AlGaN/GaN based SAW-HEMT structures for chemical gas sensors

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1. Introduction

Nowadays, there is an increasing interest in identifying new piezoelectric materials where surface acoustic waves (SAW) devices can exhibit novel or improved characteristics [1]. Among them, the epitaxially grown III-nitride semiconductor materials such as AlN, AlGaN and GaN combine high SAW velocity and piezoelectric coupling with excellent thermal and chemical stability. SAW propagation directly in AlGaN/GaN heterostructure material system that defines a two-dimensional electron gas (2DEG) of the high electron mobility transistor (HEMT) was demonstrated. It enabled to integrate two different principles of gas sensing based on both SAW and HEMT. The functionality of two types of SAW structures and HEMT device was investigated. The measured amplitude characteristics of SAW structures revealed excitation at the centre peak frequency about 1.35 GHz and 1.7 GHz, respectively with a both good quality factor and stop-band rejection ratio. The detection electronic based on SAW oscillator was subsequently designed and simulated. It proved the expected function and properties.

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relatively independent of the temperature without further compensation mechanism. SAW chemical sensors operating in GHz range can be designed and integrated with wireless remote sensing applications. Excellent high sensitive gas detection (0.8 % of a monolayer coverage on the surface) should be achieved for AlGaN/GaN based SAW sensors operating in harsh conditions.

The principle of operation, detection by these SAW sensors utilizes the change in the velocity and phase of the acoustic wave propagating along the surface of the substrate with the integrated chemical absorbing layer placed between the two electro-mechanical transducers (input and output interdigital transducers – IDTs). Depending on the type of chemical and bio-agent needing to be detected, an absorbing layer for the specific chemical and bio-agent is coated on surface between the two IDTs. To increase selectivity, it is typical to employ an array of SAW devices, with different coatings used to identify specific chemicals or bio-agents.

Here, it should also be noted that the direct interaction of SAW with free carriers of 2DEG induced on AlGaN/GaN hetero-interface prevents the acousto-electric transduction in the interdigital transducers (IDTs) due to the additional insertion losses. Recently, the simple way of controlling the losses of AlGaN/GaN based SAW filters by applying a DC voltage between the fingers of the IDTs has been proposed [2]. The applied DC voltage depletes the 2DEG charge, allowing acousto-electrical transduction. Likewise, SAW filters composed of interdigital Schottky and ohmic contact fingers on AlGaN/GaN heterostructure have been proposed. SAW signals were observed when the IDTs of the SAW filters were reverse biased by a DC voltage [3]. To control the losses of AlGaN/GaN based SAW structures, a selective self-aligned SF$_6$ plasma treatment under Schottky gate fingers of IDTs was also applied for the first time [4]. The suppression of the losses could be explained by the additional depletion of 2DEG due to incorporation immobile F$^-$ ions into the AlGaN barrier layer at optimal plasma conditions (plasma power, induced bias voltage and time of treatment).

In this work we present a new approach to design and fabrication of AlGaN/GaN based SAW-HEMT structures to be applied for chemical gas sensors operating in harsh environment. A direct on-chip integrated compatibility in the process technology of SAW structure and HEMT is demonstrated. Functionality of both integrated SAW and HEMT structures is verified and simulation of integrated detection electronic is also performed.

2. Design and technology

We introduce a new approach to design and fabrication of AlGaN/GaN based SAW-HEMT structures to be applied for chemical gas sensors in harsh environments. This approach integrates two different principles of sensing and detection of gases or vapor toxic chemicals: - sensing principle based on SAW, and AlGaN/GaN HEMT. Moreover, integrated HEMT sensing device can also serve as a selective thermal heater. It can to increase the operating temperature of chemical absorbing layer placed on the gate area of HEMT, provided that thermal isolation conditions are fulfilled [5].

An undoped AlGaN/GaN heterostructures grown by metal-organic chemical vapor-phase deposition (MOCVD) on sapphire and SiC substrates were used to define interdigital transducers (IDTs) of SAW structures. A long gate length HEMT device with the chemical absorbing layer is integrated in space between IDTs, see Figs. 1, 2.

![Fig. 1. A cross-section of SAW-HEMT sensor on sapphire](image1)

![Fig. 2. A cross-section of SAW-HEMT sensor on SiC](image2)

Two different approaches were proposed to excite SAW in AlGaN/GaN heterostructure. The first one based on selective SF$_6$ plasma treatment (Fig. 1), and the second one based on selective etching of AlGaN barrier layer (Fig. 2). The both approaches were applied under Schottky Ni/Au fingers of IDTs before their deposition and patterning.

To fabricate the SAW-HEMT sensor structure, HEMT device process technology (“MESAS”-isolation, source-drain ohmic contact formation, Schottky gate formation) is combined with the process technology of IDTs. Two
IDTs, each with 20 pairs of interdigital fingers were designed for the working frequency of around 1.35 GHz. Both the width and the spacing between the fingers were designed to be 1 μm. Consequently, the SAW wavelength $\lambda$ is equal to 4 μm. Ni/Au e-beam evaporation and lift-off were carried out subsequently to form the Schottky fingers of the IDTs. A real view of fabricated SAW-HEMT structure and patterning of fingers of IDT are shown in Fig. 3 and Fig. 4, respectively.

![Fig. 3. A real view of fabricated SAW-HEMT sensor](image1)

![Fig. 4. A real view of patterning of Ni/Au fingers of IDT](image2)

3. Results and discussion

An Agilent Technologies, E8363B network analyzer with 50-Ohm terminal microprobes was used to measure S-matrices’ parameters of our SAW-HEMT structure. The influence of IDTs orientation and partial processing steps needed for HEMT device integration (MESA-isolation, gate patterning…) on SAW propagation was analyzed. A typical behavior of amplitude characteristics of both types of SAW structures without integrated HEMT device is shown in Fig. 5 and Fig. 6, respectively. The measured amplitude characteristics revealed excitation at the centre peak frequency about 1.35 GHz and 1.7 GHz in case of SF6 plasma treated (Fig. 5) and that of “MESA-etched (Fig. 6) SAW structure, respectively. Besides, as can be seen the both SAW structures exhibit a good quality factor and stop-band rejection ratio.

![Fig. 5. Amplitude characteristic of plasma treated SAW structure](image3)

![Fig. 6. Amplitude characteristic of “MESA”-etched SAW structure](image4)

The influence of HEMT integration on behavior of amplitude characteristic of SF6 plasma treated SAW structure is shown in Fig. 7. There is an interaction of SAW with a thin Pt gate of HEMT device carried out. As we can see the integrated HEMT device has no influence on resonant frequency of SAW structure. So, the sensing principle based on HEMT could also be used in this integrated SAW–HEMT sensor structure. To demonstrate functionality of the long gate length HEMT its basic dc characterization was performed. HEMT gate length and width were 200 μm and 400 μm, respectively. HEMT out-put characteristics corresponded to one half of channel width (200 μm) are
shown in Fig. 8. They demonstrate a good gate controlled saturation behavior and convenient power ability to be used for both HEMT sensing and HEMT heater applications.

For testing purpose, simple oscillator employing test SAW devices (Figs. 5, 6) in feedback loop has been designed using discrete HBTs (heterobipolar transistors). These are intended be replaced by AlGaN/GaN HEMTs in the case of monolithic integration. Final investigation of SAW oscillator accomplished by simulation in HSPICE proved the expected function and properties.

4. Conclusion

In this work we have introduced a new approach to design and fabrication of AlGaN/GaN based SAW-HEMT structure to be applied for chemical gas sensors operating in harsh environment. SAW-HEMT structure introduced should be able to detect gases using two different principles of sensing: - sensing principle based on SAW and HEMT. A direct on-chip integrated compatibility in the process technology of SAW structure and HEMT device was demonstrated. Their functionality was subsequently also verified. For testing of SAW-HEMT detection properties in real gas environment the detection electronic based on SAW oscillator was designed and simulated. It proved the expected function and properties.

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