Measurements of low gain diodes using Transient Current Technique

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Abstract

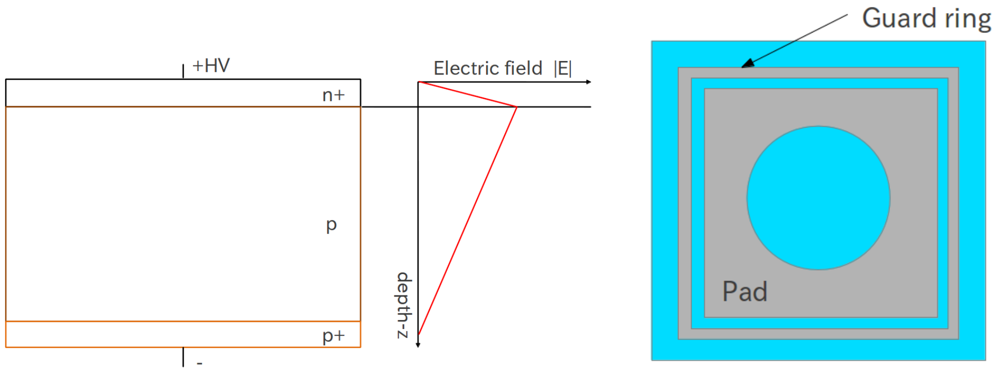
Thin silicon sensors are under investigation for the LHC upgrade (High Luminosity LHC) next decade. Thin sensors have better momentum resolution than thick ones due to reduced multiple scattering. Having a thin sensor with built-in amplification allows, in addition, to reduce the thickness without significant signal loss. These diodes have a built-in amplification layer that allows to obtain a higher signal than that of a standard diode of the same thickness. Two different techniques were employed to characterize them. Measurements of capacitance and leakage current versus bias voltage to extract the depletion voltage, and Transient Current Technique (TCT) to calculate the absolute gain of the device. Red laser is used for TCT to determine properties of charge carrier's motion. The gain of four samples is calculated with a method we call "kink method" which uses the ratio of charge induced by holes to charge induced by electrons. We also used a second method based on comparing the collected charge with a reference diode.

1 Introduction

In this section, the general structure of diode and low gain diode are discussed. The behavior of charge carriers inside the diode when a charged particle passes through is also explained.

1.1 Sensor diode

A diode consists of p-type and n-type semiconductor. The n-type semiconductor is produced by doping the silicon lattice with phosphorus (P). The n-type semiconductor has extra conduction electrons because the phosphorus has one more electron than silicon in the outer shell. The p-type semiconductor, on the other hand, is produced by doping silicon with boron (B). The p-type lacks one electron (called hole) because boron has one electron less than silicon. Around the pn-junction a depletion zone is formed which is depleted of charge carriers. By applying a reverse bias voltage, holes drift to the cathode and electrons drift to the anode. So, the depletion zone spreads from the pn-junction and the electric field increases. When a charged particle or impinging radiation crosses the sensor diode, electron-hole pairs are generated on its path. Electrons drift to the anode, holes drift to the cathode. In Figure 1, the electric field is the highest at the pn-junction because the difference of the space charge is larger there. The symbols p^+ and n^+ refer to a highly doped p-type and n-type silicon . In addition, an anode is built at the front side and a cathode is built at the back side of the diode. The sensor diode has a ring called guard ring which surrounds a pad. This structure is operated at the same potential as the pad and improves the electrical behavior of the device [1].



(a) Sensor diode and a profile of the electric field

(b) Top view of a standard pn-diode

Figure 1: (a): Schematic view of the diode. The electric field is the highest at the pn-junction. It is decreasing with distance from the pn-junction. (b): Shaded area represents Al contacts for signal extraction. The circular opening allows light injection from the top.

1.2 Low gain diode

The low gain diode is a diode which has a built-in amplification [2]. The amplification mechanism is obtained by introducing a p^+ layer between n^+ and p bulk. Because of the p^+ implant, the electric field at the $\mathrm{p^+n^+}-$juction is higher than at a normal $\mathrm{p^+n^+}-$juction. In Figure 2, a rapid increase of the electric field can be seen. When a charged particle crosses the low gain diode holes will drift to the cathode, and electrons to the anode. If the electric field is high enough, electrons will generate secondary electron-hole pairs at the high electric field region. The secondary holes also drift to the cathode.

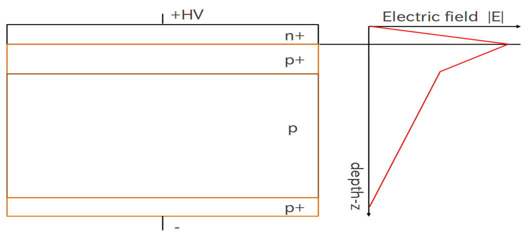


Figure 2: Low gain diode and a profile of the electric field. The electric field increases rapidly near the pn-junction due to the additional p^+ layer.

2 Experimental setup

In this section, the setups used the for CV/IV and TCT measurement are discussed.

2.1 CV/IV measurement

The CV measurement is used to find the depletion voltage V_{dep} and the full depleted capacitance C_{dep}. The IV measurement allows to extract leakage current I_{leak} as a function of bias voltage. The capacitance of the diode is expected to decrease with its thickness. The higher bias, the more thickness gets depleted. Since the depletion width is proportional to $\sqrt{V_{bias}}$, the capacitance will be inversely proportional to $\sqrt{V_{bias}}$ [1]. However, the capacitance in the diode becomes constant after a certain voltage because the thickness of depletion zone reaches the thickness of the diode.

$$C \propto \frac{1}{\sqrt{V_{bias}}} \tag{1}$$

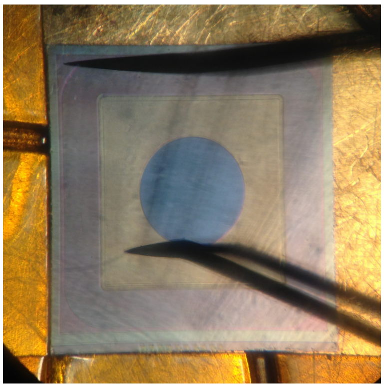


Figure 3: Setup of CV/IV measurement [3]. A top needle contacts the guard ring and a bottom needle contacts the pad. The diode size is 8mm × 8mm and pad size is 5mm × 5mm. Thickness is 300μm.

2.2 TCT setup

Transient Current Technique is an experimental method which injects charge carriers in the sensor. The drift of these charge carriers is studied, obtaining information on the electric field inside the diode out of the induced transient current. Red (λ =660nm) laser is used in these measurements. Red laser creates electron-hole pairs near the surface (depth about 10μm). As shown by Figure 4, five diodes can be measured simultaneously in TCT [4]. Fast (pico second) lasers are used because the drift time of charge carriers in silicon is of the order of 10ns or less.

2.2.1 TCT measurement of the low gain diode with red laser from back side

In Figure 5, red laser creates electron-hole pairs at the back side surface as with a standard diode (step 1). Electrons drift to the anode and holes drift to the cathode. Holes signal is too quick and gets filtered by the equivalent low pass filter characteristic of the readout circuit. Electrons generate secondary electron-hole pairs at the high electric field region (step 2). The secondary electrons signal cannot be seen for the same reason as before. The secondary holes drift to the cathode (step 3) and induce signal.

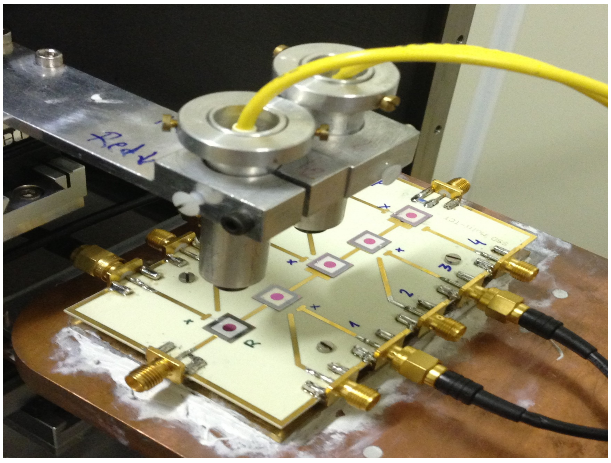


Figure 4: Top view of the TCT setup. Five diodes, one standard diode (no built-in amplification, leftmost in the picture) as a reference and four low gain diodes, are put on the board. Red and IR laser optics are mounted above and below the board. The laser intensity is set to 40% ,maximum 100mW at 100%, and frequency is 200Hz.

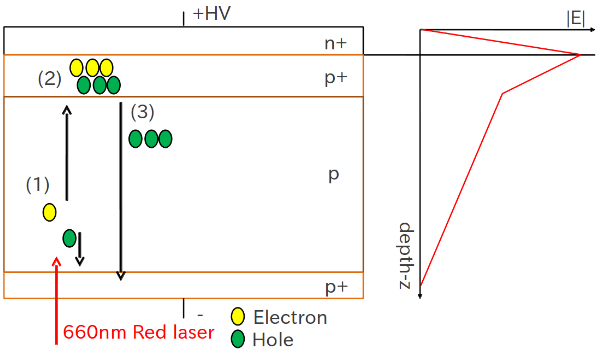


Figure 5: Schematic view of the low gain diode and profile of the electric field.

3 Gain analysis methods

The gain is calculated with two methods shown below. One uses normalization of charge and separates electron signal and hole signal. The other one uses the ratio of total charge in a standard diode to that of a low gain diode.

3.1 Kink method for red TCT

This method is based on identifying which component of the signal (see Figure 6) comes from electron drift and which comes from hole drift. As seen in Figure 5, the ratio of charge induced by holes drifting in the bulk to electrons originated from the laser will give the amplification factor per one electron. The difference between the electron and hole induced charge is best observed at maximum voltage. A kink can be clearly appreciated in the current transient waveform. The actual position of the kink is determined normally by eye. At this moment an automatic procedure for the determination of the kink position is under investigation.

$$Gain(V_{max}) = \frac{Q_h(V_{max})}{Q_e(V_{max})} \tag{2}$$

Here Q_h is charge of holes, Q_e is charge of electrons. For lower voltage we scale the collected charge by the gain at maximum voltage. By doing so, we assume that the gain scales linearly with the bias voltage (see Figure 9).

$$Gain(V) = Gain(V_{max}) \frac{Q_{tot}(V)}{Q_{tot}(V_{max})} \tag{3}$$

Here $Q_{tot} = Q_e + Q_h$, which is total charge.

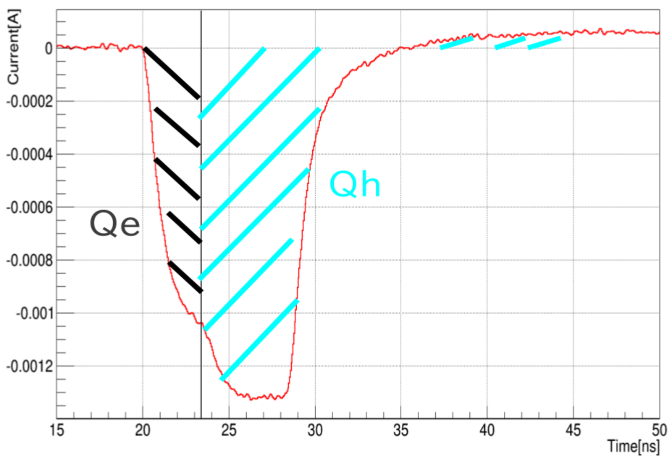


Figure 6: Schematic view of kink method. The first part of this waveform is electrons signal because (step 1 in Figure 5) without the amplification. The second part after the kink comes from multiplied holes (step 3 in Figure 5).

3.2 CCE (Charge Collection Efficiency) method

The CCE method uses a comparison of the total charge between the standard diode and the low gain diode for the calculation of the gain. The charge measured in the standard diode is constant above the depletion voltage because the standard diode has no gain. But the low gain diode has "low gain". The charge in the low gain diode is increasing with bias voltage. The ratio of the charge of standard diode to the charge of the low gain diode gives an estimation of the gain of the low gain diode. Then the gain is defined as Eq. 4.

$$Gain(V) = \frac{Q_{with\ gain}}{Q_{without\ gain}} \tag{4}$$

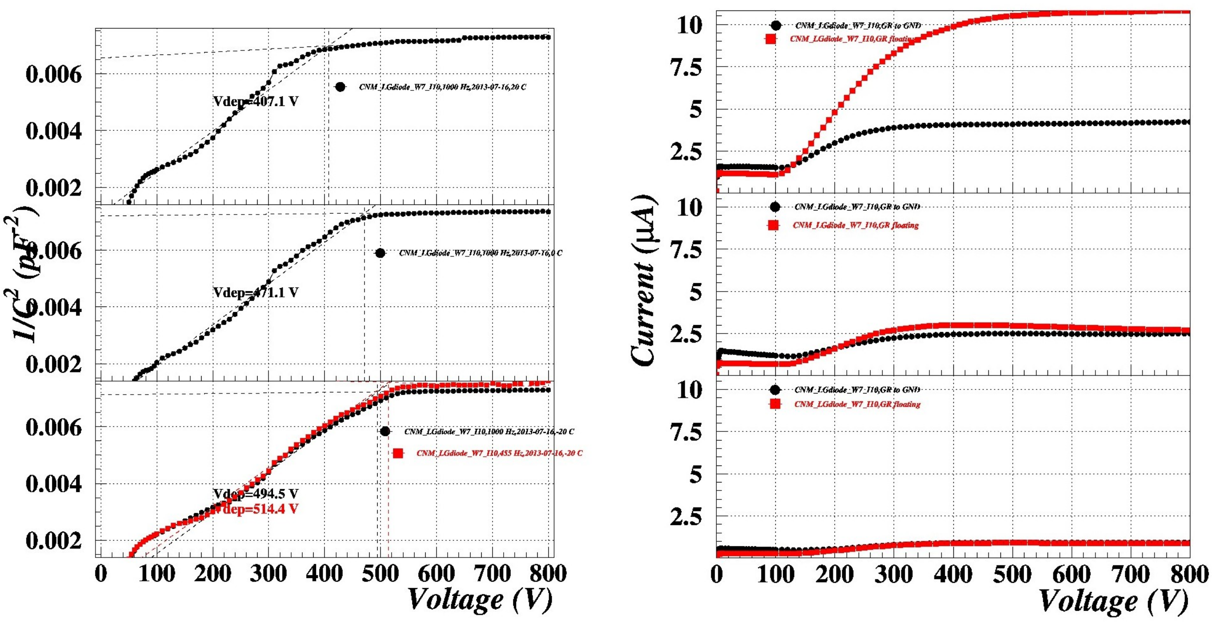
where $Q_{with\ gain}$ is the integrated charge of the low gain diode, $Q_{without\ gain}$ is a value of the integrated charge of the reference diode. W9_G8 is used as a reference.

4 Result

Several plots and tables of CV/IV and TCT measurement are in this section. Finally, the gain calculated with two methods is shown.

4.1 CV/IV measurement

The CV/IV measurements of several low gain diodes and standard diodes are used to extract the depletion voltage and leakage current. The low gain diodes come from wafer 7 and 8, standard diodes as reference come from wafer 9. In Figure 7, $\frac{1}{C^2}$ increases with the bias voltage. After depletion, it gets constant. The leakage current is higher at higher temperatures. Results are summarised in Table 1.



(a) $\frac{1}{C^2}$ vs. bias voltage (b) Leakage current vs. bias voltage

Figure 7: Result of CV/IV measurements for W7_I10 at 20 (top), 0 (center), −20 (bottom) °C. In Figure 7(a), we can fit each rising region and plateau by using first degree polynomial . The cross point is the depletion voltage. In Figure 7(b), the leakage current increases with temperature. Red points show measurements taken with guard ring floating and black points show measurements where both pad and guard ring are kept at same potential (ground).

S/N	V_{dep} [V]	I_{leak}[μA] at 800V	C_{dep} [pF]
W7_B4			
W7_C3		200	
W7_C4			
W7_C5		300 at 700V	
W7_D2		300 at 600V	
W7_E2	150	10	11.8
W7_E4	140	24	11.5
W7_E9			
W7_F3		50 at 220V	
W7_G7		50 at 110V	
W7_H10	170	10 at 400V	11.5
W7_I8	180	10	11.5
W7_I10	190	4	11.3
W7_J9		50 at 200V	
W8_C3	100	12 at 700V	14.1
W8_C5	150	70	10.5
W8_D2		300 at 350V	
W8_K8		300 at 240V	
W9_D10	50	4 at 180V	10.5
W9_E8			
W9_E9	75	4 at 370V	10.8
W9_E11	200	0.2	10.0
W9_G8	245	3	11.5
W9_H10		5 at 160V	
W9_H11		5 at 180V	

Table 1: Result of CV/IV measurement at 20 °C. Some empty cells are due to bad detector (not depleted) or broken.

4.2 TCT measurement

In Figure 8, first part (before ∼24ns at maximum voltage 900V) of this waveform is electrons signal and second part (after ∼24ns at maximum voltage 900V) comes from multiplied holes. A ”kink” in the waveform at t∼24ns can be seen.

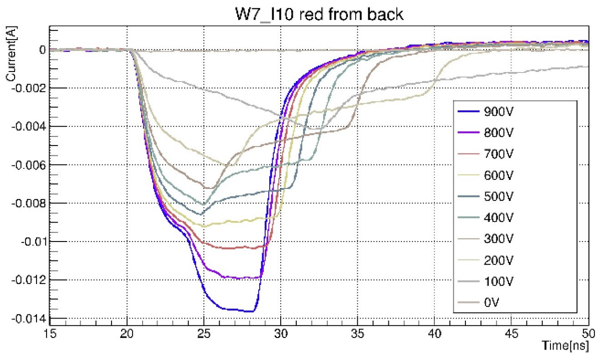


Figure 8: Result of TCT measurements. In Figure 8, at maximum voltage 900V, a kink can be clearly seen.

4.3 Gain of low gain diodes

The gain reaches about 3.0 at the maximum voltage 900V using red laser with kink method. The gain with CCE method reaches about 2.8 at the maximum voltage 900V. The different result with the CCE method could come from the heterogeneity of the wafers (standard diode comes from wafer 9 while the low gain diode comes from wafer 7). The kink method gives higher gain than CCE method in using red laser (see Figure 10-13). The results for each method are summarized in the Table 2 (kink method) and 3 (CCE method).

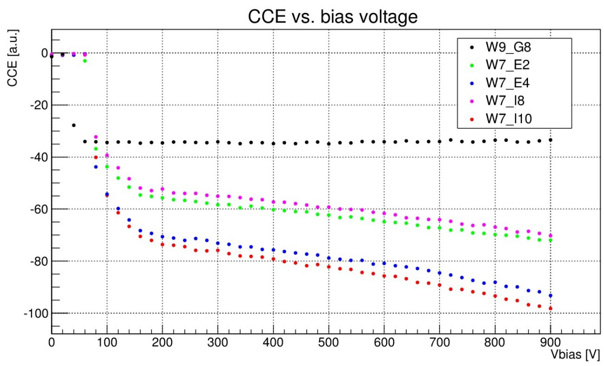


Figure 9: CCE vs. bias voltage. The CCE (here, integrated charge) value of standard diode is constant above 100V due to no amplification mechanism. But that value of low gain diodes is increasing (in absolute value) with the bias voltage due to the amplification mechanism near the pn-junction.

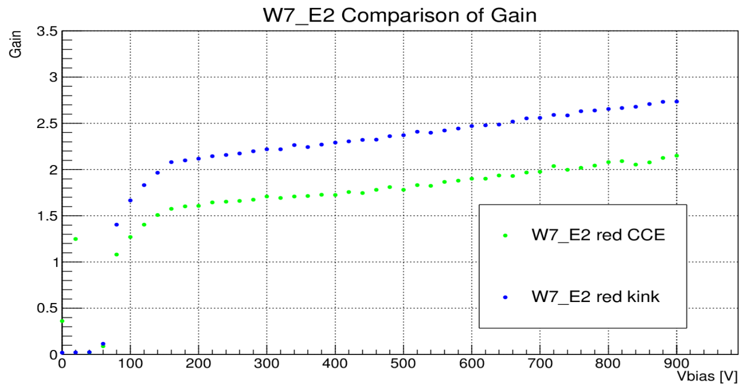


Figure 10: Gain of W7_E2. The gain reaches about 2.8 with red kink and 2.1 with red CCE. The depletion voltage is about 160V.

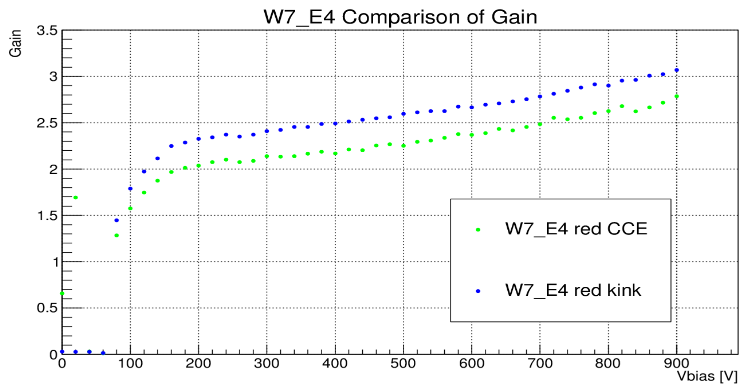


Figure 11: Gain of W7_E4. The gain reaches about 3.1 with red kink and 2.8 with red CCE. The depletion voltage is about 160V.

S/N	V_{dep} [V] in TCT	Gain at V_{dep}	Gain at 500V	Gain at 900V
W7_E2	160	2.1	2.4	2.8
W7_E4	160	2.3	2.6	3.1
W7_I8	160	2.4	2.9	3.4
W7_I10	160	2.3	2.8	3.2

Table 2: Result of the gain with red kink.

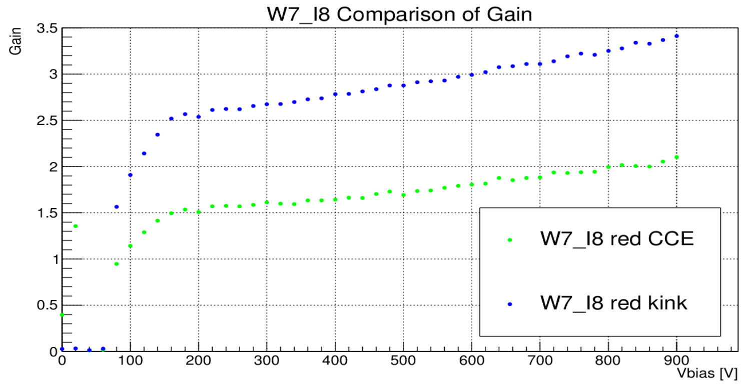


Figure 12: Gain of W7_I8. The gain reaches about 3.4 with red kink and 2.1 with red CCE. The depletion voltage is about 160V. The difference of the calculated gain is the largest with red laser.

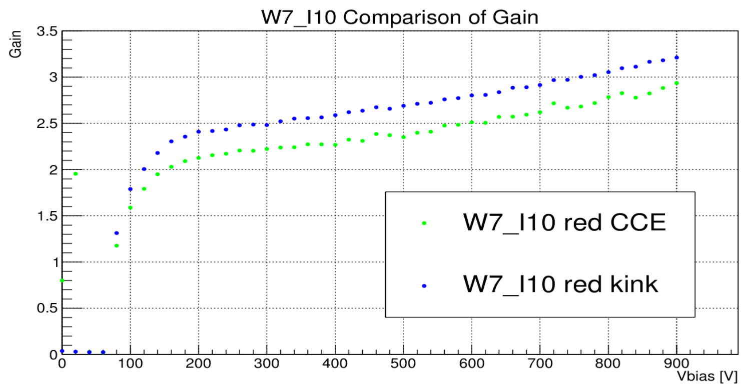


Figure 13: Gain of W7_I10. The gain reaches about 3.2 with red kink and 2.9 with red CCE. The depletion voltage is about 160V.

S/N	V_{dep} [V] in TCT	Gain at V_{dep}	Gain at 500V	Gain at 900V
W7_E2	160	1.5	1.8	2.1
W7_E4	160	2.0	2.3	2.8
W7_I8	160	1.5	1.7	2.2
W7_I10	160	2.0	2.4	2.9

Table 3: Result of the gain with red CCE.

5 Conclusion

First prototype of low gain diodes have been measured. The characterization of these diodes was done in two steps. First, the electrical characterization (CV/IV measurements) helped us to extract operation information like maximum voltage. Then the gain was characterized using red Transient Current Technique. We proposed two methods (kink method and CCE method) giving similar results with in ∼10%. The maximum gain for the standard diodes was ×3.

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References

[1] Semiconductor Detector Systems (Semiconductor Science and Technology), Helmuth Spieler,2005.

[2] G.Lutz, Semiconductor Radiation Detector, Springer 1999, chapter 9.

[3] `https://twiki.cern.ch/twiki/bin/viewauth/SolidStateDetectors/SetupCVIV`

[4] `https://twiki.cern.ch/twiki/bin/viewauth/SolidStateDetectors/SetupTCT`