Combined pH-Image Sensor based on Pass-Transistor Operation of ISFET

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Summary: Combined ISFET-APS sensor – a novel technique for simultaneous pH and image monitoring in CMOS ISFET-based Microsystems is presented. The operational concept is based on modulation of VT drop by pH fluctuations in Pass Transistor ISFET. The operational concept is followed by SPICE simulation results and by applicability discussion. The ability of the combined simultaneous monitoring of images and pH levels expands the variety of clinical applications in which the pH biotelemetry can contribute, and allows implementation of array-type multiple-mode sensing for biomedical applications.

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1 Introduction

The ability of combined ion and image sensing is an important challenge in the development of advanced biotelemetry systems. The design of image sensors in standard CMOS technology is been under extensive research during last decade, basing on Active Pixel Sensor (APS) as the common structure of the CMOS image sensor. In this study a novel concept of integration of the ISFET sensor in the structure of the APS is developed and analyzed. The novel sensor allows a simultaneous chemical and image monitoring by applying the ISFET in Pass Transistor configuration and using the threshold drops in the original APS structure.

First, the APS review is presented followed by the structure of the combined ISFET-APS sensor. The operational concept and simulation results are demonstrated. Finally, the applicability analysis of future biotelemetry microsystems is presented.

2 Combined ISFET-APS

The structure of the APS [1] is shown in Fig. 1, a. The operation is based on the charge integration mode of a photodiode. Before the integration cycle, the diode is been reset to a high voltage by the reset switch M1. The diode and its correlating node are represented by: (a) the sensing capacitance, (b) the current source that is function of photon flux during the illumination and the diode area. After the reset phase stops, the photodiode is discharged according to:

\[ C \cdot \frac{dV(t)}{dt} = -I_{\text{photo}} \]

The source follower M2 acts as a voltage buffer that drives the output. Thus, the intensity of the illumination is translated to a linear slope of the output voltage, while higher illumination causes lower final value of the output voltage after the integration.

The transistors in APS can be NMOS (more space efficient, without need in a separate well), or PMOS (less area efficient, but without body effect). Resetting to high \( V_{dd} \) voltage by NMOS transistor, as it mostly done in APS, results in losing the range of reset voltage on the photodiode to a value of \( V_{dd} - V_{T_{M1}} \), where \( V_{T_{M1}} \) is the threshold voltage of the reset transistor operating as Pass Gate. An additional \( V_{T_{M2}} \) drop occurs in the output of the sensor because of the source follower.

The operational concept of a combined ISFET-APS sensor is demonstrated in Fig. 1, b. The ISFET is integrated to APS structure and connected to the source follower. The operational concept is followed by simulation results and by applicability discussion. The ability of the combined simultaneous monitoring of images and pH levels expands the variety of clinical applications in which the pH biotelemetry can contribute, and allows implementation of array-type multiple-mode sensing for biomedical applications.

Fig. 1. Structure of APS sensor: (a) actual, (b) equivalent circuit.
The threshold drop is considered as an undesired limitation on the dynamic range of the image sensor. However, while being a drawback in standard digital or mixed-signal design, this drop is an important benefit in ISFET-based sensors. [2].

In order to take a full advantage of this effect, the reset MOSFET transistor in the APS structure has to be replaced by ISFET sensor, which will operate in a similar way as reset switch for image sensor, while producing additional data on pH level via the threshold voltage drop.

The structure of the combined ISFET-APS sensor is shown in Fig. 2. The reset transistor M2 is replaced by ISFET sensor. The gate signal of the switch is applied to the reference electrode. The electrode is common for all the ISFETs in the sensors array. This triggers the requirement for additional change in APS operation: the single reference electrode has to be constantly biased, thus the pulsation of reset signal has to be applied to the drain of the reset ISFET, while the gate is constantly kept high (for n-type sensor).

The ISFET sensor is operating as reset transistor, producing a $V_T$ drop in the initial voltage of the diode before the integration. Thus, a modulation of a signal is obtained, while the pH fluctuations influence the upper peak values of the signal in the Reset phase. After the reset, the Integration phase begins, in which the capacitor is been dis charged from the initial value, which was determined by pH value during the Reset phase, to a lower value which is determined by the intensity of the illumination. The operation in the Integration phase is identical to a regular operation of APS in image sensor. Every cycle can be referred as a simultaneous sampling of the values of pH and illumination in a certain location and time.

The APS circuit was implemented in 0.5µm CMOS technology with $3V_{PP}$ voltage supply. SPICE simulations were performed during the verification of the combined sensor. Fig. 3 presents the transient simulations of regular APS sensor operating in constant illumination. The slope and the absolute value of the discharge of capacitor are equal in every cycle. The signal is reduced by a certain gain as it passes through the source follower. The responses of both pH and image signals are preserved in the output of the APS.

The combined ISFET-APS sensor was simulated with AC waveforms imitating the pH-caused fluctuations in $V_T$ of the ISFET. Square wave was applied to the drain to provide the Reset and Integration phases. As a result of pH fluctuations, the upper bound of the output signal is modulated, due to varying $V_T$ drop, and gets the shape and values similar to the changes in $V_T$ of the ISFET. The simulation in Fig. 4 shows the detailed response of the combined sensor to various fluctuations in pH, while the illumination is constant. The responses of the combined sensors are to $1V_{PP}$ signals in 100 Hz frequency, while the sampling is performed at 1 kHz.

It can be seen, that due to the constant illumination, the slope and the absolute value of the discharge of capacitor are equal in every cycle. The signal is reduced by a certain gain as it passes through the source follower. The responses of both pH and image signals are preserved in the output of the APS.

Fig. 2. Structure of the combined ISFET-APS sensor

Fig. 3. Transient simulations of image APS sensor

Fig. 4. Response to pH fluctuations of the ISFET-APS sensor with constant illumination: (a) sinusoidal, (b) square.
3 Applicability

The ability of the combined simultaneous monitoring of images and pH levels expands the variety of clinical applications in which the pH biotelemetry can efficiently contribute [3]. Some of the examples of the applications are presented in this Section.

Neurosurgery - The measurement of pH levels correlated with image monitoring of the brain surface, allows an efficient locating and identification of trauma injuries in neurosurgery. It can be applied to various cases of clinical treatment: rapid diagnostics in emergency room, patient conditions control during the operation, continuous monitoring during the therapy and hospital admission, etc.

Gastro-Intestinal Tract Monitoring - Image sensors are used for identification of the injured areas, like blood spots, to be treated. It also useful for positioning purposes: images obtained by CMOS sensor can efficiently replace the X-ray monitoring, which is used in traditional gastroscopy, while minimizing the harmful and inconvenient conditions of the patient. The measurements of pH are of the great importance in gastro-intestinal tract monitoring. Thus the combination of both types of sensors in a single biotelemetry pill will allow an efficient and convenient monitoring.

Cells Identification - Cell recording and identification is an important research issue in bio-chemistry, neurophysiology and other biomedical fields. One example for efficient application of ISFET-APS sensor is Neuronal Recording System [4]. The monitoring of the neuronal interfaces is performed by metal recording sites on class substrate, or by ISFET sensors on silicon. In order to obtain a continuous supervision after the functionality, structure and interconnection of neural network, grown on a silicon chip or located in solution, the use of image sensors is also very efficient. Combining of the ISFET and APS sensors in arrays with 10-20µm grid will provide a platform for high-performance recording systems for neuronal monitoring.

Sperm Mobility Measurements - The combination of chemical and image sensing abilities allows deriving measurements of additional physiological parameters using data processing. One of the possible applications is the measurement of sperm mobility during fertility studies. The mobility of the sperm cells can be easily obtained by processing of the sequences of measured images. The correlation of images with pH monitoring will supply extensive information on the cells under test, while obtaining high resolution and reduced complexity of laboratory measuring system.

4 Fabrication Considerations

In order to estimate the feasibility of future implementation of the combined ISFET-APS sensor, the fabrication constraints have to be reviewed together with the resent tendencies of the technological processes.

An efficient application of combined ion-image sensor can be performed if sensors of at most 10×10µm size can be obtained. These dimensions were already achieved in CMOS imagers based on APS sensors, while in recent researches sensors with pixel size of less than 5×5µm were fabricated.

In case of the combined sensor, the ISFET embedded in the APS structure dictates individual requirements. Most of the ISFET sensors fabricated today, are relatively big, with sensing area of hundreds of square microns. These dimensions are derivative of the: (a) aspiration for good measurement statistics giving the ion interactions over limited area, (b) limitations of fabrication techniques of ISFETs in standard CMOS technology, which involves sophisticated post-processing, mostly followed by small-scale mask or manual layer application.

The demand for minimization of the ISFET sensor is obvious, and in order to be successfully integrated in APS pixel, the dimensions of the ISFET have to be of at most several square microns. This is well illustrated by Fig. 5, which presents the layout of the 10×10µm APS pixel in 0.35µm CMOS technology [5]. As can be seen the tendency of the APS design is to minimize the area of M1-M3 transistors, while increasing the illumination-sensitive area of photodiode. If the reset transistor will be replaced by ISFET, it will increase the area which is insensitive to light, and decrease the fill factor of the pixel. This compromise is essential and has to be taken into account during the design of the combined sensor.

Fig. 5. Layout of APS image sensor

It has to be noticed, that the combined sensor has two mutually-reducing dynamic ranges: (a) dynamic range of pH measurements, which is defined by the sensitivity of the ISFET and is up to 100mV (2 pH units) in clinical applications and up to 600mV (10 pH units) in general applications, (b) dynamic range
of the image sensor dependent in supply voltage and threshold drops of the transistors and is up to 2V in 0.35µm technology, reducing in each technology generation. This raises two possible constraints: (a) high dynamic range of the pH measurement reduces the dynamic range of the imager, (b) low dynamic range of the ISFET sensor reduces the immunity of the pH measurement to Fixed Pattern Noise (FPN). The FPN is a function of on-chip parameter fluctuations in the array devices. It can manifest itself in threshold voltage fluctuations of tens of mV in identical FETs, conductivity fluctuations, etc. In common image sensors, this problem is partially solved by applying Correlated Double Sampling (CDS) circuits in the readout of the sensor. This technique gets an increased importance in case of pH measurement with limited dynamic range.

An additional solution is performing the post-fabrication calibration of the sensors array, to derive the parameters of importance for each pixel, and perform adjustment of the measurements by data processing. Although it makes the production and maintenance more complex and expensive, the calibration is widely and successfully used in other sensory fields and can be effectively applied to ISFET-APS sensor.

5 Conclusions

A concept of novel chemical-image sensor was developed in this study. The combined sensor is based on integration of ISFET sensor as functional part of APS image sensor. The operational concept is based on modulation of VT drop by pH fluctuations in Pass Transistor ISFET. The design allows future implementation of array-type systems with multiple-mode sensing for various monitoring applications. The verification of the design was performed by Cadence simulations, showing an accurate response of the combined sensor to pH fluctuations.

The vision of applicability and fabrication considerations was presented, discussing various aspects of future implementations of the ISFET-APS sensor. Future progress in miniaturized ISFET fabrication in standard CMOS technologies is expected to allow integration of the ISFET in practical sensors for biomedical monitoring.

References