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Development of Ultra-Fast Silicon Detectors for 4D-tracking

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Summary. — Ultra-Fast Silicon Detectors (UFSD) are thin silicon detectors, based on the Low-Gain Avalanche Diode (LGAD) technology, designed to perform 4D-tracking. The main features of UFSD are described, together with two different sets of measurement, which demonstrate that the innovative characteristics of these sensors allow achieving a time resolution of about 30 ps up to a fluence of $\phi = 10^{15}$ n_{eq}/cm^2.

1. – Introduction

Ultra-Fast Silicon Detectors (UFSD) are innovative detectors designed to perform 4D-tracking, namely the ability of concurrently measuring, with high precision, the position and the time of passage of a particle. UFSD, in addition, are radiation-hard: indeed they can withstand a radiation fluence of $\phi = 10^{15}\, n_{eq}/\text{cm}^2$ maintaining high performances. UFSD are based on the Low-Gain Avalanche Detectors (LGAD) technology [1-3].

2. – The LGAD technology

The main element of the LGAD technology is the so-called gain layer: a thin, highly doped p^+ layer which is inserted between the n^{++} electrode and the bulk of the device (fig. 1). The gain layer locally creates a very high electric field that allows primary electrons generated by a ionizing particle to acquire enough energy to produce secondary electron-hole pairs. Only electrons are multiplied, while holes are not: in this way it is possible to achieve a controlled gain, avoiding the avalanche mode [1, 3].

The moderate gain offered by the LGAD technology and the small thickness are the fundamental elements that allow UFSD to achieve precise timing, as will be discussed in the next section. Furthermore, the low gain is crucial for the radiation hardness of these detectors [4].

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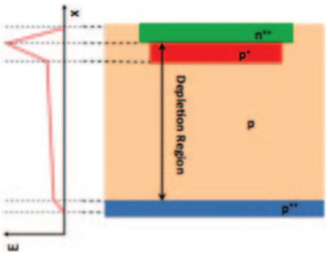

Fig. 1. – Schematic of an LGAD.

3. – The "ingrendients" of precise timing and tracking

The squared sum of two main terms defines the time resolution of UFSD:

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Landau}^2. \tag{1}$$

The jitter term is given by the ratio of the sensor rise time (t_{rise}) and its Signal-to-Noise ratio (S/N):

$$\sigma_{Jitter} = \frac{t_{rise}}{S/N}. \tag{2}$$

Therefore, in order to minimize it, a high Signal-to-Noise ratio and a small rise time are needed. The internal gain of the UFSD provides a very high S/N; the small thickness allows for short rise time.

The Landau term (σ_{Landau}), whereas, stands for the non-uniform charge deposition of a particle crossing the detector. This term decreases with the thickness of the sensor and, thus, it is small in the 50 μm thick UFSD.

Hence, the features that make UFSD optimal timing detectors are their internal gain and their small thickness. In particular, simulations show that a gain of $\sim$20 and a thickness of 50 μm provide the best timing performance.

The moderate gain and the thinnes are crucial not only for precise timing: they also allow the device to have finely segmented electrodes, which is the key characteristic for good spatial resolution [4, 5].

4. – Radiation hardness

UFSD are radiation-hard detectors: indeed, they can survive radiation fluences of about $\phi = 10^{15}\, n_{eq}/\text{cm}^2$ maintaining their performances.

The most important effect of radiations on UFSD is the disappearance of the gain layer, due to the so-called initial acceptor removal [6], which causes a worsening of the time resolution. Such effect has been extensively studied in the past years, recently leading, thanks to the efforts of the UFSD group in Torino and of the Fondazione Bruno Kessler (FBK, Italy), to a new production, called UFSD2, which features the implantation of carbon in the gain layer. As will be shown in the next section, this choice proved to be successful [7].

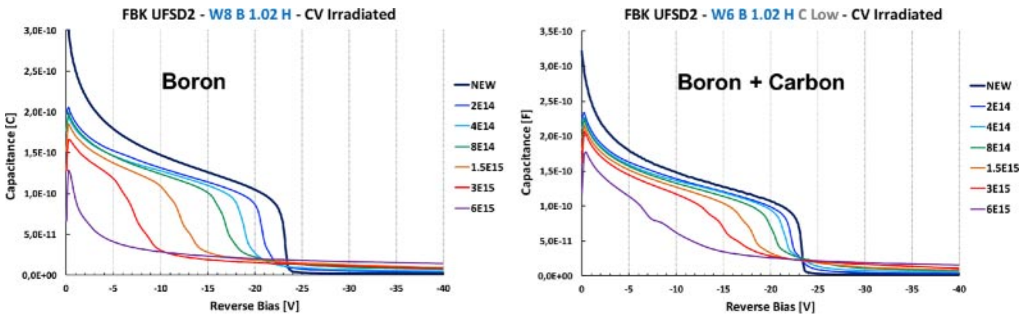

Fig. 2. – $C(V)$ measurements performed on UFSD2 sensors: boron (left), boron with carbon (right).

4˙1. *C(V) Measurements on UFSD2*. – The measurement of the capacitance of an UFSD sensor as a function of the applied bias voltage ($C(V)$ curve) offers the possibility of studying the evolution of the gain layer at different irradiation levels, thus giving important information on the radiation hardness of the device under test.

The $C(V)$ curve of an UFSD sensor has a peculiar point, named *knee*, in which the curve changes its slope. The voltage at which the *knee* (V_{knee}) occurs is proportional to the active acceptor density in the gain layer: it is therefore possible to study the evolution of the sensor's gain with irradiation by looking at V_{knee}.

In fig. 2 it is possible to see the $C(V)$ curves of UFSD2 sensors with two different flavours of gain layer, after different levels of irradiation: a standard (boron only) gain layer in the left plot, a gain layer with carbon implantation in the right one. The important result shown in these plots is that the sensor in the right plot shows a lower decrease of V_{knee} with irradiation, being therefore less prone to the *initial acceptor removal* effect. Hence, the implantation of carbon increases the radiation hardness of UFSD detectors [7].

5. – Time resolution of UFSD2

Measurements performed on a UFSD2 sensor with carbon implantation at the University of California in Santa Cruz (UCSC) using a β source, repeated for different levels of irradiation of the device, provided significative results: the device reached a time resolution $\sigma_t = 30\,\text{ps}$, up to a fluence $\phi = 1.5 \cdot 10^{15}\, n_{eq}/\text{cm}^2$, thus demonstrating very good timing and radiation hardness [8].

6. – Conclusion

Ultra-fast silicon detectors are innovative detectors designed to perform 4D-tracking, with spatial resolution $\sigma_s \sim 10\,\mu\text{m}$ and time resolution $\sigma_t \sim 30\,\text{ps}$. Such performances are achieved by means of an internal, moderate gain and a thickness of $50\,\mu\text{m}$.

The addition of carbon in the gain layer of UFSD sensors increases significantly their radiation hardness, as demonstrated by measurements performed on UFSD2 sensors produced by FBK. In addition, measurements on a UFSD2 sensor with carbonated gain layer performed at the University of California in Santa Cruz showed that they can achieve a time resolution $\sigma_t \sim 30\,\text{ps}$ up to a radiation fluence $\phi = 1.5 \cdot 10^{15}\, n_{eq}/\text{cm}^2$.

REFERENCES

[1] Pellegrini G. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **796** (2014) 149.
[2] Cartiglia N. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **845** (2017) 47.
[3] Sadrozinski H. F.-W. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **765** (2014) 7.
[4] Sadrozinski H. F.-W., Seiden A. and Cartiglia N., *Rep. Prog. Phys.*, **81** (2018) 026101.
[5] Sola V. *et al.*, *J. Instrum.*, **12** (2017) C02072.
[6] Ferrero M. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **919** (2019) 16.
[7] Cartiglia N. *et al.*, to be published in *Nucl. Instrum. Methods Phys. Res. A*.
[8] Zhao Y. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **924** (2019) 387.