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Novel Microwave Gas Sensor using Dielectric Resonator With SnO₂ Sensitive Layer

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Abstract

A new generation of passive gas sensors that works at millimeter-wave frequency (50 to 70 GHz) incorporating sensitive material is presented. The sensor uses a microwave planar dielectric resonator operating with whispering-gallery-modes. The dielectric resonator (DR) is covered by SnO₂ thin film as sensitive layer. A gas adsorption makes the SnO₂ effective dielectric parameters changing namely its permittivity. Such changing modifies the resonance frequency of the resonator. Here, the proof of concept is demonstrated thorough full wave simulations. This sensor is a passive circuit and has great potential for wireless sensing network applications.

Keywords: RF gas sensor, Dielectric resonator, Whispering gallery mode.

1. Introduction

The explosion of the market telecommunications allowed the emergence of new wireless gas sensors operating at microwave and millimeter frequencies [1].

The existing semiconductors sensors generally composed by sensitive layer such as TiO₂, SnO₂, WO₃, etc are famous due to their high sensitivity for gases and low cost production. In presence of gas, the electrical properties of these materials change and lead a modification in their conductivity.

This kind of sensor works at high temperatures what increases their power consumption. Their functioning with low frequencies requires techniques of modulation to insure the wireless connection and consequently the system becomes cumbersome and requires batteries [2, 3].

In microwave domain, the dielectric resonator is a good candidate for gas detection due to its large surface area and sensitivity for external environments. These main issues raised potential to be used a very high efficient structure in this context [4]. The excitations of the dielectric resonator (DR) with whispering-gallery-modes (WGM) have many advantages over the conventional excitation transverse electrical (TE) or transverse magnetic(TM) modes.

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DR acting on WGM mode has relatively large dimensions and a higher quality factor. Moreover, it can be excited differently, and can run in the azimuthally direction, that gives it potentialities to detect gas perturbation from every direction. In this study, we design and simulate a DR structure coupled with microwave waveguides in coplanar technology. This coupling allows very high selective performances [5].

A material such as SnO_2 is used as the sensitive layer, as it is very sensitive to gas adsorption. Moreover, this metal oxide presents permittivity relaxation at very high frequency due to the presence of gases, which could be exploited to build a new detector in the microwave regime [6, 7].

2. Design of the gas detector based on whispering-gallery-modes

In this study, we design and simulate a DR structure that incorporates a SnO_2 sensitive layer coupled with microwave waveguides in coplanar topology for high performance in term of gas sensitivity.

The proposed resonator-based sensor is shown in Fig.1 (a). It consists of two main blocks: the coplanar waveguides (CPW) (see fig.1 (b)) used for electromagnetic propagation and the DR with SnO_2 layer used for gas detection (see fig.1 (c)). These two parallel CPW are deposited over a $\text{SiO}_2/\text{SiN}_x$ membrane with Ti/Au metallization with adapted sizes: $\epsilon_r=1.09$, $L=13\text{mm}$, $W=300\mu\text{m}$, $S=30\mu\text{m}$ and $H_{\text{metal}}=1\mu\text{m}$ that give following impedance characteristics: 75Ω . We chose the DR material composition with BaZnTaOxide from TEMEX CERAMICS because it presents also many advantages as resonant modes of frequency determined by the dimensions, high Q-factors, more compact, higher temperature stability and easy to use [8]. The DR characteristics are dielectric constant equals to 30, typical Q factor close to 15000 at 10GHz, a diameter $D_{\text{DR}}=6.5\text{mm}$ and a thickness $H_{\text{DR}}=350\mu\text{m}$. The DR is mounted above the coplanar lines by using Al_2O_3 dielectric spacer ($\epsilon_r=9.8$) [8] with diameter $D_{\text{spacer}}=2.7\text{mm}$ and height $H_{\text{spacer}}=260\mu\text{m}$. Thanks to numerical simulations, the optimal dimension of the spacer leads to a good electromagnetic coupling between the DR and the two CPW (Minimum of losses).

We chose SnO_2 material as film layer with relative dielectric permittivity of 24 [9] and with thickness of $H_{\text{SnO}_2}=10\mu\text{m}$. The whole sensor is laid out on a high resistive silicon substrate with $\epsilon_r=11.6$ and thickness of $H_{\text{Si}}=350\mu\text{m}$. The access 2 and 4 are loaded by 50Ω -impedances in order to work with band-pass filter between access 1 and 3.

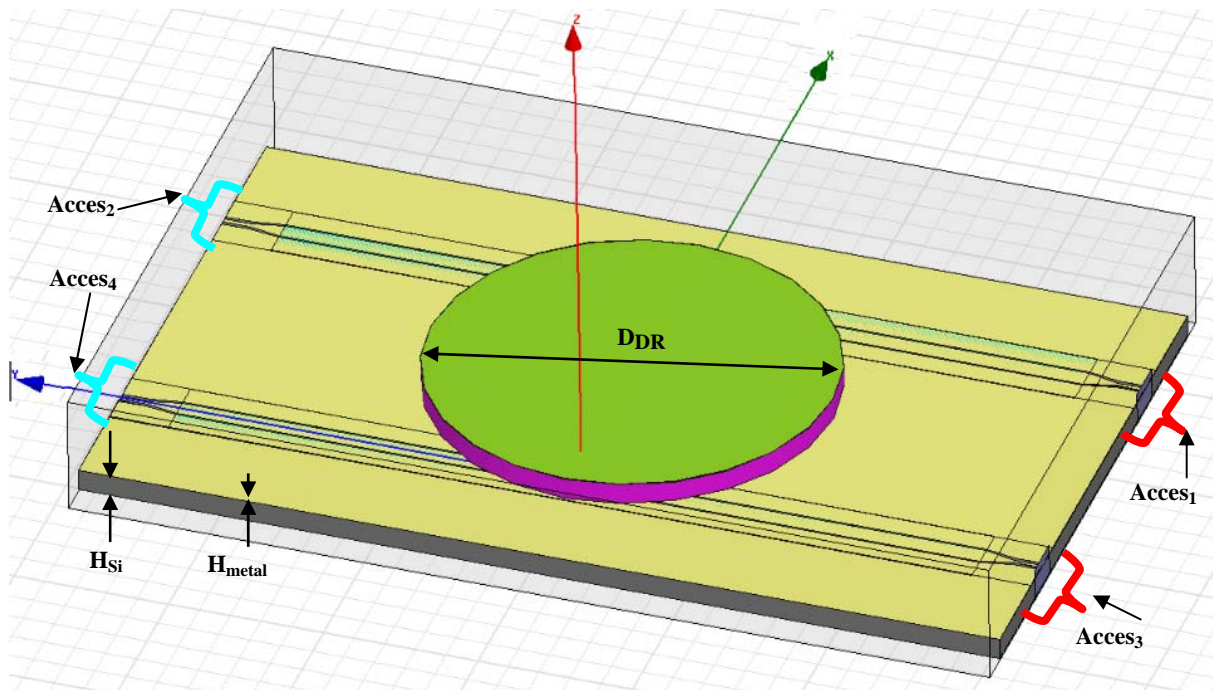


Fig. 1 (a) Sensor schematic concept: Cell used to measure the gas concentration.

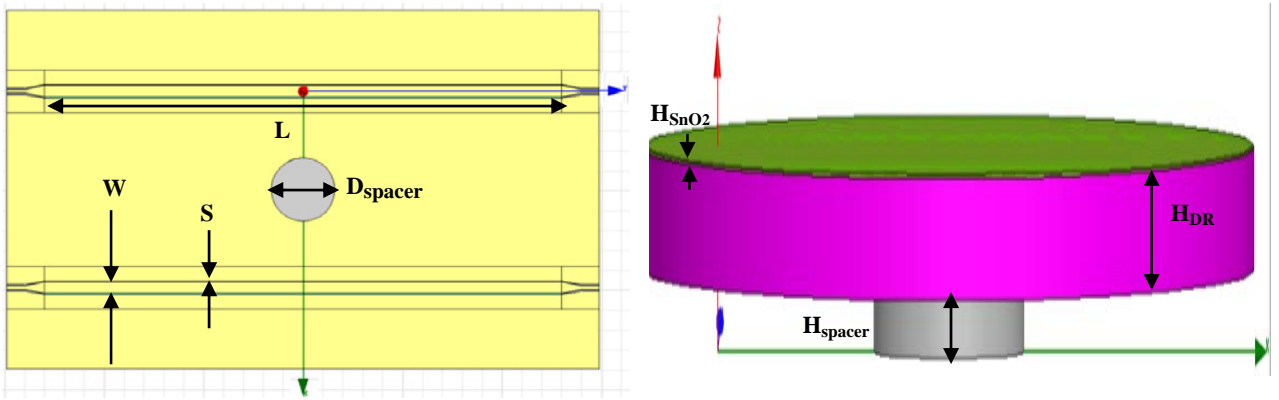


Fig. 1. (b) Two coplanar lines micro-machined; (c) Dielectric resonator with spacer.

3. Description of the detection principle and simulation results

Figure 2(a) shows the functionality of the structure in large operating frequency band. The DR design acting with $\text{WGH}_{13,0,0}$ mode shows a resonant frequency at 63.85 GHz with a quality factor of 336. The magnetic field distribution at this mode is depicted in Figure 2(b).

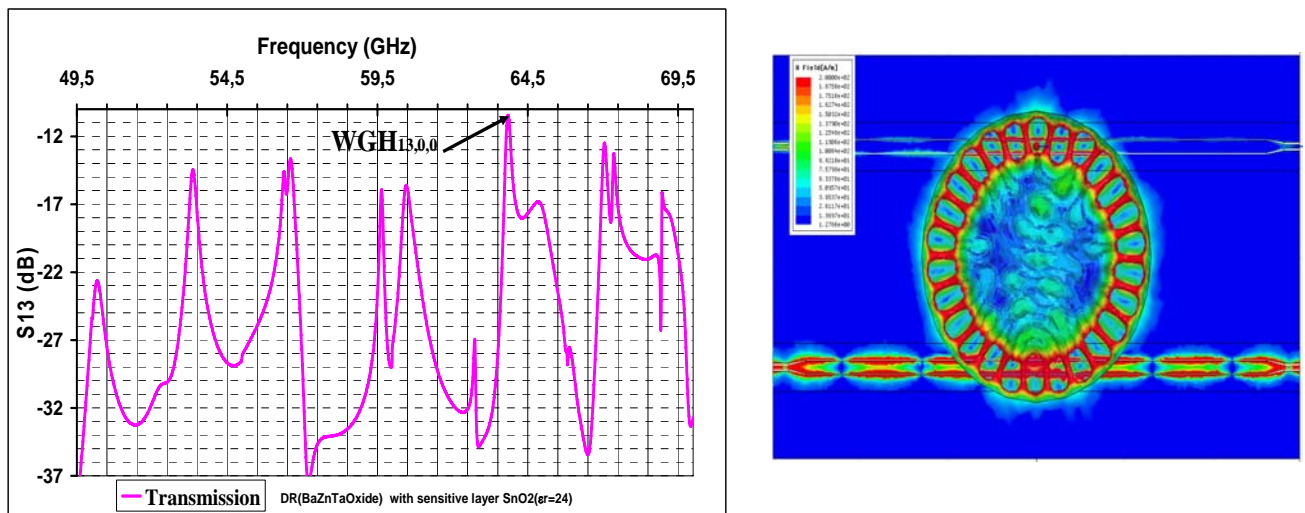


Fig. 2 (a) Simulation results of the structure coupling coefficient using full-wave electromagnetic simulation (HFSS™); (b) Amplitude of the magnetic field $\text{WGH}_{13,0,0}$ mode at 63.85 GHz.

4. Influence of Ethylene on the detector

Thanks to results presented in literature, the permittivity of SnO_2 material depends on the detected gas [10]. For example, in presence of 100 ppm of ethylene (C_2H_4) the dielectric permittivity of SnO_2 tends to decrease by 40%.

To analyze the impact of this change in permittivity on the resonant frequency (63.85 GHz), we performed full-wave electromagnetic simulations based on the Finite-Element Method (HFSS™) [11] by adopting relative

dielectric permittivity taken between 22 and 26. This variation of 10% on the permittivity of SnO₂ may be induced by the presence of 10 ppm of ethylene [6]. As shown in Figure 3, the resulting resonant frequency of WGM-based resonator takes values that can reach almost 3% on the resonant frequency at the WGH_{13,0,0} modes.

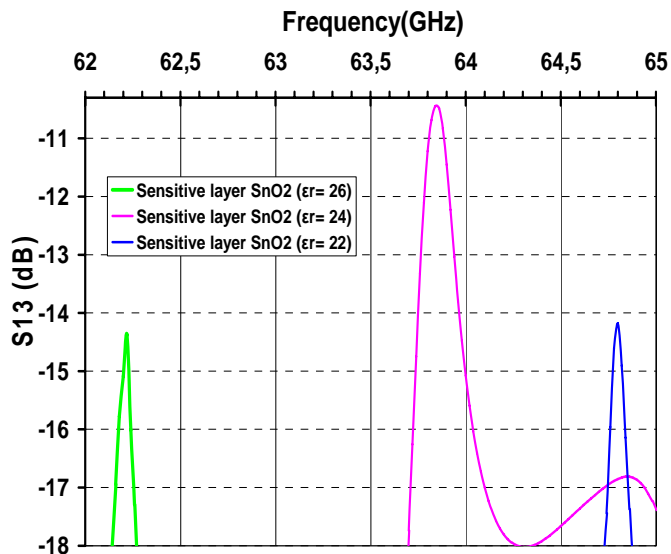


Fig. 3. Transmission coefficient at the WGH_{13,0,0} mode in presence of C₂H₄.

5. Conclusion

The potentialities of a novel microwave gas sensor using dielectric resonator has been proved thanks to full wave electromagnetic simulations. The high sensitivity in the frequency response of the proposed gas detector device based on high-Q whispering-gallery-modes is a very interesting for developing unique gas detection with ease of integration of the RF function. Gas sensor design is now under fabrication.

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