

Response of Silicon Nanowire Arrays to Humidity and Ammonia

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Summary: Ammonia (NH₃) is a corrosive gas that can pose significant risks to human health, even at low concentrations. Its presence in exhaled breath can also serve as an indicator of various health conditions. This study demonstrates that silicon nanowires (SiNWs) exhibit high sensitivity to NH₃, with notably improved performance in humid environments. Incorporation of tungsten trioxide (WO₃) nanoparticles further enhances the sensor's sensitivity and accelerates its response time under a range of humidity conditions. These findings advance the development of robust, simple, and efficient NH₃ sensors, with potential applications in both environmental monitoring and medical diagnostics.

Keywords: SiNW, gas sensing, ammonia, humidity

Background, Motivation and Objective

Silicon nanowires (SiNWs) have gained significant interest in gas sensing due to their high surface-to-volume ratio, excellent electrical properties, and straightforward fabrication process. Their unique nanoscale structure enhances interaction with target gases, making SiNWs ideal candidates for the development of sensitive and selective sensors[1].

Ammonia(NH₃) is a toxic reducing gas, and prolonged exposure can pose serious health risks. Additionally, it is recognized as a potential biomarker for specific diseases when detected in exhaled breath. Despite their promise, developing highly sensitive and selective NH₃ sensors that perform efficiently in humid environments remains a significant challenge. Humidity plays a crucial role in sensor performance, as moisture can substantially affect the adsorption and desorption of gas molecules on the sensing surface.

In this work, we investigate the gas-sensing behavior of SiNWs in response to NH₃. The fabricated SiNW structures exhibit a strong response to NH₃, with notable improvements in sensitivity under humid conditions. Furthermore, we have demonstrated the humidity sensing performance of SiNWs decorated with tungsten trioxide (WO₃) nanoparticles. This modification resulted in a promising response, particularly under varying humidity levels. The findings presented in this study contribute to the ongoing development of highly efficient ammonia sensors, with potential applications in both environmental monitoring and medical diagnostics.

Description of the New Method or System

The silicon nanowires (SiNWs) were fabricated using a metal-assisted chemical etching (MACE) method, which relies on highly anisotropic etch-

ing of silicon wafers in contact with metallic nanoparticles, specifically silver (Ag) in this case. An array of Ag nanoparticles is first formed by immersing a *p*-type silicon wafer in an AgNO₃ solution. Following deposition, immersing in a solution of hydrofluoric acid (HF) and hydrogen peroxide (H₂O₂), which facilitates the etching process, at regions where the surface is in contact with the Ag nanoparticles. After a predetermined etching time, the process is terminated by transferring the wafer into DI-water to stop the reaction. Remaining Ag residues are removed by subsequent treatment in HNO₃.

This technique produces vertically aligned nanowires with a high surface area, a key feature for gas sensing applications. In our approach, the bare SiNWs were also functionalized with WO₃ nanoparticles for improving humidity sensing. The resulting structure demonstrates exceptional performance, particularly in high-humidity environments. Our findings suggest that this design will not only enhance sensitivity but also maintains reliable functionality under humid conditions, making it a promising tool for the detection of diseases and the monitoring air pollution.

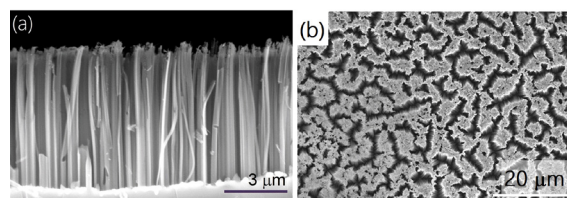


Fig. 1: (a) Cross-sectional, and (b) top-view SEM micrographs of the SiNWs structure before incorporation of WO₃.

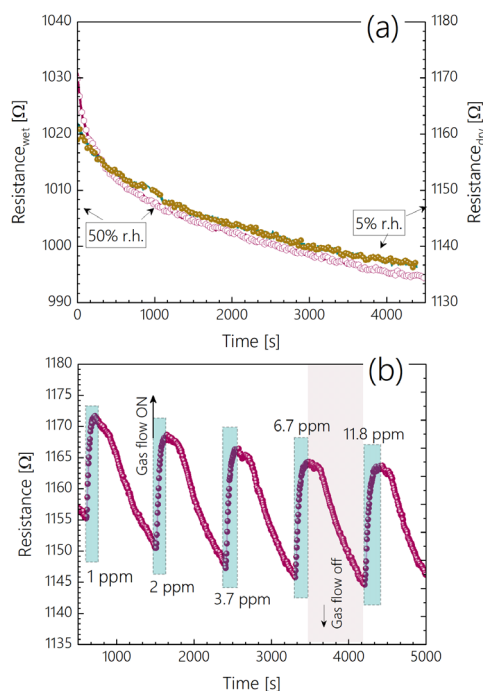


Fig. 2: Results for *p*-type SiNW response to (a) 5% and 50% r.h. and (b) to NH₃ measured at room temperature in carrier air with 50% r.h.

Results

A cross-sectional and top-view scanning electron microscope (SEM) image of the SiNW sample (Figure 1), shows that the nanowires are approximately 7 μm in length and 50 to 80 nm in diameter. Due to capillary effects and their high aspect ratio, the nanowires tend to bend and bundle together.

The electrical response of a *p*-type SiNW sensor, measured as resistance over time, is shown in Figure 2. Initial tests under varying relative humidity (r.h.) conditions at room temperature demonstrated no significant response to humidity before exposure to NH₃ gas (Figure 2(a)), confirming that humidity does not affect the sensor's baseline performance. Figure 2(b) presents the sensor's response to NH₃ at different concentrations (1 ppm, 2 ppm, 3.7 ppm, 6.7 ppm, and 11.8 ppm) under 50% relative humidity. A stable and pronounced increase in resistance was observed under 50% r.h. humidity. This change in resistance is attributed to the sensing mechanism, where the accumulation of holes at the SiNW surface decreases upon exposure to the reducing gas NH₃. A detailed description of ammonia sensing mechanism can be found elsewhere [2].

After the incorporation of WO nanoparticles, the SiNW sensor, which previously exhibited no response to humidity at both 5% and 50% r.h., became sensitive to moisture. This modification fundamentally altered the sensor's response

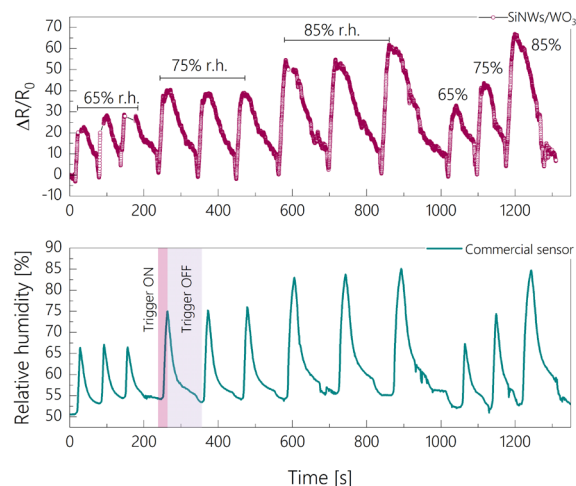


Fig. 3: Relative humidity monitored by commercial humidity sensor HTU21D (bottom plot) and the corresponding change in resistance measured over SiNWs/WO₃ structure (upper plot).

characteristics, enabling independent detection of both humidity and NH₃. Compared to previously reported structures, such as Si/WO and SiNWs/WO₃ [3, 4], the our structure demonstrate enhanced sensitivity and faster response times. Figure 3 illustrates the resistance over time for these modified structures. Current efforts are focused on optimizing the distribution of the nanoparticles to prevent agglomeration, which could negatively impact sensor performance. Once uniform nanoparticle distribution is achieved, the sensing capabilities will be systematically evaluated across a range of concentrations, underscoring the potential of these sensors for NH₃ detection in humid environments, with applications in medical diagnostics and air quality monitoring.

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