

# Optimization and Determination of Process Parameters in Thin Film SOI Photo-BJMOSFET

Hai-Qing Xie, Yun Zeng\*, Yong-Hong Yan, Guo-Liang Zhang, Tai-Hong Wang

**Abstract**—We propose photo-BJMOSFET (Bipolar Junction Metal-Oxide-Semiconductor Field Effect Transistor) fabricated on SOI film. ITO film is adopted in the device as gate electrode to reduce light absorption. I-V characteristics of photo-BJMOSFET obtained in dark (dark current) and under 570nm illumination (photo current) are studied furthermore to achieve high photo-to-dark-current contrast ratio. Two variables in the calculation were the channel length and the thickness of the film which were set equal to six different values, i.e.,  $L=2, 4, 6, 8, 10,$  and  $12\mu\text{m}$  and three different values, i.e.,  $d_{\text{si}}=100, 200$  and  $300\text{nm}$ , respectively. The results indicate that the greatest photo-to-dark-current contrast ratio is achieved with  $L=10\mu\text{m}$  and  $d_{\text{si}}=200\text{nm}$  at  $V_{\text{GK}}=0.6\text{V}$ .

**Keywords**—Photo-to-dark-current contrast ratio, Photo-current, Dark-current, Process parameter

## I. INTRODUCTION

NOWADAYS, short distance optical communications and emerging optical storage(OS) systems such as DVD applications require fast (gigahertz to tens of gigahertz bandwidth) and responsive photodetectors with high photo-to-dark-current ratio increasingly[1]-[4]. Bulk silicon detectors, however, hardly cope with these specifications, mainly in regards to bandwidth, and nonintegrated detectors are usually used due to high dark currents of photodiode and low sensitivity of MOS structure(due to only one kind of carrier and light-absorption of gate) in CMOS process under  $0.25\mu\text{m}$ [5]-[9]. This limits the ultimate performances of optical receivers circuits because of high bonding capacitor, cost, and area, which is a limitation for the deployment of local-area networks, interchip/intrachip interconnects, and for the first mile ethernet[10].

In order to achieve low dark current and high photo-current under low reverse voltage, photo-BJMOSFET (Bipolar Junction Metal-Oxide-Semiconductor Field Effect Transistor) based on SOI film compatible with CMOS process was proposed. The structure of photo-BJMOSFET is very similar to traditional MOS structure, but only ITO is applied as gate to reduce light absorption. Recombination was reduced due to depletion but not inversion region of thin film under gate

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voltage (but not high reverse voltage) to obtain low dark current and high photo-current. Consequently, it can get high sensitivity and responsibility.

In this paper, I-V characteristics of photo-BJMOSFET obtained in dark (dark current) and under 570nm illumination (photo current) are studied furthermore. Two variables in the calculation were the channel length and the thickness of the film which were set equal to six different values, i.e.,  $L=2, 4, 6, 8, 10,$  and  $12\mu\text{m}$  and three different values, i.e.,  $d_{\text{si}}=100, 200$  and  $300\text{nm}$ , respectively.

## II. DEVICE STRUCTURE

Thin film SOI photo-BJMOSFET realized in  $0.18\mu\text{m}$  SOI CMOS technology with the parameters shown in Fig.1. It is seen that the structure is very similar to that of traditional NMOS except a  $\text{P}^+\text{N}$  injection junction is formed by using  $\text{P}^+$  region instead of  $\text{N}^+$  region as drain. Furthermore, ITO is adopted as gate electrode to reduce the absorption loss of traditional gate. The thin Si film thickness,  $d_{\text{si}}$ , is equal to three different values, i.e.,  $d_{\text{si}}=100, 200$  and  $300\text{nm}$ , the front oxide thickness,  $d_{\text{FOX}}$ , is equal to  $80\text{nm}$ , the buried oxide (BOX) thickness,  $d_{\text{BOX}}$ , is equal to  $380\text{nm}$  and the thickness of substrate,  $d_{\text{sub}}$ , is equal to  $500\text{nm}$ . The length of the  $\text{N}^+$  and  $\text{P}^+$  zones,  $L_{\text{PN}}$ , is equal to  $1\mu\text{m}$  and  $L$ , the length of the channel which typically corresponds to a  $\text{P}^-$ -doping of  $10^{15}\text{cm}^{-3}$ , is equal to six different values, i.e.,  $L=2, 4, 6, 8, 10$  and  $12\mu\text{m}$ .

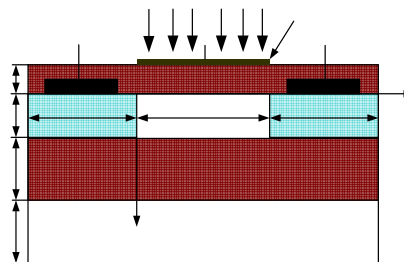


Fig. 1 Schematic cross-section of thin film SOI photo-BJMOSFET.

The absorption in ITO film is the main loss of incident light. The deposition of ITO was performed in a vacuum chamber, where the preliminary pressure was  $1 \times 10^{-3}\text{Pa}$ . Sputtering was done at a pressure of  $0.5\text{Pa}$ , at a constant power of  $100\text{W}$ . During the sputtering process, the temperature of the substrates always was kept at  $150^\circ\text{C}$  for 1.5 hours. The measurement of

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transmittance to the wavelength of ITO film is presented in Fig.2. It can be seen that the transmittance of ITO film is higher than 80% for  $\lambda$  from 500nm to 700nm, and can be adopted as gate electrode to reduce light absorption.

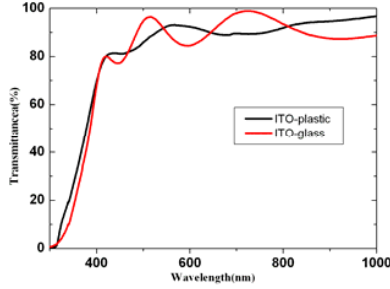


Fig. 2 Transmittance to wavelength of ITO film which was deposited on glass and plastic, respectively, with thickness is 100nm.

In photo-BJMOSFET, the depletion but not inversion region is formed by  $V_{GK}$  (the voltage between electrode G and electrode K) under lower  $V_{AK}$  (the voltage between electrode A and electrode K) in channel to decrease dark current and increase internal quantum efficiency.

In photo-BJMOSFET, we can obtain the Boltzmann distribution

$$n_{surface} = n_i e^{(\psi_s(x) - \phi_f) / \phi_T} \quad (1)$$

where  $n_{surface}$ ,  $n_i$ ,  $\psi_s(x)$ , respectively, are the electron concentration at the surface, the intrinsic concentration, surface potential at  $x$  position.

The quantity of charge per unit area in the semiconductor under oxide  $Q_C$  is given by

$$Q_C = -\sqrt{2q\epsilon_s N_A} \times \sqrt{V_i e^{-\psi_s / \phi_T} + \psi_s - \phi_T + e^{-2\phi_f / \phi_T} (\phi_T e^{\psi_s / \phi_T} - \psi_s - \phi_T)} \quad (2)$$

where  $q$ ,  $\epsilon_s$ ,  $N_A$ ,  $\psi_s$ ,  $\phi_f$  and  $\phi_T$ , are the magnitude of the electron charge, permittivity of the material, doping concentration, surface potential, Fermi potential of the material, and thermal voltage, respectively.

Expression for  $V_{GK}$  can be obtained using Kirchhoff's voltage law

$$V_{GK} = V_{FB} + \psi_S \quad (3)$$

where  $V_{FB}$  is the flat-band voltage, the expression for  $\gamma$  is as follows:

$$\gamma = \frac{\sqrt{2q\epsilon_s N_A}}{C_{OX}} \quad (4)$$

where  $C_{OX}$  is the oxide capacitance per unit area.

In depletion region (which photo-BJMOSFET operating in),  $n_{surface}$  is not larger than  $n_i$ . The charge due to the electrons in

the inversion layer  $Q_L$  can be ignored based on ideal assumption.

Thus, Equation (3) can be simplified as follows:

$$V_{GK} \approx V_{FB} + \psi_S + \gamma \sqrt{\psi_S} \quad (5)$$

then

$$\psi_S = \left( -\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{GK} - V_{FB}} \right)^2 \quad (6)$$

### III. DEVICE SIMULATION AND DISCUSSION

Numerical simulation studies were conducted by using a two-dimensional (2D) device analysis program (ATLAS by SILVACO, Inc.) implemented on a WINDOWS system [11]. This software solves the coupled semiconductor equations, Poisson's equation, and the electron and hole continuity equations. Through simulation, the field equations of the problem were solved numerically without simplifying approximations regarding the distribution and pattern of the physical mechanisms involved. (In this regard, simulation results are considered more to be dependable than the exact closed form solutions obtained from oversimplified idealizations of the actual problem.)

To obtain improved resolution in the regions of interest, the simulation required a very fine mesh in thin film where steep gradients in the electrical field were anticipated. A total of 19332 grid nodes and 38092 elements (triangles) were used in modeling the intermediate length sample ( $L=10\mu m$ ) with a commensurate increase/decrease in the number of nodes and elements for the longer and shorter samples, respectively. Gummel-Newton-based numerical algorithms were implemented and used by the simulation program in order to solve the discretized form of the field equations [12].

In order to understand the behavior of the current in the depletion region, it was essential to study in detail the volume distribution of the carriers for the entire thin film. Simulation results for the electron and hole concentrations are given in Fig.3. The data were taken from the cut line taken from the front interface to the back interface by utilizing a cut line at the middle of the channel, where zero in Fig.3 is taken to be at the front interface. For different channel length, the concentration of electrons at front interface is lower than  $10^{15} \text{cm}^{-3}$  at  $V_{GK}=1\text{V}$ . In other words, whole thin film is in depletion region at  $V_{GK}=1\text{V}$ , which is consistent with (6). It is also indicated in Fig.3 that the concentration of electrons at front interface in  $L=2\mu m$  is lower than that in other channel length due to the influence of  $V_{AK}$ .

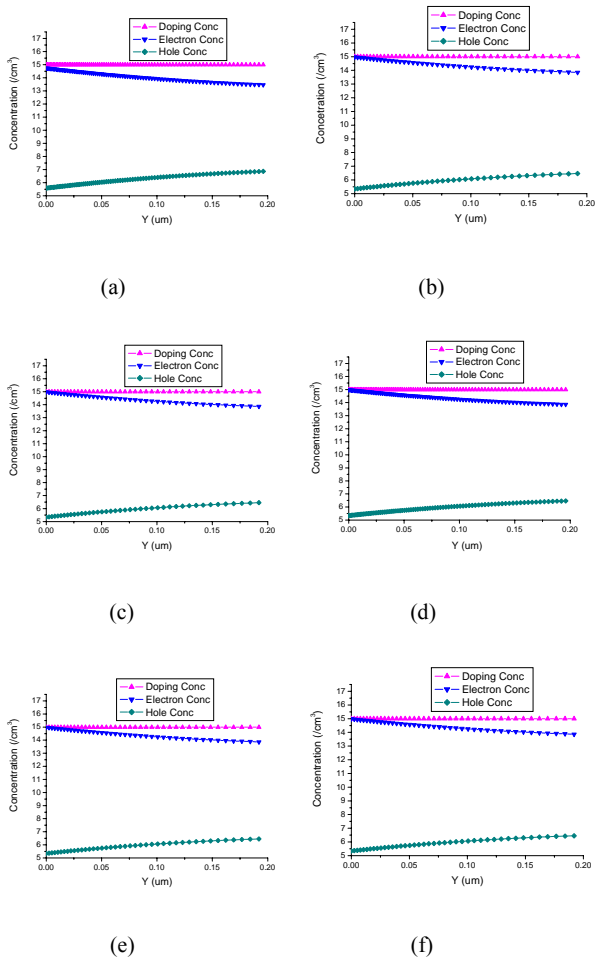


Fig. 3 Simulation results for the electron and hole concentration profiles at the middle of the channel for  $V_{GK}=1V$ . The  $d_{Si}$  is equal to 200nm and the active channel lengths are  $2\mu m$  for (a),  $4\mu m$  for (b),  $6\mu m$  for (c),  $8\mu m$  for (d),  $10\mu m$  for (e), and  $12\mu m$  for (f).

Figure 4 reports output characteristics of the device with different channel lengths and different gate voltages. Not discernible difference under different gate voltages observed in Fig.4(a) can be easily recognized as a result that depletion region in thin film is formed by  $V_{AK}$  but not  $V_{GK}$  with a channel length  $L=2\mu m$ . A similar behavior is observed in Fig. 4(b) referring to the device with a channel length  $L=4\mu m$ , with depletion effect becoming less pronounced under  $V_{GK}$  as the channel length increases. Note that for channel lengths exceeding  $6\mu m$ , the depletion effect under  $V_{GK}$  is not discernible, and pronounced differences are observed under different gate voltages. On the other hand, obvious differences are obtained from  $V_{GK}=0V$  to  $V_{GK}=0.6V$  and differences from  $V_{GK}=0.6V$  to  $V_{GK}=1.0V$  are not discernible, due to weak inversion in thin film under  $V_{GK}$  beyonding  $0.6V$ . (channel lengths exceeding  $6\mu m$ )

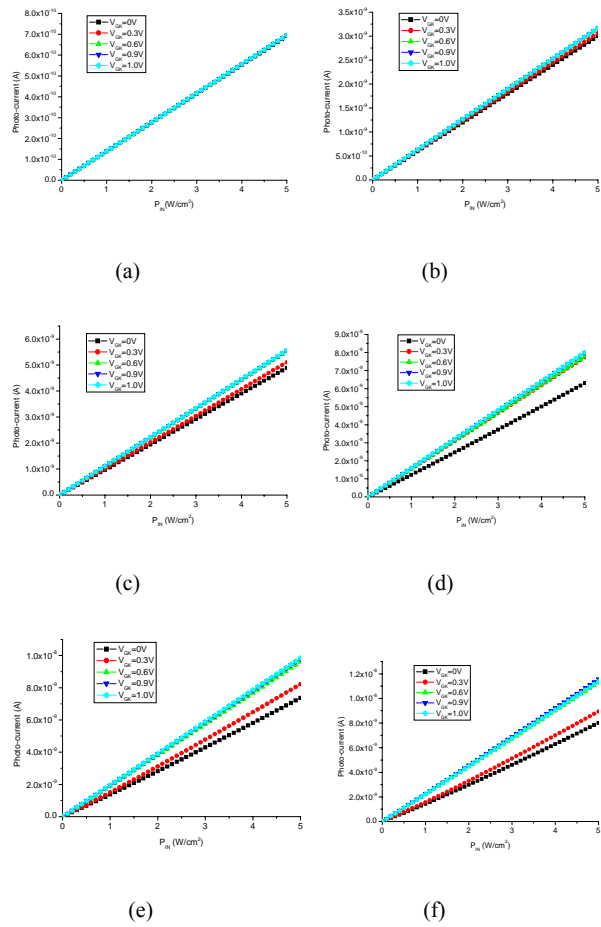


Fig. 4 Photo-current vs illuminating power corresponding to  $V_{GK}=0V, 0.3V, 0.6, 0.9, 1.0V$ , respectively, with  $d_{Si}=200nm$  and the active channel lengths of (a)  $2\mu m$ , (b)  $4\mu m$ , (c)  $6\mu m$ , (d)  $8\mu m$ , (e)  $10\mu m$ , and (f)  $12\mu m$ .

Figure.5 shows I-V characteristics of this device in dark for different channel lengths. The dark current is originated from thermionic emission of carriers. It can be seen clearly that dark currents for different channel lengths are horizontal with  $V_{GK}$  lower than  $0.6V$ , and increase rapidly exceeding  $0.6V$ . On the other hand, dark current increase pronouncedly for  $V_{GK}$  exceeding  $10\mu m$ . Furthermore, the darkcurrent is increased a little when  $V_{GK}>0.7V$ , thus demonstrating that the weak inversion region is formed on the surface.

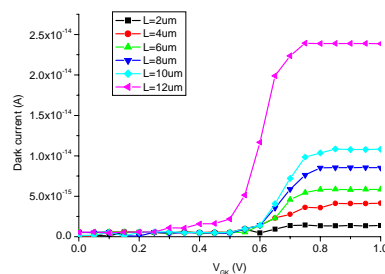


Fig. 5 Dark-current vs  $V_{GK}$  arranging from  $0.0V$  to  $1.0V$  with  $d_{Si}$

TABLE I  
THE DARK-CURRENT, PHOTOCURRENT, AND PHOTO-TO-DARK-CURRENT CONTRAST RATIOS UNDER  $5\text{W}/\text{cm}^2$  LIGHT INTENSITY AND  $V_{GK}=0.6\text{V}$

Channel length( $\mu\text{m}$ )	Photocurrent (A)	Dark-current (A)	Photo-to-dark -current contrast ratios
2	6.95e-10	4.56e-16	1.52e6
4	3.16e-09	1.38e-15	2.29e6
6	5.53e-09	1.41e-15	3.92e6
8	8.0e-09	1.41e-15	5.67e6
10	9.61e-09	1.41e-15	6.82e6
12	1.13e-08	1.17e-14	9.66e5

=200nm and the active channel lengths  $L=2\mu\text{m}$ ,  $4\mu\text{m}$ ,  $6\mu\text{m}$ ,  $8\mu\text{m}$ ,  $10\mu\text{m}$ , respectively.

The dark-current, photocurrent, and photo-to-dark-current contrast ratios under  $5\text{W}/\text{cm}^2$  light intensity and  $V_{GK}=0.6\text{V}$  for photo-BJMOSFET are listed in Table I, which indicates that photo-current and dark current both increase along with increasing channel length. The greatest photo-to-dark-current contrast ratio is achieved at  $L=10\mu\text{m}$ .

Reports output characteristics of the device with different film thicknesses and different gate voltages for  $L=10\mu\text{m}$  are depicted in figure 6. It is indicated that photocurrent increases along with increasing film thickness under the same  $V_{GK}$ . However, influences of  $V_{GK}$  under different film thicknesses are pronounced and similar with each other.

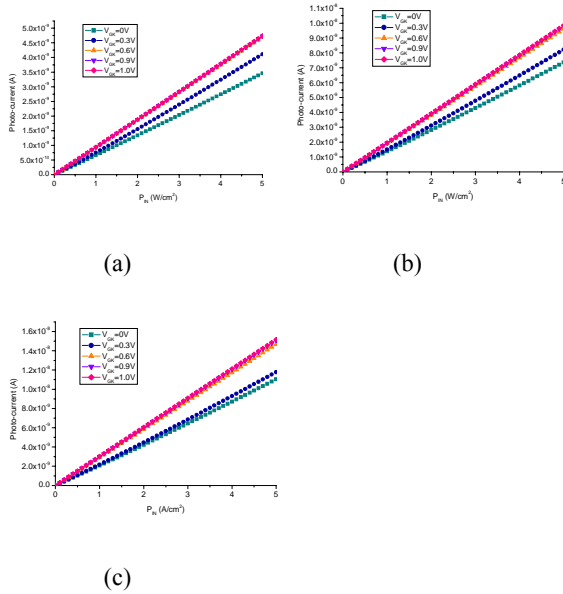


Fig.6 Photo-current vs illuminating power corresponding to  $V_{GK}=0\text{V}$ ,  $0.3\text{V}$ ,  $0.6$ ,  $0.9$ ,  $1.0\text{V}$ , respectively, with  $L=10\mu\text{m}$  and the thin Si film thickness of (a) 100nm, (b) 200nm, and (c)300nm.

Figure.7 shows I-V characteristics of this device in dark for different film thicknesses. It can be seen clearly that dark currents for different film thicknesses are horizontal with  $V_{GK}$

lower than  $0.6\text{V}$ , and increase rapidly exceeding  $0.6\text{V}$ . Furthermore, the darkcurrent is increased a little when  $V_{GK}>0.7\text{V}$ , thus demonstrating that the weak inversion region is formed on the surface.

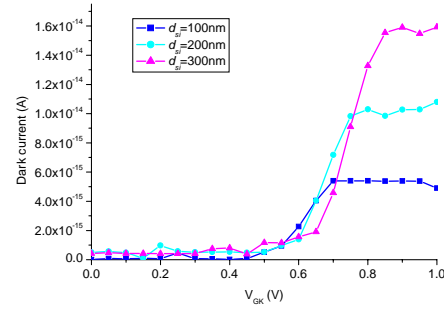


Fig. 7 Dark-current vs  $V_{GK}$  arranging from  $0.0\text{V}$  to  $1.0\text{V}$  with  $L=10\mu\text{m}$  and the thin Si film thickness  $d_{Si} = 100\text{nm}$ ,  $200\text{nm}$ ,  $300\text{nm}$ , respectively.

#### IV. CONCLUSION

ITO film which transmittance is higher than 80% for  $\lambda$  from  $500\text{nm}$  to  $700\text{nm}$  is adopted as gate in photo-BJMOSFET fabricated on SOI film to reduce light absorption. Thin film is in depletion but not inversion region by gate voltage. I-V characteristics of photo-BJMOSFET obtained in dark (dark current) and under  $570\text{nm}$  illumination (photo current) are studied furthermore to achieve high photo-to-dark-current contrast ratio. Numerical simulations are performed by 2D Atlas. Gummel-Newton-based numerical algorithms were implemented and used by the simulation program in order to solve the discretized form of the field equations. Two variables in the calculation were the channel length and the thickness of the film which were set equal to six different values, i.e.,  $L=2, 4, 6, 8, 10, \text{ and } 12\mu\text{m}$  and three different values, i.e.,  $d_{Si}=100, 200 \text{ and } 300\text{nm}$ , respectively. The results indicate that obvious performance is observed when channel lengths exceed  $6\mu\text{m}$  and dark currents for different film thicknesses are horizontal with  $V_{GK}$  lower than  $0.6\text{V}$ , and increase rapidly exceeding  $0.6\text{V}$ . Thus, the greatest photo-to-dark-current contrast ratio is achieved with  $L=10\mu\text{m}$  and  $d_{Si}=200\text{nm}$  at  $V_{GK}=0.6\text{V}$ .

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