Enhancement of Ion-Sensitive Field-Effect Transistors through Sol-Gel Processed Lead Zirconate Titanate Ferroelectric Film Integration and Coplanar Gate Sensing Paradigm

Dong-Gyun Mah 1, Seong-Moo Oh 2, Jongwan Jung 2* and Won-Ju Cho 1,*

1 Department of Electronic Materials Engineering, Kwangwoon University, Gwangun-ro 20, Nowon-gu, Seoul 01897, Republic of Korea; madong13@kw.ac.kr
2 Department of Nanotechnology and Advanced Materials Engineering, Sejong University, Seoul 05006, Republic of Korea; 17011353@sju.ac.kr (S.-M.O.)
* Correspondence: chowj@kw.ac.kr; Tel.: +82-2-940-5163

Abstract: To facilitate the utility of field effect transistor (FET)-type sensors, achieving sensitivity enhancement beyond the Nernst limit is crucial. Thus, this study proposed a novel approach for the development of ferroelectric FETs (FeFETs) using lead zirconate titanate (PZT) ferroelectric films integrated with indium–tungsten oxide (IWO) channels synthesized via a cost-effective sol-gel process. The electrical properties of PZT-IWO FeFET devices were significantly enhanced through the strategic implementation of PZT film treatment by employing intentional annealing procedures. Consequently, key performance metrics, including the transfer curve on/off ratio and subthreshold swings, were improved. Moreover, unprecedented electrical stability was realized by eliminating the hysteresis effect during double sweeps. By leveraging a single-gate configuration as an FeFET transformation element, extended-gate (EG) detection methodologies for pH sensing were explored, thereby introducing a pioneering dimension to sensor architecture. A measurement paradigm inspired by plane gate work was adopted, and the proposed device exhibited significant resistive coupling, consequently surpassing the sensitivity thresholds of conventional ion-sensitive field-effect transistors. This achievement represents a substantial paradigm shift in the landscape of ion-sensing methodologies, surpassing the established Nernst limit (59.14 mV/pH). Furthermore, this study advances FeFET technology and paves the way for the realization of highly sensitive and reliable ion sensing modalities.

Keywords: ferroelectric field-effect transistors (FeFETs); ion-sensitive field-effect transistors (ISFETs); lead zirconate titanate (PZT) ferroelectric films; extended gate ion-sensitive field-effect transistors (EG-ISFETs); methodologies for pH sensing; sensitivity enhancement; resistive coupling

1. Introduction

The continuous development of industries emphasizes the importance of ion sensitivity measurement, particularly pH measurement, in various fields, such as biology, medicine, and environmental monitoring [1–3]. Consequently, several studies have focused on ion-sensitive field-effect transistor (ISFET) technology, which holds potential for label-free detection, high sensitivity, fast response time, and compatibility with complementary metal-oxide-semiconductor (CMOS) processes [4–6]. In typical ISFETs, the transducer unit and the sensing membrane are integrated into a single platform. However, frequent sensitivity measurements degrade the reliability of the transducer unit, leading to the proposal of the extended gate ion-sensitive field-effect transistor (EG-ISFET), which separates the transducer and the sensing membrane [7–9]. Recently, extensive research has been conducted on the transducer, sensing membrane, and overall sensor platform structure to improve the sensing characteristics and process costs of EG-ISFETs [10–13]. However, studies that comprehensively address the performance enhancement of both the
transducer and the sensor platform structure are not widely reported. Therefore, in this study, we fabricated a cost-effective transducer and evaluated its electrical performance and reliability. Additionally, we introduced a resistive coupling method to replace the previously studied vertical dual-gate and coplanar gate structures to achieve sensitivity exceeding the Nernst limit [14–17].

Initially, we focused on the enhancement of the characteristics of the transducer unit to drive innovative advancements in EG-ISFET technology. As part of this approach, we fabricated ferroelectric field-effect transistors (FeFETs) incorporating lead zirconate titanate (PZT) ferroelectric films and indium--tungsten oxide (IWO) channels. The PZT films were synthesized through a cost-effective sol-gel method [18–21]. PZT films exhibit high residual polarization, low coercive voltage, and compatibility with silicon processes within integrated circuits. Further, integration with amorphous oxide semiconductor channels facilitates the implementation of low-power consumption and excellent on/off performance characteristics [22,23]. However, PZT films exhibit counterclockwise hysteresis in the transfer curve owing to typical polarization characteristics, which can result in reliability and reproducibility issues when applied to ISFET platforms [24,25]. Consequently, PZT films are subjected to thermal treatment to form a thin trapping layer approximately 2 nm thick [26–28]. Traditional dual sweeps exhibit polarization and charge trapping characteristics in counterclockwise and clockwise directions, respectively [29]. By balancing these two characteristics, we optimized thin-film transistors (TFTs) for the transducer unit, consequently achieving outstanding performance metrics: a hysteresis voltage of less than 10 mV, subthreshold swing (SS) of 88.75 mV/dec, and a current on/off ($I_{on/off}$) ratio of approximately $10^{9}$. The performance metrics achieved are noteworthy when compared to bottom gate structure transistors based on PZT thin films, particularly in terms of $\mu_{FE}$, SS, and $I_{on/off}$ ratio. To facilitate the use of the proposed device as a transducer in the sensor platform, preliminary DC bias tests were conducted to observe threshold voltage changes in the transfer curve [30]. Excellent consistency exceeding 99% across various read currents ($I_{REF}$) was confirmed.

Consequently, in this study’s EG-ISFET platform, a single-gate configuration PZT-FeFET was employed as the transducer unit, with an $\text{SnO}_2$ sensing membrane. A sensitivity similar to the Nernst limit was realized in pH sensitivity measurements [31,32]. Further, we adopted an innovative resistive coupling method inspired by the plane gate in the sensor platform [33]. Through adjustments to the resistance ratio between the control gate (CG) resistance ($R_{CG}$) and the sensing gate (SG) resistance ($R_{SC}$), we achieved a high sensitivity of 287.2 mV/pH, which surpassed the traditional Nernst limit of 59.14 mV/pH. Moreover, to ensure the reliability of the proposed platform, we verified the measurement sensitivity, hysteresis, and drift effects according to pH value [34,35]. In addition, direct comparisons and evaluations with results obtained using the existing single-gate-based EG-ISFET method for the case of $R_{CG}/R_{SC} = 1$ were conducted.

Thus, our innovative approach, which ingeniously engineered the polarization and trapping characteristics, achieved unprecedented electrical performance improvements in FeFET technology and clearly overcame the limitations of the sensing mechanism imposed by the polarization characteristics being studied [36–38]. Furthermore, the successful implementation of sensitivity amplification via integration with the self-resistive coupling sensing platform demonstrated the feasibility of creating an efficient single-gate structure platform, surpassing the existing complex and high-cost transducer fabrication methods.

2. Materials and Methods

2.1. Material Specifications

The fabricated EG-ISFET comprised transducer and sensing units. For the fabrication of the sensing unit, glass substrates (7059 glass; Corning Inc., New York, NY, USA), indium--tin oxide (ITO) sputter target (purity $\geq 99.99\%$, THIFINE Co., Ltd., Incheon, Republic of Korea), $\text{SnO}_2$ sputter target (purity $\geq 99.99\%$, THIFINE Co., Ltd.), polydimethylsiloxane (PDMS; Sylgard 184 silicon elastomer; Dow Corning, Midland, MI, USA), and Ag/AgCl
electrode (Horiba 2080-06T; Kyoto, Japan) were utilized. Further, sensitivity to pH buffer solution (Samchun Chemical, Pyeongtaek, Republic of Korea) was measured. To fabricate the transducer unit, the following materials were employed: indium–tungsten oxide (IWO) sputter target (purity \( \geq 99.99\% \), THIFINE Co., Ltd.), ITO sputter target (purity \( \geq 99.99\% \), THIFINE Co., Ltd.), lead acetate trihydrate (\( \text{Pb(CH}_3\text{CO}_2\text{)}_2 \cdot 3\text{H}_2\text{O} \)), Ti-isopropoxide and Zr-propoxide (Zr:Ti = 52:48), Pt (purity \( \geq 99.99\% \), THIFINE Co., Ltd.), and Ti (purity \( \geq 99.99\% \), THIFINE Co., Ltd.), \( \text{SiO}_2 \) (purity \( \geq 99.99\% \), THIFINE Co., Ltd.).

2.2. Formation of PZT Thin Film and Fabrication Process of FeFET

The fabrication process flow of the device, as illustrated in Figure 1, is as follows. A PZT thin film was fabricated on a Pt/Ti/SiO\(_2\)/Si substrate using the sol-gel method. The PZT thin film was deposited via spin-coating at a rotation speed of 3000 rpm for 30 s. Subsequently, to promote evaporation and combustion of volatile substances and minimize film cracking, it was dried on a hot plate at 150 °C for 1 min, followed by annealing at 450 °C for 7 min and then at 650 °C for 3 min. To achieve the desired thickness, the annealing processes were repeated six times, yielding a 300 nm thick PZT film. Further, for film crystallization and intentional trap layer formation, furnace annealing of the PZT film was conducted at 650 °C for 30 min. Thereafter, an IWO channel layer with dimensions of 60 µm width \( \times \) 120 µm length was deposited to a thickness of 20 nm using RF sputtering. Given the high conductivity of IWO, it is essential to engineer the off-current characteristics. Therefore, optimization was achieved through a comprehensive parameter evaluation extracted from the transfer curves of PZT-IWO FeFETs with IWO channel thicknesses of 20, 35, and 50 nm. Subsequently, ITO was deposited to a thickness of 100 nm and consequently patterned using a lift-off process to form source and drain electrodes measuring 120 µm \( \times \) 150 µm. To enhance the electrical properties of the IWO semiconductor, the deposited film was annealed in a 300 °C oxygen environment for 30 min. Considering the predominant conductivity of indium in the IWO material, an engineered optimal channel thickness was determined, and the annealing conditions were optimized to enhance electrical characteristics such as the \( \text{I}_{\text{on/off}} \) and \( \text{SS} \).

![Figure 1. Formation of thin film and trap layer through thermal treatment of sol-gel PZT, and fabrication process of FeFET.](image-url)
2.3. Fabrication of pH Selective EG Sensing Unit

This study addressed the limitations of sensing platforms reliant solely on a single device, such as traditional ISFETs, particularly the issue of reduced transistor lifespan resulting from repeated measurements. To circumvent this challenge, a separate sensing unit (EG) and transducer (FeFET) were fabricated [39]. The EG was designed to relay applied potential changes, arising from variations in surface ion concentration, to the transducer gate. This was achieved via the deposition of a 300 nm thick ITO layer onto a glass substrate measuring 1.5 cm × 3 cm. Subsequently, a 50 nm thick SnO₂ layer (sensing layer) was deposited onto the ITO layer to serve as a receptor for detecting surface potential changes corresponding to variations in the pH buffer solution. In addition, to facilitate contact with the pH buffer solution, a polydimethylsiloxane (PDMS) reservoir was affixed atop the sensing layer. Finally, a reference electrode (Ag/AgCl) was positioned approximately 3 mm away from the sensing layer within the PDMS reservoir for immersion in the buffer solution.

2.4. Design of a Self-Resistive Coupling Circuit for Sensitivity Amplification

Single-gate based EG-ISFETs are plagued by the limitations of the Nernst limit, which has prompted significant research efforts aimed at enhancing the sensitivity performance. Consequently, methods to improve device structure, such as the introduction of vertical dual-gate and coplanar gate structures, have emerged, shifting focus beyond the transducer’s electrical operation excellence alone. However, the complexity and cost of platform fabrication, coupled with inefficiencies in sensitivity adjustment, have resulted in new challenges. These challenges were addressed by designing an innovative self-resistive coupling circuit. The sensitivity amplification mechanism was similar to co-planar gate type sensor platforms using the CG and SG concepts. However, we introduced a simple and efficient approach by incorporating resistors into the EG-ISFET sensor platform. The surface potential change resulting from the adsorption and desorption of hydrogen ions in the sensing unit, connected to RSG, along with the operating voltage supplied by Agilent 4156B precision semiconductor parameter analyzer (Hewlett-Packard Co., Palo Alto, CA, USA) connected to RCG, was capacitively coupled to FG (VFG), which was applied to the gate voltage of FeFET. Specifically, artificial adjustment according to the ratio of the control gate resistor (RCG) to the sensing gate resistor (RSG) was performed. Consequently, the stability and superior sensitivity amplification of the innovative sensor platform were successfully validated through pH sensitivity measurements at various resistance ratios.

2.5. Device Characterization

The deposition thickness of all materials during the fabrication processes of the transducer and sensing units was measured using the Dektak XT Bruker stylus profiler (Bruker, Hamburg, Germany). The electrical characteristics of the transducer and its operational performance as a sensor platform were evaluated using a precision semiconductor parameter analyzer (Agilent 4156B), in conjunction with a DC power supply. In addition, measurements were conducted within a dark box to minimize external interference factors such as light and noise. Finally, sensitivity measurements were performed for pH 3, 4, 6, 7, 9, and 10 buffer solutions.

3. Results and Discussion

3.1. Electrical Characteristics and Mechanism of PZT-FeFET

The inherent operational characteristics of the transducer unit within the proposed EG-ISFET sensor-based self-resistive coupling platform are considered pivotal factors. Therefore, the semiconductor characteristics of the FeFET, encompassing both transfer and output characteristics, must be assessed. Specifically, enhancements in the Ion/Idi, SS, and mobility facilitate swift responses to variations in pH and ion concentration, thereby improving the real-time monitoring. Moreover, the absence of hysteresis in the dual-sweep
transfer curve operation ensures the reliability of the semiconductor device for repetitive sensing measurements.

As depicted earlier in Figure 1, intentional polarity and trap characteristics interaction were induced via the formation of a trapping layer on the surface of the PZT thin film through conventional thermal annealing (CTA) processes at elevated temperatures. Figure 2a illustrates the double-sweep transfer curve of the PZT-FeFET, revealing exemplary transistor behavior characterized by a threshold voltage ($V_{th}$) of 0.6 V, SS of 85.75 mV/dec, $I_{on/off}$ of $1.91 \times 10^8$, and mobility of 15.87 cm$^2$V$^{-1}$s$^{-1}$. The bottom Pt serves as the gate, with voltage applied via the Agilent 4156B, while the drain voltage was set to 1 V.

![Figure 2a](image.png)

**Figure 2.** Transfer characteristics ($V_G$–$I_D$) curves of the PZT FeFET: (a) double sweep, and (b) direction of hysteresis with respect to polarization and trapping. The inset in (b) illustrates the output characteristics of the PZT-FeFET. The mechanisms, depicting the relative magnitudes of polarization and trapping, are as follows: (c) polarization dominance, (d) trapping dominance, and (e) interaction between polarization and trapping.

In Figure 2b, the salient features of the double-sweep curve are depicted under conditions of polarization and charge trap dominance. In general, anticlockwise hysteresis is observed during the backward sweep owing to the dielectric properties of the PZT thin film caused by polarization. In contrast, clockwise hysteresis occurs when electrons are trapped at the interface between the channel and the insulating layer owing to the presence of a trapping layer. During the dynamic phase where the gate voltage sweeps from its maximum (Max. $V_G$) to 0 V, the polarization characteristics (Figure 2c) and trapping behaviors (Figure 2d) synergize. This yields a device with minimal hysteresis, as evidenced by the 10 mV hysteresis value depicted in Figure 2e. Further, the inset in (b) presents the output curve characteristics of the PZT-FeFET, measured in 11 steps by varying $|V_G-V_{th}|$, as 0–6 V.

Table 1 presents the performance parameters of PZT-based FETs for the devices fabricated in this study and those from earlier studies [29,40–43]. To enable a comprehensive comparison, an analysis of the parameters extracted from the transfer curves was conducted. First, the hysteresis window ($V_H$) was derived from the transfer curve upon the application of a gate voltage ($V_G$) through a double sweep. Without considering the anticlockwise and clockwise directions that appeared according to the dominant characteristics of polarization and trapping, the absolute value of the $V_H$ was summarized. The $V_{th}$ was extracted using the constant-current method, employing a predetermined drain current ($I_{dh}$) value that considered the channel’s width and length. In addition, the SS was extracted...
within the range where the $I_{ds}$ value shifted from $10^{-10}$ to $10^{-9}$ A. The field-effect mobility ($\mu_{FE}$) was derived using the equation $[I_{ds}/V_g] \times [L/(W C_{ox} V_d)]$, where $W$ and $L$ represent the width and length of the channel, respectively, and $C_{ox}$ denotes the capacitance per area extracted from the metal-PZT-metal capacitor. Finally, the $I_{on/off}$ was calculated based on the maximum $I_{on}$ value at the highest $V_g$ and the minimum $I_{off}$ value at approximately $V_g = 0.5$ V.

### Table 1. Comparison of transfer curve parameters for PZT film-based FeFETs.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$V_H$ (V)</th>
<th>$V_{th}$ (V)</th>
<th>SS (mV/dec)</th>
<th>$\mu_{FE}$ (cm$^2$V$^{-1}$s$^{-1}$)</th>
<th>$I_{on/off}$ (A/A)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGZO</td>
<td>4</td>
<td>1.2, 2.6</td>
<td>1250</td>
<td>1.5, 3</td>
<td>$1.5 \times 10^6$</td>
<td>[40]</td>
</tr>
<tr>
<td>IGZO</td>
<td>0.5</td>
<td>-</td>
<td>330</td>
<td>10.23</td>
<td>$9.5 \times 10^6$</td>
<td>[41]</td>
</tr>
<tr>
<td>MoS$_2$</td>
<td>0.01</td>
<td>0.2−0.4</td>
<td>85.9</td>
<td>10.01</td>
<td>$\sim 10^8$</td>
<td>[29]</td>
</tr>
<tr>
<td>ITO</td>
<td>1.2</td>
<td>-</td>
<td>88</td>
<td>-</td>
<td>$10^5$</td>
<td>[42]</td>
</tr>
<tr>
<td>IGZO</td>
<td>3.5</td>
<td>-</td>
<td>520</td>
<td>14.2</td>
<td>$5.6 \times 10^7$</td>
<td>[43]</td>
</tr>
<tr>
<td>IWO</td>
<td>0.01</td>
<td>0.8</td>
<td>85.75</td>
<td>15.87</td>
<td>$1.91 \times 10^5$</td>
<td>This work</td>
</tr>
</tbody>
</table>

Figure 3a presents a comparison of the $V_H$ and $\mu_{FE}$. $V_H$ was widely distributed across 0.01–4 V. This indicated that the proposed device exhibited relatively high stability at the interface between the PZT thin film and the channel as well as in terms of the operating characteristics of the channel. In terms of $\mu_{FE}$, the excellent conductivity of IWO resulted in the devices exhibiting a mobility that was 5.86 cm$^2$V$^{-1}$s$^{-1}$ higher than similar devices with comparable hysteresis window values. Figure 3b presents a comparison of the SS and $I_{on/off}$ ratio. Notably, among devices with excellent SS values ranging between 85 and 90 (mV/dec), the fabricated device demonstrated the best performance characteristics.

3.2. DC Bias Test for the Application of PZT-FeFET as Transducer

Variation in the pH value and DC bias voltage can change the potential difference applied to the gate of the transducer. This indicates the existence of a fundamental mechanism that affects the \( V_{th} \) of the transfer curve [44–47]. Therefore, prior to integrating the PZT-FeFET into the SG-based EG-ISFET sensor platform, measurements were conducted to assess the performance of the transducer through a DC bias test. Figure 4a illustrates a schematic of the DC bias test. An Agilent 4156B was used to apply the voltage, and the effective voltage applied to the gate was adjusted by varying the magnitude of the DC bias in the power supply. Specifically, to evaluate the comprehensive performance of the device’s operating voltage range, we applied a wide range of gate voltages from \(-3 \) V to \(6 \) V, which exceeded the gate voltage sweeping range shown in Figure 2a. Figure 4b presents the characteristics of 15 steps of the transfer curve measured by varying the DC bias voltage from \(0.7 \) V to \(-0.7 \) V in \(0.1 \) V increments during the voltage sweep. Figure 4d–f present enlarged data of transfer curves at various \( I_{REF} \) levels (0.1, 1, and 10 nA). To verify the accuracy and consistency of the \( I_{REF} \) in three cases owing to changes in the DC bias voltage, the change in the reference voltage was measured based on the voltage at a DC bias voltage of \(0.7 \) V. Considering the fitted data presented in Figure 4c, the slopes for \( I_{REF} \) of 0.1, 1, and 10 nA were 0.92, 0.89, and 0.91, respectively, with good linearity of 99.91%, 99.87%, and 99.75%, respectively. Considering the potential interference from the power supply and external resistance elements between measurements, the results of the DC bias test demonstrated sufficient reliability when compared to the ideal slope value of 1. Thus, the DC bias test confirmed the capability of measuring subtle sensitivity changes owing to potential differences in the manufactured device.

![Figure 4](image_url)

**Figure 4.** (a) Schematic illustrating the DC bias test using PZT-FeFET. (b) Transfer curve spanning the gate voltage range from \(-3 \) V to \(6 \) V (with DC bias varying from \(0.7 \) V to \(-0.7 \) V in \(0.1 \) V steps across 15 increments). (c) Variation in reference voltage according to DC bias at \( I_{REF} \) levels (0.1, 1, and 10 nA). Enlarged transfer curves corresponding to the \( I_{REF} \) levels: (d) \( I_{REF} = 0.1 \) nA, (e) \( I_{REF} = 1 \) nA, and (f) \( I_{REF} = 10 \) nA.

3.3. SG-Based EG-ISFET for pH Sensing

The validation of the suitability of using PZT-FeFET as a transducer underwent several stages, culminating in the sensitivity measurements based on ion concentration variations...
using an actual sensor platform. Figure 5a shows the proposed sensor platform, which was implemented in an EG-ISFET type structure featuring separate transducer and sensing units. Figure 5b shows the characteristics of the transfer curve of the transducer as the pH value varied from 3 to 10. These characteristics, indicating off and currents below 10 pA and above 10 µA, respectively, within the gate voltage sweep range (−1 V to 3 V), demonstrated sufficient reliability compared to both the operational characteristics of the FeFET and those obtained from the DC bias test. Consequently, the reference voltage shift (ΔVREF) value was fitted based on variations in the pH values, as shown in the enlarged data presented in Figure 5b, as depicted in Figure 5c. The results yielded an R² value of 99.79 and a sensitivity of 57.2 mV/pH at an IREF of 1 nA. Compared to the well-known Nernst limit of 59.14 mV/pH, a slight sensitivity difference of 1.94 mV/pH was observed, affirming the excellent sensitivity characteristics of the proposed sensor platform despite its separation into a transducer and sensing unit.

**Figure 5.** (a) Schematic of a PZT single-gate FeFET transducer with SnO2 EG sensing units. (b) VG-ID curves of the EG-ISFET for different pH buffer solutions. The inset in (b) highlights data pertaining to the IREF region. (c) Reference voltage shift (ΔVREF) as a function of pH value.

### 3.4. Sensitivity Amplification by Self-Resistive Coupling

This study implemented an innovative sensor platform that mimicked the functionality of a co-planar gate-TFT type transducer using a self-resistive coupling approach. Figure 6a presents the equivalent circuit illustrating the resistive coupling phenomenon. Through precise adjustments to the ratio of RCG to RSG using resistors, we evaluated the amplification ratios for three scenarios: 1:1, 3:1, and 5:1. Initially, RCG and RSG were connected in series, and the total resistance (RCG + RSG) is denoted as RT in Equation (1). The operational voltage VCG of the transducer and the surface potential change VSG induced by the sensing unit were capacitively coupled to the VFG of the transducer gate for operation. Consequently, VFG can be expressed as shown in Equation (2), and VCG as shown in Equation (3). This indicated that the potential change (ΔVSG) was amplified by the ratio of RCG/RSG, which changed the CG voltage (ΔVCG), as indicated in Equation (4). Thus, minor potential changes at the sensing gate (SG) can be enhanced through the resistive coupling effect and detected at the control gate (CG). Figure 6b summarizes the ΔVREF across the transfer curve depicted in Figure 6c-e concerning pH values. It was confirmed that ΔVREF was amplified with sensitivities of 58.7, 130.9, and 287.2 mV/pH, corresponding to changes in the RCG:RSG ratio, respectively. Consequently, the sensitivity increased by 2.23, 2.19 times, and up to 4.89 times, respectively, depending on the resistive ratio, thereby demonstrating maximum amplification. Moreover, the linearity of ΔVREF for each resistive coupling ratio exhibited reliability values of 99.18%, 99.74%, and 99.72%. Compared to the sensitivity of 57.2 mV/pH for the single-gate EG-ISFET shown in Figure 5c, the value of 58.7 mV/pH for the 1:1 ratio confirmed the positive potential of the proposed resistive coupling platform.

\[ RT = R_{CG} + R_{SG} \]  
\[ V_{FG} = \frac{R_{SG}}{R_T} V_{CG} + \frac{R_{CG}}{R_T} V_{SG} \]
Figure 6. (a) Schematic of the equivalent circuit demonstrating the resistive coupling effect. (b) Amplification of pH sensitivity corresponding to various \( R_{CG}:R_{SG} \) ratios. \( V_{G-I} \) curves illustrating the resistive coupling effect for different pH buffer solutions: (c) 1:1, (d) 3:1, and (e) 5:1.

3.5. Non-Ideal Effects of the Proposed Sensor Platform

The integration of the extended-gate (EG) concept into the sensing platform highlights the necessity of verifying the stability and reliability of chemical or physical reactions on the sensing membrane. This verification was achieved through the evaluation of hysteresis and drift effects [48–50]. Hysteresis measurements were conducted 35 times at 2-min intervals along a designated pH loop: 7, 10, 7, 4, and 7, with the hysteresis voltage defined as the difference between the reference voltages at the first and last pH 7 buffer solution. Further, drift measurements were performed during a 10-h exposure to a pH 7 buffer solution. The measured drift rate (RD) was the variation in the reference voltage per hour caused by ions penetrating the sensing membrane over a sufficient period, based on mechanisms such as hopping or trap-limited transport [51]. Initially, the hysteresis and drift effects of the traditional SG-based EG-ISFET (SG mode) and the proposed resistive coupling EG-ISFET (RC mode) were compared directly. As shown in Figure 7a, the \( V_{IH} \) for the two types of platforms was recorded at 5.8 and 6.1 mV, respectively. The difference of 0.3 mV was considered within an acceptable range for sensor platform application. Figure 7c shows the values of drift voltage variation, with the RD in SG and RC modes exhibiting similar characteristics of 4.24 and 4.48 mV/h, respectively. Subsequently, the hysteresis and drift effects for the RC mode with \( R_{CG}:R_{SG} \) ratios of 1:1, 3:1, and 5:1 were compared. As depicted in Figure 7b, the hysteresis voltages were 6.1, 10.1, and 15.8 mV for 1:1, 3:1, and 5:1, respectively, indicating that the values increased according to the resistive ratio. Consequently, as shown in Figure 7d, the drift rates were 4.48, 6.82, 9.19 mV for 1:1, 3:1, and 5:1, respectively, similarly illustrating that the values varied as per the resistive ratio.
Table 2. pH sensing characteristics of SG mode and resistivity coupling mode.

<table>
<thead>
<tr>
<th>Amplification Ratio (R_{CG}/R_{SG})</th>
<th>Hysteresis Voltage (mV)</th>
<th>Drift Rate (mV/h)</th>
<th>Sensitivity (mV/pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>×1 (SG mode)</td>
<td>5.8</td>
<td>4.24</td>
<td>57.2</td>
</tr>
<tr>
<td>×1 (RC mode)</td>
<td>6.1</td>
<td>4.48</td>
<td>58.7</td>
</tr>
<tr>
<td>×3 (RC mode)</td>
<td>10.1</td>
<td>6.82</td>
<td>130.9</td>
</tr>
<tr>
<td>×5 (RC mode)</td>
<td>15.8</td>
<td>9.18</td>
<td>287.2</td>
</tr>
</tbody>
</table>

4. Conclusions

This study aimed to realize comprehensive advancements in two key aspects: the fabrication of transducers with excellent electrical properties and the establishment of an innovative sensor platform. Initially, we proposed a pioneering methodology to develop FeFETs via the integration of PZT ferroelectric films with IWO channels. Leveraging cost-effective sol-gel processing, we substantially augmented the electrical characteristics of PZT-IWO FeFET devices. Key performance parameters such as the on/off ratio (85.75) and subthreshold swing (1.91 × 10^8) of the transfer curve were notably enhanced. Moreover, our successful annealing process effectively mitigated the hysteresis effects during double sweeps, thereby ensuring incomparable electrical stability. To apply the proposed FeFET to a sensor platform, we conducted DC bias tests to ascertain reliability, consequently achieving an exemplary sensitivity of 57.2 mV/pH in the EG-ISFET structure. This indicated an improvement over conventional ISFET methodologies. Moreover, by harnessing
a single gate EG-ISFET, introducing an innovative sensor architecture based on resistive coupling for pH detection, and fine-tuning the resistive ratio between the $R_{CG}$ and the $R_{SG}$, a remarkable sensitivity enhancement of 287.2 mV/pH was achieved. Consequently, this study demonstrates significant advancements in FeFET technology and offers promising applications across different domains. By integrating FeFET technology into a self-resistive coupling sensing platform, precise pH measurements can be enabled. Overcoming selectivity potential issues, such as the cross-sensitivity of the SnO$_2$ sensing membrane to other ions, would provide solutions to various challenges in healthcare and environmental monitoring. Additionally, for the successful commercialization and practical implementation of this integrated approach, future research focusing on structural improvements such as miniaturization and packaging is necessary. In conclusion, the results of this study, based on the FeFET technology in the enhanced platform, have the potential to establish it as a crucial component in advanced ion detection systems.

**Author Contributions:** D.-G.M.: conceptualization, formal analysis, methodology, investigation, data curation, visualization, resources, and writing—original draft. S.-M.O.: investigation, resources. J.J.: investigation, resources, writing—review and editing. W.-J.C.: conceptualization, methodology, investigation, resources, formal analysis, funding acquisition, supervision, validation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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