Photoelectric Characterization of Intended Source UTBB 1T FDSOI Based Image Sensor

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Research Article

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Abstract

This paper presents the photoelectrical performance evaluation of proposed intended source Ultra Thin Body Bias (UTBB) 1T-FDSOI based image sensor and also a comparative analysis has done with conventional 1T-UTBB based image sensor [1]. The photoelectrical conversion in proposed image sensor is achieved by utilizing back biasing in intended source UTBB FDSOI based MOSFET. In the proposed intended source Ultra Thin Body Bias (UTBB) 1T-FDSOI based image sensor, the photoelectrical conversion is done within the substrate region (well region) and that signal is read out by MOSFET placed on SOI substrate. The comparative analysis between proposed image sensor and conventional 1T-UTBB based image sensor has performed on the basis of various parameters such as back-bias voltage, thickness of buried oxide (BOX) layer and doping concentration. In this investigation the proposed image sensor has found better light sensitivity in contrast with conventional image sensor. The performance evaluation of proposed image sensor has done by TCAD simulations.

I. Introduction

The advent of silicon-on-insulator (SOI) technology become an important revolution in semiconductor industry due to its proper isolation created by buried oxide (BOX) layer. Moreover, some of its important property like better immunity reduced latch-up issues, lower parasitic capacitances, reduced short channel-effect, higher switching speed, least hot carrier effect provides a better opportunity as compared with conventional MOSFET for higher electrical performances [2]. With addition of BOX layer in SOI MOSFET parasitic capacitances and leakage current is drastically reduced and this property of SOI devices makes its useful in high frequency and low power consumption circuitry. Since Si Waveguide have excellent confinement of optical signal and also have a low loss of optical signal, so important features of SOI substrate make it possible to be used in electronics and photonics circuitry [3]. On the basis of better electrical performance of SOI MOSFET, it is also find application in image sensor. Today image sensor become an essential needs and find application in space and navigation, consumer electronics (smart phone, digital camera, optical mouse, and in medical equipment) and also in biological inspection [4]-[6]. The performance of traditional image sensor are categorize in two types, first is charge coupled device based image sensor (CCD image sensor), second is complementary metal-oxide-semiconductor image sensor (CIS) [7],[8]. The thick depletion region is used in charge coupled image sensor for collection of light signal and also utilizes these region for conversion of photon to electron and then these converted electron transferred to the output terminal. CCD sensors are more advantageous than CIS sensor in terms of certain parameter like high fill factor and high quantum efficiency. These advantages comes because of structural change in CCD like in CCD one pixel cell is comprises of single MOS capacitor with semi-transparent gate, however CIS utilizes one single photodiode and three different transistor, one transistor for resetting the image sensor, one transistor for driving the source follower and one additional transistor for addressing. Because of structural complexity of CIS sensor cell CIS sensor is inferior in high fill factor and high quantum efficiency. Moreover, performance of CIS sensor is much better than CCD sensor since it have reduced noise performance, low power consumption, high speed and

also its compatibility with peripheral logic circuit makes it low cost and adaptive for large scale production. There are various researcher proposed different traditional CIS sensor with three-dimensional integration technology so that problem of inferior fill factor and quantum efficiency of conventional CIS sensor has been overcome but this integrational technology has certain limitation like design and process complexity [9]. Another way to get rid of inferior fill factor and low quantum efficiency, a new active pixel image sensor using single transistor has been proposed where without transferring charge carrier to the output node, A MOSFET which is arranged on top silicon layer is used for sensing the photo generated-electron [10]. Moreover various structures has been also proposed and presented where single transistor is used to sense the photo-generated carrier, and magnifying within same transistor and then read directly [11]-12].

Today's, there is rapid progress in decreasing structure size in semiconductor technology. Therefore, miniaturized image sensor are more viable. Thus, in order to get a miniaturized image sensor, the pixel size of image sensor has been continuously scaled so that better performance of the image sensor is achieved[13]-[14]. With scaled pixel size of image sensor, it is easy to get high resolution of camera sensor and also the requirement of better image quality is achieved[15].

An ultra-thin body bias (UTBB) based SOI MOSFET has been continuously developing since its gate terminal has better ability to control the channel so it has least off-state current [16]. In order to achieve high performance in UTBB FDSOI MOSFET back biasing is used to change the threshold voltage of FDSOI MOSFET placed on top silicon layer above the buried oxide region[17],[18]. Again due to interface coupling effect, threshold voltage of the MOSFET is also affected by photo-generated electron gathering at BOX/Si substrate interface [19]. Various researcher demonstrate a new type of image sensor which is basically one transistor image sensor by integrating UTBB devices with photodiode, this photodiode built on SOI substrate is used to collect light flux and due to capacitive coupling effect photo-generated carrier causes threshold voltage shifting in both n-type and p-type field effect transistor [20].

In this paper we proposed and demonstrate an intended source UTBB 1T FDSOI based image sensor and comparative analysis has been done between conventional 1T-UTBB based image sensor and intended source UTBB 1T FDSOI based image sensor (proposed) to evaluate the photoelectric characteristics of both devices. Moreover after finding better sensitivity in intended source UTBB 1T FDSOI based image sensor (proposed) as compared to conventional 1T-UTBB based image sensor, its performances dependency on various parameter such as by varying dimension parameter and also by varying terminal voltages is again analyzed and simulated. In this proposed device when negative back voltage is applied on substrate terminal a depletion layer form below buried oxide (BOX) layer and upon illumination light photon is collected inside depletion region and these photon is converted in electron hole pair by electric field setup inside substrate region. These photo generated electrons are collected at BOX/Si substrate interface and because of interface coupling effect threshold voltage modulation will occur which will change the on-state current and threshold voltage of the n-MOSFET placed on the top Si layer. Now when voltage is applied on gate terminal of the n-MOSFET, drain current of n-MOSFET is read and hence, the evaluation of light intensity will be done. Thus an intended

source UTBB 1T FDSOI based image sensor (proposed) is able to sense light signal, amplify it properly and then read out the amplified signal. TCAD tool Sentaurus [21] is used to simulate and analyze the performance of our intended source UTBB 1T FDSOI based image sensor (proposed). 2D ray tracing method is opted for optical simulation. The analytic low field mobility model, parallel electric field dependency model, Lombardi CVT model, Shockley–Read–Hall (SRH) generation recombination model are used for electrical Simulation.

II. Proposed Device Structure And Characterization

The cross-sectional schematic for simulation and modeling of conventional 1T-UTBB based image sensor and proposed intended source UTBB 1T FDSOI based image sensor is illustrated in Fig. 1(a) and Fig. 1(b). The proposed device structure is constructed as a conventional 1T-UTBB FDSOI MOSFET which is placed on SOI substrate. The thickness of top silicon layer is 6nm and the thickness of buried oxide (BOX) layer is 10nm. The length of the source and drain region are taken as 200nm out of which 100 nm (L_{gap}) length is used for the light exposure on the device. Further, the length of the channel region is about 22nm so the total pixel size of the proposed image sensor is about 422nm and a p+ back bias contact is taken at bottom of the p⁻ substrate region for improving the photo electrical performance of the proposed device. The main structure parameter of both conventional and proposed image sensor is depicted in Table I. In the proposed device the p-type substrate region is lightly doped so that a thick depletion layer is formed below the BOX region.

Further, in order to secure low loss of light intensity, light photons are passes only through the large gap region and upon illumination through large gap region the photo-generated electron are collected below BOX/Si substrate interface. During light exposure on the device, drain terminal voltage (V_d) is set-up to 0.7V and back bias terminal voltage (V_b) is setup to -0.7V. On applying the negative biasing at lightly doped p-type substrate a thick depletion layer and an electric field formed below BOX/Si substrate interface and due to this the absorbed photons are converted into photo-generated carrier and under the influence of electric field the photo-generated electrons are move towards the interface of BOX/Si substrate. Further, the electrons are gathered under the BOX/Si substrate interface and due to this electrostatic potential under BOX/Si substrate interface becomes negative [1]. Moreover under light illumination condition the more negative charges are collected under BOX/Si substrate interface and because of electrostatic coupling [19] more positive charges are collected above the BOX/Si interface region. Further, these positive charges are nullified by

applying more positive gate voltage and due to this the threshold voltage is increases which increases the change in on-state ($|\Delta I_{on}| = |I_{on} - I_{dark}|$) current with increasing light intensity .

Figure 2. shows the change in electrostatic potential under BOX/Si substrate interface region of proposed image sensor. As can be inferred from Fig. 2, under dark condition, the electrostatic potential under BOX/Si substrate interface (just below channel region) is positive whereas after illuminating the light

potential is drop drastically under BOX/Si substrate interface

from 0.45V to -0.5V. Moreover, with increasing light intensity the collection of photo-electron under BOX/Si substrate interface is increases and due to this the electrostatic potential continuously reduces and become more and more negative.

Table I: Device specification of proposed intended source UTBB 1T FDSOI based image sensor and conventional 1T UTBB based sensor

Device Specification	Proposed intended source UTBB 1T FDSOI based image sensor	Conventional UTBB 1T image sensor
Channel length (nm)	30	30
Si thickness (nm)	6	6
BOX thickness (nm)	10	10
Well depth (nm)	30	500
Exposer region width(nm)	100	200
Channel doping (cm^{-3})	5e^{16}	5e^{16}
Drain and n^+ source doping (cm^{-3})	1e^{20}	1e^{20}
n^- source doping (cm^{-3})	1e^{17}	-
p^- substrate region (Well) doping (cm^{-3})	5e^{16}	5e^{16}
P^+ region doping (cm^{-3})	1e^{20}	-

Therefore, with large variation in electrostatic potential the threshold voltage of MOSFET built on the top silicon layer is enhanced.

The transfer characteristic of proposed intended source UTBB 1T FDSOI based image sensor is demonstrated in Fig. 3. This characteristic is obtained by taking device under dark and varying light intensity condition. The light intensity

are varied from $100\mu\text{W}/\text{cm}^2$ to $1\text{ W}/\text{cm}^2$. The wavelength of the light taken as 550 nm. As can be inferred from characteristic, the threshold voltage of proposed device increases after light illumination and this is continuously increases with increasing light intensity. However, after illumination the change in on-state current ($|\Delta I_{\text{on}}| = |I_{\text{on}} - I_{\text{dark}}|$) of the proposed device is increases with increasing light intensity [1]. The variation in on-state current and threshold voltage with respect to varying light intensity is illustrated in Fig. 4(a) and 4(b). It is clearly observed from both the plots, the proposed device has increasing $|\Delta I_{\text{on}}|$ and $|\Delta V_{\text{th}}|$ with increasing light intensity. The reason behind this result is, the electrostatic potential under

increases from 0.37 mA/μm to 0.49 mA/μm and $|\Delta V_{th}|$ increases from 78 mV to 94 mV with light intensity increasing from 100 μWatt/cm² to 1Watt/cm². However, the V_{th} value is extracted at constant I_d (drain current) of 10^{-8} A/μm. Therefore, it can be observed from the both plots, the change in $|\Delta I_{on}|$ and $|\Delta V_{th}|$ with varying light intensity demonstrate the light detection property of proposed image sensor [10]. Further, the variation in of proposed image sensor [10]. Further the variation in threshold voltage ($|\Delta V_{th}|$) with light intensity and back biasing is specified as light induced voltage shift (LIVS) which is defined by following equation [22].

$$LIVS = |\Delta V_{th}| = V_{t_light} - V_{t_dark} [22]$$

As can be inferred from Fig. 4(a), the light induced voltage shift is higher for higher light intensity .

After investigating the light detection property of proposed image sensor, we decided to comprehensively survey the photo-electrical performance of both proposed and conventional image sensor. Therefore, the input characteristic of both the image sensor under dark and light illumination condition of 1W/cm² is demonstrated in Fig. 5(a) and 5(b). It can be clearly seen from both plots, after

illumination the threshold voltage is increases and drain current slightly decreases. The reason behind is, during light illumination upon the image sensor photon will be converted into electron hole pair and all electron are get collected under BOX/Si substrate interface.

Further, the direction of electric field under the buried oxide layer is pointed downward due to negative back biasing and because of this electric field, photo-generated electron are collected under BOX/Si substrate interface. Therefore electrostatic potential decreases and threshold voltage of both image sensor increases and on-state current decreases slightly. Although, after evaluating the change in on-state current ($|\Delta I_{on}| = |I_{on} - I_{dark}|$) in both the plot it can be observed that change in on-state current ($|\Delta I_{on}| = |I_{on} - I_{dark}|$) for proposed device is higher than the conventional device which illustrates the better photoelectrical performance of the proposed device. Furthermore, the change in on-state current ($|\Delta I_{on}| = |I_{on} - I_{dark}|$) and change in threshold voltage ($|\Delta V_{th}|$) at various light intensity is also studied. The variation in on state current ($|\Delta I_{on}|$) and threshold voltage ($|\Delta V_{th}|$) for both image sensors under various light intensity condition illustrated in Fig. 6(a) and Fig. 6(b). For conventional image sensor $|\Delta V_{th}|$ increases from 99.5mV to 129.5mV and $|\Delta I_{on}|$ increases from 0.157 mA/μm to 0.215mA/μm when light intensity increases from 100μWatt/cm² to 1Watt/cm² whereas for proposed image

sensor $|\Delta V_{th}|$ increases from 78mV to 94mV and $|\Delta I_{on}|$

increases from 0.37 mA/μm to 0.495mA/μm when light intensity increases from 100μWatt/cm² to 1Watt/cm².

Thus, it can be inferred from Fig. 6(a) and Fig. 6(b), for proposed device the change in on-state ($|\Delta I_{on}|$) current at each value of light intensity is also higher than the conventional image sensor which shows

in contrast with conventional image sensor. Moreover the

variation in threshold voltage for proposed device under different light illumination condition is least as compared to conventional image sensor.

iii. Impact Of Various Parameter On The Performance Of Proposed Image Sensor

After investigating photo electrical performance of the proposed device, we have discussed other parameter that affect the performance of the proposed image sensor. These parameter are drain to substrate (back bias) voltage, buried (BOX) oxide thickness and well doping concentration (substrate doping). The discussions are given in below section A, B and C.

Impact of drain to substrate (back bias) voltage on the performance of proposed image sensor.

The impact of drain to substrate (back bias) voltage on the photo-electrical performance of the proposed image sensor is depicted in Fig. 7. This plot shows the shift in threshold voltage with respect to different drain to substrate voltage

(V_{ds}) at a constant light intensity of 10mWatt/cm^2 . For $V_{ds} = 0.7\text{V}$ the threshold voltage under dark condition is about 38mV but it have increases to 82mV at light intensity of 10mWatt/cm^2 . Moreover, for $V_{ds} = 2.1\text{V}$ the shift in threshold voltage is about 135mV under dark condition and it is enhanced by 155mV after illuminating the proposed image sensor by light intensity of 10mWatt/cm^2 . It can be inferred from plot, the shift in threshold voltage under light illumination condition is higher in contrast with shift in threshold voltage under dark condition which explains the higher shift in threshold voltage that provides better sensitivity of the proposed image sensor.

Impact of Buried oxide (BOX) thickness on the performance of proposed image sensor.

Another parameter that affect the photo-electrical performance of the proposed image sensor is buried oxide (BOX) thickness which is illustrated in Fig. 8. The evaluation is done at BOX thickness of 10nm , 14nm and 18nm and the incident light intensity taken as constant i.e 1Watt/cm^2 for each value of BOX thickness. Therefore, the electrostatic potential under BOX/Si substrate interface does not varied with varying buried oxide thickness but it will provide more back bias modulation (shift in threshold voltage and on-state current) with thinner Buried oxide thickness [1]. The electrostatic potential under Box/Si substrate interface has illustrated in Fig. 8. It can be inferred from plot, for proposed device the electrostatic potential under BOX/Si substrate interface (just below channel region) is approximately constant i.e -0.7V at each value of BOX thickness. Furthermore, Fig. 9 and Fig. 10 described the variation in on- state current and variation in threshold voltage with varying BOX thickness. It can be clearly seen from Fig. 9 and Fig. 10, the variation in on-state current ($|\Delta I_{on}|$) and threshold voltage ($|\Delta V_{th}|$) is higher for least BOX thickness (10nm) but the reduction of TBOX provides improved electrostatic potential and hence improve the shift in I_{on} and V_t but BOX Thicknesses below 10nm results in quantum effects such as tunneling and the main function of isolation of the BOX is bypassed. Also, the parasitic capacitances

increases and the performance of the transistor deteriorate hence both proposed and conventional devices provides better photo-electrical performance at least BOX thickness of 10nm.

Further, the Fig. 9 (a) and Fig. 9 (b) demonstrates, the conventional image sensor have $|\Delta V_{th}|$ value is 55.9mV for 20nm BOX thickness and it is improved to 134.4mV for reduced BOX thickness of 10nm. Whereas, for proposed image sensor the $|\Delta V_{th}|$ value shifted from 69.6mV to 94mV with reducing BOX thickness from 18nm to 10nm. Thus both plot depicted the change in threshold voltage is higher for 10nm thickness of the BOX layer which explain the light sensitivity is better for 10nm thickness of the BOX layer. Furthermore, this result also reveals the electrostatic potential under BOX/Si substrate interface has provide more back bias modulation (change in threshold voltage and on-state current) with thinner BOX thickness. Moreover, Fig. 10 (a) and Fig. 10 (b) describes the change in on-state current ($|\Delta I_{on}|$) for both conventional and proposed device which explain sensitivity performance of the both proposed and conventional devices. It can be clearly seen from Fig. 10 (a), the conventional device have $|\Delta I_{on}|$ is 0.078mA/ μ m for 20nm BOX thickness and it is improved to 0.215mA/ μ m for reduced BOX thickness of 10nm whereas Fig. 10 (b) demonstrate, for proposed image sensor the $|\Delta I_{on}|$ value shifted from 0.292mA/ μ m to 0.494mA/ μ m with reducing BOX thickness from 18nm to 10nm. Therefore, it can be analyzed that, Both plot shows the change in on-state current ($|\Delta I_{on}|$) is higher for 10nm thickness of the BOX layer. Moreover, the comparative analysis reveals the proposed device have higher variation in on-state current for each value of BOX thickness in contrast with conventional device thus proposed device have better reliability to be find application in higher sensitive image sensor. Further, the variation in threshold voltage with change in BOX (buried oxide) thickness is specified by body factor (BF) which is defined by following equation [22].

$$BF = \frac{dV_t}{dV_b}$$

$$BF \propto \frac{T_{ox}}{T_{si}(T_{box})} \quad [22]$$

Here V_b and V_t is back bias (substrate bias voltage) and threshold voltage of proposed image sensor. It can be clearly observed from above equation, higher variation in threshold voltage ($|\Delta V_{th}|$) is achieved at least value of the buried oxide thickness (BOX) which is also analysed by Fig. 9 (b) .

Impact of doping concentration in p⁻ substrate region (well region) on the performance of proposed image sensor.

The performance of proposed device also have a dependency upon doping concentration in p⁻ substrate region (well region). The p⁻ substrate region (well region) is mainly used by proposed device for light photon collection and also for conversion of these photon into photo-generated carrier. The performance of both image sensors also depends upon the doping concentration of p⁻ substrate region below the BOX region. The comparative plot for variation in on-state current with different doping concentration of p⁻ substrate region is illustrated in Fig. 11 for both image sensors.

It can be clearly observed from Fig. 11, after light illumination both conventional as well as proposed device shows the decreasing variation in on-state current with respect to increasing doping well concentration the reason behind is dependency of depletion layer thickness formed below the BOX/Si substrate interface and doping concentration of the p^- substrate region (well region) which is inversely proportional to doping concentration of the p^- substrate region (well region). Therefore, with a negative back biasing applied on image sensor a depletion layer formed below the BOX/Si substrate interface and after illuminating the image sensor the photo-generated electron gathered into this depletion layer. Thus, when doping concentration of well region increases the depletion layer thickness is decreases and hence reducing the count of photo-generated electron collection. Therefore it can be clearly analyzed that electron collecting efficiency of image sensor degraded and performance of the image sensor is also degraded. Moreover, From Fig. 11(a) and Fig. 11(b) a comparative analysis demonstrates, besides degrading the performance of both device, proposed device still have higher $|\Delta I_{on}|$ for each value of well doping concentration in contrast with conventional device which explains, higher on-state current variation in proposed device provides better sensitivity of light as compared to conventional image device.

IV. Conclusion

Photo-electric characteristic of proposed image sensor is evaluated in this article. Photo-electric property of proposed device is based on black-bias modulation caused by photogenerated carrier in well (substrate) region. The comparative analysis between proposed and conventional device is also evaluated. The impact of drain to substrate (back bias) voltage, buried oxide (BOX) thickness and well doping concentration (substrate doping) on the performance of both the proposed and conventional device is studied well. Photo-electric property of proposed image sensor based on light induced voltage shift is also shown in this article which is described by variation in threshold voltage shift (ΔV_{th})

and variation in on-state current ($|\Delta I_{on}|$) which is continuously increases with increasing light intensity and back biasing. Comparative analysis presents higher sensitivity of proposed device in contrast with conventional device which is analysed by change in on-state current ($|\Delta I_{on}|$) with increasing light intensity thus the comparative result shows in proposed device, variation in on-state current ($|\Delta I_{on}|$) is higher with increasing light intensity in contrast with conventional device. Comparative performance analysis based on varying BOX thickness is also present in this article that reveals the proposed device have higher variation in on-state current for each value of BOX thickness in contrast with conventional device. Comparative analysis based on another parameter that is well doping concentration

(substrate doping) reveals that proposed device still have higher $|\Delta I_{on}|$ for each value of well doping concentration (substrate doping) in contrast with conventional device. Thus proposed device have better reliability to be find application in higher sensitive image sensor.

Declarations

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Ethics Approval- Authors freely agreed and gave their consent for the publication of the paper.

Consent to participate- Yes

Consent for publication- Yes

Availability of Data and Materials- The datasets generated and analysed during the current study are not available.

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Compliance with Ethical Standards

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Figures

Figure 1

Structure schematic of (a) conventional 1T-UTBB based image sensor and (b) proposed intended source

Figure 2

Electrostatic potential under BOX/Si substrate interface of proposed intended source UTBB 1T FDSOI based image sensor

Figure 3

The transfer characteristic for proposed intended source UTBB 1T FDSOI based image sensor.

Figure 4

- (a): $|\Delta V_{th}|$ variation with light intensity in proposed intended source UTBB 1T FDSOI based image sensor
(b): $|\Delta I_{on}|$ variation with light intensity in proposed intended source UTBB 1T FDSOI based image sensor.

Figure 5

Transfer characteristic of (a) Conventional 1T UTBB based image sensor [1] (b) Proposed intended source UTBB 1T FDSOI based image sensor.

Figure 6

- (a): $|\Delta I_{on}|$ variation with light intensity in both proposed and conventional 1T-UTBB image sensor [1]. (b): $|\Delta V_{th}|$ variation with light intensity in both proposed and conventional 1T UTBB image sensor [1].

Figure 7

V_{th} variation with drain to substrate voltage under dark and light intensity of 10mWatt/cm² and wavelength of 550nm in proposed image sensor.

Figure 8

Electrostatic potential under Box/Si Substrate with different Box thickness for proposed image sensor. The light intensity is 1Watt/cm² and wavelength is 550nm.

Figure 9

$|\Delta V_{th}|$ with different Box thickness for both (a) conventional and (b) proposed image sensor. The light intensity is 1Watt/cm² and wavelength is 550nm.

Figure 10

$|\Delta I_{on}|$ with different Box thickness for both (a) conventional and (b) proposed image sensor. The light intensity is 1Watt/cm² and wavelength is 550nm.

Figure 11

$|\Delta I_{on}|$ Variation with p- well (p- substrate region) doping concentration in (a) proposed and (b) Conventional image sensor. The light intensity is 10mWatt/cm² and wavelength is 550nm.