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17 March 1986**SILICON RADIATION DETECTOR ANALYSIS USING BACK ELECTRON BEAM INDUCED CURRENT : BACKEBIC**

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ABSTRACT

A new technique for the observation and analysis of defects in silicon radiation detectors is described. This method uses an electron beam from a Scanning Electron Microscope (SEM) impinging on the rear side of the P⁺N junction of the silicon detector. Because of the charge collection properties of the junction created in high-purity silicon crystal, the electron beam probes silicon defects resulting from either the processing or the raw material, exactly as during use as a nuclear radiation detector. In the BACKEBIC approach the electron beam of the SEM hits the rearside of the P⁺N junction. The holes created diffuse thermally in the non-depleted volume, or drift in the depleted volume towards the junction electrode. Because of the long lifetime of minority carriers in high-purity silicon crystal the hole collection efficiency is large. Because of the low diffusion speed of minority carriers in non depleted region, the capture cross section of trapping centres is large and influences the EBIC current collected at the junction. The method therefore allows a sensitive probe of trapping centre regions either localized at the junction surface or in the overall volume of the silicon crystal.

Introduction

The radiation environment in which semiconductor particle detector are used, generally degrades their electrical characteristics.

Very often, other degradations are already present before exposing the detectors to radiation.

These defects within the devices have their origin during the growth of the crystal or during detector processing.

For long term applications, it is necessary to avoid the use of detectors having such defects since their performance is deteriorated.

It is also quite desirable to develop new device structures that have a lower sensitivity to radiation damages.

Detector electrical performance analysis

Since this type of device simply consists of shallow reverse biased junctions in a monocrystal of silicon, the most evident test is the measurement of the diode reverse current versus the applied voltage.

This "leakage" current should be as low as possible and the diode breakdown voltage has to be high enough to allow the depletion of the whole thickness of the device.

In good detectors the limiting current is mainly due to generation-recombination of electron-hole pairs within the depleted region. It can be as low as 70 nA.cm⁻³ at full depletion, as reported by Kemmer [1].

Such excellent junctions are not easy to fabricate when large surfaces are required.

For example in the CERN UA2 proton-anti-proton collider : 432 7-segment detectors with a junction area of 24,4 cm² per device, will be used [2].

The excess leakage current usually has its origin along the edges of the planar junctions where the electrical field is enhanced by the depletion layer curvature.

Structures using a guard ring may eliminate this problem. When this guard ring does not reduce the excess current, the generation-recombination regions have to be found within the silicon crystal.

The new analysis technique, that we describe here, is well suited to identify these buried defects.

Radiation damage

These damage results mainly from introduction of defects which act as generation-recombination centers and as trapping centers.

It is known that the most radiation sensitive part of the detectors is the passivation silicon oxide which covers, at the surface, the edges of the junctions.

The electron beam of a SEM (Scanning Electron Microscope) with electron energy of less than 200 KeV does not produce structural damage in silicon. However it may induce artifacts in SiO_2 layers and SiO_2 -Si interfaces.

These induced defects are fixed positive charges due to holes of low mobility in the silicon oxide and to high density trapping centres at the SiO_2 -Si interface.

Detector SEM analysis

As shown on figure 1 the principle of the Scanning Electron Microscope is quite simple.

It has the great advantage of permitting a combination of several video pictures obtained from selective detectors sensing different phenomena created by the impact of the electron beam.

On this figure two detectors are drawn : one to sense secondary electrons (SE mode) and the other to sense the electron beam induced current in a sample (EBIC mode).

Figure 1

SEM principle in SE and EBIC modes

The interest of the EBIC mode resides in the fact that the specimen being analysed itself acts as the detector or "collector" of induced charges from the electron beam that make up the video signal.

Since the electron beam of the SEM is a constant current source, the EBIC video picture reveals spatial variations in the charge collection efficiency.

The junction space-charge layer of a silicon radiation detector is well suited to collect electron-hole pairs created by an electron beam and therefore is well adapted for EBIC analysis.

Figure 2

Electron range R_e versus electron beam energy E_b

Figure 3
"Pear shape" of electron-hole isoconcentrations due to the impact of a focused electron beam

Figure 2 gives the electron range R_e in some semiconductors and metals versus the electron beam energy E_b .

Figure 3 shows contours of equal concentration of the spatial electron-hole pair from well focused electron beam impinging on a solid.

Figure 4 presents the space charge layer width W versus dopant concentration N_B for abrupt, one-sided p-n junctions in silicon. These curves are plotted from the well known equation.

$$W = \left(\frac{2 \epsilon (V_{bi} + V_a)}{q N_B} \right)^{1/2}$$

were ϵ = Si dielectric constant
 V_{bi} = Junction built-in voltage
 V_a = Applied reverse junction polarization
 q = Electronic charge
 N_B = Bulk doping concentration

Figure 4
Depletion layer width vs dopant concentration and applied voltage

Figure 5 gives some information on the hole diffusion length L_h . This parameter is of interest to us since the bulk silicon of our particule detectors is slightly n doped ($\sim 5 \text{ kcm}$). The same figure presents also a rough evaluation of the EBIC current to be expected in our SEM analysis.

BOLE DIFFUSION LENGTH L_h

Einstein relation : $\frac{D_h}{\mu_h} = \frac{kT}{q}$

Hole diffusion length : $L_h = (D_h \cdot \tau_h)^{1/2}$

$L_h = \left(\frac{\tau_h kT}{q} \right)^{1/2}$ D_h = hole diffusion cte
 μ_h = hole mobility
 τ_h = hole life time

At room temperature and with $\tau_h = 10^{-8} \text{ s}$. and $\mu_h = 600 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
 from Leamy [3] $L_h = 1.3 \text{ mm}$ in our $5 \text{ k}\Omega \text{ cm}$ n Si.

EBIC CURRENT LEVEL

If the electron energy loss in the aluminium layer covering the Si is = 10 KeV and electron-hole pair energy formation is in Si = 3,6 eV.

$$I_{EBIC} = \frac{I_{beam} (E_{beam} - 10 \text{ KeV})}{3,6}$$

In our case I_{beam} will be = 10^{-9} A and $E_{beam} = 30 \text{ KeV}$.

Typical $I_{EBIC} = 5,6 \text{ nA}$.

Figure 5
Typical hole diffusion length and EBIC current to be expected in our SEM analysis of silicon particles detectors

CERN detector analysis with SEM Front EBIC mode

In order to localize the sources of high reverse currents in some CERN Si junction detectors, we have attempted SEM EBIC analysis. To this purpose our device was scanned with the electron beam on the "front" shallow p+ side of the junction as shown on figure 6.

By adjusting the reverse polarization of the abnormal analysed junction just below its too low breakdown voltage, we were able to trigger, with the electron beam, an avalanche at the place where the junction had a "weak spot".

Figure 7 shows some of these spots along one edge of a bad junction.

Figure 6
Front EBIC method principle

Figure 7
"Weak spots" along a junction edge in front EBIC mode

The front EBIC method, used to reveal too low breakdown has already been reported by Leamy [3] in a failure analysis on integrated circuits.

Although this EBIC mode is quite efficient for the identification of weak spots on the junction periphery, it is not the case for defects deeply buried in the silicon.

Back EBIC mode

In order to have minority carriers, generated by the electron beam, going through the whole thickness of the detector, we have attempted a scan of the electron beam on the n+ side of the detector, the so-called "back side".

In this case the video signal current is created by holes which traverse the device, thus probing its internal structure.

Figure 8 shows the back EBIC principle.

Figure 8
Back EBIC method principle using a thin depleted region (low junction reverse bias)
Wd = depleted layer
Wnd = non depleted layer

If the diffusion length L_h of the minority carriers is large compare to the device thickness, and if they are moving in the vicinity of a high recombination region, they will be absorbed and thus not collected as video current. These regions will appear as white spots on the SEM picture.

In figure 9 (a) such a white spot is seen (an artificial contrast enhancement creates the alternate black and white rings) which was easily found in a bad detector segment.

It was less easy to find the corresponding defect on the front side of the diode, as shown on figure 9 (b), using the SEM in SE mode. The size of the defect is only a fraction of one μm . However, if the total observed segment current ($3 \mu\text{A}$) passes through this defect, a current density of about 10^3 Acm^{-2} may explain the appearance of this defect, which looks like a molten crater.

This defect might be related to processing conditions but could also be initiated by a defect existing on the starting silicon material.

Figure 9 (a)

Back EBIC picture of part of a leaky segment. The white line is the measured EBIC current profile along a cross section of this device part

Figure 9 (b)

The same defect found in SEM SE mode on the front side of this leaky segment

A second example of back EBIC analysis is shown in figure 10 (a). On a part of a microstrip detector, the EBIC signal is collected simultaneously on 80 strips. The recombination spot occupies nearly all the area, but the responsible defect, which was found on the rear side at the center of the spot using SEM SE mode, is also rather small as shown on figure 10 (b).

The large area of low collection efficiency is easily explained by thermal diffusion during the long migration distance of the holes before reaching the collecting depletion region.

On the figure 9 (b) we did not find this effect of lateral diffusion since the defect was on the "collection" front side.

Figure 10 (a)

Back EBIC picture of a region of 80 microstrips connected together. The recombination spot spreads out over many strips

Figure 10 (b)

Rear side defect cluster, found by SEM SE mode, at the center of the recombination spot

In both the above examples, we have shown that, on either device face, a responsible "visible" defect which is probably processing dependent, can be identified.

Most of the time, the region of low collection efficiency revealed by the back EBIC method could not be correlated with "visible" defects, because they were buried in the bulk silicon. These will be called "lattice bulk defects".

Effect of reverse junction biasing on back EBIC image contrast

The figures 11, 12, 13 and 14 were obtained with back EBIC mode on the same good detector, by a junction reverse bias of respectively 15, 45, 60 and 85 volts. With an 85 volt bias, the device was in full depletion.

Figure 11
Back EBIC image of a good segment.
Va reverse = 15 volts

Figure 12
Back EBIC image of the same good segment.
Va reverse = 45 volts

Figure 13
Back EBIC image of the same good segment.
Va reverse = 60 volts

Figure 14

Back EBIC image of the same good segment.
Va reverse = 85 volts. The segment is in full depletion

At full depletion the contrast of the EBIC image is lost. We have the following explanation for this effect : when the detector is not strongly depleted, minority carriers (holes) have a long travel distance before reaching the collecting depletion region. During this travel they only undergo a thermal diffusion since the speed of the hole motion in the undepleted region is very low. Therefore the "recombination cross section" of holes is high when they meet strong recombination regions. This explains the strong back EBIC contrast.

In the depleted region the speed of hole motion is very high (about four orders of magnitude higher than in the undepleted region). The "recombination cross section" is strongly reduced and, when the detector is totally depleted, the back EBIC contrast is lost.

The striations seen on figure 11, 12 and 13 may be explained by residual dislocations produced during wafer sawing. It seems that the subsequent etching of the wafer was not sufficient to remove these dislocations.

We initially thought they were due to doping inhomogeneities produced during crystal growth. This should however not be the case since, to reach such a high silicon purity, one can only use float zone crystals.

The two contrasted vertical lines correspond to interstrip regions where trapping center density is high at the Si-SiO₂ interface.

Figure 15 shows an example of a large mechanical defect having only a small electrical influence. On the device back side the SEM SE picture reveals a deep long scratch. The back EBIC image gives only two small recombination spots along this scratch.

Figure 15

Superposition of SE and EBIC images of a mechanical scratch giving only two small recombination spots in back EBIC mode

Back EBIC electron beam scanning speed

A slow scanning speed is required to avoid phantom images. This image distortion is created by the "pear shape" of the electron-hole cloud generated by the electron beam.

As the minority carriers have a long lifetime in such a high purity silicon crystal, the electron-hole cloud will be stretched out behind the scanning motion.

Other possible interesting investigations with SEM on particle detectors

An analysis by front EBIC of the selfcuring effect on premature breakdown spots along the junction edges. The selfcuring effect is known to be due to hot electrons injected from the junction and trapped in the SiO₂ passivation layer. These negative fixed charges can induce a localized inversion layer in silicon and then displace the junction away from its defect.

A measurement of the effective carrier lifetime in back EBIC mode by the observation of the phantom image, and by changing the electron beam scanning speed. This measurement will be useful to subsequently check the radiation damage to the bulk silicon, by comparing lifetime before and after nuclear radiation exposure on some reference detectors.

Conclusion

The SEM is a quite powerful tool to analyse particle silicon detectors.

The known front EBIC mode is well suited to studies of the junction periphery and as well the passivation layer and its interface with silicon. Unfortunately it creates artifacts.

The new back EBIC mode is a non-perturbative method since the rear side of the detectors is free of a radiation sensitive dielectric layer.

The back EBIC mode permits the determination of these defects present in the whole volume of the device that are electrically active and therefore potentially damaging to detector operation.

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