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TIME-RESOLVED X-RAY DETECTION USING MOS-C DETECTORS*

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Summary

To develop a fast x-ray detector with a memory, we have performed experiments with metal-oxide-semiconductor capacitor (MOS-C) devices. For time-resolved recording of the x-ray pulse, a linear array of detectors is uniformly irradiated while the elements are sequentially biased at Δt time intervals; significant positive charge trapping occurs in each element of the array only during the period Δt when the high field bias is applied across the dielectric. Detection of 10-ns resolution has been recorded. Time-resolution is presently limited by the bandwidth limitation of the bias strobing method.

Introduction

Time-integral detectors using a linear array of MOS-C devices have proven to be successful in detecting x-rays with energy less than 50 keV and dosage in device up to 10^6 rads.¹ The MOS-C detectors are especially suitable in an environment of low-energy x-ray photons of very high flux density. A major feature of the MOS-C detector is that the three functions of detection, memory, and readout are integrated in a single device. Because of the memory feature of the device it becomes interesting to explore the possibilities of developing a time-resolved detector, i.e., a detector capable of recording information for a controlled time duration Δt and of retaining that information for later electronic processing.

A time-resolved detector with a memory would have important application in minimizing the bandwidth requirement for fast detector systems. As an example, the transmission of fast-rise-time signals from a radiation detector over a long distance poses a major problem with respect to the bandwidth requirement of the coaxial cable. Wherever possible, it is desirable (1) to use an interim storage (or memory) at the detector site, and (2) to sample the information content of the signal at a low rate in order that the sampled information be within the bandwidth capabilities of the transmission system. In this paper we consider the application of MOS-C devices for use as fast detectors with memories, also we report on experiments where we have performed detection with low energy x-rays with time resolution less than 10 ns.

Time Framing Recorder

The detection scheme is based primarily on the trapping of charge carriers (generated by Compton electrons due to x-rays) in a dielectric layer.² A 0.5- μ m-thick SiO₂ layer is thermally grown on a silicon wafer (10 Ω -cm p-type). An aluminum ohmic contact is then made to the substrate of the silicon; also, an array of aluminum field plates are evaporated onto the surface of the SiO₂. Each detector element is comprised of a rectangular 0.05 by 0.5 cm field plate. Eleven detector elements with 0.25-cm center-to-center spacing are fabricated on a 3.2-cm diameter silicon wafer.

Fig. 1. Time-resolved detection using a linear array of MOS-C devices.

A time framing recorder can be fabricated by utilizing a linear array of detectors that is scanned time sequentially. For time resolved detection of an x-ray pulse, the linear array of detectors is irradiated uniformly as shown in Fig. 1, while the elements are sequentially biased-on for a Δt time interval. Since the detector sensitivity is dependent upon the bias applied during irradiation (e.g., when the bias is switched from 0 to 100 V), significant positive charge can be stored in each element only during the period in which it is biased-on. In this manner we are able to measure the absorbed dosage for each interval of time.

Either of two bias modes (Fig. 1) can be used: delta function strobing (DFS) or step function strobing (SFS). The bias voltage is derived from a photodiode driven into saturation by the x-ray pulse. We are able to obtain 20 A, saturated photocurrent with rise time of 5 to 20 ns dependent on the intensity of the x-ray signal by using a NaI scintillator in conjunction with an ITT, 2.5-in photodiode operated at 4 kV. If this photocurrent is appropriately fanned out to 7 channels in a 50- Ω transmission line as shown in Fig. 2, 70-V

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Fig. 2. Bias pulse fan-out.

Fig. 3. Time-resolved detector.

bias levels in the SFS mode can be impressed on the MOS-C elements with a minimum delay time of 15 ns to the first channel. Rise time can be reduced to 5 ns with a pulse shaper using a Krytron tube, but with a minimum delay time of 30 ns to the first channel. A time-resolved detector is shown in Fig. 3. The cover has been removed to show the distribution lines and terminating resistors. The 3.6 ns rise time in the detector system is due primarily to the 150 pF capacitance of the detector rather than the distribution system.

Readout of the stored charge is accomplished by measuring capacitance of the MOS-C detector element. If surface states at the SiO_2 -Si interface are neglected, the equivalent circuit of the detector consists of the oxide capacitance C_{ox} in series with the depletion capacitance C_D of the silicon. Because the trapped positive charge is related to the x-ray dosage, the MOS-C readout mode provides a simple method for determining the magnitude of the positive charge. Capacitance vs applied bias (C vs V) is measured before and after irradiation as shown in Fig. 4. The amount the capacitance dip has shifted in voltage, called the flat band voltage shift ΔV_{FB} , after irradiation

Fig. 4. MOS-C readout scheme.

tion is a measure of the x-ray dosage. It is to be noted that the primary function of the silicon wafer (other than as a substrate for growth of the SiO_2) is to provide C_D for the readout mode. The C_D is bias voltage dependent and, being in series with C_{ox} , will provide for the capacitance dip as shown in Fig. 4. Positive charges stored in the dielectric will affect a negative voltage shift in ΔV_{FB} . A rapid, simple method for observing the C vs V curve is on an oscilloscope using a negative linear sweep of submillisecond duration (obtained from the sum of a positive linear sweep and a negative square pulse), as shown in Fig. 4. Because of an inversion layer at the surface of the silicon wafer, it is important that the bias be linearly swept from accumulation to inversion for a bias having submillisecond duration. Therefore the waveform of the bias should have a positive rather than a negative slope (i.e., the bias waveform is switched from 0 to -100 V and then linearly increased to 0 V, rather than having the waveform linearly decreased to -100 V and then switched to 0 V).

Memory Writing Rate

Memory storage in an MOS-C device occurs by the immobilization of holes in traps for periods ranging in months. For application to time-resolved detection, the memory writing rate is determined by the lifetime of the carriers. Carrier lifetime should be less than the sequential scanning period Δt of the detector element; otherwise, serious distortion of the signal could occur. For example, distortion will occur in the recorded signal, if the ionized holes in time interval 1 of Fig. 1 are not trapped in the same time interval, but instead the holes are trapped in time interval 2. Similarly, if the ionized electrons are not trapped in the time interval prior to Δt (where no bias field has been applied), these electrons will contribute to the perturbation in the electron density in a later time window and, hence, will cause an error in the density of trapped holes.

For holes³ and electrons,⁴ the product of mobility μ and the lifetime τ before trapping in SiO_2 is

$\mu_h \tau_h \leq 10^{-10}$ cm²/V, and $\mu_e \tau_e = 10^{-9}$ cm²/V, respectively. The mobility of electrons⁵ in SiO₂ is about 10 cm²/V-sec; therefore, the mean lifetime of the electrons before trapping is about $\tau_e \approx 10^{-10}$ sec, and for the holes $\tau_h \leq 10^{-10}$ sec for an assumed mobility for the holes of one-tenth of that of the electrons. Because the detector sensitivity is higher with applied field ($\sim 10^6$ V/cm) it would appear that the sweep out-time of the electrons should be less than the lifetime of the electrons to minimize electron trapping (or recombination with the trapped holes), for an assumed hole lifetime less than the time required to sweep the electrons out of the SiO₂ layer. (A saturation velocity greater than 5×10^5 cm/sec for the electrons in the amorphous SiO₂ would satisfy the above criteria.)

It would be useful to confirm by direct experiment that the carrier lifetime is less than a nanosecond. The basic experiment for carrier lifetime has been the measurement of detector sensitivity vs the time duration T of the bias field applied to the detector for an x-ray pulse width much less than T. The bias pulse is triggered coincidentally with the x-ray pulse. Device sensitivity vs T should be constant until T approaches the carrier lifetime at which time device sensitivity should begin to decrease. Initially, experiments were performed with a Blumlein x-ray source having 40-ns FWHM (10 ns jitter). Detector sensitivity remained constant as the bias pulse width was decreased to the base width (100 ns) of the x-ray pulse. With the Blumlein source, the carrier lifetime was determined to be less than 100 ns. Experiments are in progress to extend the measurements to the 1 to 10 ns range. An electron beam source with a pulse width of 1 ns is used. The electron pulse is generated by sweeping the beam across an aperture in the collection system. A small diameter (0.075 cm) MOS-C is mounted in a 50-Ω coaxial collector structure. The bandwidth of the collector system (basically determined by capacitance of the MOS-C) restricts to 5 ns the rise and fall time of the applied bias pulse to the MOS-C. Preliminary results indicate a drop-off in the detector sensitivity when the bias pulse is delayed approximately 5 ns with respect to the electron beam pulse. Thus, confirming the carrier lifetime to be less than 5 ns.

Detector Calibration

If x-rays irradiate a MOS-C device, the flat-band voltage shift is given by

$$\Delta V_{FB} = \int g dD, \quad (1)$$

where g is the rate the flat-band voltage is integrated with respect to the dosage D at a given bias voltage v_b . The incremental dosage can be written in terms of the intensity I and the incremental time dt

$$dD = I dt, \quad (2)$$

hence, the flat-band voltage shift with respect to the intensity is

$$\Delta V_{FB} = \int g I dt. \quad (3)$$

Initially, the detectors are calibrated using a Picker x-ray machine with either a molybdenum or a tungsten target tube. The resulting calibration curve is the ΔV_{FB} vs D curve, as shown in Fig. 5. The g factor is obtained from Fig. 5 by graphical differentiation and is plotted in Fig. 6 as g vs D. Finally,

Fig. 5. Flat band voltage vs dosage.

Fig. 6. g-factor vs dosage.

from Figs. 5 and 6, g is re-plotted against v_b with ΔV_{FB} as a parameter. (See Fig. 7.) This curve is utilized in determining the g-factor, as discussed in Appendix A.

For strobe pulses having a very short rise and fall time with respect to the time interval Δt , the average intensity expressions as derived in Appendix B simplify with $a = b = 0$. For the SFS bias mode, the intensity from Eq. (12) becomes

$$\bar{I}_n = \frac{\Delta V_{FBnS} - \Delta V_{FB(n+1)S}}{\Delta t(g_v^T - \bar{g}_0)_n}, \quad (4)$$

and for the DFS bias mode, the intensity from Eq. (18) becomes

$$\bar{I}_n = \frac{\Delta V_{FBnD} - \Delta V_{0D}}{\Delta t(g_v^T - \bar{g}_0)_n}, \quad (5)$$

where the subscript n identifies the channel number, the subscripts S and D in ΔV identify the SFS and the DFS bias modes, respectively.

Test Results

Test results of time-resolved detection at 20-, 10-, and 5-ns intervals are given for x-ray detection using the sequentially scanned MOS-C detector. The x-ray source was a dense plasma focus (DPF) device.* The x-ray pulse provides about 5 mcal/cm²

* Operated for Kirtland Air Force Base, New Mexico, by Physics International, San Leandro, Calif.

for a 10-cm source distance in less than 100 ns pulse width for the total x-ray spectrum (predominantly less than 50 keV). Several examples are given in Fig. 8 for time resolved detection using the MOS-C detectors for both bias modes and for different rise times of the bias pulse. The detectors were placed 20 cm from the source except that for the 5 ns test the detectors were placed 10 cm from the source. It is of major importance that finite differences occur for ΔV_{FB} vs the channel number. The corresponding bar graphs for the x-ray intensity vs time using the approximation given in Eqs. (4) and (5) are also shown in Fig. 8 (first-order correction is shown by the dotted line, the corrections required in the other two cases are within the cross-hatched, experimental error). Shown below the intensity bar graph is the real time signal of the total x-ray spectrum as measured with a photodiode-scintillator detector. The intensity bar graph for the 5-ns window is not shown because of the requirement of a second-order correction. Finite differences in ΔV_{FB} of approximately 1 V are still recorded using the poor quality strobe, bias pulse shown in Fig. 8(d). Further development in the strobe system is in progress. By the use of one avalanche transistor per channel, the rise time and the delay time can be improved to a few nanoseconds. The required fast rise time trigger signal to the avalanche transistor will be provided from a saturated photodiode-scintillator operated at a lower voltage than that described under Time Framing Recorder.

In the DPF machine there is not necessarily a time correlation between the various portions of the x-ray spectrum. Therefore, it is not possible to compare the test results from the time-resolved MOS-C detectors to test results of the real time photodiode signal because the MOS-C detectors respond primarily to the lower end of the x-ray spectrum whereas the photodiode-scintillator detector responds to the total spectrum. Further experiments are in preparation to compare the time-resolved MOS-C test data to the real time signals. The

Fig. 8. Test results.

photomultiplier-scintillator detector, which provides the real time signal, will be used in conjunction with a bent crystal spectrometer.¹ A shielded cut-out form will be used in the spectrometer-scintillator interface to simulate the low energy portion of the spectrum that the MOS-C devices detect.

Conclusion

Time resolved detection of low-energy x-ray pulses can be performed using MOS-C detectors. The sensitivity of the detectors as a function of the applied bias makes the detection possible. X-ray pulses of energy less than 50 keV and approximately 100 ns long have been time resolved at 20-, 10-, and 5-ns intervals. The minimum usable time interval is governed not only by the carrier lifetime but also the time required to sweep electrons from the SiO_2 . Corrections must be applied to the output signal when the rise time of the strobe bias pulse is comparable to the time resolved interval.

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Fig. 7. g-factor vs bias voltage.

Appendix A

Estimates for the Average g-Factor

Examples are given to demonstrate the method for estimating the average g-factor in connection with Fig. 7 for a strobe pulse having a peak amplitude of 100 V.

- Consider an infinitesimally short strobe pulse rise and fall time. (a) In the SFS bias mode assume $\Delta V_{FB1} = 25$ V, $\Delta V_{FB2} = 20$ V, and the change in the flat-band voltage in the first time window ($t_1 - t_2$) is $\Delta V_{FB1} - \Delta V_{FB2} = 5$ V. Assume that the intensity varies linearly in a given time window; hence, the average g from Fig. 7 is $\bar{g}_v = 49 D_0^{-1}$ V/rad for an average $\Delta V_{FB} = 2.5$ V since ΔV_{FB} varies between 0 and 5 V in the time window. (b) In the DFS bias mode assume $\Delta V_{FB1} = 5.5$ V, $\Delta V_{FB0} = 0.5$ V, and the change in the flat-band voltage in the first time window ($t_1 - t_2$) is $\Delta V_{FB1} - \Delta V_{FB2} = 5$ V. The average $\bar{g}_v$ is the same as that estimated for the case of the SFS bias mode.
- Consider a strobe pulse with a linear rise in the window time of Δt as shown in Fig. 9 for $\Delta V_{FB} = 5$ V. A dynamic g-curve (labeled A) is superimposed on the g-curves of Fig. 7, since the bias changes linearly with respect to time from 0 to 100 V and the change in the flat-band voltage also changes linearly from 0 to 5 V. The average value is determined by $\bar{g}_A = \int_0^{100} g_A dv_b / 100$ and has an average value of $\bar{g}_A = 38 D_0^{-1}$ V/rad.
- Consider a strobe pulse in the DFS bias mode having a linear ramp for both the rise and fall portion of the pulse, as shown in Fig. 10. Assuming a 5-V, flat-band voltage shift to be contributed equally from the first and second time interval, then ΔV_{FB1} varies from 0 to 2.5 V in the first time interval and from 2.5 to 5 V in the second time interval. The dynamic g curve for the rise ($\bar{g}_R$) and fall portion ($\bar{g}_F$) of the pulse is shown in Fig. 10. From these curves the average value is $\bar{g}_R = 40 D_0^{-1}$ V/rad and $\bar{g}_F = 36 D_0^{-1}$ V/rad, the average g-factor being slightly greater on the rise portion than the fall portion.

Similarly, other dynamic curves can be drawn corresponding to various pulse waveforms for the determination of the average g-factors.

Appendix B

Relationship for Intensity

Consider an x-ray pulse in which time-resolved detection is performed using the SFS bias mode as shown in Fig. 11(a). If the strobe pulse has a finite rise time, the g-factor will be different for each time interval of the bias pulse. The flat-band voltage shift in the first time interval (or in the first channel of the array of detectors) becomes

$$\Delta V_{FB1} = \int_0^{t_1} g_0 I_0 dt + \int_{t_1}^{t_2} g'_v I_1 dt + \int_{t_2}^{t_3} g_v I_2 dt + \int_{t_3}^{t_f} g''_v I_f dt \quad (6)$$

Fig. 9. Dynamic g-curve for linear ramp.

and for the second time interval (or the second channel)

$$\Delta V_{FB2} = \int_0^{t_1} g_0 I_0 dt + \int_{t_1}^{t_2} g_0 I_1 dt + \int_{t_2}^{t_3} g'_v dt + \int_{t_3}^{t_f} g_v I_f dt. \quad (7)$$

Since g_0 (at 0 V bias) is almost constant with respect to the dosage level (see Fig. 6), the difference between the flat-band voltage shift for adjacent channels is

$$\Delta V_{FB1} - \Delta V_{FB2} = \int_{t_1}^{t_2} (g'_v - g_0) I_1 dt + \int_{t_2}^{t_3} (g_v - g'_v) I_2 dt \quad (8)$$

since

$$\int_{t_3}^{t_f} g''_v I_f dt \approx \int_{t_3}^{t_f} g_v I_f dt, \quad (9)$$

if $\Delta t \ll$ total pulse width.

Fig. 10. Dynamic g-curve for triangular strobe.

In terms of the average intensity $\bar{I}_1$ and $\bar{I}_2$ and the average $\bar{g}$ in their respective time intervals,

$$\Delta V_{FB1} - \Delta V_{FB2} = (\bar{g}'_v - \bar{g}_0)_1 \bar{I}_1 \Delta t + (\bar{g}_v - \bar{g}'_0)_2 \bar{I}_2 \Delta t, \quad (10)$$

where the subscript 1 and 2 for the $\bar{g}$ -factor differences identify them for the given time windows of $(t_2 - t_1)$ and $(t_3 - t_2)$, respectively. From Eq. (10) the intensity $\bar{I}_1$ can be written as

$$\bar{I}_1 = \frac{\Delta V_{FB1} - \Delta V_{FB2}}{\Delta t (\bar{g}'_v - \bar{g}_0)_1} - \left[\frac{(\bar{g}_v - \bar{g}_0)_2}{(\bar{g}'_v - \bar{g}_0)_1} - 1 \right] \bar{I}_2, \quad (11)$$

where $(\bar{g}_v - \bar{g}'_0)_2 = (\bar{g}_v - \bar{g}_0)_2 - (\bar{g}'_v - \bar{g}_0)_2$ and with the assumption that $(\bar{g}'_v - \bar{g}_0)_2 / (\bar{g}'_v - \bar{g}_0)_1 \approx 1$. Generally $(\bar{g}_v - \bar{g}_0)_2 > (\bar{g}'_v - \bar{g}_0)_1$ so that the second term in Eq. (11) becomes negative. Hence for the SFS bias mode,

$$\bar{I}_1 = \frac{\Delta V_{FB1} - \Delta V_{FB2}}{\Delta t (\bar{g}'_v - \bar{g}_0)_1} - a \bar{I}_2, \quad (12)$$

where

$$a = \frac{(\bar{g}_v - \bar{g}_0)_2}{(\bar{g}'_v - \bar{g}_0)_1} - 1. \quad (13)$$

A similar analysis can be performed with the DFS bias mode for time resolved detection for an x-ray pulse as shown in Fig. 11(b). The flat-band voltage shift in the first time interval (or the first channel) becomes

$$\Delta V_{FB1} = \int_0^{t_1} g_0' I_0 dt + \int_{t_1}^{t_2} g_v' I_1 dt + \int_{t_2}^{t_3} g_v'' I_2 dt + \int_{t_3}^t g_0 I_1 dt. \quad (14)$$

In the SFS bias mode the flat-band voltage shift of adjacent channels was subtracted to obtain the intensity, as in Eq. (10); however, in the DFS bias mode the intensity is obtained by subtracting the flat-band voltage at 0 V bias from Eq. (14):

$$\Delta V_{FB1} - \Delta V_{FB0} = \int_{t_1}^{t_2} (g_v' - g_0) I_1 dt + \int_{t_2}^{t_3} (g_v'' - g_0) I_2 dt. \quad (15)$$

Fig. 11. Bias modes.

where

$$\Delta V_{FB0} = \int_0^{t_1} g_o I_o dt + \int_{t_1}^{t_2} g_o I_1 dt + \int_{t_2}^{t_3} g_o I_2 dt + \int_{t_3}^{t_f} g_c I_f dt. \quad (16)$$

As in the SFS bias mode case, g_o is considered to be constant with respect to dosage. In terms of the average parameters, Eq. (15) is rewritten

$$\Delta V_{FB1} - \Delta V_{FB0} = (\bar{g}_v^I - \bar{g}_o)_1 \Delta t + (\bar{g}_v^II - \bar{g}_o)_2 \bar{I}_2 \Delta t. \quad (17)$$

For the DFS bias mode, the intensity I_1 is

$$\bar{I}_1 = \frac{\Delta V_{FB1} - \Delta V_{FB0}}{\Delta t (\bar{g}_v^I - \bar{g}_o)_1} - b \bar{I}_2. \quad (18)$$

where

$$b = \frac{(\bar{g}_v^{II} - \bar{g}_o)_2}{(\bar{g}_v^I - \bar{g}_o)_1}. \quad (19)$$

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