第 24 卷第 3 期 半 导 体 学 报 Vol. 24, No. 3
2003 年 3 月 CHINESE JOURNAL OF SEMICONDUCTORS Mar., 2003

Numerical Simulation and Analysis of Bipolar Junction Photogate Transistor for CMOS Image Sensor

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Abstract: A new photodetector ——bipolar junction photogate transistor is presented for CMOS image sensor and its analytical model is also established. With the technical parameter of the 0.6μm CMOS process, the bipolar junction photogate transistor is analyzed and simulated. The simulated results illustrate that the bipolar junction photogate transistor has the similar characteristics of the traditional photogate transistor. The photocurrent density of the bipolar junction photogate transistor increases exponentially with the incidence light power due to introducing the injection p^+ n junction. Its characteristic of blue response is rather improved compared to the traditional photogate transistor that benefits to increase the color photograph made up of the red, the green, and the blue.

Key words: bipolar junction photogate transistor; photodetector; CMOS image sensor

EEACC: 4250; 2560B

CLC number: TN303 **Document code:** A **Article ID:** 0253-4177(2003)03-0250-05

1 Introduction

Over the past years, the CMOS image sensor which is mostly based on standard CMOS technique has been increased dramatically in the possession of advantages such as low voltage, low power consumption, random access of the image data, applicability for the on-chip signal processing and realizing the integrated single-chip compared with CCD imagers, which are especially important for imagers system to implement in a way of lower power, lower voltage and the miniaturization[1,2]. The photodetector elements play an important role in design of CMOS imager pixel. In a standard CMOS process several parasitic junction devices, either p-well or n-well, can be used as photodetectors like photodiode, phototransistor and photogate transistor. Despite of the current gain of phototransistor, it results in a large gain of photocurrent. The dark noise and other noise may also increase at the same time[3]. Most of CMOS imagers use the photodiode to carry out the function of the photo-charge convert because of its low dark current and other noise[4,5]. Although the photogate transistor has poor blue response because the gate material absorbs that part of the spectrum, a quantitative study of CMOS photogate transistor sensors illustrate the chip can perform as well as CCD imagers if the standard CMOS technique is modified to increase the quantum and to reduce dark current[6~9].

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Received 12 June 2002, revised manuscript received 2 October 2002

In this paper a new photodetector——bipolar junction photogate transistor is presented for CMOS image sensor. This new structure has two advantages: (1) Due to an injection p^+ n junction introduced, the bipolar junction photogate transistor can increase the photo-charges' readout rate and improve the operating speed of CMOS image sensor; (2) The pixel based on the bipolar junction photogate transistor can increase the fill factor, reduce the pixel size, and operate in a low power. With the technical parameter of the 0.6μm for CMOS process, the bipolar junction photogate transistor is analyzed and simulated[10]. The simulated results illustrate that the bipolar junction photogate transistor has the similar photo-response characteristics of the traditional potogate transistor. Its photo current density increases exponentially with the incidence light power due to introducing the injection p^+ n junction. Its characteristic of blue respond is rather improved compared to the traditional photogate transistor.

The rest of the paper is organized as follows. In section 2, we describe the structure of bipolar junction photogate transistor and its main principle of operating. In section 3, the analysis model of the bipolar junction photogate transistor is deduced. In section 4, we simulate and analysis the characters of the bipolar junction photogate transistor in detail. Finally, some conclusions are drawn in section 5.

2 Structure and operation principle of bipolar junction photogate transistor

2.1 New structure

CMOS photogate transistor pixel is borrowed from CCD image sensor actually. The MOS capacitance is the core for the photogate transistor to store up the photo-charges when the potential trap is become applied the voltage V_{PG}. Figure 1 shows the cross-section of photogate transistor on p-Si substrate. Figure 2 shows the cross-section and the modeling schematic diagrams of the bipolar junction photogate transistor.

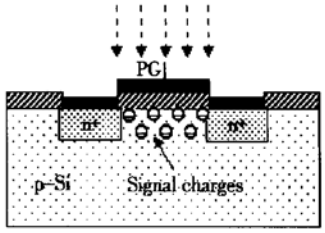

Fig. 1 Cross-section of photogate transistor on p-Si substrate

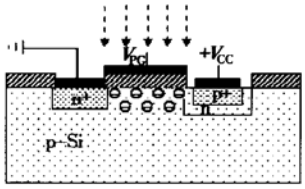

Fig. 2 Cross-section and modeling schematic diagrams of bipolar junction photogate transistor on p-Si substrate

Although the MOS capacitance is still the core for the bipolar junction photogate transistor, it is different from the photogate transistor that an injection p^+ n junction is introduced which is fabricated in n-well and the n-layer plays a role in isolating the collected charges under the gate oxide from the floating diffusion p^+ region. The photo-charges (electron) drift through the p^+ n junction by the applied electronic field. On the other hand, the p^+ n junction injects the carriers (hole) into the channel to carry the photo-charges. Therefore the bipolar junction photogate transistor can increase the photo-charges' readout rate and improve the operating speed of CMOS image sensor.

2.2 Operation principle

The operation principle diagram of bipolar junction photogate transistor is following according to Fig. 2. Firstly, applying a positive voltage V_{PG} to the gate, the potential trap, which takes on a strong attraction for the minor carriers (electron), comes into being in the interface between the Si and SiO_2. And

then, the electrons from the photo-generated carriers are stored up in the potential trap, and the hole is excluded into the substrate. Finally a part of the signal charges (electron) drift through the p^+ n junction by the applied strong electronic field when adding the supply + V_{cc} to the p^+ region. On the other hand, the p^+ n junction injects the holes into the channel to carry the signal charges by the compound current. Therefore, the photocurrent is composed of both the drift current and the compound current. The bipolar junction photogate transistor may not only increase the photo-charges' readout rate but also improve the operating speed of CMOS image sensor.

3 Modeling bipolar junction photogate transistor

Figure 2 shows the modeling schematic diagrams of bipolar junction photogate transistor. The polysilicon grid (PG) is held at V_{PG}. The photo-generated charges are collected beneath the gate oxide. When applying the voltage + V_{cc} in the p^+ region, the signal charges pass through the p^+ n junction by the way of the mixed current composed of both drift current and couple current.

When the bipolar junction photogate transistor is exposed in the incidence light, the transition probability of the electron in the semiconductor is positive to the optical field. Therefore, the photo current is

$$I_p = \alpha P = \eta \frac{qP}{hv} \tag{1}$$

where $\alpha = \eta q / hv$ represents the photoelectric converted factor. The P is the incident optical power, and the η is called the quantum efficiency.

On the assumption that the minor carriers in the potential trap is provided by the photo-generate charges when the voltage V_{PG} changes suddenly from 0 to V_{cc}, the drop voltage on the MOS capacitance is

$$V_M = -\frac{Q_S}{C_{OX}} = -\frac{I_P}{qC_{OX}} \tag{2}$$

where $C_{OX} = \varepsilon_{OX} / T_{OX}$.

The pn junction characteristic obeys the following equation.

$$I_d = I_0 [e^{q(V_{CC} - V_M)/kT} - 1] \tag{3}$$

According to the current's continuous principle, we can obtain $I_p = I_d$. On the basis of formula (1), (2), and (3), the photo-generated charges is

$$Q_S = \frac{I_P}{q} = \frac{I_0}{q} [e^{q(V_{CC} + \frac{\eta P}{hv C_{OX}})/kT} - 1] \tag{4}$$

The surface potential V_S is an important physical parameter to describe the capability of the potential trap.

$$V_S = V + V_0 - (V_0^2 + 2VV_0)^{1/2} \tag{5}$$

where $V = V_{PG} - V_{FB} - Q_S / C_{OX}$ and $V_0 = \varepsilon_s \varepsilon_0 q N_A / C_{OX}^2$. Therefore, we build the relation of P, V_{cc}, V_{PG}, and η by formula (4) and (5) to describe the characteristic of the bipolar junction photogate transistor.

4 Analysis and simulation of bipolar junction photogate transistor

Figure 3 shows the varied trend of the relation of the gate voltage and the surface potential when the impure density is $10^{15} cm^{-3}$ under the oxide thickness varied from 0.1μm to 0.3μm and the oxide thickness is 0.1μm under the impure density varied from $N_A = 10^{14} cm^{-3}$ to $N_A = 10^{16} cm^{-3}$. The surface potential grows with the gate voltage. When the impure density or the oxide thickness is constant, the surface potential decreases with the increasing of the oxide thickness or the impure density.

Figure 4 illustrates the relation between the signal charge and surface potential. With the signal charge increasing, the surface potential is decreasing when the gate voltage is constant. The number of signal charge is larger at the gate voltage 3V than that at

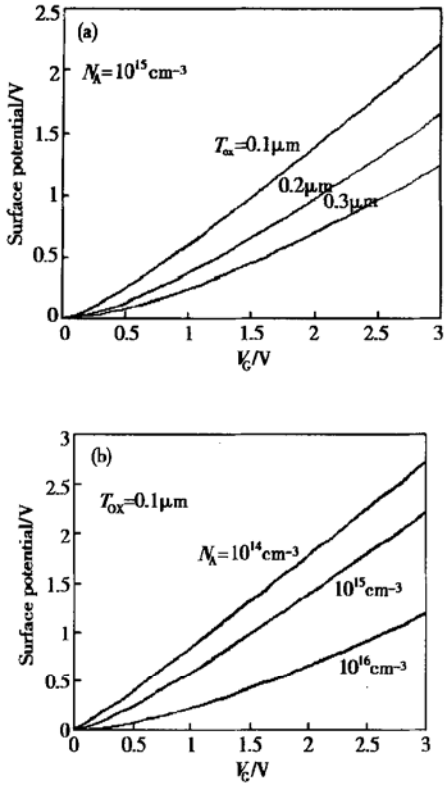

Fig. 3 Relation of surface potential and gate voltage

The gate voltage value is $V_{PG}-V_{FB}$.

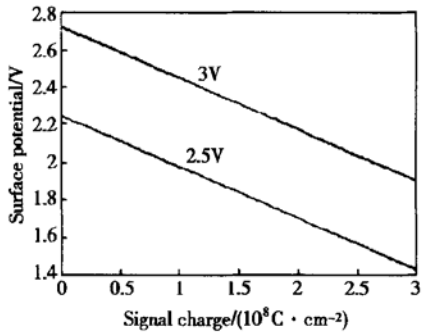

Fig. 4 Relation of surface potential and signal charge

the gate voltage 2.5V when the surface potential is fixed. Both the simulated spectral response of the bipolar junction photogate transistor using the parameter of the 0.6μm CMOS process and the spectral response of the traditional photogate transistor[8] are shown in Fig. 5. These results are deduced under the assumption that the oxide is transparent and the absorbing coefficient of polysilicon is the same as single crystal silicon. The solid line represents the spectral response of bipolar junction photogate transistor and the dashed line indicates the spectral response of traditional photogate transistor. Because the spectral responding range of the bipolar junction photogate transistor extends larger than that of the traditional photogate transistor, it will widen the sensitivity of CMOS images. Especially in the wavelength of about 500nm that is absorbed partly in the traditional photogate transistor, we can draw a conclusion that the blue respond characteristic has been rather improved compared to the traditional photogate transistor from Fig. 5, which benefits to the increase of the color photograph made up of the red, the green and the blue.

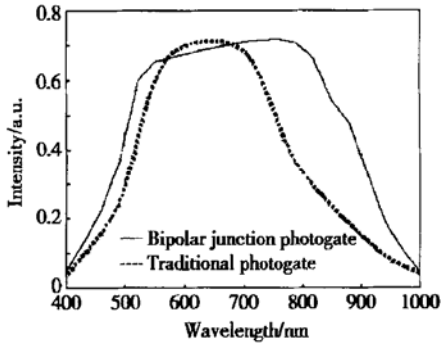

Fig. 5 Spectral response

Figure 6 illustrates that the photo current density of the bipolar junction photogate transistor versus the incidence light power under the applied voltage 3.3V. From the curve we know that the photo current density increases exponentially with the incidence light power due to introducing the injection p^+ n junction. From this point we can explain that the reason that its blue response has largely improved is that the photo-carriers, which is produced by some blue photons, has been read out before they compound. Other-

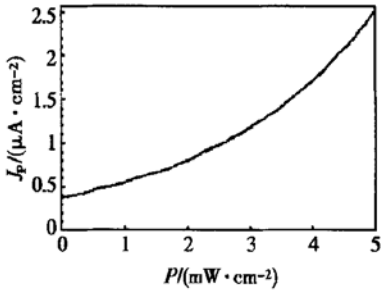

Fig. 6 Photo current density of bipolar junction photogate transistor versus incidence light power

wise, the photo current density of the bipolar junction photogate transistor has improved largerly, which means that its operating rate is quicker than the traditional photogate transistor.

5 Conclusions

A new photodetector ——bipolar junction photogate transistor has been presented for CMOS image sensor in this paper. Under the technical parameter of the 0.6μm CMOS process, the simulated results illustrate that the bipolar junction photogate transistor has the similar photo-response characteristics of the traditional photogate. The photo current density of the bipolar junction photogate transistor increases exponentially with the incidence light power due to introducing the injection p^+ n junction. Its blue responds characteristic has been rather improved compared to the traditional photogate transistor that benefits to the increase of the color photograph made up of the red, the green and the blue.

References

[1] Schanz M, Brockherde W, Hauschild R, et al. Smart CMOS image arrays. IEEE Trans Electron Devices, 1997, 44(10): 1699

[2] Fossum E R. CMOS image sensor: electronic camera-on-a-chip. IEEE Trans Electron Devices, 1997, 44(10): 1689

[3] Shinohara M. A bipolar detector with smart functions. IEEE Trans Electron Devices, 1997, 44(10): 1769

[4] Nixon R H, Kemery S B, Pain B, et al. 256×256 active pixel pixel sensor camera-on-a-chip. IEEE J Solid-State Circuits, 1996, 31(12): 2046

[5] Yonemoto K, Siumi H. A CMOS image sensor with a simple fixed-pattern-noise-reduction technology and a hole accumulation diode. IEEE J Solid-State Circuits, 1996, 35(12): 2038

[6] Blanksby A, Loinaz M, Inglis D, et al. Noise performance of a color CMOS photogate transistor image sensor. In: IEDM Digest, 1997: 861

[7] Loinaz M J, Singh K J, Blanksby A J, et al. A 200mW, 3.3V, CMOS color camera IC producing 352×288 24-b video at 30 frames/s. IEEE J Solid-State Circuits, 1998, 33(12): 2092

[8] Blanksby A J, Loinaz M J. Performance analysis of a color photogate transistor image sensor. IEEE Trans Electron Devices, 2000, 47(1): 55

[9] Lulé T, Benthien S, Keller H, et al. Sensitivity of CMOS based imagers and scaling perspectives. IEEE Trans Electron Devices, 2000, 47(11): 2110

[10] Zeng Y, Jin X L, Yan Y H, et al. Numerical simulation of BJ-MOSFET on current-voltage characteristics. Chinese Journal of Semiconductors, 2000, 21(11): 1069

用于 CMOS 图像传感器的双极结型光栅晶体管特性的数值模拟与分析

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摘要: 提出一种用于 CMOS 图像传感器的新型光电检测器 ——双极结型光栅晶体管, 并建立了其解析模型. 基于 0.6μm CMOS 工艺参数的模拟结果表明双极结型光栅晶体管具有传统光栅晶体管的特性, 但与传统光栅器件相比, 随着入射光功率的增加, 双极结型光栅晶体管的光电流密度呈指数式增长, 且其蓝光响应特性得到改善.

关键词: 双极结型光栅晶体管; 光电检测器; CMOS 图像传感器

EEACC: 4250; 2560B

中图分类号: TN303 **文献标识码**: A **文章编号**: 0253-4177(2003)03-0250-05

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2002-06-12 收到, 2002-10-02 定稿