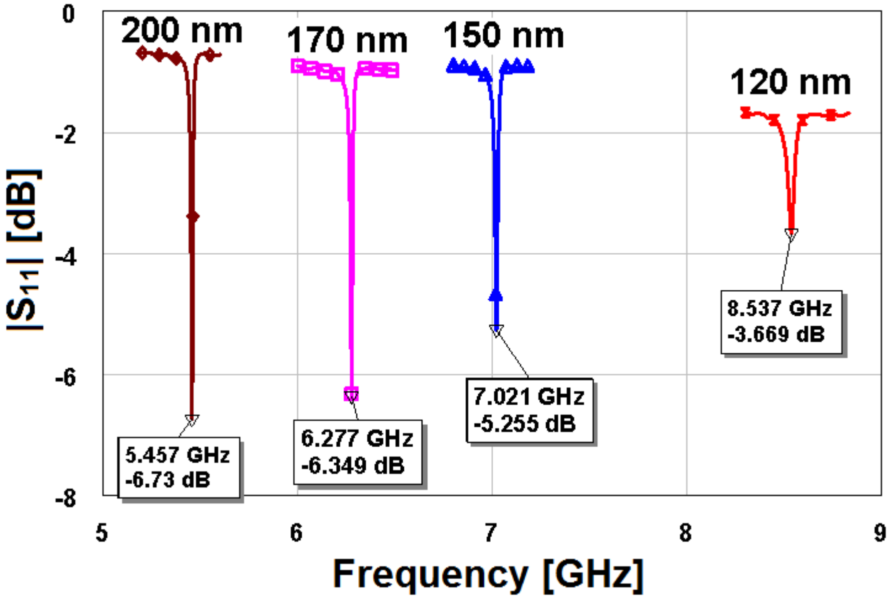
(a) SEM photos of the single-port SAW structure with coplanar waveguide pads
(b) detail of the nano-lithographic process

IDT structure details:

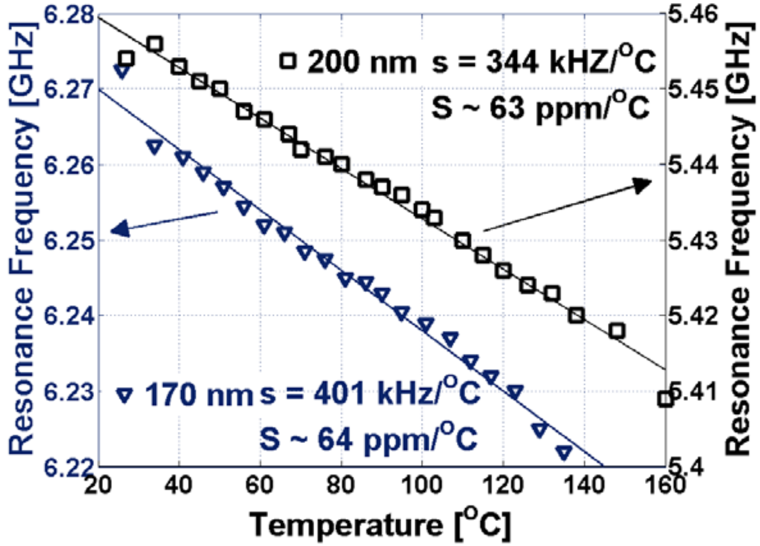
- 150 fingers, 50 reflectors placed at 0.95 µm distance from the IDTs;
- metal thickness (Ti/Au) 100nm;
- **finger width 200, 170, 150, 120 nm;**
- finger length 100 µm.

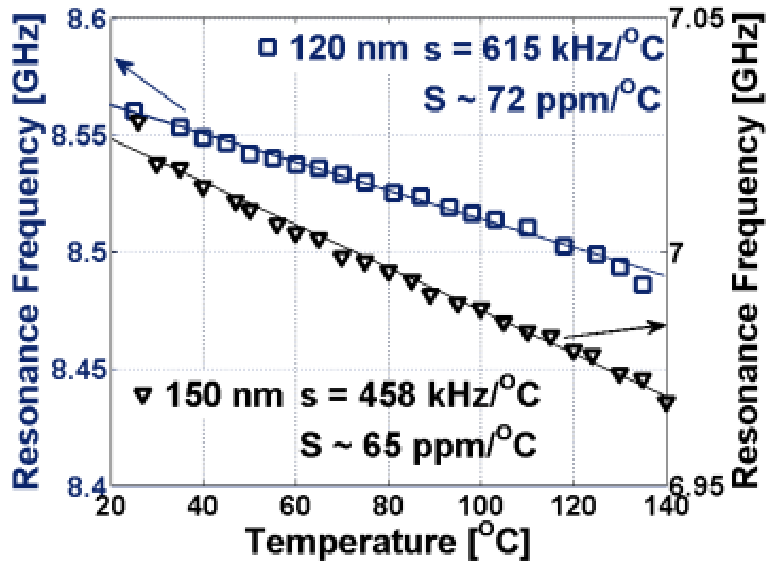
A. Müller, G. Konstantinidis, I. Giangu, V. Buiculescu, A. Dinescu, A. Stefanescu, A. Stavrinidis, G. Stavrinidis, A Ziaei, International Microwave Symposium - IMS 2014, Tampa, USA, session "TH2F: Sensors and Sensor Systems" pp. 1-4

Sensitivity vs. resonance frequency analysis



Room temperature characterization

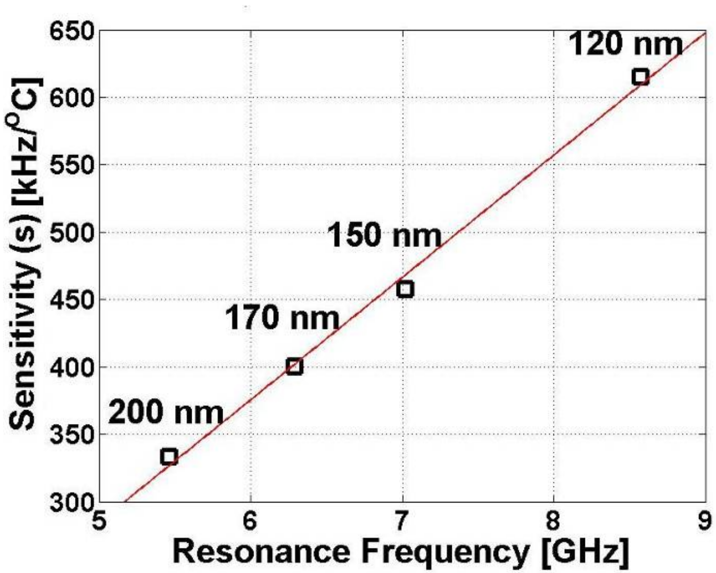


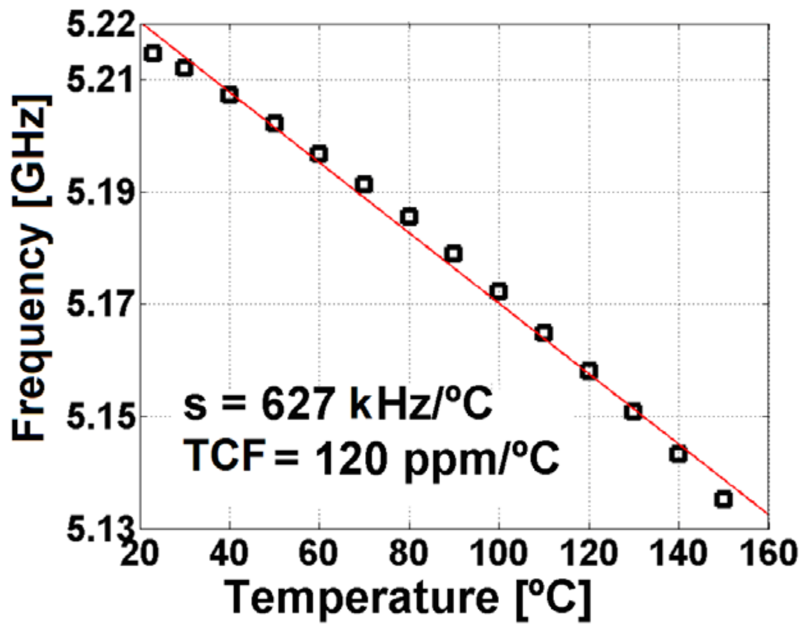


Resonance frequency vs. temperature for all four SAW structures

Hot plate characterization

Sensitivity vs. resonance frequency analysis





s has a linear variation with the resonance frequency

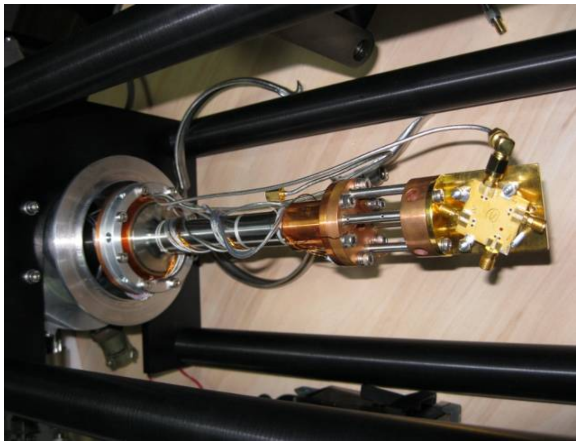
s = df/dT

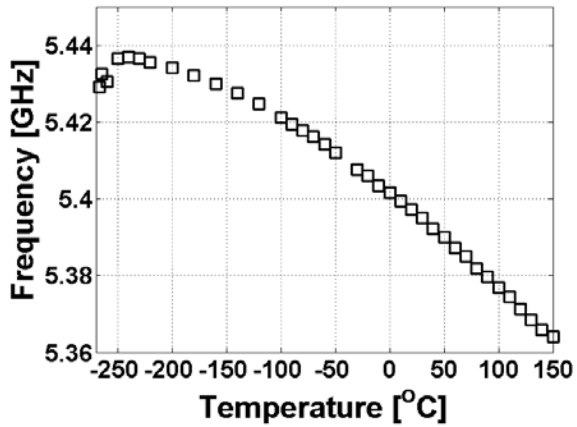
Resonance frequency vs. temperature for a membrane supported IDT structure (150 fingers, 50µm length, 200nm width) on GaN/Si membrane

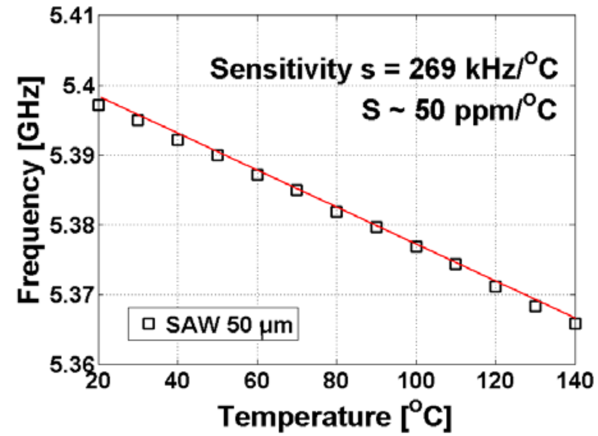
Significantly higher sensitivity and TCF are obtained for membrane supported SAW resonators

Cryostat characterization

SAW T sensors in the test fixture characterized in the -268 to +150 ºC temperature range using a cryostat (SHI-4H-1 from Janis Research company, LCC)







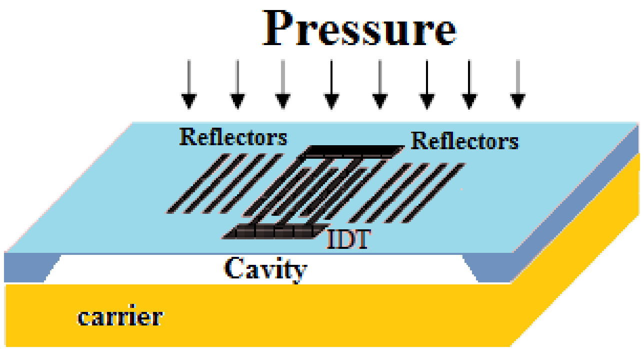
Resonance frequency vs T for SAW structure having 200 nm finger/interdigit spacing width; linear variation of the resonance frequency vs. T in the range 20-150ºC

At low temperatures (20-70 K) SAW devices have very stable resonance frequency with T variations, which is interesting for communication applications.

A. Müller, G. Konstantinidis, V. Buiculescu, A. Dinescu, A. Stavrinidis, A. Stefanescu, G. Stavrinidis, I. Giangu, A. Cismaru, A. Moldoveanu, ***Sensors and Actuators A*** *209, pp. 115 -123,* ***Mar. 2014***

Pressure GaN based GHz operating SAW sensors

The resonance frequency shift vs. pressure for a single SAW resonator is used in measurements



Schematic of the pressure sensor mounted on the carrier (cross-section)

Pressure changes:

v – the phase velocity

L – the dimensions

Classical piezoelectric materials such as Quartz, ZnO, LGS and $LiNbO_3$ have been widely used for manufacturing SAW pressure sensors.

G.A. Borrero et al., *Sensors and Actuators A*, 2013, pp. 204–214 ($LiNbO_3$ 65 MHz)
S.C. Moulzolf, et al. *IEEE International Ultrasonics Symp.*, 2012, pp. 1224 – 1227 (LGS 340 MHz)

Pressure GaN based GHz operating SAW sensors

Single resonator GaN SAW based pressure sensor structure

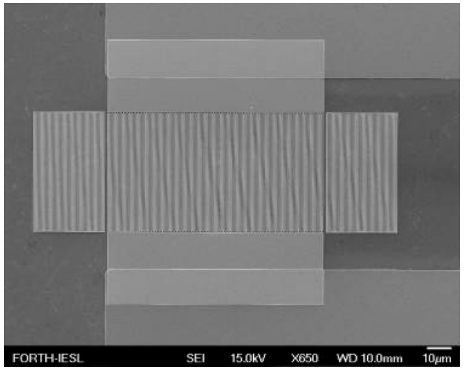
IDT details:

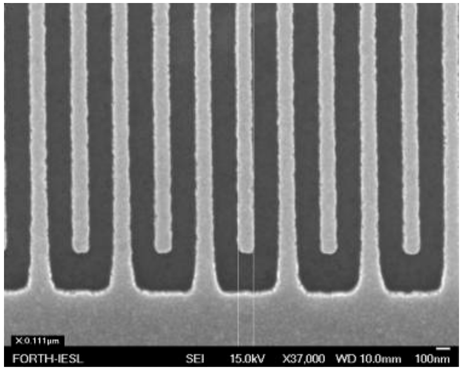
- 150 fingers and 50 reflectors with a length of 50 µm
- finger and finger/interdigit spacing width = 200 nm

IDTs are centered on the 500 µm x 500 µm square membrane consisting of:

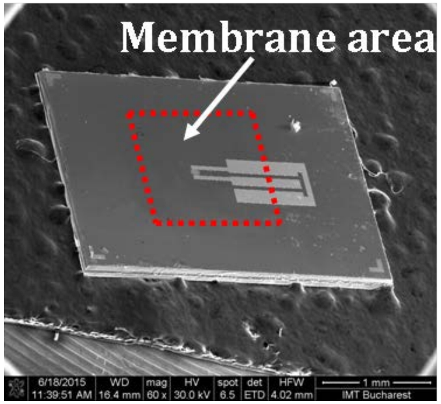
α – type structures: GaN/Si (1.2 µm / 10 µm) membrane;

β – type structures: 1.2 µm thin GaN membrane





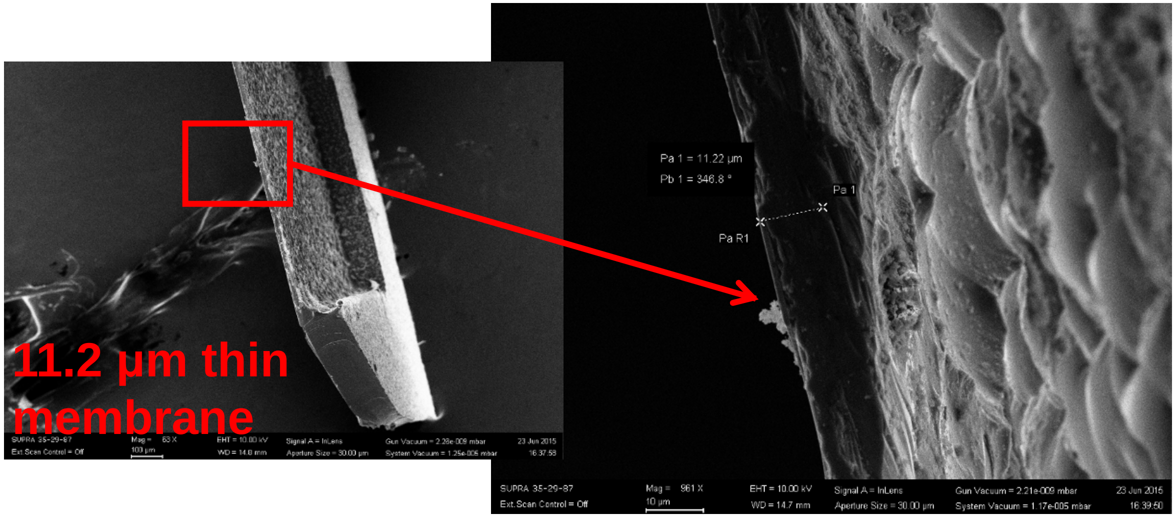
IDT structure detail



Top SEM photo of the structure

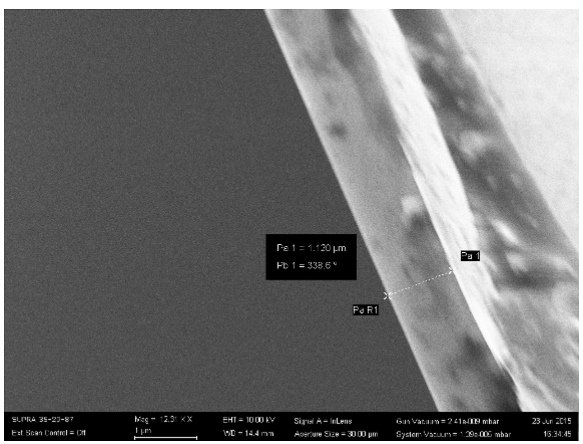
Pressure GaN based GHz operating SAW sensors

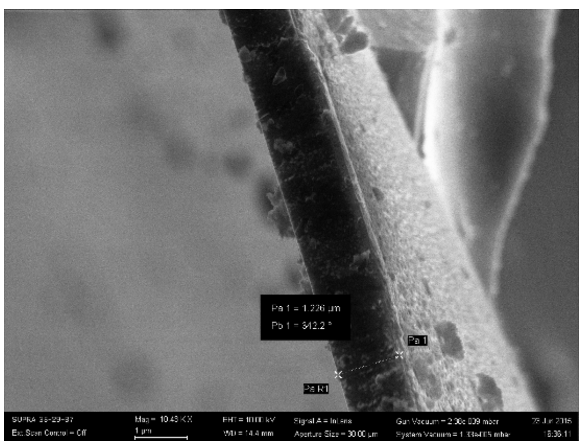
Experimental development



α – type structures:

GaN/Si (1.2 µm/10 µm) membrane



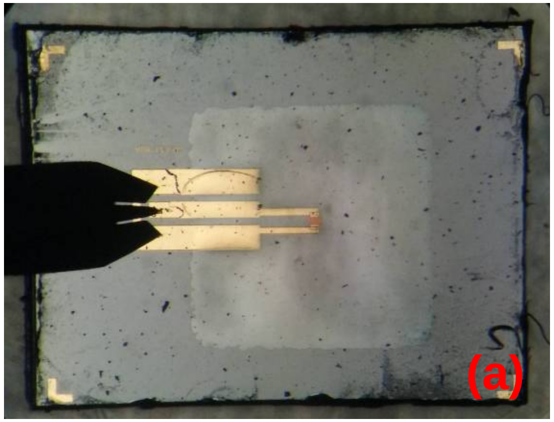


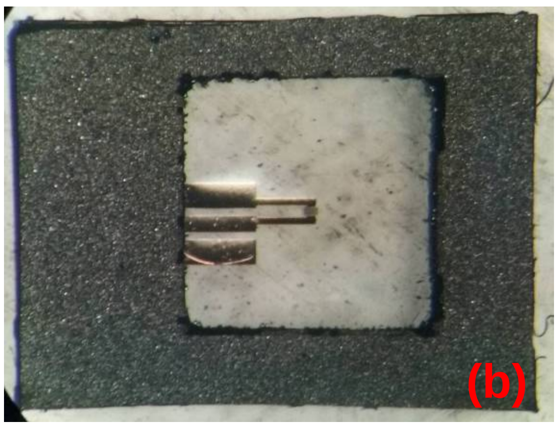
β – type structures:

1.2 µm thin GaN membrane

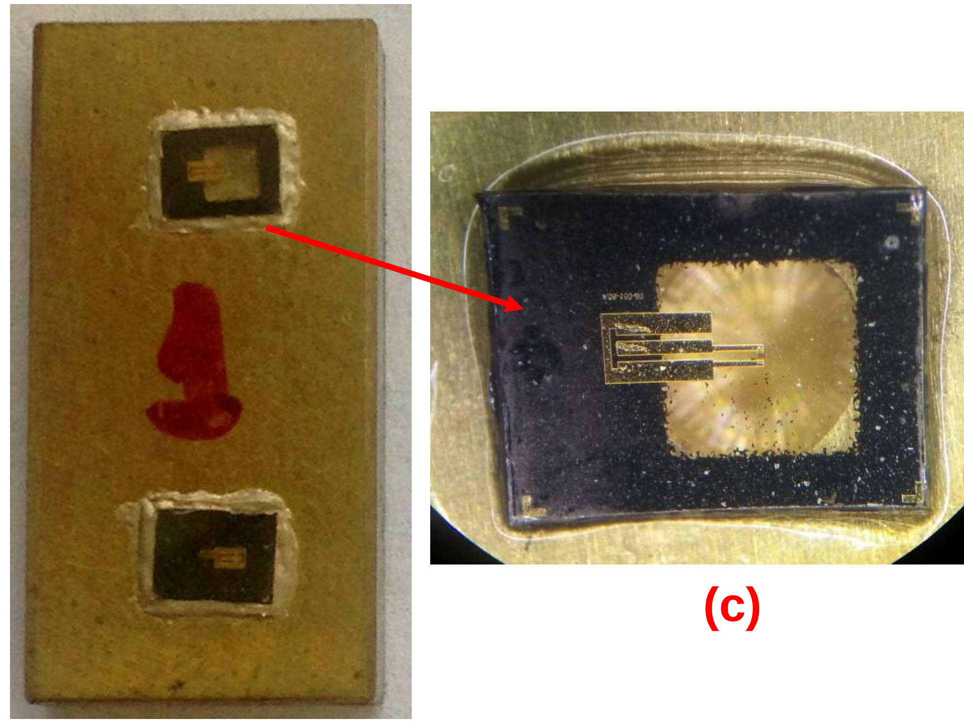
Pressure GaN based GHz operating SAW sensors

Experimental development





Top (a) and bottom (b) photo of the β – type pressure sensing chips



(c)

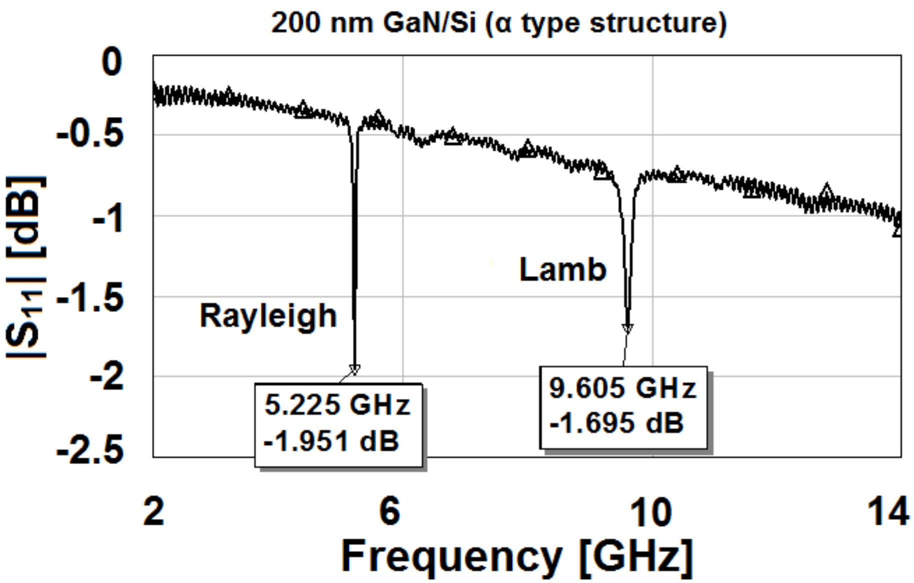
Structures mounted on a carrier to be placed in the pressure chamber (c)

(1.2 µm thin transparent GaN membrane supported pressure sensing structures)

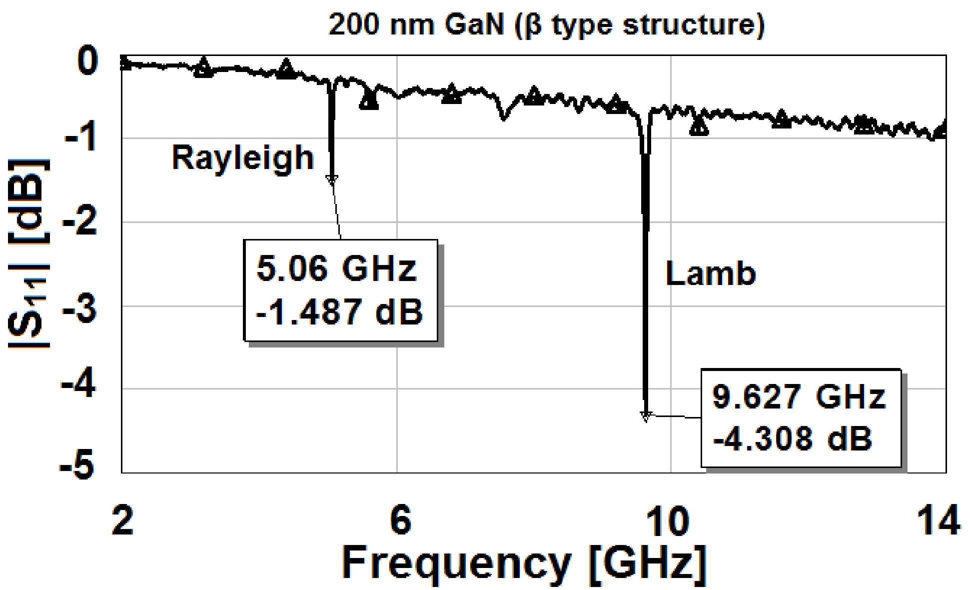
Pressure GaN based GHz operating SAW sensors

Atmospheric pressure, room temperature resonance frequency

α – type structures: GaN/Si (1.2 μm/10 μm) thin membrane



β – type structures: 1.2 μm GaN thin membrane



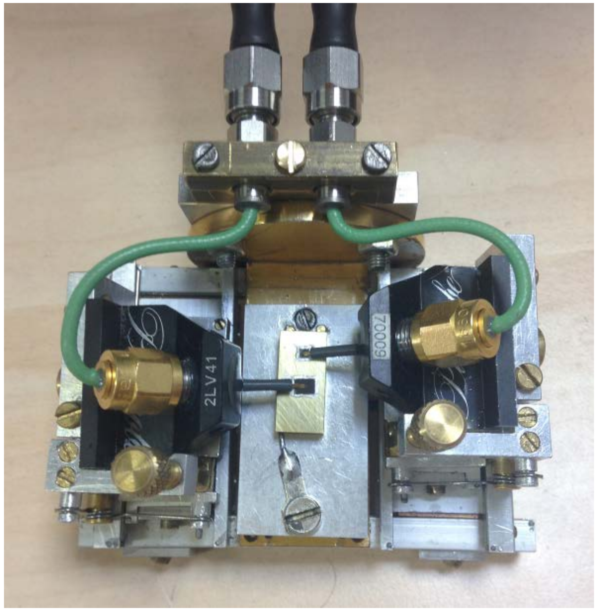
A. Müller, A. Stavrinidis, I. Giangu, A. Stefanescu, G. Stavrinidis, A. Pantazis, A. Dinescu, G. Boldeiu, G. Konstantinidis, IEEE MTT-S Int. Microwave Symp. (IMS), WE1A, San Francisco, USA, 2016

Pressure GaN based GHz operating SAW sensors

Pressure measurement set-up

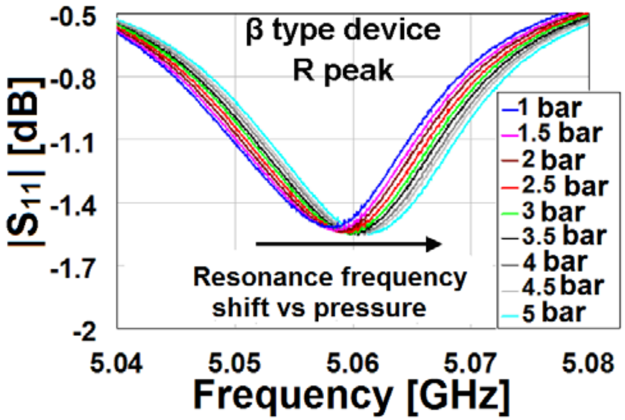
- Devices from the chamber connected to VNA through coaxial connectors
- Pressure can be changed through two valves:
  - one for increasing the pressure
  - one for letting the N_2 out of the tank

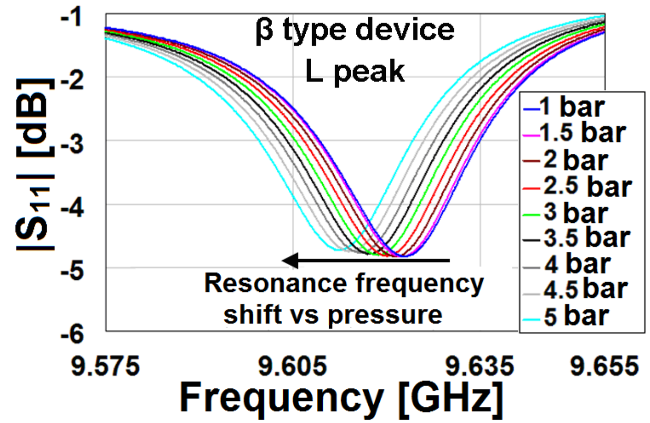
In-house on-wafer S parameter measuring set-up



In-house temperature controlled pressure chamber

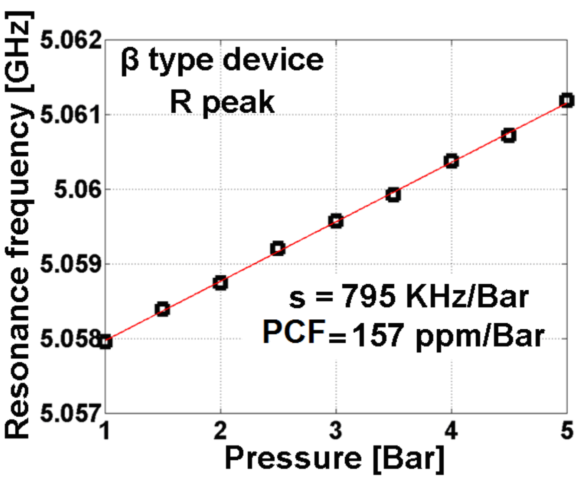
Sensitivity vs. resonance frequency analysis





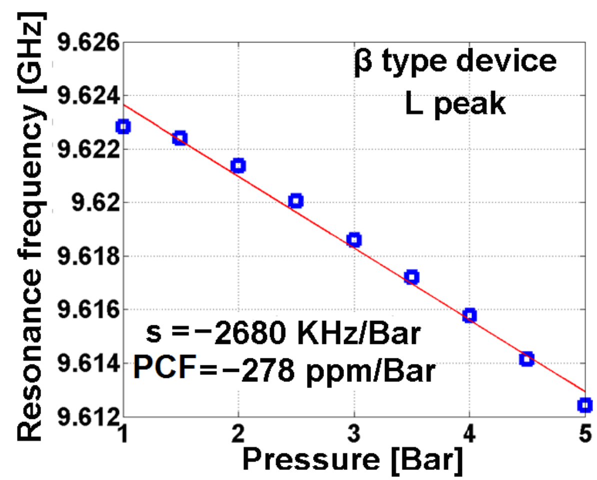
β-type structures:

GaN (1.2 μm) membrane



$$s = \frac{df}{dp}$$

$$PCF = \frac{1}{p}\frac{df}{dp}$$



A. Müller, A. Stavrinidis, I. Giangu, A. Stefanescu, G. Stavrinidis, A. Pantazis, A. Dinescu, G. Boldeiu, G. Konstantinidis, IEEE MTT-S Int. Microwave Symp. (IMS), WE1A, San Francisco, USA, 2016

Sensitivity vs. resonance frequency analysis

Type/peak	Membrane	s_p (kHz/Bar)	PCF (ppm/Bar)	f_0 (GHz)
α/ Rayleigh	GaN/Si 1.2/10 µm	-346	-66	5.22
α/ Lamb	GaN/Si 1.2/10 µm	1101	115	9.6
β/ Rayleigh	GaN 1.2 µm	795	157	5.06
β/ Lamb	GaN 1.2 µm	-2680	-278	9.62

α - type structures GaN/Si (1.2 µm/10 µm) membrane:

- for the Rayleigh mode the resonance frequency decreases with increasing pressure (the slope, s_p, and PCF are negative) similar with most pressure sensor structures
- for the Lamb mode the frequency increases when pressure increases (the slope, s_p, and PCF are positive)

β - type structures GaN (1.2 µm) membrane: the behaviour is reversed

This behavior can be explained considering the different proportions in which the two terms in the expression of the frequency shift, $(\Delta f/f) = (\Delta v/v) - (\Delta L/L)$, contribute for each mode. The stress induced frequency shift by the pressure on different modes is determined by different elastic constants.

•The Lamb mode is more pressure sensitive than the Rayleigh one

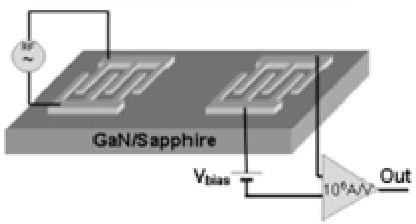
GaN based GHz operating SAW filters

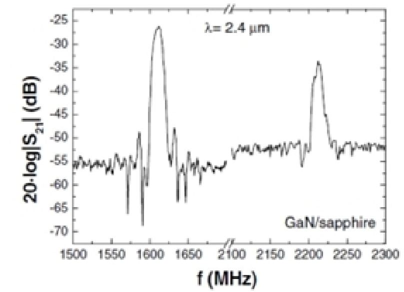
State of the Art

Face-to-face resonators on GaN/Sapphire; λ_{ac} = 2.4 µm

- ❑ Two resonance frequencies: 1.62 GHz as Rayleigh mode and 2.225 GHz for the Sezawa propagation mode
- ❑ **Transmission losses are -27 dB and out-of-band rejection is 30 dB at 1.62 GHz**
- ❑ **The losses are -35 dB and the out-of-band rejection is 20 dB at 2.225 GHz**
- ❑ Bandwidth 30 MHz

*T. Palacios et al, **IEEE Ultrasonics Symposium**, vol.1, pp. 57 – 60, **2002***



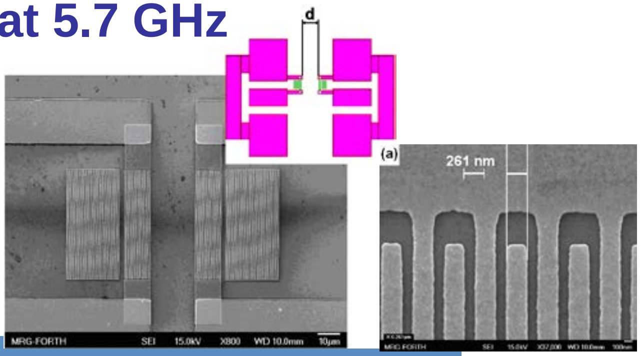


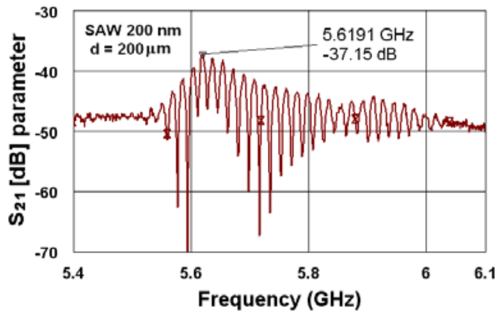
Face-to-face SAW structures on GaN/Si; λ_{ac} = 0.8 µm

First GaN/Si based SAW structures: two SAW IDTs (100 fingers) placed face-to-face at 100 µm; fingers/interdigits 200 nm wide and 200 µm length

- ❑ **Transmission losses -33 dB at 5.7 GHz**
- ❑ **Out-of-band rejection 10 dB**

*A. Müller, et al, **IEEE Electron Devices Lett**. Vol. 31, pp 1398-1400, **Dec 2010***

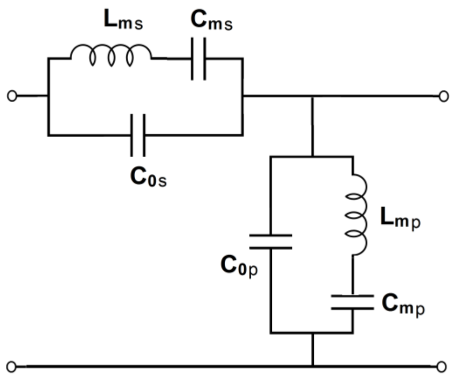


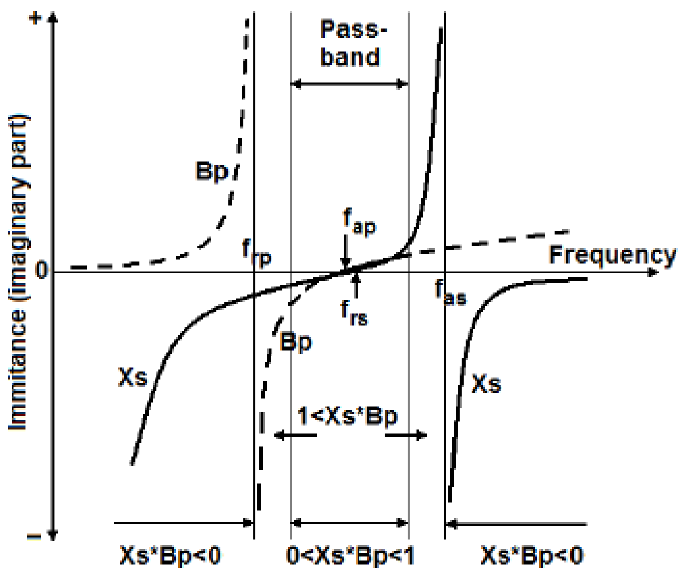


GaN based GHz operating SAW filters

Band-pass and band-stop filters based on single-port resonators

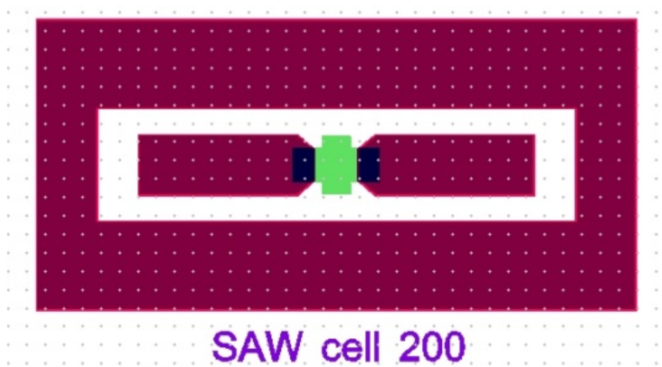
Regular ladder type SAW filter which has SAW resonators both in the series arms (S) and the parallel (P) arms





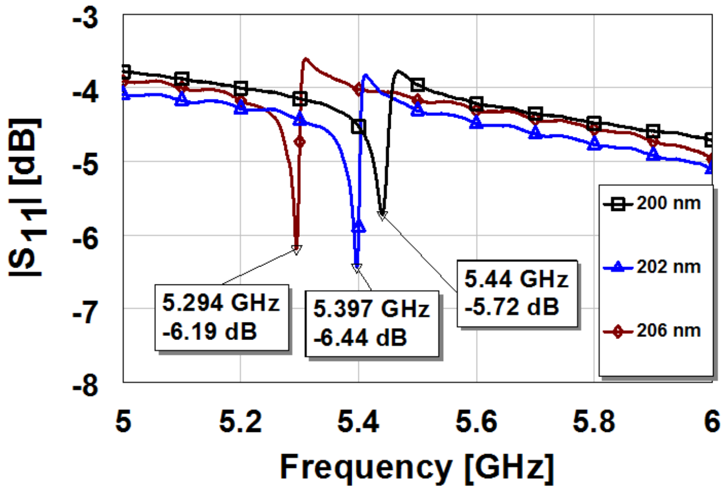
Single-port GaN SAW resonators are used as unit cells for the series and parallel elements

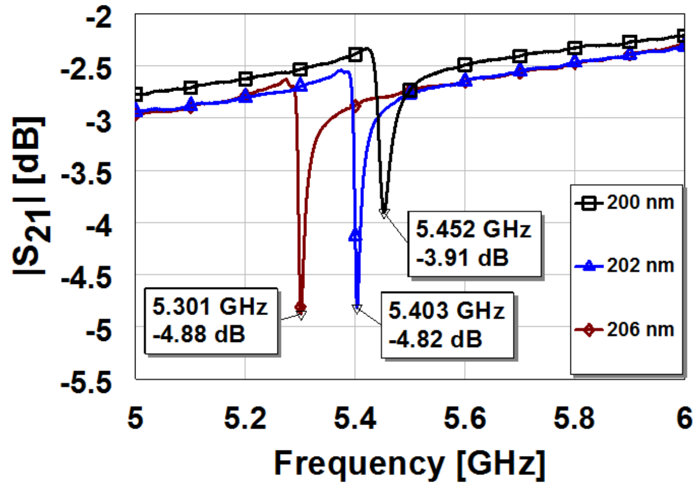
Simple SAW cell configuration (one-port SAW) with 50…400 fingers and interdigit spacing; 50 reflectors on each side of the IDT; finger widths 200, 202, 204, 206 nm, 100 nm and 90 nm metalization thickness and 30…50 µm length



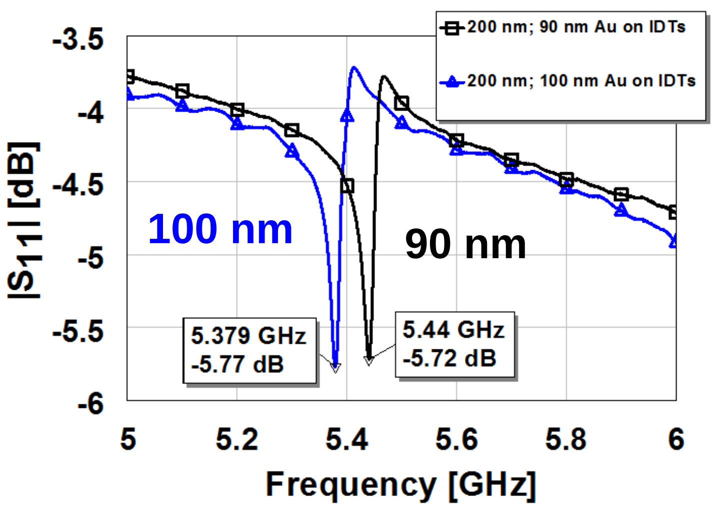
SAW single-type structures

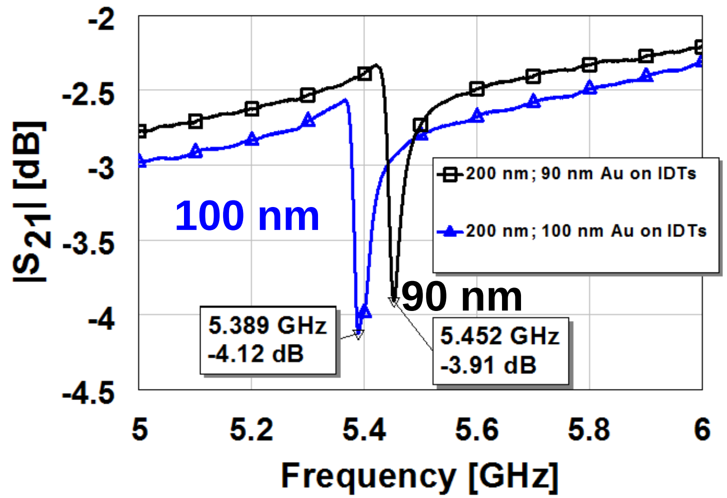
Comparison between SAW structures having IDTs with: 200, 202, 206 nm finger/interdigit width and 200 nm finger/interdigit width with 90, 100 nm metal thickness





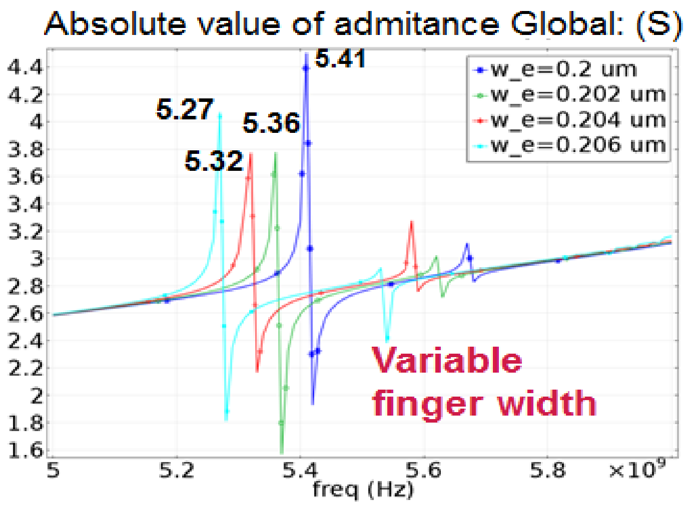
Frequency shift: ~ 46 MHz / 2 nm change of finger / interdigit spacing width

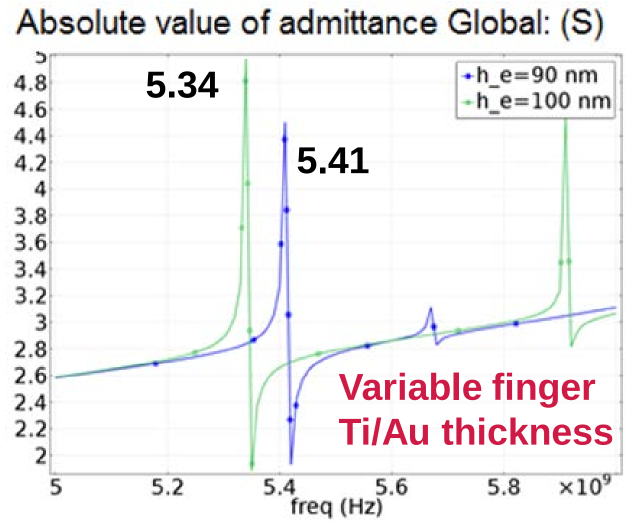




Frequency shift ~ 65 MHz / 10 nm change of metallization thickness

Electromechanical modeling of single SAW resonator





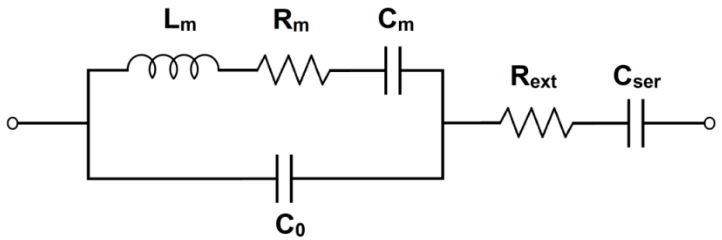
Electrode width [nm]; case (a) (metallization thickness 90 nm)	Frequency extracted from simulation [GHz]	Frequency extracted from experiment [GHz]
200	5.41	5.44
202	5.36	5.39
204	5.32	5.33
206	5.27	5.29
Metallization thickness [nm]; case (b) (electrode width 200 nm)	Frequency extracted from simulation [GHz]	Frequency extracted from experiment [GHz]
90	5.41	5.44
100	5.34	5.37

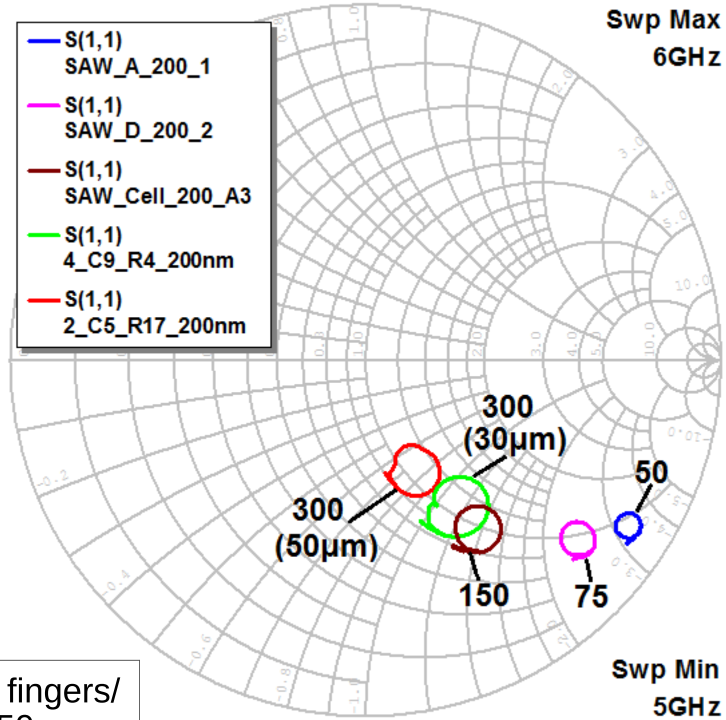
Errors are less than 1%

Series resonator frequency behaviour vs IDT topology

Single-type GaN SAW resonators:

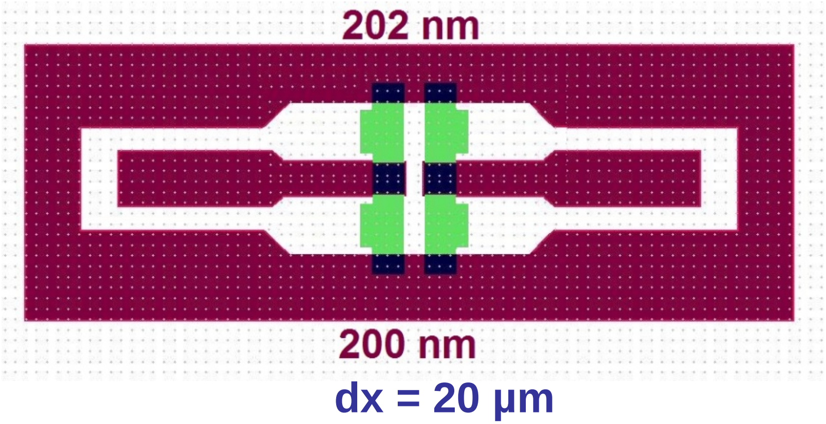
- 50…300 fingers
- 50 reflectors
- width of fingers: 200 nm
- length of fingers: 30 µm, 50 µm

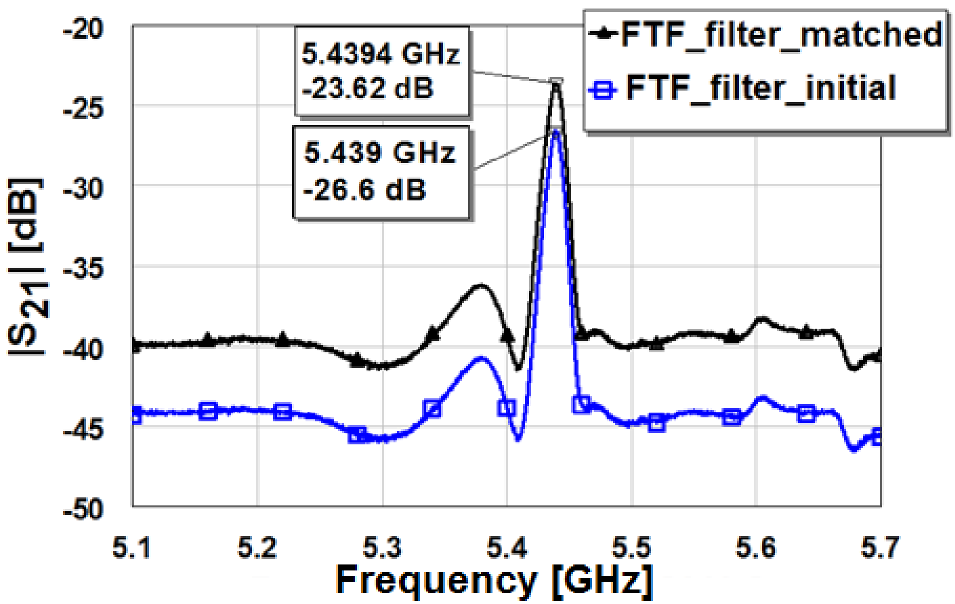


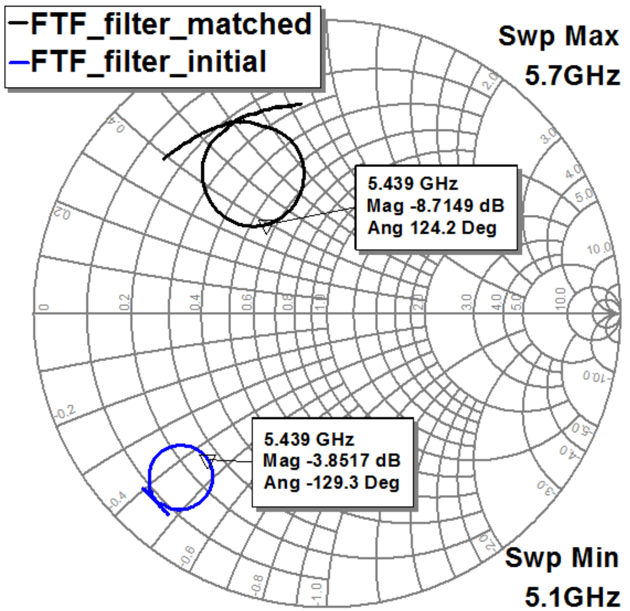


Symbol	300 fingers/ 30µm	300 fingers/ 50µm	150 fingers/ 50µm	75 fingers/ 50µm	50 fingers/ 50µm
L_m	185.2 nH	184.5 nH	186.4 nH	189.6	194.5 nH
C_m	4.62 fF	4.65 fF	4.60 fF	4.57 fF	4.52 fF
R_m	12.4 Ω	17.6 Ω	24.7 Ω	31.4 Ω	33.9 Ω
C_0	1.454 pF	1.536 pF	1.106 pF	0.802 pF	0.653 pF
R_{ext}	3.45 Ω	3.72 Ω	6.67 Ω	9.67 Ω	10.82 Ω
C_{ser}	0.704 pF	1.536 pF	0.542 pF	0.236 pF	0.151 pF

Face-to-face band-pass SAW filter

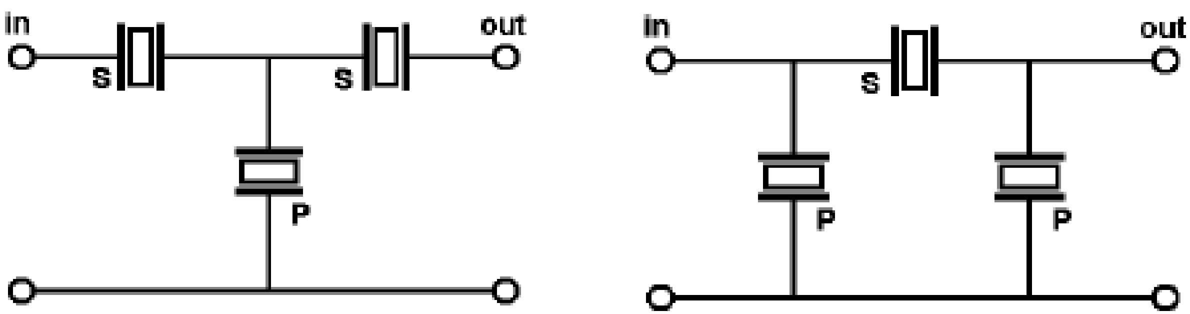


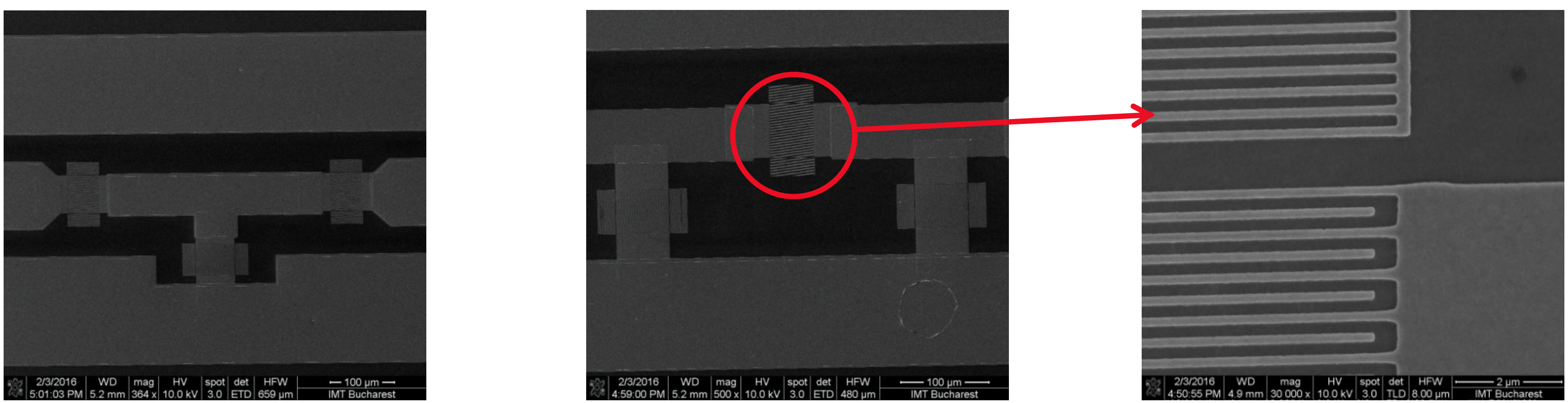




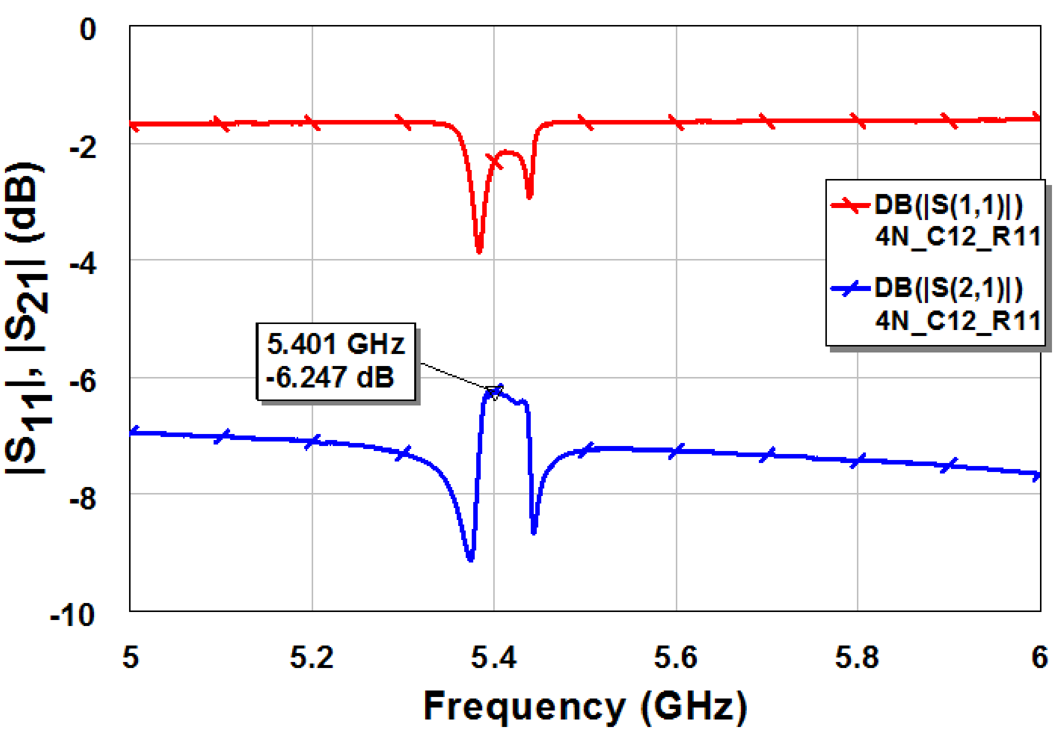
Ladder type SAW filters

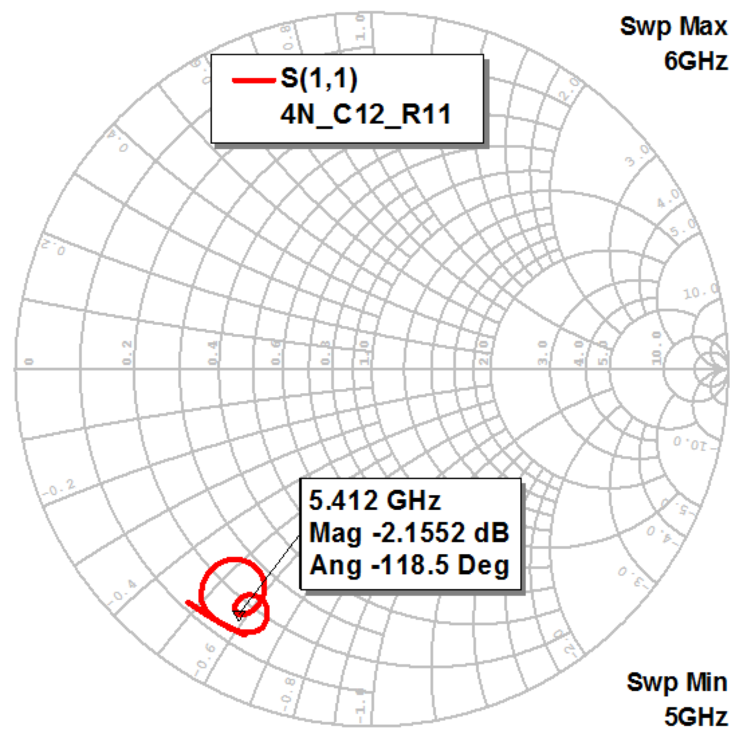
- **T and π – type SAW filter** configurations:
  - (i) 2 IDTs have 200 nm finger/ interdigit spacing width and one IDT has a different width: 202, 204, 206 nm;
  - (ii) all IDTs have 200 nm finger/ interdigit spacing width and one IDT has a 100 nm metallization thickness and the other two have 90 nm thickness





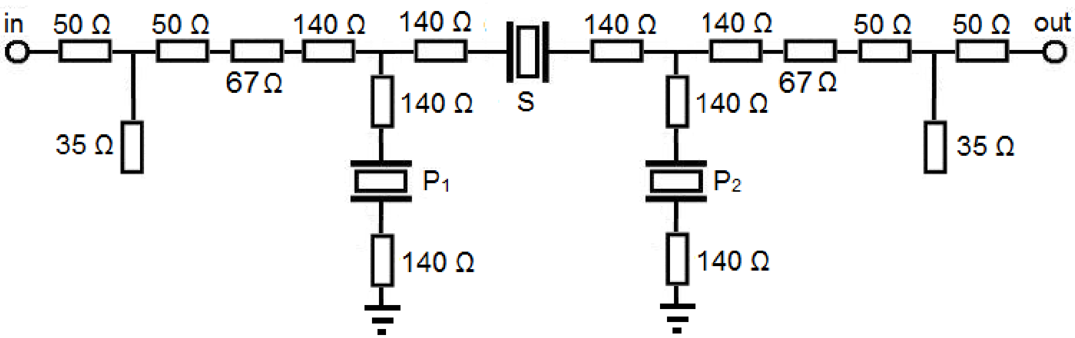
Π-shape band-pass filter – first results

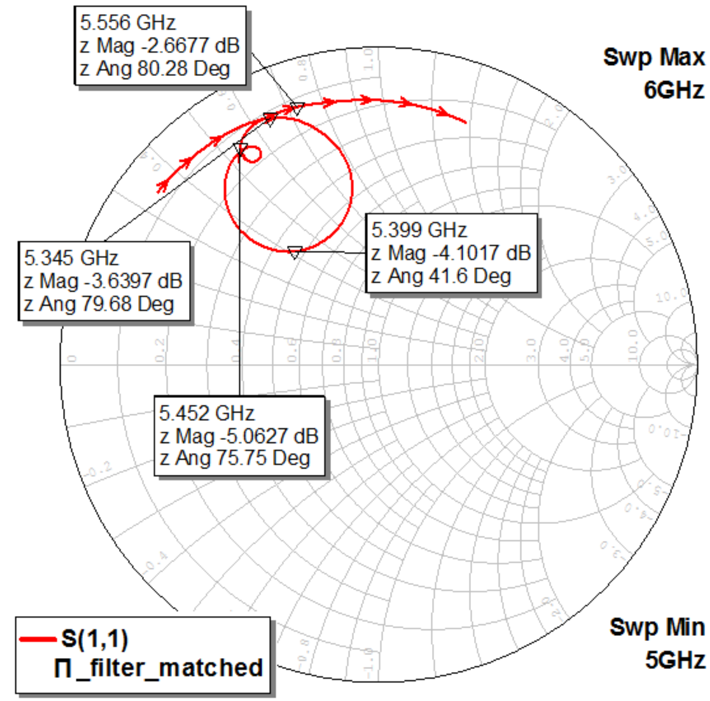


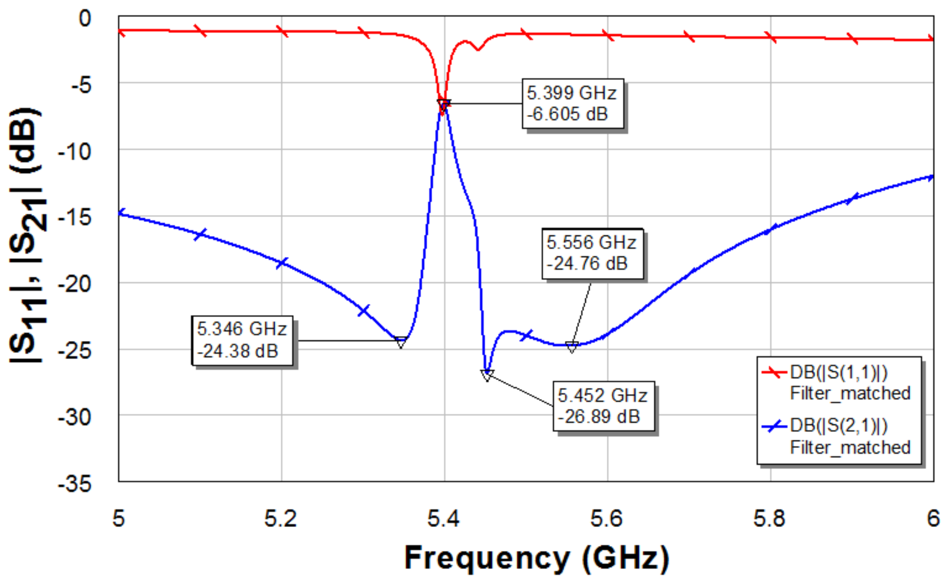


S-parameter measured results for Π-shape band-pass filter with 300 fingers (30 µm length, 200 nm / 202 nm)

Π-shape band-pass SAW filter

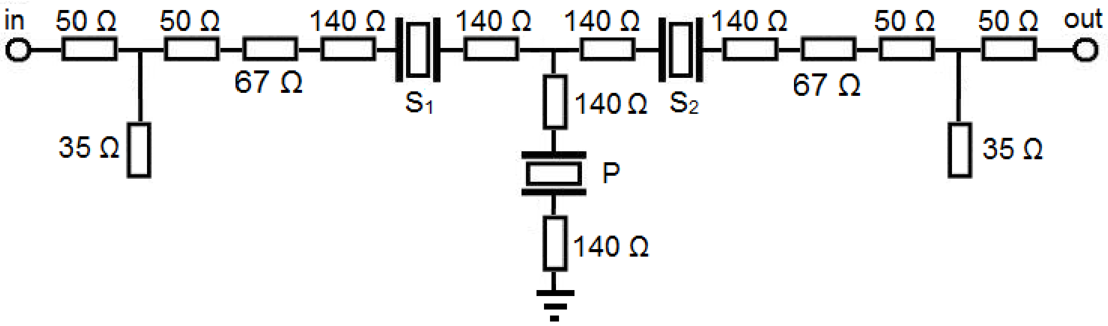


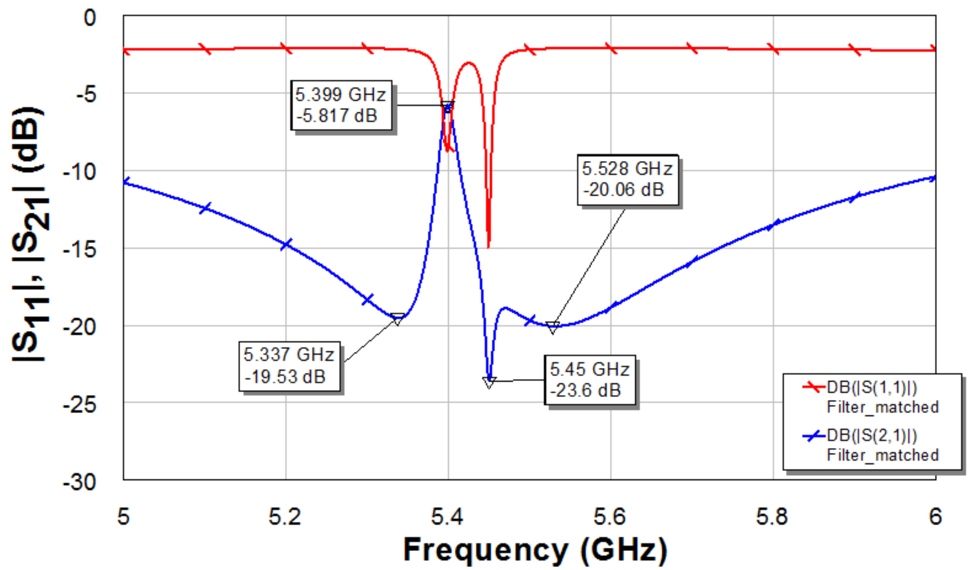


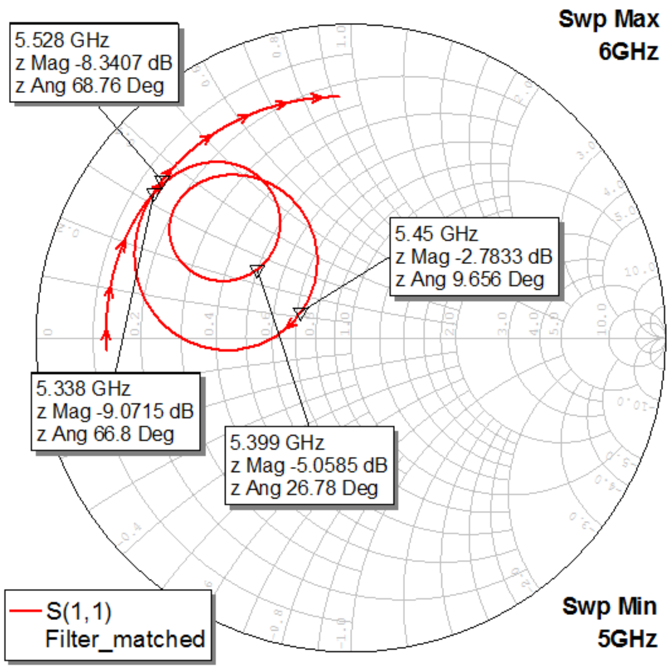


S-parameters for Π-shape band-pass filter with 300 fingers (30 µm length) built with SAW resonators and elements to compensate the series capacitor C_{ser} and to improve filter matching

T-shape band-pass SAW filter

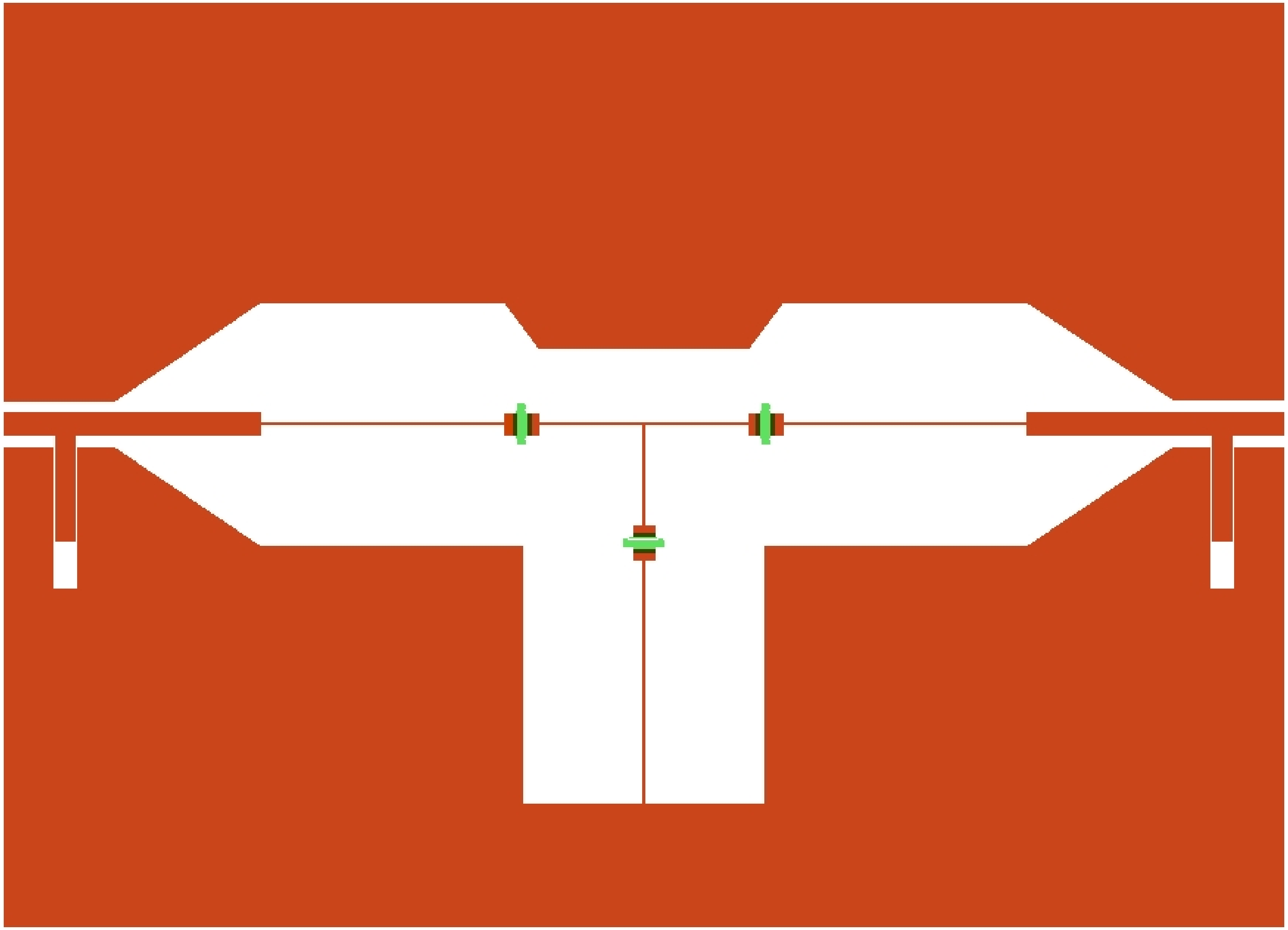




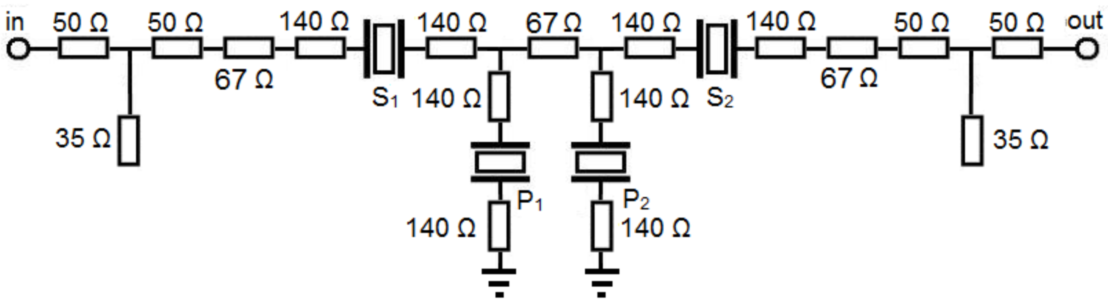


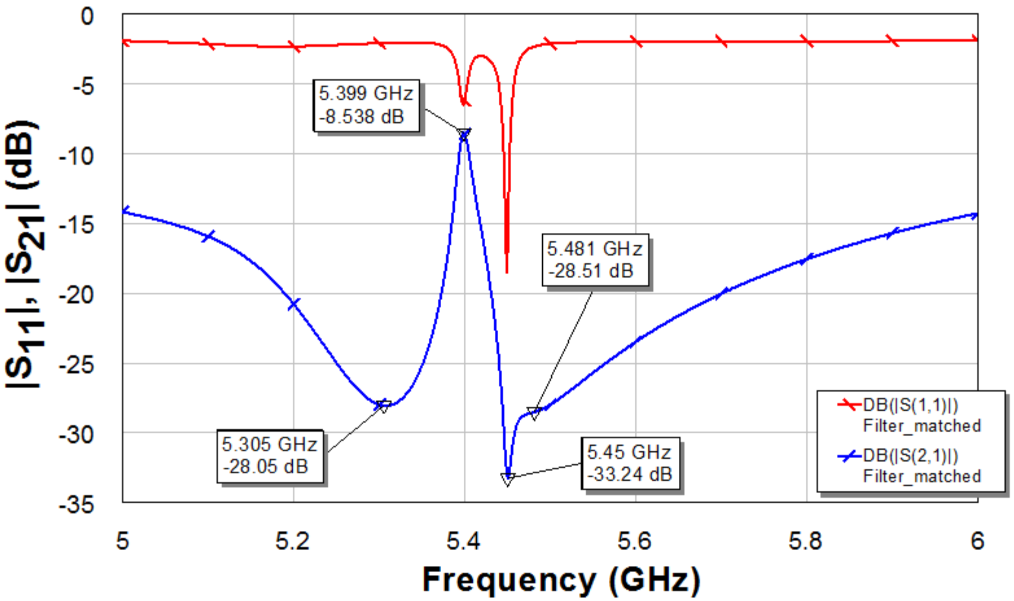
S-parameters for T-shape band-pass filter with 300 fingers (30 µm length) built with SAW resonators and elements to compensate the series capacitor C_{ser} and to improve filter matching

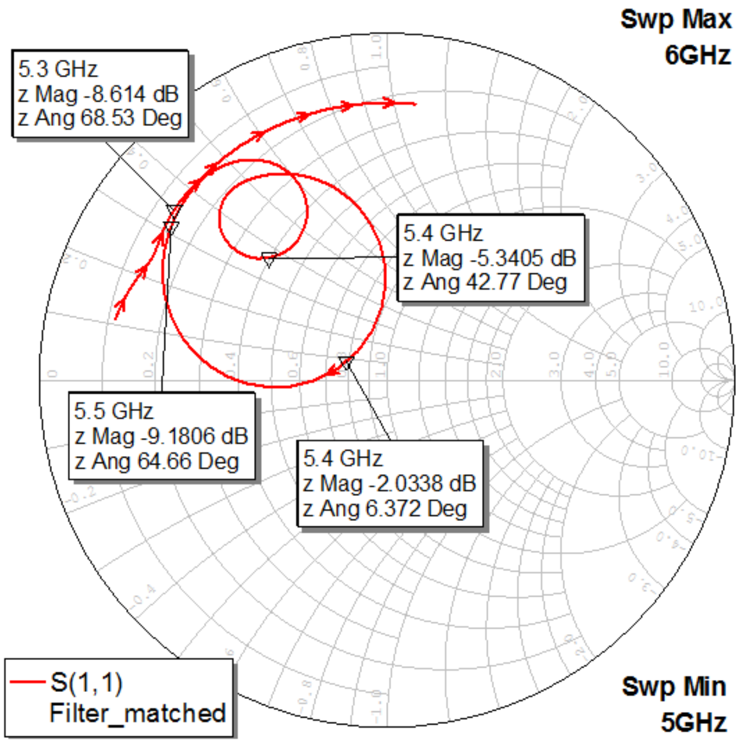
T-shape band-pass SAW filter - layout



Γ-shape band-pass SAW filter







S-parameters for Γ-shape band-pass filter with 300 fingers (30 µm length) built with SAW resonators and elements to compensate the series capacitor C_{ser} and to improve filter matching

Conclusions

- Novel temperature sensor structures consisting of GaN single-port SAW resonators SAW with Rayleigh mode resonance higher than 5 GHz have been developed and characterized; structures supported on a thin GaN/Si membrane with a total thickness of 11 µm shown very high sensitivity (627 kHz/ºC and 120 ppm/ºC), values which are about 2-2.5 times higher compared with similar structures manufactured on bulk material.
- The novel SAW pressure sensing structures have demonstrated high sensitivity and PCF, especially those based on Lamb mode (more pressure sensitive than the Rayleigh mode) and on thinner membranes; there are different signs of sensitivity and PCF with respect to the structure type and the resonance mode.
- First experiments to develop reliable ladder-type and face-to-face band-pass SAW filter structures on GaN/Si, operating above 5 GHz, were presented. Ladder-type filters based on single-port SAW resonators have shown good insertion loss results but more efforts have to be made as concerns out-of-band rejection. The face-to-face resonator topology provides much better out-of-band rejection but with rather high insertion losses. More configurations are under development to obtain a proper balance between these characteristics.

Thank you for your attention!

The authors acknowledge the support of the ESA-IPL-PTS-CBI-LE-2015-1011 contract "Microwave filters based on GaN/Si SAW resonators, operating at frequencies above 5 GHz"