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UV-Assisted Gate Bias Cycling in Gas-Sensitive Field-Effect Transistors †

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Abstract: Static and dynamic responses of a silicon carbide field-effect transistor gas sensor have been investigated at two different gate biases in several test gases. Especially the dynamic effects are gas dependent and can be used for gas identification. The addition of ultraviolet light reduces internal electrical relaxation effects, but also introduces new, temperature-dependent effects.

Keywords: gas sensors; SiC-FET; dynamic operation; gate bias cycled operation; linear discriminant analysis

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1. Introduction

Chemical sensors suffer from poor selectivity which is one of the main obstacles hindering their widespread use. Temperature cycled operation (TCO) has long been used to increase the selectivity of metal-oxide semiconductor (MOS) sensors [1] and has recently been shown to be applicable to field-effect transistors based on silicon carbide (SiC-FETs) as well [2]. SiC-FETs can be produced using standard semiconductor processing, but current devices still exhibit a larger thermal time constant than typical MOS sensors, resulting in longer sampling times for TCO. However, they offer additional parameters which can be cycled very rapidly, one of them being the gate bias.

The static influence of the gate bias on the sensor's gas response and gate bias cycled operation (GBCO) have been investigated in some works [3,4], but it is still unclear how a gate bias cycle should be designed for best (and quickest) performance. Dynamic effects after inducing a thermodynamic equilibrium on the sensor surface have shown great potential for MOS sensors [5], which could be reached with gate bias steps for gas sensitive FETs (GasFETs). Preliminary measurements have also shown a more stable sensor signal when constant ultraviolet (UV) light was applied, which is why the difference between operation with and without UV light is also briefly discussed in this work.

2. Materials and Methods

The GasFET sensor is based on silicon carbide and is, thus, also known as SiC-FET. Its general internal design [6] follows that of a field-effect transistor with drain, source, and gate electrodes. A porous catalyst, here iridium, is sputtered on top of the gate insulator (SiO_2). The porosity is important since it provides three-phase boundaries between gas, catalyst, and insulator, as well as allows spill-over of gas-related species between catalyst and insulator. A sensor signal is generated through ions on top of the insulator, like protons from hydrogen-containing gases, or addition or removal of oxygen anions through oxidizing or reducing gases. The sensor is an n-type normally-on FET, and the sensor signal, sampled at 10 Hz, is the drain current at 4 V drain-source voltage.

The sensor is mounted on a ceramic heater and placed inside a stainless-steel measurement chamber facing an UV-LED with an emission peak at 406 nm. The gas flow (100 mL/min, dry air as carrier gas) and composition in this chamber are controlled by a gas mixing apparatus similar to [7]. The test gases are supplied from commercial gas cylinders and diluted with mass flow controllers (MFCs) to reach concentrations of 20 ppm hydrogen (H_2), 400 ppm carbon monoxide (CO), and 50 ppm ammonia (NH_3), supplied one after the other. In an additional step, the gas flow was replaced with 100 % nitrogen (N_2) which leaves only trace amounts of oxygen (O_2) in the gas mixture and is used as reference.

During the measurement, the gate bias was changed between −2 V and +2 V (100 s each), resulting in a 200 s long gate bias cycle. The sensor temperature was changed every two hours in steps of 25 °C from 225 °C to 300 °C. Afterward, this temperature cycle begins anew with the next gas supplied. Only the average of the last ten gate bias cycles on each temperature plateau are used in the evaluation to let the sensor equilibrate after temperature or gas changes. The described measurement was done twice with the UV-LED switched on and off, respectively.

3. Results and Discussion

3.1. Influence of the UV Light

The sensor signal changes considerably upon UV irradiation. Figure 1 shows the normalized raw signal with (b) and without (a) UV light. All signals have been normalized by division through T^{-x}, where T is the sensor temperature in K and x has been experimentally determined to be 3.2265 without UV radiation at a gate bias of −2 V. This normalization eliminates a large part of the sensor signal's temperature dependence by compensating the effect of the electron mobility $\mu(T)$.

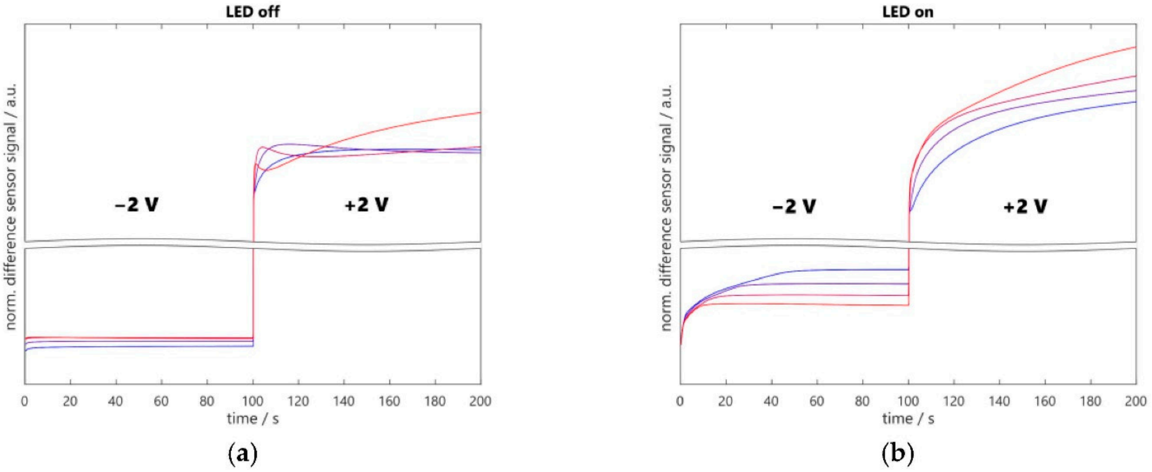


Figure 1. Normalized raw signal in air over time (**a**) without and (**b**) with UV irradiation for four different temperatures (blue 225 °C, red 300 °C). Note that the break and axis limits of the y-axis were chosen such that the upper and lower parts of the diagram have the same scaling, but not necessarily the same offset.

The normalization equalizes the signals well at −2 V when no UV light is irradiated, and at +2 V only the signal at the highest temperature diverges. UV light then introduces a new, temperature-dependent effect which is clearly seen from the signal spread at both gate biases in Figure 1b. A significant part of photons emitted by the LED have an energy larger than the band gap of 4H-SiC (3.23 eV) and, thus, create a constant amount of additional charge carriers in the channel resulting in a higher current. This, however, does not explain the temperature dependence. A possible explanation could be the removal of electrons trapped in the insulator, which would lead to a signal increase and according to [8] only happens under UV light.

The effect on the positive gate bias plateau gains complexity when the LED is switched off. While the signal increases steadily under UV light, it shows a short peak followed by a dip and then a slow increase without UV light. Additionally, the time constants of all these effects show a strong temperature dependence, which is remarkable considering the small temperature range (225–300 °C).

Due to the presumably more stable signal, only the signals under UV light will be considered in the following discussion.

3.2. Influence of the Gate Bias

The effects discussed so far are mainly of electrical nature and, thus, not gas dependent. The SiC-FET signal is much more sensitive to temperature or gate bias changes than to changes in the atmosphere, so that the large electrical signals mostly cover the relatively small gas response. To enhance the gas response, the signal in N_2 has been subtracted from the signals in all other gases in Figure 2. This figure shows an obvious gas dependence of this difference signal. For clarity, these difference signals are from here on referred to simply as "signal".

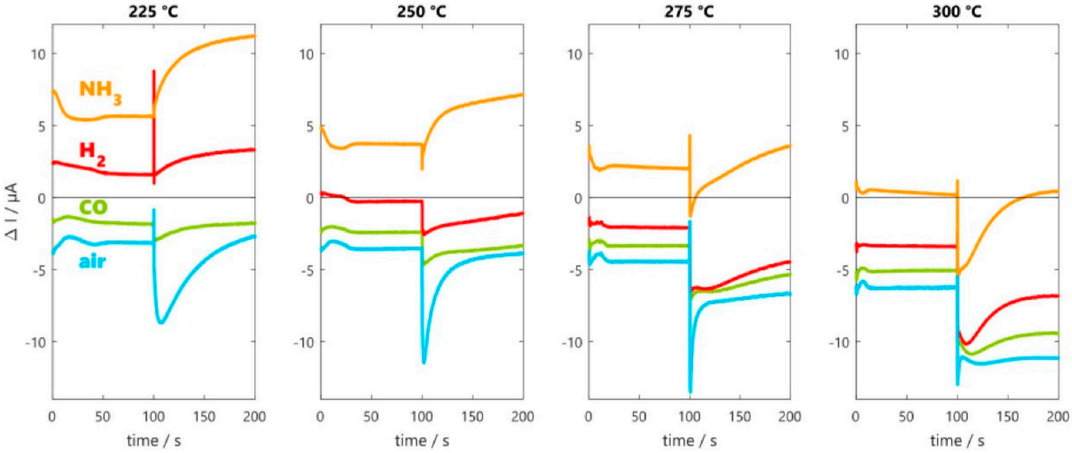
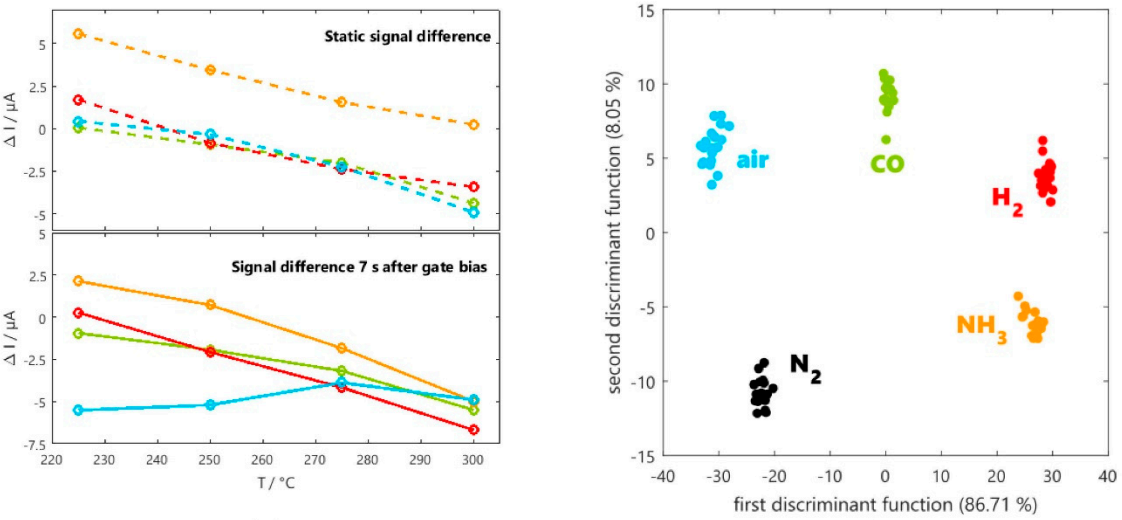


Figure 2. Difference signals with UV irradiation with the signal in N_2 as reference.

The signal offsets are plausible. Air reduces the signal through the addition of oxygen anions (compared to the oxygen-free N_2 reference). CO removes a small fraction of these anions, resulting in a slightly higher signal, whereas both H_2 and NH_3 cannot only remove oxygen but can also add hydrogen cations, which raise the signal through their positive charge which leads to an increase of the signal compared to the neutral surface (N_2 reference). Note that the H_2 signal is probably lower because of the comparatively small concentration provided.

Whether the static difference, i.e., the difference between the signals at 99 s and 199 s, is positive or negative depends on both the gas and sensor temperature. For the lowest temperature, the signal at positive gate bias is higher (NH_3, H_2) or equal to the signal at negative gate bias. The overall signal decreases with increasing temperature, however, the part at positive gate bias decreases significantly quicker. At the highest temperature, the NH_3 signals are roughly equal at positive and negative gate bias, and all other signals are significantly lower on the positive gate bias plateau. This change happens at almost equal rates (Figure 3a, top), which suggest a common cause, most likely the added oxygen compared to the N_2 reference.

The relaxation effects, particularly after the step to the positive gate bias, are relatively complex with at least two different time constants. While further investigations are necessary to explain all of the observed effects, they are clearly gas dependent (Figure 3a, bottom) and can be used for gas discrimination with data-based models. The linear discriminant analysis (LDA) in Figure 3b classifies all five gases correctly based on six slopes which describe the shape of the dynamic effects.



(**a**) (**b**)

Figure 3. (**a**) The difference between the signal at positive and negative gate bias decreases with the same rate for all gases (color legend given in (**b**)), while dynamic effects (represented by the difference between baseline at negative gate bias and the signal 7 s after the step) are gas dependent. (**b**) Six slopes have been extracted at different points in time from the signals (not shown). Using them as features for an LDA discriminates all five gases perfectly from each other.

4. Conclusions

UV light was employed to reduce internal electrical effects in a GasFET sensor. At the same time, the UV light introduced new, temperature-dependent effects. Static and dynamic responses to five different gases were examined at +2 V and −2 V gate bias. Especially the observed dynamic effects are gas-dependent and can be used with a data-based model to discriminate all gases from each other. Further investigation is needed to fully understand the observed temperature- and gas-dependent dynamic effects.

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Conflicts of Interest: The authors declare no conflict of interest.

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