Silicon-carbide-based MEMS for gas detection applications

Jean-François Michaud[1*], Marc Portail[2], Daniel Alquier[1], Dominique Certon[1], Isabelle Dufour[3]

1 GREMAN UMR-CNRS 7347, University of Tours, INSA Centre Val de Loire, 16 rue Pierre et Marie Curie, 37071 TOURS Cedex 2, France

2 CRHEA, CNRS-UPR10, rue Bernard Gregory, 06560 Valbonne, France

3 IMS UMR-CNRS 5218, University of Bordeaux, 351 cours de la libération, 33405 Talence Cedex, France

*jean-francois.michaud@univ-tours.fr

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Abstract. Gas sensors are devices that can detect and/or discriminate gases in their surroundings. Some of these devices are based on vibrating structure covered with a coating sensitive to the species to detect. But such a layer can cause device failures issues like ageing, low reliability and high response time. Nonetheless, gas sensors are of importance for industrial environments in many applications. In addition, in some cases, the sensors must operate in harsh environments, that can lead to a severe degradation of the devices.

In this paper, we propose to review ~~2~~ different MEMS devices, without any sensitive layer, for gas detection applications. The objective is to measure a physical property of the gas in order to determine its concentration. With the ~~2~~ microsystem devices, limits of detection as low as 0.2% has been obtained, illustrating the capabilities of the structures elaborated. And in our case, due to the absence of sensitive film that must be adapted according to the species to detect, it leads to generic sensors, compatible with many different gases. Moreover, by combining the measures of 2 physical parameters, the discrimination of the gases, with their respective concentrations, is accessible.

1. Introduction

Nowadays, Micro-Electro-Mechanical-Systems (MEMS) are present quite everywhere, in different fields of applications that can be separated in 4 main families: mechanics, optics, radiofrequency or biology. Usually, the active structure of MEMS devices, that can be bridges, beams, plates or membranes, are elaborated using silicon (Si), or related materials such as silicon nitride. But, with these materials, depending on the type of the targeted application, it may be necessary to associate a cooling system or a shielding against radiation to the device. These additional elements add volume and weight, which is in complete contradiction with the desire for miniaturization sought for MEMS. Moreover, in application fields such as space or aeronautics, an increase in weight leads to a drastic increase in costs [1].

Thanks to its properties, these problems can be circumvented by using silicon carbide (SiC) to achieve MEMS devices. Indeed, this material presents attractive physical properties, such as its resistance to radiation or its chemical inertness. These particularities make it an ideal candidate for the elaboration of MEMS devices.

Among the various silicon carbide polytypes, contrary to what is observed for the elaboration of electronic devices where 4H-SiC is dominant, the cubic polytype (3C-SiC) is perfectly appropriate to address MEMS applications [2]. Indeed, since this polytype can be grown heteroepitaxially on Si substrates, most of the technological steps developed for silicon can be used to complete SiC-based MEMS using 3C-SiC.

In the literature, different fields of application have been addressed with SiC-based MEMS, but typically with a resonator as a common point, which can be lateral [3] or vertical [4]. For this type of application, the benefit of using SiC is justified by its mechanical properties. Actually, based on the Young's modulus of this material, the resonance frequencies are about 40% higher than those obtained with an equivalent Si-based device [5]. It can lead to key improvement, for example in the field of Atomic Force Microscopy where the resolution of the measure is closely linked to the resonance frequency of the beam [6]. Cantilevers can also be used as a tool, for example to determine the Young's modulus of the material involved [7]. In addition, thanks to both chemical inertness and radiation resistance, silicon carbide is compatible with harsh environments.

For gas sensing applications, very few SiC devices are referenced in the literature, but one can notice that commercial sensors systems based on 4H-SiC are available since 2007, from SenSiC AB company [SensiC]. The technology involved is not fully described but these SiC devices commercialized for combustion control, small and medium-scale power plants, seem based on the behaviour of electrical devices. Indeed, transistors, MOS capacitors or Schottky diodes, using an active film such as palladium, platinum or iridium, have been already described in the literature for gas sensing applications. Typically, the chemical interaction between the gas and the sensor device leads to a modification of the electrical characteristics. For example, such an interaction between the gas and the gate contact of a MOS structure changes the electric field across the structure, that modulates the current. Therefore, any shift of the electrical performances can be assigned to a modification of the environment. For complementary information, a detailed review on these structures can be found in [Andersson]. The capability to address gas sensing applications with silicon carbide nanosheets synthesized from graphene oxide has been also demonstrated. Actually, hazardous gases like acetone, methanol, ethanol and ammonia, have been detected with such SiC nanosheets at high temperature (500°C) [Sun]. The detection principle is not fully understood but it seems that molecules are chemisorbed by the SiC layer, that leads to drastic changes on the electronic properties of the SiC film [Zhao]. But in both cases, the gas detection is intimately correlated to the interaction between the SiC layer and its environment, leading to specific sensors.

In this paper, we present the fabrication and the use of 3C-SiC microcantilever-based devices to address gas detection applications, without functionalized coating. The absence of a sensitive coating leads to more versatile sensors as, for each specie to detect, it is not mandatory to identify an appropriate layer to chemically react with the gas. In addition, it leads to more reliable sensors, with no need of calibration during the sensor's life cycle. Moreover, uncoated sensors are more robust as it has been shown that using a sensitive coating compromises the long-term stability of the sensor, mostly due to ageing of the coating.

Additionally, another MEMS structure, based on a vibrating membrane so-called Capacitive Micromachined Ultrasonic Transducer (CMUT), is also presented and investigated in detail. Even if it is still, at the moment, not based on 3C-SiC material (silicon nitride membrane), we have chosen to report results of such

devices as our group explored new routes to elaborate CMUT using 3C-SiC material [8][9]. This also gives us the opportunity to compare the performances of the two device types, paving the future of SiC CMUT as efficient gas sensors.

2. Experimental

To achieve 3C-SiC microcantilevers, silicon carbide material was grown on (100) silicon wafers, by means of Chemical Vapor Deposition (CVD) technique, using a two steps process [10]. The growth was done in a homemade horizontal hot wall resistively heated reactor, using a mixture of propane and silane as gas precursors diluted in hydrogen (H/Si ratio ~ 2500) at 200mbar. After *in situ* silicon surface preparation at high temperature, SiC nucleation was initiated under propane at 1070°C (carbonization) followed by an epitaxial growth stage under propane and silane at 1350°C, with a C/Si ratio close to unity. For the purpose of this study, the thickness of the 3C-SiC films was close to 10µm. After the growth, a Chemical-Mechanical-Polishing (CMP) treatment was done to obtain a final surface roughness (Ra) below 1nm.

These 3C-SiC/Si(100) epi-wafers were then used for the microcantilever fabrication, using 5 photolithographic steps: to form some alignment crosses for the subsequent mask levels, to define the 3C-SiC cantilevers, to isolate 3C-SiC material from the following contacts, to define the metal acting as the electrodes for the electromagnetic actuation and inductive detection and, finally, to release the 3C-SiC cantilevers from the rear side, by etching the Si substrate. To optimize the process, illustrated in Fig. 1, the same metal stack has been chosen for the electrodes to achieve both actuation and detection contacts: titanium (50nm) and gold (300nm) on top of it. The most challenging step of the process was the release of the cantilevers, as the method used must be compatible with the front face. In other words, the rear etching of the Si substrate has to be carried out while preserving the integrity of the front face, namely the 3C-SiC cantilevers and their associated contacts. Consequently, to prevent the front face of any potential degradation, a protective layer has been used on this side to perform the rear face etching with potassium hydroxide (KOH). This 500nm thick protective layer, developed in GREMAN laboratory, was deposited in an inductively coupled plasma equipment, thanks to C_2H_4 and CHF_3 precursor gases [11]. This layer acts as an etch-stop film, that leads to the protection of the metallic layers of the front face during the KOH etching.

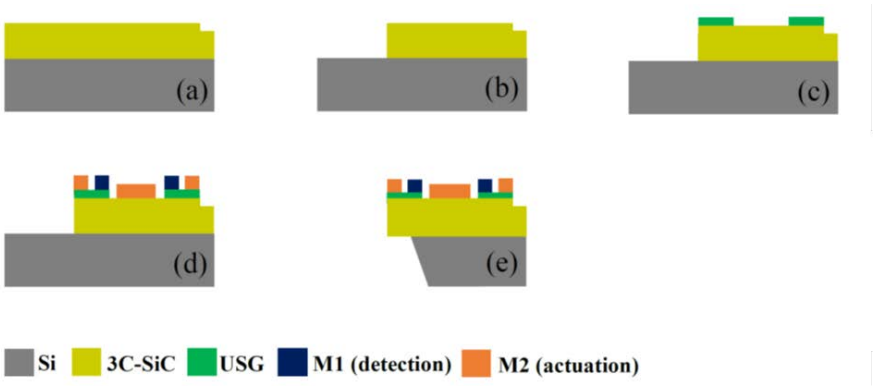

Fig. 1. Schematic process flow of 3C-SiC cantilevers fabrication, composed of 5 photolithographic steps: (a) patterning alignment crosses, (b) defining cantilevers geometries, (c) introduction of an isolation layer to separate 3C-SiC and metal contacts, (d) metal deposition for electromagnetic actuation and inductive detection and (e) cantilever releasing from the rear side, by etching the Si substrate with KOH**, adapted from [Priya]**.

Following this 5-stage process, the electromagnetic actuation and inductive read-out cantilevers were completed, as schematised on Fig. 2.

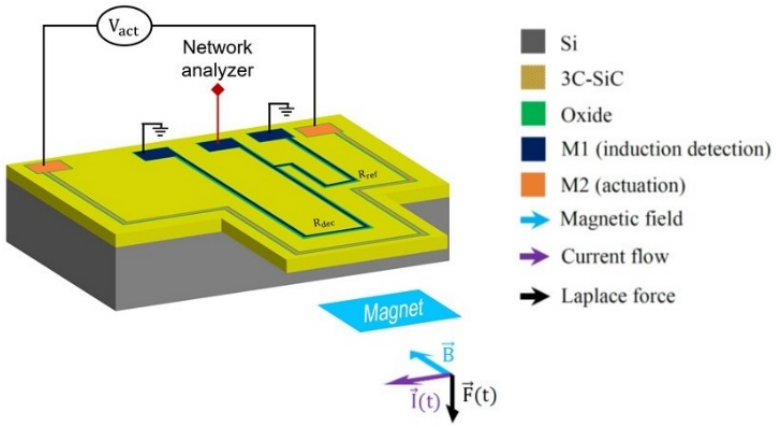

Fig. 2. 3C-SiC-based microcantilever using electromagnetic actuation and inductive detection, for gas detection**, adapted from [Priya]**

For gas detection applications, another MEMS structure than 3C-SiC microcantilevers has been also investigated. As already mentioned, MEMS devices are always composed of a moving part, that can be a bridge, a beam, a plate or a membrane. This last one is the basis of a particular MEMS device: the capacitive micromachined ultrasonic transducers. The first CMUT devices were achieved in late 1980s, but the real emergence of CMUT started thanks to process improvements using surface micromachining, by M.I. Haller and B.T. Khuri-Yakub, in 1993 [12]. In our case, CMUT were elaborated on high resistivity 6” silicon substrates, with a 1.2µm thick silicon dioxide film grown by thermal oxidation. Afterwards, a 450nm thick highly doped polysilicon (PolySi) layer was deposited by low pressure CVD (LPCVD) on top of the silicon substrate oxidized,

then structured to act as the bottom electrode. Subsequently, a sacrificial oxide (PSG: PhosphoSilicate Glass) was deposited by plasma enhanced CVD at 400°C. This PSG layer was then dry etched to define the cavity of the future CMUT. Therefore, the thickness of this layer leads to the cavity height. The 400nm thick silicon nitride (SiNx) CMUT membrane was then deposited, by LPCVD, using dichlorosilane (H_2SiCl_2) and ammonia (NH_3) precursor gases. Subsequently, the sacrificial layer was etched thanks to hydrofluoric acid (HF), through excavation holes, to release the SiNx membrane. After etching, the excavation holes were sealed to maintain the cavity under vacuum, using Undoped Silicon Glass (USG). The last step of the process consists in top electrode aluminium deposition and patterning, using a 450nm thick layer deposited by sputtering. The schematic structure of the CMUT is presented in Fig. 3.

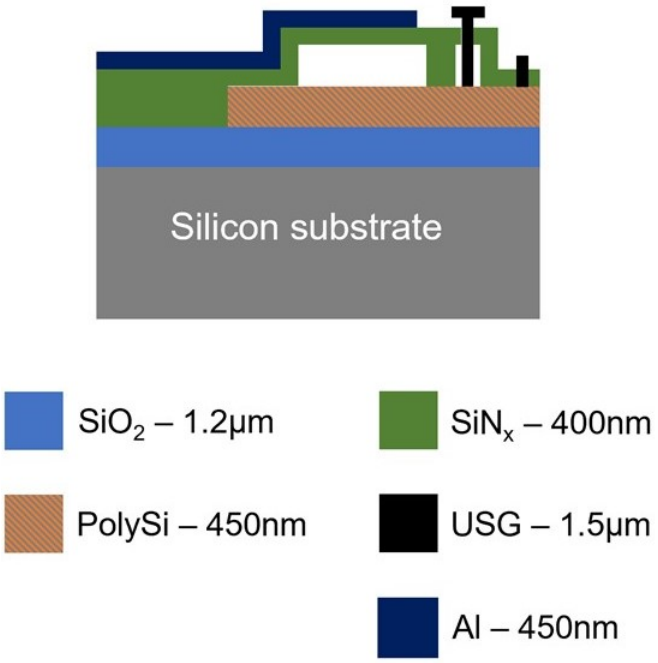

Fig. 3. Schematic depiction of a CMUT elaborated thanks to surface micromachining, composed of a highly doped polysilicon bottom electrode, a silicon nitride membrane and an aluminum top electrode.

Based on their structure, CMUT can be considered as a parallel plate capacitor, with a fixed bottom electrode and a mobile top electrode deposited on a suspended membrane, that can be actuated electrostatically. With membrane dimensions of 32µm x 32µm, the CMUT resonance frequencies are around 8MHz, that generates ultrasonic waves. These devices were initially developed for ultrasound emission in air [13] but since they suffered of a lack of sensitivity and bandwidth, applications have progressed for ultrasound transduction in liquid media. When CMUT technology radiates waves in liquid medium, it shows a very high frequency bandwidth, typically more than 100 %, which makes it suitable for medical imaging applications [14]. It explains why these devices are considered as a promising substitute to the conventional PZT-based (Lead Titanate Zirconate) transducers.

After cleanroom processing, the elaborated stuctures were then diced and prototyped to carry out further electrical characterization and gas mixture analysis. The chips were glued on specially designed printed circuit boards (PCB). Afterwards, the glued chips were baked at 150°C for one hour, to improve the adhesion between the PCB and the chip. Then, wedge bonding was performed using 25µm diameter aluminum wires. An example of a final prototype, composed of 4 3C-SiC cantilevers, is presented in Fig. 4. Each 3C-SiC cantilever of this prototype has typically a 500µm length (L) and a 500µm width (b). For remind, it has been previously demonstrated with silicon cantilevers that uniform rectangular ones are more suitable for mass density measurement than other tested T- and U-shapes [15]. Moreover, wide and short beams are more sensitive to the mass density variation; the sensitivity of rectangular beams being proportional to b/L^2, as predicted by an analytical model **developed** in [16]. For these dimensions, the resonance frequency and the quality factor of the 3C-SiC cantilevers, evaluated in air, are 28.55kHz and 357, respectively.

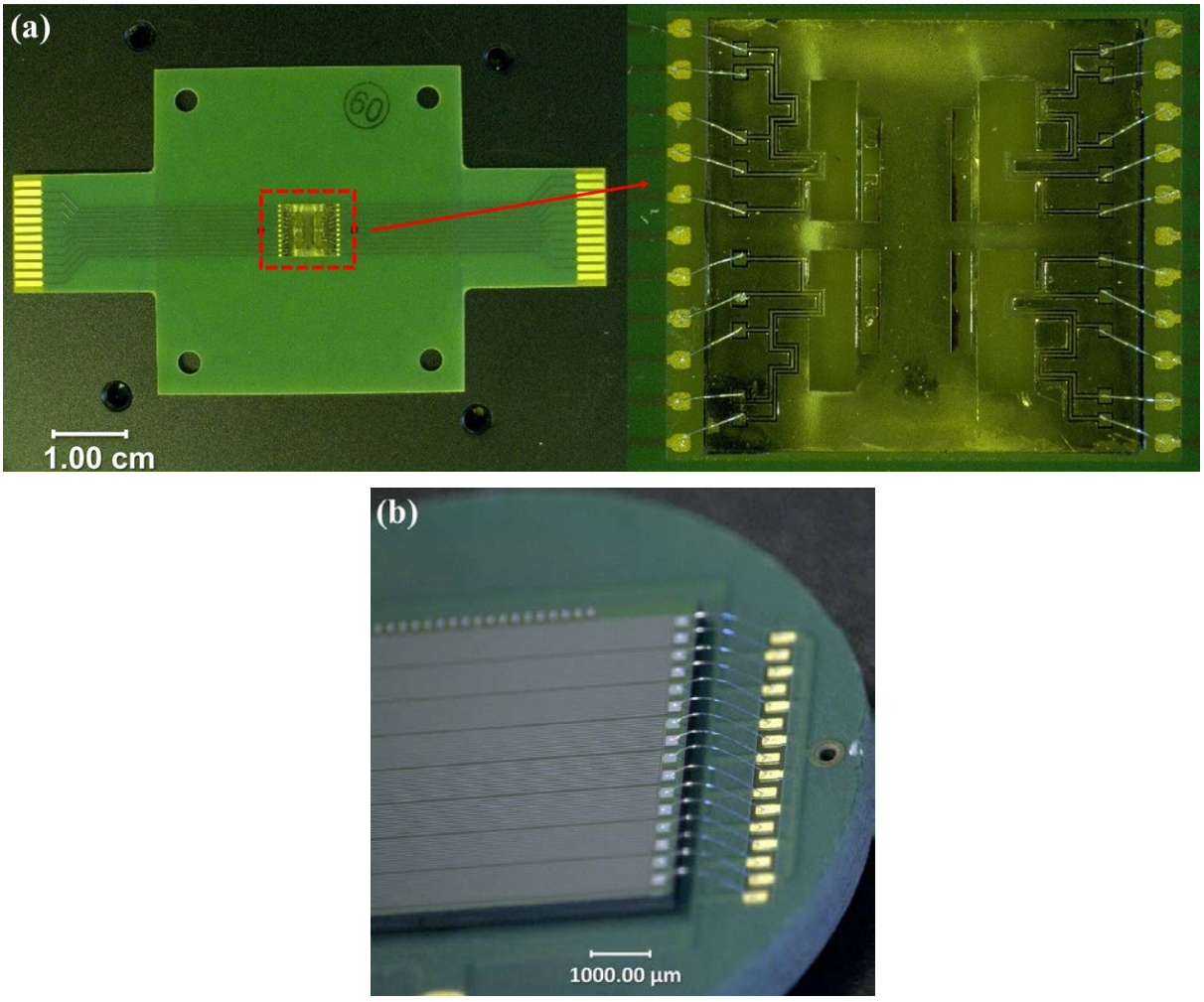

Fig. 4. (a) Fully packaged prototype and optical microscopic view of wedge bonded 3C-SiC cantilevers on PCB, using 25µm diameter aluminum wires and (b) optical microscopic view of wedge bonded CMUT on PCB.

The packaged prototype was then placed inside a hermetic cell which allows the gas flow during the measure, and the dynamic behavior of the structures was determined under different gas mixtures. The experimental protocol is illustrated in Fig. 5, in the case of gas detection using 3C-SiC cantilever. The gases are provided from industrial grade bottles and mixed using flowmeters, monitored by a computer, to vary the concentrations.

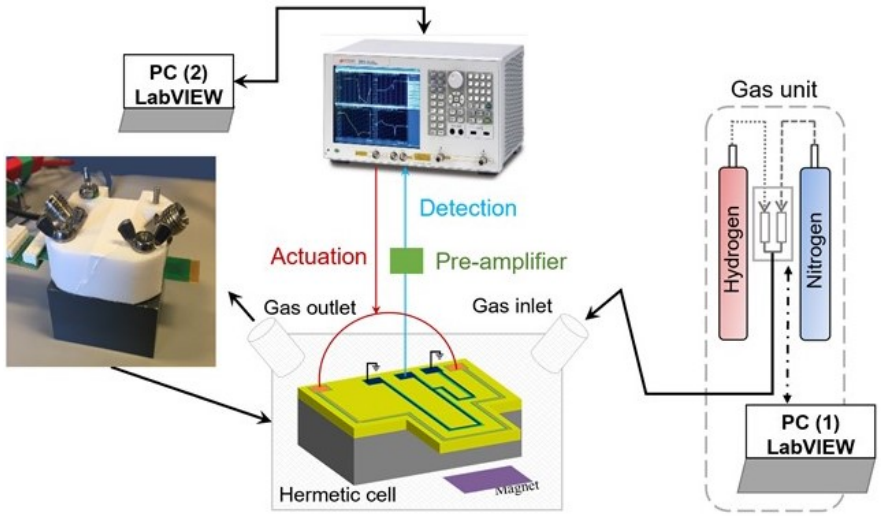

Fig. 5. Gas measurement protocol using 3C-SiC cantilevers, **, adapted from [Priya]**

For the measurement using 3-SiC cantilever, an alternative current circulates through the conductive wire placed at the cantilever periphery and, thanks to the magnetic field collinear to the longitudinal axis of the beam, a Laplace force is created at the end of the cantilever. It induces out-of-plane vibrations, influenced by the gas environment, that can be detected. The conventional method used for monitoring the resonance frequency shift of any vibrating structure consists of searching for the resonant peak, on the amplitude spectrum, and tracking the change in the corresponding frequency. But the variation of the resonance frequency can be nearly insignificant according to the gas environment modifications. For instance, using a silicon microcantilever (length=1mm, width=1mm and thickness=10µm, resonance frequency approximately 23kHz), a concentration of 0.2% of H_2 in N_2 corresponds to a resonance frequency change of approximately 0.25 Hz, that means a variation of only 10 ppm on the resonance frequency. Therefore, due to the noise measurement, identifying precisely the resonant peak location can be very tricky, so the conventional method does not prove to be sufficiently accurate to measure such a small resonance frequency shift. Consequently, instead of using the shift of the resonance frequency detected thanks to the amplitude, we have used the phase spectrum, as detailed in [17]. In this case, the fit of the phase spectrum around the resonance frequency, by a straight line, using least-squares method, allows one to eliminate noise on the phase and then optimize the detection. Therefore, the results presented subsequently have been obtained thanks to this detection method.

The specific characterization method used for the CMUT will be presented in the next paragraph.

3. Results and discussion

3.1. SiC microcantilevers for gas detection

For all the experiments, hydrogen and carbon dioxide (CO_2) gases, diluted in nitrogen, have been investigated. Nitrogen has been used as its molar mass is very close to the one for air (28g/mol for N_2 vs. 29g/mol for air). In this study, the proportion of the gas analysed was ranging from 0% to 2%, as presented in Fig. 6 where the change in resonance frequency of the cantilever is presented as a function of the surrounding gas concentration. As expected, the change in resonance frequency is positive when the gas is lighter than N_2, that is the case for H_2, and negative when the gas is heavier, as observed with CO_2. Moreover, the shift depends on the molar mass of the gas compared to the one of N_2. It explains why the variation of the resonance frequency is positive and around 3.3Hz for a H_2 concentration of 2% in N_2 whereas is negative and limited to 2.5Hz for a CO_2 concentration of 2% in N_2. Based on these figures, limits of detection (LOD) can be also assessed for the 2 different gases considered, using this SiC-based gas sensor. Measurements of 0.2% of H_2 and 0.25% of CO_2, in N_2, have been achieved (Fig. 6), indicating that LOD are a little bit lower than these concentrations. With coated sensors, lowest LOD can be reached. For example, using a palladium-coated nanomechanical bean resonator, Henriksson *et al.* succeeded to measure a H_2 concentration of 0.02%, that means one order of magnitude lower than our results [18]. But, as mentioned previously, the presence of sensitive layers can cause device failures issues.

Besides, for hydrogen, the LOD is more than one order of magnitude lower than the lowest flammable concentration of this gas, evaluated to 4% in air, that illustrates the potential of these structures for security applications. And thanks to the physical properties of silicon carbide, these 3C-SiC-based MEMS devices could be operated in harsh environment, for example to detect H_2 release in the forthcoming underground facility, dedicated to the storage of high-level and medium-level-long-lived radioactive wastes, in France [19]. As these wastes will remain radiative for several hundred thousand years, it is essential to monitor the concentration of hydrogen, to be able to alert before to reach the lower flammable concentration of this gas.

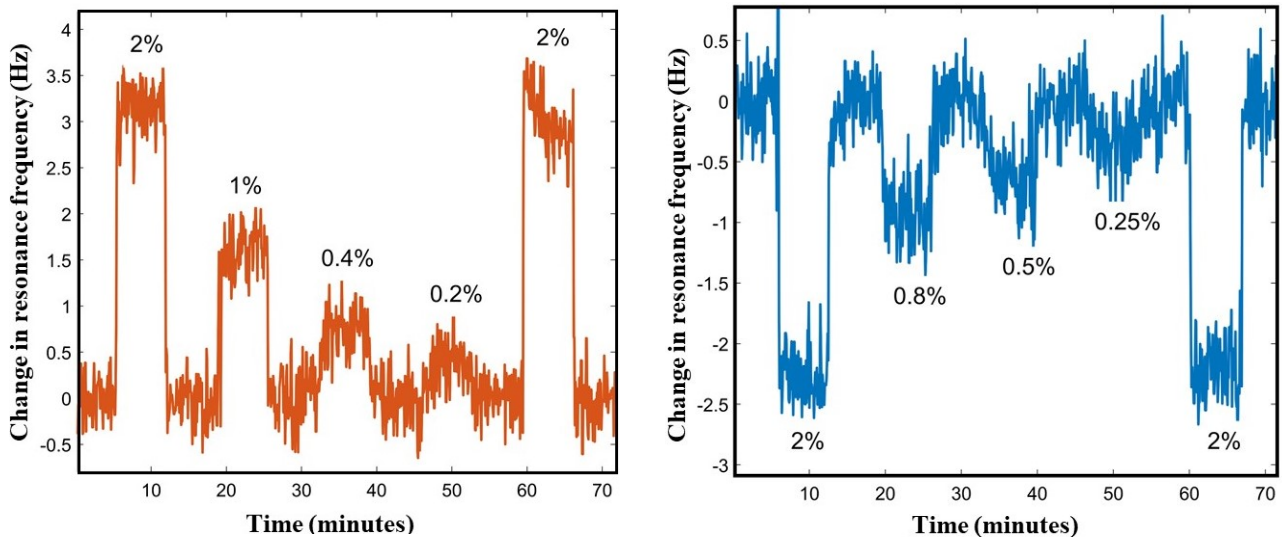

Fig. 6. Change in resonance frequency of 3C-SiC cantilevers, as a function of the surrounding gas concentration, for H_2 in N_2 (left) and CO_2 in N_2 (right). Detections as low as 0.2% for H_2 and 0.25% for CO_2, in nitrogen, have been achieved.

Moreover, as already mentioned, gas sensing is mainly addressed using chemically functionalized or coated sensors, that can cause device failures like ageing, low reliability, and high response time. In our case, due to the absence of sensitive layer, these concerns are circumvented, and our devices are perfectly suitable for binary gas mixture monitoring. However, uncoated sensors selectivity is poor or non-existent, that could be a substantial weakness of this technology to monitor gas environments composed of more than one gas in air. Fortunately, by measuring simultaneously several physical properties it should be possible to discriminate the gases and to determine their concentrations. This proposal will be evaluated in the next paragraph.

3.2. Capacitive micromachined ultrasonic transducers for gas detection

The same experimental protocol than previously has been used to monitor the dynamic response of the CMUT, under different gas mixtures. As it was the case with 3C-SiC-based cantilevers, a modification of the gas acoustic properties surrounding the CMUT leads to a shift of the resonance frequency [20]. This method led to a LOD of 0.04% for H_2 in N_2, that means one order of magnitude lower than the LOD obtained with the unoptimized 3C-SiC cantilevers. In addition, another property of the CMUT seems interesting for gas detection. As explained, a CMUT can act as an ultrasonic emitter as it can generate an acoustic wave. But according to the polarization applied, it can be used also as a receiver. Therefore, at lower frequencies than the resonance, that means in the 1MHz range against 8MHz for the resonance, face to face CMUT can be used to perform time-of-flight measurements. So, in this case, we measure the time taken by an acoustic ultrasonic wave to travel from the CMUT emitter array to the CMUT receiver array, passing through the gas to be characterized. As the speed

of sound is severely affected by the environment, as illustrated in table 1, this property could be highly beneficial for gas sensing application.

Table 1. Speed of sound, in different gas environments.

Gas	CO_2	O_2	CO	Air	N_2	CH_4	He	H_2
Speed of sound (m/s) 20°C - 1.015bar	267	326	336	343	349	446	1010	1310

The results of time-of-flight measurements, also performed for hydrogen and carbon dioxide in nitrogen, are presented in Fig. 7. As anticipated, with hydrogen, as the speed of sound is higher than in nitrogen, the change is negative, whereas it is positive with carbon oxide, as the speed of sound is lower for this gas. Based on the results, we can estimate a limit of detection between 0.15% and 0.05% for H_2 and between 0.30% and 0.1% for CO_2, diluted in nitrogen. These results are very encouraging but, up to now, we have only considered a combination of 2 identified gases, so the use of this method could be limited to specific cases.

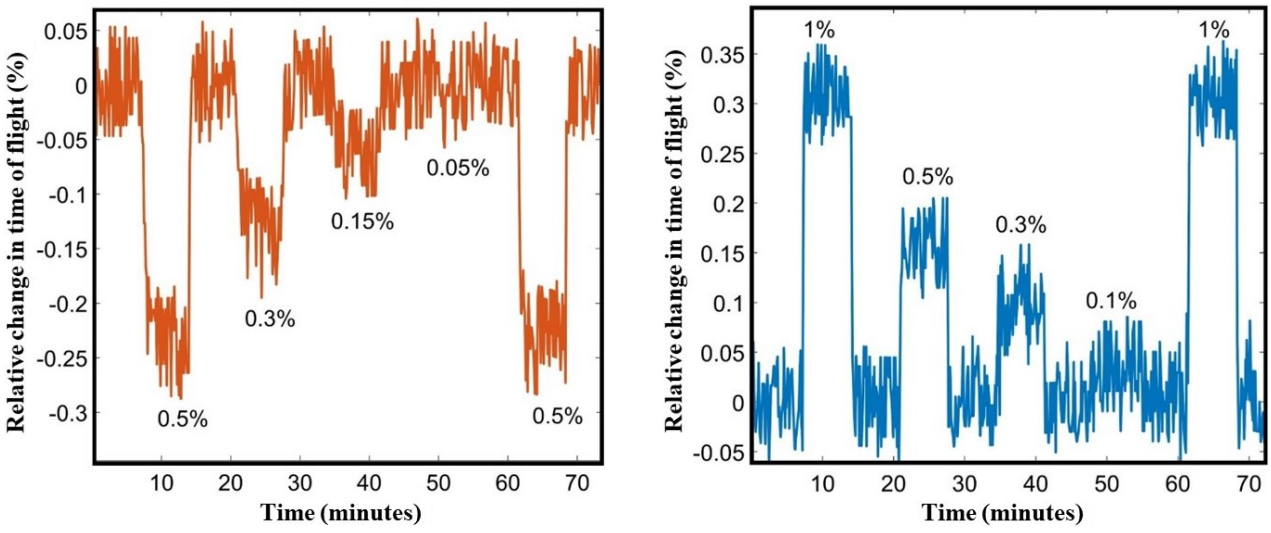

Fig. 7. Relative change in time-of-flight, using capacitive micromachined ultrasonic transducers, as a function of the surrounding gas concentration, for H_2 in N_2 (left) and CO_2 in N_2 (right). Detections as low as 0.15% for H_2 and 0.30% for CO_2, in nitrogen, have been achieved.

In this study, we try to exploit some physical properties of the gas: the mass density that induces a modification of the resonance frequency (for both cantilevers and CMUT) and the speed of sound, that impacts the time-of-flight (CMUT). Another physical parameter, that can be detected with CMUT devices, could also play a major role for gas detection: the ultrasonic attenuation coefficient of the gas. Indeed, when a continuous ultrasonic sine wave is sent from the CMUT array emitter to the CMUT array receiver, separated by a distance

d, the signal arrives exponentially attenuated after travelling the gas. Once the travelling distance d between the 2 CMUT faces is fixed, the attenuation of the sine wave is only linked to the gas environment. For these measurements, the distance between the CMUT arrays was about 5mm.

The result of the attenuation coefficient measurement is presented in Fig. 8, for 3 different gases in air: H_2, CO_2 and CH_4. As it was the case for the time-of-flight parameter, the variation of the attenuation coefficient, as a function of the gas, can be positive (H_2 and CO_2) or negative (CH_4). But, in this case, the prediction of the evolution is not trivial as the attenuation coefficient is related to several physical parameters of the gas: its viscosity and volume viscosity, its thermal conductivity and its isobaric heat capacity [21]. Beyond this statement, the most underlining result is probably the result itself as, thanks to this new physical parameter, as highlighted in Fig. 8, it is also possible to determine a gas concentration.

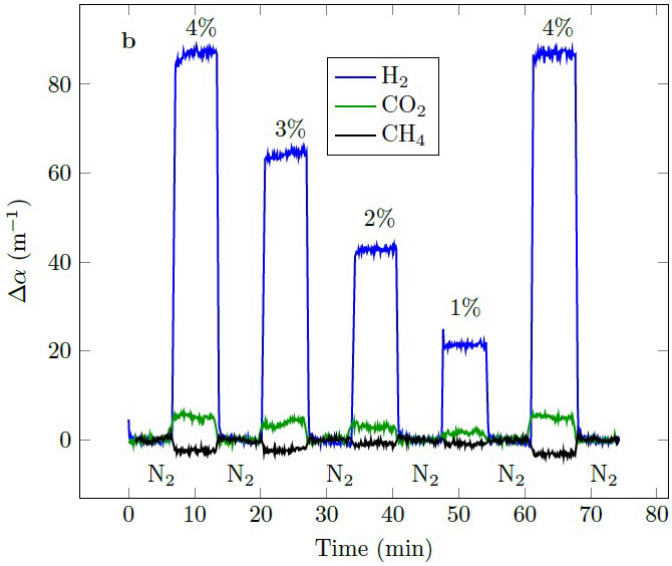

Fig. 8. Evaluation of the gas attenuation coefficient, obtained with time-of-flight measurements at 1MHz, for 3 different gases diluted in nitrogen.

As previously explained, the attenuation coefficient depends on several physical parameters of the gas, whereas the time-of-flight in only related to the speed of sound. Based on this observation, we tried to combine these 2 parameters, TOF & attenuation coefficient, as a function of the gas environment. The results, presented in Fig. 9, also underline the influence of the humidity rate (HR), from 0 to 100%, and of the temperature (T), from 10 to 30°C, for a pure nitrogen gas.

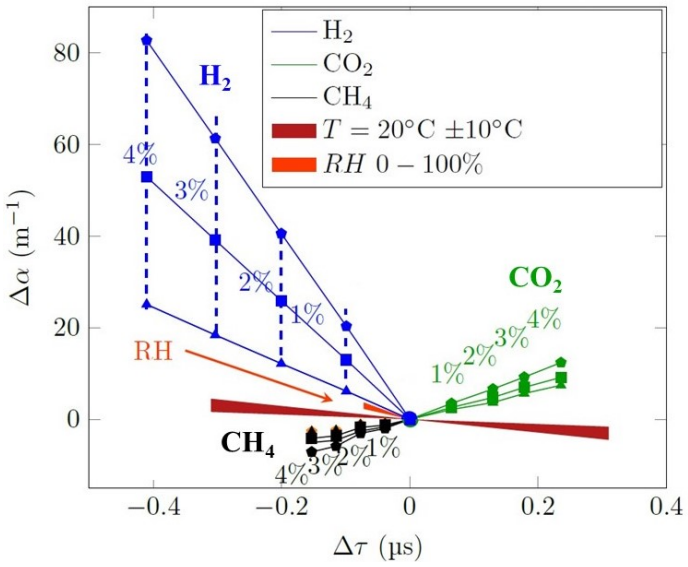

Fig. 9. Evolution of the attenuation coefficient α and the time-of-flight τ determined with CMUTs arrays, from a pure nitrogen gas (reference 0-0 on the graph), according to the gas environment. The influence of both the humidity rate (RH) and the temperature (T) is also presented, for comparison**, adapted from [21].**

The 0-0 point in Fig. 9 corresponds to a pure nitrogen gas, in normal conditions. From this middle point, each modification of the gas composition results to another point, that corresponds to only one possible couple of values for the attenuation coefficient and the time-of-flight. In addition, even for minor gas variations, each point of the graph, which corresponds to a particular gas mixture, cannot be attributed to a variation of the humidity rate or of the temperature of the gas. In other words, combining the measure of 2 different physical parameters leads to the discrimination of the gas with their respective concentrations. This approach is very motivating as, contrary to what is observed with more conventional gas sensors presenting a coating layer [22], this kind of sensors can be considered as a generic sensor as it is possible to measure a large panel of gases, without any modification of the CMUT topology. As a consequence, such structures can be used to address different niche markets without any long development process, as the method is not related to specific gases. It is not the case with classical coated sensors where, for each specie to detect, it is necessary to develop an appropriate sensitive layer to react with the gas. In addition, as sensitive coatings are subjected to sorption or redox phenomena, our method should lead to more persistent sensors, even if the reliability of our devices was not yet evaluated. The only weakness could be the material involved for the elaboration of the CMUT. Actually, the basis of the CMUT is the silicon nitride membrane, which is not suitable for harsh environments. To perform the same measurements in hostile conditions, silicon carbide would be more adapted. A cMUT using a silicon carbide membrane has been already mentioned in the literature [Zhang]. But, in this case, the silicon carbide layer was deposited thanks to DC sputtering, resulting in an amorphous material. Moreover, silicon nitride is still one of the materials constituting the cMUT, then not suitable to operate in harsh environments. In our case, based on preliminary results obtained by our consortium on this topic, as we already succeeded to obtain a

crystalline 3C-SiC membrane on a 3C-SiC pseudo-substrate, we are confident to be able to achieve, in the future, full 3C-SiC-based capacitive Micromachined Ultrasonic Transducers [23][24].

4. Conclusion

Whether in the field of mechanics, optics, radiofrequency or biology, for different applications, MEMS devices are widely spread. One of the various applications of MEMS devices is gas sensing. For this matter, the detection of the gas is conventionally achieved thanks to a coated sensor, where the sensitive layer interacts with the specie to detect. However, even if coated sensors are by far the most used solution in gas sensing, this active layer can cause device failures like ageing, low reliability and high response time. In addition, for specific applications, the sensors can be subjected to harsh environments. In this case, silicon or silicon-based materials, that are commonly used to complete MEMS devices, are not appropriate. But thanks to its huge physical properties, silicon carbide is a promising material to complete efficient MEMS devices.

In this paper, we have reviewed the use of ~~presented~~ 2 different structures for gas detection applications, with a common characteristic: the absence of any sensitive layer. In this way, the gas sensing is based on the measure of a physical property of the gas, without any chemical interaction between the sensor and its surrounding environment. With 3C-SiC-based microcantilevers using electromagnetic actuation and inductive detection, we succeeded to measure different gas concentrations, with a limit of detection as low as 0.2% and 0.25%, respectively for H_2 and CO_2, in nitrogen. Thanks to the physical properties of 3C-SiC, these devices will be operational in severe environments, for example to detect hydrogen release in the future underground facility devoted to the storage of nuclear wastes. Actually, as this gas is flammable at a concentration of 4-70% in air, its continuous monitoring is mandatory. And due to the radioactive environment, the use of 3C-SiC-based sensors will be precious.

Capacitive Micromachined Ultrasonic Transducers have been also studied. With these devices, time-of-flight measurements led to limits of detection in the same range than those obtained with 3C-SiC-based microcantilevers: 0.15% for H_2 and 0.30% for CO_2, in nitrogen. With these devices, we have also monitored a physical property of the gas: its attenuation coefficient. The time-of-flight parameter is linked to the speed of the sound whereas the attenuation coefficient is related to several physical parameters of the gas (viscosity, thermal conductivity, isobaric heat capacity). Then, a gas mixture, composed of different gases at different concentrations, can present only one possible combination for these 2 physical parameters. As a result, by measuring simultaneously these values, we succeeded to discriminate the gases with their respective concentrations. This approach is very motivating as, contrary to what is observed with more conventional gas sensors including a coating layer, this kind of sensors can be considered as a generic sensor as it is possible to measure a large panel of gases, without any modification of the device topology.

CRediT authorship contribution statement

Jean-François Michaud: Writing - original draft, Supervision, Project administration, **Marc Portail**: Writing - review & editing, **Daniel Alquier**: Writing - review & editing, Supervision, **Dominique Certon**: Writing - review & editing, Supervision, **Isabelle Dufour**: Writing - review & editing, Supervision, Project administration, Funding acquisition

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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