

Article

Pd-Gated N-Polar GaN/AlGaN High-Electron-Mobility Transistor for High-Sensitivity Hydrogen Gas Detection

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Abstract: Hydrogen gas sensing is critical for energy storage, industrial safety, and environmental monitoring. However, traditional sensors still face challenges in selectivity, sensitivity, and stability. This work introduces an innovative N-polar GaN/AlGaN high-electron-mobility transistor (HEMT) with a 10 nm Pd catalytic layer as a hydrogen sensor. The device achieves ppm-level H₂ detection with rapid recovery and reusability, which is comparable to or even exceeds the performance of conventional Ga-polar HEMTs. The N-polar structure enhances sensitivity through its unique polarization-induced 2DEG and intrinsic back barrier, while the Pd layer catalyzes H₂ dissociation, forming a dipole layer that can modulate the Schottky barrier height. Experimental results demonstrate superior performance at both room temperature and elevated temperatures. Specifically, at 200 °C, the sensor exhibits a response of 102% toward 200 ppm H₂, with response/recovery times of 150 s/17 s. This represents a 96% enhancement in sensitivity and a reduction of 180 s/14 s in response/recovery times compared to room-temperature conditions (23 °C). These findings highlight the potential of N-polar HEMTs for high-performance hydrogen sensing applications.



Academic Editor: Evgeniy N. Mokhov

Received: 13 May 2025

Revised: 27 May 2025

Accepted: 6 June 2025

Published: 18 June 2025

Citation: Ge, L.; Bai, H.; Teng, Y.; Yang, X. Pd-Gated N-Polar GaN/AlGaN High-Electron-Mobility Transistor for High-Sensitivity Hydrogen Gas Detection. *Crystals* **2025**, *15*, 578. <https://doi.org/10.3390/cryst15060578>

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Keywords: N-polar; GaN/AlGaN; high-electron-mobility transistor; H₂ sensor

1. Introduction

Hydrogen gas sensing has increasingly become critical in applications such as energy storage, industrial safety, and environmental monitoring. With the global push towards sustainable energy solutions, hydrogen is emerging as a key player in the energy transition. However, the safe utilization of hydrogen requires reliable sensing technologies to detect leaks and monitor concentrations in various settings. Traditional hydrogen sensor materials, similar to SnO₂ [1], ZnO [2], TiO₂ [3,4], etc., often suffer from limitations such as poor selectivity, low sensitivity, and instability under harsh conditions [5–7]. These shortcomings have driven researchers to seek innovative materials and advanced device architectures that can overcome these challenges and provide robust hydrogen sensing capabilities.

To address these challenges, wide-bandgap semiconductor materials, such as gallium nitride (GaN), have emerged as promising candidates for advanced sensing applications [8–11]. GaN-based high-electron-mobility transistors (HEMTs) have garnered significant attention due to their high electron mobility and excellent thermal and chemical

stability [12–14]. The unique electronic properties of GaN enable these devices to operate efficiently in extreme environments, making them ideal for gas-sensing applications. Conventional Ga-polar HEMT-based sensors have been widely studied and have demonstrated remarkable performance in hydrogen gas detection [15–17]. Sokolovskij et al. designed an embedded MIS-structured Pt-AlGa_N/GaN HEMT H₂ sensor, achieving post-gate-recess responses of 2.1% (from 0.4%) for 5 ppm H₂ and 42.2% (from 13.2%) for 300 ppm H₂, with a 250 ppm H₂ response/recovery time of 4.3 min/13.6 min [18]. Chahdi et al. also developed a Pt-AlGa_N/GaN HEMT sensor, which shows rapid H₂ response even at high temperatures but lacks H₂ selectivity in O₂/H₂ environments [19]. Despite these advancements, Ga-polar HEMTs have shown limitations in response speed and selectivity, necessitating further exploration to optimize their performance for specific sensing requirements.

Recent studies have highlighted the advantages of N-polar HEMTs over Ga-polar HEMTs for hydrogen gas sensing. N-polar HEMTs exhibit higher affinity for hydrogen molecules and unique structural benefits, such as an intrinsic back barrier that enhances sensitivity to surface charge changes [20]. The distinct electronic structure of N-polar HEMTs provides a favorable environment for efficient charge transfer and interaction with hydrogen molecules [21]. This is further enhanced by the polarization-induced two-dimensional electron gas (2DEG) at the GaN/AlGa_N heterojunction interface. The sensing mechanism of N-polar HEMTs involves the modulation of the 2DEG conductivity when hydrogen gas interacts with a functional layer deposited on the gate. This interaction alters the surface potential, thereby modulating the 2DEG channel conductivity. For instance, palladium (Pd) is commonly used as a functional layer due to its excellent catalytic properties for hydrogen dissociation [22]. The dissociated hydrogen atoms diffuse to the heterojunction interface, altering the charge distribution and modulating the Schottky barrier height. This change in barrier height results in measurable variations in the drain–source current of the HEMT device, enabling the detection of hydrogen gas concentration [23].

We further investigate the temperature dependence and selectivity of the N-polar HEMT-based sensor towards different gases. The sensitive mechanism of the Pd-gated N-polar HEMT-based sensor to hydrogen gas is also analyzed from a comprehensive perspective of chemistry and physics. This study offers profound insights into the design and optimization of hydrogen sensors based on N-polar HEMTs, which are anticipated to play a pivotal role in future industrial and environmental monitoring systems.

2. Experiments

As shown in Figure 1, the epitaxial stack of the HEMT-based sensor was grown on a sapphire substrate via metal–organic chemical vapor deposition (MOCVD). The structure includes a 2 µm semi-insulating GaN buffer layer, an 8.5 nm Si-doped GaN layer ($\text{Si} = 4 \times 10^{18} \text{ cm}^{-3}$), a 25 nm Si-doped graded AlGa_N back barrier ($\text{Al} = 0\text{--}27\%$, $\text{Si} = 4 \times 10^{18} \text{ cm}^{-3}$), an 18 nm unintentionally doped AlGa_N (uid-AlGa_N) barrier, a 1 nm AlN interlayer, and a 10 nm unintentionally doped GaN (uid-GaN) channel layer. The two-dimensional electron gas (2DEG) forms at the interface between the GaN channel and the AlGa_N barrier layers due to the combined effect of polarization and modulation doping provided by the Si-doped AlGa_N back barrier. The AlN interlayer reduces alloy scattering and enhances the 2DEG mobility.

The sensors were fabricated through micromachining processes. First, the wafer was ultrasonically cleaned in acetone and isopropyl alcohol for 10 min each to remove organic contaminants and improve surface cleanliness, and the devices were isolated using low-damage mesa inductively coupled plasma (ICP) dry etching with BCl₃/Cl₂ mixed gas (48:6 ratio) under a radio-frequency power of 300 W, achieving an etching rate of 500 nm/min. Subsequently, Ti/Al/Ni/Au (20/120/50/100 nm) was deposited as

source and drain electrodes via electron-beam evaporation (EBE) under a base pressure of 1×10^{-7} Torr. After metal liftoff, rapid thermal annealing was performed at 750 °C for 30 s in a nitrogen atmosphere to form ohmic contacts. Then, a 10 nm Pd metal layer was deposited on the sensitive gate area using EBE at a deposition rate of 0.3 Å/s, followed by metal liftoff to complete the sensor fabrication. The sensitive region dimensions were $50 \times 400 \mu\text{m}$, and the gate-to-source/drain distance was $5 \mu\text{m}$. The wafer was diced into individual devices, which were wire-bonded to a PCB substrate for gas-sensing measurements.

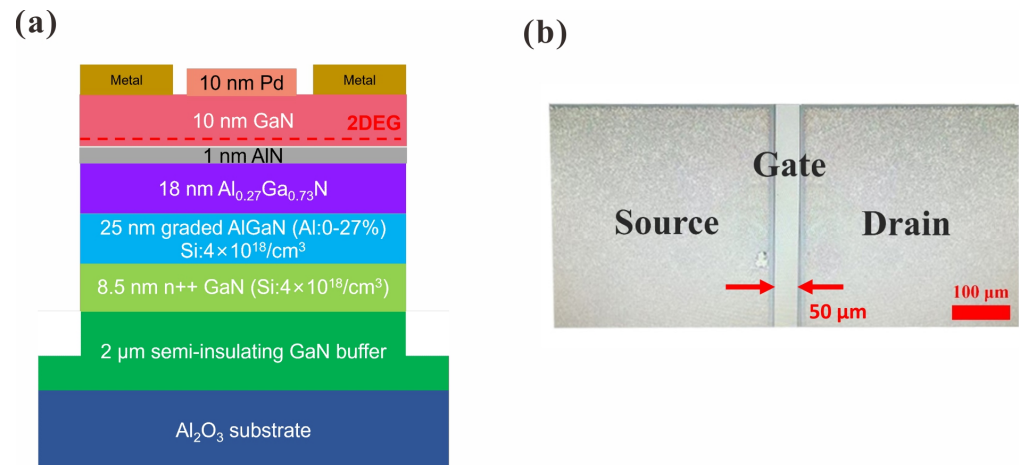


Figure 1. (a) Schematic cross-section of the studied Pd-gated N-polar GaN/AlGaN HEMT sensor. (b) Top-view optical micrograph of the fabricated sensor.

3. Results and Discussion

As shown in Figure 2, the Ti/Al/Ni/Au ohmic contact resistance of the device was characterized using the transmission line model (TLM) method with the Keithley 4200 semiconductor parameter analyzer. The device exhibited ohmic behavior with a very low contact resistance (R_c) of $0.6 \Omega \cdot \text{mm}$ and a specific contact resistivity (ρ_c) of $5.73 \times 10^{-6} \Omega \cdot \text{cm}^2$.

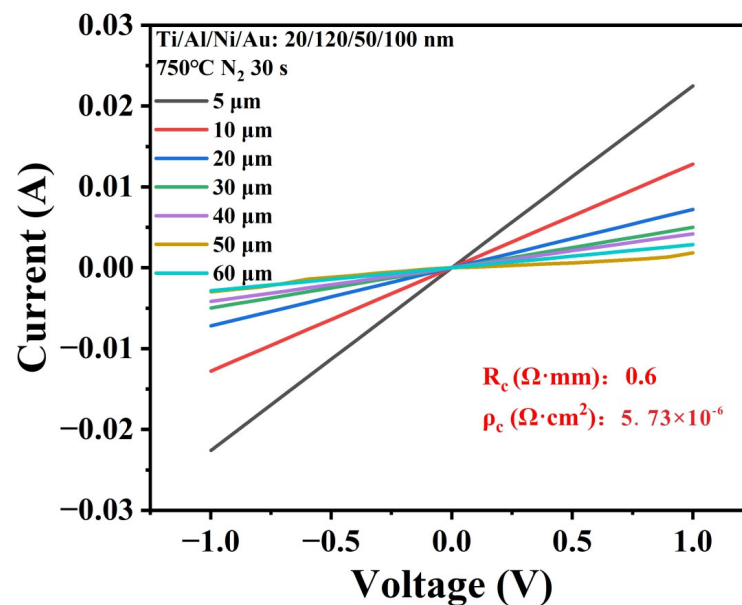


Figure 2. The I-V curves among pads with different spacings annealed at 750 °C in N_2 for 30 s.

As shown in Figure 3a, the gas-sensing test system consists of a reaction chamber (volume: 50 mL) where the sensor is placed. The source and drain electrodes of the

sensors are connected to a Keithley 2400 sourcemeter operating in constant-voltage mode ($V_{ds} = 0.3$ V) with a sampling rate of 10 data points per second. The operating temperature of the sensor is controlled by a PID-regulated heating stage (accuracy: ± 1 °C) located below the chamber, which continuously monitors the temperature via a K-type thermocouple. All test gases are standard gases (purity > 99.999%) diluted in synthetic air ($O_2:N_2 = 21:79$) using a gas dilution device (MF 2600; flow rate range: 0.1–5 L/min; dilution ratio resolution: 0.01 ppm). During testing, the sensor is first stabilized in synthetic air for 30 min to record the baseline current (I_{Air}) under steady-state conditions (drift < 1% per hour). A predetermined concentration of H_2 is then injected into the sealed chamber through a mass flow controller (MFC) with $\pm 2\%$ accuracy. The examination surroundings were sustained at an ambient temperature of 23 °C ± 0.5 °C and a relative humidity (RH) of $40 \pm 3\%$. When the sensor current reaches relative saturation, the chamber is opened to expose the sensor to air again. The sensor response is calculated using the formula $S = (I_{H_2} - I_{Air})/I_{Air} \times 100\%$. The response/recovery time is defined as the time required for the sensor current to rise/fall to 90% of the relative equilibrium value.

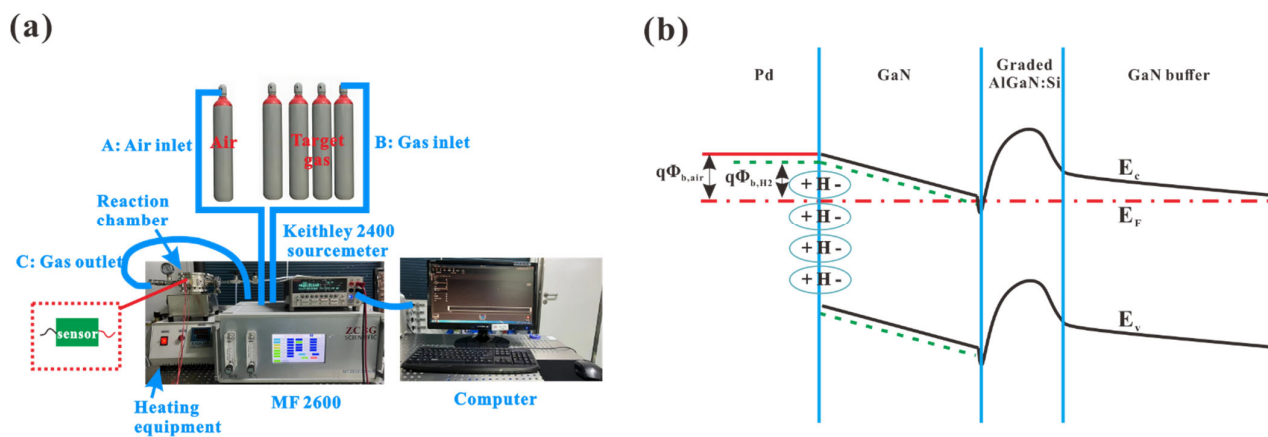
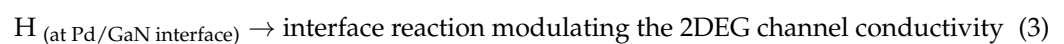
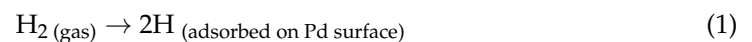


Figure 3. (a) Schematic diagram of the gas test system. (b) Gas-sensing mechanism of the GaN/AlGaN HEMT-based sensors.

As shown in Figure 3b, the 2DEG is generated at the N-polar GaN/AlGaN interface due to piezoelectric and spontaneous polarization. When the device is exposed to H_2 gas, H_2 molecules are adsorbed onto the Pd gate and dissociated into H atoms. These H atoms then diffuse through the catalytic Pd metal to the Pd/GaN interface. These processes can be represented as follows:



At the Pd/GaN interface, the adsorbed H atoms form a dipole layer, which lowers the effective Schottky barrier height Φ_b and increases the 2DEG concentration, and hence results in an increasing I_{ds} . Higher H_2 concentrations lead to an increase in dipole density at the Pd/GaN interface, resulting in larger changes in Φ_b and I_{ds} .

Figure 4a–f illustrate the gas-sensing performances of the N-polar GaN/AlGaN HEMT device at room temperature (23 °C) and elevated temperature (200 °C). The I–V characteristics exhibit a significant increase in drain–source current (I_{ds}) with increasing H_2 concentration from 10 to 100 ppm, as shown in Figure 4a,d. This increase is attributed to the formation of a dipole layer at the Pd/GaN interface upon H_2 exposure, which reduces

the Schottky barrier height (Φ_b) and increases the 2DEG concentration. The dynamic current response (Figure 4b,e) and response percentage (Figure 4c,g) further confirm the device's rapid and linear response to H_2 at 23 °C and 200 °C, while the sensor operating at 200 °C has higher sensitivity due to accelerated H_2 adsorption and dissociation processes. Figure 4g shows the temperature dependence of the sensor response, where the response percentage increases with temperature, reaching a maximum of 200 °C, and then showing a slight decrease at 250 °C. This trend indicates optimal sensing performance at 200 °C. Figure 4h presents the relationship between the sensor response and H_2 concentration at 23 °C and 200 °C, with fitting curves showing a linear relationship at low concentrations. The fitting equations are $y_1 = 0.518x_1 - 0.753$ ($R^2 = 0.99$) at 23 °C and $y_2 = 1.025x_2 - 0.636$ ($R^2 = 0.99$) at 200 °C, where y is the sensor response and x is the H_2 concentration in ppm. Notably, at 200 °C, the sensor exhibits a response of 102% to 100 ppm H_2 , which is 1.96 times higher than the response of 52% at room temperature. Figure 4i,j compare the response and recovery times at 23 °C and 200 °C, and the results show that the sensor has shorter response and recovery times at higher temperature (150 s response and 17 s recovery at 200 °C versus 330 s response and 31 s recovery at 23 °C). This improvement is attributed to faster H_2 adsorption/dissociation processes and efficient desorption of H atoms from the Pd/GaN interface at higher temperatures. Figure 4k demonstrates excellent repeatability at 200 °C, with consistent responses to 100 ppm H_2 over multiple cycles. Figure 4l highlights the device's selectivity to H_2 over other gases (H_2S , SO_2 , NO_2 , NH_3 , CO), attributed to the specific catalytic action of the Pd gate. These results indicate that the N-polar HEMT device is highly suitable for practical H_2 detection applications, offering fast response, high sensitivity, good selectivity, and stability.

Figure 5 presents the response of the N-polar GaN/AlGaIn HEMT sensor to 100 ppm H_2 under different RH conditions. As humidity rises from 40% to 85%, the sensor's response declines slightly, and its response/recovery times lengthen somewhat. This may stem from water molecules competing with H_2 for active sites on the Pd surface and forming a water film that hinders H_2 diffusion, thereby slightly reducing the response and prolonging the response/recovery times. Additionally, humidity-induced changes in the surface chemistry of the GaN/AlGaIn interface can alter the charge distribution and 2DEG properties, affecting the sensor's performance. Notably, even at 85% RH, the sensor retains over 90% of its response, demonstrating its robustness and reliability in varying humidity conditions. This makes the N-polar GaN/AlGaIn HEMT sensor a promising candidate for practical hydrogen detection applications, especially in environments with uncontrollable humidity.

In Table 1, compared to our N-polar HEMT sensor, traditional Ga-polar HEMT-based hydrogen sensors often exhibit slower response and recovery times, and some require higher operating temperatures [18,24–27]. Some also demand elevated temperatures to achieve comparable sensitivity, which can be less practical for real-world applications. In contrast, our N-polar HEMT sensor not only operates at a relatively low temperature of 200 °C but also delivers exceptional sensitivity and markedly faster response and recovery times. This makes it highly suitable for efficient hydrogen detection in practical scenarios. Moreover, some sensors, despite being able to operate at relatively low temperatures, exhibit a rather low response to H_2 [28,29].

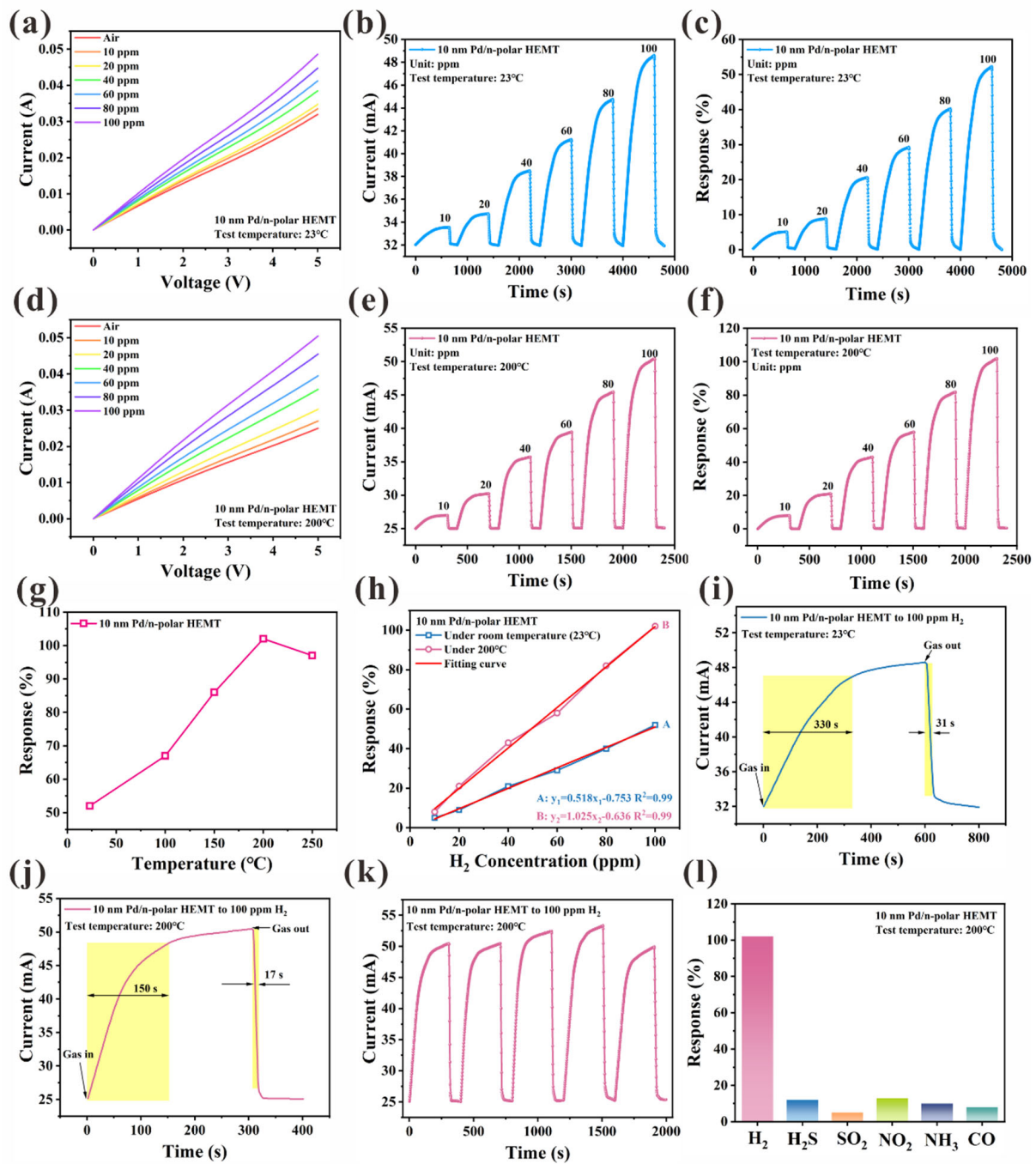


Figure 4. (a) The sensor output characteristics when exposed to different concentrations of H_2 at 23 °C. (b,c) Current/response change curves of the sensor towards various H_2 concentrations at 23 °C. (d) The sensor output characteristics when exposed to different concentrations of H_2 at 200 °C. (e,f) Current/response change curves of the sensor towards various H_2 concentrations at 200 °C. (g) The sensor response curve varies with temperature. (h) Fitting curves of sensor response with H_2 concentration at 23 °C and 200 °C. (i,j) Response/recovery time curves of the sensor to 100 ppm H_2 at 23 °C and 200 °C. (k) Repeatability test of the sensor for 100 ppm H_2 at 200 °C. (l) Selectivity of the sensor towards 100 ppm of various interfering gases at 200 °C.

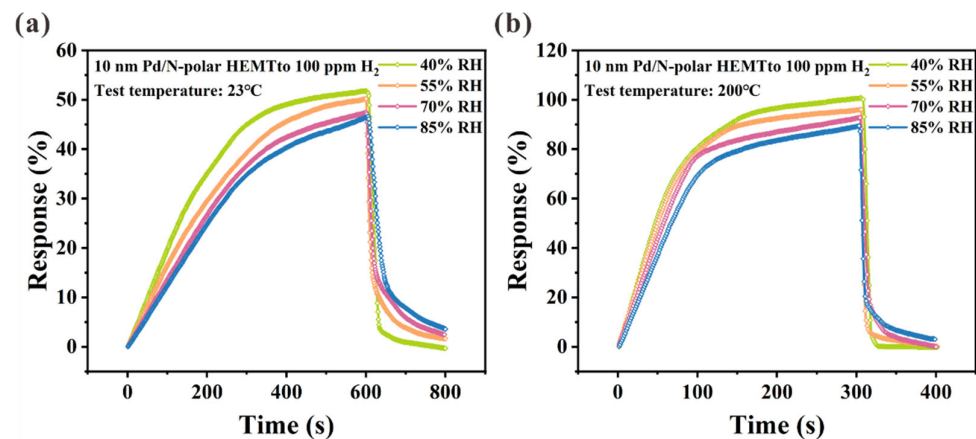


Figure 5. (a) Response change curves of the sensor towards various RHs at 23 °C. (b) Response change curves of the sensor towards various RHs at 200 °C.

Table 1. Comparison of the H₂ detection properties of traditional sensors.

Hydrogen Gas Sensor	H ₂ Conc.	Temp. (°C)	S	T _{res} /T _{rec}	Ref.
Pt-AlGaIn/GaN	250 ppm	240	42.2%	4.3 min/13.6 min	[18]
Pt/AlGaIn/GaN	4%	350	33%	-	[24]
Pd/AlGaIn/GaN	1000	230	78%	-	[25]
Pt/AlGaIn/GaN	500	200	7.6%	342 s/1539 s	[26]
Pt-AlGaIn/GaN	300	240	145.8%	2.5 min/8.85 min	[27]
Pt/AlGaIn/GaN	10,000 ppm	126	13.7%	28 s/36 s	[28]
Pd/AlGaIn/GaN	10,000 ppm	100	26.3%	53 s/76 s	[29]
Pd-gated/N-polar GaN/AlGaIn	100 ppm	200	52%	330 s/31 s	This work
	100 ppm		102%	150 s/17 s	

4. Conclusions

In this work, we demonstrate a selective GaN/AlGaIn HEMT-based hydrogen sensor with a 10 nm Pd catalytic layer as the sensitive layer. Our device achieves ppm-level H₂ detection with rapid recovery and reusability, underscoring the potential of N-polar HEMTs for high-performance hydrogen sensing applications. Utilizing the high electron mobility, intrinsic back barrier, and high sensitivity to surface charge changes of N-polar HEMTs, the device achieves excellent sensing performance. Tests show that the fabricated sensor exhibits rapid, linear, and reversible H₂ responses at room and elevated temperatures. At 200 °C, the response to 100 ppm H₂ is 102%, 1.96 times higher than that at room temperature, with significantly reduced response/recovery times. The sensor also shows superior selectivity to H₂ and good repeatability, indicating great potential for practical hydrogen detection applications and highlighting N-polar HEMTs as valuable advanced sensing platforms.

Author Contributions: Conceptualization, L.G. and Y.T.; Data curation, L.G.; Formal analysis, L.G.; Funding acquisition, X.Y.; Investigation, L.G.; Methodology, L.G.; Project administration, Y.T.; Resources, X.Y. and H.B.; Software, L.G.; Supervision, Y.T.; Validation, L.G.; Visualization, L.G.; Writing—original draft, L.G.; Writing—review & editing, L.G. and Y.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (62375028) and the Natural Science Foundation of Henan Province (No. 252300421579).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors have no conflicts of interest to disclose.

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