Single resonator GaN/Si SAW based temperature sensor

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ABSTRACT

This paper presents temperature sensors consisting in single resonator SAW structures manufactured using a deep submicron e-beam nano-lithographic process on GaN/Si. The room temperature resonance frequency of the GaN/Si based SAW structures is around 5.7 GHz. The resonator structures were measured in the 23-130^{o}C temperatures range. The sensititivity was determined in this temperature range and an increase of more than 20% was obtained for the sensitivity of the single resonator structure compared with the face-to-face double resonator SAW type structures, manufactured on the same wafer. These results are analysed and explained taking into consideration the contribution of the two terms in the temperature coefficient of frequency expression. Preliminary results regarding the encapsulated temperature sensor structure is also presented.

Keywords: SAW resonator, temperature sensor, GaN

1 INTRODUCTION

Microwave integrated circuits based on GaN are able to work at high temperatures because of the wide band gap of this semiconductor material. In the same time, the temperature in GaN based MMICs has to be carefully monitored. A possible way to measure the temperature in MMICs is based on a SAW type device. A lot of research and industrial developments have already used SAW based delay lines, based on quartz, or $LiNbO_3$, for temperature measurements [1, 2]. The temperature is usually determined wireless, by RFID type measurements, although wired temperature reading is preferred in some applications.

The use of GaN based SAW type sensors can have a major advantage for temperature measurements in GaN MMICs because of the possibility of monolithic integration of the temperature sensor and the possibility to place the sensing structure very close to the hot areas of the GaN MMICs.

GaN is a material with good piezoelectric properties, but only recently reliable SAW structures working at frequencies above 2 GHz have been reported by the authors [3].

The influence of temperature in the SAW frequencies is given by the thermal coefficient of frequency (TCF). TCF was measured in the 50-400 K range for AlN (–68 $ppm \cdot C^{-1}$) and GaN (– 43 $ppm \cdot C^{-1}$) [4]. It can be shown that TCF depends on the type and thickness of the piezoelectric layers as well as on the expansion coefficient of the substrate [5], which means that there is the possibility to manufacture either temperature sensitive or temperature compensated devices, depending on application, by properly choosing piezoelectric layers and substrates.

This paper presents SAW devices manufactured on GaN/Si resonating in the 4-6 GHz frequency range, used as temperature sensors. We will show the resonance frequency vs. temperature determinations performed on single resonator structure and on a two, face to face, resonator structure. In contrast with other applications, the resonance frequency shift is used for the temperature determinations. Very high resonance frequency has as effect an increase of the sensitivity, to a few hundred of kHz/^{o}C. This simplifies the signal processing electronics.

2 GAN BASED SAW SENSOR STRUCTURE MANUFACTURING AND CHARACTERIZATION

First measurements of the temperature variation of the resonance frequency for GaN/Si based SAW structures were performed on the "face to face" structures presented in [3]. The structure consists in two SAW IDT structures placed face to face at 100 µm. Each IDT structure has 100 fingers and 100 interdigits. The fingers have a length of 200 µm, a width of 200 nm. The metallization thickness of the fingers is 100 nm (Ti/Au 5/95 nm).

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 specific pads of the structure. The structure was heated using a hot plate and temperature determinations have been performed in the 23-100°C temperature range.

The temperature dependence of the resonance frequency for these SAW structures was determined using the transmission parameter S_{21} as shown in Fig. 1.

In the 23-100^{o}C temperature range, the dependence of resonance frequency vs. temperature can be linearly approximated. We have determined the sensitivity of 240 KHz/^{O}C which corresponds to S =43 ppm/^{O}C (Fig. 2).

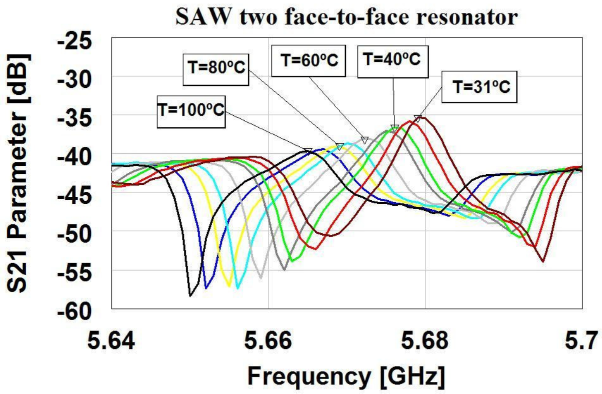

Fig. 1 The variation of S_{21} parameter vs temperature

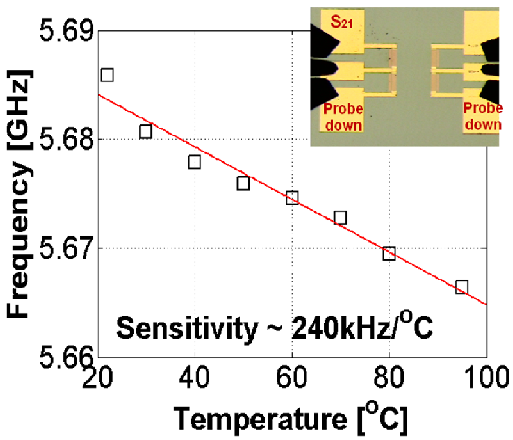

Fig. 2 The SAW structure and the temperature dependence of the resonance frequency obtained from S_{21}

Next determinations were obtained using the reflection parameter S_{11} (measurements performed with only one probe). The variation of parameter S_{11} at different temperatures is shown in Fig. 3. The sensitivity was 329 KHz/°C which corresponds to S= 59 ppm/°C (Fig. 4).

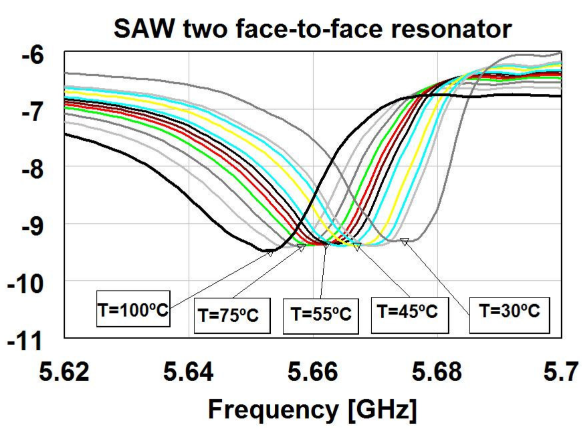

Fig. 3 The variation of S_{11} parameter vs temperature

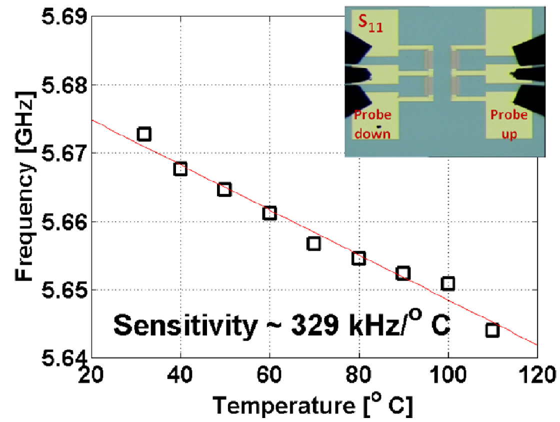

Fig. 4 The SAW structure and the temperature dependence of the resonance frequency obtained from S_{11}

New test structures have been manufactured on GaN/Si wafers grown on high-resistivity (111)-oriented silicon wafers, obtained on a commercial basis from NTT-AT, Japan. A buffer layer (composed by AlN and AlGaN) with a total thickness of 0.2μm was grown between the silicon (400 μm thick) wafer and the 1 μm-thin undoped GaN top layer. The new SAW structure, presented in Fig. 5, is a single resonator structure, having an interdigitated transducer with 100 fingers and 100 interdigits and 60 reflectors, placed on both sides of the IDT at a distance of 0.95 μm. The fingers have a length of 200 μm, a width of 200 nm and a thickness of 100 nm (Ti/Au 5/95 nm).

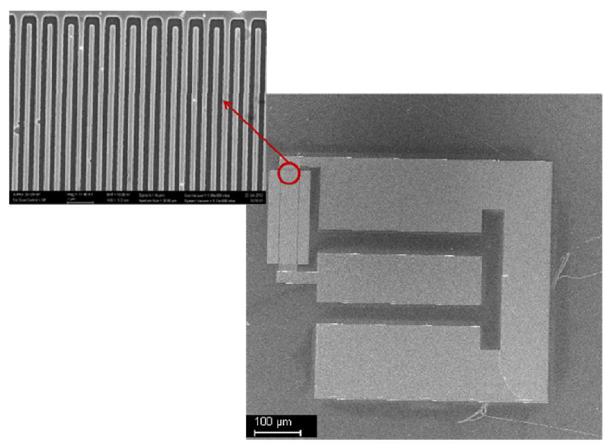

Fig.5 Single resonator SAW test structure; the inset presents details of the nanolithographic IDTs and reflectors

The structures were manufactured using the process presented in [3] based on conventional photolithography, e-gun metallization (Ti/Au) and lift-off technique for pads formation and followed by a deep submicronic e-beam nano-lithographic process on GaN/Si, for the interdigitated transducer (IDT) manufacturing.

The Q factor for the S_{11} resonance improved, typical values of about 320 have been obtained.

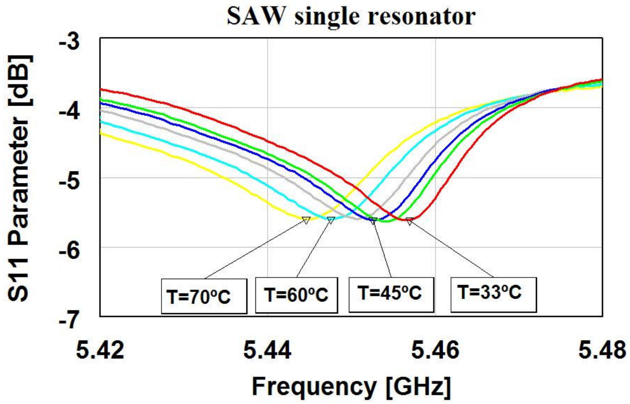

Fig. 6 S_{11} "on wafer" characterization for single SAW resonator structure, Q = 321

We have determined an increased sensitivity to values of 356 KHz/^{O}C which corresponds to S = 65 ppm/°C (Fig. 7).

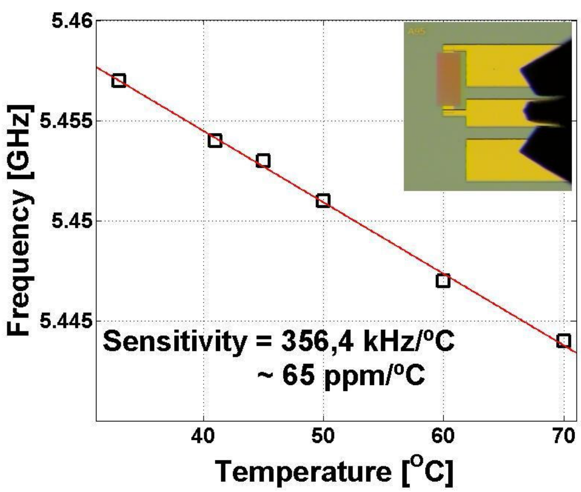

Fig. 7 The temperature dependence of the resonance frequency obtained for SAW single resonator from S_{11}

An increase of more than 20% was obtained for the sensitivity of the resonator structure, compared to the face-to-face resonator structure. The explanation of higher temperature sensitivity extracted from S_{11} measurements results from the equation (1).

$$TCF = \frac{1}{f}\frac{df}{dT} = \frac{1}{v}\frac{dv}{dT} - \frac{1}{L}\frac{dL}{dT} = \frac{1}{v}\frac{dv}{dT} - \alpha \qquad (1)$$

In (1) *TCF* is the temperature coefficient of frequency, *f* is the frequency, *v* is the sound velocity, *T* the temperature, *α* the expansion coefficient of GaN and *L* is the width of the structure.

If one of the probes is up or, we measure a single resonator structure, (i.e. S_{11} measurement) the first term, describing the propagation, in equation (1) reduces its influence compared with the second term (the "dilatation term"). As the two terms, have opposite signs, the sensitivity increases.

There are other potential advantages of using frequency change in a single SAW resonator instead of transmission between two SAW resonators or delay lines such as: (i) avoid the high transmission loss, present in all reported face-to-face coupled resonators on GaN, making the signal processing difficult; (ii) quite high Q of the S_{11} parameter which also simplifies signal processing electronics.

3 TEMPERATURE SENSOR DEVELOPMENT

Complete characterization of the temperature SAW sensor needs also information about assembled device on different packages or other kind of carriers, because these are closer to the real working conditions compared with on-wafer placement, already described above. Indeed, the behaviour of a packaged device can be influenced by external parasitic elements, usually associated with assembly process and carrier type: wire-bonding inductances, pad capacitances, etc.

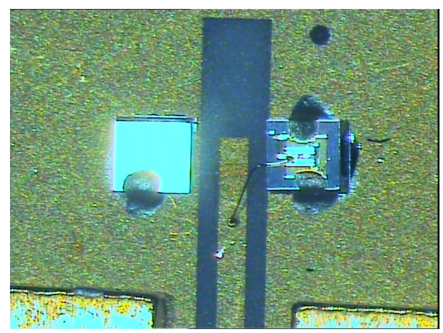

Fig. 8 SAW resonator assembled on a CPW-type test board (ceramic substrate is used)

Fig. 8 presents the photograph of a SAW resonator chip attached to a coplanar (CPW) transmission line test circuit manufactured on alumina substrate. Both transmission line section and associated ground plane are gold plated, in order to allow reliable chip and gold wire bonding. The test circuit is provided with a precision SMA connector.

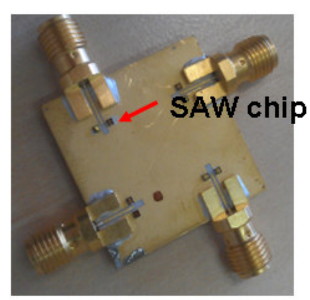

Fig. 9 The ceramic wafer with four CPW transmission lines, each having SMA connectors

Figure 9 presents the complete ceramic test board, which allows assembling of up to four resonator structures connected to edge mounted SMA connectors. This model is suitable for multiple resonators testing in a commercial oven, using precision coaxial cables connected to the VNA.

Preliminary measurements of resonance frequency vs. temperature on the “encapsulated” chips have proved sensitivities close to their corresponding values measured “on wafer”.

4 CONCLUSIONS

GaN based SAW temperature sensors have been manufactured for the first time. In contrast with other SAW sensor structures, manufactured on other piezoelectric materials (Lithium Niobate, Quartz), where delay lines or face to face resonators have been used, in this paper, the frequency shift vs. temperature for a single resonator structure was analyzed. The temperature GaN based SAW structures have the resonance in the GHz frequency range, The resonator structures were measured in the 23-130ºC temperature range. An increase of more than 20% was obtained for the sensitivity of the single resonator structure compared with face-to-face double resonator structures manufactured on the same wafer.

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