Nuclear Instruments and Methods in Physics Research A 730 (2013) 226–231

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Ultra-fast silicon detectors

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ARTICLE INFO

Available online 20 June 2013

Keywords:
Fast silicon sensors
Charge multiplication
Thin tracking sensors
Silicon strip
Pixel detectors

ABSTRACT

We propose to develop a fast, thin silicon sensor with gain capable to concurrently measure with high precision the space (~10 μm) and time (~10 ps) coordinates of a particle. This will open up new application of silicon detector systems in many fields. Our analysis of detector properties indicates that it is possible to improve the timing characteristics of silicon-based tracking sensors, which already have sufficient position resolution, to achieve four-dimensional high-precision measurements. The basic sensor characteristics and the expected performance are listed, the wide field of applications are mentioned and the required R&D topics are discussed.

1. Introduction

We propose an ultra-fast silicon detector (UFSD) which 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 PET to mass spectroscopy or particle tracking.

We plan to develop a single device able to concurrently measure with high precision the space (~10 μm) 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. Since UFSD are extremely thin, they will make use of the internal charge multiplication in silicon sensors; a recent very active field of investigations within the CERN based RD50 collaboration [2].

In the following, we describe the principle of the UFSD, their properties and expected performance, followed by a section on measured pulse shapes. We present improvements in present applications and potential new applications with an UFSD system, and discuss required research.

2. Principle of UFSD

We propose to develop silicon sensors with time resolution a factor 100 better than what is possible today.

This proposal has to overcome a crucial limitation: given that the drift velocity in silicon saturates at about 10^7 cm/s, the collection time of electrons inside a silicon layer of ~300 μm is ~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, the charge collected from a thin active layer might not be enough to achieve good time resolution. We propose to exploit charge multiplication to increase the charge yield of very thin silicon sensors so that they can generate ultra-fast timing signals [1].

2.1. Gain in silicon sensors

The observation by several RD50 groups [2] of moderate gain in silicon sensors creates the opportunity for producing thin, very fast silicon sensors, which can work at extremely high-rates without dead-time issues. Up to now, the interest in moderate charge multiplication has been confined to mitigate charge collection loss due to trapping in irradiated sensors [3–6]. Our proposal is, instead, to make use of charge multiplication, with a gain of 10–100, to boost the small amount of charge collected in thin silicon sensors and to develop silicon sensors with ultra-fast timing information.

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http://dx.doi.org/10.1016/j.nima.2013.06.033

It has been demonstrated that in silicon sensors the charge multiplication factor α, which is responsible for the charge gain, has an exponential dependence on the electric field [7,8]. At the breakdown field in silicon sensors, E_{max}=270 kV/cm, the maximum achievable multiplication is limited to about ~1/μm for electrons and ~0.1/μm for holes. N_0 electrons, drifting a distance d, with a charge multiplication factor α become N_{Tot} electrons:

$$N_{Tot} = N_0 e^{\alpha * d}$$

For example, one electron drifting 5 μm in a field E_{max}=270 kV/cm with α=0.746 μm^{-1} from Ref. [7] generates a gain $g=N_{Tot}/N_0$=42. The effect of gain in silicon is similar to multiplication in gases employed in many detector applications and we can identify the parameter α with the first Townsend coefficient [9].

The electric field strength, however, is not a free parameter that can be set independently to obtain a high value of alpha, since it depends on the sensor bias. There is therefore interplay among biasing conditions, geometry and gain. To obtain the best possible timing performance, the charge collection time should be kept as short as possible. This requirement, combined with the saturation of the drift velocity, limits the region from which the charges can be collected to a thin volume close to the electrode (n^{++} implant in n-on-p sensors).

2.2. *Effect of sensor thickness: electrical field, collected charge, collection time, and capacitances*

To illustrate the problem, we consider a pad silicon sensor made by a single diode with a linear electric field and the bias voltage V_{bias} chosen so that the field at the p–n junction is at the maximum useful value, i.e. E_{max}=270 kV/cm. For this configuration, Table 1 lists, as a function of the resistivity, for two choices of sensor thickness, the voltage to obtain full depletion (VFD), the applied bias voltage (bias), the minimum electric field E_{min} inside the sensor and the associated gain g.

The table shows two important facts: (i) the maximum gain is obtained when the bias voltage is much larger than the bias voltage needed for full depletion VFD: $V_{bias}/VFD \gg 1$ and (ii) throughout the entire sensor bulk the electrons are moving at the highest possible velocity since the field exceeds everywhere 20 kV/cm, the field required for saturating the drift velocity [10].

The thickness of the active area determines several key parameters of the sensor. Considering two possible geometries, (i) a 50 μm × 50 μm pixel and (ii) a 1 mm-long strip ("striplet") with 50 μm pitch, Table 2 shows, as a function of sensor thickness, the backplane capacitance, the number of electrons that form the signal, the collection time, and the gain required to reach an acceptable signal level, 2000 electrons for the pixel, and 12,000 electrons for the strip sensor. The expected signal before gain is taken from Ref. [11].

Table 1
Voltage of full depletion VFD, bias voltage, minimum electric field and gain for silicon sensors of two different thicknesses and various resistivity values with the condition that the maximum electric field is E_{max}=270 kV/cm.

Resistivity [kΩ-cm]	Thickness [um]							
	20				5			
	VFD [V]	Bias [V]	E_{min} [kV/cm]	Gain	VFD [V]	Bias [V]	E_{min} [kV/cm]	Gain
0.01	453				28	107	157	3.0
0.02	227	314	44	19	14	121	214	4.9
0.1	45	495	225	4.9×10^3	2.8	132	258	9.1
1	4.5	535	265	1.7×10^5	0.28	135	268	10.9
10	0.45	540	270	2.9×10^5	0.028	135	270	11.3

Table 2
Silicon sensor characteristics for various thicknesses of the active area.

Thickness [μm]	Back-plane capacitance		Signal [# of e^-]	Collection time [ps]	Gain required	
	Pixels [fF]	Strips [pF/mm]			For 2000 e^-	For 12000 e^-
1	250	5.0	35	13	57	343
2	125	2.5	80	25	25	149
5	50	1.0	235	63	8.5	51
10	25	0.50	523	125	3.8	23
20	13	0.25	1149	250	1.7	10.4
100	3	0.05	6954	1250	0.29	1.7
300	1	0.02	23334	3750	0.09	0.5

Thinning sensors increases the back-plane capacitance. If one requires noise performance of thin sensors to be comparable to thick ones, one would limit the back-plane capacitance to be not much larger than the interstrip capacitance (200 fF for existing pixel sensors and 1 pF/cm for n-on-p strip sensors). This limits the thickness of pixel sensors to be larger than 1 μm and one of the strip sensors to be larger than 20 μm.

From the values shown in Table 2, pixel sensors offer very attractive combinations of moderate gain, small capacitance, and short collection time. Up to now, a gain of 6.5 has been reported in studies with epitaxial pad sensors [6]: this fact makes us confident that with a full research program we can achieve higher gains. Due to the high value of backplane capacitance, strip sensors cannot be made as fast as pixel sensors; however, a 1 mm long and 5 μm thick "mini-strip" offers a quite fast collection time, 50–100 ps, with a moderate value of capacitance (~1 pF).

3. Properties of thin segmented sensors

3.1. *Sensor options: epitaxial and thinned float zone*

A key part of the project is the possibility to mold the design of UFSD to the needs of different fields. For example, in medical applications such as PET, the sensor can be adapted, via backside etching, to detect visible light while in charge particles detection this is not necessary. Likewise, in applications such as x-ray crystallography at energies below 5 keV and sensors of ~20 um thickness. or dose counting the read-out chip can be designed, due to the very fast input pulse, to have unmatched single particle counting capabilities, while in time-of-flight experiments the fast input pulse is exploited to reduce the uncertainty on the time of arrival.

Thin epitaxial sensors are easily produced since they consist of a low-resistivity electrode (n^{++}) implanted in a high-resistivity p-epitaxial layer of silicon, deposited on a thick low-resistivity p^{++} substrate and the read-out chip is bump bonded to the sensor, Fig. 1a. In this configuration, they are very efficient in detecting charged particles. However, this configuration does not allow the detection of visible photons since the sensitive epi-layer is sandwiched between two fairly thick low-resistivity layers, the substrate and the ASIC.

As the detection of visible photons is one of the main fields of application of UFSD (for example PET and robotic vision), we foresee to employ backlit thinned high-resistivity Float Zone (FZ) sensor, Fig. 1b. In this technique one processes a FZ wafer of normal thickness and removes the excessive material at the backside by etching. Several groups have produced back-etched thin sensors [12–14], down to 15 μm thickness. In particular we propose to adapt a backside thinning method using a selective