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"Double-sided Silicon Strip Detectors in Pisa"

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Abstract

In the last years several hundreds of large ($\sim 25\text{cm}^2$) double-sided silicon strip detectors have been designed and tested in our Pisa-INFN laboratory. These detectors are currently used in ALEPH and L3 vertices, and in other field of applications as well. We present the tests performed on a single detector, and we discuss some results on the test structures inserted in each wafer in order to measure the relevant, process-dependent, quantities which determine the detector performances.

Paper presented at the 6th Pisa meeting on advanced detectors,
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INTRODUCTION

In the past years, about 400 double-sided Silicon strip detectors have been designed and tested by the PISA-ALEPH vertex group. The design of the detectors and of the complete mask layout have been done by INFN-PISA, while the wafer processing has been carried out by CSEM, Neuchatel, according to a process outline specified by INFN. All testing operations have been done in the PISA-INFN laboratory. In particular, we have dealt with:

- 48 $\sim 5 \times 5 \text{ cm}^2$ detectors in the years 1987-8, used as prototypes for the ALEPH vertex detector [1],
- 306 $\sim 5 \times 5 \text{ cm}^2$ detectors in 1989-93 (fig 1a). This design is named "HODO 4", and is currently used for the ALEPH vertex detector [2],
- 24 $\sim 4 \times 7 \text{ cm}^2$ detectors in 1991 (design named "HODO 5") which formed the first batch for the L3 vertex detector [3],
- 22 $\sim 5 \times 6 \text{ cm}^2$ detectors in 1994 (fig 1b) ("HODO 6") which are the first prototypes for the improved version of the ALEPH vertex detector [4].

Figures 1a-1b show pictures of the detectors, fabricated on high resistivity ($>6 \text{ k}\Omega\text{-cm}$), n-type, Silicon 4" wafers. They were $300 \mu\text{m}$ thick, $\langle 111 \rangle$ oriented. Around the main detector, we have inserted several test structures, in order to measure the relevant process-dependent quantities, which determine the detector performances. We have also inserted other test structures for R&D purposes, like transistors and pixels, and a smaller strip detector, $1.4 \times 1.4 \text{ cm}^2$, shown in fig 1a, which is used in digital radiography studies by the RADIN group [5], and for high precision tracking applications (e.g. beam telescopes)[6].

All detectors are segmented into strips on both sides, to measure at the same time two orthogonal coordinates of high energy particles crossing them, with a spatial resolution of about $10 \mu\text{m}$ or better. The differences among the various versions, apart from their dimensions, mainly consist in the design of the biasing resistors.

In this paper we first describe the working principles and the biasing scheme of the detectors (section 1), then we report the results on the leakage currents (section 2) and on the the most important measurements done on test structures (section 3). Last we briefly discuss the production yield and present our conclusions (section 4). When it will not be specified, we shall be concerned with the "HODO 4" detectors, fabricated for the present version of the ALEPH vertex detector.

1. WORKING PRINCIPLES AND BIASING SCHEME

All detectors are fabricated doping one side of the wafer, named "junction side", with a p^+ implantation segmented in strips, thus forming rectifying contacts. These strips are $12 \mu\text{m}$ wide and have a pitch of $25 \mu\text{m}$, and each strip is directly in contact with an Aluminum metallization. The whole surface of the detector is surrounded by a metallized p^+ implantation, the guard ring, which is used to bias the detector and to stop the edge currents as well.

On the opposite side, named "ohmic side", we have implanted n^+ strips with a $50 \mu\text{m}$ pitch, in a direction which is orthogonal to the strip direction on the junction side. Each n^+ strip is metallized. A p^+ strip (without metallization) is inserted between two consecutive n^+ strips, to isolate them when the detector has been completely depleted, as already discussed in reference [2]. There is also a metallized n^+ guard ring, around the ohmic side, with the same purposes of the one on the junction

side: biasing the detectors and stopping the edge currents.

The detector turns out to be intrinsically DC coupled, and therefore each strip needs an external capacitor to be AC coupled to electronics: in ALEPH this has been done using an "ad hoc" chip. Respect to intrinsic AC-coupled detectors, the increased complexity in bonding and assembly of the system, is, according to us, negligible with respect to the advantages of a simpler process and of a high production yield for the detectors. The depletion voltages range from 10V (for 2 particular batches) up to a maximum of about 60V, corresponding to an effective doping of the bulk from $N_b = 1.4 \times 10^{11} \text{cm}^{-3}$ up to $N_b = 8.4 \times 10^{11} \text{cm}^{-3}$, as confirmed by C-V measurements on diodes in the test structures.

The strips on the junction side are biased using the punch-through mechanism [7]. All p^+ strips end $4\mu\text{m}$ apart from the guard ring, which is kept at ground voltage: when a positive bias is given on the opposite side, the p^+ strips charge up to a voltage such that the leakage current of the strip is equal to the punch-through current. This voltage can be measured, and it is reported (figure 2) as a function of the bias voltage: the potential in the working point is just a few volts. The dynamic resistance between the strip and the guard ring is inversely proportional to the leakage current itself, and it is approximately $1\text{G}\Omega$ at 100pA (the typical value of the strip leakage current). This value is completely satisfactory, although it is not exactly predictable, since it depends on the leakage current.

The bias of the n^+ strips on the ohmic side is done using the n accumulation layer induced by the positive fixed oxide charge at the Silicon-Silicon dioxide interface. In fact the n^+ strips terminate $500\mu\text{m}$ apart from the guard ring, and the p^+ blocking strips are shaped in such a way to leave a n -type surface channel between each individual n^+ strip and the guard ring. The value of the resistance of this channel is shown in figure 3 versus the bias voltage: below the depletion it is low since it is dominated by the bulk conductivity, but at depletion it reaches the working value, which ranges from few $\text{M}\Omega$ to $50\text{M}\Omega$, depending on the design and on the process spread.

2. LEAKAGE CURRENT MEASUREMENTS

We have measured the total leakage current of the detectors by simply connecting the guard rings on both sides. The total current as a function of the bias voltage is usually almost constant up to the complete depletion of the detector, followed by a moderate increase. We have observed that the currents after cutting the detectors are usually lower than before, because in the latter case the guard ring collects also a diffusion current coming from the undepleted region of the wafer surrounding the main detector. The complete statistics on the current of the 306 "HODO 4" detectors is reported in figure 4: the most probable value is around 200nA and 73% of the detectors have a leakage current lower than $1\mu\text{A}$.

In order to measure the number of bad strips and to understand the origin of the leakage current as well, we always make automatic scans of the strips on both sides. On the junction side we measure the current of each individual strip, and on the ohmic side we also measure the isolation of each strip with respect to the neighbouring ones and the bias resistance to the guard ring. The result of a current scan is shown in figure 5a (junction side) and 5b (ohmic side): the current on the junction side is around 100pA and on the ohmic side is about twice as large, since the strip pitch is $50\mu\text{m}$ instead of $25\mu\text{m}$. Few strips have a leakage current greater than 1nA , and only 4 more than 500nA . We define a "good" strip if its leakage current is smaller than 10nA (for the ALEPH vertex detector, this

is where the shot noise starts to be a significant fraction of the electronic noise), if it is isolated from the neighbouring ones, and (for the ohmic side strips) if its bias resistance is in the range 5-50MΩ. The percentage of the good strips is an important quality factor, since it is proportional to the detector efficiency, and we use it in the definition of "good" detector.

We note that the average total current of a detector (~200nA) is just the product of the average strip current (100pA on the junction side, 200pA on the ohmic side) times the number of strips (2000 on the junction side, 1000 on the ohmic): we conclude that the currents on our detectors have a negligible contribution from edge effects. Moreover, we have tried to evaluate the contributions to the current of a strip due to bulk generation and to surface generation. At total depletion the former can be expressed by the formula:

$$i_b = qn_i p d L / 2 \tau, \quad (\text{eq. 1})$$

where q is the electric charge, n_i is the intrinsic carrier concentration, p is the strip pitch (25μm), d the wafer thickness (300μm), L the strip length (5cm) and τ is the carrier lifetime generation. Using for τ the values of 10-100ms measured in the test structures (section 3), i_b ranges from 3 to 30 pA. On the contrary, the surface generation current can be expressed by:

$$i_s = q n_i w L S_0 / 2, \quad (\text{eq. 2})$$

where q , n_i , L are the same of eq. 1, w is the gap between p^+ implantated strips and S_0 is the surface generation velocity. Since $S_0 = 10\text{-}25$ cm/s, as measured on dedicated test structures, i_s ranges from 60 to 140 pA, and we conclude that this is the dominant contribution to the leakage current.

3. TEST STRUCTURE MEASUREMENTS

As seen in sections 1 and 2, the most important quantities that determine the detector performance are the bulk doping density, the charge carrier generation lifetime, the surface generation velocity and the oxide charge at the Si-SiO₂ interface. The first two are measured using diodes, the third using gate controlled diodes and the last using MOS capacitors: all of these devices are inserted in the test structures placed around the main detector.

In the p^+nn^+ diode we first measure the capacity versus the bias voltage (curve (a) on the right scale of fig.6): it shows a dependence given by:

$$C(V) = \frac{\epsilon A}{d \sqrt{V/V_{td}}} \quad \text{for } V < V_{td} \quad (\text{eq.3})$$

where V is the reversed applied voltage, V_{td} the total depletion voltage, d the detector thickness, A the diode area and ϵ the dielectric constant of Silicon. The depletion voltage is better evaluated by plotting C^{-2} (curve (b) on the left scale): there is a linear dependence up to the depletion voltage, showing that the bulk doping is constant, followed by a plateau.

The other measurement we usually perform on diodes is the current - voltage dependence. For a good diode the current reaches a plateau at the depletion: making the hypothesis that this current is totally due to bulk generation, we can evaluate the carrier generation lifetime τ :

$$\tau = q n_i A d / 2 i_d, \quad (\text{eq.4})$$

where i_d is the asymptotic value of the current, A the diode area and the other values are defined after eq.1. τ usually ranges from 10 to 100ms, but on some wafers we have also got larger values, such as 0.4-0.5 s.

In the gate-controlled diode (GCD) we measure the surface generation velocity, plotting the diode

current as a function of the gate voltage: this curve is shown in figure 7 for different values of the bias voltage. Changing the gate potential, the GCD region under the oxide is brought, starting from accumulation, to depletion and then into the inversion condition. In accumulation and inversion only the bulk current is observed, while in depletion also the electron-hole pairs generated at the surface are collected: an increase Δi in the diode current is measured. The surface generation velocity is then given by:

$$s_0 = 2\Delta i / qn_i S \quad (\text{eq.5})$$

Standard values for s_0 are 10-25 cm/s, a bit high for <111> Silicon.

In the MOS capacitors we estimate the oxide charge density (Q_{ox}) measuring the capacitance (C) as a function of V, the bias voltage. For $V=0$ the bulk is not depleted, and in the surface under the oxide there is an electron accumulation layer, due to the positive oxide charges. Increasing V, the accumulation layer is removed and then the bulk is depleted until the surface is brought into inversion: the capacitance drops to a lower value. From the curve we can evaluate the voltage (V_{fb}) at which the flat-band condition is reached, and we can compute the number of oxide charges at the Si-SiO₂ interface: we obtained values from 2×10^{11} to 9×10^{11} charges/cm², which is a reasonable value for <111> oriented Silicon.

4. CONCLUSIONS

We have described the main, large scale, tests performed on the double-sided DC coupled Silicon strip detectors designed by us. The average leakage current at the operation voltage is about 200nA for 25cm² detectors, and we have shown that this current is mostly (70-90%) due to surface generation centers. We have also presented several measurements done on test structures, to help in the comprehension of the device behaviour and in the diagnosis of the bad detectors.

Moreover, on the basis of the test performed on the 306 "HODO 4" detectors, we can define a "good" detector, that is quite safe for the installation in a vertex detector, if it verifies the two following conditions:

- (i) leakage current < 3μA and stable with time,
- (ii) percentage of bad strips (defined in section 2) < than 1%.

With these constraints, the percentage of "good" detectors is 74.5%, and this is the quantity that we define as the "production yield". The remaining 25.5% detectors are rejected because of the current cut (17.6%) and the number of bad strips (6.9%), three wafers (1%) were damaged in the handling. We must specify that, if a detector fails both conditions (i) and (ii), it is computed in the group of the detectors rejected because of the current cut.

At the end, we point out that the DC coupling choice has allowed us to limit the number of steps in the wafer processing, and therefore the costs of the masks and of the wafer processing have been contained.

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FIGURE CAPTIONS

- 1) The detectors inserted in 4" Silicon wafers:
 - a) "HODO 4" (1989)
 - b) "HODO 6" (1994)
- 2) Electric potential of a strip on the junction side as a function of the bias voltage
- 3) Ohmic side resistance in function of the bias voltage between a n^+ strip and the guard ring
- 4) Current distribution at the working voltage for the 306 "HODO 4" detectors.
- 5) Leakage current in function of the strip number:
 - a) junction side
 - b) ohmic side
- 6) Reversed bias voltage (V) dependence of:
 - a) the diode capacity (C) on the right scale,
 - b) C^{-2} on the left scale.
- 7) Gate-controlled diode current in function of the gate voltage for different values of the bias voltage.

REFERENCES

- [1] G.Batignani et al., Nucl. Instr. and Meth., A277, 147 (1989)
- [2] G.Batignani et al., Nucl. Phys. (Proc. Suppl.) 23A, 297 (1991)
- [3] B.Alpat et al., Nucl. Instr. and Meth., A315, 197 (1992)
- [4] P.Coyle's talk at this meeting
- [5] M.Conti's talk at this meeting
- [6] J.Straver et al., CERN-PPE/94-26
- [7] P.Holl et al., IEEE Trans. Nucl. Sci., NS-36, 251 (1989)

FIG 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

a

b

FIG. 6

FIG. 7