Impactron—A New Solid State Image Intensifier

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***Abstract*—This paper describes the theory of operation and up to date achieved performance of a new image sensor concept that is using Impact Ionization to multiply photo-generated charge before sensing. It is shown that the charge multiplication based on a single carrier impact ionization is almost noiseless. This allows detected signal charge to be amplified directly in the charge domain and be always kept above the charge detector amplifier noise floor. Charge is repeatedly transferred in a CCD fashion through high field regions where the impact ionization occurs. Even though the impact ionization has a low probability and the high field regions are short the number of transfers is large and significant charge gains are obtained. The developed charge multiplication structure can be easily incorporated into pixels of any standard CCD image sensor and included in the image sensing area, the memory area, or any other vertical or horizontal CCD register with a minimum area penalty. This feature thus provides high flexibility in designing new sensors with various performance characteristics suitable for an extreme low light level imaging. The paper describes in detail the theory of charge multiplication and excess noise generation that is supported by the measured data obtained form the test image sensors. The measurement methods that are used to characterize the charge multiplication gain and noise are also described in detail.**

***Index Terms*—Avalanche multiplication, CCDs, image intensifiers, image sensors, impact ionization, low light level imaging, single photon detection.**

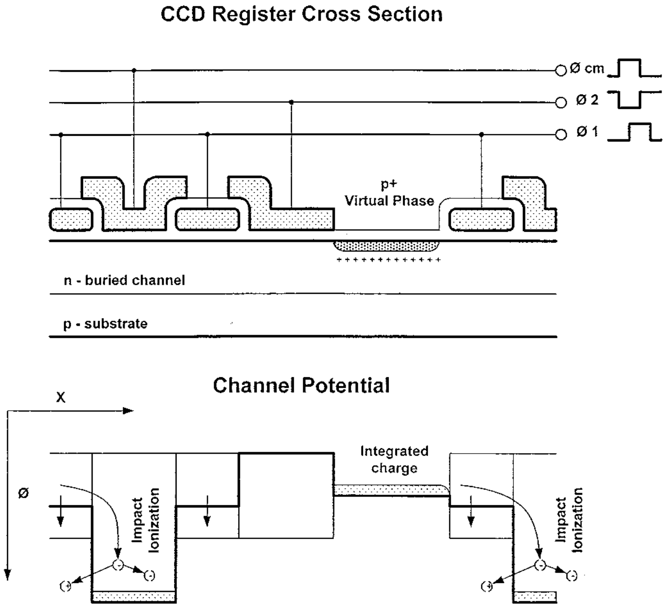

Fig. 1. Cross section of a typical CCD register that contains the CCM structure and that was fabricated using the split gate virtual phase technology.

I. INTRODUCTION

THE charge domain multiplication using impact ionization (II) has been proposed previously to improve sensitivity and noise of existing CCD image sensors [1]–[4]. Since it seems difficult to reduce the noise floor of existing charge detection amplifiers to a single electron, particularly at high clocking frequencies, it is beneficial to focus attention on multiplying photo-generated charge directly in the charge domain before its conversion into a voltage. The charge multiplication can be achieved by creating a high-field region between the two neighboring gates of a standard CCD structure and charge can be injected into this field. When electrons traverse the high field region they gain energy that is immediately dissipated through the lattice scattering and perhaps also through the impurity scattering processes. However, when the field is high enough, the energy gain increases to a point where another energy dissipating mechanism takes place. This is impact ionization. It is well known that the threshold for the impact ionization is relatively sharp and may be dependent on the crystallographic orientation [5]. The electrons involved in ionizing collisions have to satisfy both the momentum and the energy conservation rules, which lead to only a small variance in the II process. The small variance is important for noise, since many consecutive CCD charge transfers are required to achieve a reasonable charge multiplication gain. The large variance would result in noise adding up and defeating the purpose of multiplication. In the following sections it will be shown that a reasonable window of operation for achieving the well controlled multiplication gain and at the same time low noise can be found.

II. THEORY OF IMPACTRON OPERATION

A cross section along the charge transfer channel of a typical CCD register that includes the charge carrier multiplier (CCM) structure is shown in Fig. 1. The process used for the device fabrication was the standard virtual phase (VPCCD) process [6] where the single polysilicon gate was split into several sections as shown in the figure. The gate ϕ_{cm} is completely surrounded by the gate ϕ_1 in order to avoid local high field regions that usually occur for example in corners of rectangular geometries. When the gate ϕ_1 is gradually biased to its high clocking level electrons begin to transfer from the virtual phase region into the high field region that was created previously by the high gate bias of ϕ_{cm}. During this process some electrons undergo impact ionization and new electron hole pairs are created. The new electrons are collected in potential wells and added to the original signal. The holes escape either to the substrate or to channel stops and do not participate in the multiplication process any further. By lowering bias on the gates in a suitable order charge can be transferred either to the next VP region or back to the original well from where it has originated. If the CCM structure

Manuscript received March 19, 2001; revised May 23, 2001. The review of this paper was arranged by Editor D. Verret.

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Publisher Item Identifier S 0018-9383(01)08374-5.

is located in the image sensing area the charge multiplication process can be performed, for example, at the end of the integration period just before the transfer into the memory or vertical registers. In the case of CCM located in the serial register, charge can be multiplied as it progresses in one direction toward the readout amplifier.

The charge multiplication gain depends on the high level bias of the charge multiplication gate ϕ_{cm} and on the number of transfer pulses. Both of these can be easily varied when the CCM is incorporated in the sensor image area. For the case of CCM located in the serial register the number of transfers is determined by the register design and only the clock amplitude controls the gain.

However, the most important parameter of the charge multiplication process is its noise. It is customary to characterize noise in Image Intensifiers by introducing the excess noise factor F [7] as follows:

$$F^2 = \frac{1}{M^2} \cdot \frac{\sigma_m^2}{\sigma_i^2} \tag{1}$$

where

σ_m standard deviation of the multiplied number of electrons;

σ_i standard deviation of the injected number of electrons;

M average multiplication gain.

Since the multiplication process in CCD consists of many individual steps, it is necessary to understand how the number of steps affects noise.

When two random processes A, and B are cascaded, the standard deviation of the resulting process follows the formula [7]

$$\sigma_{AB}^2 = n_B^2 \sigma_A^2 + n_A \sigma_B^2 \tag{2}$$

where n_A and n_B are the average numbers of carriers entering each process. By repeatedly applying (2) N times, where N is the number of CCD transfers, and combining the result with (1), it is possible to express the excess noise factor F in terms of the multiplication gain n_o and the standard deviation σ_o of a single multiplication step

$$F^2 = 1 + \sigma_o^2 \frac{\left(1 - \frac{1}{M}\right)}{n_o(n_o - 1)} \tag{3}$$

where $M = n_o^N$. Since it is expected that the multiplication gain of a single step is very close to unity, the formula can be further simplified and approximated as follows:

$$F^2 \approx 1 + \sigma_o^2 N \frac{\left(1 - \frac{1}{M}\right)}{\ln(M)}. \tag{4}$$

This result is suitable for comparison with experiments, since it depends only on one unknown parameter σ_o. This parameter in turn depends on the material used for building the CCD and it also depends on the temperature, since the temperature affects the band structure of the material and the carrier scattering processes. By measuring excess noise as function of the number of multiplication steps N it is possible to find the value of σ_o. Finding the theoretical value for σ_o and comparing it with the experimental result, however, will be left for future work since this requires overcoming many computational obstacles that are beyond the scope of the paper. An approximate estimate for σ_o can be found by considering that the impact ionization threshold is smeared by the interactions with phonons. By comparing the corresponding energies this becomes

$$\sigma_o \approx \left(\frac{E_p}{E_t}\right). \tag{5}$$

Using the minimum impact ionization threshold for silicon $E_t = 1.18$ eV [5], and the dominant phonon energy $E_p = 51$ mV [9] the result is $\sigma_o = 0.043$. This estimate suggests that a relatively large number of transfers can be used before excess noise grows much larger than unity. The small size of σ_o is an advantage for the single carrier impact ionization process used in this device. The electrons always start from the same initial condition before the impact ionization occurs. This can be contrasted with the avalanche multiplication processes where the multiplied electrons continue to be accelerated and continue to ionize. This leads to a larger excess noise factor as can be seen for example in the recently published work on CMOS image sensor that is using avalanche photodiode pixels [8].

To predict the dependency of multiplication gain on the gate bias the formula for the carrier multiplication coefficient α, derived by Okuto and Crowell [9], can be used

$$\alpha(F) = \frac{eF}{E_t} \cdot \exp\left(a - \sqrt{a^2 + x^2}\right) \tag{6}$$

where

a $= 0.217 \cdot (E_t/\hbar\omega_o)^{1.14}$;

x $= E_t/eFL$;

e electron charge;

F electrical field;

$\hbar\omega_o$ dominant phonon energy;

L carrier mean free path.

Since the field between the gates is not very uniform (6) would have to be integrated over the carrier mean traveling path. However, this would unduly complicate the calculations. To simplify the problem it is assumed that a constant effective field F_{eff} is acting over an effective carrier traveling path L_{eff}. The field intensity in silicon is also reduced by the presence of the gate oxide and by the finite depletion depth. It will thus be further assumed that: $F_{\text{eff}} = \beta \cdot ((V_{cm} - V_g)/L_{\text{eff}})$ where the V_{cm} is the multiplication gate high bias, V_g is the register gate bias at which the carriers begin their injection into the high field region, and β is the reduction factor in Volts. Finally, it will be assumed that the field is relatively week leading to $x \gg a$. This approximation is some times called the Shockley's "lucky electron" model [5]. With these assumptions and simplifications (6) can be recast in the form suitable for a comparison with the measurement as follows:

$$\ln\left(\frac{M^{1/N} - 1}{V_{cm} - V_g}\right) = A_o - \frac{B_o}{V_{cm} - V_g} \tag{7}$$

where

M $= (1 + \alpha \cdot L_{\text{eff}})^N$;

A_o $= a + \ln(e\beta/E_t)$;

B_o $= (E_t/e\beta) \cdot (L_{\text{eff}}/L)$.

III. GAIN AND NOISE MEASUREMENTS

The multiplication gain of the Impactron is easily measured. It was found that the most straightforward way is to vary the light intensity and measure the output with the CCM turned on and off respectively. At the same time the excess noise was also evaluated. Selecting an average pixel of the array and statistically evaluating its output for many frames accomplished this task. Both the mean and variance are found and used to calculate the excess noise factor F. Assuming that the input photon flux obeys the Poisson statistics and that the system conversion gain "A" that relates the number of detected electrons to the measured voltage v_m is known, (1) can be transformed as follows:

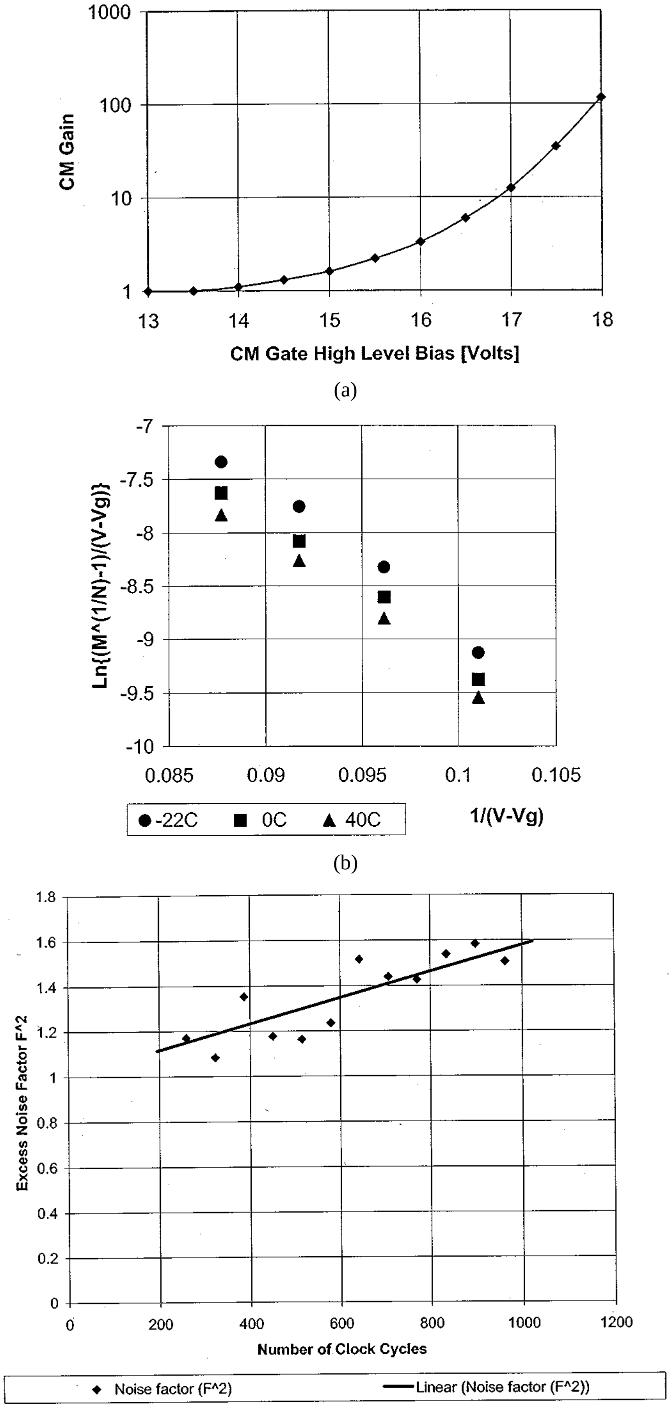
$$F^2 = \frac{1}{M \cdot A} \cdot \frac{\langle v_m^2 \rangle - \langle v_m \rangle^2}{\langle v_m \rangle}. \qquad (8)$$

The result for the multiplication gain M plotted as function of the high clocking bias level V_{cm} for $N = 400$ is shown in the graph in Fig. 2(a). From the graph it can be seen that the multiplication gain up to 120 has been achieved with modest clock high bias levels.

Fig. 2(b) shows the plots of the multiplication gain versus $1/(V_{cm} - V_g)$ for $V_g = 3$ V and for several temperatures according to (7). The data shows a good agreement with the predicted linear dependency. The multiplication gain depends on the temperature and is larger for the lower temperatures mostly due to the mean free path temperature dependency. It is not easy to derive a simple formula for the gain dependency on the temperature, since many parameters such as the band gap and the carrier effective masses are involved. The plots in Fig. 2(b) allow the extraction of the value for the carrier mean free path from the constant B_o. From the graphs we have $B_o \cong 120$. Assuming that $\beta = 0.8$ and $L_{\mathrm{eff}} \cong 0.6$ μm, the mean free path is $L = 50$ Å. This is a reasonable result.

The excess noise factor F^2 is plotted for $M = 14$ as function of N in a graph shown in Fig. 2(c). During this test the high clocking level V_{cm} was adjusted for each N to keep the multiplication gain M approximately constant. From this graph it can be observed that excess noise depends on N linearly as predicted by (4). From the data it is also possible to extract the value of σ_o, which is $\sigma_o = 0.04$. This compares well with the value presented in the previous section considering that only a simple estimate was used.

It is, however, necessary to mention that the noise measurements are notoriously difficult and that many spurious factors can affect the results. For example, unexpected problems can be encountered with the long-term stability of the light source and with the temperature variations of samples during the measurement. These and other uncovered problems such as the carrier trapping in the gate dielectric layers will be addressed in future publications.

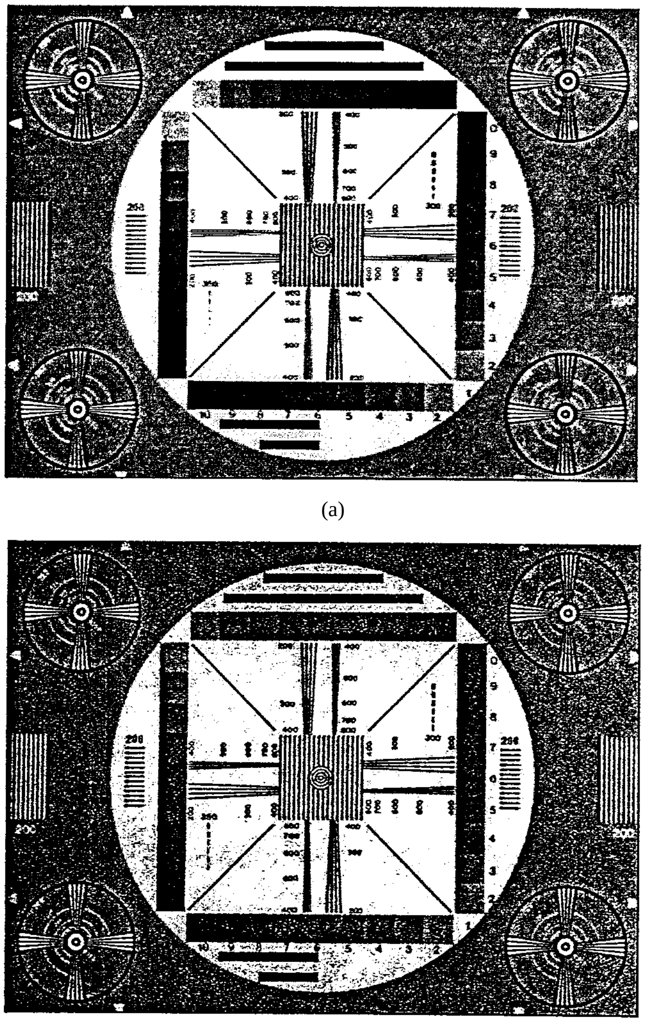


(c)

Fig. 2. (a) Graph of the charge multiplication gain as function of the multiplication gate high clock bias level. (b) Graphs of the charge multiplication factor as function of $1/(V_{cm} - V_g)$ according to (7) for different temperatures. (c) Graph of the excess noise factor as function of the number of transfers. In this test V_{cm} was adjusted for each N to keep M approximately constant at $M = 14$.

IV. DISCUSSION OF THE TEST RESULTS

From the graph in Fig. 2(c), it is concluded that a reasonable number of transfers that will keep the excess noise factor below $F^2 = 1.3$ is approximately 400. The CCM gain that was used with this number of transfer was approximately 14. However, the gain can be easily increased to more than 50 and the single photon detection (SPD) is possible. The multiplication gain of devices with the multiplier in the image area pixels, however, is limited by the well capacity of the pixels. The multiplication is also different for each pixel, which produces a large fixed pattern noise. This needs to be corrected by a complicated off chip



(a)

(b)

Fig. 3. (a) Photograph of the test target imaged by an experimental CCD sensor (680 H × 500 V pixels) with the CCM turned off. (b) Photograph of the same test target imaged by the same CCD image sensor with the CCM turned on and with the ND filter, which reduced the light intensity 32 times, inserted in front of the lens.

signal processing if such devices are to be used for high quality imaging. For this reason another device with the multiplier in the serial register was designed and tested. The photographs of the test target with the CCM gain turned off and with the CCM gain equal to $M = 32$ are shown in Fig. 3(a) and (b), respectively. The picture with the CCM gain turned on was obtained by inserting a neutral density filter, which reduced the light intensity 32 times, in front of the lens. The dark current limited the noise floor of this device. To achieve the SPD operation a moderate cooling or shorter integration times are required.

V. CONCLUSIONS

A novel high sensitivity solid-state image sensor concept has been developed and tested. The concept includes charge multiplication function in its operation that is similar to one used in the vacuum tube Image Intensifiers. The charge multiplication is performed directly in the charge domain before charge is converted into a voltage. This obviates problems associated with the present day image sensor high charge detection amplifier noise floors. The charge multiplication is based on a single carrier II process that occurs when carriers are transported through the regions with high electric field. It is shown theoretically and confirmed by measurements that the single carrier II is a low noise process that allows the development of image sensors with a superb, single photon, low light level sensitivity. The charge multiplication process was modeled by the impact ionization formula derived by Okuto and Crowell and a good agreement with the experiment was found.

ACKNOWLEDGMENT

The author would like to thank the management of Texas Instruments, Inc., for the kind permission to publish the measurement results. His sincere appreciations are extended to all members of the Texas Instruments Japan DISP group and, in particular, to T. Nishiwaki for building the evaluation camera and taking the test pattern pictures, to S. Ohta and T. Tachibana for the measurement of CCM gain versus gate voltage and temperature, and to H. Shibuya and S. Kashima for coordinating the device development and evaluation programs. The author also thanks Miho process engineering and manufacturing groups for their dedicated effort and an extraordinary support provided during all phases of development of these devices.

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