Micromachining and Nanoprocessing of GaN/Silicon for SAW and UV Photodetector Manufacturing

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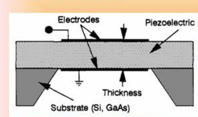
OUTLINE

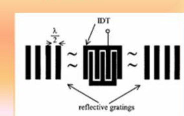
- Introduction - Acoustic devices and WBG materials
- SAW resonators on GaN/Si
- GaN membrane supported UV photodetectors
- Conclusions

Acoustic devices and WBG materials

Acoustic resonators

FBAR | **SAW**





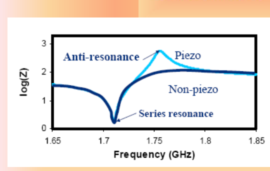
$d = \lambda/2 = v_s/2f_r$ (resonance)

$f_r = v_s/2d$

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

$f_r = v_s/4w$;

v_s~km/s; d, w ~ μm ; f_r ~ MHz …..GHz



Piezo materials have 2 resonances

Resonance occurs when the input impedance is at a minimum and *anti-series (parallel) resonance* occurs when it is at a maximum.

In the first case the current is maximum

In the second it is minimum

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 ℃,
- 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,

Acoustic devices in the GHz range obtained by micromachining and nanoprocessing of the WBG semiconductors – AlN and GaN

Why to increase the operating frequency?

•Mobile telephony is going from 3G to 4G. It is expected that the 4G systems to work in the 3 - 6 GHz frequency range.
•Wireless local area networks (WLAN), for high speed computer interconnections are envisaged for SAW structures operating around 5 GHz
•Sensors based on SAW and FBAR structures have the sensitivity ~f^2

Classical technologies for SAW resonators and filters bas ed on non semiconductor materials (quartz, lithium niobate) are limited at requencies < 2 GHz

Most of the FBAR structures reported in the last years, were manufactured on ZnO, material incompatible with monolithic integration

Using technologies based on WBG semiconductors (GaN/Si) silicon type processing can be used; acoustic devices working in the GHz range, can be monolithic integrated with other circuit elements (including HEMT transistors), in wireless circuits.

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. ***FBAR structures operating in the GHz frequency range can be obtained using micromachining techniques to manufacture submicronic membranes on AlN/Si and GaN/Si***
2. **The use of nanolithography to fabricate the interdigitated transducer (IDT) with lines and interdigits 100-300nm wide will resulting an increasing of the operating frequency of the SAW structures on GaN/Si and AlN/Si in the GHz frequency range**
3. **Micromachining of GaN and the use of nanolithography can improve UV photodetector performances**

AlN/Si

•Deposition by magnetron sputtering
•Coupling coefficient 6%

GaN/Si

•Deposition by MBE and MOCVD
•Coupling coefficient 2-4%
•Nanolithography a big challenge
•Monolithic integration with HEMT transistors is possible

Best results obtained up to now on AlN

- 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, 2005*].
- SAW device operating in the 8 GHz range [M. B. Assouar, O. Elmazria, P Kirsch, P Alnot, V. Mortet, " High–frequency surface acoustic wave devices based on AlN/diamond layered structure realized using e- beam lithography", Journ of Appl. Phys. 101, 114507, June 2007]

- 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].*
- *FBAR strucures manufactured on AlN/diamond working at 8GHz [R. Lanz, P. Muralt, "Band pass filters for 8 GHz using solidly mounted Bulk Acoustic Wave Resonators", IEEE Trans. on UFFC, Vol. 52 , pp. 946–946, June 2005]*
- *FBAR strucures manufactured on AlN/Si working at 5 GHz 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).*

Results obtained on GaN

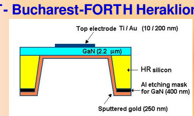
On GaN no FBAR resonators have been reported before 2006

- **FBAR structures resonating at 1.2 GHz** : A. Muller, D. Neculoiu, D. Vasilache, D. Dascalu, G. Konstantinidis, A. Kostopoulos, A. Adikimenakis, A. Georgakilas, K. Mutamba, C. Sydlo, H.L. Hartnagel, and A. Dadgar, "GaN micromachined FBAR structures for microwave applications" Superlatices & Microstructures, vol 40, pp. 426-431, Oct. 2006
- **FBAR structures resonating at 6.3 GHz** A. Müller, D. Neculoiu, G. Konstantinidis, A. Stavrinidis, D. Vasilache, A. Cismaru, M. Danila, M. Dragoman, G. Deligeorgis and K. Tsagaraki "6.3 GHz Film Bulk Acoustic Resonator Structures Based on a Gallium Nitride/Silicon Thin Membrane" Electron Devices Letters, vol 30, no 8, pp 799-801, August 2009.
- SAW **strucures working at 2.2 GHz (GaN/Saphire)** T Palacios, F. Calle, J. Grajal, E. Monroy, M. Eickhoff, O. Ambacher, F. Omnes, " High frequency SAW devices on AlGaN: Fabrication, Characterization and integration with optoelectronics", IEEE Ultrasonics Symposium, pp 57-60, 2002

GaN/Si FBAR Resonators

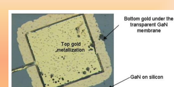
First GaN membrane FBAR structures (1)

IMT- Bucharest-FORTH Heraklion-TU Darmstadt 2006

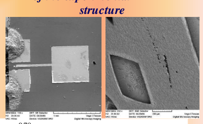


Cross section of the FBAR structure with the evaporated Ti/Au for the top metallization and sputtered Au for the bottom contact. Sputtered Al is used as mask for the bulk-micromachining of the membrane

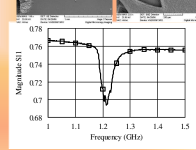
GaN membrane supported FBAR structures before backside etching



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



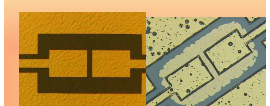
- Conventional contact lithography, e-gun Ti/Au (10nm/200nm) evaporation (top).
- Lift-off techniques to define the FBAR structures on the top.
- Backside lapping of the wafer to a thickness of about 150µm.
- Al layer deposition (400nm) on the bottom (as mask during the RIE of silicon).
- Backside patterning 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.



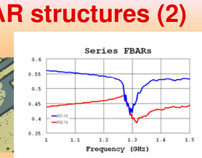
Return losses vs frequency for the GaN membrane supported FBAR structure

The thickness of the membrane was 2.2µm

First GaN membrane FBAR structures (2)



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



- 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

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

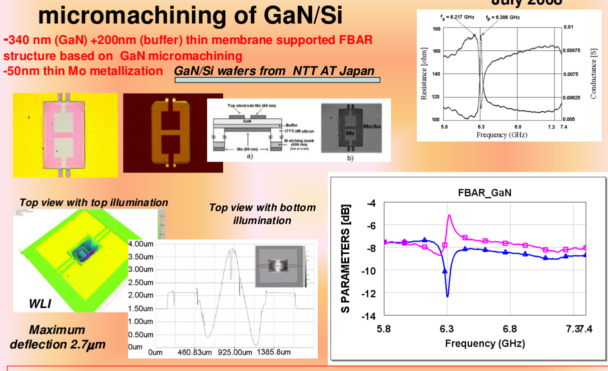
The GaN on silicon structure grown by MOCVD (Azzuro Ltd. Magdeburg)

The thickness of the membrane was 2.2µm

GaN FBARs obtained by micromachining of GaN/Si

IMT and FORTH July 2008

-340 nm (GaN) +200nm (buffer) thin membrane supported FBAR structure based on GaN micromachining
-50nm thin Mo metallization *GaN/Si wafers from NTT AT Japan*

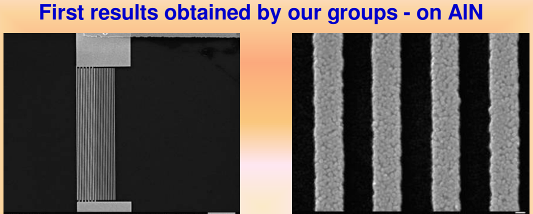


A. Müller, D. Neculoiu, G. Konstantinidis et al. "*6.3 GHz Film Bulk Acoustic Resonator Structures Based on a Gallium Nitride/Silicon Thin Membrane*" **Electron Devices Letters, vol 30, no 8, August 2009, pp 799-801**

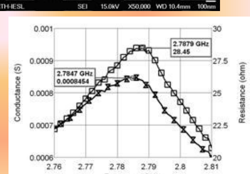
GaN/Si SAW Resonators

SAW devices for GHz applications with nanolithographic IDTs First results obtained by our groups - on AlN

AlN

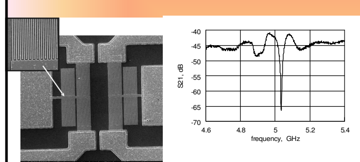


Experimental AlN SAW structure for GHz applications manufactured and measured at IMT-Bucharest . Fingers and pitches with a width on 300 nm have been obtained with the nanolithographic equipment (Vega-SEM and Elphy Plus EBL)



IMT-FORTH-NIMP 2007

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



Results 2009
Resonance > 5GHz !!

Best results on AlN/Si !

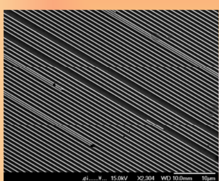
Fingers and interdigits 250 nm wide

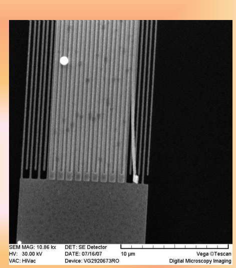
D. Neculoiu, A. Müller, G. Deligeorgis, A. Dinescu, A. Stavrinidis, D. Vasilache, A. Cismaru, G. E. Stan and G. Konstantinidis, "AlN on silicon based Surface Acoustic Wave resonators operating at 5 GHz"

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





Results on GaN/ Si for the first runs (2007)

Nanolithography on GaN -a challenge

E-beam lithography is the most versatile technique to manufacture submicronic devices on Silicon and also GaAs; resolutions down to 20nm can be obtained.

On GaN and AlGaN the high resitivity of the wafer , the charging and the big atomic mass of Ga impede the evacuation of electrons injected by the e beam As a result, Au can not be lifted-off after the e beam process.

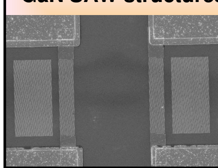
Techniques used to avoid these drowbacks;

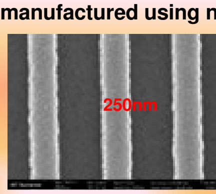
-two steps lithographic process

-a very thin Al deposition on the substrate to overcome charging effects

-very thin metalization layers .

GaN SAW structures manufactured using nanolithography



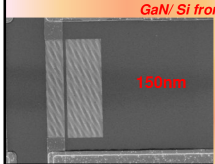


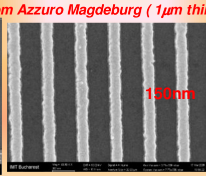
GaN

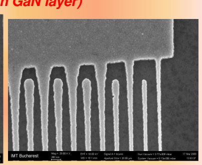
SAW resonators on GaN/Si with fingers and interdigits 250nm wide (up) and 150nm wide (down) *patterned in IMT on the new "E-Line" equipment*

PMMA 200nm thick metaization Ti/Au 100nm thick

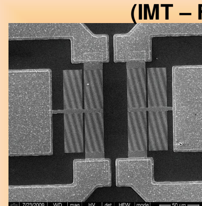
GaN/ Si from Azzuro Magdeburg (1µm thin GaN layer)

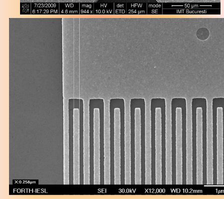






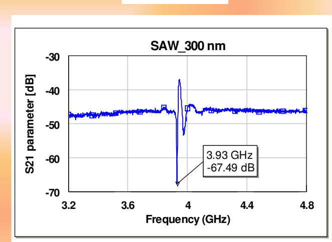
Recent results SAW on GaN/Si -1 (IMT – FORTH Dec 2009)



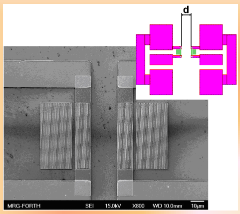


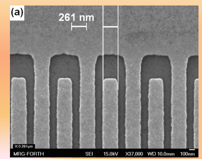
GaN SAW structure with fingers and interdigits **300 nm** wide resonating at a frequency close to 4 GHz

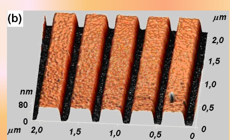
unpublished



Last results (1)





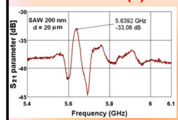


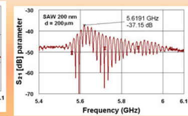
SEM photo of the test structure. The distance between the IDTs was d= 20 µm; for the other test structures it was d=100, 200 and 600 µm. The inset presents a schematic of an entire structure, including the connection pad

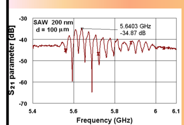
Detail of the nanolithogrphic process with fingers and intedigits nominally 200 nm wide developed on the GaN surface: a) SEM photo and b) AFM image

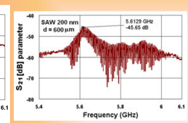
A Muller, D Neculoiu, G. Konstantinidis et al. "SAW devices manufactured on GaN/Si for frequencies beyond 5 GHz," Electron Devices Lett. Vol. 31, Dec 2010, in press. (DOI 0.1109/ LED.2010. 2078484)

Last results (2)







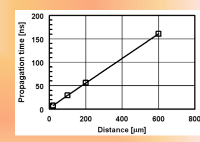


A Muller, D Neculoiu, G. Konstantinidis, A. Dinescu, G. Deligeorgis, A. Stavrinidis, A. Cismaru, M. Dragoman and A. Stefanescu "SAW devices manufactured on GaN/Si for frequencies beyond 5 GHz," Electron Devices Lett. Vol. 31, Dec 2010, in press. (DOI 0.1109/ LED.2010. 2078484)

The transmission measurements for the SAW test structure having a 20 µm, 100 µm, 200 µm and respectively 600 µm distance between the IDTs

Using the Time Domain Reflectometry – Band-pass Impulse Response technique (an option available for the VNA), the propagation times between the IDTs were determined as 8 ns, 29.5 ns, 56.5 ns and 161 ns, for the four distances between the IDTs. The ripple frequencies that modulate the transmission responses in are in very good agreement with the reverse of above propagation times (125 MHz, 34 MHz, 18 MHz and 6.2 MHz, respectively).

V=3740m/s



The propagation time vs the distance between the IDTs

Comments

- Only the Rayleigh mode was observed from the wideband microwave measurements. Sezawa or lossy pseudo-bulk modes, reported for GaN/sapphire,or GAn/SiC have not been observed.
- We believe that this is due the fact that the speed of sound in the silicon substrate is much lower than in sapphire and the Hk product (H is the GaN layer thickness and k =2π/λ) for our structures, is relatively high (approximately 8)
- The high transmission losses of the test structures can be reduced by more than 20 dB by employing appropriated matching networks at the input and output port.

GaN membrane supported UV photodetectors

Applications

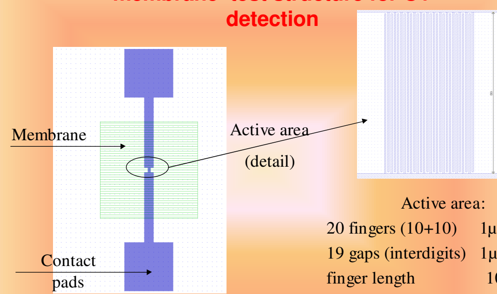
To manufacture imaging systems, flip-chip mounting and backside illumination are used.

Usually GaN layers on grown on Sapphire are employed for backside illumination [8]. Sapphire is a rather expensive material is not transparent to extreme UV light.

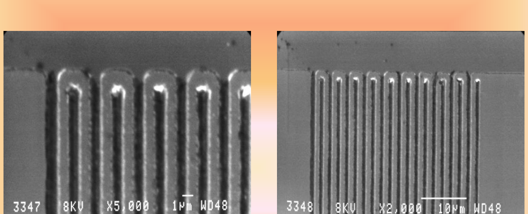
Another solution for backside illumination is to manufacture membrane supported UV photodetectors, using micromachining technologies of GaN/Si.

2008

The layout of the first MSM GaN membrane test structure for UV detection

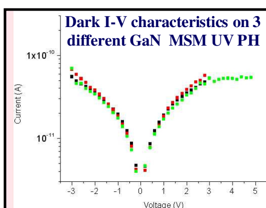


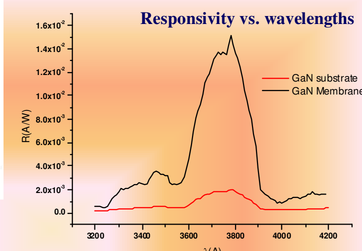
Active area:
20 fingers (10+10) 1µm wide;
19 gaps (interdigits) 1µm wide;
finger length 100 µm
nontransparent metallization Ni/Au (20nm/100nm)

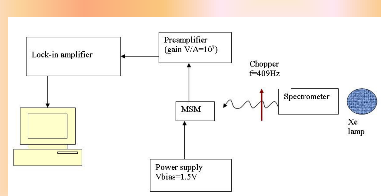


SEM photos of the 1 µm wide Ni/Au (20nm/100nm) lines The interdigit width was also about 1 µm

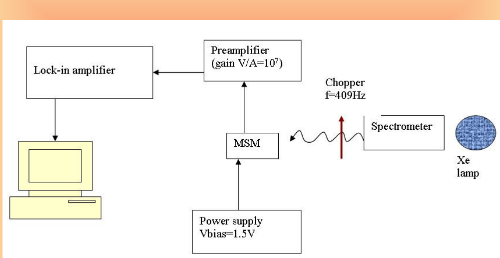
A. Müller, et al. „GaN membrane metal–semiconductor–metal ultraviolet photodetector", Applied Optics, Vol. 47, No. 10, 2008, pp 1453-1456







Optical measurements set-up

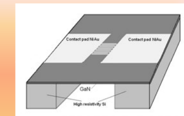


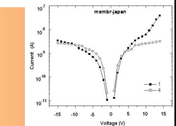
Optical measurements set-up

Membrane supported UV PD with fingers/interdigit spacing 500nm wide First promissing results -2008

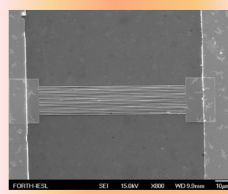
MSM UV Photodetector structures supported on a thin GaN membrane.

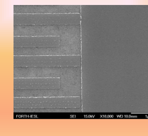
- A very thin, semi-tansparent metalization (NiAu 5/10nm) was used.
- Fingers and interdigits 500nm wide have been obtained The yield was about 3-4%
- For smaller dimensions the yield was zero!





GaN

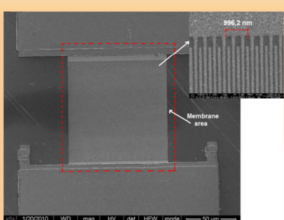




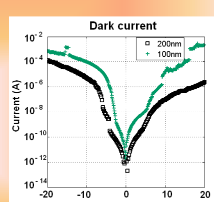
SEM photo (left)and detail (right) for the 0.5 µm wide finger/ interdigit detector structure manufactured on a 0.78 µm thin GaN membrane

A. Muller , et al., "GaN membrane-supported UV photodetectors manufactured using nanolithographic processes" Microelectronics Journal, 40 (2009), pp. 319-321

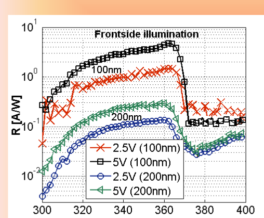
2010-unpublished



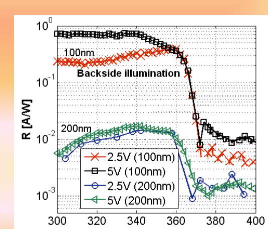
SEM photo of the GaN membrane UV detector structure with finger/interdigit spacing 100 nm wide; the inset presents a detail of the MSM structure obtained using a single metal/ resist layer nanolithographic process



Dark current vs. applied voltage for the two different test structures.



Responsivty vs. wavelength for front side illuminated UV photodetector structures with fingers and interdigit spacing 100 and 200nm wide at different applied voltages.



Responsivty vs. wavelength for backside illuminated UV photodetector structures with fingers and interdigit spacing 100 and 200nm wide at different applied voltages.

There is an absorbtion in the GaN layer.For 0.3 µm it can be up to 10 times, but it is visible respnsivities are still high

If the dimmensionn of the backside mask is increased the contacts are illuminated and the rersponsivity can increase .

CONCLUSIONS

•We have demonstrated that GaN/Si, a piezoelectric material compatible with monolithic integration with active devices like HEMTs, can be used to manufacture high quality SAW devices operating at frequencies higher than 5 GHz.

•The IDTs of the test SAW structures, having fingers and interdigit spacings 200 nm wide have been successfully manufactured using e-beam lithography.

• Further reduction of fingers/interdigits spacing width is possible and further increase of the operating frequency will be achieved.

•UV membrane supported photodetector structures have been obtained using micromachining of GaN/Si and nano-lithographic techniques on GaN

Thank you !