III-Nitride based SAW resonators and sensors; emerging applications developed in collaborative European projects

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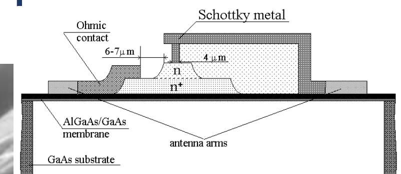
Outline

- History
- Acoustic devices on III -Nitride layered structures
- SAW devices on GaN/Si.
- SAW devices T sensors on GaN/Si AlN/Si GaN/SiC
- A smart systems integration using GHz operating T sensor (developments in a FP7 and in a Horizon Europe project)
- Superior propagation modes (Sezawa, Lamb) and their utility in applications (T and pressure sensors)
- SAWs and T sensors on GaN/SiC, AlN/Si
- SAWs on ScAlN and their use in SAW/SW coupling and in sensors

❑ Micromachined Circuits for Microwave and Millimeter Wave Applications MEMSWAVE Project No. 977131 (1998 – 2001)

- **Coordinator:** IMT-Bucharest**; Partners:** FORTH Heraklion, ITC-IRST Trento Uppsala University, Tor Vergata Univ. Rome, CNR-M2T Rome, HAS-MFA Budapest, ISP Kiev, Microsensor Kiev Ltd.
- **Project nominated between the 10 finalists for the Descartes Prize 2002 of the European Commission**
- **MEMSWAVE conference became an itinerant European event (2000 - 2016)**



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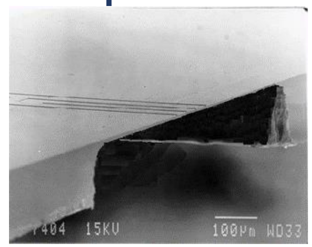
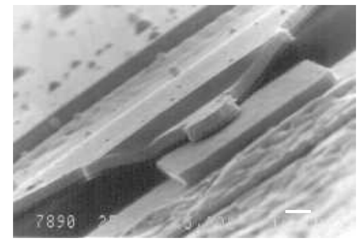
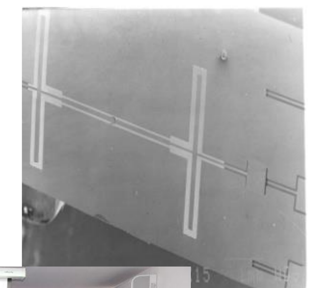
- A. Müller, et al, ***Journal of Micromechanics and Microengineering***, No.10, pp.130-135, 2000
- A. Muller, C. Konstantinidis, et al, ***Journal of Micromechanics and Microengeneering***, 11 (2001) pp. 1-5
- G. Konstantinidis, A. Muller et al., ***Journal of Micromechanics and Microengineering,*** Vol 13, pp. 353-358, 2003



SEM photo of 77 GHz cascaded open end series stubs CPW filter on GaAs membrane



Details of the Schottky diode area



The final review meeting (Sinaia, 2001)

At the finalists presentation for the Descartes prize (Munich, 2002)

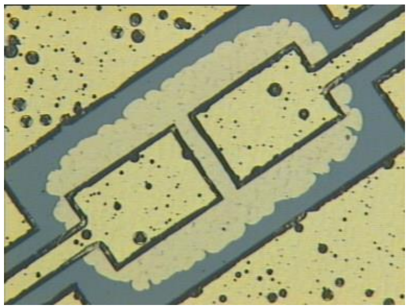
15 years after the end of the MEMSWAVE project at the MEMSWAVE workshop 2016 - Bucharest

History

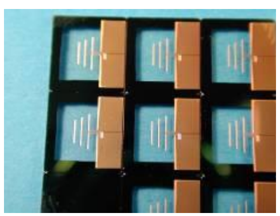
❑ AMICOM FP6 NoE (2004-2007)

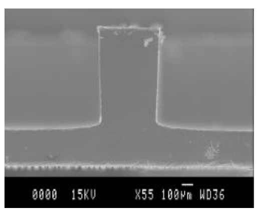
- **Coordinator:** LAAS CNRS Toulouse**; 25 Partners**

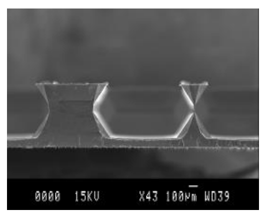
First GaN membrane FBAR structure IMT, FORTH, TUD (2006)

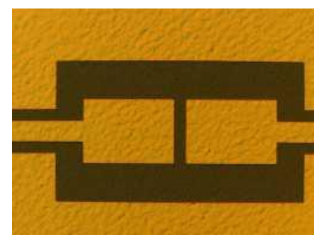


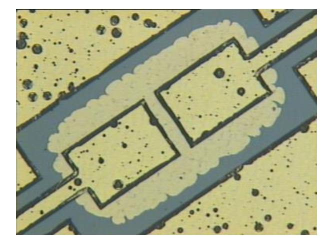
- A. Pantazis, D. Neculoiu, et. al, ***Journal of Micromechanics and Microengineering***, vol. 15, pp.S-53-S59, 2005
- D. Neculoiu, G.Bartolucci, et. al., ***Electronics Letters***, vol.40, No.3, pp. 180-182, 2004
- M. Saadaoui, P. Pons, R. Plana, et. al., ***Journal of Micromechanics and Microengineering***, vol.15, Nr 7, pg. S65-S71, 2005
- A. Muller, D. Neculoiu, D. Vasilache, et. al., ***Superlatices & Microstructures***, 40, 2006, pp. 426-431



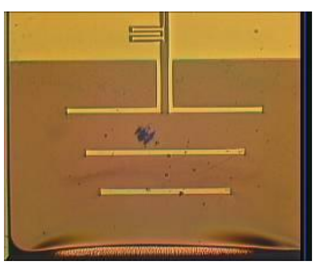


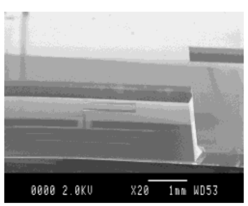




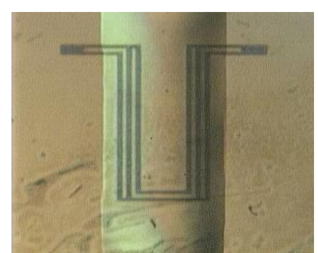


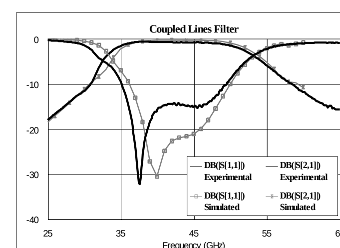
GaN membrane supported series connection of two FBAR structures (test structures); The thickness of the membrane was 2.2 µm





Yagi-Uda antennae structures manufactured using backside etching processing - 2004 (IMT-LAAS)





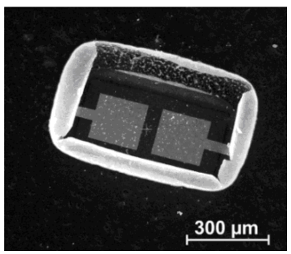
GaN membrane supported filter

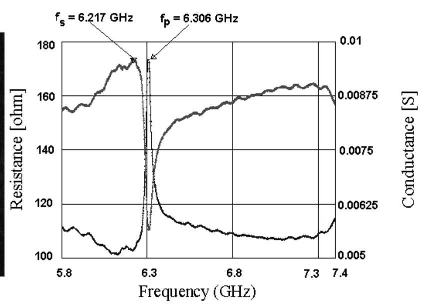
History

❑ Microwave, Millimetre Wave and Optical Devices, based on Micro-Electro-Mechanical Systems (MEMS) for Advanced Communication Systems and Sensors (FP7 REGPOT MIMOMEMS) (2008 - 2011)

• **Coordinator:** IMT-Bucharest**; Twining Partners:** LAAS-CNRS Toulouse, FORTH Heraklion

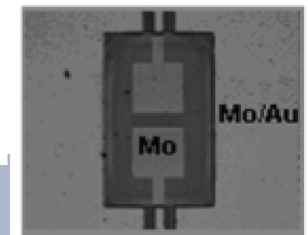
•Novel microwave and characterization equipment (MIMOMEMS + 2 national projects)



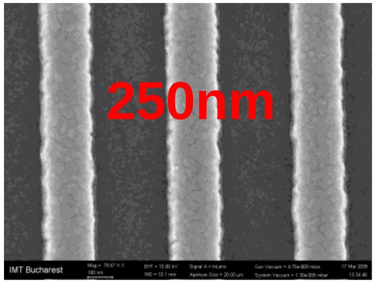


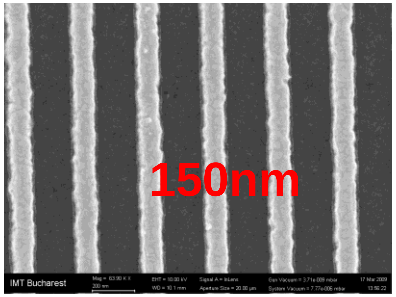
- **Thin membrane supported FBAR structure**
- 340 nm (GaN) + 200nm (buffer) GaN membrane
- 50 nm thin Mo metallization

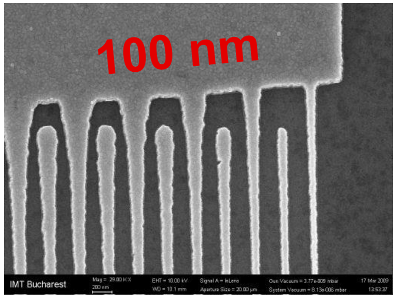
A. Müller, D. Neculoiu, G. Konstantinidis et al. ***Electron Devices Letters***, vol. 30, 2009, pp. 799-801

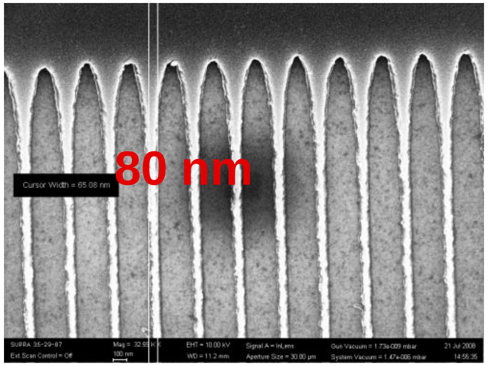


❑ New equipment (national project) and successful development of e-beam nanolithography in IMT

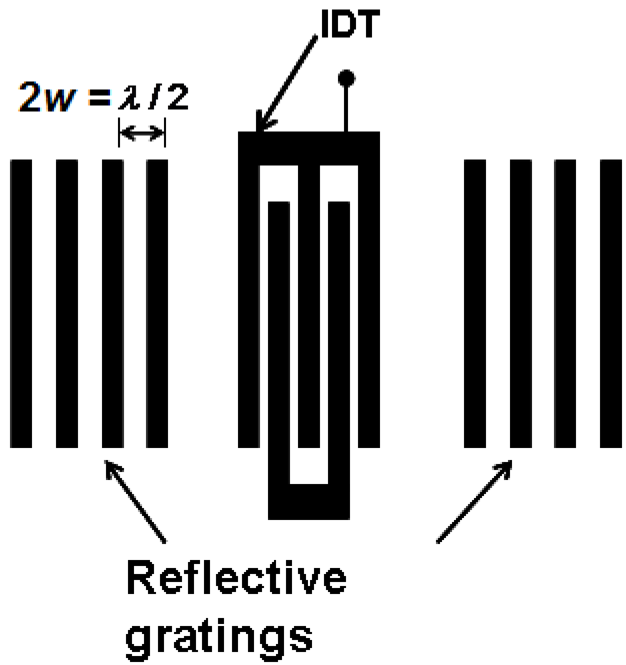








SAW principle

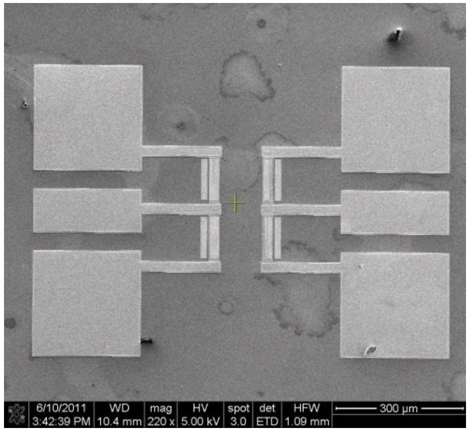


$$2w = \lambda / 2 = v_s / 2f_r$$

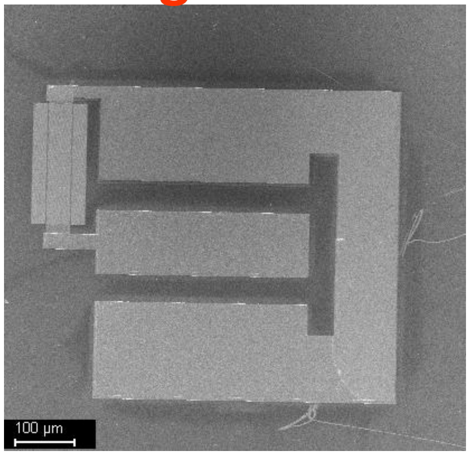
$$f_r = v_s / 4w$$

Vs ~ km/s; w ~ µm; fr ~ MHz … GHz

Two port (face to face) SAW resonator



SAW single resonator



WBG semiconductors for acoustic devices- main advantage: increasing the resonance frequency

- Most acoustic devices (SAWs and FBARs) used in communication applications and sensors are based on classical non-semiconductor piezoelectric materials (quartz, $LiNbO_3$, lithium tantalate, etc). They have very good piezoelectric properties but their operation frequency is limited to values below 2 GHz.
- Communication (5G and above) need higher frequencies
- Sensors for various physical parameters with wireless data transmission and battery-less operation are important applications of SAW resonators. Increasing the operation frequency of the SAW increase the sensitivity and (also the TCF).
- An exotic application: coupling of Surface Acoustic Waves With Spin Waves and control of SW via SAW. For fitting the SAW resonance with the FMR high order (and low amplitude) harmonics of the Lithium Niobate based SAW are used. Increasing the SAW resonance frequency makes possible to fit the fundamental SAW resonance frequency with the FMR.
- WBG semiconductor thin layered structures offer the possibility to obtain and use in applications superior modes (with higher frequency for the same pitch dimension)
  - the Sezawa mode for the Slow on Fast (SoF) structures (when the phase velocity in the overlayer is smaller than the transverse bulk phase velocity in the substrate like in the case of GaN/Si; GaN/SiC)
  - the Lamb mode in WBG semiconductor membranes

WBG semiconductors for acoustic devices

- Most WBG semiconductor layered structures are compatible with advanced nanolithograpphic processes and micromachining technologies

Acoustic devices manufactured on quartz, $LiNbO_3$, langasite, etc., can not be monolithic integrated with other active devices. GaN based SAWs can be monolithic integrated in GaN MMICs; AlN/Si and ScAlN/Si are CMOS compatible

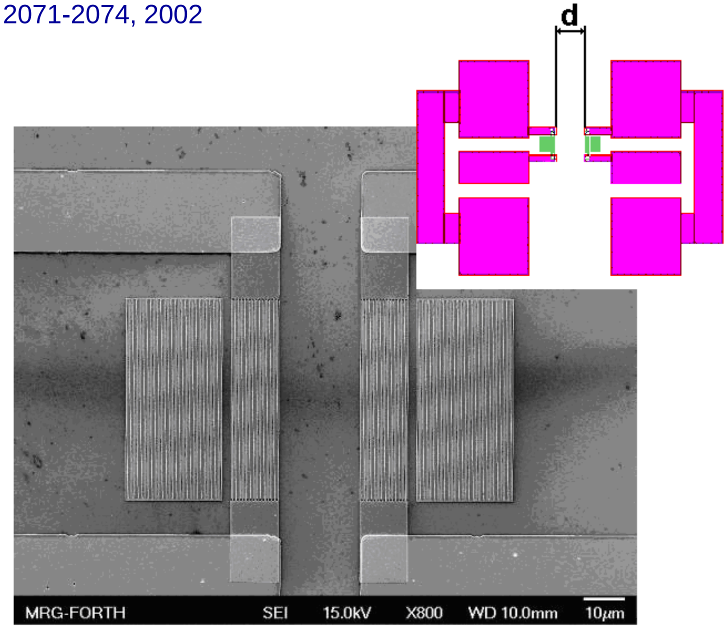
Progress in deposition/growing of high quality piezoelectric WBG semiconductor layerd structures like AlN and GaN on sapphire, diamond, SiC and Si substrates has initiated an intensive research in the development of acoustic devices on WBG semiconductors.

Recently a lot a progress has been done on the development of ScAlN a very interesting material still in research

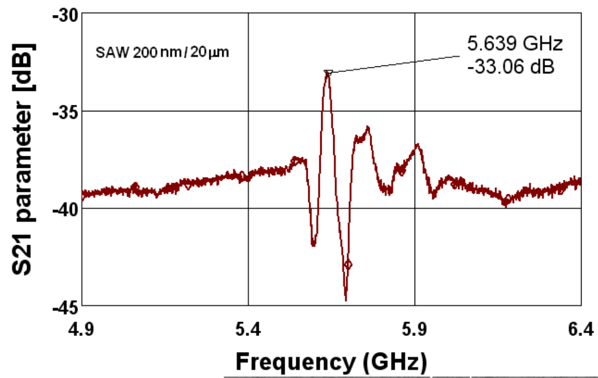
5.7 GHz GaN/Si based SAW structure with an IDT with fingers/intedigit spacing 200nm wide (2010)

Previous works: SAW structures resonating at 2.2 GHz (IDTs: 600 nm wide finger/interdigit spacing)

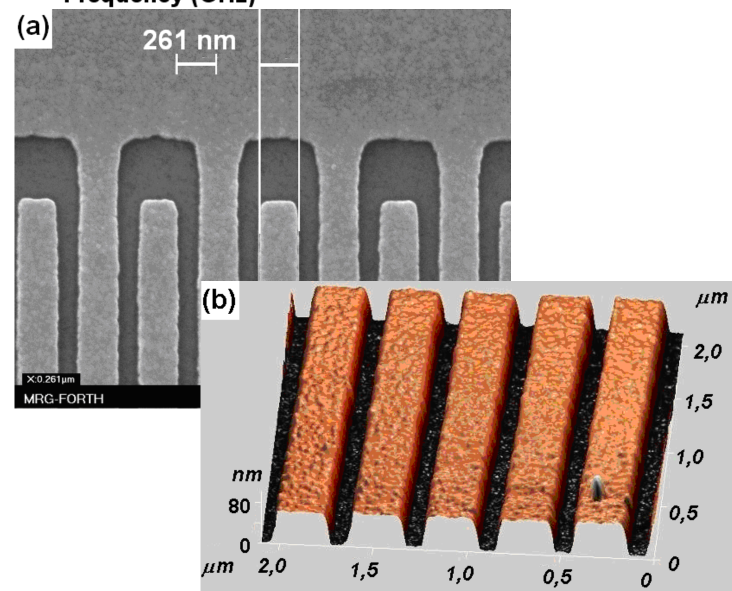
- T Palacios, F. Calle, J. Grajal, E. Monroy, M. Eickhoff, O. Ambacher, F. Omnes, IEEE Ultrasonics Symposium, pp 57-60, 2002
- T. Palacios, F Calle, E. Monroy, F Munoz , J. Vac. Sci. Tech. B 20, pp. 2071-2074, 2002



SEM photo of the test structure. The distance between the IDTs was d= 20 µm; The inset presents a schematic of an entire structure, including the connection pad



The transmission measurements for the SAW test structure having 20 µm distance between the IDTs



Detail of the nanolithogrphic process with fingers and intedigits nominally 200 nm wide developed on the GaN surface: a) SEM photo and b) AFM image

A. Muller, D. Neculoiu, G. Konstantinidis et al. Electron Devices Lett. Vol. 31, pp 1398-1400, Dec 2010

Potential advantages of GaN SAW based T sensors

- Microwave integrated circuits based on GaN are able to work at high temperatures because of the wide bandgap of this semiconductor material. In the same time, the temperature in GaN based MMICs has to be carefully monitored. Here it is necessary to use SiC and not Si as substrate.

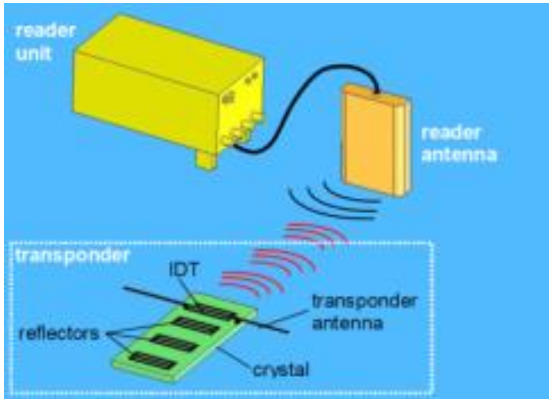
- In contrast with silicon based circuits, where a pn junction, placed close to the hot areas of the IC, can be easily used for precise temperature determinations, different techniques must be used for T measurements in GaN based MMICs.

- Monolithic integration of a GaN SAW based T sensor in the GaN MMIC can be a reliable solution; also hybrid integration can be used.

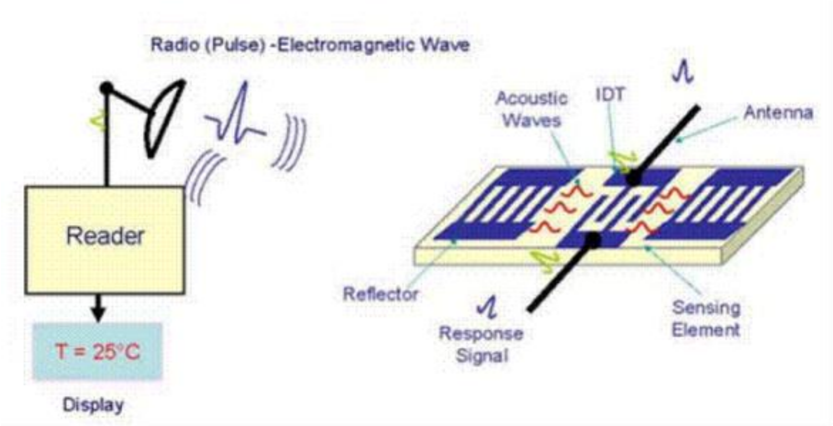
- A SAW based T sensor is fully compatible with wireless data reading (often necessary because of the high temperatures and harsh environmental conditions). Wired data transmission can be also used.

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

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



[R. Fachberger, et.al, "Wireless SAW based high-temperature measurement systems" IEEE Intl. Freq. Control Symp. 2006, pp. 358-367]



[D. S. Stevens, et al, "Applications of Wireless Temperature Measurement Using SAW Resonators", Fourth International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, Chiba University, Japan, 2010]

Temperature sensitivity definition

s=df/dT; a higher resonance frequency means an increased sensitivity An increased sensitivity results in simpler signal processing electronics.

S=1/fx(df/dT)=TCF is in a first approximation frequency independent; Some topological parameters like metallization thickness and ratio can influence the value of S.

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

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

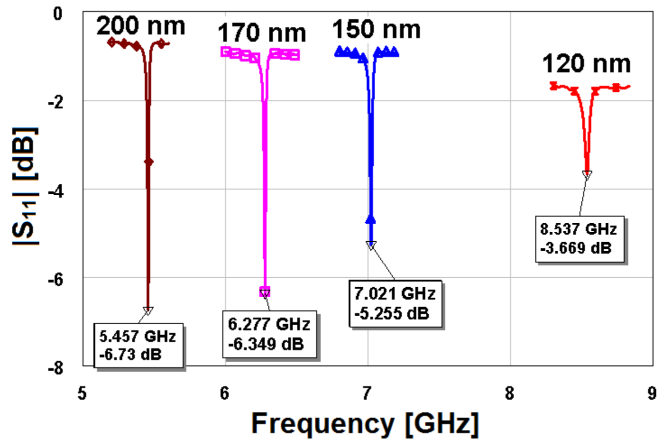
There is the reported value of **43 ppm/ºC for S** [1,2] for GaN (determinations in the 50 – 400 K temperature range and for hk >> 1 (h is the GaN epi-layer thickness; k=2π/λ); on wafer measurements, for face to face resonators)

Resonance frequency changes with the temperature because of change in v – the propagation term and change in L – the expansion term

[1] T. Palacios et. al., Mater. Sci. Eng. B 93, 154 (2002)

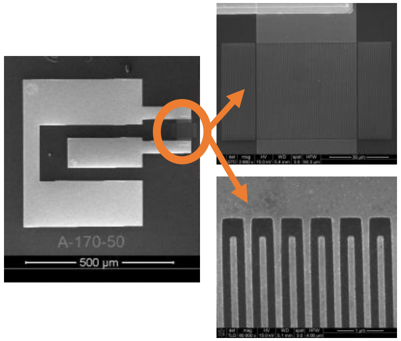
[2] F. Calle, et. al., Phys. Stat. Sol. (c) 2 (3) 976–983 (2005)

T Sensor; Room temperature characterization

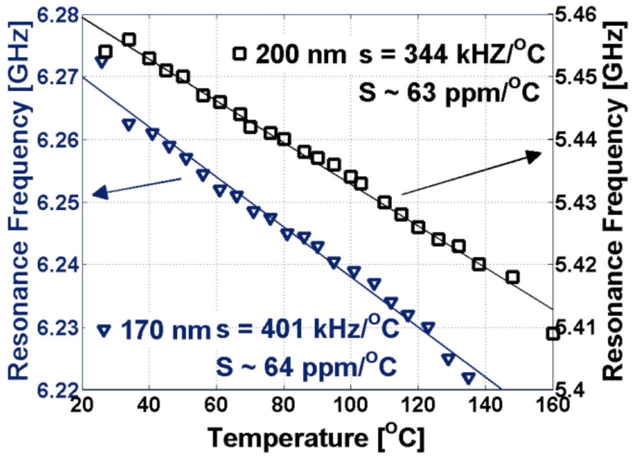


- A. Müller, G. Konstantinidis, I. Giangu, V. Buiculescu, A. Dinescu, A. Stefanescu, A. Stavrinidis, G. Stavrinidis, A Ziaei, *International Microwave Symposium -IMS 2014, Tampa, USA, session "TH2F: Sensors and Sensor Systems" pp. 1-4*
- A. Müller, G. Konstantinidis, V. Buiculescu, A. Dinescu et. al., *Sensors and Actuators: A Physical* 209, pp. 115-123, 2014

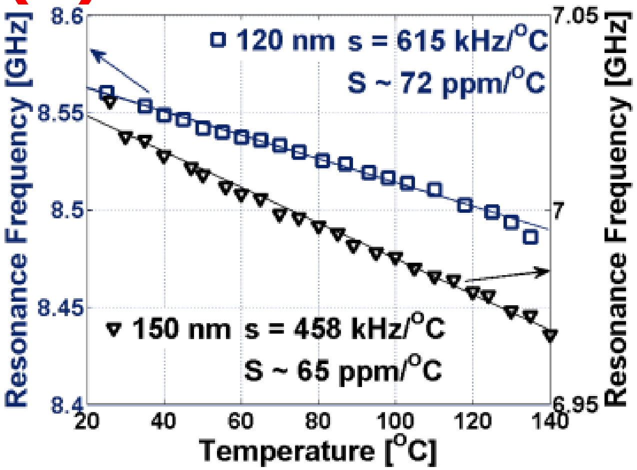
Sensitivity(s) and TCF (S) measurements



One port SAW resonator

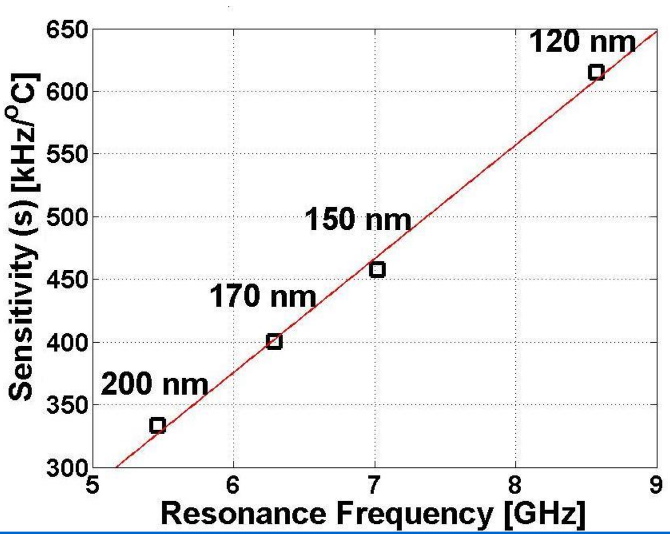


Resonance frequency vs. T for SAW structures with 170 nm and 200 nm digit/interdigit spacing width.



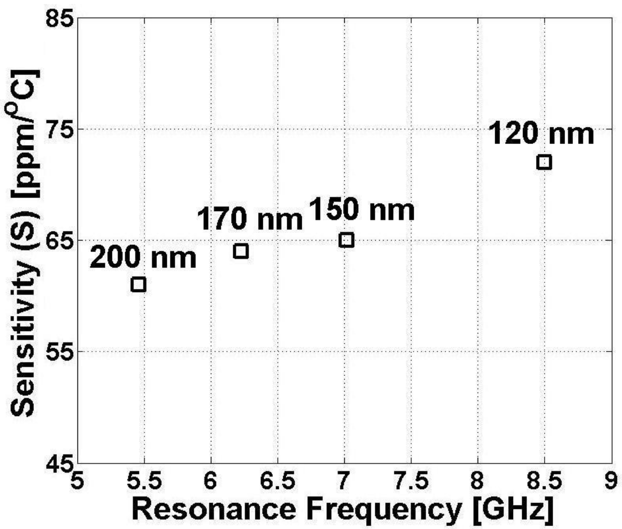
Resonance frequency vs. T for SAW structures having 120 nm and 150 nm digit/interdigit spacing width.

Sensitivity s and TCF(S) vs. resonance frequency



s has a linear variation with the resonance frequency

s= df/dT



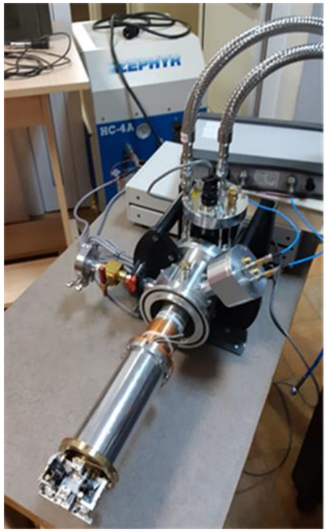
An increase of S (TCF) with the resonance frequency is observed.

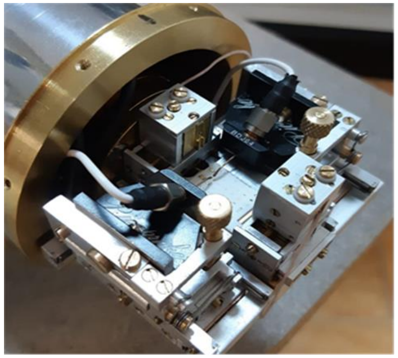
A more compact structure has as effect an increased contribution of the expansion term compared with the propagation term, in the TCF expression

S=1/f x(df/dT)=TCF

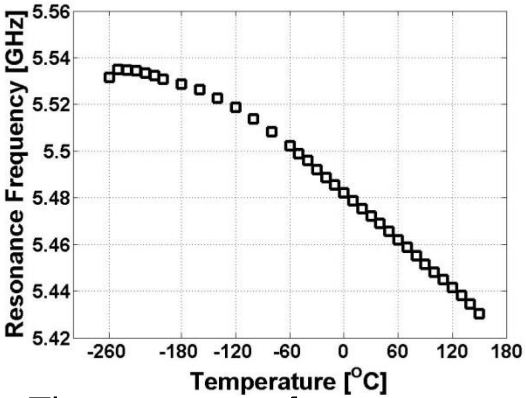
Cryostat characterization

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

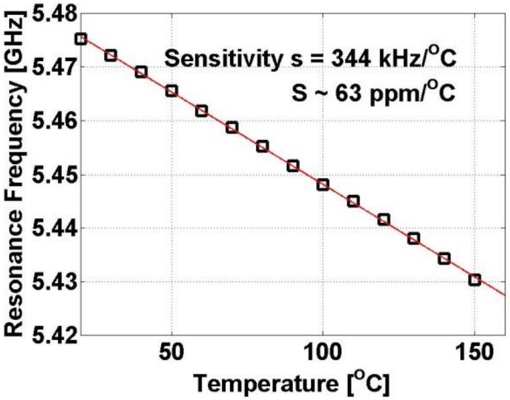




Operate in the 5-500 K temperature range



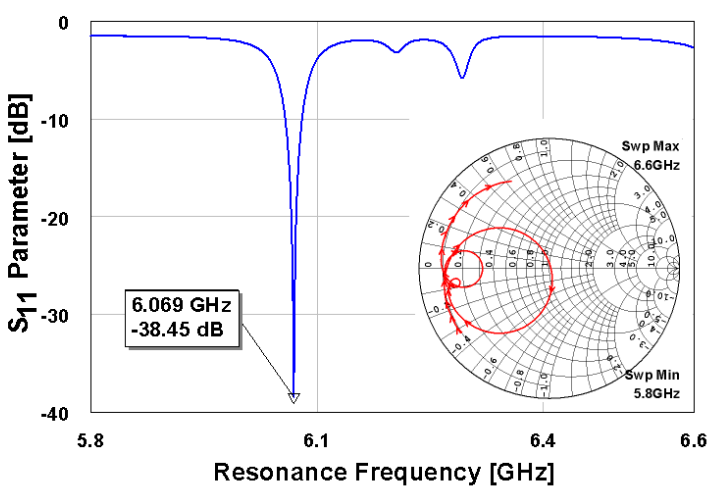
The resonance frequency vs. temperature a for SAW structure with w_{IDT} = 200 nm



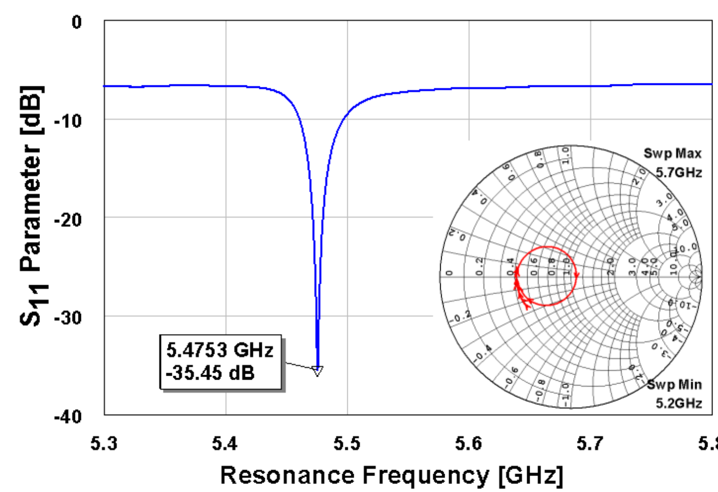
The linear variation of the resonance frequency vs. temperature in the range 20-150 ºC

- ❑ At low temperatures (20-70 K) SAW devices have a resonance frequency very stable with T variations, which is interesting for communication applications
- ❑ Linear variation of s vs. T in the -40 to +150 ºC temperature range

Wafer diced into chips, followed by chip assembly on special designed ceramic wafer provided with four CPW transmission lines, each having SMA connectors



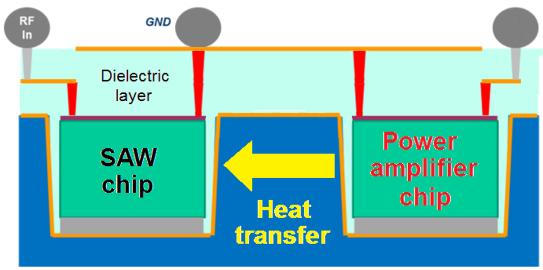
Room temperature resonance frequency for the structure having the finger/interdigit spacing 170 nm wide, mounted on the ceramic carrier



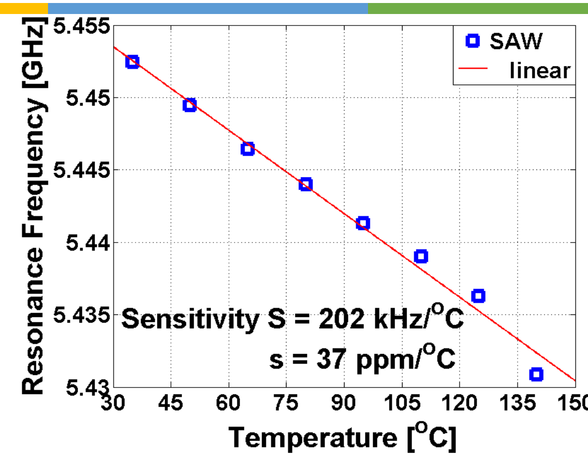
Room temperature resonance frequency for the structure having the finger/interdigit spacing 200 nm wide, covered with BCB and mounted on the ceramic carrier.

Smart integration of high power electronics for industrial and RF applications (FP7 IP SMARTPOWER) (2011 - 2016) coordinator: Thales TRT

- **Coordinator** Thales Research & Technology, France; 15 partners from 7 countries



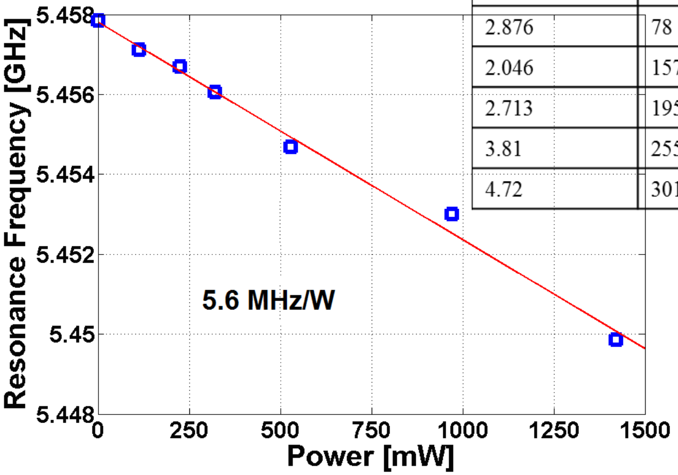
The HPA hybrid integrated with the T sensor



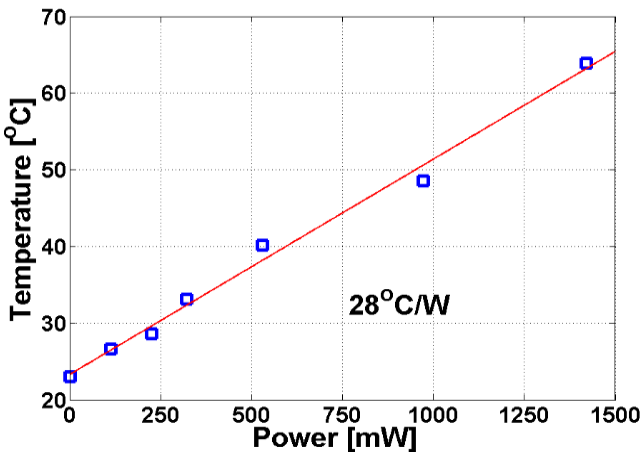
The T SENSOR (EMBEDDED) - calibration curve; Resonance frequency vs.T

HPA bias parameters

V_D [V]	I_{DS} [mA]	Power [mW]
0	0	0
2.22	51	113.22
2.876	78	224.32
2.046	157	321.22
2.713	195	529.035
3.81	255	971.55
4.72	301	1420.72



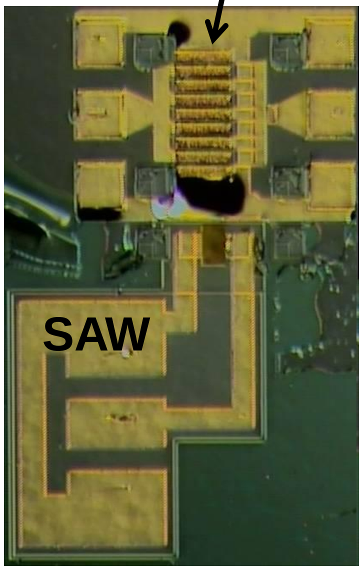
Resonance frequency of the embedded T sensor vs. HPA power dissipation



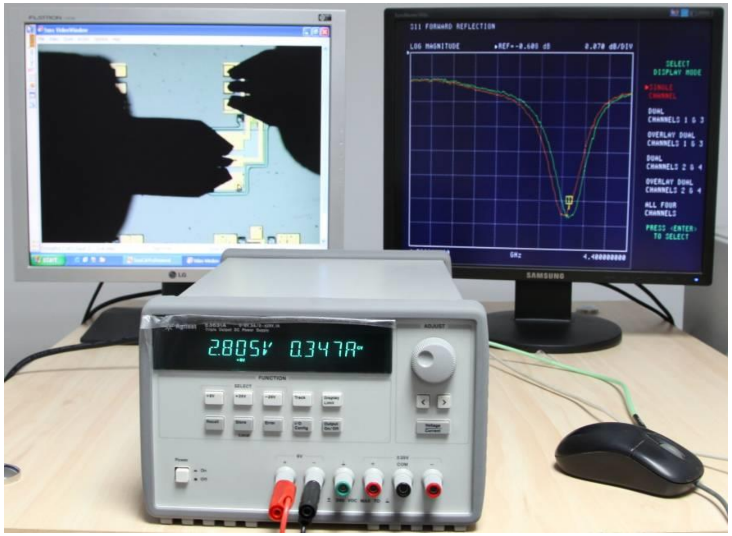
Temperature vs. power dissipated in the HPA measured with the integrated SAW sensor

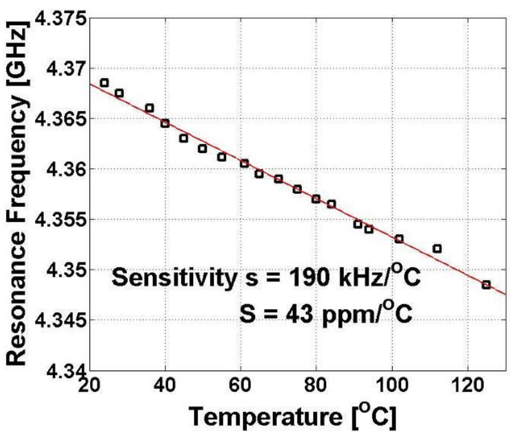
Another topology for the integration of the GaN SAW T sensor with a HEMT structure (FORTH and IMT)

Work of FORTH and IMT will be used in the running Horizon Europe NANOMAT project



- **SAW-HEMT** sensor structure: an AlGaN/GaN heterostructure, grown by MOCVD on (111) Si substrates, was used to fabricate on it a power HEMT and a SAW to demonstrate in situ power transistor heat monitoring (for monolithic integration)
- The SAW structure is processed on the GaN buffer layer of the AlGaN structure

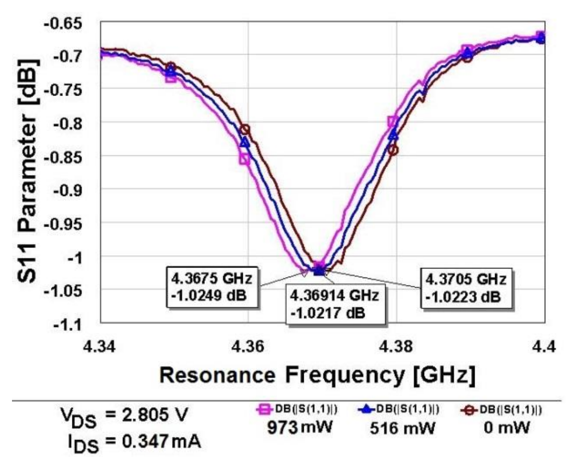




Measured heating ~ 16°C

I_{ds} = 0.347 mA and
V_{ds} = 2.805 V (P = 973 mW)

On wafer measurement results



Possibilities to increase the resonance frequency- The Sezawa propagation mode

•**Increasing the resolution of the nanolihographic process**

•**Exploitation of confined modes which appear in the "slow on fast" structures.**

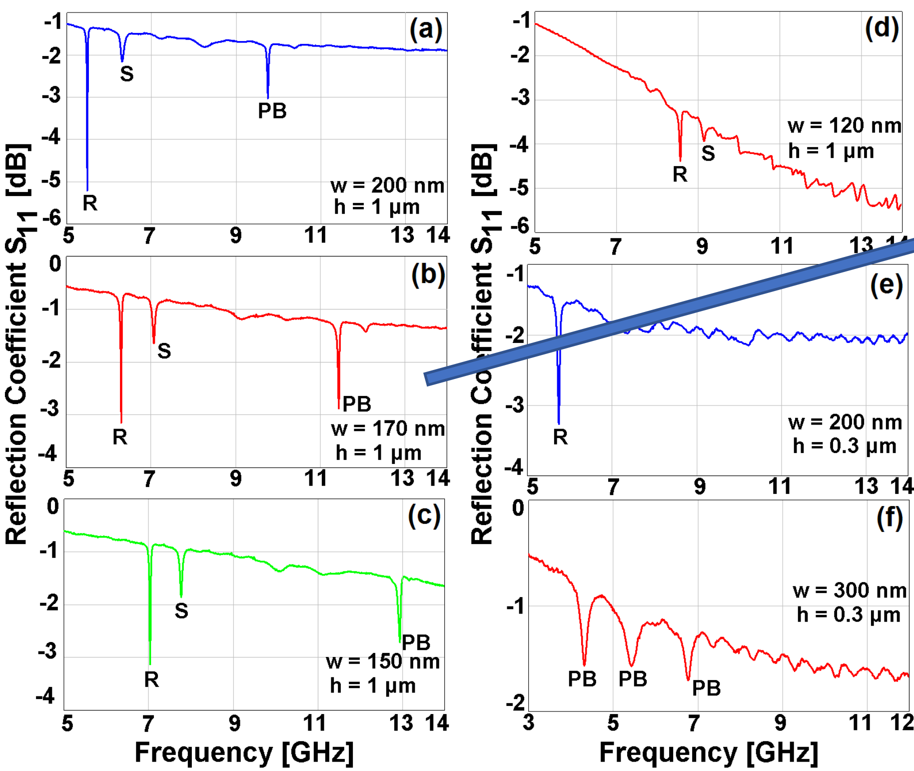
•In contrast to bulk structures, in thin layer SAW type structures, higher order Rayleigh modes, called Sezawa modes can appear. The Sezawa mode appear only if the value of bulk transverse velocity in the substrate, v_{ts}, is higher than transverse velocity in the over-layer (v_{tl}) and for a restricted number of values of the hk parameter.

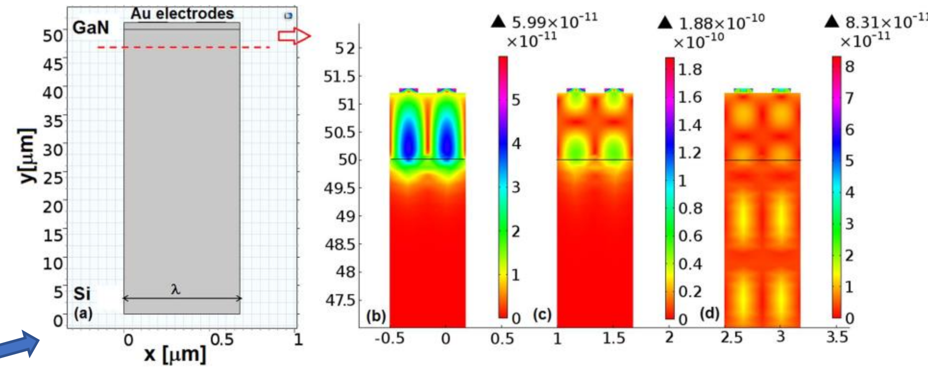
This is the case of GaN/Si GaN/Sapphire, GaN/SiC, AlN/Diamond etc.

•Sezawa modes have higher phase velocities than the fundamental Rayleigh mode.

Rayleigh Sezawa and pseudo bulk resonance frequencies measurements and simulations for different values of the product hk

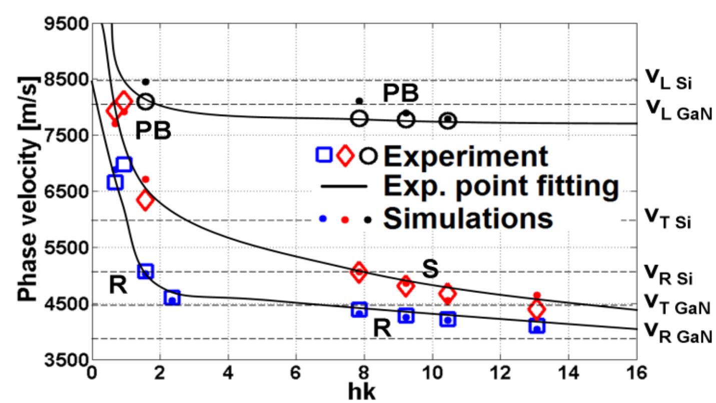
GaN/Si





Simulation results: geometry (a) total displacement for Rayleigh (b), Sezawa (c) and pseudo bulk (d) mode resonances w_{IDT} = 170 nm

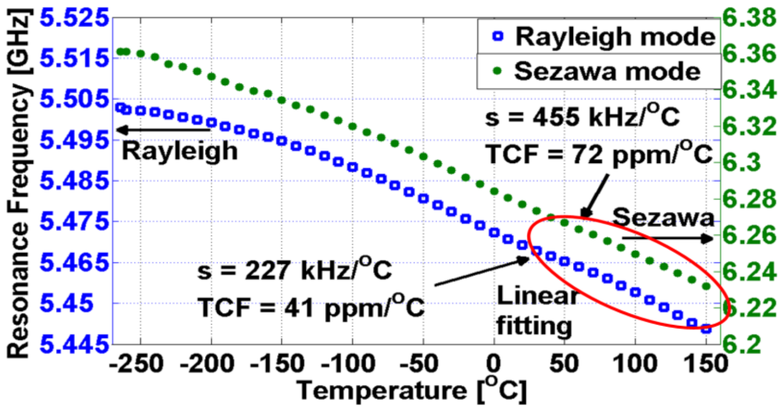
$$hk = 2\pi h/\lambda = 2\pi h/4w$$



Phase velocity vs. hk for the R and S modes (GaN/Si SAW structures with finger/interdigit spacing different widths).

A. Muller, I. Giangu, A. Stavrinidis, A. Stefanescu, G. Stavrinidis, A. Dinescu, G. Konstantinidis, "Sezawa Propagation Mode in GaN on Si Surface Acoustic Wave Type Temperature Sensor Structures Operating at GHz Frequencies" ***IEEE Electron Device Letters*****, Vol. 36, no. 12, 2015, pp. 1299 – 1302**

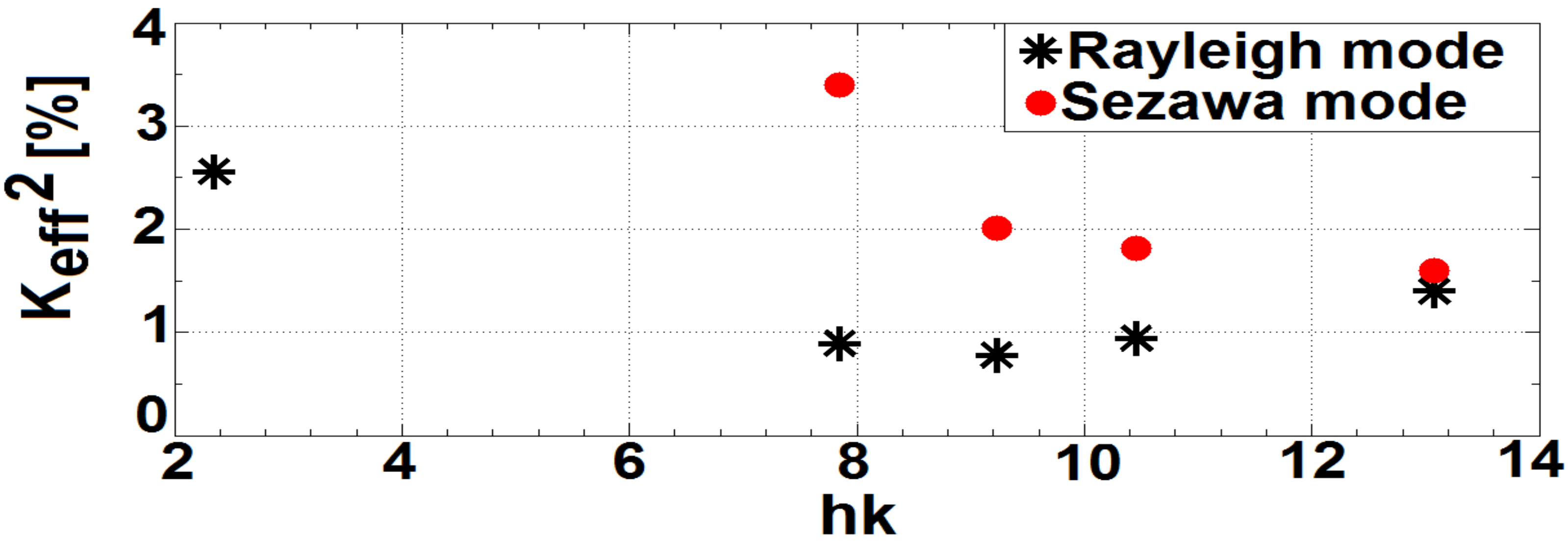
GaN/Si Rayleigh vs Sezawa T sensors



Resonance frequency shift vs. temperature for the R and S modes (GaN/Si SAW structures with finger/interdigit spacing 200 nm wide).

Finger/interdigit spacing		200 nm	170 nm	150 nm
Rayleigh mode	Resonance frequency (GHz)	5.51	6.28	7.032
	s (kHz/°C)	227	318	338
	TCF (ppm/°C)	41	50	48
Sezawa mode	Resonance frequency (GHz)	6.29	7.03	7.75
	s (kHz/°C)	455	526	543
	TCF (ppm/°C)	72	74	70

Experimental determination of the coupling coefficient

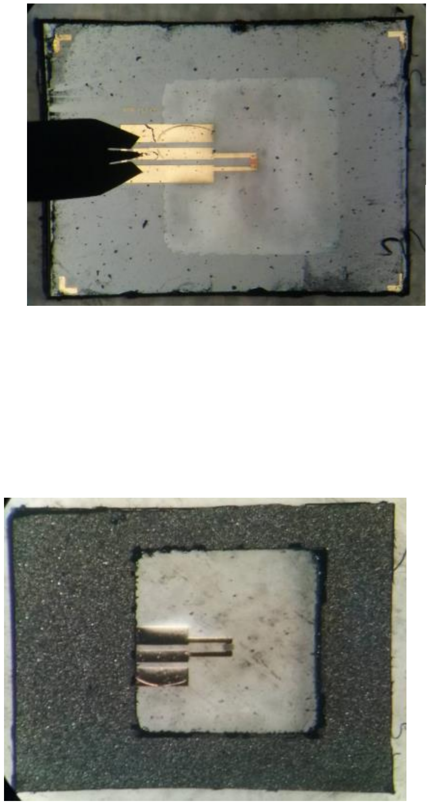


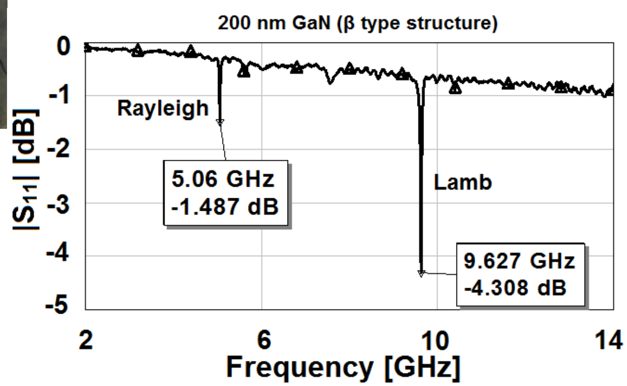
Coupling coefficient: $$k_{eff}^2 = \frac{\pi^2}{4}\frac{f_p - f_s}{f_p}$$

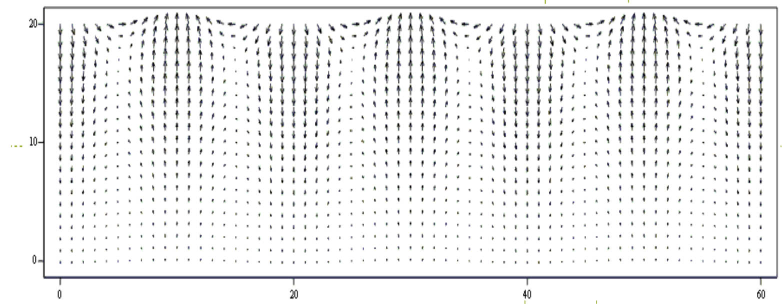
The weak point of the GaN Rayleigh is drastically improved

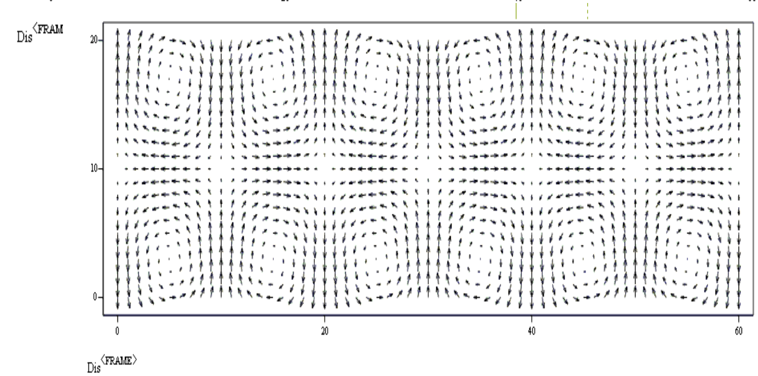
The Lamb mode

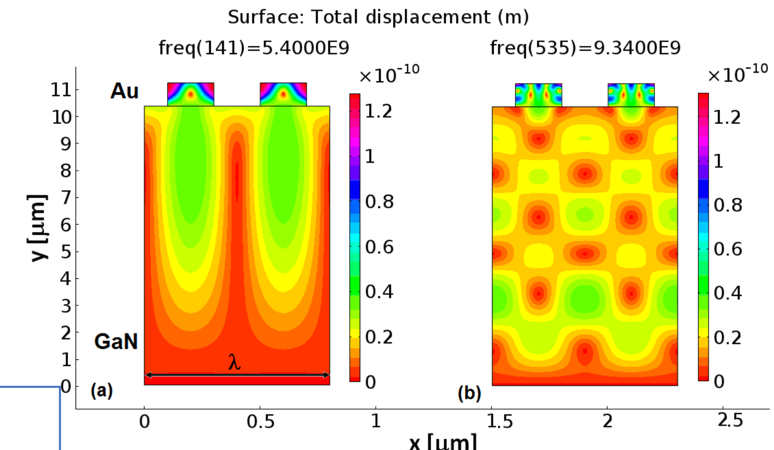
www.me.sc.edu/Research/lamss/research/Waves/sld004.htm











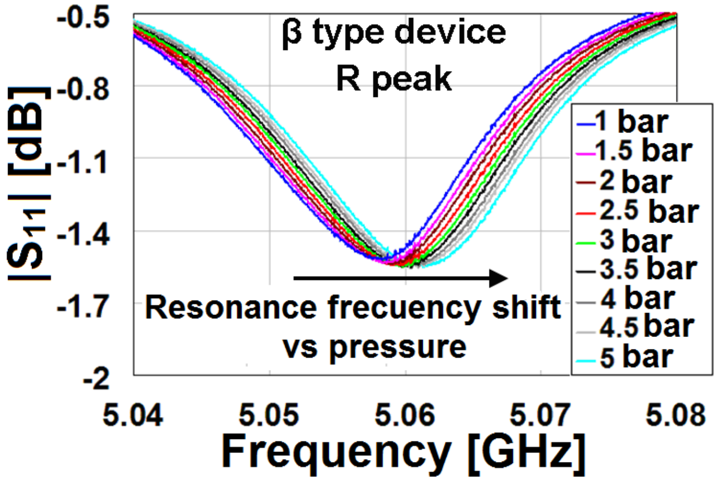
1.2 µm thin transparent GaN membrane supported Pressure+temperature sensing structures

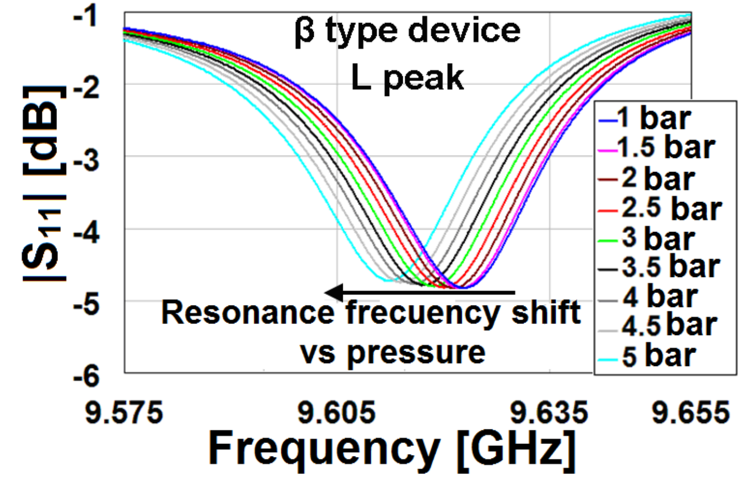
A. Müller, G. Konstantinidis, I. Giangu, G. Adam, A. Stefanescu, A. Stavrinidis, G. Stavrinidis, A. Kostopoulos, G. Boldeiu, A. Dinescu "GaN membrane supported SAW pressure sensors with embedded temperature sensing capability" *IEEE Sensor Journal, 2017, vol. 17, no. 22, Nov. 2017, pp. 7383 – 7393,*

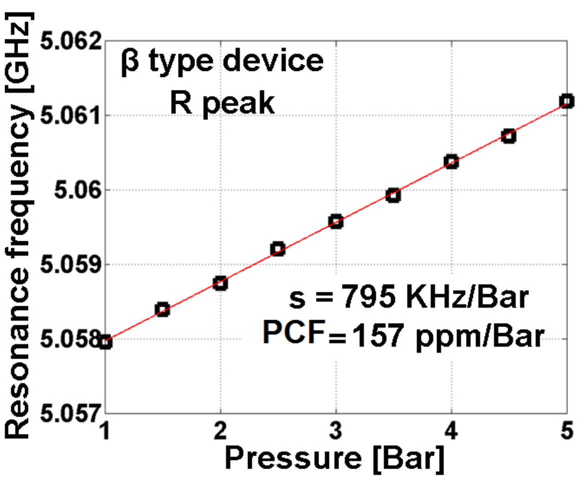
Our wave-shape simulations

Resonance frequency vs. pressure measurements

β type structures: GaN (1.2 μm) membrane

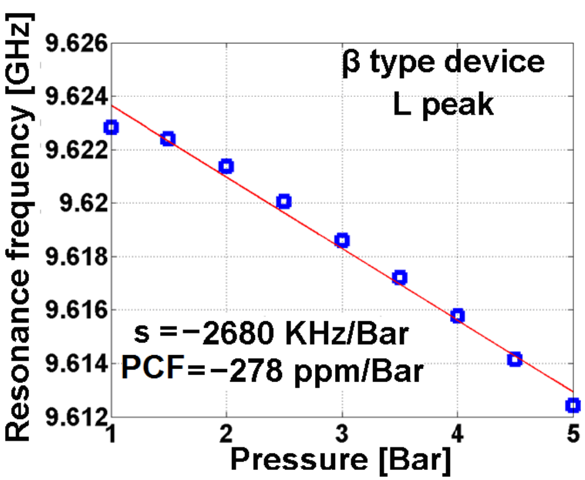




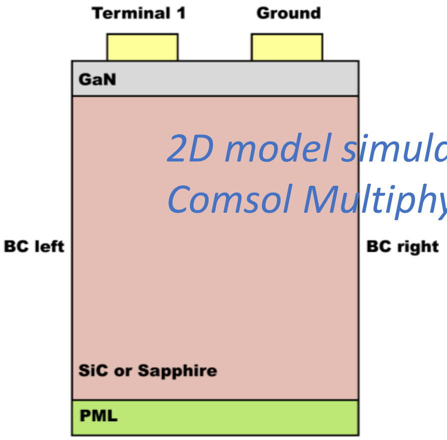


$$s = \frac{df}{dp}$$

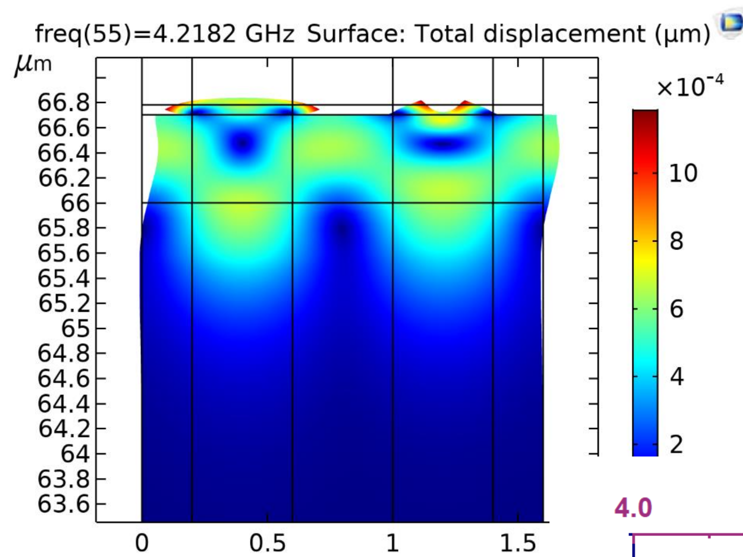
$$PCF = \frac{1}{p}\frac{df}{dp}$$



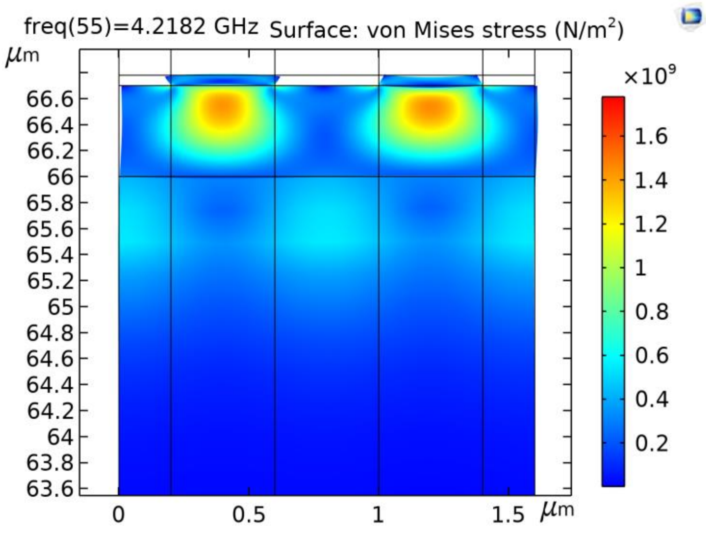
GaN/SiC SAW devices as temperature sensors



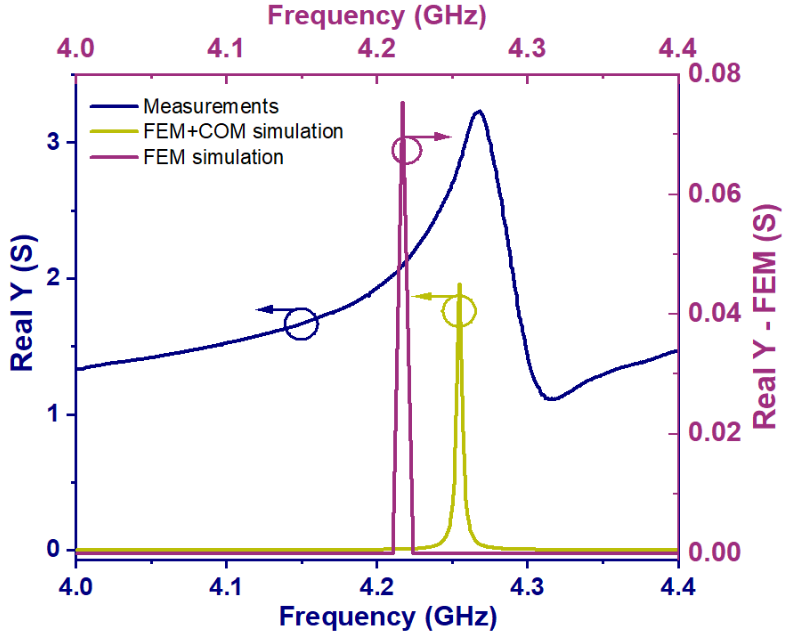
2D model simulated in Comsol Multiphysics



Total displacement at resonance frequency at room temperature



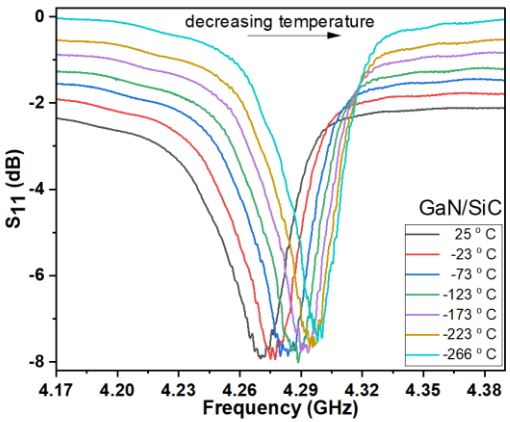
Stress at resonance frequency at room temperature

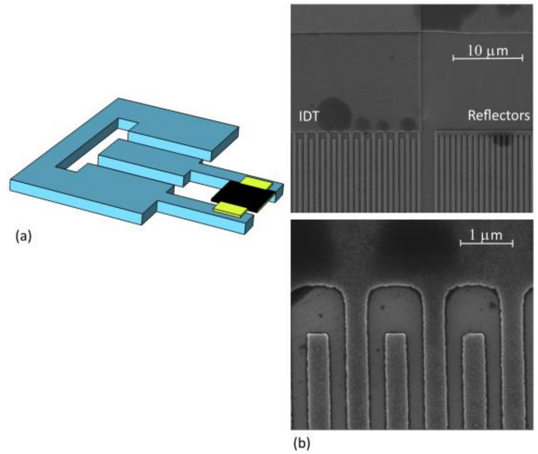


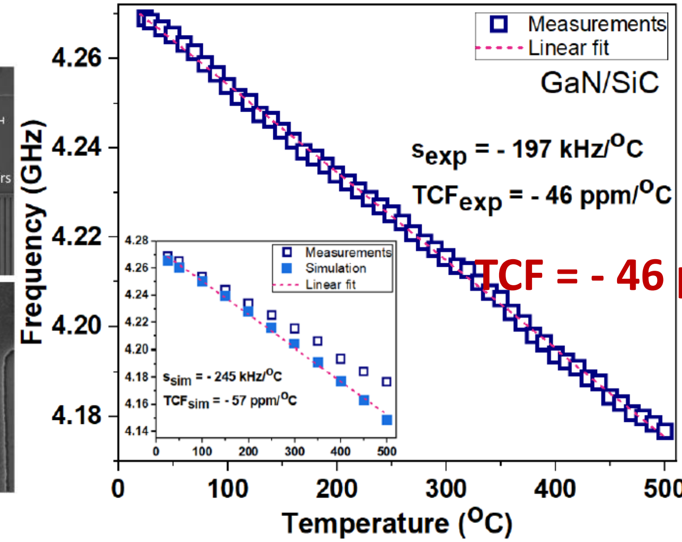
Real part of the admittance at 25°C extracted from the coupled FEM – COM simulation (yellow) compared to the measurements (dark blue) and to FEM simulation (violet)

One port SAW resonators

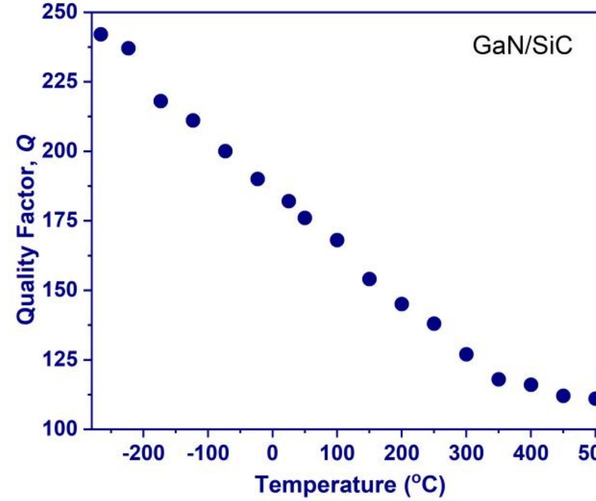
IDT finger width: 400 nm
IDT finger length: 100 mm
Ti/Au thickness on IDT: 5/75 nm

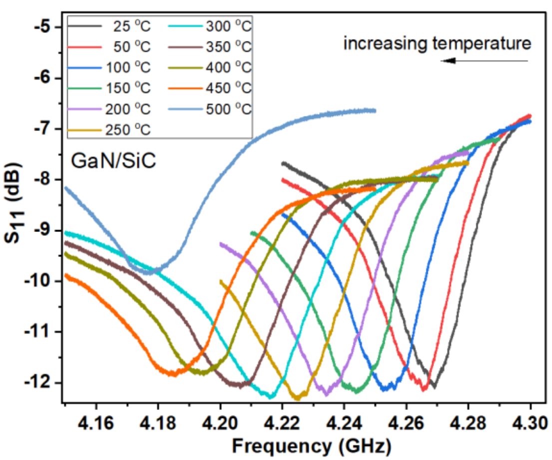






TCF = - 46 ppm/°C



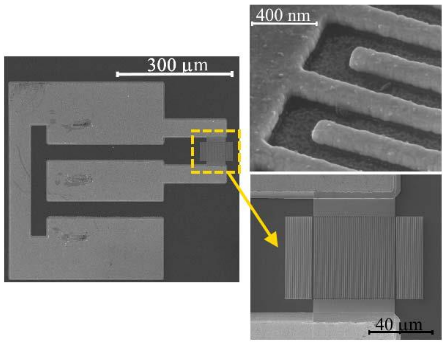


Surface Acoustic Wave Resonator under test (500°C) on a modified probe station

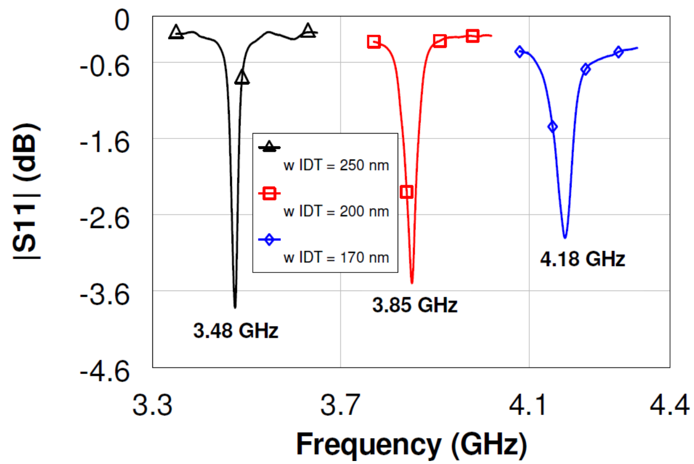
Measurements up to 500 °C
(developed at NASA)

- **George Boldeiu, George E. Ponchak, Alexandra Nicoloiu, Claudia Nastase, Ioana Zdru, Adrian Dinescu and Alexandru Müller, *IEEE Access, 10 (2022) pp.741–752***

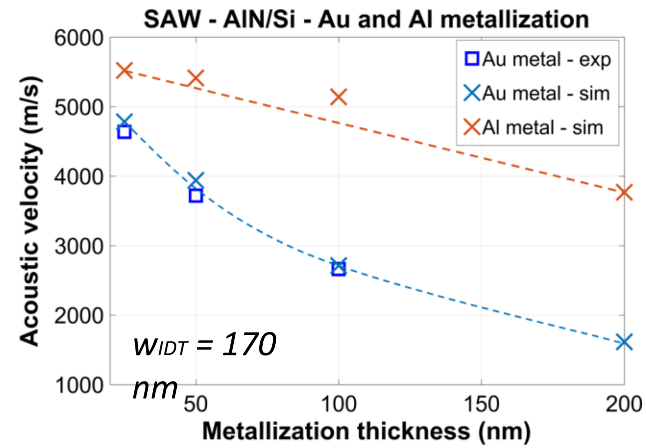
Temperature sensor based on AlN/Si SAW structures



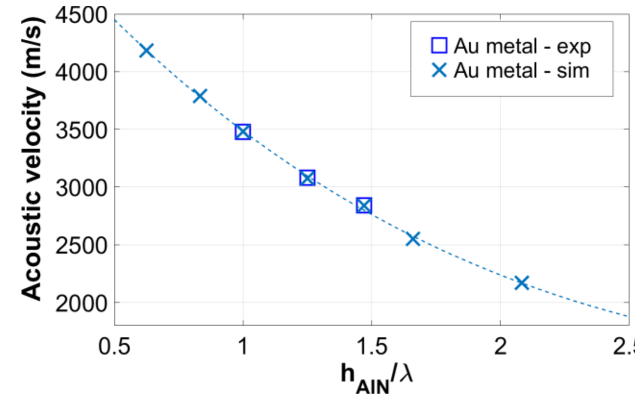
SAW structure on AlN/Si with170 nm digit/interdigit spacing *(150 fingers 50 µm long)*



Room temperature resonance frequency for wIDT = 170 nm, 200 nm and 250 nm



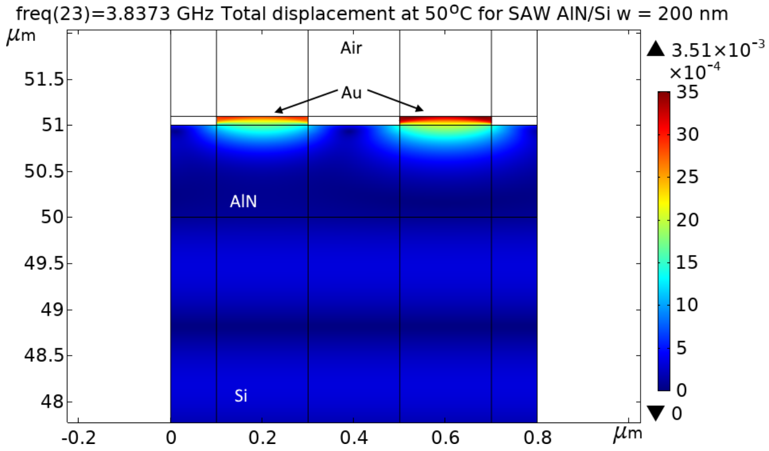
Experimental and simulated phase velocity vs. Au or Al metallization thickness



Dispersion curve for AlN/Si SAW structures Experimental and simulated phase velocity vs. the acoustic wavelength

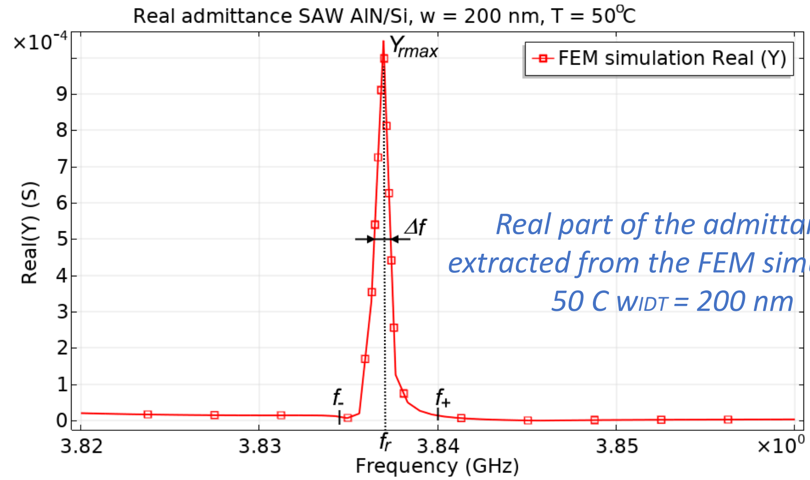
Coupled simulation based on FEM and COM

COMSOL Multiphysics



SAW AlN/Si 2-D FEM simulation

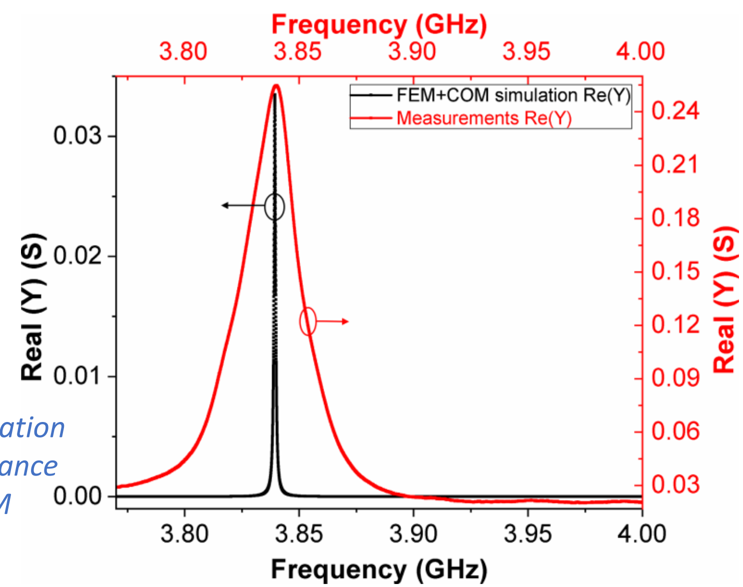
Total displacement, w_{IDT} = 200 nm; 50 ˚C



Real part of the admittance extracted from the FEM simulation 50 C w_{IDT} = 200 nm

For the first time, a coupled simulation based on FEM and COM was implemented in order to simulate the behavior of the AlN/Si at different temperatures

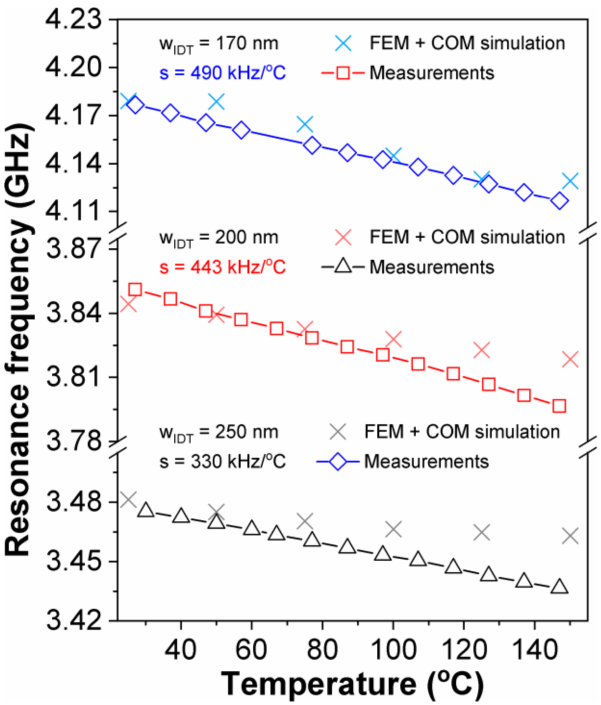
- **A. Nicoloiu, G. E. Stan, C. Nastase, G. Boldeiu, C. Besleaga, A. Dinescu and A. Müller, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 68 (5) (2021) pp.1938–1948***



Experimental and simulation Real part of the admittance coupled FEM – COM simulation

50 C, w_{IDT} 200 nm

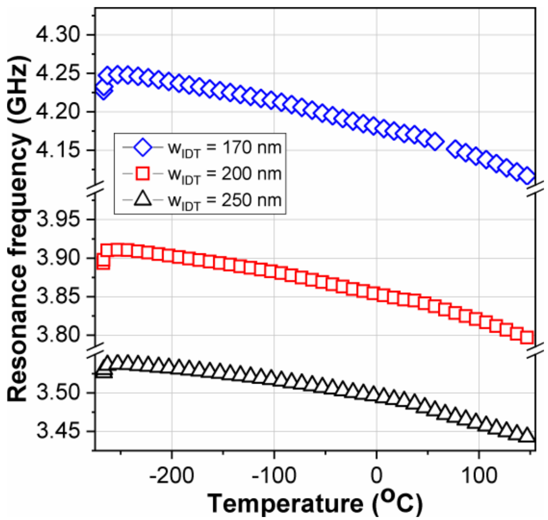
AlN/Si SAW structures - Performances as temperature sensor



Simulated and measurement results resonance frequency vs. temperature SAW structures on AlN/Si

WIDT = 250nm, 200nm, and 170 nm;

23˚C ≤ T ≥150˚C

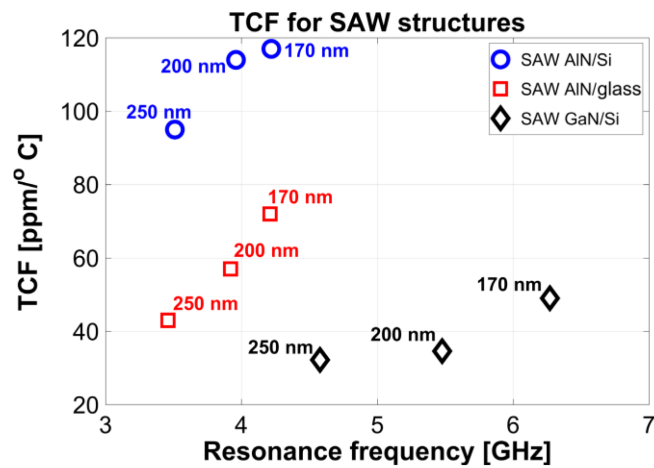


Resonance frequency vs. temperature

SAW structures on AlN/Si

wIDT = 250 nm, 200 nm, and 170 nm;

-267˚C ≤ T ≥ 150˚C



TCF vs. resonance frequency AlN/Si, AlN/glass, and GaN/Si SAW structures

wIDT = 250nm, 200nm, and 170 nm;

Comparison between temperature sensor based on AlN/Si and GaN/Si SAW structures

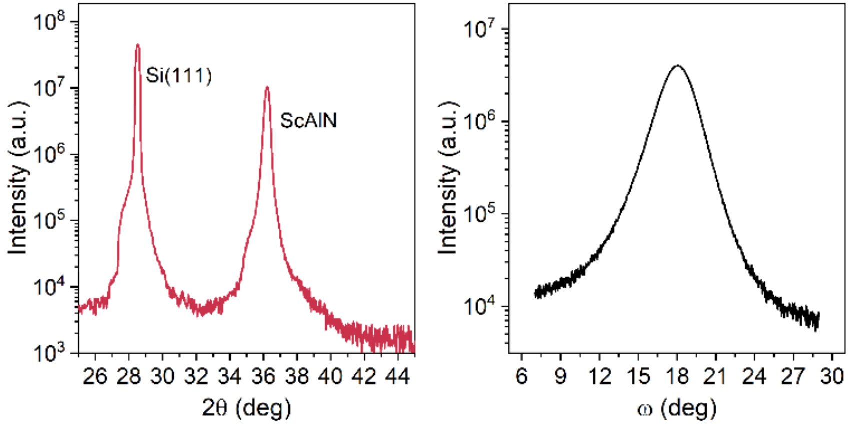
	AlN/Si			GaN/Si		
wIDT (nm)	170	200	250	170	200	250
Fres (GHz)	4.18	3.85	3.48	6.26	5.48	4.57
v (m/s)	2842	3080	3480	4256	4384	4570
S (kHz/C) 23-150 C	490	443	330	313	190	147
TCF (ppm/C) 23-150 C	117	114	95	49	35	32

AlN-based SAW-type sensors
better values for the sensitivity and TCF than GaN/Si-based structures

ScAlN/Si a novel promising material for GHz operating piezo devices

ScAlN is a novel material and a great candidate for acoustic devices fabrication, due to its excellent piezoelectric properties: high phase velocity, high coupling coefficient, k^2_{eff}, high Q-factor, high values of piezoelectric constants, surpassing the reported values for other group III-nitrides.

The material is still in research and the its crystalline quality after deposition on a Silicon Full Width at Half Maximum of the rocking curve, which is about 2.5 degrees, compared with GaN/Si where 0.5 degrees. We have purchased ScAlN, with a Sc concentration 30% from a member of the CHIRON FET OPEN project consortium

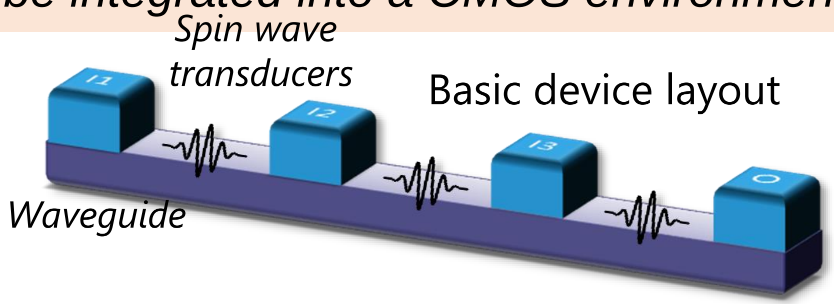


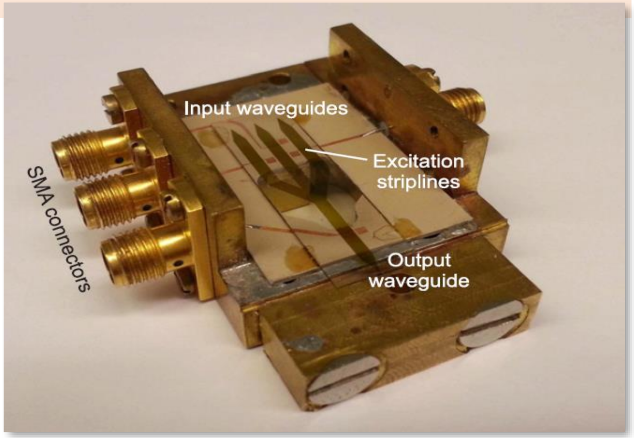
XRD diagram for the ScAlN (30% Sc doped) films grown on Si <111> (left) and the Rocking curve corresponding to ScAlN (right). **SOLMATES**

Spin Wave Computing for Ultimately-Scaled Hybrid Low-Power Electronics (2018–2022)

H2020 FET-OPEN: Coordinator: IMEC Leuven (BE), Dr. C. Adelmann –
CPartners: *U. Paris-Sud (FR), TU Kaiserslautern (DE), Solmates BV (NL), CNRS (FR), FORTH Heraklion (GR), IMT-Bucharest (RO), THALES SA (FR), TU Delft (NL).*

CHIRON will fabricate basic logic gates, such as inverters and majority gates, demonstrate their operation, and assess their performance. As transducers between the CMOS and spin wave domains in hybrid circuits, CHIRON will develop magnetoelectric and multiferroic nanoresonators, based on nanoscale acoustic resonators, which bear promise for high energy efficiency and large output signal. This technological proof of principle is complemented by the design of digital hybrid spin wave–CMOS circuits that show the advantages of spin wave computing and can be integrated into a CMOS environment.





Prototype of spin wave majority gate

Spin waves = wave-like excitations of magnetization in ferromagnetic medium

Computation by wave interference: ***majority gate***

FET proposal statistics at the beginning of 2017

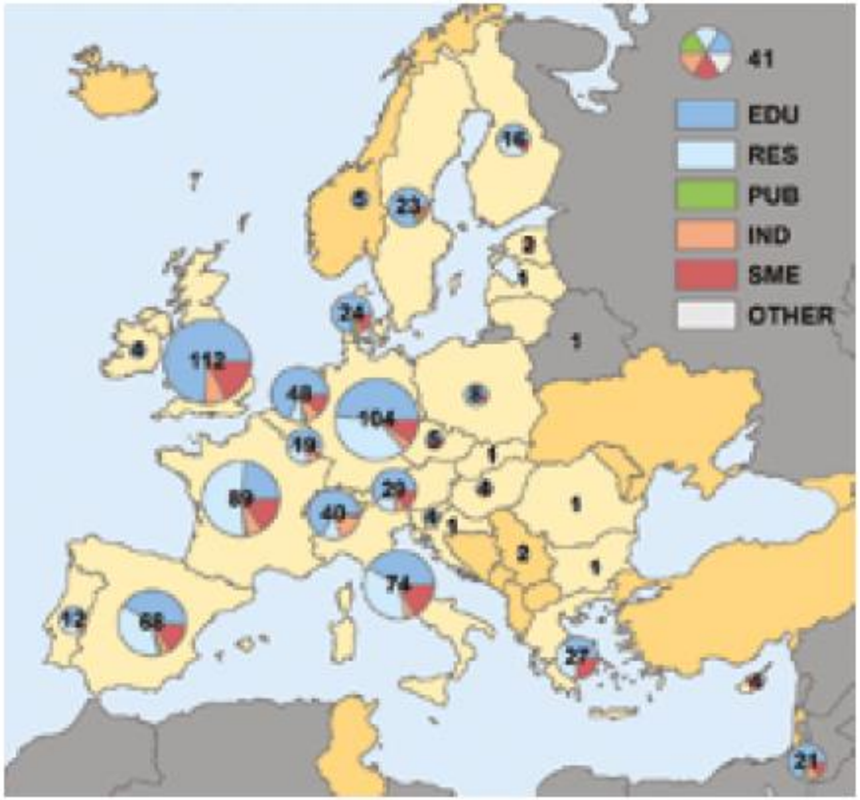


Figure 2. Number of FET-Open funded participants by country.

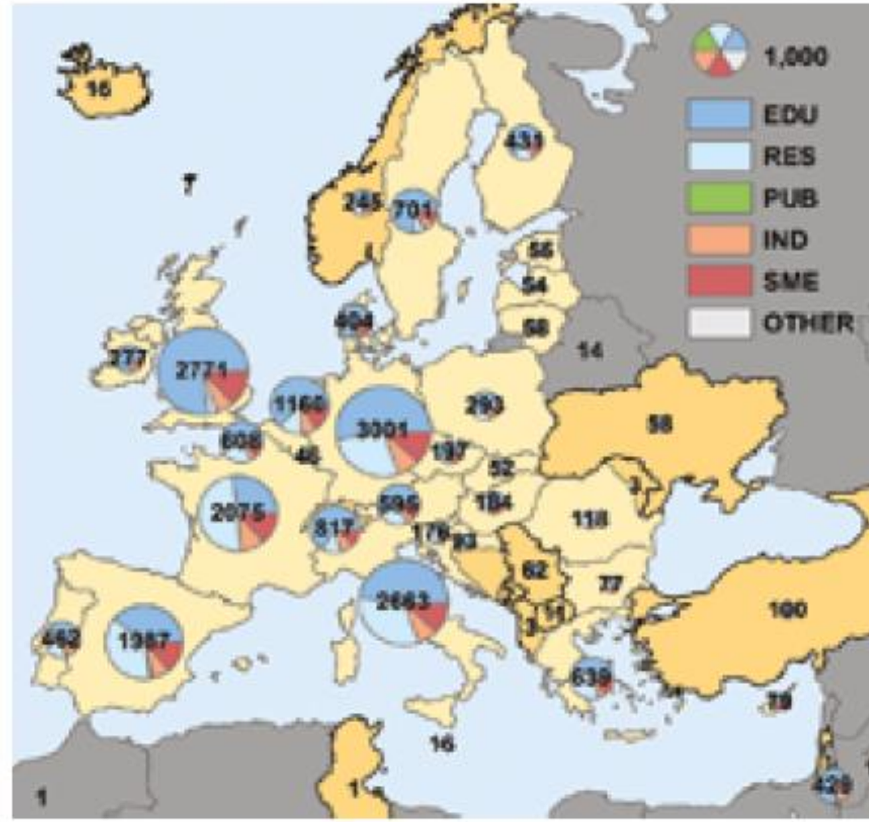
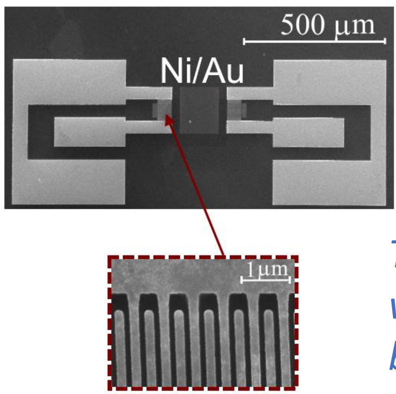


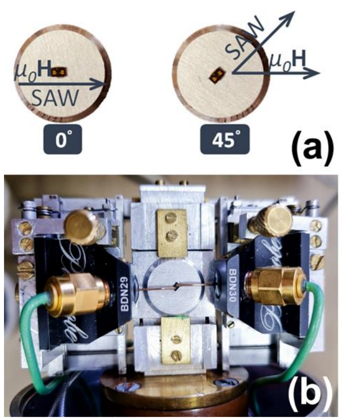
Figure 3. Number of applicants by country.

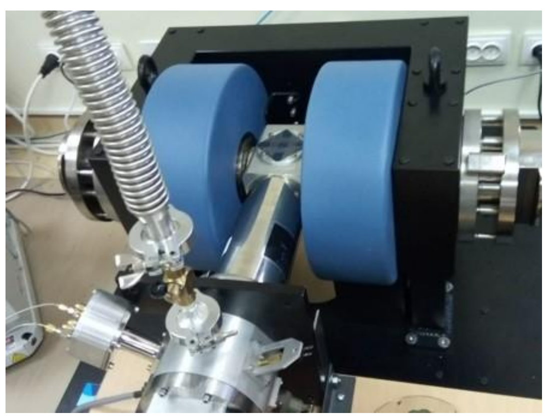
Source: https://www.kowi.de/portaldata/2/resources/horizon2020/coop/fet-open-2014-2017.pdf

ScAlN based SAW resonators for Surface Acoustic Waves/Spin Waves Coupling

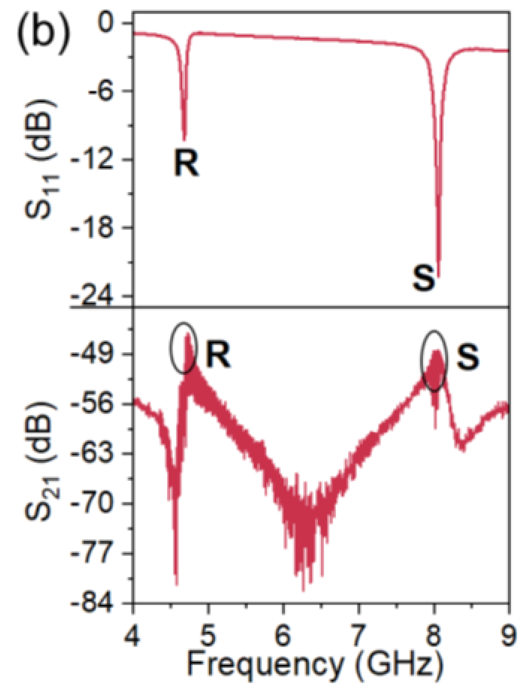


Two-port SAW device with a MS layer placed between the two IDTs



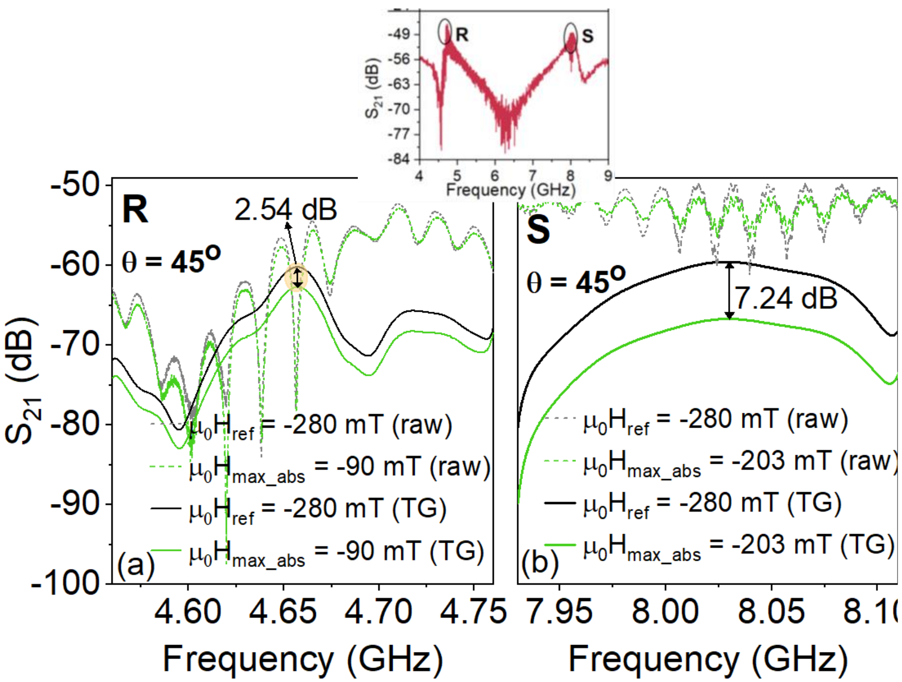


Measurement set-up

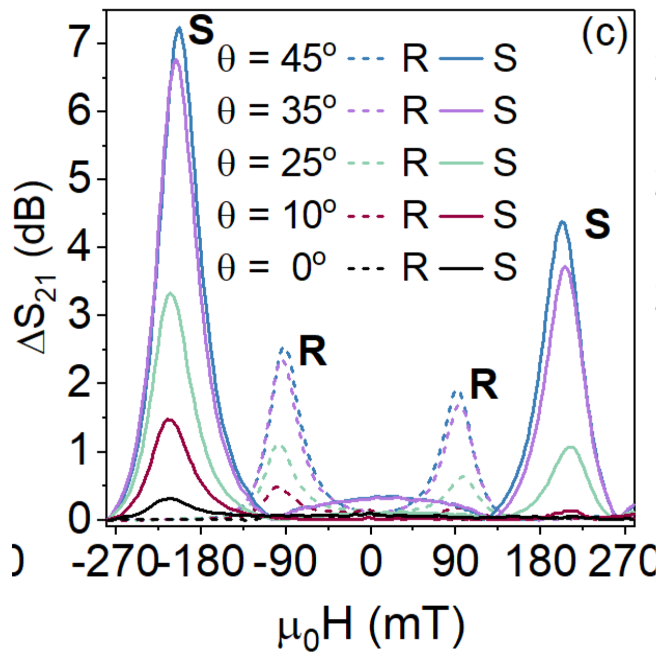


Reyleigh and Sezawa modes

I. Zdru, C Nastase, L.N. Hess, F. Ciubotaru, A. Nicoloiu, D. Vasilache, M. Dekkers, M. Geilen, C. Ciornei, G. Boldeiu, A. Dinescu, C. Adelmann, M. Weiler, P. Pirro and A. Müller, *IEEE Electron Device Letters, 43 (9) 2022, pp. 1551-1554*



Reference value μ0Href - dashed ***black*** *curve*
Value of maximum absorption observed μ0Hmax_abs - dashed ***green*** *curve for Rayleigh (a) and Sezawa (b) modes*
Time gated-(TG) data processing *– solid curves*

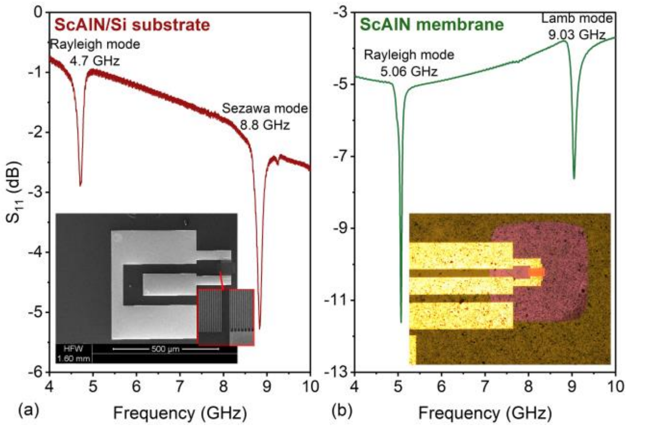


ΔS_{21} vs $\mu_0 H$ for R and S modes for different values of *the magnetic field*

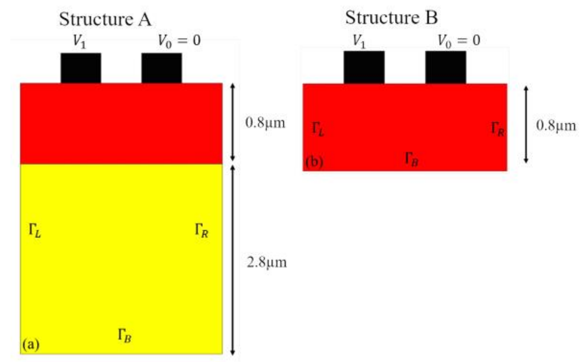
Temperature sensors based on ScAlN SAW resonators

Structure A on the bulk ScAlN/Si

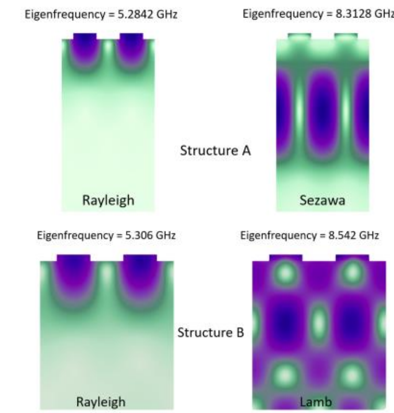
Structure B on the 0.8 μm thin ScAlN membrane



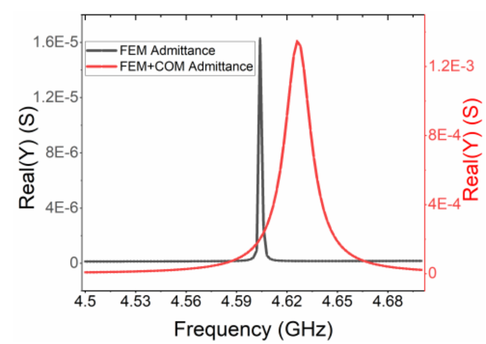
S_{11} parameters for structures A (a) and B (b); inset: SEM image of 150 nm width IDTs (a) and optical image (top view) of the 0.8 μm thin ScAlN membrane supported SAW resonator (b)



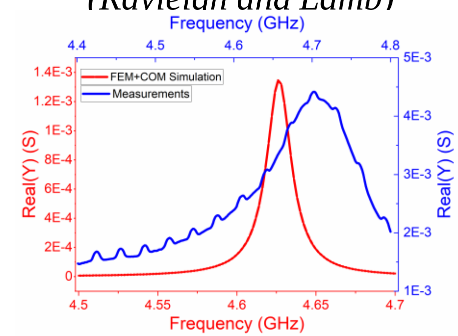
Geometrical parameters and boundary conditions for Structures A and B



Mode shapes for structures A (Rayleigh and Sezawa) and B (Rayleigh and Lamb)

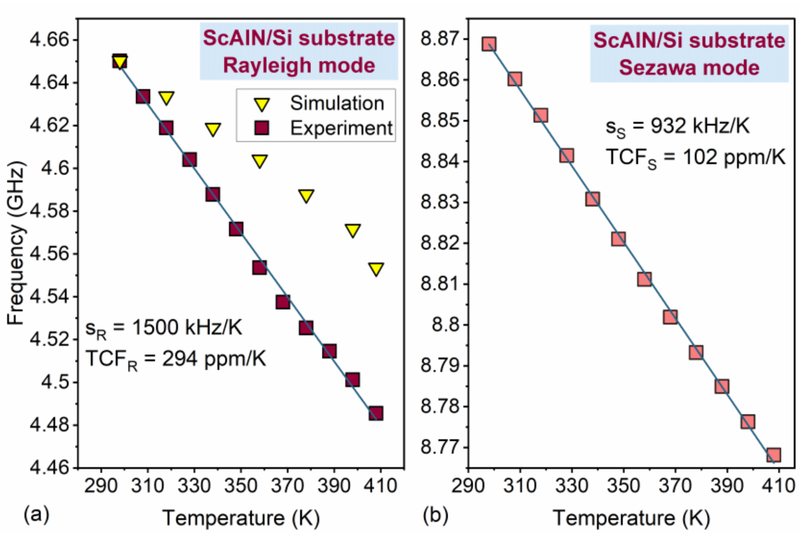


Real admittance comparison between FEM simulation and COM calculation for Structure A (Rayleigh mode)

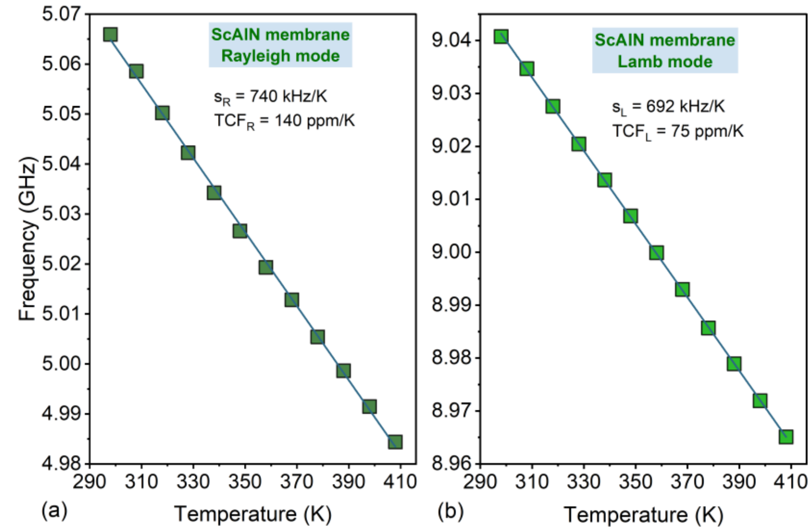


Real admittance between COM simulations and measurements (structure A (Rayleigh mode)

Unpublished results



Resonance frequency variation vs. temperature between 298 K and 408 K for structure A: Rayleigh mode (measurements and simulations) (a) and Sezawa mode (b)



Resonance frequency variation vs. temperature between 298 K and 408 K for structure B: Rayleigh mode (a) and Lamb mode (b)

Wafer	ScAlN/Si		ScAlN membrane	
Mode	R	S	R	L
f_r (GHz)	4.6	8.8	5.06	9.03
s (kHz/K)	1500	932	740	692
TCF (ppm)	294	102	140	75

Unpublished results

A. Nicoloiu, G, Boldeiu, C, Nastase, M, Nedelcu, C, Ciornei, I, Zdru, G, Stavrinidis, D, Vasilache, A, Stavrinidis, A, Dinescu, G, Konstantinidis and A, Müller, ***Transducers 2023***, 25-29 June 2023, Kyoto, Japan – **accepted paper**

Thank you for your attention!

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