NANOPROCESSING AND MICROMACHINING TECHNOLOGIES OF GaN/Si FOR SENSORS AND FILTERS OPERATING AT FREQUENCIES ABOVE 5 GHz

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INTRODUCTION

The quality of thin GaN layers possessing good piezoelectric properties, grown or deposited on SiC, Diamond, Sapphire and Si substrates has improved drastically in the last years [1, 2]. Also the radiation hardness and high temperature functionality of GaN make this material appropriate to operate in harsh environments. At the same time, nanolithographic techniques have been developed to avoid the charging effects typical to electron beam lithography on GaN [3]. Nowadays, resolutions lower than 50 nm can be readily obtained on this material.

The operating frequency of surface acoustic wave (SAW) devices manufactured on bulk piezoelectric materials like lithium niobate, quartz, lithium tantalite etc. is limited to 2 GHz. SAW devices operating at frequencies above 5 GHz can improve the performances of radar and communication processing circuits. Moreover, GaN based SAW devices working at high frequencies are reliable solutions for sensor applications as the sensitivity increases with the operating frequency. Surface acoustic wave devices manufactured on classical non-semiconductor piezoelectric materials are widely used for temperature [4], gas concentration [5], pressure [6] and relative humidity [7] sensors, due to their high sensitivity and reliability [8].

In sensor applications, the sensitivity increases with the resonance frequency. The sensitivity is proportional with the square of the resonance frequency for mass, humidity and gas sensors [9] while for pressure and temperature sensors the sensitivity is proportional with the resonance frequency [10]. A higher operation frequency leads to increased sensitivities for sensor structures manufactured on GaN. There are three major advantages of using GaN type SAWs in sensor technologies: the possibility to use them in harsh environments (including high and low temperatures), the fully compatibility with wireless data transmission and battery less operation and the potential advantage of monolithic integration with signal processing circuit elements including HEMT transistors.

In the case of sensors a single-port resonator SAW type structure can be used as sensing element [11, 12]. This avoids the high transmission losses typically to face to face resonators on GaN. These losses appear due to the low coupling coefficient of GaN compared to the classical non-semiconductor piezoelectric materials.

This work will present progresses obtained by our team in the manufacturing of temperature sensor structures based on GaN/Si SAW resonators as well as on filter test structures manufactured on the same material.

TECHNOLOGICAL DEVELOPMENT

Both types of presented devices (filter and sensor) consist of single-port SAW resonator structures manufactured using advanced micromachining of GaN/Si and nano-processing technologies. The GaN/Si wafers have been obtained on a commercial basis from NTT-AT Japan. The first step in the manufacturing of SAW devices was the patterning and deposition of the connection pads using conventional photolithography, e-gun metallization (Ti/Au 20 nm/300 nm) and lift-off technique. A direct electron beam lithography (EBL) writing employing PMMA resist with a thickness of 200 nm was developed, for the IDT structure. A Ti/Au (5 nm/75 nm) layer was deposited by e-gun evaporation and selectively removed by lift-off process. Ti is used only to improve the adherence. Its small thickness has no influence on the behavior of the structure [13]. A third “overlay mask” was used to eliminate possible interruptions between the IDTs and the pad metallization layers because of the different metal thickness. A second 20/200 nm Ti/Au layer was deposited and selectively removed using lift-off technique [11]. A SEM photo of the single-port resonator test SAW structure, having 200 nm finger width and interdigit spacing, is presented in Fig. 1.

The single-port resonator SAW structures, used in this work for temperature determinations, have the active area (the IDTs) supported on a membrane. After top size processing, the 525 µm thick Si substrate was thinned down to 100 µm by lapping. A square backside mask with the edge of 500 µm was applied, centering the topside IDT. Deep reactive ion etching (DRIE) has been used for selective removal of the Si substrate and SAW structures supported on a thin GaN/Si (1.2 µm / 10 µm) membrane have been successfully manufactured.

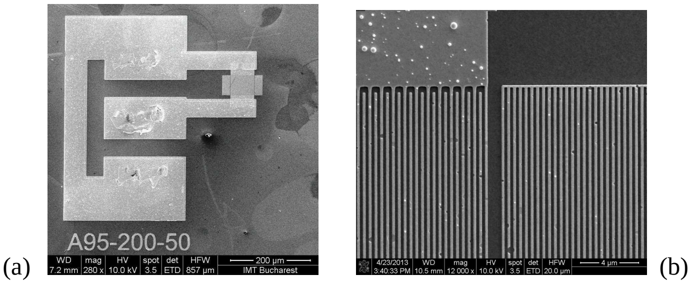


Fig. 1. SEM photos of the single-port SAW structure (a) and detail of the nano-lithographic process (b).

NOVEL TEMPERATURE SENSORS STRUCTURES BASED ON GAN SAW RESONATORS SUPPORTED ON THIN MEMBRANES

The SAW structure supported on a thin GaN/Si (1.2 µm/10 µm) membrane, used also as pressure sensing element [14], was characterized as temperature sensor. The variation of the resonance frequency for the Rayleigh mode peak vs. temperature was determined in a cryostat setup, in the -268 ºC - +150 ºC temperature range. The obtained results for the 20 ºC - 150 ºC are presented in Fig. 2. The linear approach of the resonance frequency vs. temperature showed a sensitivity of s = 627 kHz/ºC (TCF = 120 ppm/ºC). This value was about 2.5 times higher than those obtained on bulk SAW devices in our previous results [11, 12, and 15].

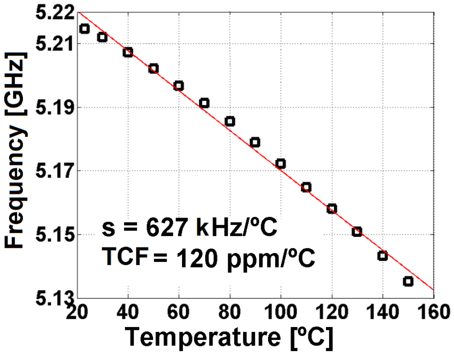


Fig. 2. Temperature sensitivity determinations for the SAW structure supported on a 11.2 µm thin GaN/Si membrane.

MICROWAVE FILTERS BASED ON GaN SAW RESONATORS

In the last decade, a lot of effort has been done to develop AlN and GaN SAW devices based filters with reasonable low losses dedicated to real applications, but, up to now, SAW filter structures based on GaN or AlN, useful in real applications have not yet been fabricated.

The highest resonance frequency reported before 2010, for a SAW structure on GaN (on Sapphire) was 2.225 GHz [16]. The first resonance occurred at 1.62 GHz and it was identified as Rayleigh, the second resonance at 2.225 GHz being Sezawa type. The structure was a face-to-face SAW resonator with an acoustic wavelength of 2.4 µm (finger/interdigit spacing 600 nm wide). The resonator shown -27 dB transmission losses and 30 dB out-of-band rejection for the Rayleigh resonance as well as -35 dB losses and 20 dB out-of-band rejection for the Sezawa resonance; in both cases the bandwidth was about 30 MHz.

SAW filters having 28 µm wavelength, fabricated on 2 µm-thick piezoelectric GaN layer grown on unintentionally doped LT GaN buffer layer, were reported in [17], operating at much lower frequencies (Rayleigh mode peak at

200 MHz and Sezawa mode peak at 350 MHz). For the Rayleigh mode peak (200MHz) the insertion losses were -36 dB and the out-of-band rejection was 10 dB. For Sezawa mode peak (350 MHz), the insertion losses were -26 dB and the out-of-band rejection was 20 dB.

In 2011, at Ann Arbor Univ. Michigan a special resonator/filter structure based on GaN-on-silicon thin film piezoelectric on substrate (TPoS) has been reported [18]. The structures have been fabricated on epitaxial GaN layer grown on a silicon-on-insulator (SOI) substrate. It is a single-port filter with a complex structure, fabricated on a membrane with an active area of 260 x 240 μm^2 (the Si layer is etched from the backside). There is an interdigitated transducer (IDT) type structure on the top consisting of electrodes 10 µm wide and interdigit spacing of 3 µm. The fifth-order thickness resonance mode occurs at 2.1 GHz, the band-pass response having -14 dB transmission losses and 15 dB out-of-band rejection, with 20.2 MHz bandwidth.

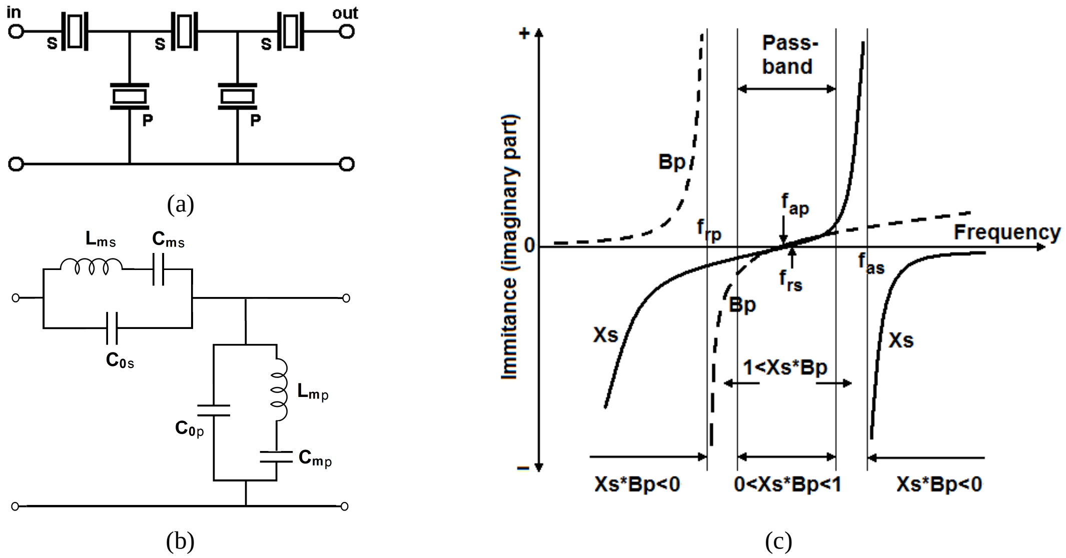
In 2014, Fe-doped GaN epitaxial films with wurtzite structure were grown on (0001) sapphire substrate and interdigital transducers (IDTs) of SAW delay lines were fabricated [19]; the reported insertion loss was -25.5 dB, at 237.8 MHz center frequency for the Fe-doped GaN, with 25 dB out-of-band rejection.

SAW structures resonating at 5.7 GHz have been reported by our group in 2010 [20], using IDTs with fingers/interdigit spacing 200 nm wide. This represents the state of the art with respect to the resonance frequency for GaN based SAW. The structure was manufactured using face to face resonators, this representing the simplest filter structure based on SAW resonators. The transmission losses were -33 dB at 5.7 GHz and the out-of-band rejection 10 dB.

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

The architecture of ladder type filter has been well known in the design of ceramic filters and quartz filters. As the equivalent circuit of component resonators of these mechanical filters is similar to that of single-port SAW resonator, the idea of the ladder type filter can be simply applied to SAW filter design [21, 22].

The regular ladder type SAW filter which has SAW resonators both in the series arms (S) and the parallel (P) arms is shown in Fig. 3 (a). Both resonators are single-port SAW resonators and their resonant frequencies are slightly different from each other. The basic section of a ladder type filter is shown in Fig. 3 (b), where the equivalent circuit of the SAW resonator without lossy elements is used. In this case, the impedance of the series-arm resonator (Z_s) and the admittance of the parallel-arm resonator (Y_p) are imaginary.



(a)

(b)

(c)

Fig. 3. Ladder type filter with SAW resonators (a); operation of the basic section of a band-pass ladder type filter: lossless equivalent circuit (b); position of resonant frequencies for the two resonators (c).

For a band-stop filter, the resonant frequency of the shunt resonator (f_{rp}) is designed to nearly equal the anti-resonant frequency of the series-arm resonator (f_{as}).

Single-port GaN SAW resonators

To build ladder type structures single-port GaN SAW resonators will be used as unit cells for the series and parallel elements. The parallel resonators are designed and manufactured for a slightly different frequency than the series one. This is obtained by changing the fingers width and interdigit spacing of the parallel resonator compared with the series one or by changing the thickness of the fingers metallization.

Single-port resonator structures have been simulated, designed and fabricated in order to analyze the dependence of the resonance frequency on the physical characteristics of the resonators and to establish the equivalent circuit of the GaN SAW single-port resonator structures.

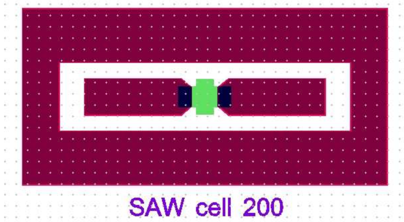


Fig. 4. Single-port series resonator for “on-wafer” measurements.

We fabricated single-port SAW resonators having 150 fingers and interdigit spacing and 50 reflectors (placed at 0.95 µm distance to the interdigitated transducer). The width of the fingers varies between 200 and 206 nm, the length is 50 µm and the thickness of the Ti/Au metallization is 10/80 nm or 10/90 nm. The structures are fed by means of 50 Ohm coplanar waveguide transmission lines for “on-wafer” measurements (Fig. 4).

In Fig. 5 are presented the results of S-parameter measurements performed on single-port series resonators with different widths of fingers and interdigit spacing as well as for different values of metallization thickness.

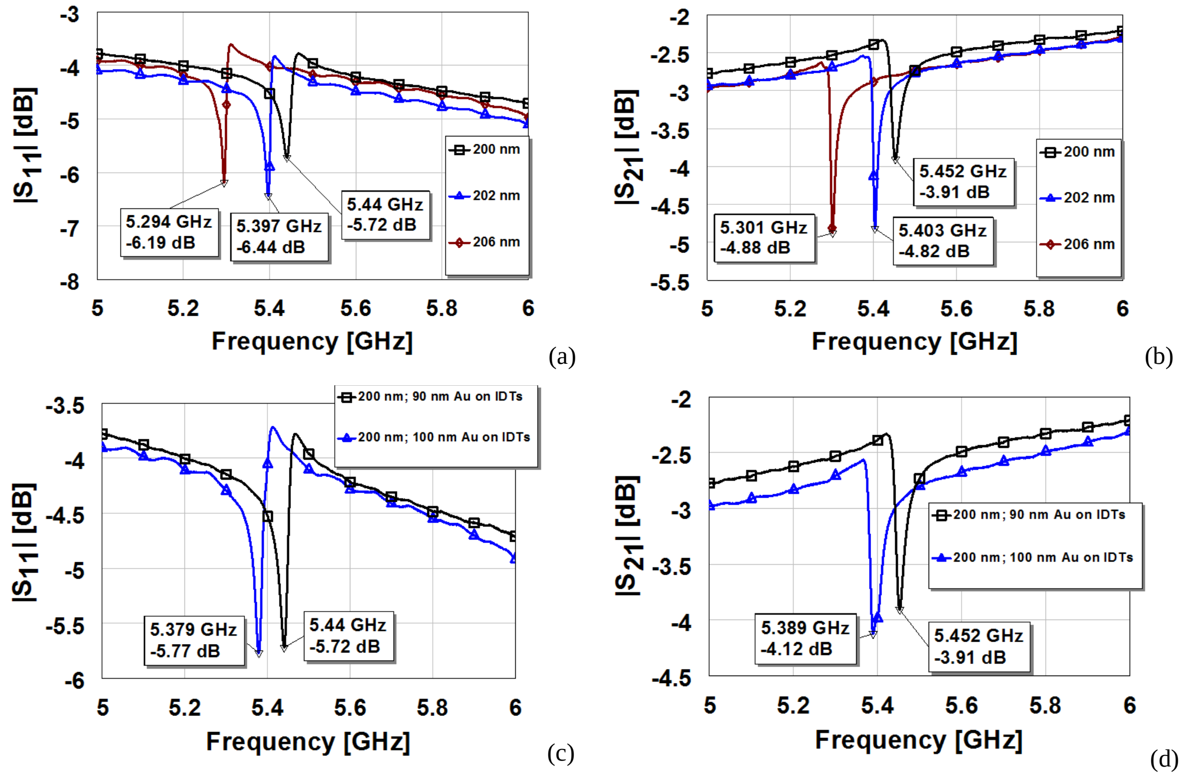


Fig. 5. S-parameter measurement results for single-port series resonators: with 90 nm metallization thickness and various widths of fingers and interdigit spacing (a) S_{11}, (b) S_{21}; with 200 nm widths of fingers and interdigit spacing and different values of metallization thickness (c) S_{11}, (d) S_{21}.

S parameters have been measured with a Vector Network Analyzer 37397D from Anritsu with a PM5 “on wafer” set-up from Suss Microtec, using the measuring pads of the structures.

As shown in Table 1, the measured values of resonance frequencies are in very good agreement with the simulated values for different widths of fingers and interdigit spacing as well as for different values of metallization thickness (errors are less than 1%).

Table 1. Resonance frequency extracted from simulations and experiment

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

According to simulations and to all measurements we performed, the effect of technological parameters on the resonance frequency of the single-port GaN/Si SAW shown a frequency shift of 46 MHz / 2 nm change of finger/interdigit spacing width and a frequency shift of 65 MHz / 10 nm change of metallization thickness. A combination of these two parameters will be used to obtain smaller differences between the resonant frequencies. The resolution of this procedure (to obtain reproducible results) is 2 nm as concerns finger/interdigit spacing width and 4 nm as concerns metallization thickness.

Single-port GaN SAW Resonator Equivalent Circuit

Starting from the classic equivalent circuit reported for bulk FBAR and SAW resonators [23], an equivalent circuit for single-port GaN SAW resonators was developed, allowing us to understand the influence of various physical parameters of the resonators and to design better SAW filter structures.

The configuration of the equivalent circuit that fits the behavior (S-parameters vs. frequency) of the single-port series GaN SAW resonator is shown in Fig. 6. It is represented by a motional capacitor C_m, in series with a motional inductor L_m, and together in parallel with a static capacitor C_0; the acoustic loss can be represented simply by considering a series resistor R_m to the other two motional elements (L_m, C_m).

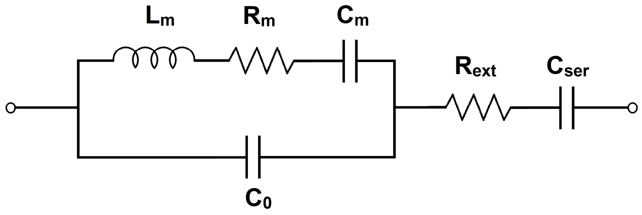


Fig. 6. Single-port GaN SAW resonator equivalent circuit.

Compared with the original one, the equivalent circuit of single-port GaN SAW resonator includes a series resistor R_{ext} that represents the resistive loss due to the metallization of the structure (IDT electrodes, transmission line segments) and a series capacitor C_{ser} (which is essential to model the capacitive behavior of the single-port GaN SAW resonator).

The values of equivalent circuit lumped elements, obtained by model extraction, for the five types of SAW resonators (with 300 / 150 / 75 / 50 fingers, 50µm and 30µm long, with 200 nm width) are presented in Table 2. The measured S-parameters for all five types of single-port resonators have shown an excellent agreement with the S-parameters that have been computed using the extracted parameters.

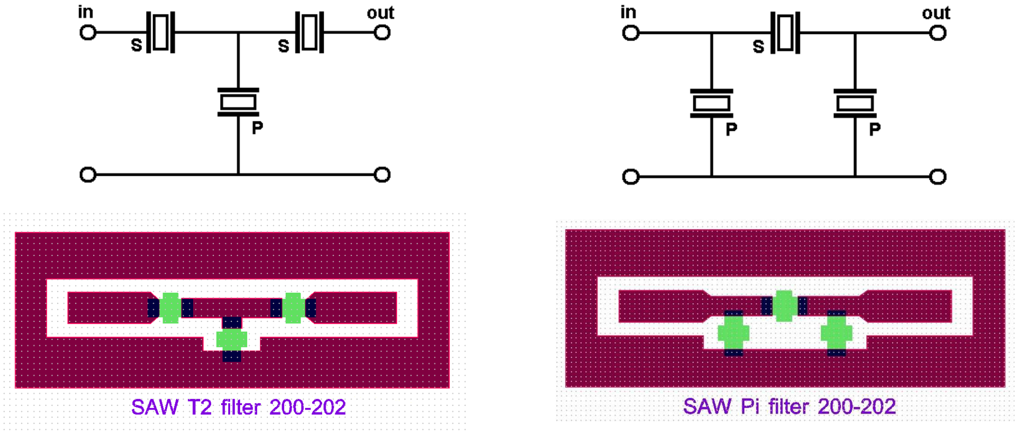
Table 2. Equivalent circuit elements extracted from simulation and experiment

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

One can notice that resistor R_m has rather high values, which increase the insertion loss of the GaN SAW filter equipped with single-port resonators, but – to a greater extent – also affect the rejection depth on both sides of the pass-band, without any possibility to be compensated by using any external components (transmission lines or lumped elements). It is important to mention that the increase of the number of fingers leads to lower values of the series resistor R_m.

T-shape and Π-shape filter structures based on GaN SAW single-port resonators

Based on single-port GaN SAW resonators, several simple ladder filter structures (T-shape and Π-shape – Fig. 7) have been designed, manufactured and tested.



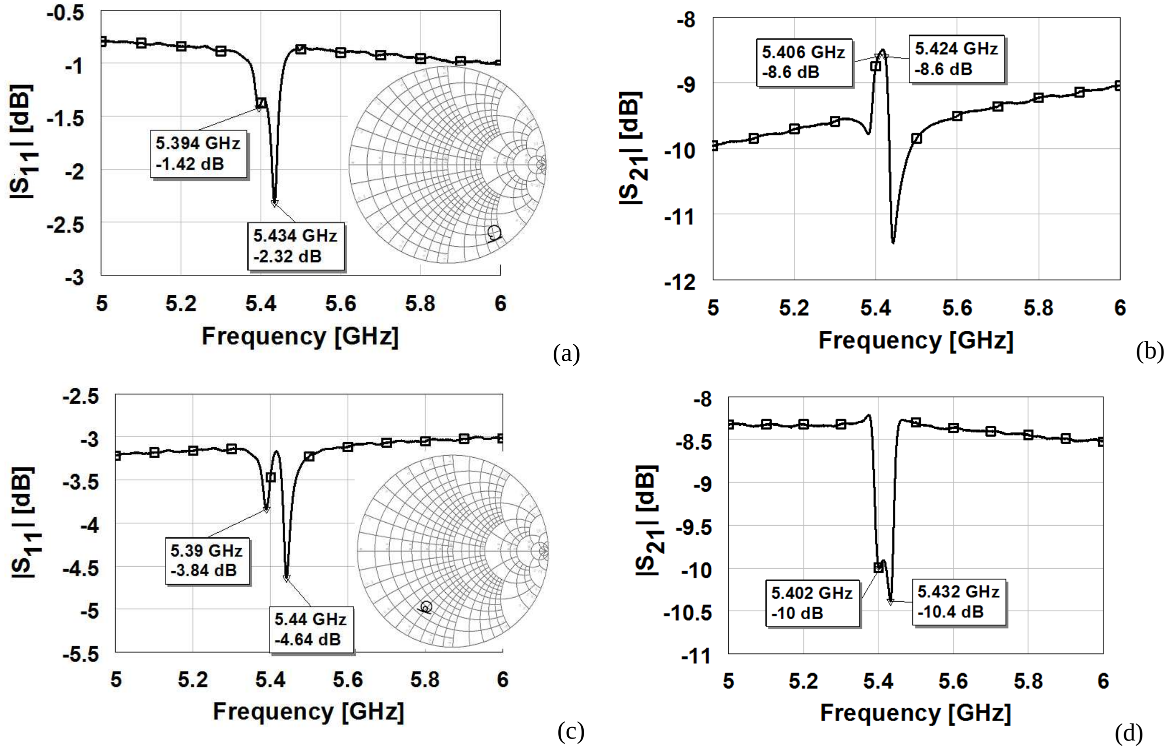
(a) (b)

Fig. 7. T-shape (a) and Π-shape (b) SAW filters for “on-wafer” measurements.

In Fig. 8 (a), (b) are presented the S-parameter measurement results for a T-shape pass-band filter with series resonators (described above, 90 nm metallization thickness) having 200 nm finger width and a shunt resonator (the same configuration as the series one) with 202 nm finger. Results for a Π-shape band-stop filter with 200 nm finger width shunt resonators and a series resonator with 202 nm finger are shown in Fig. 8 (c), (d). Similar results (but with wider frequency responses) were obtained for band-pass and band-stop filters with 200 nm finger width and interdigit spacing, having metallization thickness 90 nm for the series resonators and 100 nm for the shunt resonator.

One can notice the band-pass and band-stop shapes of transfer characteristics, with acceptable insertion loss values, but the filters show low values of the ratio between the insertion loss and rejection. This behavior is caused by several factors: rather high value of the series resistor R_m (24.7 Ω is the value found for the single-port resonators with 150 fingers, 50 µm long), the presence of the series capacitor C_{ser} , and the poor matching between the filter structure and the 50 Ω characteristic impedance of the measurement setup.

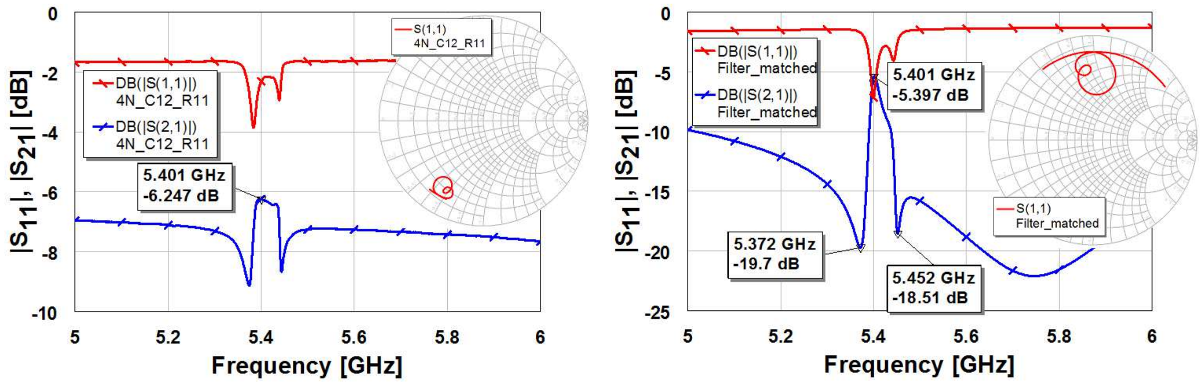
To decrease the series resistor value, single-port resonators with shorter fingers and interdigit spacing (30 µm length) and large number of fingers (300 fingers) were used (R_m = 12.4 Ω). The S-parameter measurement results for Π-shape bandpass filter with 202 nm width of fingers and interdigit spacing for the shunt resonators and 200 nm for the series one are shown in Fig. 9 (a). Using high characteristic impedance (100 Ω) transmission lines (1.25 - 1.26 mm length) to



(a) (b) (c) (d)

Fig. 8. S-parameter measurement results for: T-shape band-pass filter with 200 nm wide fingers for the series resonators and 202 nm for the shunt one: (a) S_{11}, (b) S_{21}; Π-shape band-stop filter with 200 nm wide fingers for the shunt resonators and 202 nm for the series one: (c) S_{11}, (d) S_{21}.

compensate the series capacitance C_{ser} of the single-port resonators as well as simple Γ sections (with L = 0.86 nH series inductances and C = 0.56 pF shunt capacitors) for a better matching of the filter, the transfer characteristics of the filter are significantly improved, as shown in Fig. 9 (b): -5.4 dB insertion loss at 5.4 GHz, 31 MHz bandwidth (at -3dB) and about 14 dB out-of-band rejection close to the pass-band region. Similar results were obtained if the series matching inductances are replaced with 1.4 mm long 50 Ω transmission line segments. The matching solution depends on the connections to adjacent circuits or to the package (for stand-alone filters).



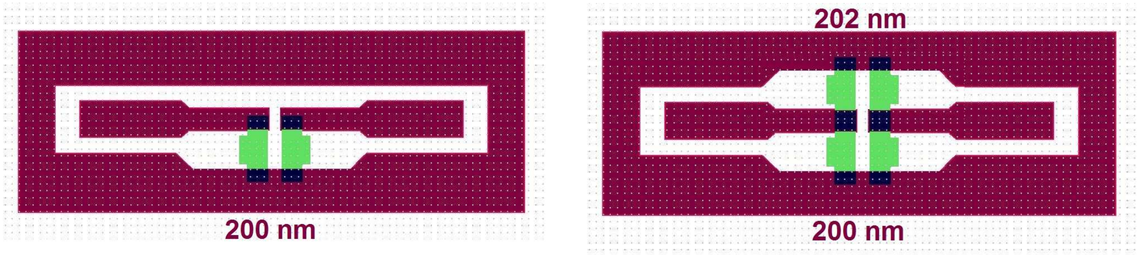
(a) (b)

Fig. 9. S-parameter results for Π-shape band-pass filter with 300 fingers (30 μm length) having 202 nm wide fingers for shunt resonators and 200 nm for the series one: (a) filter built only with SAW resonators; (b) filter built with SAW resonators and elements to compensate the series capacitor C_{ser} and to improve filter matching.

More complex ladder-type filter structures are under development in order to increase the out-of-band rejection (with some cost as concerns the insertion loss values).

Band-pass filters based on face-to-face resonators

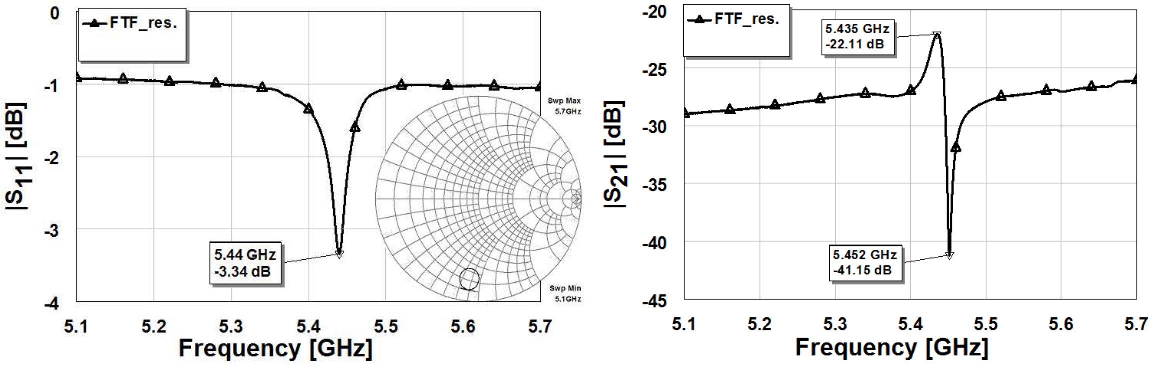
In order analyze the solutions to obtain a better shape (the ratio between the attenuation in the stop-band and the insertion losses) of the transfer characteristic of the GaN SAW band-pass filters, we designed and fabricated face-to-face SAW resonators and band-pass filters (Fig. 10).
The face-to-face GaN SAW structures consist of interdigital transducers (IDT) with 100 electrodes of 80 µm length, with 20 µm distance between the two IDTs; each IDT has 50 reflectors (placed at 0.95 µm distance to the interdigital transducer, outside of the face-to-face structure). The widths of fingers and interdigit spacing are 200 nm for the face-to-face SAW resonators and 200 nm and 202 nm for the band-pass filter. The thickness of the Ti/Au metallization is 10/80 nm for both types of structures. The structures are fed by means of 50 Ω coplanar waveguide transmission lines for “on-wafer” measurements (similar with the configurations used for single-port structures).



(a) (b)

Fig. 10. Face-to-face SAW resonator (a) and face-to-face SAW filter structure

The behavior of the face-to-face resonator from Fig. 10 (a) is shown in Fig. 11.

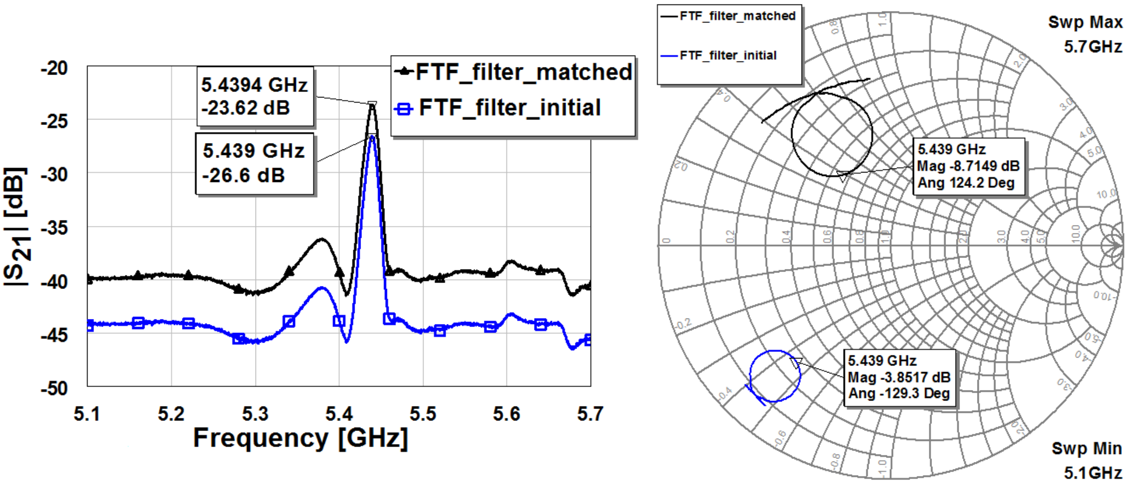


(a) (b)

Fig. 11. S-parameter measurement results for face-to-face SAW resonator: (a) S_{11}, (b) S_{21}.

One can notice that the $|S_{21}|$ swing between the series and the parallel resonance frequencies (about 20 dB) is much higher than the swing for single-port resonators (3-4 dB), but the losses are also much larger.

The S-parameter measurement results of the face-to-face SAW filter from Fig. 10 (b) are shown in Fig. 12 (blue traces). The insertion loss of the filter is 26.6 dB and the rejection of the out-of-band signals is 17.5 dB. One can notice that the input/output impedance is far from 50 Ω – as shown on the Smith diagram in Fig. 12 (b). An improvement of the insertion loss can be obtained by matching the filter (black traces) using Γ sections with L = 1.2 nH and C =0.56 pF; a compromise between the loss improvement and decrease of the out-of-band rejection was made. The matched filter has shown 23.6 dB insertion loss and about 16 dB out-of-band rejection.



(a) (b)

Fig. 12. Improvement of the face-to-face SAW band-pass filter by matching: (a) S_{21}, (b) S_{11}.

In order to improve the insertion loss and to increase the out-of-band rejection of the face-to-face GaN SAW filters, more refined structures are under development.

CONCLUSIONS

In the first part of the paper, a novel temperature sensor structure consisting of a single-port resonator SAW having the Rayleigh mode resonance at about 5 GHz, supported on a thin GaN/Si membrane with a total thickness of 11 µm, is presented. A very high sensitivity (627 kHz/ºC corresponding to 120 ppm/ºC) has been obtained, values which are about 2-2.5 times higher compared with similar structures manufactured on bulk material.

In the second part of the paper, first experiments developed in order to obtain reliable ladder-type as well as face-to-face type band-pass SAW filter structures on GaN/Si, operating at frequencies above 5 GHz, are described. Ladder-type filters based on single-port SAW resonators have shown optimistic results regarding insertion losses but more efforts have to be made as concerns out-of-band rejection. The face-to-face resonator topology provides much better out-of-band rejection but with rather high insertion losses. More complex configurations will be developed to obtain a proper balance between insertion losses and out-of-band rejection characteristics of the band-pass SAW filters on GaN/Si.

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