Electrical Characterization and Study of Current Drift Phenomena and Hysteresis Mechanism in Junctionless Ion-Sensitive Field-Effect Transistor

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Abstract

A comprehensive study of the drain current drift mechanism and hysteresis phenomena in fabricated p-channel junctionless ion-sensitive field-effect transistor (JL-ISFET) has been investigated for the first time. The current drift measurements have been performed through transient analysis of drain current, under different pH and liquid-gate bias (Vlg). Further, time-dependent gate-capacitance (CG) has also been analyzed to see the effect of hydroxyl ions (OH−) in the sensing film (Al2O3). The hysteresis has also been investigated for different pH loop (7 → 3 → 7 → 11 → 7 and 7 → 11 → 7 → 3 → 7) and times (960s, 1500s, and 1920s). It has been observed that the drift of JL-ISFET occurs because of chemical modification of the sensing film, due to OH−. The proposed device exhibits a threshold voltage sensitivity of 58.2 mV/pH that is near the Nernstian limit. Further, the hysteresis width and maximum drain current drift are measured as ∼ 1.3 mV and 2.4 μA (∼ 75%), respectively.

Keywords Drift · Hysteresis · ISFET · Junctionless

1 Introduction

Continuous growth in nano-fabrication technology results in extensive research on biosensors, capable of detecting tiny biological species such as protein, virus, DNA, enzyme, and antibodies [1–5]. In recent studies, pH-sensors have been used in different fields, such as environmental condition monitoring, chemical and biological process monitoring, and food manufacturing and processing [6]. Particularly, field-effect transistor (FETs)-based ion-sensitive field-effect transistor (ISFET) have gained interest as a promising candidate to be used as a point-of-care device for sensing applications due to their advantages, including existing CMOS process compatibility, miniaturized sensor size, low power consumption, portability, real-time, and label-free detection [7–10]. Despite their advantages, the ISFETs conventionally need ultra-shallow differentially doped junctions between source-channel-drain regions, which is very difficult and expensive at smaller nodes.

A non-classical junctionless field-effect transistor (JL-FET) approach have been introduced to overcome the aforementioned issues in conventional ISFETs [11, 12]. JL-FETs have a uniformly doped channel, and their fabrication is easy as compared to conventional MOSFETs, [13, 14]. Further, Junctionless transistors are governed through bulk conduction instead of surface conduction [15]. In our previous work, we demonstrated the effect of channel width on threshold voltage and drain current sensitivity of p-channel junctionless ISFET (JL-ISFET), with threshold voltage sensitivity near to theoretical Nernstian limit [16].

When all the intrinsic analysis of the ISFETs has been performed, there is still a gradual and monotonic variation in the output voltage with the time [17]. This effect is known as drift. The drift effect always remains in the whole process of characterization [18]. The drift effect does not depend on the sensing film/interface; it depends on the electrodes, circuits used, and the device itself. Further, the memory effect also known as hysteresis phenomena occurs due to the slow response of the ISFETs [19]. The hysteresis occurs when
the output voltage is different each time when the ISFET is tested many times at the same pH solution. This difference in the output voltage is known as hysteresis width. Hence, the non-ideal effects such as drift and hysteresis, have to be studied and measured for the extension of the applications of the ISFETs.

Despite the better sensitivity of the p-channel JL-ISFET, the accuracy of the measured results in a biosensor, gets affected by the hysteresis and current drift. In this regard, the drain current drift and hysteresis of p-channel JL-ISFET have been investigated for the first time in this paper. The origin of the current drift mechanism has been investigated by measuring drain current \( I_d \) and gate capacitance \( C_G \) as a function of time for different pH (5, 7, 9) and liquid \(-\) gate bias \( V_{lg} = -1V, -2V, -3 V \). Further, hysteresis in p-channel JL-ISFET has also been investigated for different loop path \( 7 \rightarrow 3 \rightarrow 7 \rightarrow 11 \rightarrow 7 \) and \( 7 \rightarrow 11 \rightarrow 7 \rightarrow 3 \rightarrow 7 \) and loop times (960s, 1500s, and 1920s), to study the impact of hydroxyl ions \( (OH^-) \) on the sensing film. Finally, a comparison of the hysteresis width has also been performed for devices with different sensing films. Section II presents the fabrication method and measurement setup of the p-channel JL-ISFET. Section III presents the electrical characterization, drift, and hysteresis analysis of p-channel JL-ISFET in subsections A, B, and C, respectively.

## 2 Device Fabrication

The physical dimensions of the fabricated p-channel JL-ISFET for different layers deposited can be seen in Table 1.

### 2.1 Fabrication

Fabrication process steps have been discussed in detail in [16]. A batch of the boron-doped wafer was oxidized for 1 hour, at 1000 °C in the furnace to grow 50 nm \( SiO_2 \). Further, 60 nm of \( Si_3N_4 \) was deposited by LPCVD (diffusion bay) at 800 °C. 50 nm of polycrystalline silicon was deposited through CVD. The samples were put to annealing chamber for dopant activation followed by boron doping in the diffusion bay. The wafers were subjected to the first optical lithography for patterning of the polySi wire. Polysilicon wires were obtained through dry etching (Oxford plasma lab RIE-100). The buried insulator layers between polysilicon wire and substrate were inserted for back-gating [20]. A very thin (5 nm) layer of \( Al_2O_3 \) was deposited through the atomic layer deposition method. Second level Photolithography followed by wet etching (BOE) of sensing film was done to pattern the \( Al_2O_3 \) film aligned on polySi wire. For contact pads, 150 nm of Cr/Au was deposited through sputtering. Further, the third level lithography was performed through lift-off to obtain the source and drain contact pads. The samples were later kept in the furnace at 350 °C for obtaining the better metal- polySi contact. The 150 nm of the passivation layer \( (SiO_2) \) was deposited and patterned through PECVD and lithography (followed by BOE), respectively, to protect the source and drain from the solution under test. For back-gating, 150 nm Cr/Au was deposited on the backside of the wafer. Furthermore, a thin \( Al_2O_3 \) film was deposited on the top-side of the wafer through atomic layer deposition to prevent any contact of the solution with contact pads, for long time measurements, and to increase the shelf life of the device. Further, an open window in the gate region was formed with resin epoxy for the confinement of the test solution [21].

### 2.2 Device Structural Characterization

The Polysilicon and sensing oxide film \( (Al_2O_3) \) thickness were measured through ellipsometry and found to be 52.9 nm and 4.95 nm, respectively. The sheet resistance polysilicon film was done by the four-point probe method on three points of the wafer and found to be 121.67, 120.46, and 120.24 \( \Omega/\square \) is shown in Fig. 1a, confirms the uniform doping of the device layer. The top-view scan electron image of the sensor fabricated through a CMOS-compatible process for experimental analysis is shown in Fig. 1b, shows the minimum channel width obtained was 2 microns. The fabricated wafer was later kept in UV-O_3 ambience for making the surface hydrophobic for the confinement of the test solution.

### 2.3 Measurement Setup of pH Sensor

The electrical measurements have been performed on the wafer level through a semiconductor parameter analyzer (Agilent B1500A). The micro-manipulators with needles were placed above sensing film over the channel region and a window was then etched to provide access to the contacts. The test pH solutions were drop-casted through a micro-pipette. The micro-pipette was attached with another manipulator’s arm and placed over the sensing area. The micro-pipette was connected with the syringe through the
silicone tubing. The syringe enables control over the flow of the test solution. All the measurements have been performed on devices with a channel width of 15 μm, as a maximum sensitivity (threshold voltage and drain current) on it have been reported in our previous work [16]. All the measurements have been performed in a dark environment to avoid the effect of light. The pH test solutions were prepared and calibrated through MK 6 digital pH meter.

3 Results and Discussion

3.1 Electrical Characteristics of Junctionless ISFET

To evaluate the sensing performance of p-channel JL-ISFET, the pH sensitivity measurement has been done through the shift in the threshold voltage of the device under different pH (3 to 11). The transfer characteristics have been obtained by sweeping the $V_{lg}$ from 0 to -3 V and a low drain voltage ($V_{ds}$) of -1 V has been applied for the suppression of possible secondary effects [20]. It has been observed from Fig. 2b that a decrease in hydrogen ion concentration at the interface results in a decrease in the threshold voltage (absolute value). Further, the JL-ISFET device exhibits a threshold voltage ($V_{th}$) sensitivity of $\sim 58.2$ mV/pH. It is very important to note that the drain current ($I_D$) of ISFETs varies to some extent even in the same pH solution. So in case of measurement of drain current ($I_D$) shift only due to pH shift, it is very important to stabilize the device in the buffer solution before any measurement.

3.2 Drift Analysis of Junctionless ISFET

To understand the drift phenomena in p-channel JL-ISFET, the transfer characteristics have been analyzed before and after the transient analysis under fix condition (pH = 9, $V_{lg}$ = -2V, and $V_{ds}$ = -1V) as shown in Fig. 3a. An evident drain current shift of 1.32 μA ($\sim 63\%$) has been measured from the difference in the maximum drain current before and after transient analysis. The hydroxyl ions ($OH^-$) contribute a
major role and should be concerned for drain current drift in the p-channel JL-ISFET. However, the drift phenomena can not be described by the ionic diffusion because of the very low mobility of hydroxyl ions through the sensing oxide film [22]. The drift in p-channel JL-ISFET can be explained through the modification (hydration) of the sensing film surface due to its reaction with hydroxyl ions.

It has also been explained in previous studies [23], [24] that the sensing film surface reaction with hydroxyl ions results in its permanent dipole moment reduction that further reduces its capacitance ($C_{ox}$). This effect can be represented as a series combination of the capacitance of the oxide subjected to hydration ($C_{ox,hyd}$) and the intrinsic (non-hydrated) oxide capacitance ($C_{ox,int}$), that can be seen in Fig. 3b.

For further detailed investigation of the current drift phenomena in p-channel JL-ISFET, the transient drain current measurements have been performed for different pH and $V_{lg}$ as shown in Figs. 3 and 4 respectively. It has been observed from figures that under fixed bias conditions ($V_{lg} = -2$, $V_{ds} = -1$V, and pH = 5, 7, 9) and ($pH = 9$, $V_{ds} = -1$V, and $V_{lg} = -2$ to -1V), the drain current of the device decreases throughout the transient analysis as shown in Figs. 4a, b and c and 5a, b and c respectively. It has also been observed that there is an increase in the current drift with an increase in pH and supplied $V_{lg}$. Therefore, distinct devices with same dimensions have been used for characterization at each pH and $V_{lg}$ due to the continuous degradation of drain current.

Further, for comparing the effect of pH and $V_{lg}$ on the current drift, the drain current has been normalized ($I_D/I_{D,initial}$) during the measurement time as shown in Fig. 6a and b, respectively. A drain current drift of 75.2%, 73.8%, and 63.8% has been measured for pH 9, 7, and 5 respectively, as shown in Fig. 7b. In addition, a current drift of 79.3%, 66.2%, and 41.9% have been measured for $V_{lg}$ -2 V, -1.5 V, and -1 V, respectively, as shown in Fig. 7a. From the measured current drifts, it has been observed that the drift increases with pH as the hydroxyl ions increases towards the base-side pH cycle [25].

The capacitive behavior of the p-channel JL-ISFET has also been analyzed for further analysis of current degradation. The gate capacitance ($C_G - V_{lg}$, $C_G - t$) characteristics of the device have been demonstrated in
Fig. 5 Transient characteristics of p-type JL-ISFET for a $V_{lg} = -1$ V, b $V_{lg} = -1.5$ V, and c $V_{lg} = -2$ V.

Fig. 6 Transient characteristics of JL-ISFET for different a pH, and b Liquid-gate bias.

Fig. 7 Percentage drift of junctionless ISFET for different a pH buffer, and b Liquid-gate voltages.

Fig. 8 (a) $C_G-V_{lg}$ characteristics, (b) transient $C_G$ characteristics, and (c) the transient $I_D$ characteristics of p-channel JL-ISFET with identical dimensions and bias conditions.
Fig. 8a and b, respectively. Figure 8c shows the time-dependent drain current (with similar conditions as in Fig. 8b) for a longer evaluation period of 1200 seconds. It is observed from Fig. 8b that an increase in capacitance in region 2, followed by a decrease in region 1. The capacitance change in region 1 is related to the decrease in dielectric permittivity of the sensing film due to its chemical modification (hydration), and continuous capacitance increase in region 2 may be due to etching of the sensing film by hydroxyl ions, which results in a continuous decay in the drain current.

The drain current decay phenomena has been further analyzed by measuring the gate leakage current \( I_{G} \) with respect to the \( V_{lg} \) before and after the transient measurement. A noticeable increase in gate leakage after the transient analysis can be seen from Fig. 9a. The decrease of drain current \( I_D \) despite an increase in gate capacitance (Fig. 8b and c) may be due to an increase in gate leakage current. A decrease in oxide film thickness \( t_{ox} \) due to its etching by exposing it with hydroxyl ions for long time, may also be the cause of an increase in gate leakage current. The etching phenomena is similar to \((NH_4OH/H_2O_2/H_2O)\) mixture (SC 1) cleaning method (Fig. 9b). It is also worth mentioning that, the drain current decay is indefinite for p-channel JL-ISFET.

3.3 Hysteresis Effect Analysis

The hysteresis width of the p-channel JL-ISFET is measured between the first output voltage and final output voltage for the same pH value. The hysteresis behavior was observed for different pH buffer solutions with the pH loop cycle of \( 7 \rightarrow 3 \rightarrow 7 \rightarrow 11 \rightarrow 7 \) (acid-side) and \( 7 \rightarrow 11 \rightarrow 7 \rightarrow 3 \rightarrow 7 \) (base-side) for 960 seconds. The measured hysteresis widths were 1.3, and 5.7 mV for acid-side and base-side, respectively. The difference in hysteresis width with pH loop cycles is due to the different sizes of \( H^+ \) and \( OH^- \) ions, the diffusion of \( H^+ \) ions to the buried site is faster than the diffusion of \( OH^- \) ions [26].

Further, the hysteresis width for different loop time (960 s, 1500 s, and 1920 s) has also been investigated. The hysteresis width for the pH loop path of \( 7 \rightarrow 3 \rightarrow 7 \rightarrow 11 \rightarrow 7 \) were measured and found to be 1.3, 3.4, and 6.7 mV for 960, 1500, and 1920 second, respectively as shown in Fig. 10b. It can be inferred from the hysteresis results that the hysteresis width increases with loop time as more hydration and etching of the sensing film occur for more loop time. Table 2 represents the hysteresis widths of p-channel JL-ISFET comparison with the state of art devices with different sensing films. The data from the table demonstrates that the p-channel JL-ISFET shows
hysteresis behavior than previously reported devices. Furthermore, the p-channel JL-ISFET has lower hysteresis width than the conventional $Al_2O_3$ gate ISFET [26], which may be due to the better quality (less porosity) of the ALD deposited $Al_2O_3$ in p-channel JL-ISFET.

### 4 Conclusion

The drain current drift phenomena and hysteresis mechanism of p-channel JL-ISFET have been experimentally investigated for the first time. It has been observed that sensing film hydration and thickness reduction through hydroxyl ions are the dominating factors for drift and hysteresis. Further, it has also been observed that the current drift increases with pH and liquid-gate voltage ($V_{lg}$) as the hydroxyl ions activity increases towards the base-side. A maximum drain current drift of 75.2% and 79.3% have been measured for pH = 9 and $V_{lg} = -2$ V, respectively. Furthermore, the hysteresis behavior analysis of p-channel JL-ISFET has also been performed for different pH loop paths and loop times. It has been observed from the hysteresis characteristics that hysteresis width increases with the pH loop-time and pH loop-cycle towards the base-side.

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### Author Contributions

Jaydeep Singh Parmar, Nawaz Shafi, and Chitrakant Sahu conceived this research and designed experiments. Jaydeep Singh Parmar wrote the paper and participated in the design and interpretation of the data. Jaydeep Singh Parmar, Nawaz Shafi, and Chitrakant Sahu participated in the revisions of it.

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### Availability of data and Materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

### Declarations

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

**Conflict of Interests** The authors declare that they have no conflict of interest.

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**Table 2** Comparison of the hysteresis of the proposed device and state-of-the-art devices

| Sensing film | Hysteresis (mV) | Loop time (s) |
|--------------|----------------|--------------|
| $W O_3$ [21] | 15.7           | 1500         |
| $Al_2O_3$ [26] | 4              | 960         |
| $Si_3N_4$ [27] | 2              | 960         |
| $Tm_2Ti_2O_7$ [28] | 4.3          | 1500         |
| $Al_2O_3$ (This device) | 1.3, 3.4     | 960, 1500   |

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**Declarations**

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

**Conflict of Interests** The authors declare that they have no conflict of interest.
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