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Sensors for ultra-fast silicon detectors

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ABSTRACT

We report on electrical and charge collection tests of silicon sensors with internal gain as part of our development of ultra-fast silicon detectors. Using C–V and α TCT measurements, we investigate the non-uniform doping profile of so-called low-gain avalanche detectors (LGAD). These are n-on-p pad sensors with charge multiplication due to the presence of a thin, low-resistivity diffusion layer below the junction, obtained with a highly doped implant. We compare the bias dependence of the pulse shapes of traditional sensors and of LGAD sensors with different dopant density of the diffusion layer, and extract the internal gain.

1. Introduction

We propose an ultra-fast silicon detector (UFSD) that will establish a new paradigm for space-time particle tracking [1]. Presently, precise tracking devices determine time quite poorly while good timing devices are too large for accurate position measurement. This fact is imposing severe limitations on the potential of many applications ranging from medical positron emission tomography (PET) to mass spectroscopy or particle tracking.

We plan to develop a single device able to concurrently measure with high precision the space ($\sim 10\ \mu$m) and time (~ 10 ps) coordinates of a particle. Our analysis of the properties of silicon pixel detectors, which already have sufficient position resolution, indicates that it is possible to improve their timing characteristics to achieve this goal. In order to obtain the high signal-to-noise ratio (S/N) needed for UFSD, we will use and control the silicon sensors internal charge multiplication mechanism. This is a recent, very active field of investigations within the CERN based RD50 collaboration [2].

The development of UFSD research is poised to open up a range of new opportunities for applications that benefit from the combination of position and timing information. As explained in more detail in Ref. [3], UFSD will help sharpen PET images and monitor more accurately the dose delivered in cancer treatment. UFSD will increase the precision of time of flight (ToF) measurement in applications like mass spectroscopy, robotic vision and particle identification. Additionally, UFSD can improve particle tracking by suppressing random accidental coincidences in high-rate experiments as planned in High-Energy Physics.

UFSD are pixelated silicon sensors based on the LGAD design. In the following, we describe the principle, properties and expected performance of the UFSD. Then, we discuss the observation of internal gain in silicon sensors, a crucial part of UFSD, and the description of LGAD. We present data on I–V and C–V measurements, correlated with results from α TCT measurements, which provide both pulse shape and charge collection information and allow determination of the gain.

2. Principle of UFSD

High-rate operation of silicon sensors faces the obstacle that the drift velocity in silicon saturates at about 10^7 cm/s, and thus the collection time of electrons inside a silicon layer of 300 μm thickness is limited to ~ 3 ns. Fast silicon sensors need therefore to be very thin and be able to function even though the charge collected is reduced with respect to that of thicker sensors. However, since the time resolution of a sensor depends on the signal-to-noise ratio S/N, the charge collected from a thin active layer might not be enough to achieve good time resolution. To overcome this limitation, we propose to exploit charge multiplication to increase the charge yield of very thin silicon sensors so that they can be used in ultra-fast timing applications [1,3].

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2.1. Internal gain in silicon sensors

It has been demonstrated that in silicon sensors the charge multiplication factor, which is responsible for the charge gain (similar to the first Townsend coefficient [4] in gas multiplication), has an exponential dependence on the electric field [5,6]. Close to breakdown, at an electric field of $E = 300$ kV/cm, the achievable multiplication reaches ~0.66/μm for electrons and ~0.17/μm for holes.

As shown by simulation [7], planar sensors with uniform low doping density cannot obtain such an extended high-field region needed for avalanche charge multiplication. Moderate internal gain has been observed in silicon sensors after irradiation by several groups due to the non-uniformity of the electric field [8–11]. Thus, in order to have silicon sensors with internal gain, a non-uniform doping profile similar to silicon photomultipliers (SiPM) [12,13] or multi-pixel photon counters (MPPC) [14] is required, as explained in the next section.

2.2. Low-gain avalanche detectors (LGAD)

Low-gain avalanche detectors (LGAD), as developed by Centro Nacional de Microelectronica (CNM) [15,16], are n-on-p silicon sensors with a 300 μm thick high-ohmic Float Zone (FZ) p-bulk which have a p+ implant extending a few microns underneath the n-implant. This implant generates a large local field at a depth of about 1–5 μm, as shown in Fig. 1 [7]. The doping concentration of the p+ implant is chosen to generate a gain of 10–100, in contrast to a gain of 10^4 or more in SiPM and MPPC. LGAD sensors work by inducing multiplication for electrons, while the multiplication of holes, given the field and depth values involved, is less important. Therefore, LGAD sensors do not have a large positive feedback loop formed by concurrent electron and hole multiplication processes, present in SiPM, which causes the avalanche and the subsequent dead time. At sufficiently high bias voltage, the drift field in the remainder of the 300 μm deep bulk can be almost as high with the p+ implant ("Gain") as in sensors without it ("No Gain"), and thus the large drift field >20 kV/cm needed for fast collection of the charges [17] can be established.

2.3. Gain requirements for ultra-fast timing

Charge multiplication in silicon sensors allows increasing the signal-to-noise ratio S/N as long as the extra noise due to the multiplication process is small, which is true for fast sensors with shaping time below 1 ns, gain of about 10, and leakage current of the order 1 nA per pixel or less [18].

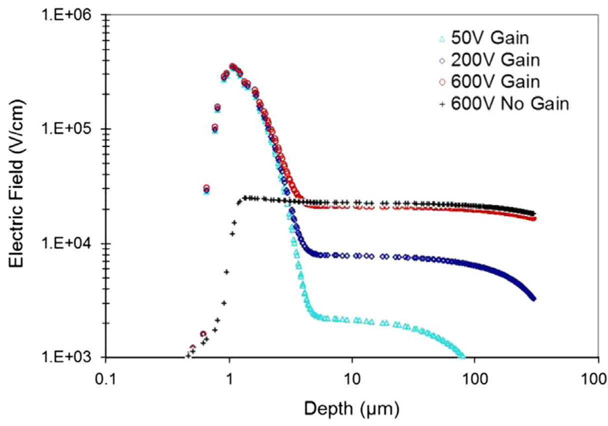

Fig. 1. Simulation of electric field profile in a LGAD ("Gain") for several bias voltages compared to the field in a pad sensor without gain ("No Gain") [7].

The time resolution σ_t, ignoring small effects due to TDC binning, can be parameterized as:

$$\sigma_t = \left[\left(\frac{N}{S} \tau_R \right)^2 + \left(\frac{\Delta S}{S} \frac{S_{thr}}{S} \tau_R \right)^2 \right]^{1/2},$$

where S is the pulse amplitude, τ_R its rise time, N the jitter due to the electronic noise and $\Delta S/S$ the time walk due to the amplitude dispersion from the Landau distribution [19] with respect to a fixed threshold S_{thr}. In the following, the rise time will be set equal to the collection time to get optimal timing performance, and this correlates the rise time and the sensor thickness. Following Ref. [20], we will assume (i) a noise $N = 1000e^-$ at a shaping time of 500 ps, and (ii) the noise scaling like $1/\sqrt{\tau_R}$ with the shaping time. These assumptions are consistent with the measured noise on the ATLAS pixels [21]. Furthermore, when assuming (iii) the threshold be set at $10 \times N$ to suppress noise counts, and (iv) a reduction of the time walk by a factor CFD due to the use of a constant fraction discriminator [20], the time resolution can be expressed as:

$$\sigma_t(\mathrm{CFD}) = \tau_R \frac{1}{(S/N)} \left[1 + \left(\mathrm{CFD} \times 10 \frac{\Delta S}{S} \right)^2 \right]^{1/2}.$$

For high-rate sensors, we look for the fastest rise time with a realistic $S/N > 30$. Then the time resolution depends on the gain as shown in Table 1, with a marked improvement with the use of a constant fraction discriminator even with a modest CFD = 1/3. For a gain $G = 10$, a rise time of $\tau_R = 800$ ps and a sensor thickness of 36 μm the time resolution will be 30–40 ps.

3. Electrical properties of low-gain avalanche detectors (LGADs)

The electrical properties of LGADs are probed with current–bias voltage (I–V) and capacitance-bias voltage (C–V) measurements. Under the assumption of a uniform planar diode, the C–V data are used to extract the depth of the depleted region x and an estimate of the doping profile.

3.1. Comparison with no-gain diodes

Fig. 2 shows a comparison of C–V curves between a LGAD and a pad sensor without gain. The bias dependences of $1/C^2$ (Fig. 2a) and of the depth of the depleted region (Fig. 2b) shows for the LGAD a shift in the depletion of the bulk due to the need to deplete the p+ implant located directly below the junction. The apparent step in the capacitance curve at bias of ~100 V for the LGAD and ~50 V for the no-gain pad (corresponding to an apparent depth of the about 200 μm in both sensors) is still being investigated but it is believed to be caused by a fairly complex interplay between the oxide charge on the surface and the deep implant at the edge of the n+ electrode in the process of lateral depletion [7].

Table 1
Time resolution for fastest rise time allowed by $S/N > 30$ as a function of gain.

Gain G	τ_R [ps]	Thickness [μm]	Time resolution [ps]			
			No CDF	CFD = 1/10	CFD = 1/5	CFD = 1/3
1	3000	130	282	132	139	154
10	800	36	85	30	33	40
100	200	9	29	7.5	9.0	11.6

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