THE RADIATION HARDNESS OF HIGH RESISTIVITY NEUTRON TRANSMUTATION DOPING SILICON.

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1. Introduction

It is well known that point defects generated by gamma-radiation in Si are mobile and can form complexes as V-O, V-P, V2 etc. The same is true for defects created by neutron radiation but on top of these defects clusters having an average size of 10^{-6} cm are introduced. These clusters behave as dispersed centers. They are large scale traps for free carriers and their capture radius is enhanced by the built-up of a local electrical field. Hence the capture of vacancies by clusters could be a mean to increase the radiation hardness of Si-detectors.

2. Absorption of vacancies by impurity centers

It has been shown by the ROSE collaboration [1,2] that the introduction of oxygen in Si has a beneficial effect on the radiation hardness. When the concentration of O is much higher than the concentrations of P or B the formation of A-centers (V-O) predominates and it is proportional to the concentration of O and to that of the vacancies (V). Therefore the carrier removal by the E-centers (P-V) is suppressed. There exists also a beneficial contribution from residual boron atoms, which have a large capture radius for vacancies. This has been put forward in a recent report of RD48 [3,4].

3. Absorption of vacancies by other precipitation centers

If Si is doped with isovalence elements as Sn or Ge in a sufficiently high concentration (more than 10^{18} cm^{-3}) mechanical stress is built up because of the difference in the atomic radii. These stress centers become also sinks for point defects and improve the radiation hardness. However, the presence of the impurities deteriorates the life-time of the free carriers and therefore these materials are hardly suited as particle detectors.

4. Absorption of vacancies by NTD Si

We have carried out some research on the behavior of NTD Si n-and p-type produced in a nuclear reactor. We took ordinary FZ-Si material as a control sample and compared it to NTD Si. The samples were irradiated either by gamma radiation from a ^{60}Co-source or by fast neutrons from a reactor having an effective energy of about 1 MeV.

4.1 Experimental results

The free carrier densities were measured at different fluences. The results are reported in Tables 1 and 2. We notice that the carrier removal rate under gamma-radiation is an order of magnitude less in the NTD Si samples than in the control sample. The same phenomenon, however much more attenuated, can be observed with neutron radiation. The difference is certainly due to the cluster formation under neutron irradiation. High resistivity (10 to 40 kOhm cm) p-type NTD Si material does not show a noticeable difference with respect to normal FZ-material under irradiation. This can be explained by the fact that high resistivity p-type NTD Si needs an order of magnitude less neutron flux than n-type Si for its production.

4.2 Defects in FZ Si

Material for Si detectors is normally free of dislocations and other similar defects. However the growing speed of the crystal can influence the formation of some defects, which can be visualized by selective edging. For example, if Si is grown with a speed less than 3 mm/min, a surplus of Si atoms (interstitials) can form A-microdefects, which are dislocation loops in the planes <110> and <111> and are slightly propagated along <110>. Their dimensions are 1 to 3 10^{-4} cm and their densities vary from 10^{4} to 10^{6} cm^{-3}. If the growing speed is about 4 mm/min, B-microdefects of interstitial-type can originate, which are flat squares or rhombs in the plane <100>. Their dimensions vary from 2 to 5 10^{-6} cm and their concentration from 10^{6} to 10^{8} cm^{-3}. Finally, if the growing speed is larger than 5 mm/min a deficiency of Si atoms, called D-microdefects of vacancy-type, can be observed. They have typical dimensions of 4 10^{-7} to 6 10^{-7} cm and concentrations of about 10^{12} cm^{-3}. Transmission Electron Microscopy (TEM) observations have shown that these defects can have almost an amorphous structure indicating that V-O act as germs for such amorphous associations. Since the A-defect is a dislocation loop of interstitial-type, it creates a local compression, which in turn can capture vacancies. Then the vacancies compensate the positive charge around the dislocations. The same holds for B-defects. On the other hand D-defects are of vacancy nature and interact with impurities and point defects.

4.3 Defects in NTD Si

The starting material for neutron doping was free of A- and B-defects. After irradiation with neutrons no large defects are observed by selective edging. However, after the transmuted material has been annealed at 850 ^{0}C large clusters of vacancy-type diffuse as bubbles to the surface while the clusters of interstitial-type are transformed into dislocation loops. If this material is further irradiated the dislocation loops, positively charged, act as sinks similar to the A-defects.
We remark that the clusters created by the fast neutrons [5] have about the same size as B-defects (10^{-6} cm). The average radius of clusters produced by 24 GeV protons is 3.3 10^{-6} cm. So, if we admit that neutron transmutation produces B-type defects we can expect that these defects constitute effective sinks for vacancies and that they are also precipitation centers for impurities. The existence of precipitation centers is confirmed by the observation that in n-type NTD Si the doping is 15 % less than the calculated value as given by the neutron fluence from the reactor.

4.4 Annealing of D-defects

Finally, we want to mention the attempt to remove D-defects. By introducing nitrogen, D-defects can be annealed at least to some extend as can be shown by Li^+ diffusion (6). Another way would be to introduce a getter which generates intrinsic interstitial atoms able to dissolve D-defects. For this we propose to put a phosphoric glass (POCL3) on the Si surface, which could absorb the vacancies in the D-defects.

5. Conclusion

It has been shown experimentally that Si-detectors become more radiation tolerant when the starting material is produced by neutron transmutation doping followed by a thermal annealing process. Hence we recommend the use of NTD Si material (> 1kohm). Furthermore this material should be highly compensated by boron which is an effective sink for vacancies.
Detailed work is still carried out at the reactor of the Institute of Nuclear Research (INR) of Ukraine.

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Table 1 ***γ-irradiation***

Fluence ^{60}Co cm^{-2}	NTD		Control	
	concentration N cm^{-3}	removal rate $\Delta N/\Phi$ cm^{-1}	concentration N cm^{-3}	removal rate $\Delta N/\Phi$ cm^{-1}
0	$1{,}4\cdot10^{12}$	–	$3{,}4\cdot10^{12}$	–
$1{,}6\cdot10^{14}$	$1{,}4\cdot10^{12}$	0	$2{,}67\cdot10^{12}$	$4{,}5\cdot10^{-3}$
$4{,}8\cdot10^{14}$	$1{,}33\cdot10^{12}$	$1{,}5\cdot10^{-4}$	$2{,}16\cdot10^{12}$	$4{,}0\cdot10^{-3}$
$1{,}6\cdot10^{15}$	$9{,}8\cdot10^{11}$	$2{,}6\cdot10^{-4}$	$1{,}7\cdot10^{12}$	$1{,}1\cdot10^{-3}$

Table 2: ***Irradiation with fast neutrons***

Fluence fast neutrons cm^{-2}	NTD		Control	
	concentration N cm^{-3}	removal rate $\Delta N/\Phi$ cm^{-1}	concentration N cm^{-3}	removal rate $\Delta N/\Phi$ cm^{-1}
0	$1{,}4\cdot10^{12}$	–	$1{,}0\cdot10^{13}$	–
$4{,}6\cdot10^{11}$	$1{,}1\cdot10^{12}$	0,66	$9{,}2\cdot10^{12}$	1,74
$9{,}6\cdot10^{11}$	$6{,}4\cdot10^{11}$	0,79	$8{,}5\cdot10^{12}$	1,56