# High-Precision Probing of Molecules Using THz CMOS Chips: Principles and Applications in High-Accessibility Sensors and Clocks

*(Invited Talk)*

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## Abstract

Polar molecules posses quantized rotational energy states. A transition between two states can be excited when an externally-applied electromagnetic (EM) wave matches the rotational resonance frequency. Interestingly, the rotational energy is normally very low, which makes the transitions locate mostly in the millimeter-wave and low-THz bands. At certain low pressure levels, when the linewidth of the transitions is mainly limited by the Brownian motion of the molecules, the quality factor of the lines is close to one million! That enables gas sensing with a selectivity that is much higher than in mass spectroscopy and infrared (IR) spectroscopy. The high spectral concentration of the transition energy also increases the SNR of the detection. Unfortunately, due to the long-existing challenges in the implementation of THz hardware, THz rotational spectroscopy was previously only adopted in astronomical instruments (for inter-stellar dust detection) and bench-top gas analyzers (for gas mixture identifications).

Recent progress of CMOS-based THz electronics makes it possible to realize molecular sensing using low-cost silicon chips. In 2017, we demonstrated a CMOS-based spectrometer using a dual-frequency-comb architecture with a seamless coverage from 220 to 320 GHz [1]. It breaks the conventional performance tradeoff between bandwidth and efficiency, and realizes record total radiated power (5.3 mW) and sensitivity (noise figure NF=15$\sim$20 dB) in CMOS THz circuits. False-alarm-free detection of gas mixture with a sensitivity (without any pre-centration of sample) of a few *ppm* (part-per-million) is demonstrated [2], showing the feasibility of high-performance while ultra-portable gas sensors for breath analysis, pollution monitoring, etc.

Next, we further apply the CMOS spectrometer technology into the area of high-precision time keeping, which was previously dominated by costly atomic clocks invovling high-complexity electro-optical constructions. By probing the exact low-THz transition frequency of carbonyl sulfide (OCS), we innovate a chip-scale molecular clock using a fully-electronic CMOS spectrometer [3], [4]. The OCS gas is encapsulated inside a single-mode waveguide, enabling miniaturization of the clock. Consuming only 66 mW of power, the clock chip delivers an Allan deviation of $3\times10^{-10}$, and is expected to further increase the stability to the $10^{-12}$ level using an OCS gas cell with low out-gassing/leakage and improved wave coupling [4]. In this talk, the principles and designs of the molecular clock will be introduced. In addition, recent studies and experimental results of the clock regarding its robustness against temperature change and external magnetic field are presented [5]. With the elimination of the need for any temperature-stabilizing oven or magnetic shield, the molecular clock offers a highly-simplified solution for miniature frequency references, making it possible to realize atomic-clock-grade time keeping in mainstream, cost-sensitive equipment. With the ever-increasing operation speed of CMOS transistors, as well as the recent MEMS-based THz waveguide technologies [6], we believe a monolithic molecular clock in standard CMOS process is on the horizon (Fig. 1).

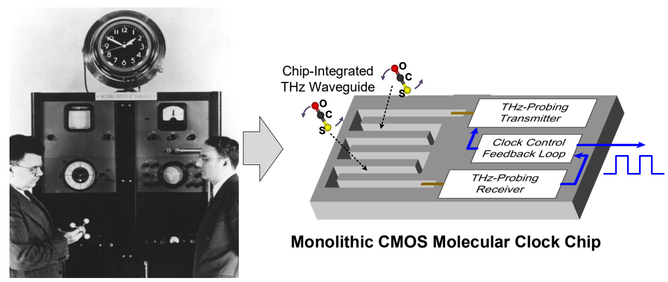


Fig. 1: Evolution from the first ammonia molecule clock in 1949 [7] to a monolithic CMOS carbonyl sulfide molecule clock.

## References

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Usually, a high percent of the uncertainty is related to the behaviour of the measuring optical or tactile probe. To reduce this eect, the behaviour of the measuring probe is characterized under similar environment conditions, by using an external test bench. H. Nouira et al.: Ultra-high precision CMMs and tactile and optical scanning probes. 204-p3. 3.1 Optical confocal chromatic probe. A Terahertz Molecular Clock on CMOS Using High-Harmonic-Order Interrogation of Rotational Transition for Medium-/Long-Term Stability Enhancement. Article. Sep 2020.Â  Chip-scale molecular clocks (CSMCs) perform frequency stabilization by referencing to the rotational spectra of polar gaseous molecules. With, potentially, the â€œatomicâ€ clock grade stability, cm $^3$ -level volume, and < 100-mW dc power, CSMCs are highly attractive for the synchronization of the high-speed radio access network (RAN), precise positioning, and. distributed array sensing.Â  A monolithic THz transceiver generates a high-precision, wavelength-modulated probing signal. The complementary metal oxide demiconductor (CMOS) process is the most commonly used procedure in semiconductor industry. A photodiode is basically a p-n junction operated under reverse bias.Â  These features make CMOS photodiodes easy to be a personalized healthy care instrument, and a high-throughput sensor. Recently, a CMOS photodiode has been used to monitor Pseudomonas fluorescens 5RL bacterial cells [5]. However, to our knowledge, there have been no reports in which a biochemical reaction has been coupled to CMOS photodiodes. CMOS can be obtained by integrating both NMOS and PMOS transistors over the same silicon wafer. In Nâ€“well technology an n-type well is diffused on a p-type substrate whereas in P- well it is vice- verse. CMOS Fabrication Steps.Â  Making of CMOS using P well Technology. The p-well process is similar to N well process except that here n-type substrate is used and p-type diffusions are carried out. For simplicity usually, N well process is preferred. Twin Tube Fabrication of CMOS.Â  Epitaxial layer protects the latch-up problem in the chip. The high purity silicon layers with measured thickness and exact dopant concentration are grown. Formation of tubes for P and N well. Thin oxide construction for protection from contamination during diffusion processes.