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GaN/SiC based surface acoustic wave structures for hydrogen sensors with enhanced sensitivity☆

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ABSTRACT

In this article, we present an application of GaN/SiC heterostructures for Surface Acoustic Wave (SAW) hydrogen sensors with enhanced sensitivity. We demonstrate that the mass-loading sensitivity of such sensors can be increased by using shorter acoustic wavelengths and by confining the acoustic wave energy in an epitaxial waveguide. The effect of different Rayleigh-like modes on the mass-loading sensitivity is also discussed. The SAW wavelength-dependent phase and group velocity and electromechanical coupling constants were determined from electrical measurements. The outcome was used to design a microwave SAW delay-line oscillator. Its sensing characteristics are presented. The oscillator frequency shift was larger than 60 kHz after exposure to 1000 ppm H_2/N_2. The sensor reaction time was about 12 s for the same sensing conditions at room temperature.

1. Introduction

Gallium nitride (GaN) is a semiconductor that has become a very well-established material for the fabrication of LED, microwave power transistors, and many different types of sensor. However, it is still very costly to grow bulk GaN. Hence, different authors have grown bulk GaN on sapphire [1,2], $LiAlO_2$ [3] substrates, and SiC [4]. Special attention is paid to the growth of GaN on silicon (Si) [5,6] as it is compatible with standard Si bulk micromachining processes. In general, thick GaN layers are mainly deposited by metalorganic chemical vapor deposition (MOCVD). They are mainly used as buffer layers in High Electron Mobility Transistors (HEMTs) based on AlGaN/GaN or InAlN/GaN heterostructures. Fabrication costs of such heterostructures can be reduced by growing reasonably thin GaN layers (few micrometres thick).

GaN-based surface acoustic wave (SAW) sensors are very promising for use in harsh conditions because GaN is a wide bandgap material and it also exhibits stable piezoelectric and mechanical parameters. The SAW electro-mechanical detection principle allows for operating such sensors in high radiation environments. Moreover, GaN is also suitable for biosensing applications because of its biocompatibility. However, it is necessary to make such devices more sensitive. To reach this goal, most authors generally work towards the improvement of chemical absorbing layers [7–16].

Therefore authors commonly use various nanostructured materials (with an enhanced surface-to-volume ratio, which is required to efficiently bind gas molecules). For example, Sadek et al. [9] used nanostructured ZnO nanorods grown on $LiNbO_3$ (with a large electro-mechanical coupling) as hydrogen sensitive layers. ZnO is a semiconductor material with oxygen vacancy sites that are involved in chemisorption processes. The authors achieved at 265 °C a large frequency shift of 274 kHz (related to a change in the thin film resistivity induced by the acousto-electrical effect [10,17]). Ippolito et al. [13] also demonstrated a SAW sensor that exhibited an improved response performance. The sensor was manufactured on a substrate with a large electro-mechanical coupling constant ($LiTaO_3$), and it was coated by a catalyst activated WO_3 chemiresistive overlayer. The sensor frequency shift was 303 kHz upon exposure to 1250 ppm H_2. However, to enable the chemisorption of H_2, it was necessary to activate the semiconducting material at 270 °C. A similar approach was reported by Fechete et al. [15]. A maximum frequency shift of ~250 kHz was reached at an optimal temperature of 290 °C. The approach based on semiconductor metal

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oxide absorbing layers requires heating the layers to activate them chemically. This is a particular disadvantage, which makes problematic using such sensors in low power battery-powered systems.

Unlike these authors, our motivation was to suppress the contribution of the acousto-electrical effect [17] on the response of a sensor, as it increased the SAW device passband attenuation and made the design of amplifier circuits at microwave frequencies more complicated as a large open loop gain was required.

One can enhance the sensitivity of such sensors to surface perturbation in a completely different way: one can locate the energy of acoustic waves as close as possible to the surface of a crystal [17]. This can be done by shortening acoustic wavelength using interdigital transducers (IDTs) of sub-micrometer dimensions, defined by e-beam lithography. Still another approach is to increase the sensitivity by confining the acoustic wave energy within a very thin acoustic waveguide. Most authors used this method to excite shear-horizontal waves for sensing in liquid environments [18,19]. However, Takagaki et al. [4] showed that using a GaN/SiC system, the Rayleigh-like modes are preferably excited in epitaxial piezoelectric GaN waveguides. Therefore, we chose MOCVD-grown GaN epitaxial layers on SiC substrate thanks to their high quality with a very low concentration of defects [20]. This enables the on-wafer integration of a SAW sensor with a HEMT transistor amplifier [21] and the fabrication of multi-detector sensor arrays for fast online analysis. However, such as-formed acoustic waveguide shows a very strong acoustic velocity dispersion [4] and a wavelength-dependence of effective electromechanical coupling coefficients [22]. Because of high SAW phase velocities in both GaN and SiC layers, it becomes feasible to design SAW sensors for a microwave range. However, to design and simulate such devices, it is necessary to use a reliable equivalent model. Therefore, certain acoustic wave physical properties must be known. The most important parameters are the phase velocity and its dependence on wavelength, electromechanical coupling factor and mass-loading influence of SAW velocity.

In the first part of this article, we describe the fabrication of GaN/SiC-based SAW sensors. In the next, electrical properties of the sensors are presented and then the basic acoustic quantities of both epitaxial films and metallic gratings are extracted. We investigate the effect of wavelength and excitation mode on the mass sensitivity of the proposed sensor. We finally demonstrate a prototype of a sensor based on a microwave SAW delay line oscillator with improved sensing response.

2. Experimental

2.1. Sensor design and fabrication

An undoped GaN(3 nm)/AlGaN(17 nm)/GaN(1.7 μm) heterostructure was grown by MOCVD on a 470 μm thick *c*-axis SiC substrate layer. This material system allows for the fabrication of HEMT and SAW elements on a single chip [23]. To eliminate the 2-DEG screening effect on SAW excitation, a shallow MESA insulation etch was performed [23]. This removed the top GaN cap and AlGaN barrier layer. IDT transducers were oriented to radiate SAWs in the [1 1 $\underline{2}$ 0] direction. The schematic cross-section of a proposed sensor structure is depicted in Fig. 1a. Fig. 1b shows an optical photograph of the fabricated structure.

The design of SAW-oscillator-based sensors has already been well documented in several publications [24–26]. However, at microwave frequencies, it becomes more complex due to the need to simulate the electronic circuit of the whole oscillator including parasitic elements [27]. Otherwise, it may happen that oscillator will generate spurious signals caused by additional resonances of the abovementioned unwanted stray reactances.

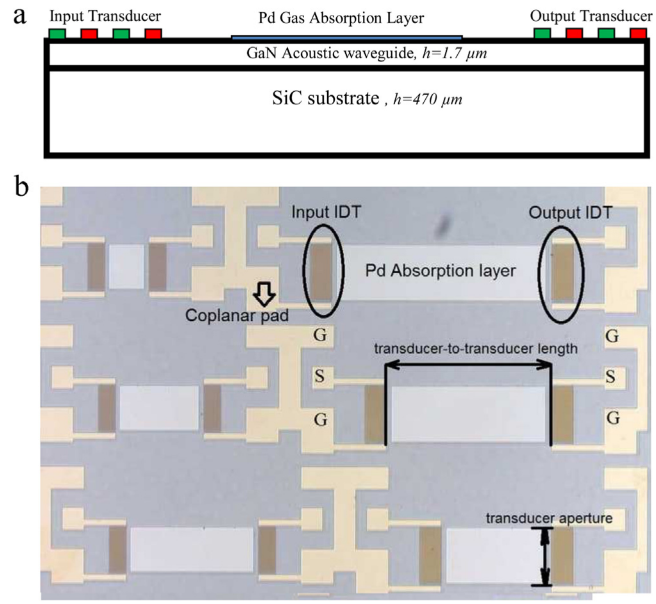

Fig. 1. (a) Schematic SAW structure cross-section. (b) Fabricated structure photograph.

However, unlike the SAW filters for e.g. television intermediate frequency, cellphone diplexers, etc., the requirements for transmission characteristic shape of SAW-filter-based sensors are not so severe. The key parameters to be achieved are low insertion losses and linear phase characteristics within the filter passband. Therefore, one can allow for some trade-offs in their design. The interdigitated transducers were designed as a compromise between electrical parameters and fabrication reproducibility. Especially, the IDTs fabricated by e-beam lithography are very prone to electrical short circuits caused by lift-off defects. Therefore, the number of interdigital fingers was reasonably limited to ensure the reproducibility of the process. The acoustic aperture of the interdigital transducer is also subjected to certain limits. If the IDT fingers are long, their series resistance will become significant. Therefore, an additional attenuation due to ohmic losses will occur. Moreover, longer thin IDT fingers are susceptible to cut-off or short circuits.

Therefore, both IDT were designed as a compromise between the fabrication ability (minimum probability of defects) and the transducer optimal input admittance. Two types of transducer were designed: solid electrode uniform comb transducer (Fig. 2a) and split electrode transducer (Fig. 2b). They are also schematically shown in Fig. 1. The nominal finger width w and spacing s were equal and their nominal dimensions were 1, 0.8 and 0.5 μm for three batches of sensors. The acoustic wavelength Λ was thereby equal to 4, 3.2 and 2 μm for the solid-electrode transducers and 8, 6.4 and 4 μm for the split-electrode transducers, respectively. Ni(20 nm)/Au(100 nm) Schottky contacts were patterned on top of the GaN epitaxial layers by electron beam lithography and lift-off to form the interdigital transducers. The metallization ratio $\eta = w/(w+s) = 0.5$ was carefully maintained by optimizing the e-beam radiation dose [28] for periodic gratings. The number of interdigital pairs N was 20 and the transducer acoustic aperture A was 50 Λ. For the purpose of SAW phase velocity measurement, the front-to-front transducer distance L was altered within 50–200 Λ. The transducer-to-transducer distance was kept short to avoid a diffraction-induced increase of insertion loss and the ripple in amplitude and phase characteristics.

On different structures, the partial length (L-2g) of the propagation path (40–190 Λ) was covered by a 100 nm thick Pd hydrogen