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Highly sensitive capacitive MEMS for photoacoustic gas sensing

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Nowadays, there are three main categories of gas sensors: electrochemical sensors, material based sensors, and optical gas sensors. However, among them, only optical gas sensors like those used in Tunable Diode Laser Spectroscopy (TDLS) combine high selectivity and sensitivity as the laser line width is much narrower than the target gas lines. However, TDLS requires a long optical path, which limits compactness. A new approach is thus needed. Photoacoustic spectroscopy (PAS) is a technique derived from TDLS replacing optical detection with acoustic detection. When the modulated laser light is absorbed by the target gas, it generates localized heating causing pressure variations. This acoustic wave is measured using an acoustic detector as microphone (MPAS), quartz tuning fork (QEPAS) or cantilever (CEPAS). This technique is independent of the optical path, enabling operation with very small volumes of gas and real-time measurements.

Among all the PAS techniques, only our integrated MEMS, proposed in 2019 [1], is designed for PAS to avoid the different drawbacks of the others techniques : MPAS is sensitive to external noise, QEPAS presents a small energy collection and CEPAS is not very compact due to a bulky optical read-out mechanism. Its structure is capable of minimising viscous damping while optimising photoacoustic energy collection and maintaining a high nominal capacitance. The resonator design was achieved by a combination of an analytical model outlined in [2] and COMSOL simulations. The resulting MEMS device, referred to as an H-square and shown in Fig 1, consists of two main mechanically coupled components: a central segment primarily dedicated to photoacoustic energy harvesting and lateral sections dedicated to electrical transduction. In Fig 1, the laser beams are focused above the central area, below which there is a deliberate gap to prevent squeeze film attenuation. When the modulated light is absorbed, the resulting acoustic wave causes the H-square to move. This motion induces a change in capacitance, which is then converted into a voltage signal. Comparative measurements were made between the MEMS device and a QEPAS on-beam experiment in which the laser passes between the tines of the quartz tuning fork. Both experiments were performed under identical conditions. Despite being exposed to the same acoustic pressure, the H-square resonator and the quartz tuning fork exhibited resonant frequencies of 23.6 kHz and 32 kHz, respectively.

The photoacoustic measurements were performed using calibrated concentrations of methane. An Allan-Werle deviation analysis was used to assess the sensitivity and stability of the sensors. The results, shown in Fig 2, revealed significant differences in performance. With a 1 second integration time for first harmonic detection, the MEMS device achieved a limit of detection (LOD) of 104 ppmv [3], compared to 163 ppmv for the on-beam QEPAS technique. In addition, Allan deviation analysis for first harmonic detection at 1 second integration time showed a Normalised Noise Equivalent Absorption Coefficient (NNEA) of $8.6 \cdot 10^{-8} \text{ cm}^{-1} \cdot \text{W}/\sqrt{\text{Hz}}$ for the MEMS device, surpassing the NNEA of $1.3 \cdot 10^{-7} \text{ cm}^{-1} \cdot \text{W}/\sqrt{\text{Hz}}$ observed for the standard QEPAS-based sensor. In perspective, it is clear that the use of an acoustic cavity is crucial to enhance the acoustic force and minimise potential photothermal noise, thereby improving the signal-to-noise ratio (SNR). While QEPAS has demonstrated a gain factor of 30 using an acoustic cavity [4], [5], our expectations exceed this benchmark. In our case, the gain is expected to be even higher as for Cantilever-Enhanced Photoacoustic Spectroscopy (CEPAS), where the coupling between the acoustic cavity and the cantilever is optimized [6].

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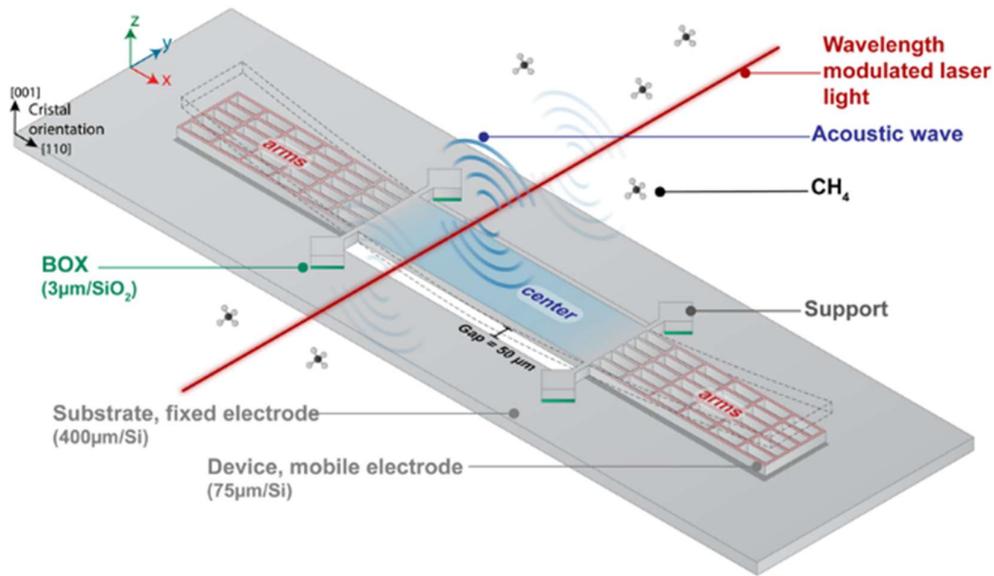


Figure 1. Schematic illustration of H-square resonator deflection under photoacoustic excitation. The resonator is divided in two parts: the center part dedicated to the photoacoustic energy collection, and the arms dedicated to the capacitive transduction.

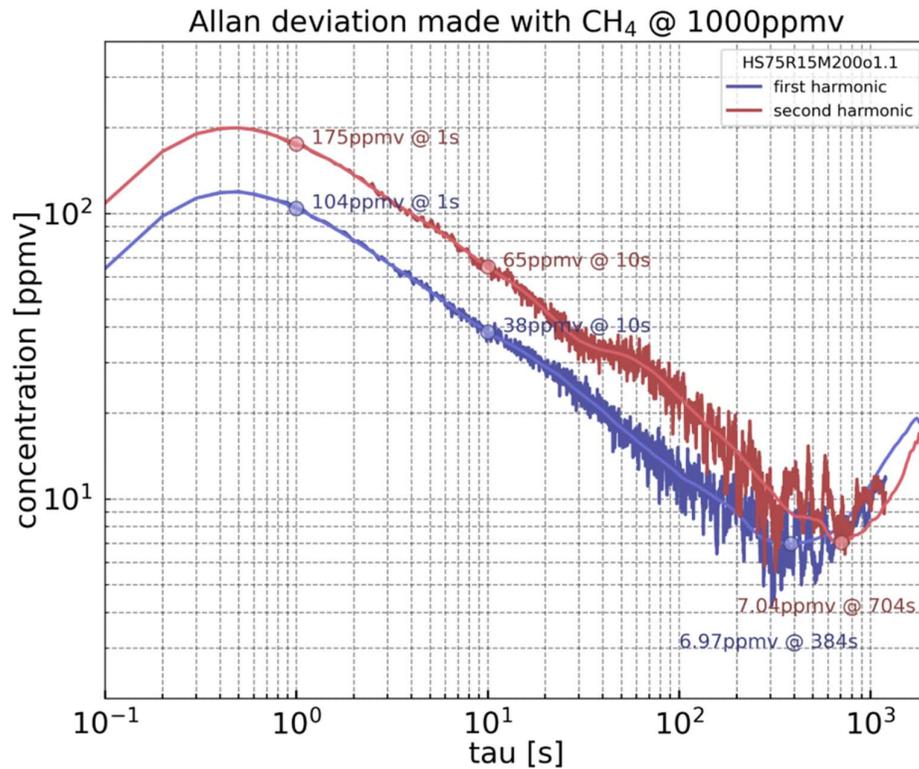


Figure 2. Allan-Werle deviation calculated from a 30 minutes acquisition for the 1f and 2f mode with 1% of CH₄ concentration and time constant of 100ms.