Micromachining and nanoprocessing of GaN/Si for GHz acoustic resonators and UV photodetecting applications

A. Müller, G. Konstantinidis, D. Neculoiu
A. Dinescu, M. Dragoman, Alina Cismaru

IMT Bucharest, 32B, Erou Iancu Nicolae Street,
077190 Bucharest, Romania,
FORTH-IESL-MRG Heraklion, PO Box 1527, Crete, Greece

alexandru.muller@imt.ro

OUTLINE

- Introduction
- GaN/Si FBAR resonators
- GaN/Si SAW resonators
- UV photodetectors on thin GaN membranes
- Conclusions

The most common WBG materials are **SiC, GaN and AlN**

WBG materials exhibit unique physical properties like:

► high breakdown field
► high electron saturation velocity
► high sound velocity
► strong piezoelectric effects
► high power capabilities
► high temperature environment

GaN and AlN present pronounced **piezoelectric properties**.

All these properties make them very attractive for **microwave and millimeter wave applications** and also for creating a **new generation of sensing devices** capable of working in harsh environments at temperatures higher than 600 °C.

►Surface Acoustic Wave (SAW) and
►Film Bulk Acoustic Resonators (FBAR)

have a major interest in the fabrication of **radio frequency (RF)**

1. **filters for mobile and satellite communication systems,**
2. **various forms of data transmission (WLAN).**

- Most **SAW resonators** used in the actual mobile communication systems are manufactured on quartz, lithium tantalite or lithium niobate.
- Classical technologies for **FBAR resonators** are based on ZnO sputtered layers.

It becomes very difficult to achieve **low-loss** and sharp-cut off filters working **at frequencies higher then 2 GHz** using the **classical SAW and FBAR** technologies

Because

►The cellular phone 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 to 6 GHz**.

► Using **MEMS micromachining** techniques and **nanolithography**, applied to **WGB materials** it is possible to obtain **devices with low losses**, and **high operating frequency**

► Also is **important the possibility of monolithic or hybrid integration with other circuit elements (e.g. HEMT transistors)**, *because these materials (**GaN, AlN**) can be grown or deposed on semiconductor wafers (high resistivity GaAs or silicon)*

Sensors based on SAW and FBAR structures have the sensitivity ~f^2

WBG semiconductor technologies

1. The **sub-micron** thickness of the GaN or AIN membrane in **FBAR** devices can increase their operating frequency

2. The use of **nanolithography** *(fingers and interdigits 100–300 nm wide),* to fabricate the interdigitated transducer (IDT) of the **SAW** structures will resulting an increasing of operating frequency

3. Micromachining for GaN/Si and the use of **nanolithography** for the MSM interdigitated structure can improve **UV photodetector** performances and permits back-side illumination

AlN/Si

- Deposition by magnetron sputtering
- Sound velocity 9000 m/s ☐
- Coupling coefficient 6% ☐
- Band gap 6.3 eV

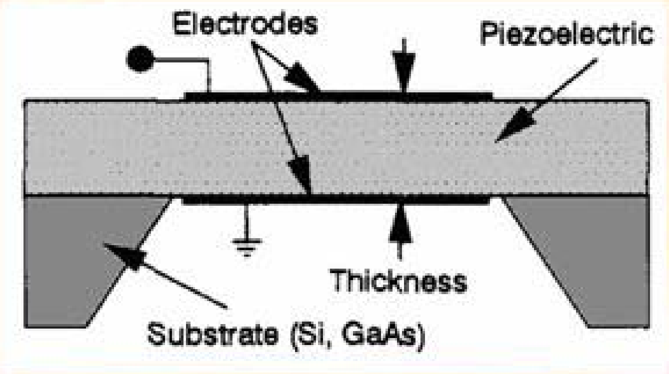
GaN/Si

- Deposition by MBE and MOCVD
- Sound velocity 7000 m/s ☐
- Coupling coefficient 2% ☐
- Nanolithography a big challenge ☐ ☐
- Monolithic integration with HEMT transistors is possible ☐
- Band gap 3.4 eV ☐ for UV photodetection

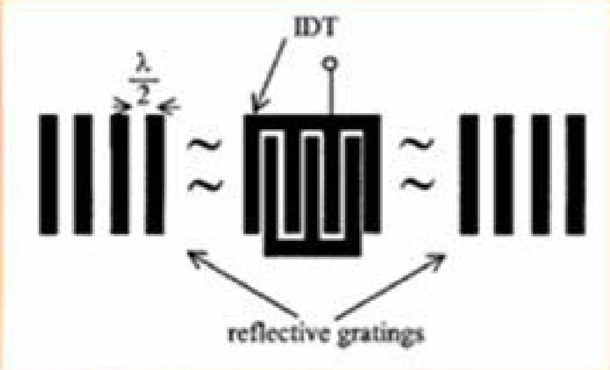
NANOTECHNOLOGY AND NANOPROCESSING

FBAR-Film Bulk Acoustic Resonator **Surface Acoustic Wave Resonator**

FBAR



SAW



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

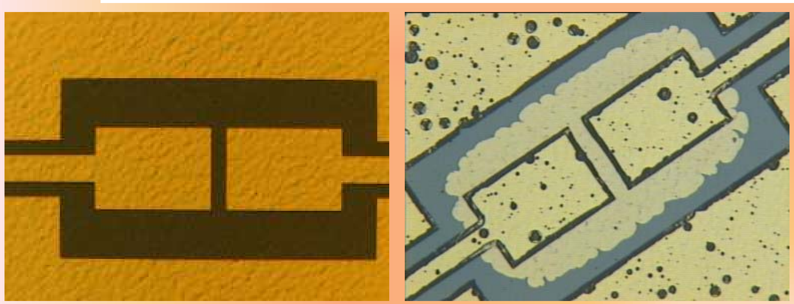
$f_r = v_s/2d$

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

$f_r = v_s/4w$;

v_s ~ km/s; d, w ~nm, f_r ~ GHz

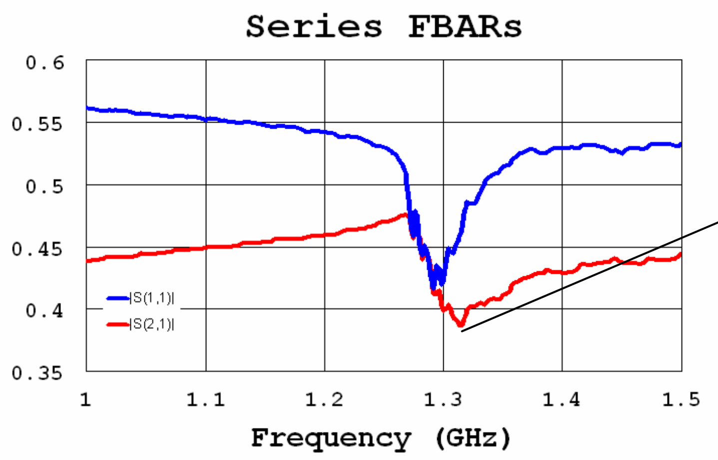
We develop for the first time
a FBAR structure on a thin membrane!
increasing drasticaly the resonance frequency !



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

IMT- Bucharest-FORTH Heraklion –TU Darmstadt 2006

The GaN on silicon structure grown by MOCVD (Azzuro Ltd. Magdeburg)



2.2 μm thin membrane

f_r = 1,3 GHz

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, pp 426-431**

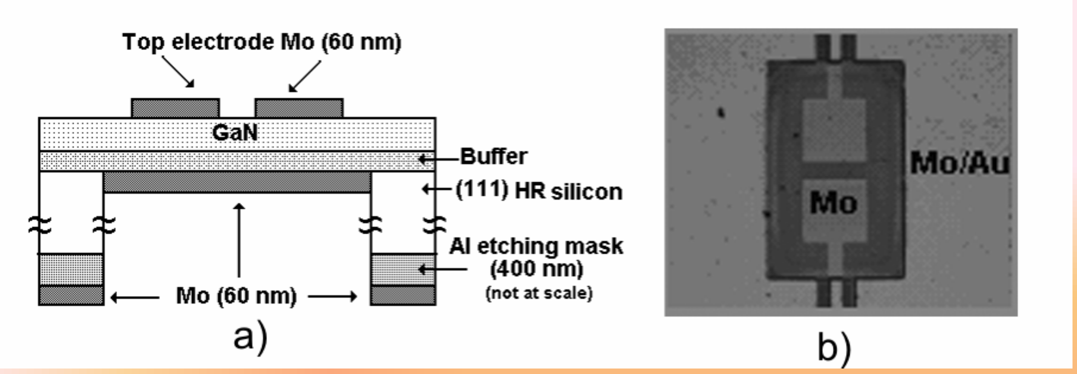
6.3 GHz resonance on a GaN FBAR obtained by micromachining of GaN/Si (1)

IMT and FORTH
July 2008

-**540nm** {340 nm (GaN) +200nm (buffer)} thin membrane supported FBAR structure based on GaN micromachining

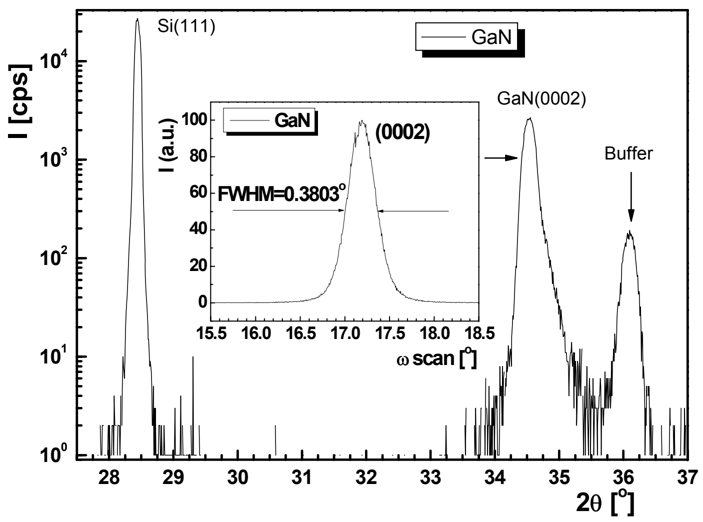
-50nm thin Mo metallization <u>*GaN/Si wafers from NTT AT Japan*</u>

Top view with top and bottom illumination

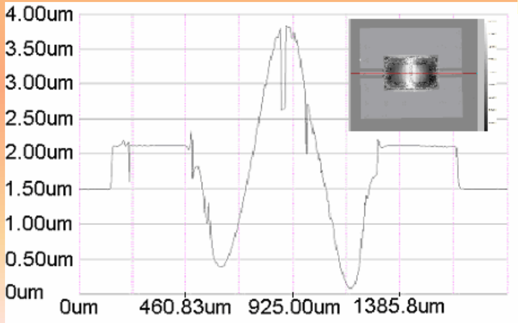


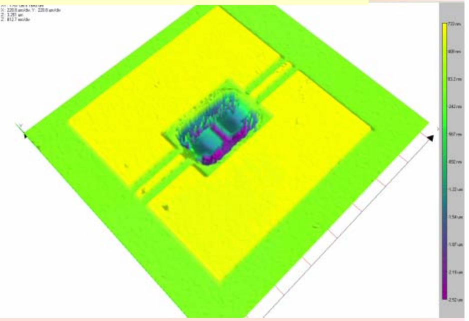
Cross section

XRD



White Light Interferometer

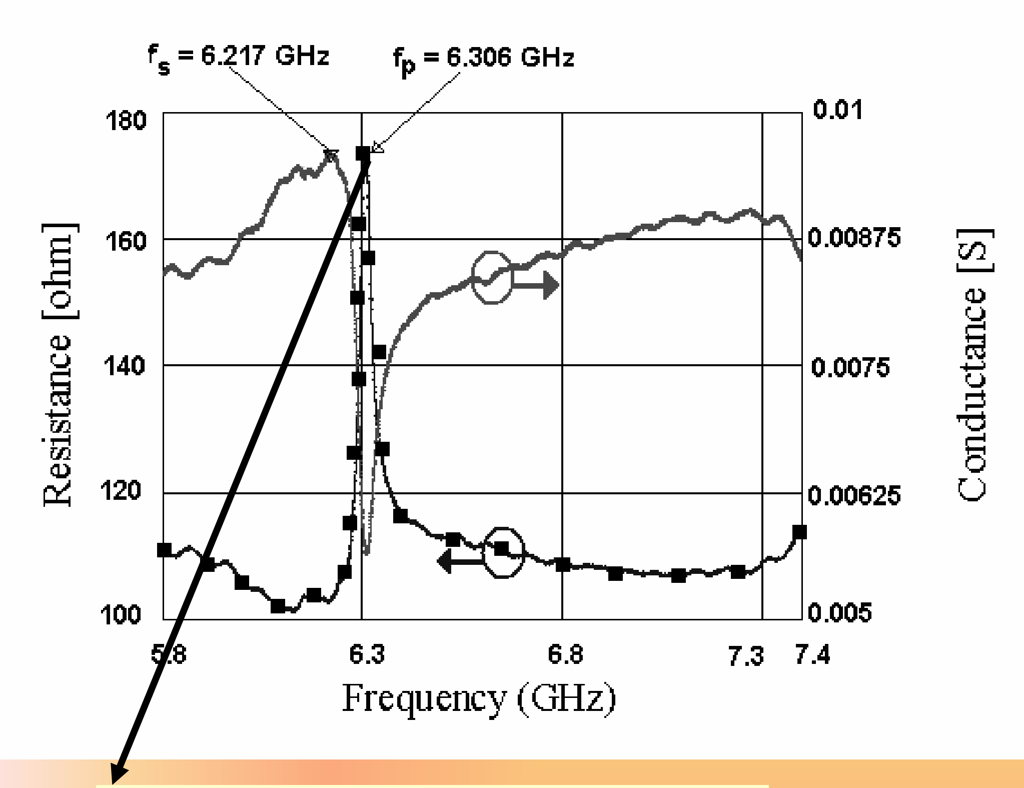




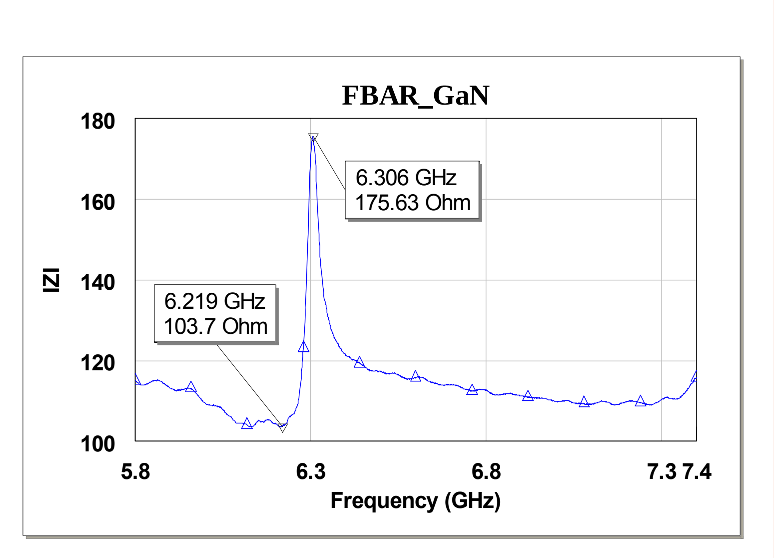
Maximum deflection 2.7μm

6.3 GHz resonance on a GaN FBAR obtained by micromachining of GaN/Si (2)

IMT and FORTH
July 2008



(VNA) Vector Network Analyzer characterization in microwaves



f_r=6.3 GHz

540 nm thin membrane

Qp=1130

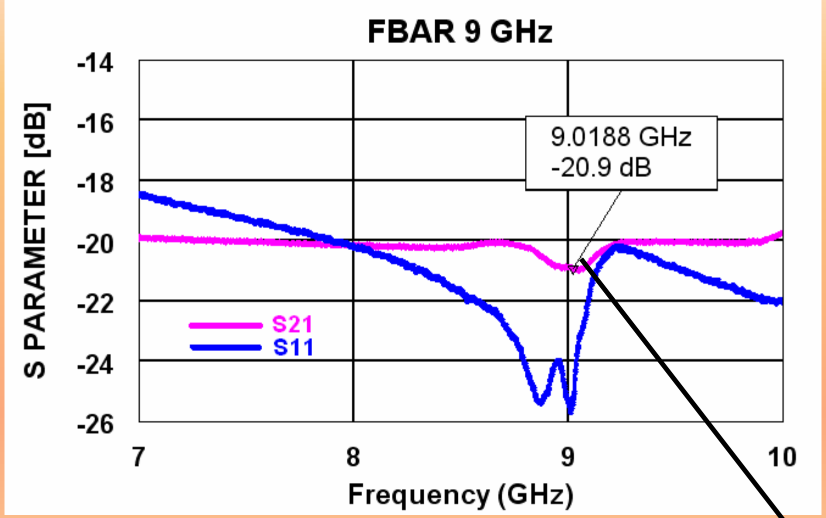
Qsp= $f_{sp}/(f_2-f_1)$, where fsp is the resonance frequency (series or parallel), f_1 and f_2 are the frequencies at which the magnitude of the input impedance is ½ from its resonance (anti-resonance) value

A. Müller, D. Neculoiu, G. Konstantinidis et al. "*6.3 GHz Film Bulk Acoustic Resonator Structures Based on a Gallium Nitride/Silicon Thin Membrane***"**

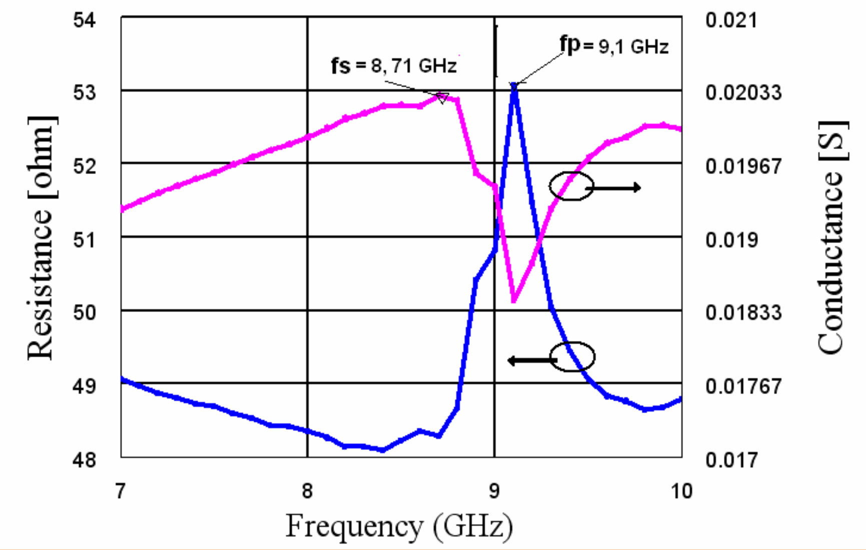
IEEE Electron Devices Letters , vol 30, no 8, August 2009, pp 799-801

Last results

- It is under test a run processed in Dec 2009
- **350nm** **{200 nm (GaN) +150nm (buffer)} thin membrane supported FBAR structure based on GaN micromachining ,**
- **50nm thin metallization (top) and 120nm bottom**



S parameter of the FBAR series connection structure



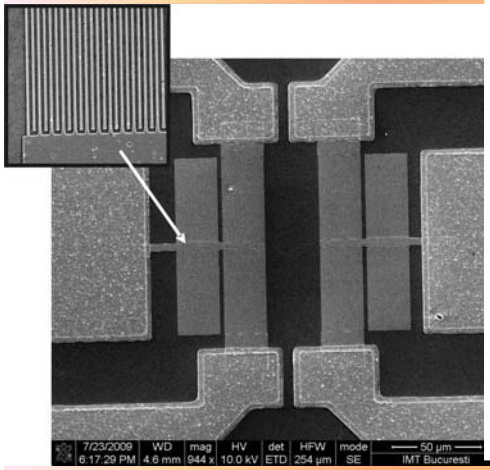
Resistance and conductance of the FBAR series connection structure

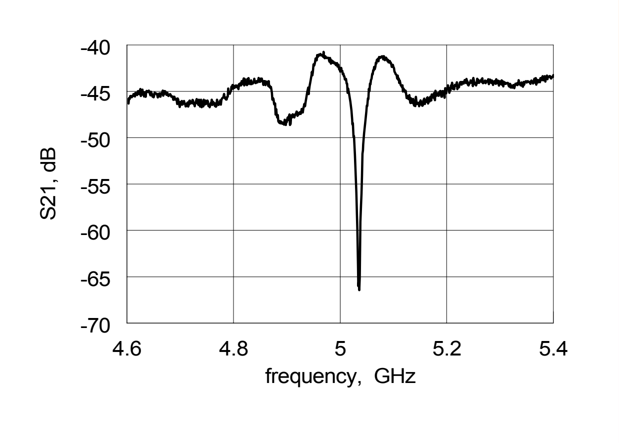
f_r= 9 GHz

350 nm thin membrane

(Preliminary results)

SAW devices for GHz applications with nanolithographic IDTs
Results obtained on AlN (IMT-FORTH-NIMP)





Results 2009

Resonance > 5GHz !!

Best results up on AlN,

First results on AlN/Si !

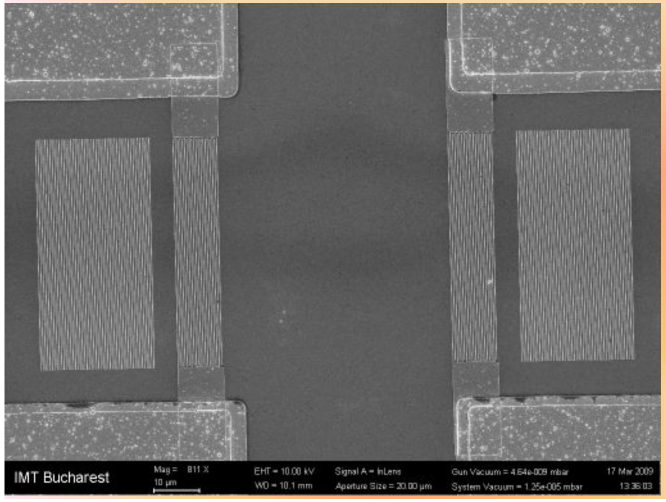
Fingers and interdigits
250 nm wide

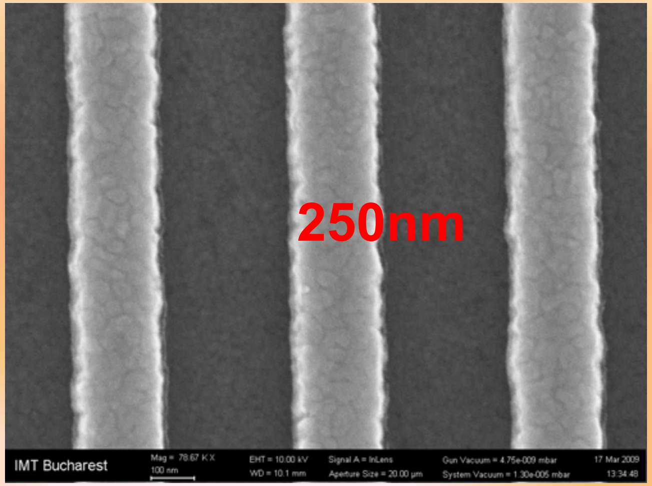
D. Neculoiu, A. Müller, G. Deligeorgis, A. Dinescu, A. Stavrinidis, D. Vasilache, A. Cismaru, G. E. Stan and G. Konstantinidis, “AlN on silicon based Surface Acoustic Wave resonators operating at 5 GHz”

Electron. Lett. 45, 1196 (2009)

Best previous result obtained before was a SAW on AlN (but on diamond not on silicon) operating at 4.5 GHz [*P. Kirsch et al. Appl Phys. Lett.88, 223504, 2006*]

GaN SAW structures manufactured using nanolithography



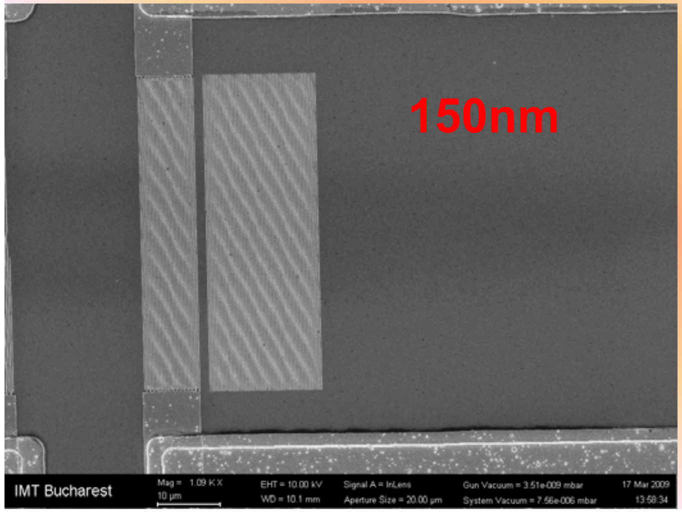


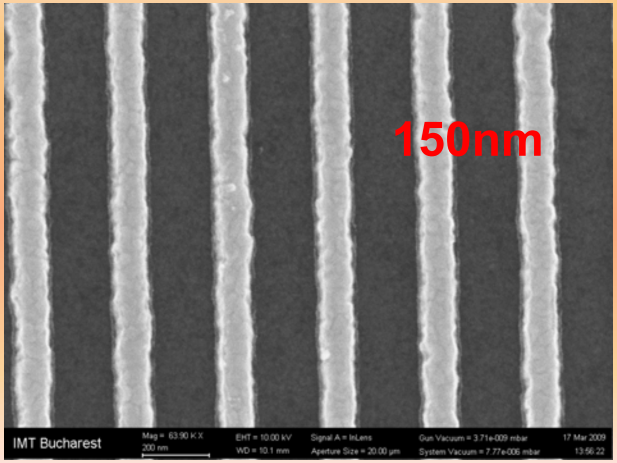
GaN

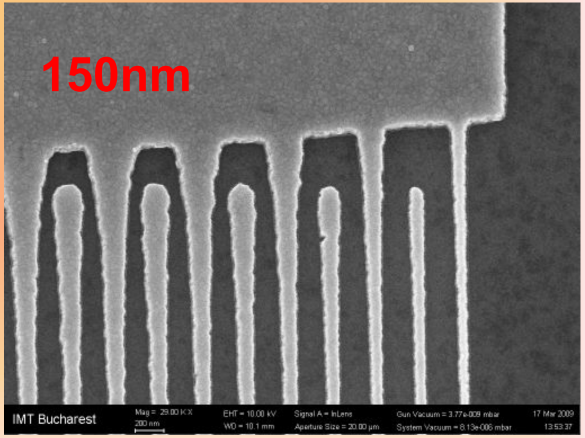
February 2009

SAW resonators on GaN/Si with fingers and interdigits 250 nm wide (up) and 150nm wide (down) *patterned in IMT on the new*

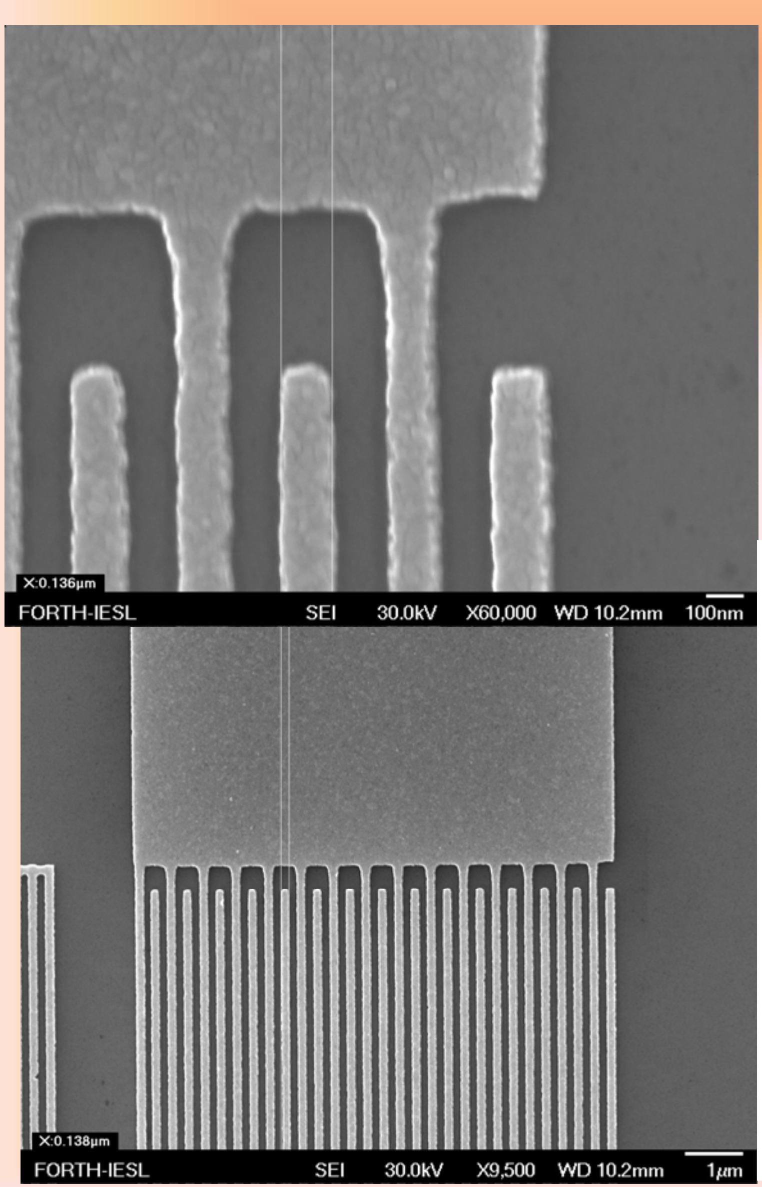
"E-Line" equipment from Raith (electron beam lithography)





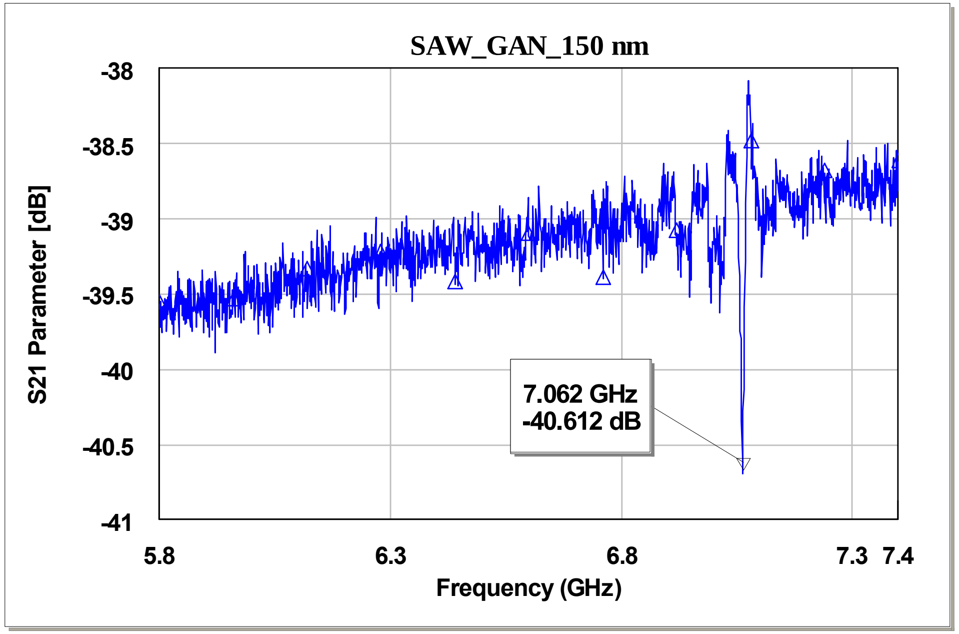


Recent results SAW on GaN/Si -1
(IMT – FORTH 23 Dec 2009)



GaN SAW structures with fingers and interdigits 150 nm wide resonating at a frequency 7 GHz

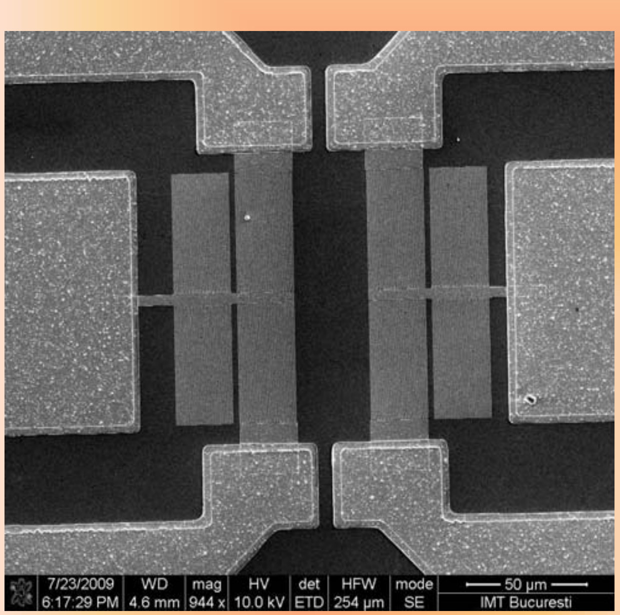
unpublished

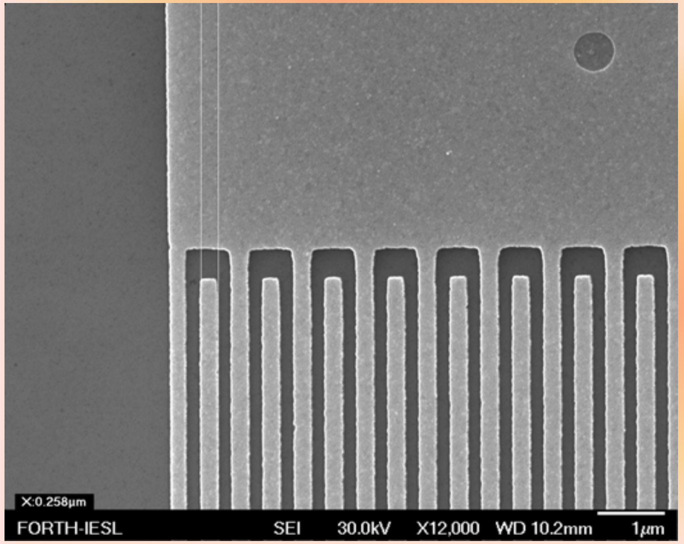


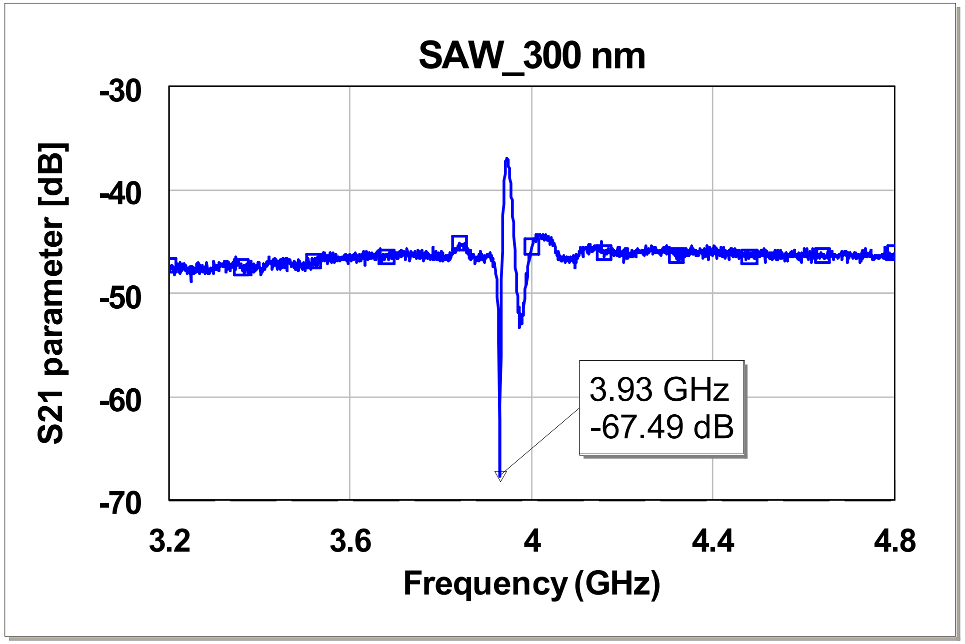
Recent results SAW on GaN/Si -1
(IMT – FORTH 23 Dec 2009)

GaN SAW structure with fingers and interdigits 300 nm wide resonating at a frequency close to 4 GHz

unpublished







UV photodetectors

UV photodetectors 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.

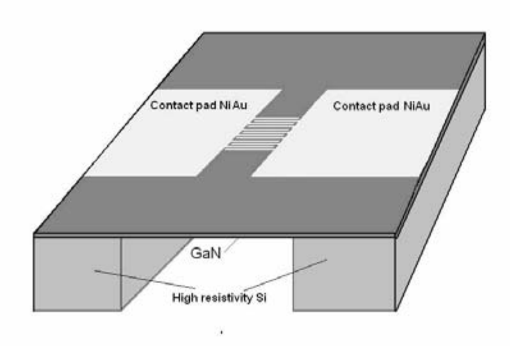
Most used photo detectors devices are based on metal-semiconductor metal (MSM) interdigitated structures due to their simplicity

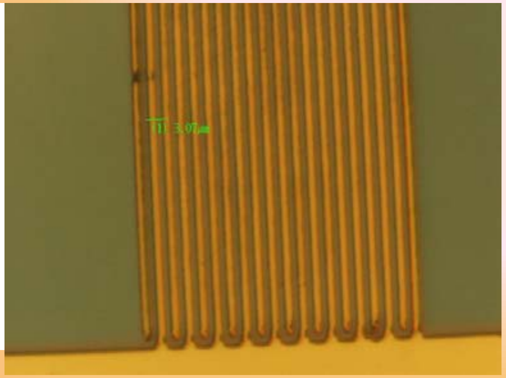
The main ideea was to manufacture a UV photodetector on a membrane

Potential advantages:

1. reduction of losses,
2. increased responsivity,
3. possibilty of back-side illumination

MSM GaN membrane test structure for UV detection (first run 2007)





2.2 µm thin GaN membrane

1 µm wide digit and interdigit

A. Müller, G. Konstantinidis, M. Dragoman, D. Neculoiu, A. Kostopoulos, M.Androulidaki, M. Kayambaki and D. Vasilache „GaN membrane metal–semiconductor–metal ultraviolet photodetector”

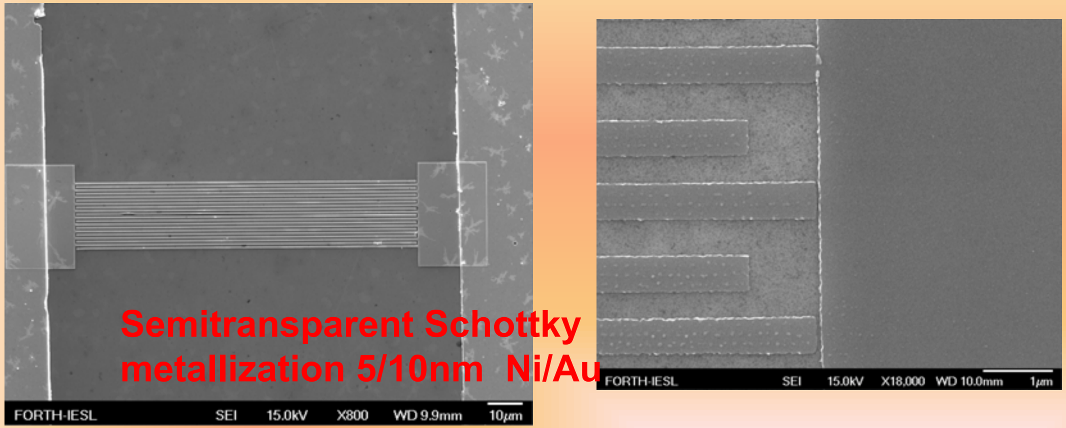
APPLIED OPTICS, Vol. 47, No. 10, 2008, pp 1453-1456

Membrane technology+ Nanolithography

MSM GaN membrane test structure for UV detection (second run 2008)

Higher responsivity !

Very low dark current !



Semitransparent Schottky metallization 5/10nm Ni/Au

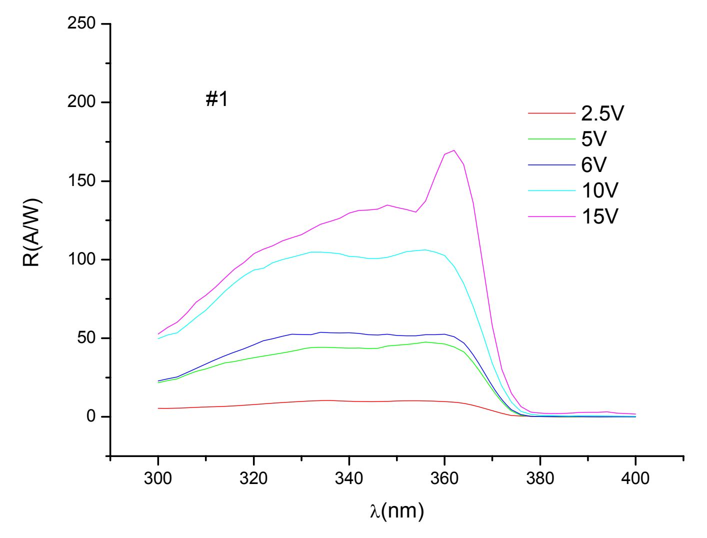
SEM photo (left)and detail (right) for the 0.5 µm wide finger/ interdigit detector structure manufactured on a 0.78 µm thin GaN membrane

***780 nm** (0.28 buffer+0.5 GaN) thin membrane*

***500 nm** wide finger/ interdigit detector structure*

A.Muller , 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 photodetectors manufactured using nanolithographic processes"

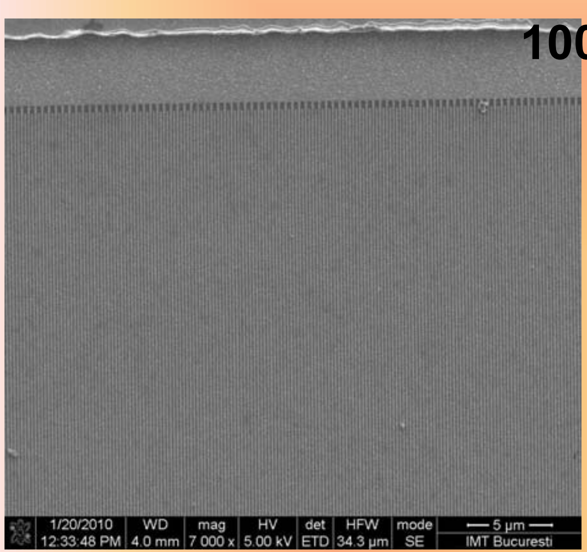
Microelectronics Journal, 40 (2009), pp. 319-321



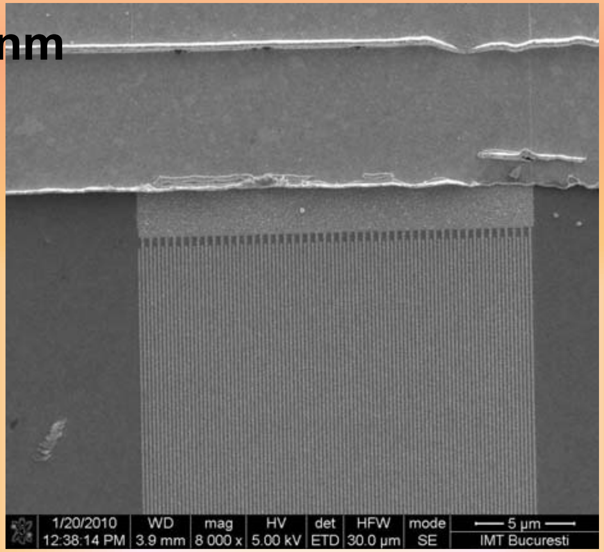
Responsivity vs wavelength for the 0.5µm finger / interdigit for two UV detector structures- manufactured on 0.78µm thin GaN membrane

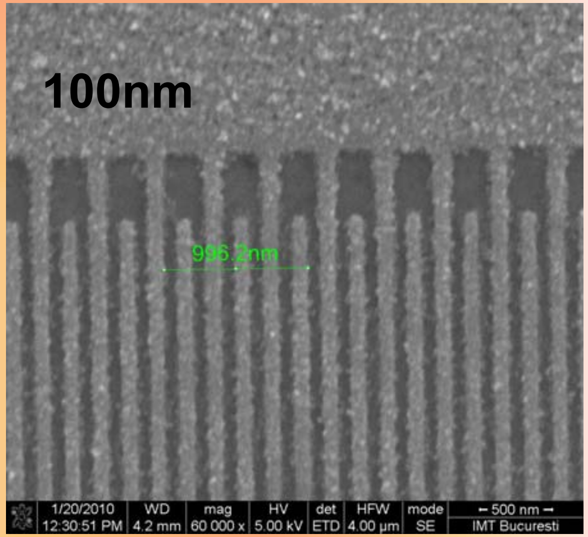
RECENT resuts (IMT-FORTH Dec 2009)

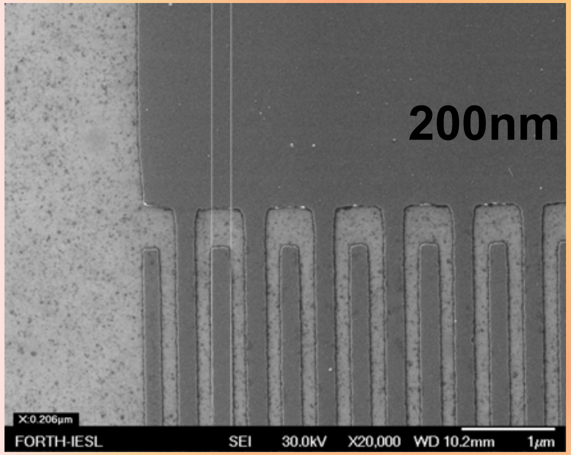
characterization in progress

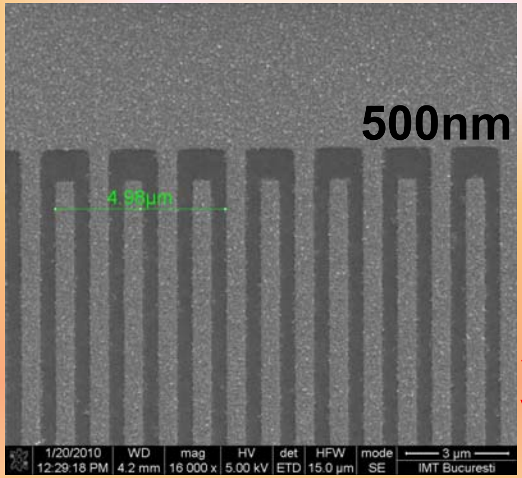


100nm









- **Excellent yeld! for GaN where nano processing is very difficult**
- **Structures with fingers and intedigits 100nm, 200nm, 500nm succefully achieved due to a very reliable nano-lithographic process (E-Line equipment)**

5/10nm Ni/Au

NANOLITHOGRAPHY AT IMT

CONCLUSIONS

- First FBAR structures on GaN/Si have been developed a suspended technology based on very thin (up to 350nm) self sustainable membranes has been developed having a resonance at 6.3 GHz (with Q>1100) and more, has been obtained.

- Nanolithographic process was successfully developed on GaN/Si. IDTs with fingers and interdigits 150nm and 250nm wide have been obtained with an yield of about 70-75%. SAW structures resonating at frequencies in the 5-7 GHz have been obtained for the first time on GaN.

- A new type of UV photodetector structure, based on micromachining and nanoprocessing of GaN/Si has been developed, for the first time. The new structure has low dark current, very high responsivity and offers the possibility of back-side illumination.

Acnowledgements

The author agnowledge:

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ANCS for the support under the MIMFOMEMS and GIGASABAR PNII projects

Thank you for your attention !