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Low-gain avalanche detector, activity of research and development

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Summary. — Low-Gain Avalanche Detectors (LGAD) are silicon detectors with output signals about a factor of 10 larger than those of traditional silicon detectors, but with noise comparable with that of traditional silicon detectors. LGAD combine the advantages of avalanche photodiodes (APD) and those of traditional silicon detectors and exploting their signal amplitude. The LGAD are suitable for the design of timing detectors, reaching, according to the simulation, a time resolution of a few tens of picosecond. The LGAD detectors optimized for timing performances are called Ultra Fast Silicon Detectors (UFSD).

1. – Introduction

To make accurate time measurements with silicon detectors it is necessary to maximize the ratio between signal and noise, therefore the signal should be large and it should have a fast rise time (*i.e.* fast slew rate), keeping the noise small. Detectors with these features are thin detectors (fast signal) and they have internal signal multiplication (large signal). The signal multiplication is a crucial matter of silicon detector: the multiplication needs an eletric field of 300 kV/cm, but, if applied externaly to the detectors, such electric field causes the breakdown of the devices. The solution to have signal multiplication without breakdown it is to insert an internal gain into the detectors, this is the basic idea of LGAD.

UFSD [1, 2] are types of detectors that exploit the effect of charge multiplication of LGAD and are designed and optimized to measure time with high accuracy, [3, 4]. LGAD are n - in - p detectors, with a thin gain layer of several microns below the n electrode. Figure 1 shows a schematic of a LGAD (structure: n^{++} - p^{+} - p - p^{++}), with its typical electric field profile shown on the side of the picture. The n^{++} layer is the cathode ($N_D \sim 10^{19}/\,\mathrm{cm}^3$), underneath the cathode there is the thin gain layer p^{+} ($N_A \sim 10^{16}/\,\mathrm{cm}^3$). Cathode and gain layer are implanted in a high ohmic p bulk ($N_A \sim 10^{12}/\,\mathrm{cm}^3$), and the detector anode is a thin p^{++} layer ($N_A \sim 10^{19}/\,\mathrm{cm}^3$) [5].

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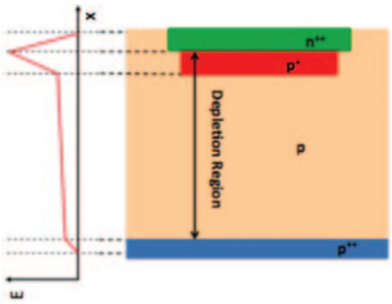

Fig. 1. – Schematic of a Low-Gain Avalanche Detector.

2. – Detector signal

In a silicon detector a minimum ionizing particle (MIP) creates electron-hole pairs (75 electron-hole pairs per micron). The free charges generated by a particle into the detector depletion region, under the influence of the electric field generated by an external bias voltage, drift toward the electrodes (electrons to cathode and holes to anode). Electrons and holes, for electric field large enough, reach a drift velocity of $100\,\mu$m/ns, therefore in a traditional detector (tickness of $300\,\mu$m) the signal collection time is about 3 ns.

The shape of the signal current [6] can be calculated using the Ramo's theorem [7], eq. (1). This theorem states that the current induced on an electrode by a charge carrier is proportional to its electric charge q, to the drift velocity v of the charge carrier and to the weighting field E_W:

$$I \propto q v E_W . \tag{1}$$

2˙1. *Drift velocity.* – The drift velocity is the mean velocity of the charge carriers induced by an electric field inside the depletion region of the detector, generated by external bias voltage. The drift velocity of electrons and holes depends on their mobility ($\mu_e = 1450\,\mathrm{cm^2/Vs}$, $\mu_h = 450\,\mathrm{cm^2/Vs}$); for value below 300 kV/cm, it has a linear dependence on the electric field, while for higher values the drift velocity saturates ($v_{sat} \sim 10^7$ cm/s). The drift velocity of eletrons reaches saturation for values of electric field lower than for the holes. A strong requirement to perform accurate timing measurements with silicon detectors is to have uniform signals. This condition requires a uniform velocity of all carriers, so they should have saturated velocity. Therefore UFSD needs to be designed to hold electric fields above 300 kV/cm without causing electric breakdown.

2˙2. *Weighting field.* – The weighting field is a mathematical tool used to describe the coupling between the charge carriers and the read-out electrode. A good timing measurement needs a uniform coupling: this means that the weighting field should be as uniform as possible, so that the coupling of charges generated far to the electrode is as strong as the coupling of charges near it.

The weighting field depends on the geometry of the detector: the best geometry configuration is similar to a parallel-plate capacitor. Figure 2 shows a simulation of the weighting field for two different strip geometries. The simulation was made with the program Weightfield2 [8], a simulator for silicon and diamond detectors. On the left side

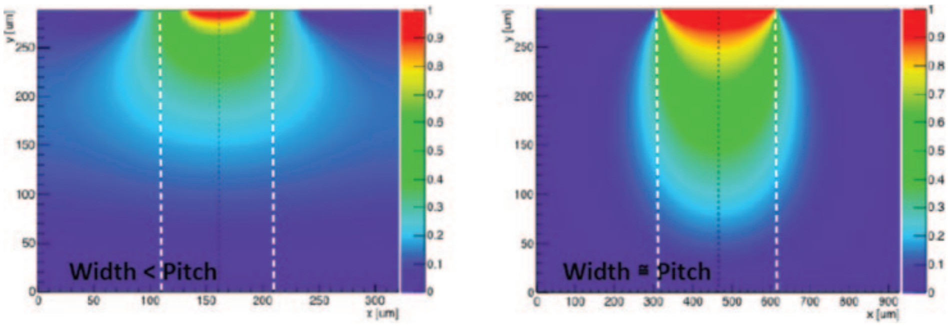

Fig. 2. – Weighting field simulation for two different strip geometries: on the left the geometry is 100 μm pitch and 50 μm strip implant width, on the right the geometry is 300 μm pitch and 290 μm strip implant width.

of fig. 2 there is the simulation of a structure with pitch 100 μm and strip implantation of 50 μm (width < pitch); on the right side, there is a structure with pitch 300 μm and width 290 μm (pitch $\sim$ width). The simulation shows that for the first geometry, the weighting field is not uniform along the x-axis of the detector. Therefore the signals generated by particles impinging far from the electrode have a bad coupling with it. On the contrary, the coupling is better for the second geometry, on the right side of the fig. 2.

3. – Thin and thick detector signal

The total charge induced by a particle inside a silicon detector is equal to the integral over time of the sum of the electrons and holes currents:

$$\int [i_e(t) + i_h(t)]\, \mathrm{d}t = q. \tag{2}$$

Suppose to have a single electron-hole pair in a thin and in a thick detector: the signal shape is different for the two sensors, even though the area is the same ($Area = q$). The thin detector has faster signal with larger amplitude, while the thick detector has slower and smaller signal, fig. 3 (left). If instead we consider the signal generated by a MIP traversing the two sensors, obviously there is a greater number of charge carriers inside the thick detector, than inside the thin one, fig. 3 (right).

However, since the number of charge carriers is proportional to the thickness d and the weighting field to $1/d$ the signals induced into the two sensors have the same amplitude, with the same slew rate, fig. 3 (right):

$$\frac{\mathrm{d}V}{\mathrm{d}t} \propto \frac{G}{d}. \tag{3}$$

However, if the sensors have gain, than the gain contribution is stronger in thin detectors. The signal amplitude is proportional to the detector gain (G), while the signal rise time depends on sensor thickness (d), eq. (3).

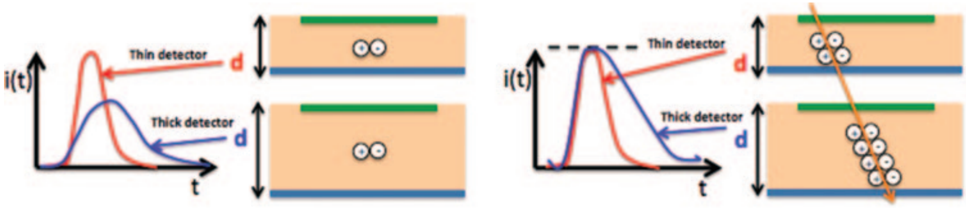

Fig. 3. – Comparison between signal shape in two detectors with different thickness. Left: the signals of a single electron-hole pair, right: the signals induced by the same particle that crosses the two detectors.

4. – Read-out electronics for UFSD

The time performances of a system using UFSD have a strong dependence on the sensor and on the read-out electronic. A detector can be modelled as a current generator in parallel to a capacitance C_{det} (capacitance of detector). The current signal generated into the detector is amplified by an amplifier with an input resistance R_{in}, fig. 4. The model in fig. 4 has two important time costants, that affect the time measurement: the first one is the collection time (t_{Col}) of the signal, the second one is the time costant of the electronics ($t = R_{in}C_{det}$). The latter depends on the capacitance of the detector and on the input resistance of the amplifier. For good time measurement it is necessary that the RC time costant is smaller than the collection time, so that it will not degrade the slew rate of the signal. Therefore it is important to couple low input impedance amplifiers with low capacitance detector.

4˙1. *Choice of optimum amplifier*. – There are two amplifier architectures to do time measurements: the current amplifier (CA) and the charge sensitive amplifier (CSA). These two amplifiers have different features; the CA is faster than CSA and this is an advantage when the signal has fast slew rate. The CSA instead integrates, with a shaper, the signal and for these reasons has a lower noise than the CA amplifier.

Figure 5 (left) shows a simulation with Weightfield2 of the current signal induced by a MIP in a 300 μm thick detector with gain 10; the total current is the contribution of electrons and holes current after the multiplication process. Weightfield2 can also simulate the signal amplification using CA and CSA amplifier models, fig. 5 (right). The integration effect made by the CSA shapes the signal, while the output signal of the CA is an amplified copy of the current signal induced by the particle. The CSA and CA are two possible amplifiers for time measurements, the choice of one of the two depends on the capacitance of detector: if the capacitance is enough to smooth out the noise effects, than the CA amplifier is the best choise, alternatively the CSA is needed.

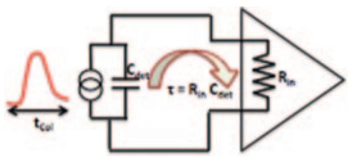

Fig. 4. – Coupling model between detector and amplifier.

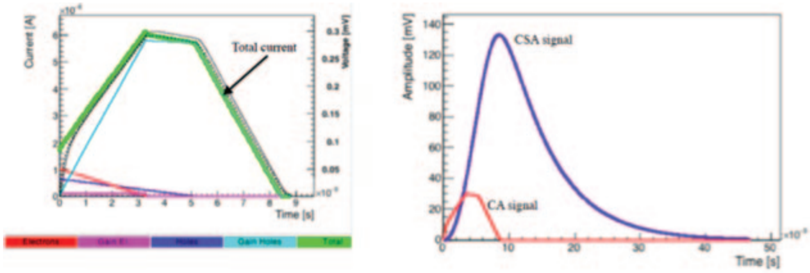

Fig. 5. – On the left: UFSD simulated current signal for 300 μm thick and gain 10; on the right: amplifier output signal simulation for two different amplifiers, current amplifier (CA) and charge sensitive amplifier (CSA).

5. – Conclusion

In this proceeding we present the UFSD sensors as an application of LGAD and we conclude that a good detector geometry to do time measurements is a geometry for which the weighting field is uniform. The signal amplitude depends on the detector gain, while the signal rise time depends on the sensor thickness. The time costant of the read-out electronics has to be smaller than the signal rise time.

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