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BCD-A New High Performance Nondestructive Charge Detection Concept for CCD Image Sensors.

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Abstract

This article describes the theory of operation and characterization results of a new charge detection amplifier, which detects charge that moves in the bulk of a silicon CCD channel. The charge detection is nondestructive and, therefore, kTC noise free. The new detector is suitable for a very high speed and a low noise operation needed in high-resolution CCD image sensors.

A simple gradual channel transistor approximation is used to derive the first order device model which then predicts the charge conversion sensitivity, linearity, and noise. The derived theoretical results are compared with detail measurements that include the measurement of conversion gain, linearity, reset feed through, noise, and hot carrier effects. Finally, from the analysis and from the measurement results, it is concluded that the BCD (Bulk Charge Detection) concept is superior to today's state-of-the-art FD (Floating Diffusion) charge detection amplifiers in high-speed applications.

I. Introduction

In high performance and high-resolution CCD image sensors it is not easy to accomplish low noise signal readout. In a previously published work[1], it was concluded that a non destructive charge readout, such as the one using Floating Gate (FG), is potentially more advantageous and has a better noise floor performance at higher speeds than the traditional approaches based on Floating Diffusion (FD)[2]. It was found, however, that the conversion gain of the FG amplifier is typically lower than that of a comparable FD design and that it is difficult to improve it even if various novel FG biasing schemes are used. This is the main problem of the FG approach.

The nondestructive charge readout, however, still remains a very attractive alternative for the high speed applications, since it is simpler, faster, and does not require Correlated Double Sampling (CDS) signal processing for the removal of kTC noise. The nondestructive charge readout is kTC noise free.

It is the purpose of this article do describe a new nondestructive charge readout structure (Bulk Charge Detector: BCD) that does not require any biasing element connected to the sensing node and which is not based on the FG approach. The performance of the described BCD device is thoroughly investigated and theoretically modeled in this work. The effects such as hot hole impact ionization and amplitude response non-linearity, observed under certain biasing conditions, are characterized and explained. The described findings have not been previously discussed in the literature which deals with devices operating on similar charge detecting principles[4] .

II. BCD Description and the Theory of Operation.

A cross section of the BCD charge detection node with a resistive reset gate as implemented in the standard VP technology is shown in Fig. 1.

The device operation can be understood from the potential diagram also shown in Fig. 1. As the last CCD poly gate is clocked negative, electrons are transferred under the gate of the BCD detector. The BCD gate is typically held at zero or close to a zero bias. The transferred charge then modulates potential under the gate and this in turn causes a change in the potential of the source.

It is assumed that the BCD central region is connected to a constant current source or to a relatively high value resistor that supplies the necessary current to this node. The resulting change in the source potential is the desired signal that is subsequently buffered by a standard two stage source follower that drives the output terminals of the sensor. After the output signal is detected and sampled, BCD is reset by applying a short positive pulse to the reset gate.

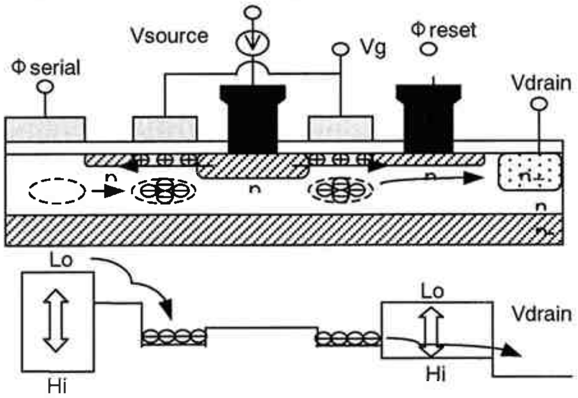

Fig.1. Cross section and corresponding potential profiles for the BCD detector located in a VP CCD channel with resistive reset gate.

This action completely removes all charge from the detector. The complete charge removal after sensing is the key feature and a very important advantage of this device. After all charge has been removed from the well, the potential returns to its original level without any uncertainty. Consequently, no kTC noise is generated.

The BCD detector, however, is not completely noise free. The hole current that flows from the p+ source to the p+ VP surrounding gate generates Johnson noise. The BCD device is essentially a standard p-channel transistor with a special body effect. The body region of the BCD transistor forms only a potential well that can be filled or completely depleted of charge.

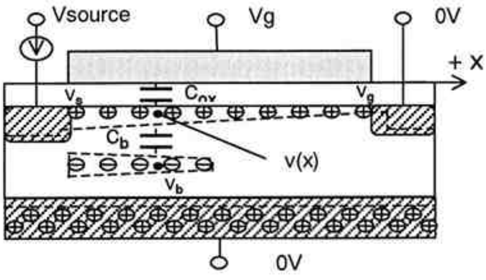

Fig.2. Gradual channel approximation model for the BCD device showing location of holes and electrons under the BCD gate.

For the most clarity and not to unnecessarily obscure the essentials of the device physics, the following simplifying assumptions will be made: The gate geometry will be considered rectangular. There will be no fixed space charge considered in the structure. There will be no fixed charge in the oxide and at the silicon-silicon dioxide interface. There will be no work function differences considered between the gate material and the silicon. Two kinds of mobile charge, holes and electrons, will be considered in the structure as is shown in Fig. 2.

With these assumptions the conversion gain formula for the BCD device is derived as follows:

Following the notation given in Fig. 2, the Gauss law for hole charge q_h in the BCD channel yields:

$$q_h(x) = C_{ox}[v(x) - v_g] + C_b[v(x) - v_b] \qquad (1)$$

where v_g is the gate potential, v_b represents the Fermi level of electrons in the well, and v(x) represents the potential at the interface where the hole current flows. C_{ox} is the gate oxide capacitance and C_b the capacitance of the electron storage well with respect to the interface. For simplicity it is assumed that both holes and electrons can be considered here as charge sheets. Using now the gradual channel approximation, the BCD drain current becomes:

$$I_d(L/W) = \mu \int_{v_s}^{v_b} [C_{ox}(v_g - v) + C_b(v_b - v)]\,dv + \mu \int_{v_b}^{v_g} C_{ox}(v_g - v)\,dv \qquad (2)$$

After carrying out the indicated integrations, Equation (2) simplifies to read:

$$I_d(L/W) = \frac{\mu}{2} C_{ox}(v_g - v_s)^2 + \frac{\mu}{2} C_b(v_b - v_s)^2 \qquad (3)$$

The next step is to calculate the total amount of charge in the well. This is accomplished by using the formula:

$$Q_b = W \cdot C_b \int_{v_s}^{v_b} (v_b - v)\frac{dx}{dv}\,dv \qquad (4)$$

Since we are interested only in the small signal response, by differentiating Equations (3) and (4) while holding I_d constant, we find that:

$$\frac{dQ_b}{dv_s} = \frac{W^2 \mu}{I_d}\{C_{ox}^2 (v_g - v_s)^2 + (C_{ox}C_b - \tfrac{1}{2}C_{ox}^2)(v_g - v_s)(v_b - v_s) - \tfrac{1}{2}C_{ox}C_b(v_b - v_s)^2\} \qquad (5)$$

For a small amount of charge in the well the difference $v_b - v_s \rightarrow 0$. Using this assumption in Equations (5) and (3), Equation (5) can be simplified as follows:

$$dQ_b / dv_s = 2C_{ox}W \cdot L \qquad (6)$$

This finally leads to a very simple formula for the conversion gain of the BCD detector:

$$S = q/(2 \cdot C_g) \qquad (7)$$

where C_g is the total effective gate capacitance of the structure.

This simple analytical formula for the conversion gain is useful in estimating noise of the BCD detector and expressing it in noise equivalent electrons. We can see that the noise power spectral density of BCD after the 1/f corner is:

$$v^2(f) = \alpha 4kT(1/g_m) \qquad (8)$$

where α is used to include noise of the BCD biasing network. By integrating the noise power spectral density over the signal base-band bandwidth ω_b, assuming only a single pole response, and by dividing the result by the previously obtained expression for the conversion gain, the expression for equivalent noise in noise electrons becomes:

$$N_{ec}^2 = \alpha \frac{kTC_g}{q^2}\omega_b L \sqrt{\frac{8 \cdot C_g}{\mu \cdot I_d}} \qquad (9)$$

From this result, we can conclude that a minimum gate length L, that is allowed by the design rules and that does not introduce large 2D effects, should be used. Also, the effective gate capacitance C_g should be kept at minimum. Finally, the bias current I_d should be maximized.

However, during the development of this detector it was found that the large biasing current can cause additional noise due to injection of hot hole generated electrons. It is thus necessary to optimize the current bias and at the same time keep the hot hole impact ionization at its minimum. Experiments addressing this topic are discussed in the next section.

There are no other parameters to be optimized in this detector. In particular, there is no significant parasitic capacitance to be considered.

The electrons are directly coupled to holes in the BCD channel. We believe that this configuration is the most optimum design that any charge detector can have.

III. BCD Testing and Characterization

The above described BCD detector was incorporated into the 1000x1000 pixel image sensor described previously [1]. The device topology including the new BCD output circuit is shown in Fig. 3.

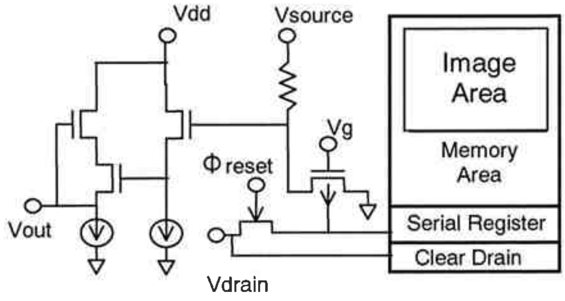

Fig.3. The topology of the BCD test image sensor showing the serial register layout and BCD amplifier circuits.

Since the image sensor parameters affected by the new amplifier are only the conversion gain, output signal waveform, and noise, we will focus in subsequent discussions only on these and list the rest in Table 1. without any other comment.

Table 1 TC281 Image Sensor Specifications

Parameters	Values
Chip Size [mm x mm]	9.0 x 15.8
Total Number of Pixels	1036 x 1010
Pixel Size [μm x μm]	8.0 x 8.0
Horizontal Clk Rate [MHz]	40.0
Saturation Output [mV]	310
Well Capacity [ke]	32
Dark Current [nA] 45degC	0.3nA
Dynamic Range [dB]	64
Sensitivity [mV/Lux]	240

Conversion Gain: This parameter was measured using the actual image sensor by alternately directing charge to the output or to the charge clearing drain shown in Fig3. By measuring the photo-generated current in the drain and the corresponding output voltage, the conversion gain can be accurately established. The results are plotted in the graph in Fig.4a. The non-linearity of the conversion curve is noticeable and it is in a qualitative agreement with Equation(5). At the same time as the image sensor was fabricated, several BCD test structures with different gate lengths and various other dimensions, were made. This allowed extraction of the effective gate length and an investigation of dependence of conversion gain on Cg. This result is given in the graph in Fig.4b. From the graph and comparing the measurement with the theoretical prediction we can conclude that the conversion gain formula holds very well.

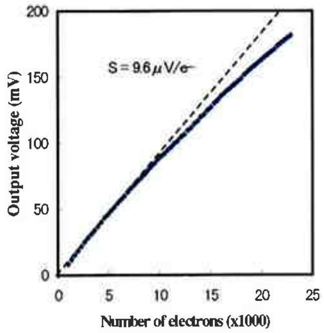

Fig.4a. Image sensor output versus number of electrons in the well. The non linear character of the response is clearly visible on the graph

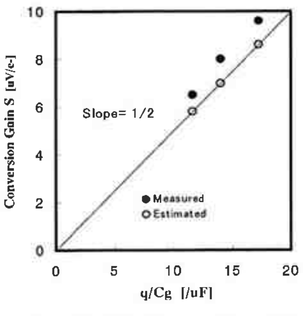

Fig.4b. Plot of conversion gain versus effective gate capacitance and a graph used to extract the effective gate length of the BCD hole channel

Reset Feed Through: Another advantage of the BCD detector is its small reset feed through. This can be seen from the oscilloscope photograph of the output signal shown in Fig. 5. The reason for the small feed through is efficient shielding effect of the BCD gate. The gate almost completely blocks any parasitic reset pulse coupling from the resistive reset gate to the BCD source. Having a small reset feed through is an important advantage for the signal processing circuits.

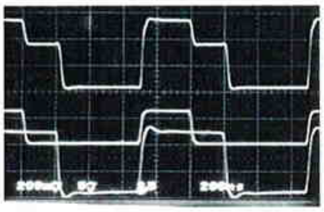

Fig.5. Oscilloscope photograph of the output signal from the test image sensor measured after a unity gain buffer. The waveform shows only a small reset pulse feed through.

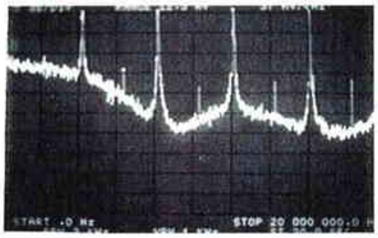

Fig.6a. Noise power spectral density of the BCD image sensor measured with the serial register clocks running continuously and a small amount of charge transported in the register.

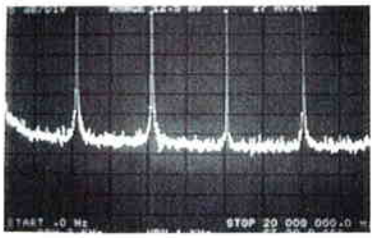

Fig.6b. Floor of the noise power spectral density of the BCD image sensor measured with the serial register clocks running continuously and no charge in the register.

Noise: Two photographs of noise measurement are shown in Fig. 6a and Fig. 6b. The first photograph represents the BCD output with some charge being clocked into the detection node when the serial register is operating continuously without any blanking intervals. The second photograph is the BCD output for the same operation but without any charge. The noise floor can be easily detected in these photographs. Since a simple resistor was used for the BCD source bias, and since it was connected to an external bonding pad, it was easy to investigate the effect of bias current on noise. The measurement of the noise floor as function of the BCD bias current is shown in the graph in Fig. 7.

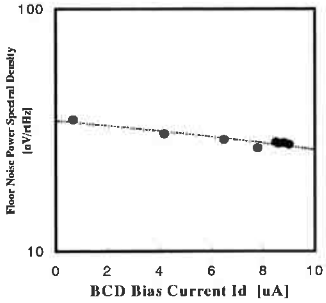

Fig.7. Floor of noise power spectral density plotted as function of the BCD bias current I_d.

Hot Carriers: The hot hole effect in the BCD structure is identical to the substrate current generation in any p-channel MOS FET transistor. When there is a large field in the vicinity of the drain, hole impact ionization causes generation of electron-hole pairs. The electrons are then added to the signal and this creates problem for noise. The measurement results are given in the graphs in Fig. 8 for various BCD gate biases and for various values of the bias current. Form these graphs it can be observed that the amount of hot hole induced charge is linearly proportional to the bias current. Charge is also strongly dependent on the BCD gate bias, since the gate bias directly determines the field at the p+ VP gate - poly gate interface. It can be seen that for the gate bias of approximately zero, the hot carrier effect is very small. From these results it is suggested that the BCD detector is more suitable for high speed operations where the integration time for hot carrier induced charge accumulation is short. The results also suggest that a close attention must be paid to the BCD gate bias level.

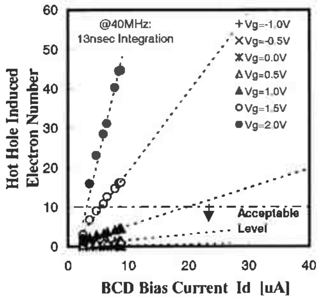

Fig.8. Hot hole induced charge in number of electrons plotted as function of the BCD bias current for different BCD gate biases.

IV. Discussion of the Test Results

In order to directly compare the theory with the measurement and not be concerned with a particular application signal bandwidth, it is better to focus attention on the noise floor power spectral densities rather than on the noise equivalent electrons. With this goal in mind, Equation (8) can be rewritten using parameters that can be directly accessed as follows:

$$v^2(f) = \alpha \cdot (\frac{4kT}{q}) A_o \sqrt{\frac{q \cdot L^2 S_o A_o}{\mu \cdot I_d}} \qquad (10)$$

where S_o is the sensor conversion gain which includes the gain of the source follower A_o.

After substituting required parameters: $A_o = 0.7$, $L = 1.2\ \mu m$, $\mu = 100\ cm^2/Vs$, $\alpha = 2.0$, and $I_d = 10\ \mu A$ into Equation (10), the result becomes: v(f) = 18 nV/RtHz. This results compares nicely with the observed noise floor. Depending on the bandwidth of the signal processing circuitry that follows the sensor, the noise equivalent electrons can be obtained from the expression:

$$N_{ee} = \frac{v(f)}{S_o} \sqrt{f_b \frac{\pi}{2}} \qquad (11)$$

For example, for the bandwidth of 40MHz the result will be N_{ee} = 12.0 electrons. It is reasonable to assume that if the hot carrier effect does not contribute more than 5-10 electrons, within the integration time that for the 40 MHz clocking speed equals 13 ns, the effect can be neglected. This level is achievable as can be observed from the measurement.

V. Conclusions

A new BCD low noise charge detection concept has been introduced in this work. A device based on this concept has been incorporated into a high resolution 1000x1000 pixel VP image sensor and characterized in detail. A simple theory has been used to derive a first order model for the device and compared with the measurements. The developed model was also useful in explaining observed non linearity in charge conversion characteristic and in explaining hot carrier effects.

From the measured performance it is concluded that this detector is superior to previously studied FG detectors and that its higher conversion gain and lower noise makes it ideal for high speed imaging. The only disadvantage identified with this device was a slight non linearity in charge conversion characteristic. However, it is assumed that in most modern applications, that use a digital signal processing, this drawback can be easily corrected. The system complications that result from this problem are more than compensated by the fact that the BCD detector is sensing charge non destructively without generating kTC noise. Therefore, no complex CDS circuits that need critical timing and that must work well at high clocking rates are required for this sensor.

Acknowledgment

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