



## DEVICE APPLICATION OF NON-EQUILIBRIUM MOS CAPACITORS FABRICATED ON HIGH RESISTIVITY SILICON

O. Malik, F. J. De la Hidalga-W

Electronics Department, INAOE, Puebla, Mexico

Emails: amalik@inaoep.mx ; jhidalga@inaoep.mx

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*Abstract —This work shows that the direct pulse-wide-modulated (PWM) output electric signal, with a duty cycle controlled by light intensity, can be obtained using a circuit that contains a saw-tooth voltage generator connected in series with a dc voltage source and a metal (semitransparent gate) oxide semiconductor capacitor (MOS-C) operating in non-equilibrium mode.*

*Amplified output signal presents positive and negative PWM waveforms that can be easily separated using diodes. The duty of the positive part is proportional to the light intensity, whereas for the negative part is inversely proportional to the intensity. The frequency operating range of this proposed instrument varies from 1 Hz to a few kilohertz. The duty cycle of the PWM output signal varies from 2 to 98 % when the incident light intensity is varying in the microwatts range. This new transducer could be useful for automatic control, robotic applications, dimmer systems feedback electronic systems, and non-contact optical position sensing for nulling and centering measurements. The detailed description of the physical and operating principles of this invented transducer are presented.*

**Index terms;** MOS-capacitor; silicon; pulse-width modulation; nulling and centering measurements.

## I. INTRODUCTION

Among well known optical sensors based on metal-semiconductor contacts or p-n junctions, metal-oxide-semiconductor capacitors (MOS-C) are known as the basic part of charge coupled devices (CCD) in imaging technique [1]. The charging and discharging processes under irradiation in such devices are possible due to non-equilibrium processes in these semiconductor capacitors [2]. On the other hand, these processes are important for determining important physical parameters of the semiconductor substrate, such as the carrier concentration, generation and recombination times of minority carriers, and the characteristics of the semiconductor-oxide interface [3-9].

In this work we present new aspects of non-equilibrium processes in MOS capacitors with the aim of extending their optoelectronic applications as sensitive optical transducers with direct quasi-digital output in the form of a pulse-width-modulated (PWM) electrical signal. These sensors with the new operating principle allow for the simplification of electronic circuits in automatic, robotic, and metrological applications.

We will discuss also the design and properties of a new optical position detector based on a bi-MOS structure that may be used as a sensitive null indicator with direct digital output in nulling and centering measurements.

## II. OPERATING PRINCIPLE

### a. Physical model

Sensors are based on non-equilibrium physical processes that occur in MOS capacitors which are initially biased by a constant voltage in the strong inversion operating mode. If a voltage pulse is added to this dc bias, an increase of the space charge region width (SCR) to a non-equilibrium value takes place. The excess minority carriers generated in the substrate lead to a reduction of the SCR width to its initial value, and the capacitor returns to its equilibrium mode. In absence of irradiation, the retention time depends on the generation rate of minority carrier in the substrate that is determined by the lifetime of minority carriers. The irradiation effectively decreases this time in comparison with dark conditions. This fact is the basis of the new optical sensors. Let us qualitatively considerate the processes occurring in the MOS capacitor, with an oxide capacitance  $C_{ox}$ , and initially biased by a dc voltage  $U_1$  in the strong inversion. At a certain time, the additional triangular voltage with amplitude  $U_2$  is applied to the gate of the capacitor as shown in Fig.1.

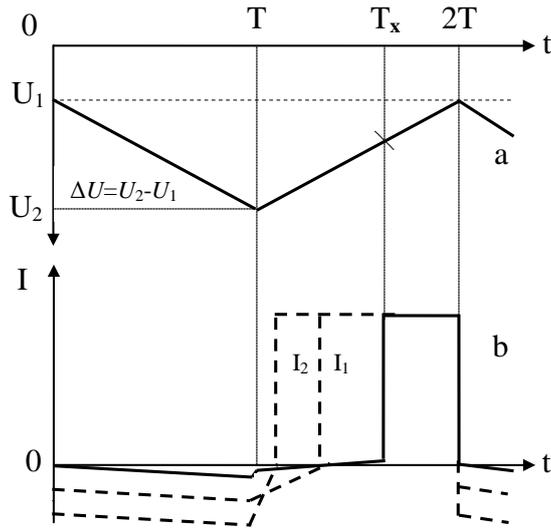


Figure 1. Schematic representation of the voltage (a) applied to the gate of the MOS capacitor, and current (b) flowing through the capacitor: solid line- under dark conditions, dashed lines- under illumination with  $I_2 > I_1$ .

At the first half-period, the increase of voltage from  $U_1$  to  $U_2$  with a voltage rate  $\Delta U/T$  leads to a time-dependent increasing SCR width, from its stationary value  $W_{inv}$  to its maximum  $W_2$  at  $t=T$  when a potential well is created. Both kind of minority carriers, those thermally generated in the SCR, and those diffused from the neutral volume of the substrate start filling this potential well and decrease the SCR width. If the flow of minority carriers is not too high, the potential well will not be filled completely during the first half period, and this process may also continue during the second half period until the voltage reaches  $U_x$ . At  $t=T_x$ , when the created potential well is filled, the MOS capacitor abruptly returns to its initial equilibrium state. At that time, the charge of the capacitor is  $C_{ox}(U_x-U_1)$  and the displacement current presents the constant value  $C_{ox}dU/dt$ . The irradiation increases the generation rate of minority carriers in the substrate, and the transition time becomes shorter than that obtained under dark conditions. This is shown in Fig.1b by dashed lines for two radiation intensities.

b. Mathematic model

The triangular voltage bias shown in Fig. 1 can be described, using absolute values, by:

$$U(t) = U_1 + \frac{\Delta U}{T}t, \quad (0 < t < T). \quad U(t) = U_2 - \frac{\Delta U}{T}(t - T), \quad (T < t < 2T). \quad (1)$$

The filling of the potential well with photo-generated minority carriers (the “charging” process) depends on the generation rate  $G$ . If the incident radiation has a low intensity, the charging of the MOS capacitor by the photo current occurs even when the functional voltage starts decreasing at the second half of the period. When the potential well is filled, the reduction of the voltage till  $U_x$  at the time  $T_x$  returns the capacitor to its initial equilibrium mode. At the time  $T_x$ , the charge stored in the potential well during the photo generation is equal to the capacitor charge at the voltage  $U_x - U_1$ . This fact can be described as:

$$\frac{qGA}{\alpha}T_x = C_{ox}(U_x - U_1) \quad (2)$$

where  $q$  is the electron charge,  $\alpha$  is the absorption coefficient of the semiconductor substrate at the wavelength of the incident radiation, and  $A$  is the gate area. The time  $T_x$ , as a function of the generation rate, can be found from (2) using the second equation of (1) for  $U_x$ :

$$T_x = \frac{2T}{1+K}, \quad K = \frac{qGAT}{\Delta U \alpha C_{ox}} \quad (3)$$

If the MOS capacitor is connected in series with a function generator (dc plus the triangular voltage), the output signal on a load resistor is a pulse with duration  $2T - T_x$ . The duration of the output pulses and the duty  $D$  for the output signal, which is the ratio of the pulse duration to the period of the triangular voltage, are proportional to the irradiation intensity. This is because a higher intensity of the incident radiation provides a faster transition of the capacitor to its equilibrium mode. Thus, the output is a pulse-width modulated electrical signal. Taking into account (3), the equation for the output signal duty can be written as:

$$D = \frac{2T - T_x}{2T} = \frac{K}{1+K}. \quad (5)$$

Taking into account that  $G = \alpha P_{opt} / Ah\nu$ , where  $P_{opt}$  is the power of the incident optical radiation with a photon energy  $h\nu$ , the inverse dependence of the duty on the incident power can be written as

$$\frac{1}{D} = 1 + \frac{qP_{opt}T}{\Delta UC_{ox}h\nu}. \quad (6)$$

The duty does not depend on the area of the capacitor. Note that in the case of a triangular voltage with period  $2T$ , the maximum duty under irradiation can be only 0.5 when  $T_x$  is equal to the half period.

To obtain a higher range of duty due to the variation of the radiation intensity, a saw-tooth time dependent voltage must be applied to the gate. In this case, the fast increasing of the voltage from  $U_1$  to  $U_2$  during time  $\Delta t$ , which usually is 1-2% of  $T$ , creates the potential well, whereas the filling of this well by the photo generated carriers occurs during the slow decrease of the voltage from  $U_2$  to  $U_1$  during  $T-\Delta t$ . Then, using similar arguments as those used for the triangular voltage, the dependence of the duty on the incident radiation power is:

$$\frac{1}{D} = 1 + \frac{qP_{opt}(T - \Delta t)}{\Delta UC_{ox}h\nu} \quad (7)$$

In this case, the duty range may vary from 0.2 to 0.9 under irradiation.

For both cases, triangular and saw-tooth voltages, there are some frequency limits. The low frequency is determined by the generation rate of minority carriers in the SCR as well as their diffusion from the neutral substrate. The low generation rate occurs at a large generation time of minority carriers. Figure 3 shows the dependence of the minimal operating frequency on the generation time of minority carriers obtained by the mathematical modeling of the MOS capacitor operating under dark and non-equilibrium conditions. The parameters used for the calculations to obtain a PWM output with a duty factor  $D=0.02$  are shown.

For example, if the generation time is  $\sim 0.5$  ms, the transition time  $T_x$  is near 2 s, the low frequency limit will be 0.5 Hz. Thus, the typical operating frequency on non-equilibrium MOS-C under illumination corresponds to a few hertz. The high limit is determined by the time response of the minority carriers with respect to the voltage variation and the reactance of the capacitor, and is in the range of a few kilohertz.

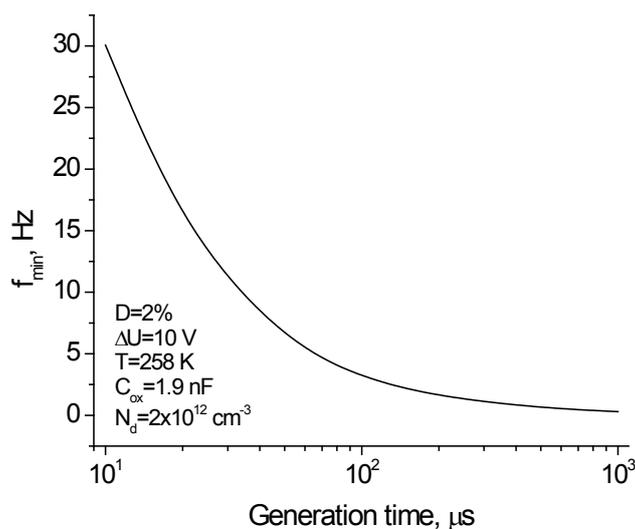


Figure 2. Dependence of the minimal operating frequency, under dark conditions of the non-equilibrium MOS capacitor, on the generation time of minority carriers.

### III. RESULTS

#### a. Fabrication and measurements of the MOS capacitors

MOS capacitors were fabricated on high resistivity (2-4 kΩ-cm) n-type silicon, with a 70 nm thermally grown oxide, and a titanium semitransparent gate. For measurements, the capacitor was connected in series with a function generator, with a dc offset and a load resistor as shown in Fig. 3. The output was obtained using a digital oscilloscope TDS 3054C, and a light emitting diode (LED), with emission at 0.9 nm, was used to illuminate the MOS capacitor.

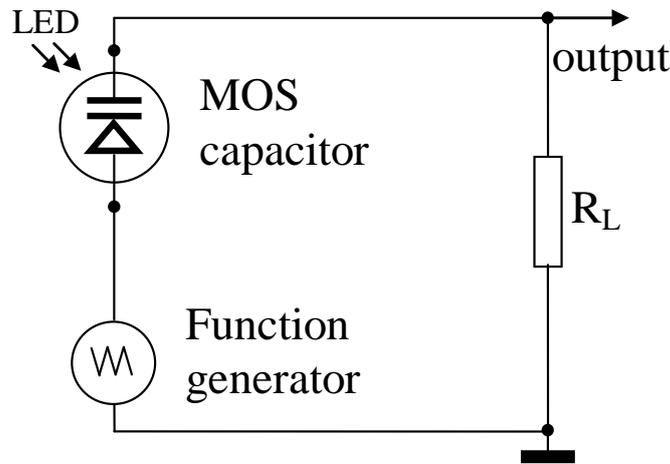


Figure 3. Circuit used for the measurement of the transducer.

#### b. Experimental results and discussion

Figure 4 shows the current for the MOS capacitor under dark conditions after applying the dc and the triangular voltages.

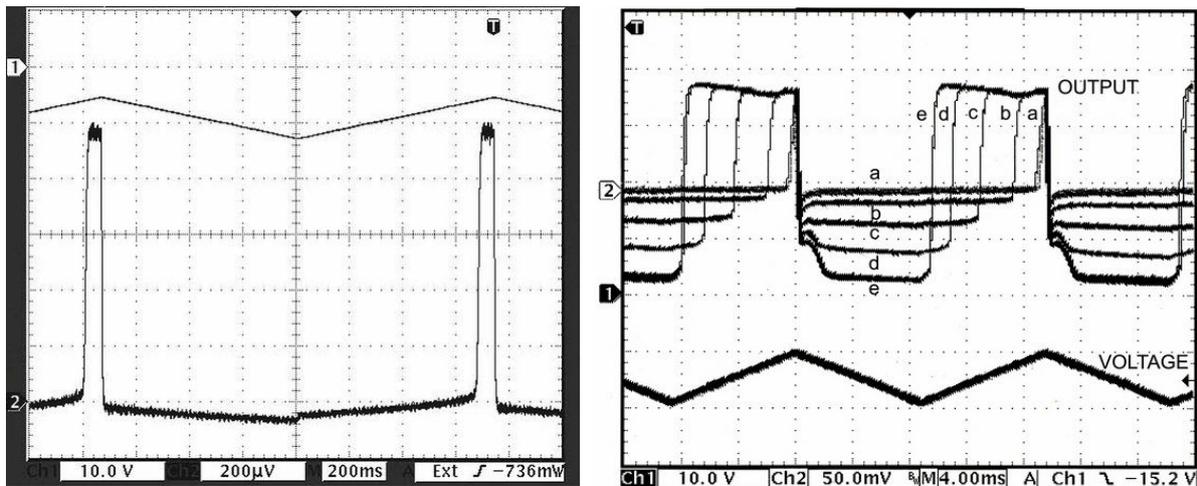


Figure 4 (left). Oscillograms for the applied dc and triangular voltages (above, scale 10 V/div) and current in dark (below, scale 200  $\mu$ V) obtained with a 50 k $\Omega$  load resistor.

Figure 5 (right). Oscillograms (4 ms/div) for the applied dc and triangular voltages (below, 10 V/div), and current (50 mV/div, curves a-e), obtained for the illuminated capacitor. Illumination increases from a to e.

The current oscillograms for the illuminated MOS capacitor were recorded for a LED incident power varying in the 20 nW to 0.5 mW range. One can see from Figure 5 the difference in the transition time for illuminated MOS-C at different illumination conditions, where capacitor was biased with the dc and triangular (60 Hz) voltages. The transition time decreases for an increasing illumination.

Figure 6 shows the oscillograms for the current of the illuminated MOS capacitor for the case of a saw-tooth voltage applied to the gate.

To obtain a “clear” PWM output signal with sharp transitions for both edges of the pulse, the signal from the load resistor was amplified by  $10^3$  times, and limited by the amplifier to 10 V. The negative part of the signal due to the photocurrent was rejected using a diode.

Figure 7 shows the oscillograms for the amplified output for the dc and triangular voltages applied to the gate of the MOS capacitor. It is evident the pulse-width-modulation nature of the output signal under different illumination levels. For the case of a triangular voltage, the maximum value of the duty is 0.5.

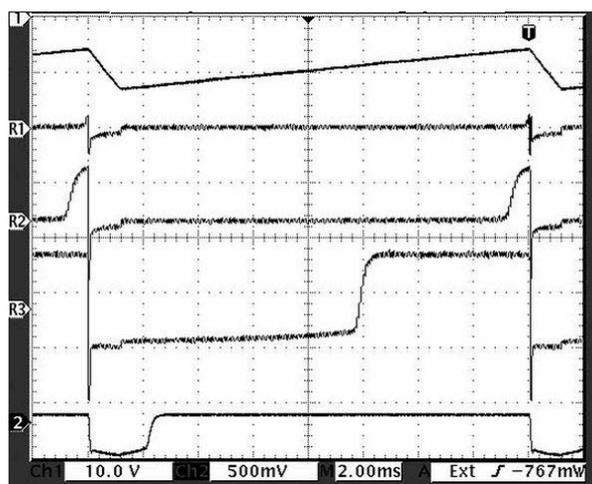


Figure 6. Oscillograms (2ms/div) for the applied voltage (above, 10 V/div) and current (500 mV/div) under dark and for three irradiation conditions. The scale for the last current

A higher range of variation for the duty, from 0.02 to 0.87, is obtained when a saw-tooth voltage is applied, as shown in Fig. 8.

From the above mentioned, these non-equilibrium MOS capacitors can be used in applications such as light-controlled sensitive transducers in automatic control and robotic circuits. Below, we present another new metrological application for these MOS capacitors.

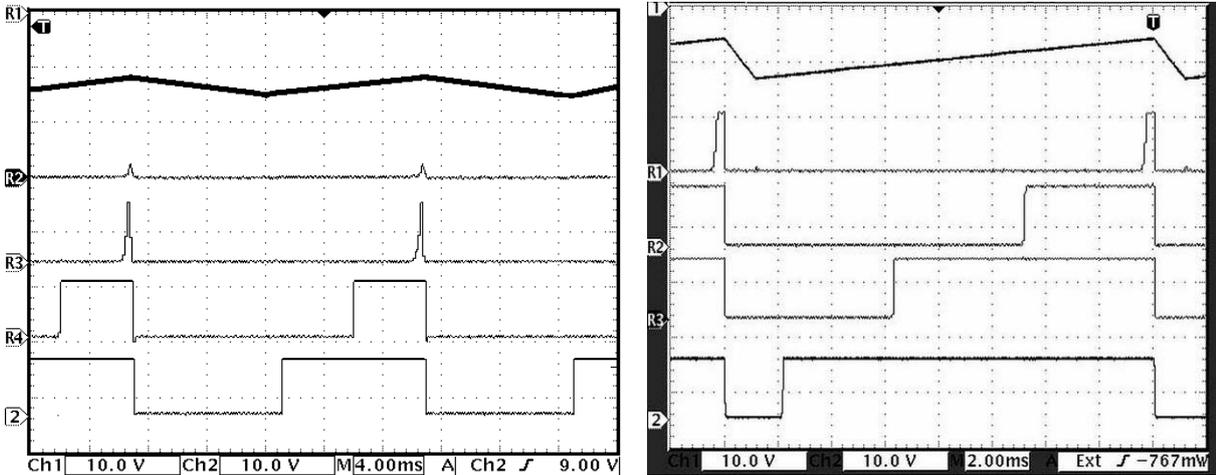


Figure 7 (left). Oscillograms (4 ms/div) for the dc and triangular voltages applied to the gate (above curve, 10V/div), and amplified output signal (10 V) under different values of illumination from the LED.

Figure 8 (right). Oscillograms (2 ms/div) for the dc and saw-tooth voltages applied to the gate (above curve, 10V/div), and the amplified output signal (10 V) under different values of illumination.

#### IV. Bi-MOS CAPACITOR AS AN OPTICAL DIGITAL TRANSDUCER FOR NULLING AND CENTERING MEASUREMENTS.

The bi-cell optical detectors are well known for position sensing. They operate under the principle of having two photodiodes separated by a small gap. These elements are generally built into a common substrate, thus their cathodes are shared. The anode or active area of each element is individually contacted. When a light spot is translated across the detector, its energy is distributed between both elements, and the difference in electrical contributions to each element defines the relative position of the light spot with respect to the center of the device. The detector provides the position information only over a linear distance of twice the spot diameter or until the edge of the spot has reached the detector gap. A linear transfer function can be obtained for a rectangular light spot because its linear movement is

proportional to the percentage of its area that shifts between the elements. The sensitivity of silicon bi-cell position detectors is 2-3 V/mm. Such detectors are most effectively used as nulling and centering devices with resolutions of 0.1 micrometers or higher. Nevertheless, these devices present analog output and an analog-to-digital signal converter (ADC) is necessary for their application in digital circuits. Additionally, the characteristics of the ADC can affect the precision in position measurements. The use of non-equilibrium processes in MOS capacitors under illumination allows for designing new devices for position sensing.

Figure 9 shows schematically the construction of our new position sensitive optical transducer.

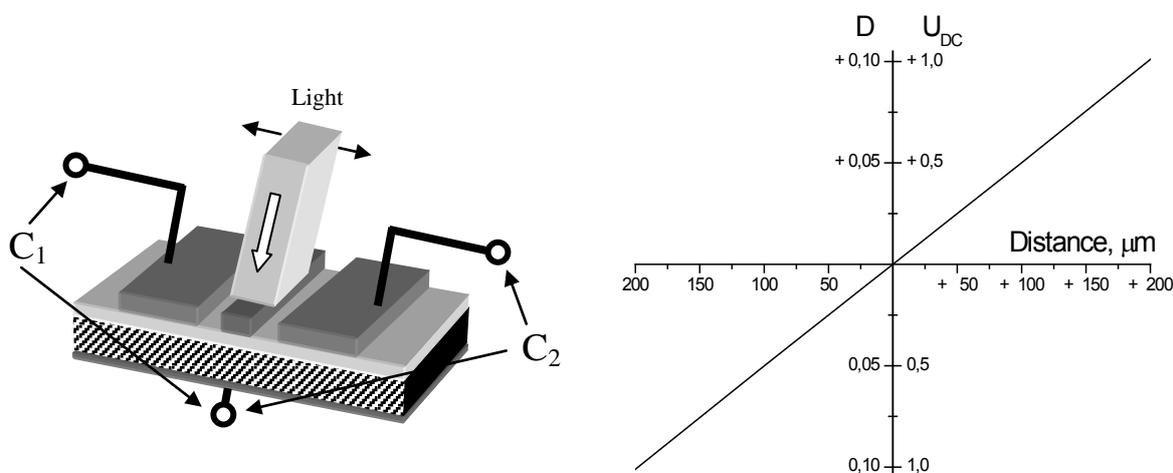


Figure 9 (left). Schematic model of the new position sensitive optical transducer.

Figure 10 (right). Calculated dependence on the light spot position for the duty (D) and  $U_{DC}$ .

Our new transducer is based on two MOS capacitors ( $C_1$  and  $C_2$ ), fabricated on the silicon substrate on a distance longer than the diffusion length of minority carriers in the substrate. Part of this area is covered by a metallic opaque shield. The size of the light spot must be a little bit larger than the width of the shield. If the spot is at the centre of the distance between both capacitors, the same generation rate is nearly found at the end of each capacitor. The electric field at the lateral SCR of the biased capacitors separates the photo-generated carriers, and equal photocurrent will flow through each capacitor. Under such conditions, and as was shown earlier, an output PWM signal with the same value of duty can be registered. A small movement of the spot will produce a misbalance in both photocurrents and consequently a difference in duty for both output electric signals. If a differential amplifier is used to record these PWM signals, the information about the spot position may be obtained from the polarity and the duty of the resulting signal. Using (6), the mathematical modeling of the sensing

characteristics of such transducer can be provided for the silicon MOS capacitors and a rectangular  $2\text{mm}\times 1\text{mm}$  light spot with a power of  $0.3\text{ mW/cm}^2$  from a LED with emission wavelength of 930 nm. The initial light intensity produces two equivalent PWM output signals with a duty of 0.5. Taken into account a variation of the incident optical power during the spot movement, the differential PWM signal (that can be supplied by a differential amplifier) was calculated as the dependence of the resulting duty (D) on the spot position. Figure 10 shows this dependence. The transfer function is linear for the spot movement till 200 micrometers. At that limit the duty of the resulting PWM signal changes to 0.1. The polarity of the resulting PWM signal shows the direction of the movement. The use of a low-pass filter allows for transforming the 10 volts output PWM signal into a dc voltage ( $U_{DC}$ ) The slope of  $U_{DC}$  allows us for obtaining conclusions about the sensitivity of this new position transducer. This sensitivity results to be two times higher than that obtained with standard bi-cell silicon analog detectors.

We also conducted the experimental modeling of the reported transducers fabricated on a high-resistivity silicon substrate. The PWM output signals from both capacitors were amplified with a two-channel transimpedance amplifier.

The amplified signals were added with the differential amplifier and recorded using a digital oscilloscope. Each capacitor was connected in the circuit configuration shown in Fig. 3. The combination of 10 V dc and 10 V triangular voltages was applied to the gates of the capacitors.

The oscillograms of the output signals with and without amplification, when the dc and triangular voltages are applied to the gate of the MOS capacitors, are shown in Fig. 11.

A non-uniform illumination means a displacement of the light spot relatively to the center of the bi-MOS capacitors. The amplified output is bipolar due to the amplification of both output signals (positive displacement and negative photo currents). Figure 12 shows the output signals added by the differential amplifier. The middle curve was obtained when the illumination of the capacitor  $C_1$  was higher than that applied to  $C_2$ . The curves presented below show the opposite case.

Thus, the principal feature of our proposed transducer is the obtaining of a direct PWM output, with a duty that indicates the position of the light spot, whereas the polarity of the output signal indicates the direction of the spot movement. A detailed characterization of our new transducers for nulling and centering measurements will be presented in a separate publication.

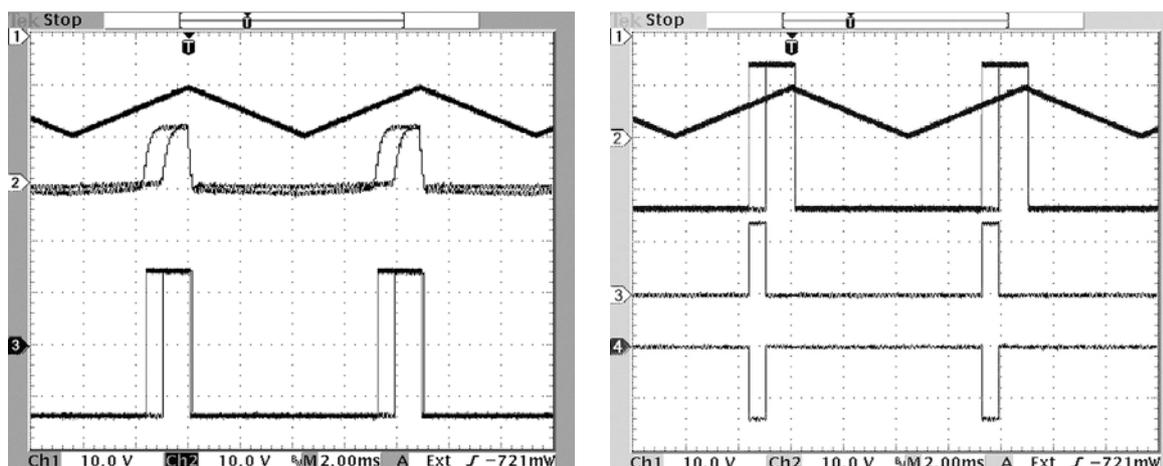


Figure 11 (left). Oscillograms for the non-amplified (middle curves) and amplified (below curves) outputs obtained for the bi-MOS capacitor under non-uniform illumination conditions. The composition of the dc and triangular voltages (top curve) are applied to both capacitor gates.

Figure 12 (right). Added output signals obtained for the bi-MOS transducer.

## V. CONCLUSIONS

In this work we show that non-equilibrium processes in MOS capacitors can be used for designing new light-controlled transducers with direct pulse-width-modulated output, with a duty proportional to the light intensity illuminating the capacitor. The amplified digital output using a rectangular waveform allows for the direct connection to a microcontroller or other logic circuitry. Such transducers are useful for different applications in automatic control and robotics systems due to their fabrication simplicity, as well as the possibility to simplify the associated electronics.

A new type of optical transducer for nulling and centering measurements is proposed using on-chip bi-MOS capacitors. Our previous mathematical and experimental modeling show interesting features of these transducers as the possibility to fix the position of a light spot by observing the duty value of the differential output signal and the moving direction of the spot through the polarity of the differential output signal. These transducers present a linear transfer function for a light spot movement of about 200 micrometers, and a two times improved sensitivity in comparison with standard analog devices.

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