

Monolithic LED Emitter-Detector for colorimetric CO₂ gas sensor

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Summary: This work presents a monolithic GaN optoelectronic platform integrated with a colorimetric indicator layer for gas sensing applications. The system integrates an InGaN/GaN LED emitter and photodetector on the same chip, enabling optical interrogation without external alignment or discrete optical components. The exposure to CO₂ of the pH-sensitive colorimetric layer results in a color change that is measured as a decrease of photodiode current. The sensor shows reproducible responses to CO₂ concentrations from 1 to 40 % operating at power range of hundreds of microwatts.

Keywords: Nitride-based LED, Nitride-based photodiode, Monolithic integration, Carbon dioxide, Colorimetric gas sensor.

Background, Motivation and Objective

Colorimetric indicators offer a simple and low-cost route for detecting chemical and biochemical species through analyte-induced optical changes. Their practical use, however, is often constrained by external optical readers, controlled illumination, camera calibration, or bulky discrete components. InGaN/GaN multiple-quantum-well structures are attractive because the same epitaxial platform can be engineered for light emission and photodetection. Monolithic GaN LEDs, photodetectors, waveguides, and monitoring elements have demonstrated compact, robust, alignment-free optical systems [1,2], and recent gas-sensing prototypes have shown that color changes can be converted into electrical signals at chip scale [3].

Nevertheless, fully integrated GaN system-on-chip interrogation of colorimetric indicators remains underdeveloped. Outstanding challenges include optical crosstalk, efficient coupling between the indicator layer and the active devices, reproducible sensing-layer deposition, and robust calibration under varying environmental conditions. Here, we develop a monolithic GaN system-on-chip that combines integrated light emission and photodetection with colorimetric indicator layer for compact, low-power, and scalable colorimetric sensing.

Description of the New Method or System

The monolithic GaN optoelectronic transducer was fabricated from an InGaN/GaN LED epitaxial stack grown on sapphire. Two junctions were processed on the same chip: one is forward-biased as the emitter, whereas the second is operated as a short-circuit photodetector. Hereafter, this architecture is referred to as a monolithic LED emitter-detector (MLED). The emitter and detector mesas were defined by ICP-RIE and contacted individually while sharing a common n-GaN layer. The integrated configuration removes the need for external alignment between discrete optical components, reducing system complexity and power consumption. The LED device emits at around 455 nm, where the selected CO₂ indicator exhibits a measurable transmission change.

The sensing layer consists of a pH dye, m-cresol purple, immobilized in a hydroxyethyl cellulose matrix [4]. A thin film was spin-coated between the MLED emitter and detector. When CO₂ dissolves in the water contained in the matrix, the local pH decreases and the dye changes from deep purple-blue to yellow. The resulting change in optical absorption is detected as a reduction in the detector photocurrent.

Results

Figure 1 shows the response of the MLED device coated with the colorimetric indicator. The LED was powered with 750 μW , and the detector photocurrent was recorded under short-circuit conditions. Upon exposure to 6 pulses of three different CO_2 concentrations, 1, 10 and 40 % in synthetic air with 50 % of relative humidity, the photocurrent of MLED device shows a clear, stable and repetitive decrease. The photocurrent decrease scales with CO_2 concentration, and repeated pulses at the same concentration showed discrepancies as low as 0.6%.

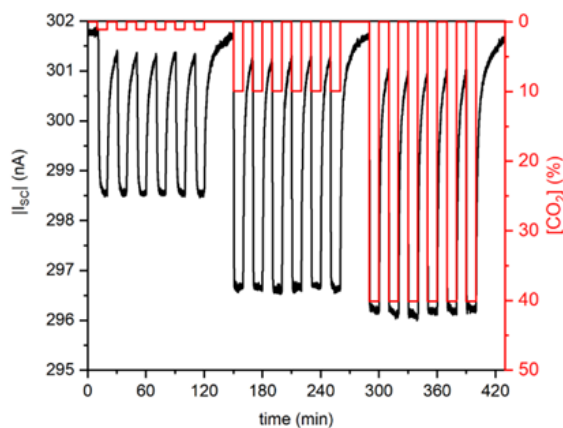


Fig. 1. Short-circuit photodiode current (photocurrent) measured with the LED power set to 750 μW while the colorimetric indicator is exposed to 6 pulses of three different CO_2 concentrations, 1, 10 and 40 % in synthetic air with 50 % of relative humidity (21°C and 1 atm).

For a given CO_2 concentration, the absolute photocurrent decrease depends on the power applied to the LED. In contrast, the relative photocurrent change is largely independent of LED power, as shown in Figure 2. The sensor response was therefore calculated from the photocurrent measured in synthetic air and under CO_2 exposure as:

$$S(\%) = \frac{I_{\text{CO}_2} - I_{\text{SA}}}{I_{\text{SA}}} \cdot 100 \quad (1)$$

Accordingly, the relative response in Figure 2 can be directly related to the CO_2 -dependent absorption change of the colorimetric indicator. Notably, these responses were obtained with LED powers between 125 and 750 μW , substantially below the 165 mW reported for an integrated microsystem based on off-the-shelf components [3].

Response times were estimated to be on the order of tens of seconds or less; the current experimental set-up requires at least 2 min to reach the target CO_2 concentration, which limits a more precise determination. Complete recovery of the baseline photocurrent was observed after CO_2 removal, although recovery times up to 10 min were required at the highest concentrations.

In summary, MLED devices enable electrical readout of absorption changes in colorimetric indicators and constitute a compact, low-power platform for CO_2 gas sensing.

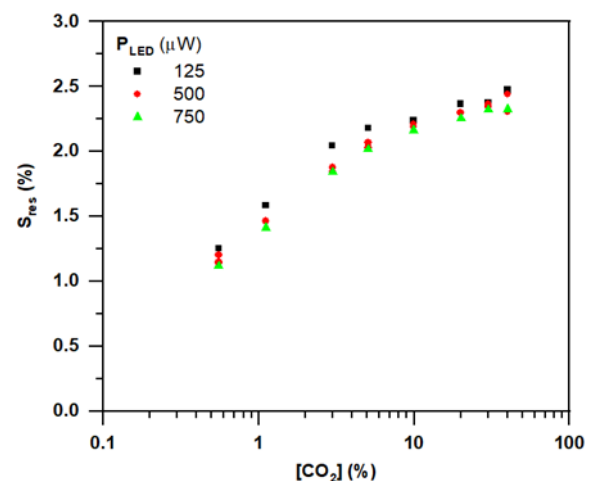


Fig. 2. Sensor Response versus the CO_2 concentration in synthetic air with a relative humidity of 50 % (21°C and 1 atm) for different LED powers.

References

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