Changes to the paper TN-2000-03

"Radiation Hard Silicon Detectors - Developments by the RD48 (ROSE) Collaboration -"

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11.9.2000 Changes to last version
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New: (Fig. 11) - included a legend for the CV-measurements

Changed (Authors list):

I.Wilhelm Nuclear Center of Charles University, Prague, Czech Republic
→ I.Wilhelm Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

G.Grigoriev → E.Grigoriev
I.Wegrzecki → I.Wegrzecka
M.Mikuz → M.Mikuž
D.Zontar → D.Žontar
J. Stefan Institute, Ljubljana, Slovenia → Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia

Added (Authors list):
L.Andricek - MPI Munich

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1. Comments

Michael Moll

-- Why did I not include all the references collaborators suggested to me?

- From some of you I received very long lists of articles to be cited in the paper. Sorry, but I am not able to include them all, since this would lead to a list of references longer than the article itself. If I include e.g. a reference to a certain kind of material investigated by one person, I should also give references to papers dealing with all the other materials investigated by other persons!
- In the introduction of the paper it is explicitly stated that not all publications can be cited and that a complete list can be found on the ROSE WWW-page!
- I do not like to cite the proceedings of the ROSE Workshop for several reasons:
  1. They are not easily accessible for the "outside" world.
  2. They are not easy to understand since they contain only transparencies and often no written explanation for the given graphs
  3. They are not refereed and therefore maybe not accepted as a reference in a journal
  4. The "authors" of the transparencies are listed as authors on this publication!

2. Changes to the authors list:

Please check the address of your institute in the list, I tried to give the addresses in a consistence way (University,City,Country).

Added:

- B. Sundby Avset -- SINTEF, Oslo, Norway
- Z.Kohout -- Czech Technical University, Prague, Czech Republic
- M.Huhtinen -- CERN, Switzerland
- T.Budzynski, P.Grabiec --- ITE, Warsaw, Poland
- A.Kaminsky -- Padova, University and INFN
- K.Stolze -- CiS Institut für Mikrosensorik gGmbH, Erfurt, Germany
- C.Wilburn -- Micron Semiconductor Ltd., Lancing, England
- G.Valvo, G.Fallica -- STMicroelectronics, Catania, Italy
- P.Burger, O. Evrard -- Canberra Semiconductor N.V., Belgium
- A.I. Ryazanov -- Kurchatov Institute,Moscow,Russia
- T.Ligonzo -- Bari University, Bari, Italy

Changed:

- **Old:** E.Weber **New:** E.R.Weber - University of California, Berkeley, Department of Materials Science and Engineering
- **Old:** T. Brodbeck, P. Ratoff **New:** T.J. Brodbeck, P.N. Ratoff
- **Old:** M.Angarano -- Bari University ; **New:** M.M. Angarano -- Perugia University
- **Old:** Padova University, Italy **New:** Padova, University and INFN, Italy

3. Changes to text and references

(names indicate who has suggested this change/spotted the error/s):
(I included only suggestions that in the end lead to some changes)

Britta Dezillie, Zheng Li, Elena Verbitskaya

- p.3, 2nd §, line 15 ; **add references**
  Old: It should be mentioned that it had been originally invented by a BNL group, several years ago, but at that time it did not lead to any sizeable enhancement of the radiation tolerance. Only the unexpected results with proton and pion irradiation, carried out in 1998, showed that the oxygenated material is highly superior in radiation tolerance.
  Suggestion: Please change this by….”has been originally invented by the Instrumentation division of BNL in 1992 [Ref.: Z. Li et al, IEEE TNS, Vol 39, No 6, 1736 (1992)]. Irradiation tests with 1 MeV neutrons did not show any effect of improved radiation hardness [Ref.: Z. Li et al, IEEE TNS, Vol.42, No 4, 1730 (1995)]. However, the used silicon material and HTLT O diffusion technique is still the same, only the particle source has been changed to protons.”
  New: It should be mentioned that it had been originally invented by the Instrumentation division of BNL in 1992 [Ref.: Z. Li et al, IEEE TNS, Vol 39, No 6, 1736 (1992)]. Irradiation tests performed at that time with 1MeV neutrons did not show any sizeable enhancement of the radiation tolerance [Ref.: Z. Li et al, IEEE TNS, Vol.42, No 4, 1730 (1995)]. Only the unexpected results with proton and pion irradiation, carried out in 1998, showed that the oxygenated material is highly superior in radiation tolerance [A. Ruzin et al., IEEE Trans. on Nuclear Science, vol.46, no.5, 1310 (1999).].

- *Section* 3.3; Charge Collection Measurements; CV <-> CCE, **added references:**
  Suggested: p.7: Charge collection measurements, line 5, the bias voltage needed “migh”t be larger

than…Please take out the word "might", and add the reference: V. Eremin et al., NIM A 372, p.388 (1996).Which proves this statement. Please after "…deduced from C/V…" add as well Ref.: V. Eremin, pres. at 4th ROSE meeting at CERN, June 14-15, 1999, CERN/LEB 99-8, p.409.
Changed: Due to trapping and ballistic deficit, the bias voltage needed ~~**might be**~~ **is** larger than the depletion voltage deduced from C/V measurements **[V. Eremin et al., NIM A 372, p.388 (1996)]**.

- *Section* 3.3; Charge Collection Measurements; Double junction, **added references:**
  Suggested: Please add to Ref 9 and 10the following 4 references:
  1.Z. Li and H. W. Kraner, BNL-46198, J. Electronic Materials, Vol. 21, No. 7, (1992), p. 701.
  2.V. Eremin et al., NIM A 360, p. 458 (1995) and presentation of the physically effects of the double junction, Hamburg (1995). 3. D. Menichelli et al., "Modelling of observed double-junction effect', Nucl. Instrum. And Meth. A 426, p. 135, (1999). 4. E. Verbitskaya et al., pres. at 4th ROSE workshop at CERN, June 14-15, 1999, CERN/LEB 99-8, p.309.
  Comment(Michael): In the paper NIMA 426 references to the former papers are given.
  New: Z. Li and H. W. Kraner, BNL-46198, J. Electronic Materials, Vol. 21, No. 7, (1992), p. 701.
  D. Menichelli et al., Nucl. Instrum. And Meth. A 426, p. 135, (1999) and literature cited there.

- *Section 5.2. p.9, line 4 from the bottom, broadening of the VV-/0 transition…;*
  Suggested: Please add Ref.: E. Verbitskaya, pres. at the 3rd ROSE workshop in Hamburg 1998, DESY proceedings.The text "*observations need to be understood in term of lattice strain*" should be taken out, because E. Verbitskaya explained this physically in her talk and is understood
  Comment(Michael): In this point I disagree !. To my opinion the broadening of the VV line is not understood at all. It is obvious that the origin of the broadening lies in the formation of clusters. However, which kind of defects (e.g. V2, I2, higher order V and I) are really contributing to the peak and to which extend these lines are broadened due to the influence of lattice strain is not obvious and understood to me. However, since writing of a paper is a democratic process, I changed the text, I just wanted to clarify my opinion.

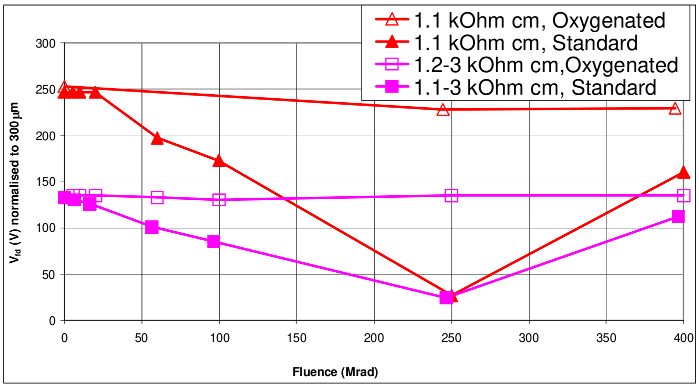
  Changed in Section 5.2:
  These observations are currently ~~need to be~~ understood in terms of the lattice strain and the inter-center charge transfer models, mentioned above.
  Sentence added after further discussion (8.9.00):
  However the details and the degree of such lattice strain need to be further investigated.

  Michael: The different models predicted so far are also contradictory in some points. Therefore I rather prefer to cite them all and leave open which model is now really describing the true physics:

  Changed in Section 5.1: **added a further reference** to paper dealing with cluster models
  The two latter observations are currently discussed within the framework of the defect cluster strain model and the inter-center charge transfer model described in refs. [Svenson, Watts, Z.Li et al., IEEE TNS (2000), conference proceedings of the IEEE 99 symposium, Seattle, WA, Oct.99].~~respectively.~~

- **Suggested text/figure to be included:**

  The ^{60}Co gamma irradiation was performed in separate steps up to 575 Mrad at BNL {1-2]. From Fig. 1 it is clear that there is a significant difference in the V_{fd} values after gamma irradiation between oxygenated and standard detectors. For the standard detectors V_{fd} reduces gradually till the space charge sign inversion (SCSI) fluence of about 250 Mrad. At this fluence, the initially positive space charge in the SCR, which density $N_{eff} = N_D^+ - N_A^-$ becomes negative due to an increasing N_A^- component. Oxygenated detectors show very little changes in V_{fd} up to 600 Mrad and do not change the N_{eff} sign. A rough extrapolation of the V_{fd} versus fluence dependence of the $V_{fd} = 0$, gives a value of $\Phi_{inv} \geq 1500$ Mrad, which is more than 6 times higher than that for standard detectors.
  Figure 1: The collected charge measured by TChT for the 1.2-3 kΩcm standard and HTLT oxygen diffused silicon detectors after a gamma dose of 575 Mrad.



Referenties:

1) B. Dezillie et al., "The effect of Oxygen Impurities on Radiation Hardness of FZ Silicon Detectors for HEP after n, p and gamma Irradiation", accepted for publication in IEEE TNS (2000).

2) Z. Li et al, "HTLT Oxygenated Silicon Detectors: Radiation-Hardness and Long Term Stability", 3rd International Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Florence June 28-30-2000, conference proceedings.

New text:

3.4. Gamma irradiation

Although this paper deals mainly with the effects of hadron irradiation it has to be mentioned that oxygen enriched silicon detectors offer a strong improvement of radiation hardness after gamma irradiation. Here only one example will be given and further details can be found in [3rd ROSE Status Report // B.C.MacEvoy and G.Hall, Presented at the 1st ENDEASD Workshop, Santorini, April 21-22 1999. Accepted for publication in Materials Science in Semiconductor Processing // Ref IEEE Britta]. Fig.xx displays a comparison between a ^{60}Co gamma irradiation of oxygenated and standard silicon [Ref IEEE Britta]. The samples were irradiated in separate steps up to 400 Mrad at BNL. A significant difference in the change of V_{fd} values after gamma irradiation between oxygenated and standard detectors is observed. For the standard detectors V_{fd} reduces gradually till the space charge sign inversion fluence of about 250 Mrad. The oxygenated detectors show only very little changes in V_{fd} up to 400 Mrad and do not change the N_{eff} sign.

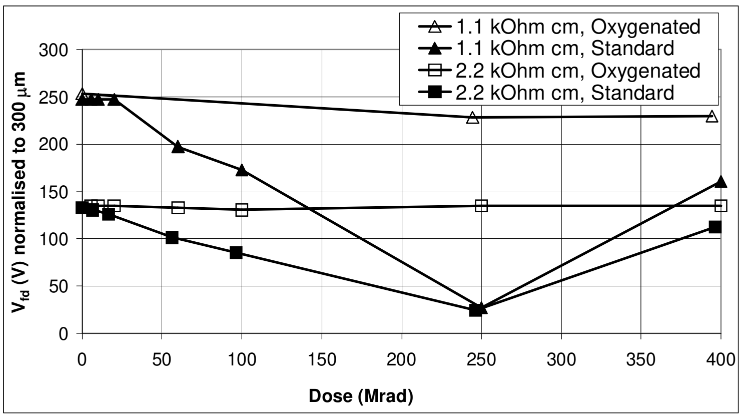


Fig 13: Depletion voltage normalised to 300μm detector thickness as a function of gamma dose for 1.1 kΩcm and 2.2 kΩcm oxygenated and standard silicon detectors.

Alexander Chilingarov:

- *Section* 3.3; Charge Collection Measurements : **writing error**
  Old: Such a laser pulse produces a **mip,** like ionization in the diode, but this way only relative results can be obtained.
  New: Such a laser pulse produces a mip-like ionization in the diode, but in this way only relative results can be obtained.

- **Acknowledgements, one sentence taken out since now all are listed as authors**
  Old: The authors wish to thank all members of the ROSE collaboration. These results could not have been achieved in a comparatively short time, without their continuous effort. At this point we would also like to express our sincere thanks to Francois Lemeilleur, co-spokesman of the collaboration since its founding in 1995 until retirement last year. His contribution has been most important for the organization and coordination of this research project.
  New: At this point we would also like to express our sincere thanks to Francois Lemeilleur, co-spokesman of the collaboration since its founding in 1995 until retirement last year. His contribution has been most important for the organization and coordination of this research project.

Marko Mikuz:

- *Section 3.3.; Charge Collection Measurements;* ***added the following reference:***
  New: G.Kramberger, V.Cindro, I.Mandic, M.Mikuz, M.Zavrtanik, "Determination of effective trapping times for electrons and holes in irradiated silicon", ATLAS Note ATL-INDET-2000-017 to be published in NIMA.

Ioana Pintilie

- Section 5 ; Examples for TSC-measurements; **reference added:**
  New: I.Pintilie, C.Tivarus, L.Pintilie, M.Moll, E.Fretwurst and G.Lindstroem; "Comparison Between Microscopic Damage Induced by Neutron and Proton Irradiation in Silicon Detectors"; Proceedings of the Second ENDEASD Workshop, Kista-Stockholm, Sweden, June 27-29,2000.

Renate Wunstorf -- thanks for careful reading and spotting many misunderstandable/wrong phrases in the text

- **Authors list:** Write the institutes in a formal correct way: Institute, University, city, country
- **Old:** Migrating silicon interstitials and vacancies escape from a region of silicon, where a high concentration of Frenkel pairs is produced by a Primary Knock-On Atom (PKA). The PKA is produced by an incident hadron.
  New: Migrating silicon interstitials and vacancies escape from a region of silicon, where a high concentration of Frenkel pairs is produced by a Primary Knock-On Atom (PKA), which is produced by an incident hadron.
- **Old:** Companies, having meanwhile adopted the RD48 process for detector fabrication, are SINTEF, CiS, Micron and ST Microelectronics. Oxygenation has also been performed by CNM-CSIC and the Instrumentation Division of BNL.
  New: Companies, having meanwhile adopted the RD48 process for detector fabrication, are SINTEF (Oslo, Norway), CiS (Erfurt, Germany), Micron (Lancing, England) and ST Microelectronics (Catania, Italy). Oxygenation has also been performed by CNM-CSIC (Barcelona, Spain) and the Instrumentation Division of BNL.

- This limitation is predominantly set by the diode (**New:** quality) (**Old:** processing), but note that a large operating voltage together with the increased reverse current leads also to an increase of dissipation power which may affect the cooling system, and, if distributed non-homogeneously, could also lead to thermal run away effects.
- 3.1 Scaling of bulk damage with NIEL - Mention the hardness factor for 24 GeV/c protons !
  New: For 23 GeV protons a hardness factor of 0.62 was used.
- **Leakage Current:** Data measured on oxygenated material do not give any ~~sizeable~~ difference to those measured on standard material.
- While the improvement in β is about a factor of 3 (**New:** for oxygen enriched material) an adverse effect is found for Carbon enrichment, see Fig. 4b.
- **Old:** In fact the operation voltage of 600V would limit the usability of standard detectors to only 3 years, while DOFZ detectors would survive almost the full 10 years period.
  New: In fact the operation voltage of 600V would allow to operate standard detectors fully depleted for only 3 years, while DOFZ detectors could be operated fully depleted for almost the full 10 years period.
- **New reference:** In fact, the ATLAS pixel group had meanwhile decided to use this RD48 developed technique [Renate Wunstorf et al., "Radiation Tolerant Sensors for the ATLAS Pixel Detector", paper presented on the 4th International Symposium on Development and Application of Semiconductor Tracking Detectors, Hiroshima, March 22-25, 2000 (these proceedings).].

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11.8.2000 Changes to last version
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Added all members of ROSE as authors