A method for non-destructive resistivity mapping in silicon detectors

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**ABSTRACT**

It is well known that the resistivity non-uniformity of silicon detectors is a crucial parameter when pulse-shape analysis is used to identify the charge and the mass of stopped heavy ions.

In this work a method is described that allows a direct absolute resistivity measurement of the detector as a function of the position (∼mm resolution). The detector is used in a reverse-mount configuration and signals are collected for various applied voltages and for various \((x,y)\) positions by using a point excitation. For each applied voltage-position combination, the average signal risetime is obtained via a digital pulse-shape analysis, finally allowing the extraction of the desired resistivity measurement as a function of the position.

The method is non-destructive and can be applied to detectors with arbitrary shapes and readout geometries. Detectors can be fully tested in the laboratory before the actual experiments, possibly rejecting before beam time those not satisfying the resistivity uniformity requirements of the experiment.

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1. Introduction

The use of pulse-shape analysis (PSA) methods for charged particle identification in silicon detectors is a promising technique for present and future Nuclear Physics experiments, under investigation by several international collaborations. Its main advantage with respect to the standard \(D\Omega/E\) technique is the lower energy threshold achievable for particle identification.

It is well known (see for example Refs. [1–3]) that the PSA performances in silicon are severely influenced by the resistivity non-uniformity of the detector. In particular it has been shown that areas of the detector characterized by different resistivity produce signals having different shapes (e.g. different risetimes), thus jeopardizing the achievable performances when the full (i.e. non ad-hoc collimated) detector area is used.

It is possible to roughly estimate the needed level of uniformity by considering existing experimental PSA data and comparing with, for example, an estimate of the effect of resistivity non-uniformity on the detector risetime. Using as an example the collimated NTD detector shown in Fig. 9 of Ref. [4], one sees that the pulse-shape-based isotopic separation between, e.g. \(^{12}\)C and \(^{13}\)C consists in a ∼0.2 ns difference in the two isopes average risetimes. Given the ∼15 ns average value, this translates into a ∼1.3% difference. Therefore, since to a first-order approximation both the transit time and the plasma time (see for example the analytical estimate in Ref. [5]) depend linearly on the depletion voltage and hence on resistivity, a given requirement on signals risetime-spread directly translates into a non-uniformity requirement. The presently available quality of off-the-shelf silicon ingots and detectors (about 5–10%) is thus clearly not adequate and quality-check procedures should be employed.

Moreover, despite the technological efforts of the semiconductor industry, presently it is quite difficult to measure (possibly in a non-destructive way) the non-uniformity of a detector at the percent level prior to its operation. It has also to be noted that this quantity may fluctuate widely from one detector batch to another, thus making a sampling-based test quite useless.

In this work a non-destructive method for resistivity mapping is proposed that allows the determination of the detector resistivity map and thus the measurement of its non-uniformity.

From the practical point of view, this allows testing of the detectors in the laboratory before the actual experiment, and rejection of those that do not match some predefined non-uniformity threshold.

2. The method

Let us briefly recall a quite standard method for detector depletion-voltage \((V_{\text{depl}})\) or resistivity \((\rho)\) determination, i.e. the
measurement of the detector capacitance $C$ as a function of the applied voltage ($V_{\text{appl}}$). Due to the semiconductor properties of the detector, the capacitance is very large for $V_{\text{appl}} \ll V_{\text{depl}}$, it lowers as a function of the applied voltage as long as $V_{\text{appl}} < V_{\text{depl}}$, finally saturating for $V_{\text{appl}} > V_{\text{depl}}$—this behavior experimentally defines the quantity $V_{\text{depl}}$. The detector resistivity can be finally obtained using the following formula [6], valid for a planar configuration and constant resistivity in the whole detector active volume:

$$ P = \frac{d^2}{2V_{\text{depl}} \varepsilon_{\text{Si}} \mu} \tag{1} $$

where $d$ is the detector thickness, $\varepsilon_{\text{Si}}$ is the silicon dielectric constant, $\mu$ is the majority-carrier mobility in the detector bulk. It is worth noting that both $V_{\text{depl}}$ and $\rho$ extracted in this way must be regarded as “average” quantities over the whole detector.

In this work we first extend the basic ideas behind the standard $C - V_{\text{appl}}$ method by defining the “local” depletion voltage $V_{\text{depl}}(x,y)$, i.e. the detector depletion voltage as a function of the position $(x,y)$—the discussed configuration is shown in Fig. 1. A collimated light pulse (or a collimated $z$ particle source), having very low penetration depth inside silicon, produces a cloud of electrons and holes that are collected by the detector. It has to be noted that, due to the collimation, only a small part of the detector is involved in this process, namely the volume defined by the source collection in the $(x,y)$ plane, by the lateral diffusion processes during charge collection, and by the detector thickness.

As shown in Fig. 1 the detector is used in a reverse-mount configuration, i.e. the used light pulse enters the detector from the low field side—this means that, when $V_{\text{appl}} < V_{\text{depl}}$, the carriers are produced in a region of nominally zero electric-field (that is the area marked as “not depleted region” in Fig. 1).

For a given position $(x,y)$, by examining the collected signals as a function of the applied voltage $V_{\text{appl}}$, we expect some “abrupt” change in the signal properties (for example the risetime) in passing from the regime of non-completely depleted detector to the over-depleted one (i.e. absence of any non-depleted region). In analogy with the standard $C - V_{\text{appl}}$ method, taking into account that the signal is governed by the properties of the interested active volume only, we thus define the “local” depletion voltage $V_{\text{depl}}(x,y)$ as the voltage where this abrupt change occurs (later we will discuss how to practically determine it).

For typical collimations ($\sim 1$ mm diameter) and detector thicknesses (hundreds of $\mu$m) one can approximate the involved active volume as a planar geometry, and thus, assuming that no appreciable change in the detector resistivity occurs along the $z$ direction, it is possible to measure the desired absolute detector resistivity $\rho(x,y)$ as a function of position by application of Eq. (1). In the case of significantly varying resistivity along the $z$ direction (not expected for thin detectors), the method can be still applied in order to find the average resistivity of the material along $z$ as a function of $(x,y)$ position. The proposed method thus somewhat resembles the well established Transient Current Techniques (TCT, [7]) but, at variance from those methods, in this work almost no hypothesis on the detector properties is made.

In Fig. 2 the used experimental setup is shown. The silicon detector under test is mounted on an $x – y$ movement with remote control, and irradiated with a collimated pulsed laser source (sub-nanosecond pulse width). It would be also possible to use a collimated $z$ source, although the need to operate in vacuum makes this solution somewhat more complex to set-up.

A collimator of $\sim 1$ mm diameter has been used during the tests. The detector output is fed into a preamplifier [8] whose charge output is connected to a digital sampling system (employing a 125 MS/s 12 bit digitizer, see Ref. [9]). Both the $x – y$ movement and the applied voltage $V_{\text{appl}}$ are remotely controlled by the acquisition system.

For each $(x,y)$ position, a $V_{\text{appl}}$ scan is performed by the control system, while recording the detector pulse shapes — the procedure is repeated until the whole detector surface has been explored. After the desired scan parameters have been introduced, no manual intervention is needed to operate the system.

By means of a digital PSA it is possible, for each event, to extract the signal risetime (the algorithms of Ref. [4] have been used). After a scan has been completed (for example about 2.5 h) are needed for a $20 \times 20$ mm$^2$ detector, with 1 mm $x – y$ resolution, $\sim 12$ different values for $V_{\text{appl}}$ and 100 Hz laser pulse rate), it is possible to extract for each $(x,y)$ position an average risetime vs. $V_{\text{appl}}$ plot — an example of such plot is shown in Fig. 3.

For $V_{\text{appl}} < V_{\text{depl}}$ the measured signal risetime is very long (hundreds of ns), due to the presence of a non-depleted region in the detector (see Fig. 1). For $V_{\text{appl}} > V_{\text{depl}}$ the signal risetime reaches the nominal value for the used detector type (practically the detector transit time) and, when compared with the $V_{\text{appl}} < V_{\text{depl}}$ regime, only a minimal dependence on $V_{\text{appl}}$ remains.

The local depletion voltage can be extracted from a plot like Fig. 3 by fitting the experimental points with a function describing the detector’s signals risetime as a function of the applied voltage. For $V_{\text{appl}} < V_{\text{depl}}$, the signal is composed of two components:

1. a slow component due to the diffusion-driven motion of carriers in the zero-electric-field volume of the detector (i.e. $z < z_0$ in Fig. 1),
2. a fast one due to carriers flying in the depleted area (i.e. $z > z_0$ in Fig. 1).

\footnote{In practice, in order to avoid excessive voltage stress to the detector, the two scans are performed in the opposite order, i.e. for a given $V_{\text{appl}}$ the full detector is scanned in the $(x,y)$ plane. In the used operating conditions, this makes it possible to change the applied voltage on the detector every $\sim 0.2$ h instead of every few seconds.}
We can estimate the slow component by using the following simple model:

- the charge density at $t = 0$ is a zero width distribution at $z = 0$,
- one carrier type (electrons for $n$-type detectors) is instantaneously collected at $t = 0$ and does not provide any contribution to the signal,
- the charge density $\rho(z, t)$ of the remaining carriers (holes for $n$-type detectors) changes as a function of the time $t$ as a Gaussian packet subject to diffusion:

$$\rho(z, t) = \frac{2Q_0}{\sigma_D \sqrt{2\pi}} \exp \left[ -\frac{z^2}{2\sigma_D^2} \right]$$

(2)

having standard deviation $\sigma_D = \sqrt{2Dt}$ ($D$ is the diffusion coefficient). $Q_0$ is the total charge released in the detector ($z \geq 0$),

- a carrier entering the depleted zone (i.e. the detector volume where the electric field is non-zero $z > z_0$ in Fig. 1) starts drifting towards the electrode, thus giving a contribution to the signal fast component (those details are not considered here).

Under these hypotheses the slow component of the charge signal is given by

$$Q_{\text{slow}}(t) = \int_{z_0}^{\infty} \rho(z, t) \, dz = Q_0 \left[ 1 - \text{erf} \left( \frac{z_0}{\sqrt{2Dt}} \right) \right]$$

The 10–90% risetime of the signal can thus be obtained by numerical solution of the equations $Q_{\text{slow}}(\tau_{90\%}) = 0.90 \cdot Q_0$ and $Q_{\text{slow}}(\tau_{10\%}) = 0.10 \cdot Q_0$, finally yielding the estimate $\tau_{\text{rise,slow}} \propto (z_0)^2$ (valid for $z_0 > 0$ that means $V_{\text{appl}} < V_{\text{depl}}$).

The measured risetime can thus be approximated with the sum of $\tau_{\text{rise,slow}}$ and of the fast-component risetime, that is of the order of the transit time in the depleted detector, and practically not dependent on $V_{\text{appl}}$ (as compared with the slow component).

The local depletion voltage can be extracted from a plot like that of Fig. 3 by fitting the data with the function

$$\tau_{\text{rise}}(V_{\text{appl}}) = \begin{cases} t_0 + a \sqrt{V_{\text{depl}}(x,y)} & \text{for } V_{\text{appl}} < V_{\text{depl}}(x,y) \\ t_0 & \text{for } V_{\text{appl}} > V_{\text{depl}}(x,y) \end{cases}$$

(3)
where \( t_0 \) and \( a \) represent the asymptotic risetime (for \( V_{\text{appl}} \gg V_{\text{depl}} \)) and the coefficient of the behavior apparent for \( V_{\text{appl}} < V_{\text{depl}} \) respectively. \(^3\) In Fig. 3 the value of \( V_{\text{depl}}(x,y) \) obtained from such a fit is also shown.

Once \( V_{\text{depl}}(x,y) \) has been extracted for all the scanned positions of the detector it is possible to apply Eq. (1) and obtain \( \rho(x,y) \) – in the next section some results obtained with this procedure will be shown.

3. Results

By using the procedure outlined in the previous section it is possible to build a bidimensional resistivity map of the used detector – in Fig. 4 a typical example is shown.

The most striking feature of the shown resistivity “landscape” is the presence of circular structures, or “striations” (very similar structures are present, with varying importance, in all the tested detectors). This is in fair agreement with the well known striations (see for example Ref. [10]) present in silicon material due to the silicon ingot growing processes – this has been verified by measuring several detectors \(^4\) belonging to the same wafer. Knowing the mask employed during the manufacturing process and how the placement of the bare silicon chips with respect to the mounting frame relates to their original placement on the wafer, it is thus possible to reconstruct the original wafer resistivity map. The result of such a procedure is shown in Fig. 5.

In the figure a partial resistivity map of three wafers has been reconstructed starting from the resistivity measurements of eight detectors – black solid lines refer to the processing mask, while an additional circle (dashed line) has been drawn to guide the eye. The picture clearly confirms the origin of the striations, concentric with the original wafer center.

In Table 1 the obtained results for some of the tested detectors are shown.

In the first four columns the detector serial number, the nominal thickness, nominal depletion voltage and nominal resistivity are reported. The fifth column (“Meas. av. \( V_{\text{depl}} \)” ) reports the average measured depletion voltage, i.e. the average of the measured \( V_{\text{depl}}(x,y) \), while in the sixth column (“Meas. av. resistivity”) the average of \( \rho(x,y) \) is shown.

As shown in Table 1, the manufacturer declared values are in fair agreement with the obtained results (for example a maximum of \( \sim 10 \) V discrepancy on the depletion voltage is present). The measured depletion voltage and resistivity after averaging over the detector surface are given as well. The detector “non-uniformity” (see text for the definition) is given in the last column.

\(^3\) Eq. (3) assumes that for \( V_{\text{appl}} \gg V_{\text{depl}} \) the fast signal component has no appreciable change in the measured risetime (as compared with the slow one) like, for example, when a slow preamplifier/electronics is used. In this case the asymptotic risetime is only due to the electronics, and does not depend on \( V_{\text{appl}} \) (like in Fig. 3). We have verified that the formula (and hence the overall method) applies also in the case of an appreciable change in measured risetime, provided that the region \( V_{\text{appl}} \gg V_{\text{depl}} \) is fitted with a voltage dependent formula like, for example, a linear dependence \( t_0 + b(V_{\text{appl}} - V_{\text{depl}}) \).

\(^4\) Unfortunately we did not have access to all detectors produced starting from a given wafer but only to a few of them, as apparent from Fig. 5.

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Table 1

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<th>Det.</th>
<th>Thickness (( \mu m ))</th>
<th>Nominal ( V_{\text{depl}} ) (V)</th>
<th>Nominal Resistivity (( \Omega \ cm ))</th>
<th>Meas. av. ( V_{\text{depl}} ) (V)</th>
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In the first columns nominal values (i.e. the manufacturer’s declared ones) for the detectors are given. The measured depletion voltage and resistivity after averaging over the detector surface are given as well. The detector “non-uniformity” (see text for the definition) is given in the last column.
4. Conclusions

In this work a method for resistivity mapping of silicon detectors has been presented. By using a collimated pulsed light source and a reverse-mount configuration of the silicon detector, surface scans of the detector are performed for different applied voltages, recording the resulting charge signal with a digital sampling system. After extraction of the average signal risetime for each position and applied-voltage, it is possible to extract a “local” depletion voltage (as defined in Section 2) and to finally obtain the desired absolute resistivity measurement as a function of the position, i.e. $\rho(x,y)$. No additional special hypothesis is needed on the detector resistivity behavior in order to apply the method.

These measurements make it possible to experimentally characterize the non-uniformity of the used silicon detectors, quantified by the FWHM variation of the resistivity across the detector area. In Table 1 results for some of the tested detectors have been reported.

This kind of non-destructive detector characterization is very important for the purpose of pulse-shape-based Nuclear Physics projects (like FAZIA [11]) where, as it is well known (see for example Refs. [1,2]), the detector non-uniformity plays a fundamental role in the attainable particle identification performances.

The detectors tested in this work have been used by the FAZIA collaboration in a R&D test at Laboratori Nazionali di Legnaro (LNL) in December 2007, providing particle identification performances in qualitative agreement with the measured non-homogeneities (i.e. good uniformity provides good particle identification and viceversa). The details and the results of that experiment will be reported in a forthcoming paper.

Acknowledgments

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References

[10] Topsil, Application Note “NTD silicon for power electronics”.