Nanoprocessing and micromachining of WBG semiconductors for acoustic devices and UV photodetection

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Outline

1. Introduction

   - WBG semiconductors and technologies

2. Development in GaN/Si and AlN/Si FBAR structures using micromachining technologies

3. Development of AlN SAW devices using nanolithographic IDTs

4. GaN membrane MSM structures for UV detection obatained by micromachining and nanoprocessing of GaN/Si

5. Conclusions

WBG semiconductors

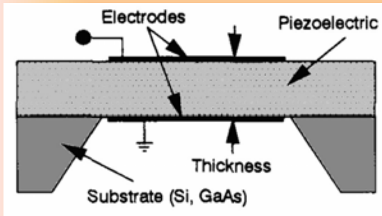
Applications:
-high power electronics
-acoustic devices for GHz applications (FBARs and SAWs)
-UV photodetectors

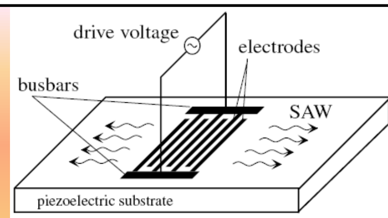
Most common WBG semiconductors are: ZnO SiC, GaN and AlN,

GaN and AlN

- GaN has high power capabilities that make it very attractive for microwave and millimetre wave applications and for creating a new generation of sensing devices capable of working in harsh environments at temperatures higher than 600 °C,
- GaN and AlN have strong piezoelectric properties.
- GaN has a high breakdown field (~3x10^6 V/cm),
- GaN has a high electron saturation velocity (~3x10^7 cm/s)
- AlN and GaN have high sound velocity,
- GaN has a direct band-gap (which confers to the photodetector a highly improved spectral selectivity).
- GaN and AlGaN compounds, due to their band gap, cover most UV detection application in the 200-370 nm range,

FBAR/SAW





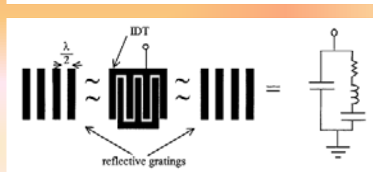


Fig. 17. SAW resonator.

d= membrane thickness

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

$f_r = v_s/2d$

w=digit width= interdigit width

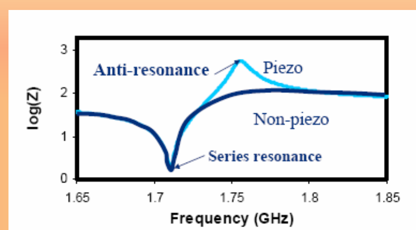
$2w = \lambda/2 = v_s/2f_r$

$f_r = v_s/4w$;

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 response of a acoustic resonator is similar to that of a multi-pole resonant circuit.***
- 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.**

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: $S \propto f^2$

•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

WBG semiconductor technologies

The WBG technologies, developed in the last years, are typical semiconductor technologies offering the compatibility with MEMS technologies, the use of nanolithography as well as the possibility of monolithic or hybrid integration with other circuit elements (e.g. HEMT transistors)

1. The sub-micron thickness of the GaN or AlN membrane in FBAR devices can increase their operating frequency
2. The use of nanolithography to fabricate the interdigitated transducer (IDT) of the SAW structures will resulting an increasing of operating frequency
3. Micromachining of GaN and the use of nanolithography can improve UV photodetector performances

•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

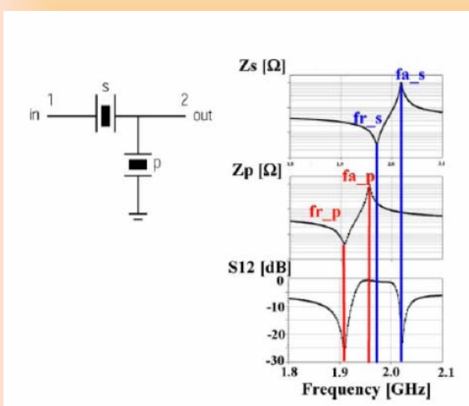
•Most FBAR structures reported in the last years were manufactured on ZnO a semiconductor incompatible with monolithic integration

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

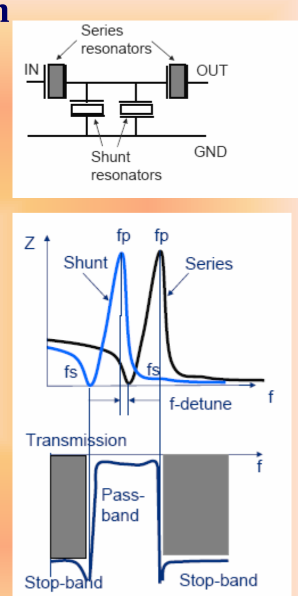
•In GHz SAW technology nanolithography for the IDT is necessary

•For FBAR structures it is necessary to develop very thin selfsustainable membranes

Filter construction

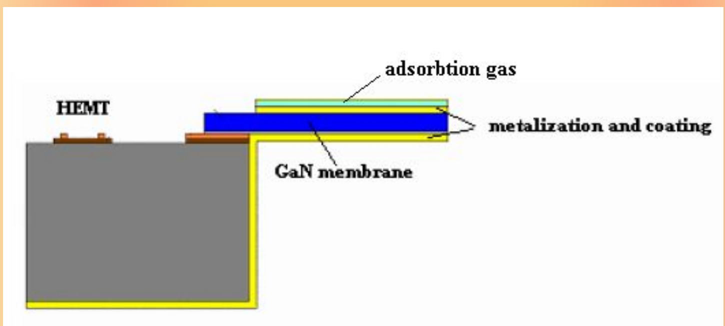


H. P. Loebl et al. "RF bulk acoustic wave resonators and filters," Journal of Elctroceramics, vol. 12, pp. 109-18, 2004.

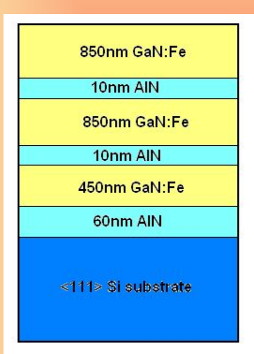


P Kirby, Presentation at 1st AMICOM Summer School, Analipsi, Greece, 2004

An emerging application of GaN FBARs/ SAWs - sensing of poison gases in harsh environmetal



The GaN on silicon structure grown by MOCVD sed for the first FBAR structures (grown by Azzuro Ltd. Magdeburg)

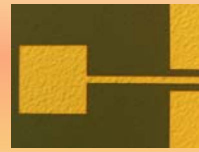


GaN membrane layer ~ 2.2μm

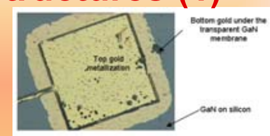
- **The first AlN layer has a buffer function**
- **The inter-layers (10 nm thick) are used in order to minimise the thermal stress and avoid the cracking of the GaN layers.**
- **The Fe doping allows to compensate the native doping in GaN layers**

First GaN membrane FBAR structures (1)

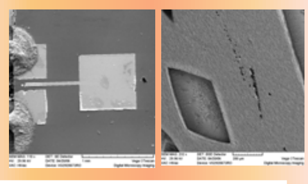
Cross section of the FBAR structure with the evaporated Ti/Au for the top metallization and sputtered Au for the bottom contact. Sputtered Al is used as mask for the bulk-micromachining of the membrane



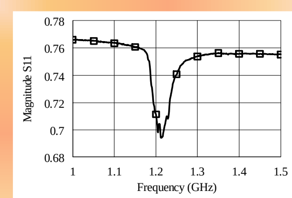
GaN membrane supported FBAR structures before backside etching



Top optical photo of the active area of the experimental F-BAR structure



- 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 2.2µm thin GaN layer using SF_6 plasma.
- Sputtering of 250 nm thin gold layer on the bottom of the wafer.

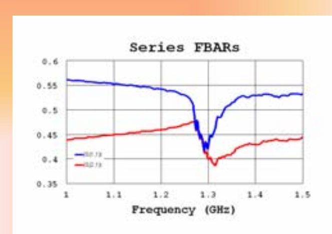


Return losses vs frequency for the GaN membrane supported FBAR structure

The thickness of the membrane was 2.2µm

First GaN membrane FBAR structures (2)

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



A. Muller, D. Neculoiu, D. Vasilache, D. Dascalu, G. Konstantinidis, A. Kosopoulos, A. Adikimenakis, A. Georgakilas, K. Mutamba, C. Sydlo, H.L. Hartnagel, A. Dadgar, "GaN micromachined FBAR structures for microwave applications", *Superlatices & Microstructures*, 40, 2006, pp426-431

The thickness of the membrane was 2.2µm

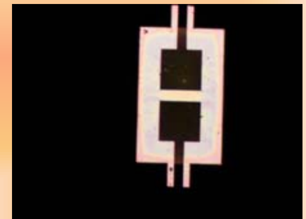
GaN FBARs

IMT and FORTH
March 2008

500 nm (GaN) +280nm (buffer) thin membrane supported FBAR structure based on GaN micromachining

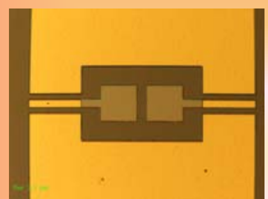
•50nm thin Mo metallization

•GaN/Si wafers from NTT AT Japan

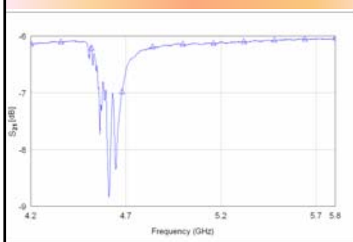


Top view; bottom illumInation

Before membrane manufacturing



Top view top illumination



Top view; top+ bottom illumination

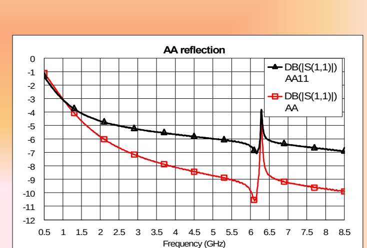
GaN FBARs

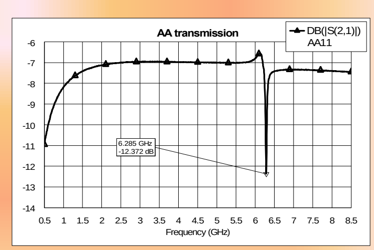
IMT and FORTH
July 2008

300 nm (GaN) +280nm (buffer) thin membrane supported FBAR structure based on GaN micromachining

50nm thin Mo metallization

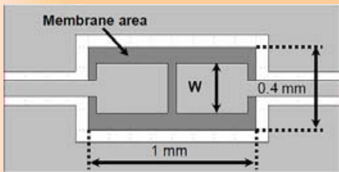
GaN/Si wafers from NTT AT Japan





Final structure (top and bottom view)

AlN FBAR structures

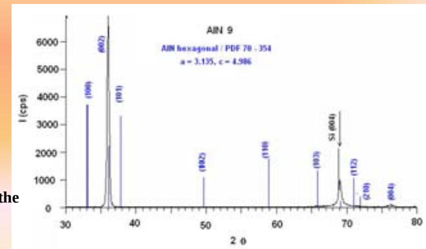


The layout of the AlN FBAR test structure

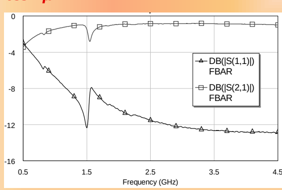
Top optical photo of the manufactured FBAR structure (w = 300µm, membrane: 1000x400µm) *Membrane thickness 2µm*

Bottom gold under the transparent AlN membrane

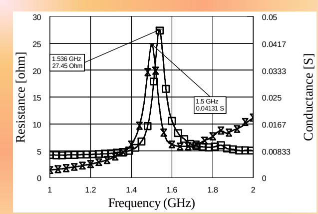
AlN on silicon



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

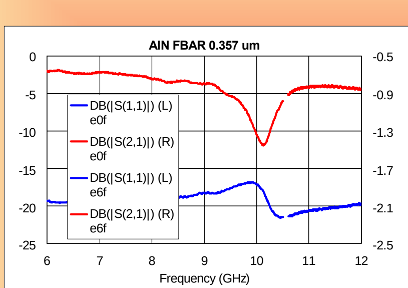


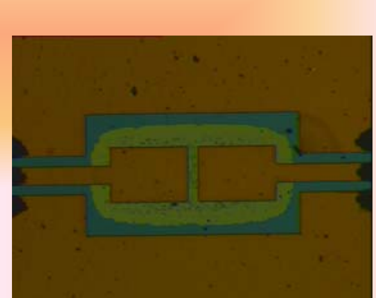
Magnitude of the measures S parameters of the AlN based FBAR 300 µm test structure



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

FBAR series connection (AlN membrane W= 0.357 µm)

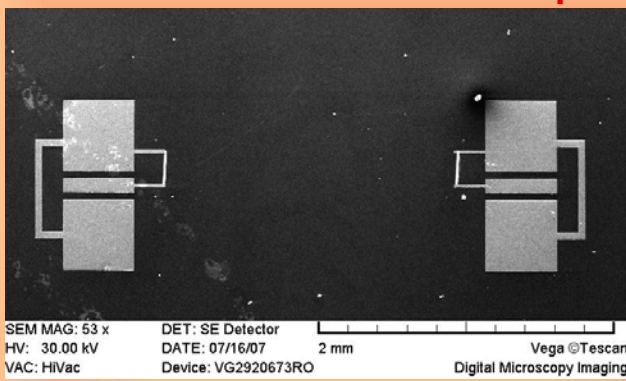




SAWs

First run

The idea of the experiment

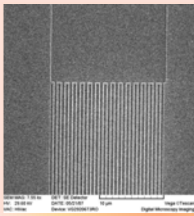


Each IDT structure has 30 digits and 29 inter-digits. The digits and inter-digits have a length of 200µm, and an equal width of 200 nm for one type of test structures and 300nm for the other type.

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).

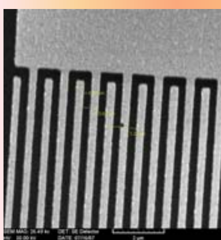
Due to the digits/interdigits dimensions, a direct writing process was used, for the IDT structure.
The design transfer on the wafer was performed using a Scanning Electron Microscope (Vega from Tescan), equipped with an Electron Beam Lithography system (Elphy Plus from Raith) (IMT).

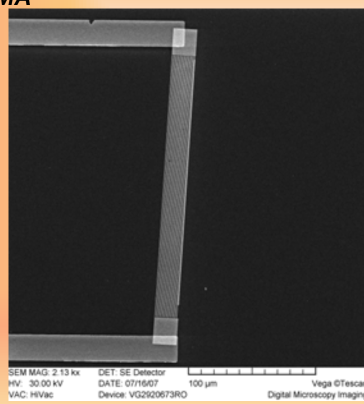
Finally, Ti/Au (20/nm/200nm) is deposited by e beam and a lift-off process, is used to remove the unwanted metal (FORTH).

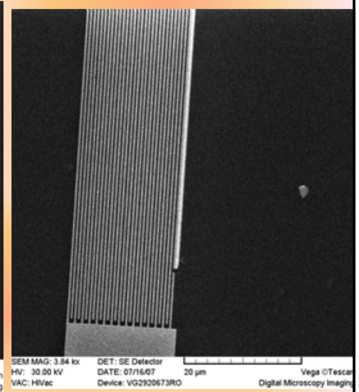


300nm lines in PMMA

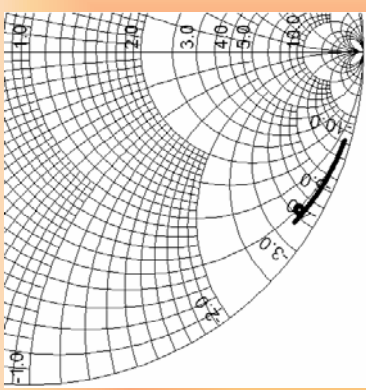
A SAW structure with an IDT having metalic fingers and pitches of 300nm



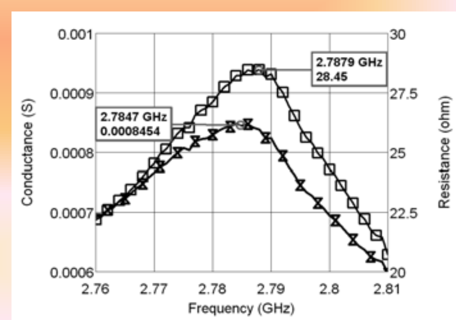




Measurement results

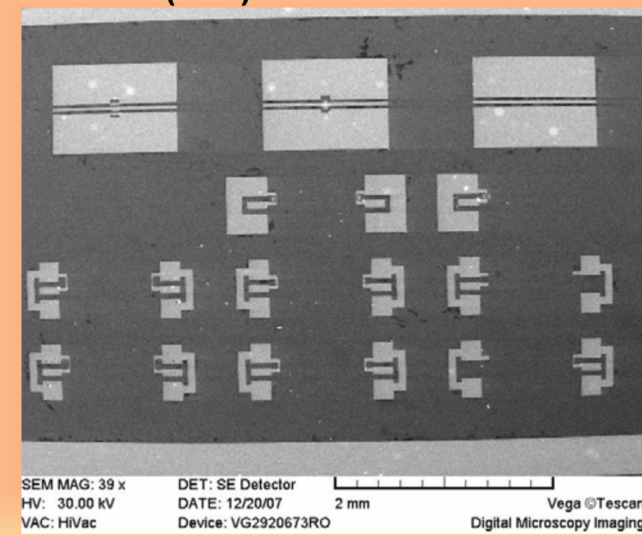


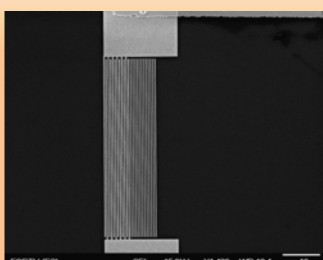
Smith chart representation of the SAW resonator input impedance (detail)

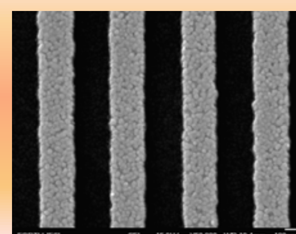


The resistance and the conductance of the SAW resonator

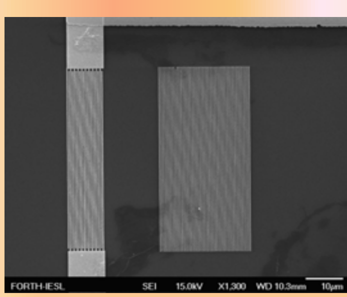
The nano-SAW test structure (AlN) second run

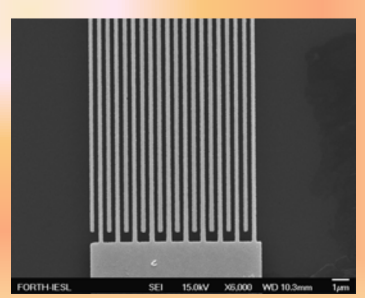




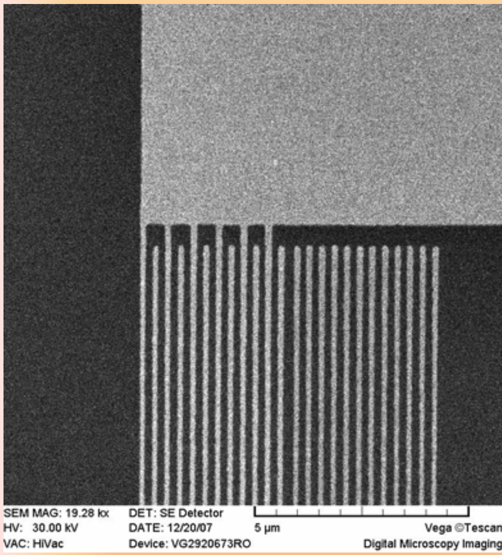


SAW test structure (W=300nm)





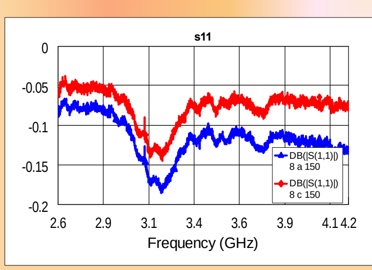
SAW test structure (W=250nm)

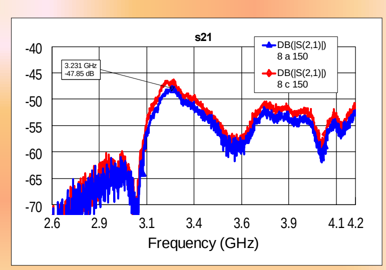


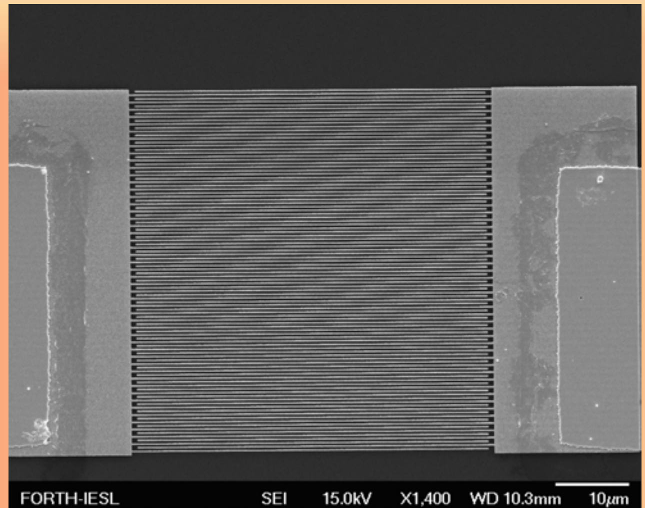
SAW structure detail (w=150nm)

Nanolithography performed at IMT with VEGA 5136 LM SEM from TESCAN and ELPHY Plus Nanolithography equipment from RAITH GmbH

SAW - AlN 0.5 µm thick; 150 nm

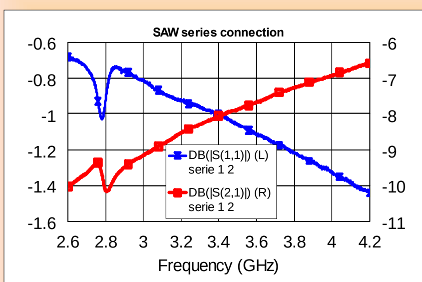


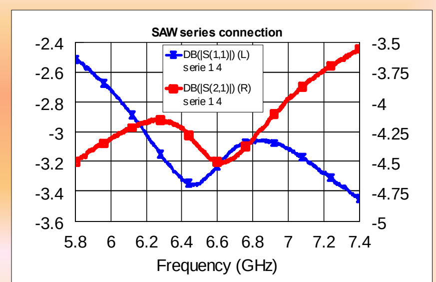


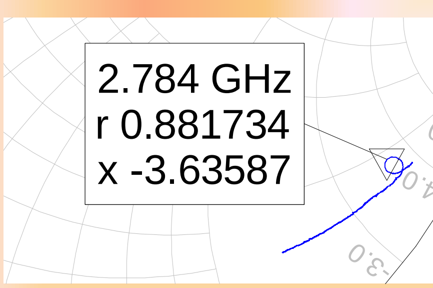


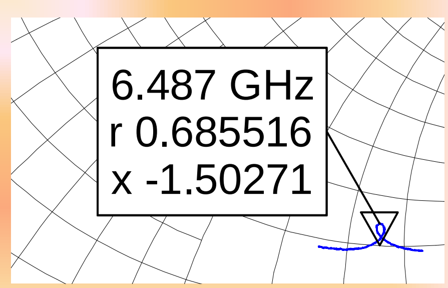
Series connection of SAWs (detail)
(w=300nm)

SAW - series connection (AlN 0.5 μm thick)









Remark

- A third run was manufactured on a thin GaN layer. The thickness of the metalization was reduced to 60nm and Molibdenum was used. For the first time nanolithography was succesful on GaN.
- An interuption between the pads and the IDT (few tens of nm wide) appeared during the process. A new run is in progress

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].*

Applications of WBG for UV photodetectors

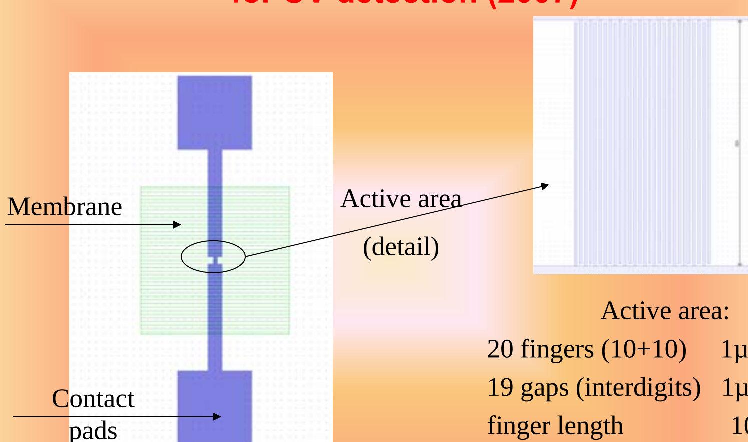
These devices have an important commercial and scientific interest for:

- engine control
- astronomy
- lithography aligners
- solar UV monitoring
- space-to-space communications,
- detection of missiles

Most of these applications fit in the optical spectrum range 200–370 nm covered by nitrides, in particular by GaN and AlGaN compounds.

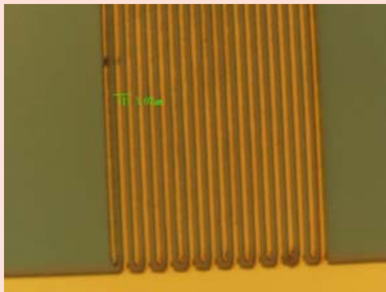
Most used photo detectors devices are based on metal-semiconductor metal (MSM) structures due to their simplicity

First MSM GaN membrane test structure for UV detection (2007)

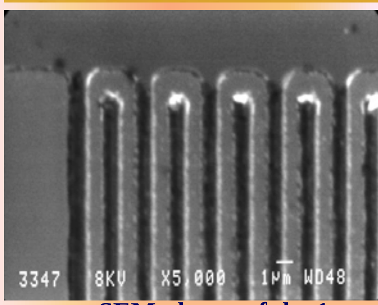


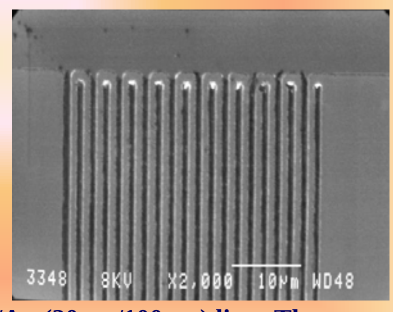
Active area:

20 fingers (10+10) 1µm wide;
19 gaps (interdigits) 1µm wide;
finger length 100 µm
nontransparent metallization
Ni/Au (20nm/100nm)

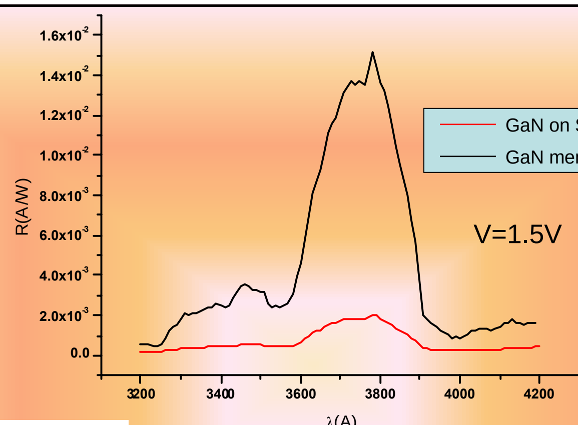


- Normal UV lithography has been used
- GaN/Si wafers from Azzuro Ltd. (Germany) have been used
- The GaN membrane was 2.2 µm thin

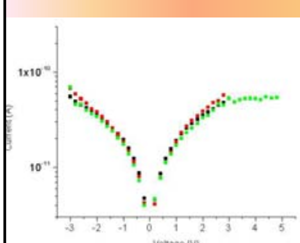




SEM photos of the 1 µm wide Ni/Au (20nm/100nm) lines The interdigit width was also about 1 µm



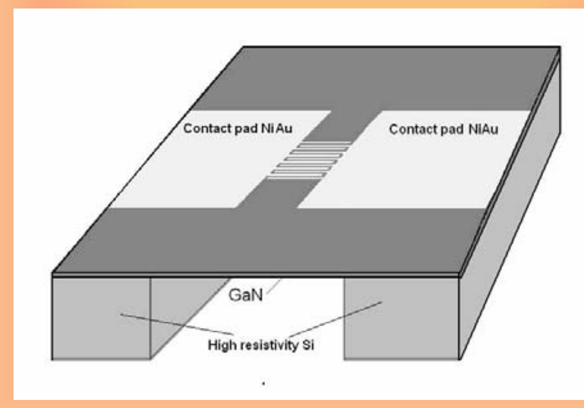
Responsivity vs.wavelenghth



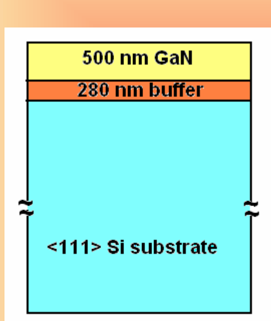
Dark I-V characteristics

A. Müller, G. Konstantinidis, M. Dragoman, D. Neculoiu, A. Kostopoulos, M. Androulidaki, M. Kayambaki and D. Vasilache „GaN membrane metal–semiconductor–metal ultraviolet photodetector" APPLIED OPTICS, Vol. 47, No. 10, 2008, pp 1453-1456

GaN membrane supported UV photo-detectors manufactured using nano-lithographic processes



RUN 2



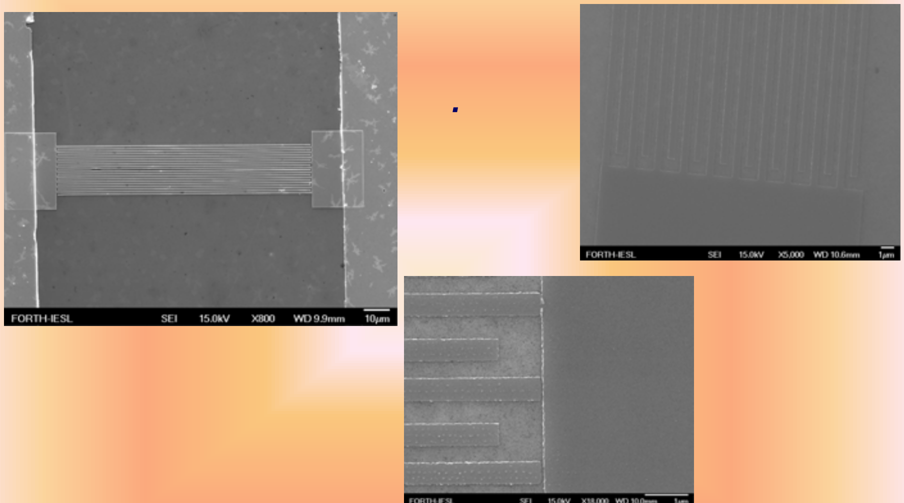
GaN/Si wafers from NTT AT Japan

- Conventional contact lithography, e-gun Ni/Au (10nm/200nm) evaporation, lift-off for the pads.
- Nanolithography (Vega SEM from Tescan and Elphy Plus EBL from Raith) to define the MSM interditated structure. PMMA about 50nm high
- e-gun Ni/Au evaporation 5nm/10nm. Lift-off techniques to define the inerdigitated MSM strucure 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 0.78 μm thin GaN layer using SF_6 plasma.

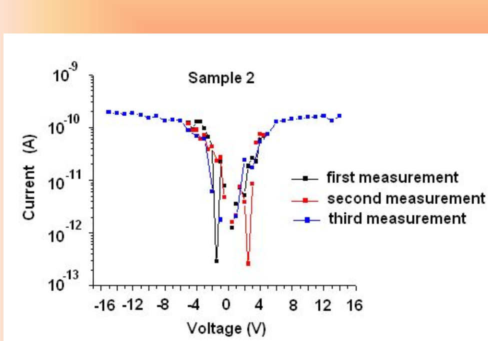
Si substrate resistivity >5 kΩcm

Membrane layer ~ 0.78μm (0.28 buffer+0.5 GaN)

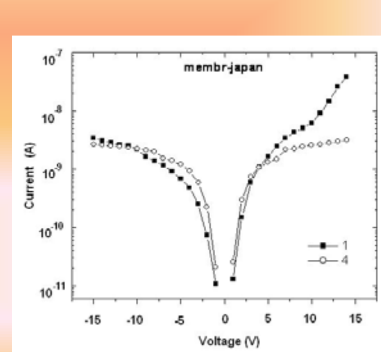
Active area of the structure ~1500 μm^2



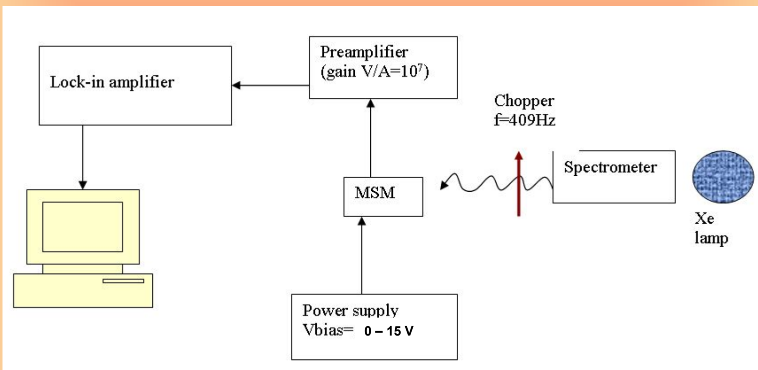
SEM photo (left)and detail (right) for the 0.5 µm wide finger/ interdigit detector structure manufactured on a 0.78 µm thin GaN membrane



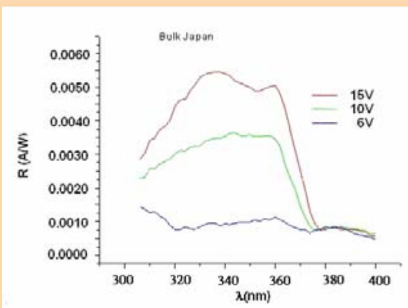
*Dark current for the 0.5µm finger / interdigit for the UV detector structure-**before** the silicon substrate removal (thickness of the GaN layer 0.78µm)*



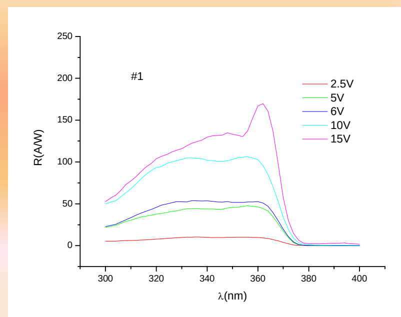
Dark current for the 0.5µm finger / interdigit for two UV termed “1” and “4” detector structures- manufactured on 0.78µm thin GaN membrane



Optical measurements set-up



Responsivity vs wavelength for the 0.5µm finger / interdigit for the UV detector structure- ***before*** *the silicon substrate removal (thickness of the GaN layer 0.78µm)*



Responsivity vs wavelength for the 0.5µm finger / interdigit for two UV detector structures- manufactured on 0.78µm thin GaN membrane

A.Müller, G. Konstantinidis, M. Dragoman, D Neculoiu, A. Dinescu, M. Androulidaki, M. Kayambaki, A. Stavrinidis, D. Vasilache, C Buiculescu, I. Petrini, A. Kostopoulos, D. Dascalu, "GaN membrane supported UV photo-detectors manufactured using nano-lithographic processes", Microelectronics Journal, 2008, in press

Discussions

•Very low dark currents (1-10 pA) at moderate voltages have been obtained for all structures

•The second run, manufactured on a thinner membrane (0.78 µm) having a MSM structure with fingers and interdigits of 0.5 µm wide, presents an unexpected high value for the responsivity (50-150 A/W for a bias in the range 6-15 V). These values are 3 orders of magnitude higher than those obtained for GaN on bulk silicon.

Discussions(2)

•The low values obtained for the responsivity for similar GaN detectors on bulk silicon (values of 1-5 mA/W for voltages in the range 6-15V) seems to confirm that responsivity measurements are correct. If we start from this assumption, it seems that we can have a major advantage using micromachining technologies to manufacture UV GaN detectors on thin membranes. As a comparison, for a 0.5 -1µm finger/interdigit detectors manufactured on GaN /sapphire a maximum responsivity of 0.3-0.5 A /W

•The MSM structure has a gain, and the membrane can increase this gain. Carriers are confined in the thin suspended membrane and can have reflections on the top and bottom of the membrane. This can be an explanation for the major influence of the micromachining on the increasing of the responsivity. It must be also noticed that we believe that the material used has a very high quality with less interface and volume defects.

•Results have to be confirmed on other structures with similar and smaler dimensions for the digit/interdigit width. Also we have to improve the yield of the process.

CONCLUSIONS

-GaN FBAR structures have been developed for the first time; Using micromachining technologies and very thin membranes resonators with frequencies up to 6.4 GHz have been obtained

-AlN FBAR resonators structures with frequencies up to 10 GHz have been obtained (using membranes with a thickness of about 0.36 μm)

-AlN SAW resonator structutes with frequencies up to 3.1 GHz have been obtained using an IDT with nanometric fingers and interdigits processed by nanolithographic techniques.

-GaN membrane UV photodetector structures with very low dark current (1…10pA) and very high responsivities (100-150A/W for 6….15V) have been obtained using micmomachining and nanoprocessing of GaN/Si.

Thank you !