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Development of 0-level Packaged Dual SAW Pressure and Temperature Sensors on GaN Thin Membranes

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Abstract. The paper presents the design, manufacturing and characterization of 0-level packaged dual SAW pressure and temperature sensors developed on GaN/Si/Mo thin membranes. Molybdenum film was deposited on the backside of membrane, to support a higher pressure. FEM simulations were performed in order to predict the mechanical behavior of the membrane. The dual sensor, consisting of single SAW resonator, was fabricated by nanolithography, while the membrane under the resonator was made by dry etching of the Silicon substrate. Dual sensors parameters (sensitivity, pressure coefficient of frequency - PCF and temperature coefficient of frequency -TCF have been measured before and after packaging. The pressure sensitivity and PCF show high values before encapsulation (1102 kHz/Bar and 126 ppm/Bar) and an insignificant dropping of the values after encapsulation.

Key-words: Dual pressure and temperature sensor; GaN membrane; package; surface acoustic wave.

1. Introduction

Surface acoustic wave (SAW) resonators have been widely developed for sensor applications due to their small size, battery less operation and compatibility with wireless data transmission, three important features when the sensors are used in harsh environmental conditions, without additional electronic circuitry for signal transmission.

Most of the research on SAW based pressure sensors was focused on delay lines or two port resonator structures, manufactured on classical piezoelectric substrates such as quartz, langasite or lithium niobate [1 – 3], which limit the resonance frequencies to 2.5 GHz. These materials have excellent piezoelectric properties but it is very difficult to further increase the SAW resonance frequency, because of the quality of their surface on which nanolithographic processes are very difficult to be adapted. An increase of the SAW resonance frequency is important in sensor applications as it enhances the sensitivity of the SAW sensor (defined as: $s = df/dx$, where f is the resonance frequency and x is the measured physical parameter – pressure, temperature, relative humidity, etc). *Gallium Nitride* (GaN) and other III-nitrides are versatile semiconductor materials, fully compatible with nanolithography and micromachining process that can be introduced in the fabrication protocol of the acoustic devices. In the last years, these piezoelectric substrates became attractive for high sensitivity temperature [4, 5] and pressure sensors [6, 7, 8] based on acoustic devices.

Encapsulation of the membrane supported devices is currently one of the most sensitive and challenging problems. Since the SAW structures have specific peculiarities and various sensing applications, a standard method cannot be developed. For the pressure sensors, the encapsulation should assure the ease of detection: in our case, the pressure should reach the detection element, which is a very thin membrane.

In this work we investigate a high sensitivity dual pressure and temperature sensor, GHz operating, based on GaN/Si/Mo membrane, and propose a method to embed it using solid silicon cap. The possibility to determine simultaneously the pressure and the temperature with the same SAW structure was demonstrated for the first time by our group in [8, 9]. A backside metallized GaN membrane supported SAW structure was exploited as dual, pressure and temperature, sensor. Such a configuration enhanced the quality factor and the coupling coefficient. FEM mechanical simulations are carried out in order to determine the stress of the membrane and the deformation of the proposed package. The fabrication and the packaging of the SAW devices are presented. The structures are characterized as pressure and temperature sensors and the sensitivity was determined before the encapsulation as well as after the capsule was bonded.

This paper represents an extension of the paper "Development of high frequency SAW devices devoted for pressure sensing" (D. Vasilache *et al.*) [10], with a different type of encapsulation (Section 3) and additional experimental measurements for pressure sensitivity and coefficient of frequency for different temperatures and temperature sensitivity and coefficient of frequency for different pressures (Section 4).

2. FEM Mechanical Simulations

Mechanical simulations were performed in COMSOL Multiphysics in order to study the stress distribution and the deformation of the membrane when pressure is applied. The simulated geometry consists of a simplified 2D model having a 500 μm x 500 μm GaN/Si/Mo membrane (1.3 μm/10 μm/ 30 nm thickness). The edges of the membrane were fixed and pressure was applied on top of the membrane structure, between 1 and 30 Bar. The ultimate strength is the value of the stress at which the material breaks. The value of ultimate strength for GaN is 4.1 GPa [11], for Si is 170 MPa [12] while for Mo was found between 324 – 690 MPa [12, 13]. The simulated value of the ultimate strength of the membrane was found at 16 Bar (Fig. 1).

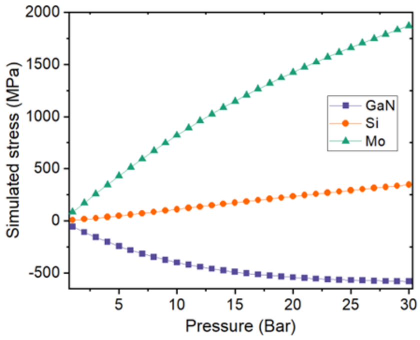


Fig. 1. Evolution of the stress when pressure is applied on the GaN/Si/Mo membrane.

The simulation model was further used to evaluate the displacement of the membrane when external pressure is varied in the range of 1 to 12 Bar. The maximum displacement appears in the center of the membrane, reaching 5.9 μm for 12 Bar pressure (Fig. 2). The value of the displacement increases with the applied pressure (Fig. 3).

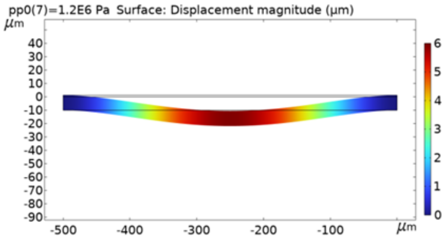


Fig. 2. Displacement of the membrane at 12 Bar.

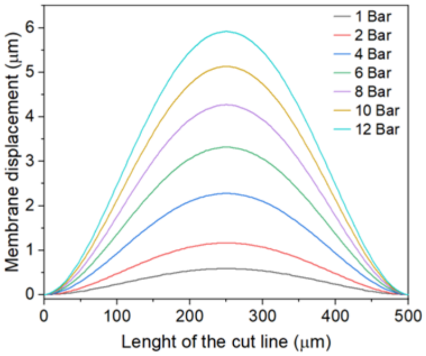


Fig. 3. Simulated values of the displacement of the package along the transversal cut line at different pressure values.

3. Development of the Packaged SAW Sensors

The development of the sensor devices has been done in two steps: first one was dedicated to the SAW sensors manufacturing, while the second one was for capsule fabrication and packaging of the sensors.

3.1. Fabrication of the membrane supported SAW devices

SAW devices have been designed to be manufactured on thin GaN layers – 1.3m thickness GaN layer, deposited on HR Silicon (obtained on a commercially basis from NTT-AT, Japan). The devices fabrication involves passing through four important technological steps using optical photolithography and *electron-beam lithography* (EBL).

First step was the deposition of the *coplanar waveguide* (CPW) used to connect the interdigitated structure the active area of the sensors. In this case, Ti/Au metallization, 100 nm thickness, was deposited by e-beam deposition; the patterning was done by lift-off process. The SAW devices having IDTs of 120 nm width were fabricated using EBL, and the metallization (Ti/Au, 5 nm/45 nm) was deposited also by e-beam.

The front side processing was completed by the deposition of an overlayer on CPW, to ensure the connection between CPW with IDTs; the metallization (Ti/Au, 20nm/230nm) was deposit and patterned in the same way as in the first step.

The last step was the manufacturing of the membranes. Due to the superior control of the etching depth, dry etching technique was chosen. For the membrane manufacturing, first the Silicon substrate was thinned down from 525 μm (initial wafer thickness) to 100 μm by lapping. For membrane fabrication a double side alignment process has been used to pattern the etching area (500 μm $\times$ 500 μm), and an RIE (*Reactive Ion Etching*) process was used to etch the silicon substrate down to 10 μm. Finally, 30 nm of Mo were deposited on the backside to support a higher pressure [10]. Fig. 4 presents a membrane supported single resonator SAW chip prepared for on wafer characterization.

3.2. Packaging of the SAW devices

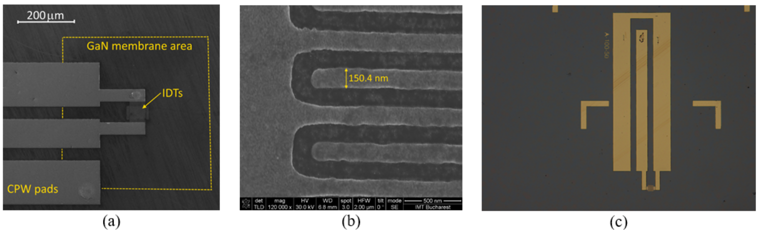
Packaging of the pressure devices was designed to assure the protection of the structures against the environment (such as dust), which can affect or perturb its functionality and, at the same time, to minimize as much as possible the variation of the pressure sensitivity values.

The capsules used for packaging were designed to be manufactured employing silicon wafers. Fabrication consists in two etching steps:

- **first one** was used for cavity manufacturing, which will be placed above the SAW device; also, the lateral walls of the cavity are etched partially, to ensure the same pressure inside and outside of the package.

- **the second one** was used for vias fabrication (from the bottom side of the wafer to the already manufactured cavity), which will facilitate the equalization of the pressure in the capsule with the external one.

Two types of capsules were designed (Fig. 5): first one (left, with interrupted walls) was bonded directly on the SAW structure, while the second one (right, with continuous walls) was bonded on the top of the first one; the vias performed are interspersed, so to not have access directly to the SAW from the top and to avoid the perturbance of the device due to the environment.



(a) (b) (c)

Fig. 4. SEM image of SAW structure (a); SEM image - detail of the IDTs developed by e-beam nanolithography (b) and optical image of the processed SAW device (c).

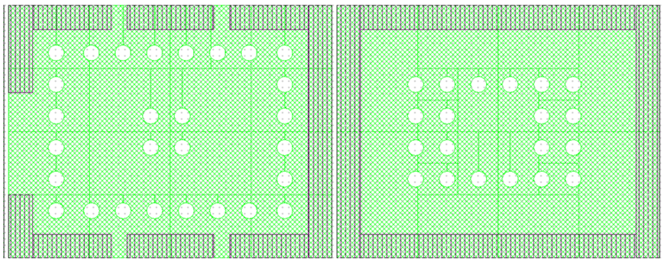


Fig. 5. Schematic view of the designed capsules.

The placement of the capsules in the center of the active IDTs area is done by a pick-and-place equipment. The capsules were bonded over the SAW devices using a non-conductive epoxy adhesive. Fig. 6 shows SEM and optical images of the packaged sensors after first (a and b) and second (c and d) level encapsulation. After the first level encapsulation, the SAW structures can be seen through the vias (Fig. 6 (a)); also, the spaces over the side walls, intended for pressure equalization, can be observed in the SEM image from Fig. 6 (b). After the second level bonding, the first level capsule can be seen through the vias (Fig. 6 (c)), and in the SEM image the two capsules can be distinguished as shown in Fig. 6 (d).

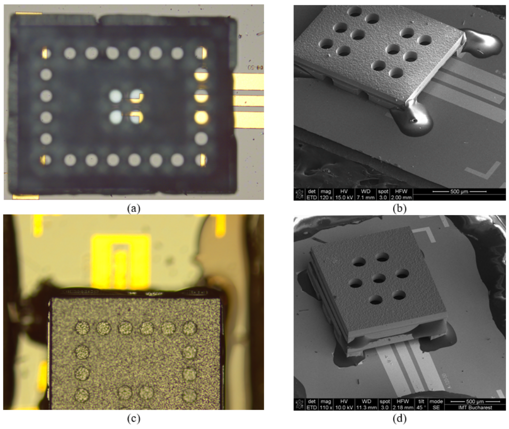

(a) (b) (c) (d)

Fig. 6. SEM and optical images of the packaged SAW structure after first level ((a) and (b)), and after second encapsulation level ((c) and (d)).

4. Measurements and Discussions

4.1. On-wafer characterization of the SAW

The reflection parameter S_{11} was measured with a vector network analyzer 37397D (Anritsu) and a pair of PM5 probes for on-wafer measurements from Suss Microtec. The first measurements were performed at room temperature and in atmospheric pressure. Two resonant frequencies higher than 8.7 GHz were identified (denoted with f_1 and f_2 in Fig. 7).

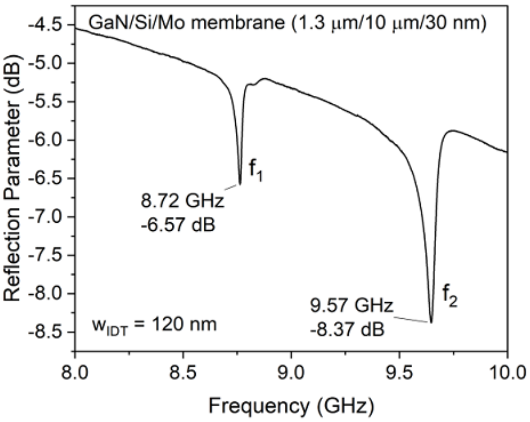


Fig. 7. Reflection parameter of the package less SAW device, measured at room temperature and at atmospheric pressure.

4.2. Pressure sensor characterization

For pressure measurements, the SAW structures were hermetically soldered on a carrier, in order to keep constant, the pressure underneath the GaN/Si/Mo membrane when external pressure is applied. The measurements were performed in a pressured chamber using Nitrogen atmosphere in the 0 to 12 Bars range, both for the SAW sensor without the solid Si cap (package less) as well as with package.

The resonance frequency shift of the reflection parameter, S_{11} *vs.* applied pressure was measured using a homemade on-wafer set-up introduced in a controllable pressure chamber with a maximum working pressure of 60 Bars and controllable temperature, manufactured by Buchi AG. Only f_1 resonance responded to the pressure variation; the second frequency is a spurious mode as confirmed by the FEM simulations.

The pressure sensitivity, $s = df/dp$, as well as the pressure coefficient of frequency $(PCF = (1/p) \cdot (df/dp))$ were experimentally determined for the packaged as well as for the unpackaged SAW structures (Fig. 8). The resonance frequency decreases with the increase of the pressure.

High sensitivity values were obtained due to the very high resonance frequency (8.7 GHz). As expected, the values of s and PCF were practically unchanged after the structures were packaged, demonstrating the viability of the encapsulation method. Experimental measurements have shown that membranes break at a pressure in the range of 14 - 16 Bars, which corresponds to the simulation results.

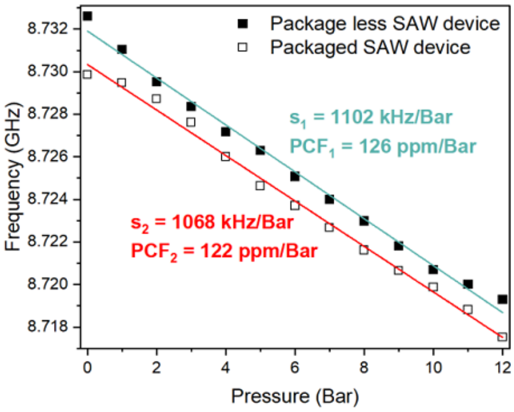
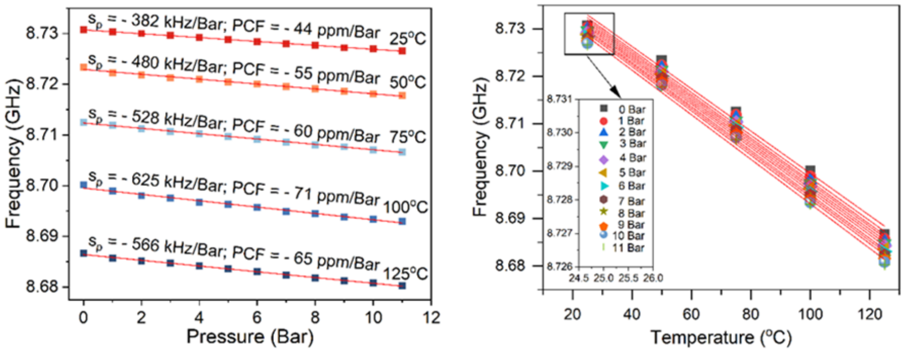


Fig. 8. Resonance frequency *vs.* pressure and the sensitivity determination.

4.3. Dual pressure and temperature sensor characterization

To determine the pressure sensitivity from 0 Bar to 11 Bar, the change of the resonance frequency, at different temperatures, was linearly approximated, as shown in Fig. 9a. A variation of the slope was obtained and pressure sensitivities (s_P) between – 382 kHz /Bar (for T = 25°C) and – 566 kHz/Bar (for T = 125°C) were achieved. The linear approximation of the resonance frequency change with temperature in the range 25°C – 125°C for different pressure values is presented in Fig. 9b.

From Table 1 it can be seen that the temperature sensitivities, s_T, at different pressure values (up to 11 Bar) varied between –446 kHz/°C (for atmospheric pressure) and –470 kHz/°C (for P = 11 Bar).



(a) Resonance frequency vs. pressure at different temperatures and the sensitivity determination

(b) Resonance frequency vs. temperature at different pressures

Fig. 9. Resonance frequency shift.

In order to determine the pressure at which the membrane breaks, the measurements performed at 125°C were continued up to 16 Bar. The sensor responded up to a pressure of 15 Bar (Fig. 9), the result being in agreement with the mechanical simulations made with COMSOL Multiphysics (Fig. 1).

Table 1. s_T and TCF at different pressures

Pressure (Bar)	s_T (kHz/°C)	TCF (ppm/°C)
0	–446	–51
1	–450	–51.4
2	–454	–52
3	–455	–52
4	–456	–52.1
5	–458	–52.4
6	–460	–52.6
7	–464	–53
8	–465	–53.2
9	–467	–53.4
10	–468	–53.5
11	–470	–54

5. Conclusions

High frequency SAW devices on GaN/Si/Mo membranes (1.3 m/10 m/30 nm) are developed through nanolithography and micromachining techniques to be explored as pressure and temperature dual sensors. The silicon capsules were manufactured and the encapsulation was carried out on two levels, for a superior protection of the structures against possible disturbing factors in the environment. FEM mechanical simulations evaluate the membrane behavior when pressure is applied. Temperature sensitivities, up to -470 kHz/°C and TCF up to -54 ppm/°C were obtained. Very high pressure sensitivity (up to 1100 kHz/Bar) and pressure coefficient of frequency (126 ppm/Bar) have been experimentally determined for the packaged, as well as, for the unpackaged SAW structures.

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