Radiation Hardness of Silicon Detectors for High-Energy Physics: From Past Searches to Future Perspectives

Seminar to honor Prof. Gunnar Lindström 80 th birthday

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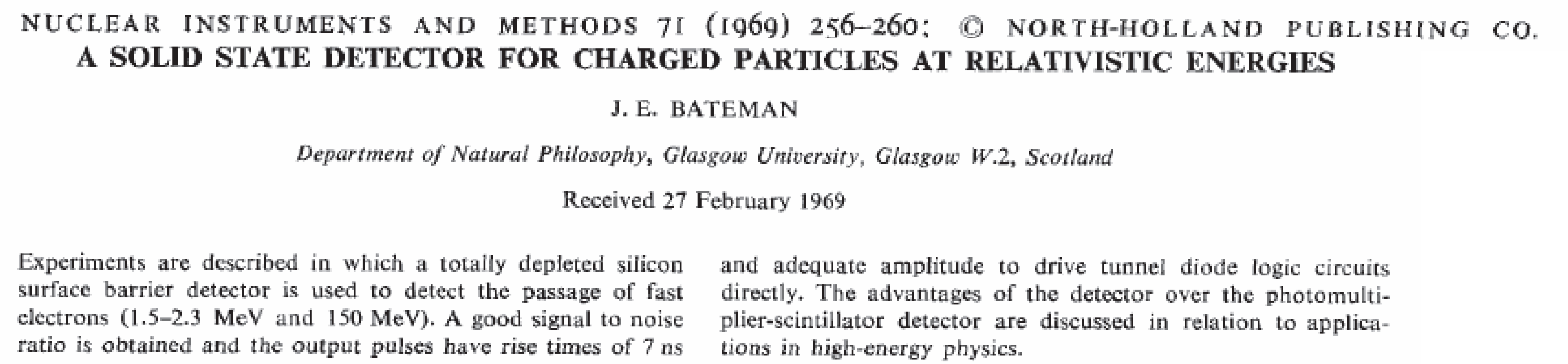
Outline

- ✓*Silicon Detectors in HEP : early studies*
- ✓*Microscopic radiation damage : early studies*
- ✓ *The ROSE Collaboration*
- ✓*The RD50 Collaboration*
- ✓ *The WODEAN Project*
- ✓*New Perspectives*

Silicon Detectors in HEP : early studies

60s: Si detectors for HEP Working Principle established



NUCLEAR INSTRUMENTS AND METHODS 71 (1969) 256–260; © NORTH-HOLLAND PUBLISHING CO.

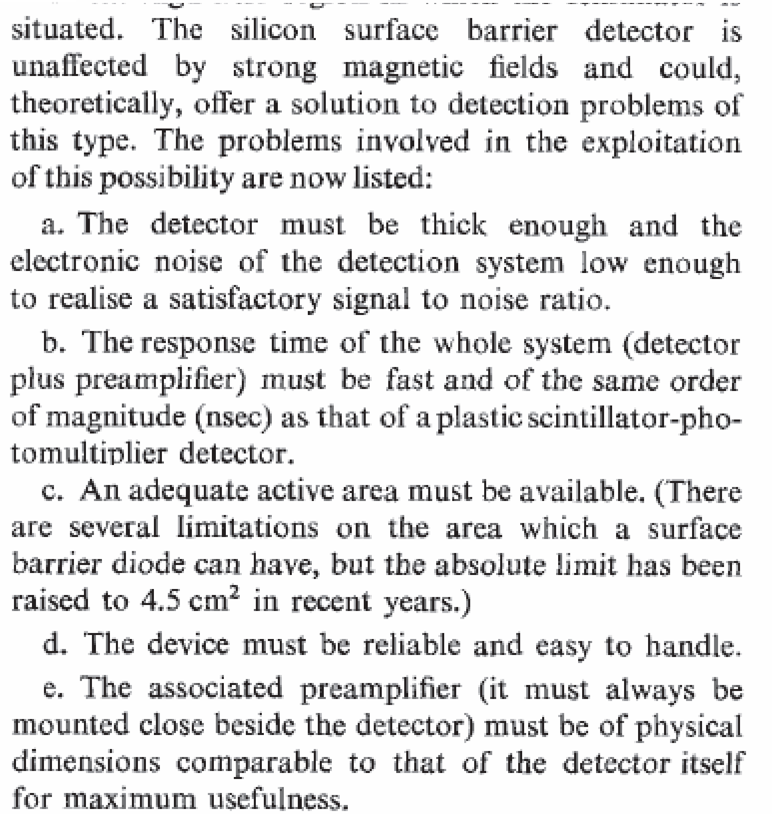
A SOLID STATE DETECTOR FOR CHARGED PARTICLES AT RELATIVISTIC ENERGIES

J. E. BATEMAN

Department of Natural Philosophy, Glasgow University, Glasgow W.2, Scotland

Received 27 February 1969

Experiments are described in which a totally depleted silicon surface barrier detector is used to detect the passage of fast electrons (1.5–2.3 MeV and 150 MeV). A good signal to noise ratio is obtained and the output pulses have rise times of 7 ns and adequate amplitude to drive tunnel diode logic circuits directly. The advantages of the detector over the photomultiplier-scintillator detector are discussed in relation to applications in high-energy physics.



situated. The silicon surface barrier detector is unaffected by strong magnetic fields and could, theoretically, offer a solution to detection problems of this type. The problems involved in the exploitation of this possibility are now listed:

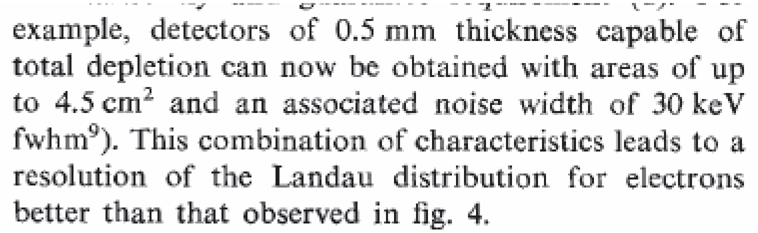
a. The detector must be thick enough and the electronic noise of the detection system low enough to realise a satisfactory signal to noise ratio.

b. The response time of the whole system (detector plus preamplifier) must be fast and of the same order of magnitude (nsec) as that of a plastic scintillator-photomultiplier detector.

c. An adequate active area must be available. (There are several limitations on the area which a surface barrier diode can have, but the absolute limit has been raised to 4.5 cm^2 in recent years.)

d. The device must be reliable and easy to handle.

e. The associated preamplifier (it must always be mounted close beside the detector) must be of physical dimensions comparable to that of the detector itself for maximum usefulness.



example, detectors of 0.5 mm thickness capable of total depletion can now be obtained with areas of up to 4.5 cm^2 and an associated noise width of 30 keV fwhm[9]). This combination of characteristics leads to a resolution of the Landau distribution for electrons better than that observed in fig. 4.

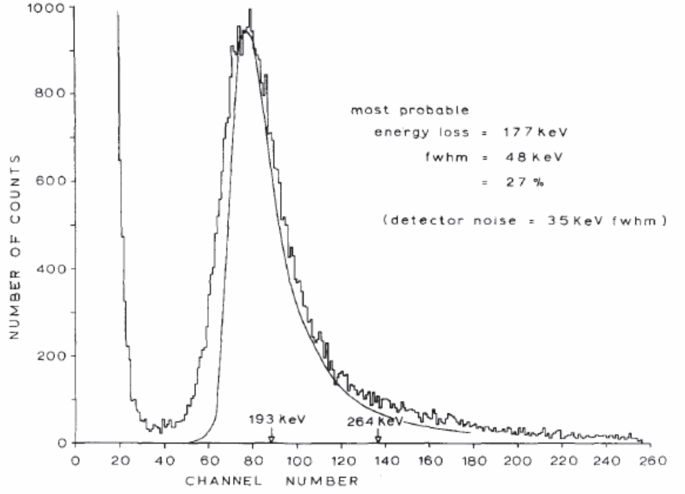


Fig. 4. Energy distribution produced in C56 by electrons of energy 150 MeV (momentum resolution ≈ 2%). The solid curve is given by Landau's theory.

Early 80s: silicon detectors start to be exploited in high energy physics experiments for precise positional measurements.

A silicon surface barrier microstrip detector designed for high energy physics

NIM *178, Issues 2-3, 15 December 1980, Pages 331-343*

E.H.M. Heijne, L. Hubbeling, B.D. Hyams, P. Jarron, P. Lazeyras, F. Piuz, J.C. Vermeulen, A. Wylie

A silicon microstrip detector was manufactured using the surface barrier technique. It has 100 strips at 200 μm pitch and it is 400 μm thick. To each strip a fast current sensitive preamplifier is connected so that minimum ionizing particles can be detected on single strips..

A multi-electrode silicon detector for high energy experiments

NIM *176, Issue 3, 15 October 1980, Pages 457-460*

S.R. Amendolia, G. Batignani, F. Bedeschi, E. Bertolucci, L. Bosisio, C. Bradaschia, M. Budinich, F. Fidecaro, L.Foà, E.Focardi *et al.*

A detector has been developed in our laboratory for proposed use in high energy experiments. It works as a MWPC in which the ionizing medium consists of a thin layer of silicon crystal. The results of the test carried out at CERN show that the detector is ideally suited for the detection of minimum ionizing particles and can provide very high spatial resolution.

A silicon counter telescope to study short-lived particles in high-energy hadronic interactions

NIM *205, Issues 1-2, 15 January 1983, Pages 99-105*

B. Hyams, U. Koetz, E. Belau, R. Klanner, G. Lutz, E. Neugebauer, A. Wylie, J. Kemmer

A telescope consisting of six silicon microstrip detectors achieving 5 μm spatial resolution for minimum ionizing particles has been built. The design and fabrication of the counters, electronics, and mechanical set-up is described, and first results of its performance in a 175 GeV/*c* beam are reported.

Proposal for a semiconductor high resolution tracking detector

P. Rehak Brookhaven National Laboratory,

NIM 211, Issues 2-3, June 1983, Pages 323-329

Nuclear Instruments and Methods 214 (1983) 253–260
North-Holland Publishing Company

CHARGE COLLECTION IN SILICON STRIP DETECTORS

E. BELAU, R. KLANNER, G. LUTZ, E. NEUGEBAUER, H.J. SEEBRUNNER and A. WYLIE
Max-Planck Institut für Physik und Astrophysik, Werner-Heisenberg-Institut, Munich, Fed. Rep. Germany

T. BÖHRINGER, L. HUBBELING and P. WEILHAMMER
CERN, Geneva, Switzerland

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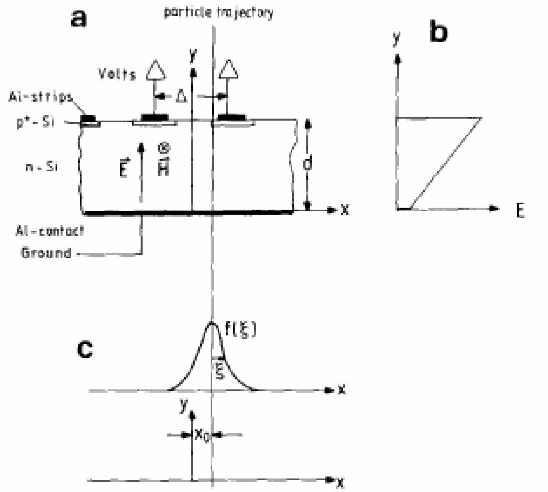
DESY, Hamburg, Fed. Rep. Germany

M. RIEBESELL **
University of Hamburg, Fed. Rep. Germany

Recently the planar process, developed for producing microelectronics, has been adapted to the fabrication of detectors for ionizing radiation [1]. One of the first applications of this new technology was the development of microstrip detectors with high spatial resolution as a vertex telescope for elementary-particle interactions at high energies [2]. In this work we describe a silicon strip detector with 20 μm pitch and analogue read-out of every channel. The response of the counter to high-energy particles has been measured as a function of applied voltage and external magnetic field. A simple model of charge transport in the detector provides a good description of the measurements. The model is used to calculate the spatial resolution of microstrip detectors and compare it with measurements. A design of a microstrip detector with improved spatial resolution is proposed.

The charge collection in silicon detectors has been studied, by measuring the response to high-energy particles of a 20 μm pitch strip detector as a function of applied voltage and magnetic field. The results are well described by a simple model. The model is used to predict the spatial resolution of silicon strip detectors and to propose a detector with optimized spatial resolution.



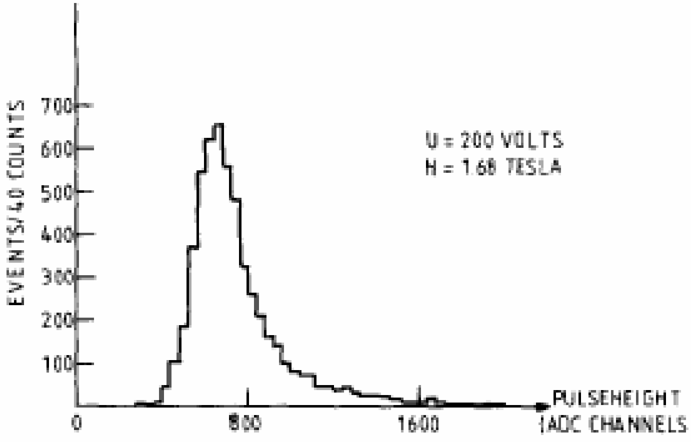


Fig. 4. Pulse-height distribution for high-energy particles with and without external magnetic field.

mid 80s: silicon for sampling calorimeter

Test measurements with a silicon-lead sandwich calorimeter for electromagnetic showers at energies between 1.5 and 5 GeV

NIM A 240, October 1985, Pages 63-68

M. Bormann, E. Fretwurst, G. Lindström, U. Pein and H. -Chr. Schleyer

A brief outline of the advantages in using silicon detectors for applications in high energy physics is given. In preparation for investigations at HERA a compact silicon-lead calorimeter for the detection of electromagnetic showers was constructed, calibrated and tested. The experimental results are in good agreement with Monte Carlo calculations.

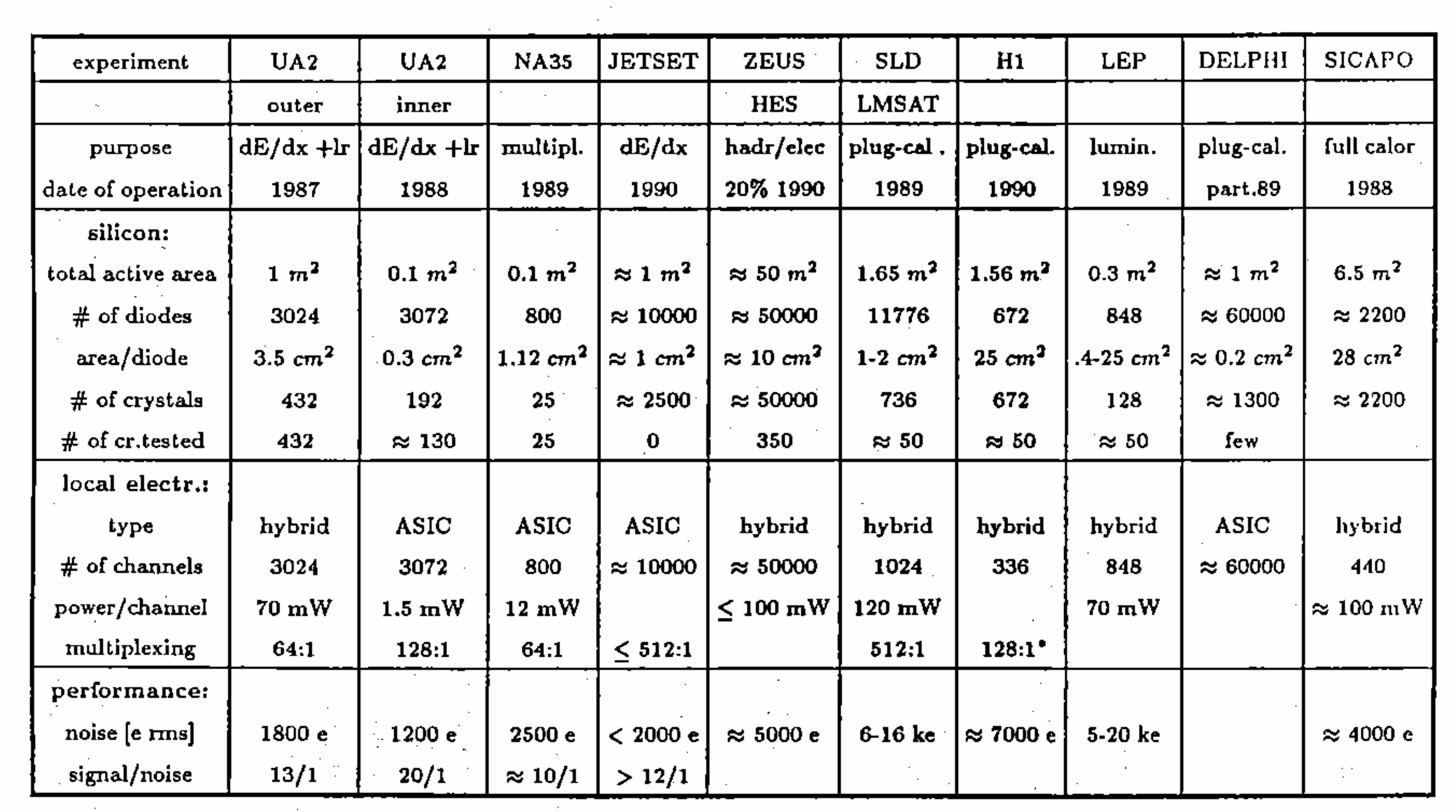
Energy resolution and longitudinal shower development in a Si/W electromagnetic calorimeter

NIM A *235, Issue 1, 1 March 1985-15 March 1985, Pages 55-60*

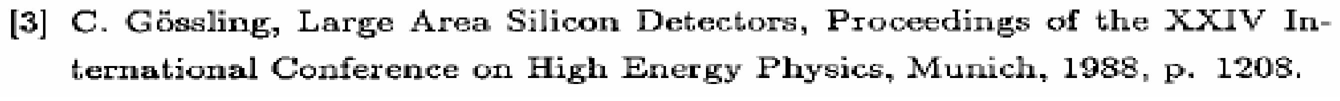
G.Barbiellini, G.Cecchet, J.Y. Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita, A. Seidman

Abstract - The performance of a silicon/tungsten sandwich calorimeter has been investigated for incoming electron energies between 4 and 49 GeV.

Summary of Large Area silicon projects as reported by Gossling in 1988



experiment	UA2	UA2	NA35	JETSET	ZEUS	SLD	H1	LEP	DELPHI	SICAPO
	outer	inner			HES	LMSAT				
purpose	dE/dx +lr	dE/dx +lr	multipl.	dE/dx	hadr/elec	plug-cal .	plug-cal.	lumin.	plug-cal.	full calor
date of operation	1987	1988	1989	1990	20% 1990	1989	1990	1989	part.89	1988
silicon:										
total active area	1 m^2	0.1 m^2	0.1 m^2	$\approx$ 1 m^2	$\approx$ 50 m^2	1.65 m^2	1.56 m^2	0.3 m^2	$\approx$ 1 m^2	6.5 m^2
# of diodes	3024	3072	800	$\approx$ 10000	$\approx$ 50000	11776	672	848	$\approx$ 60000	$\approx$ 2200
area/diode	3.5 cm^2	0.3 cm^2	1.12 cm^2	$\approx$ 1 cm^2	$\approx$ 10 cm^2	1-2 cm^2	25 cm^2	.4-25 cm^2	$\approx$ 0.2 cm^2	28 cm^2
# of crystals	432	192	25	$\approx$ 2500	$\approx$ 50000	736	672	128	$\approx$ 1300	$\approx$ 2200
# of cr.tested	432	$\approx$ 130	25	0	350	$\approx$ 50	$\approx$ 50	$\approx$ 50	few	
local electr.:										
type	hybrid	ASIC	ASIC	ASIC	hybrid	hybrid	hybrid	hybrid	ASIC	hybrid
# of channels	3024	3072	800	$\approx$ 10000	$\approx$ 50000	1024	336	848	$\approx$ 60000	440
power/channel	70 mW	1.5 mW	12 mW		$\leq$ 100 mW	120 mW		70 mW		$\approx$ 100 mW
multiplexing	64:1	128:1	64:1	$\leq$ 512:1		512:1	128:1*			
performance:										
noise [e rms]	1800 e	1200 e	2500 e	< 2000 e	$\approx$ 5000 e	6-16 ke	$\approx$ 7000 e	5-20 ke		$\approx$ 4000 e
signal/noise	13/1	20/1	$\approx$ 10/1	> 12/1						



[3] C. Gössling, Large Area Silicon Detectors, Proceedings of the XXIV International Conference on High Energy Physics, Munich, 1988, p. 1208.

… I also start working on silicon – degree thesis 1988 .. My first collaboration with Hamburg group ..

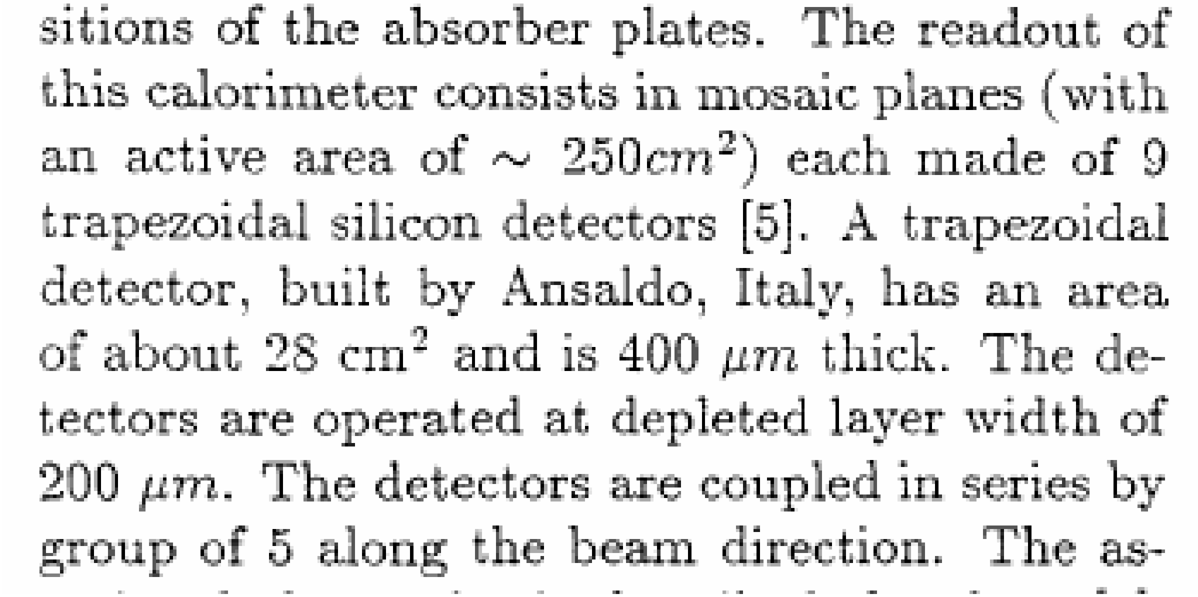
Silicon sampling hadronic calorimetry: A tool for experiments at next generation of colliders

NIM A *279, Issues 1-2*, *1 July 1989*, *Pages 57-65*

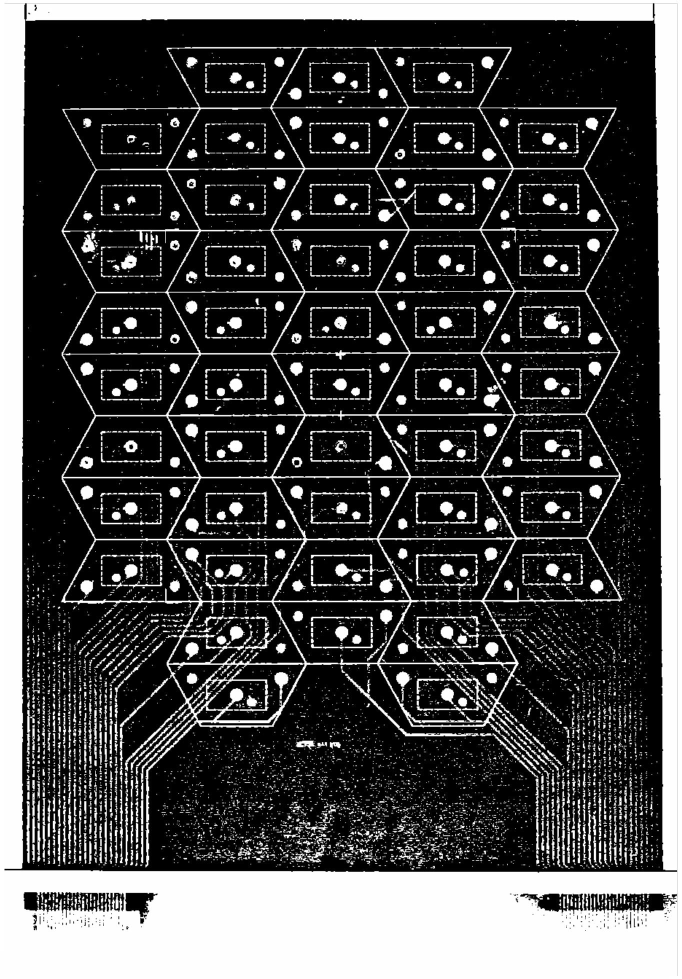
E. Borchi, R. Macii, S. Mazzoni, I. Fedder, G. Lindstroem, C. Bertrand, F. Lamarche, C. Leroy, A. Villari, M. Bruzzi, C. Furetta, R. Paludetto, S. Pensotti, P.G. Rancoita, C. Simeone, L. Venturelli, L. Vismara, J.E. Brau, N. Croituro, *et al.*

Equalization of relative response to the electromagnetic (e) and hadronic shower *(π), the* e/ π signal ratio (compensation condition) is the condition for obtaining the linear response of a calorimeter to hadronic showers and an energy resolution that improves as the incident energy increases. A new approach to the realization of the compensation condition has been proposed, taking the point of view that it is reachable by decreasing the response of the calorimeter to the shower. This has been achieved by the creation of a local hardening effect where soft electrons from the incoming shower and the flux of backwards going electrons resulting from multiple scattering in the high-Z absorber are absorbed by low-Z (G10) plates inserted between the active and the passive media. Experimental evidence for this local hardening has been observed and measured up to G10 thicknesses of 5 mm (2.5% of radiation length).

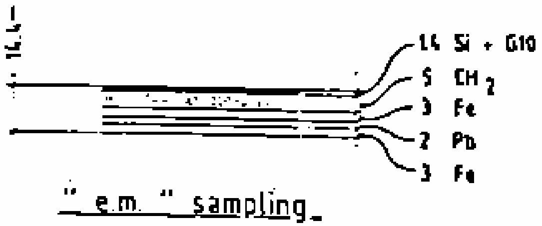
SICAPO Collaboration – The Silicon Mosaic



sitions of the absorber plates. The readout of this calorimeter consists in mosaic planes (with an active area of $\sim 250cm^2$) each made of 9 trapezoidal silicon detectors [5]. A trapezoidal detector, built by Ansaldo, Italy, has an area of about 28 cm^2 and is 400 μm thick. The detectors are operated at depleted layer width of 200 μm. The detectors are coupled in series by group of 5 along the beam direction. The as-

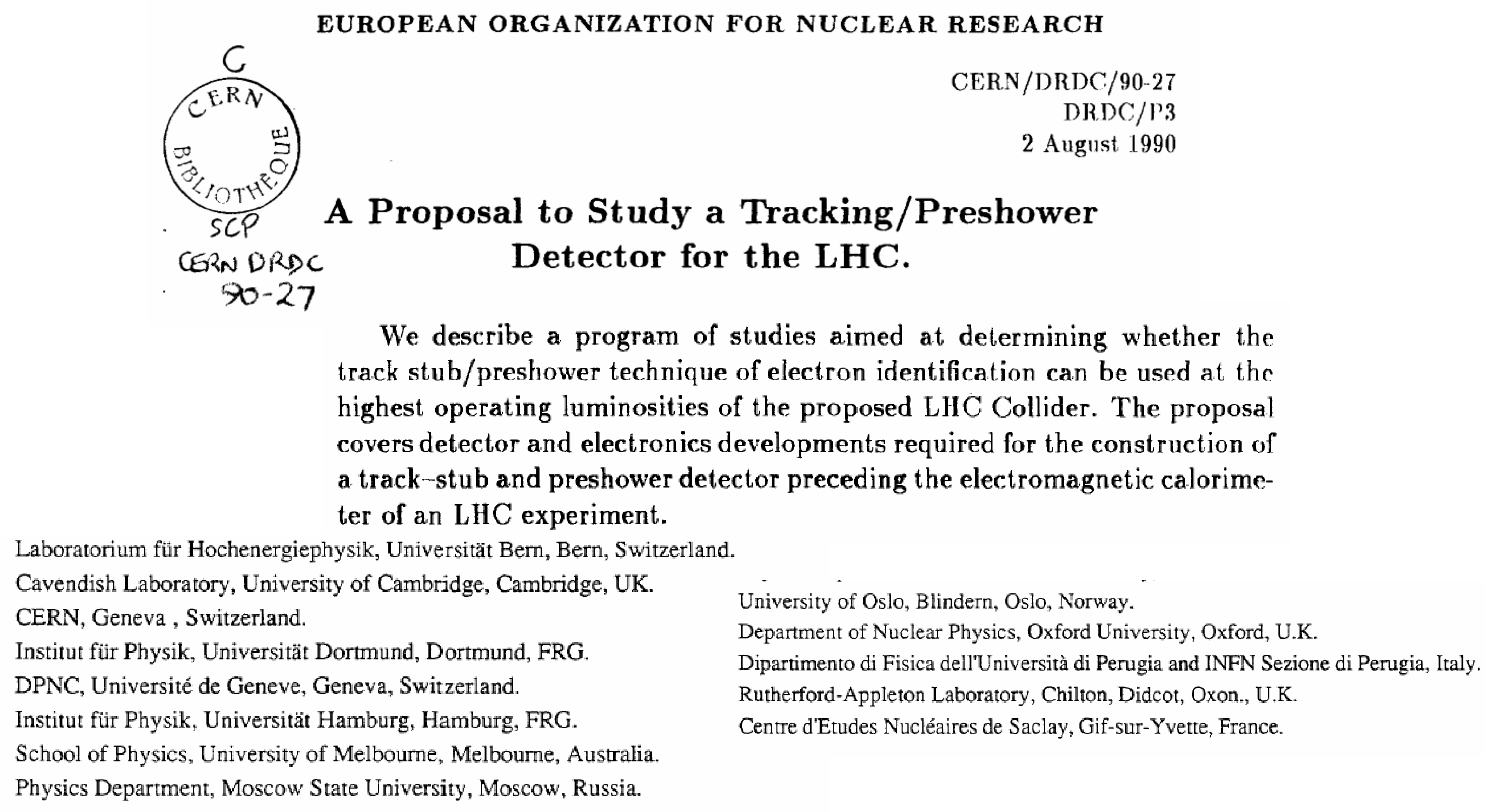


SICAPO Coll. - Proposal of a Si sampling calorimeter for SSC, Tuscaloosa, USA, 1990



RADIATION HARD SILICON S.S.C. CALORIMETER

Early 90s: silicon detectors investigated in high energy physics experiments. Two special collaborations set at CERN to investigate silicon devices and related radiation damage issues RD2 and RD20.



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/DRDC/90-27
DRDC/P3
2 August 1990

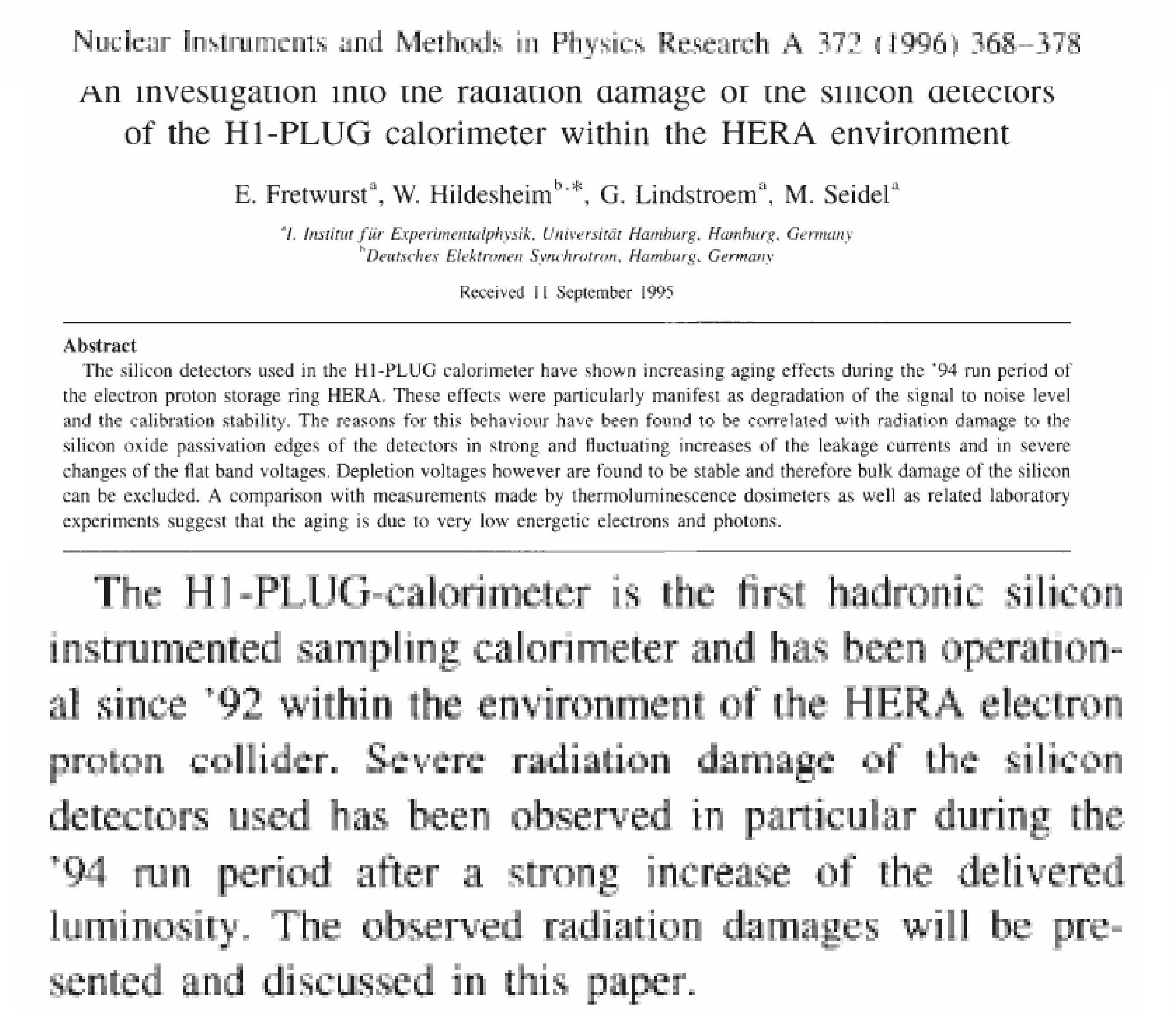
A Proposal to Study a Tracking/Preshower Detector for the LHC.

We describe a program of studies aimed at determining whether the track stub/preshower technique of electron identification can be used at the highest operating luminosities of the proposed LHC Collider. The proposal covers detector and electronics developments required for the construction of a track-stub and preshower detector preceding the electromagnetic calorimeter of an LHC experiment.

Laboratorium für Hochenergiephysik, Universität Bern, Bern, Switzerland.
Cavendish Laboratory, University of Cambridge, Cambridge, UK.
CERN, Geneva , Switzerland.
Institut für Physik, Universität Dortmund, Dortmund, FRG.
DPNC, Université de Geneve, Geneva, Switzerland.
Institut für Physik, Universität Hamburg, Hamburg, FRG.
School of Physics, University of Melbourne, Melbourne, Australia.
Physics Department, Moscow State University, Moscow, Russia.
University of Oslo, Blindern, Oslo, Norway.
Department of Nuclear Physics, Oxford University, Oxford, U.K.
Dipartimento di Fisica dell'Università di Perugia and INFN Sezione di Perugia, Italy.
Rutherford-Appleton Laboratory, Chilton, Didcot, Oxon., U.K.
Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

Radiation Damage of Silicon Detectors early recognized as a main issue !!!

90s: First studies on silicon performed by the Hamburg group :



Nuclear Instruments and Methods in Physics Research A 372 (1996) 368–378

An investigation into the radiation damage of the silicon detectors of the H1-PLUG calorimeter within the HERA environment

E. Fretwurst[a], W. Hildesheim[b,*], G. Lindstroem[a], M. Seidel[a]

[a] *I. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany*
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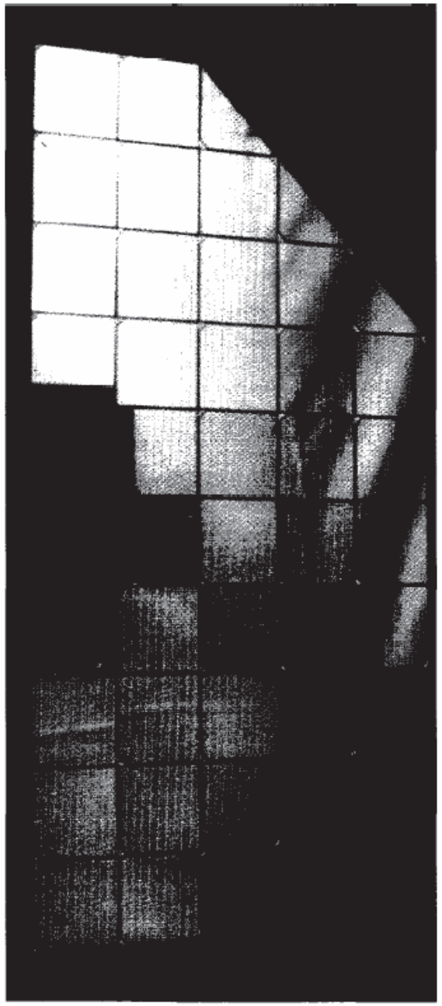
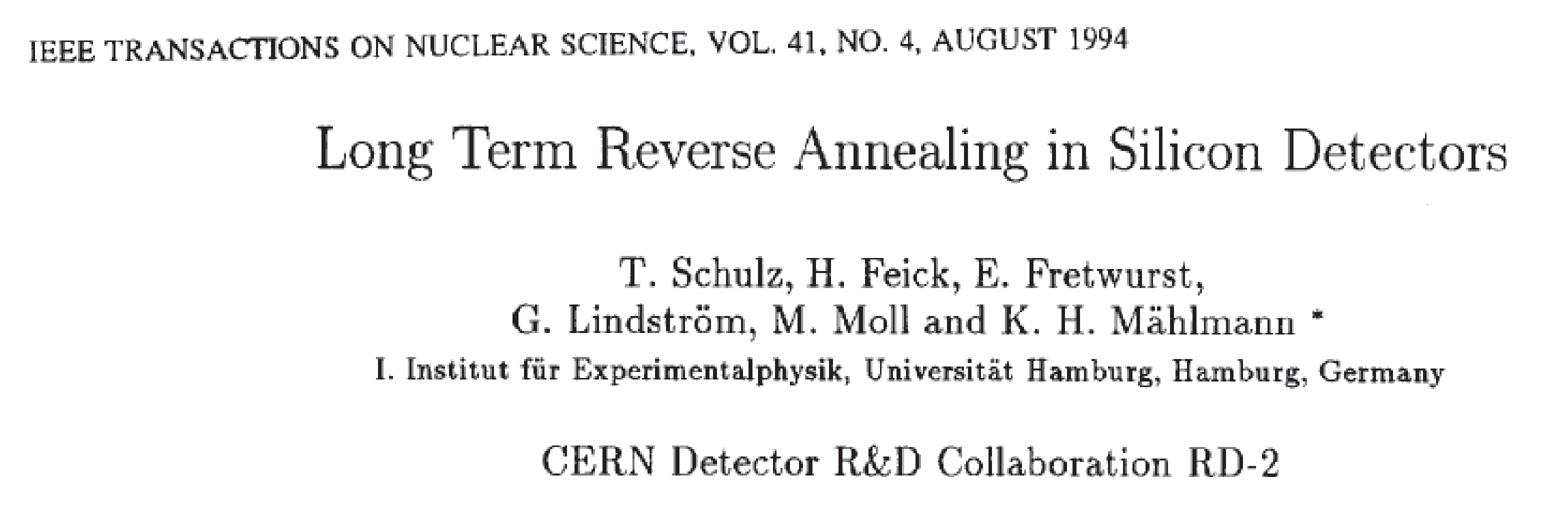
Received 11 September 1995

Abstract

The silicon detectors used in the H1-PLUG calorimeter have shown increasing aging effects during the '94 run period of the electron proton storage ring HERA. These effects were particularly manifest as degradation of the signal to noise level and the calibration stability. The reasons for this behaviour have been found to be correlated with radiation damage to the silicon oxide passivation edges of the detectors in strong and fluctuating increases of the leakage currents and in severe changes of the flat band voltages. Depletion voltages however are found to be stable and therefore bulk damage of the silicon can be excluded. A comparison with measurements made by thermoluminescence dosimeters as well as related laboratory experiments suggest that the aging is due to very low energetic electrons and photons.

The H1-PLUG-calorimeter is the first hadronic silicon instrumented sampling calorimeter and has been operational since '92 within the environment of the HERA electron proton collider. Severe radiation damage of the silicon detectors used has been observed in particular during the '94 run period after a strong increase of the delivered luminosity. The observed radiation damages will be presented and discussed in this paper.



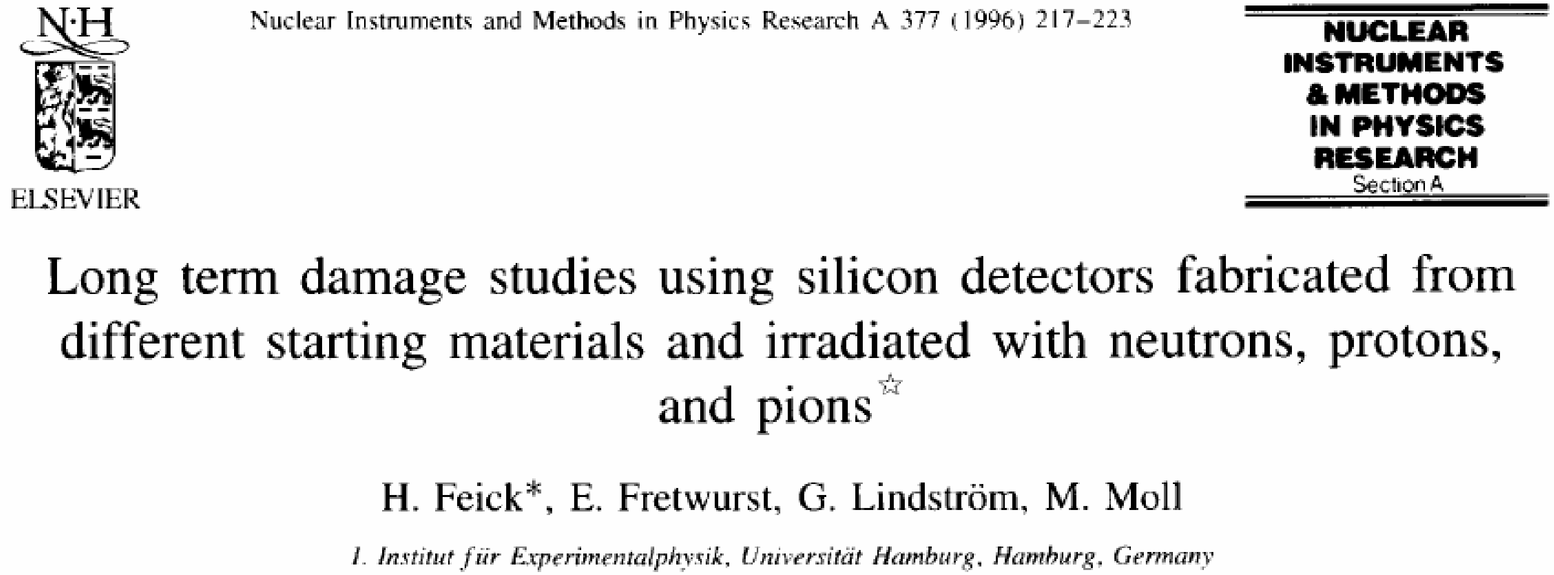


IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 41, NO. 4, AUGUST 1994

Long Term Reverse Annealing in Silicon Detectors

T. Schulz, H. Feick, E. Fretwurst,
G. Lindström, M. Moll and K. H. Mählmann *
I. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

CERN Detector R&D Collaboration RD-2



ELSEVIER

Nuclear Instruments and Methods in Physics Research A 377 (1996) 217–223

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

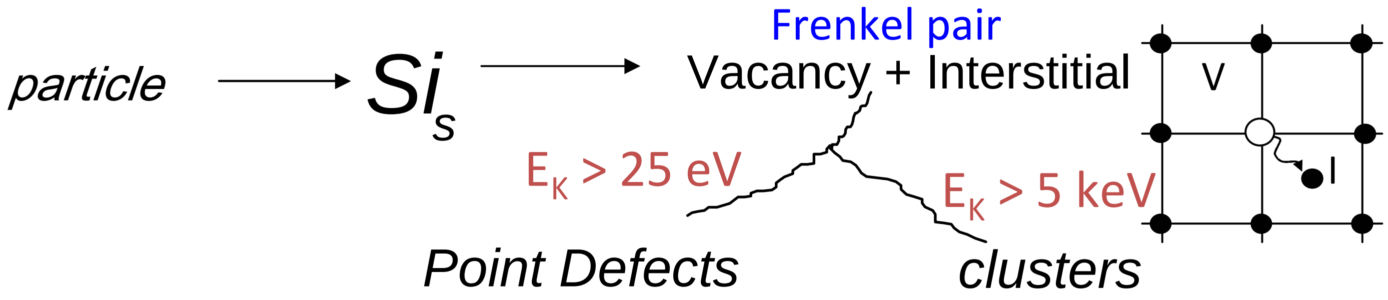
Long term damage studies using silicon detectors fabricated from different starting materials and irradiated with neutrons, protons, and pions☆

H. Feick*, E. Fretwurst, G. Lindström, M. Moll

I. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

Microscopic Radiation Damage: early studies

Radiation Damage of Silicon Detectors : understanding microscopic damage



particle → Si_s → Frenkel pair: Vacancy + Interstitial

$E_K > 25$ eV: Point Defects

$E_K > 5$ keV: clusters

- **Radiation induced defects** → **Traps**, **Recombination centres**, **Extended defects or clusters**
- **Defect Migration, secondary defects** → **Annealing**

Secondary defect formation in silicon

- **Primary defect generation**

I, I_2 higher order I

$\Rightarrow$ I -CLUSTER

$V, V_2,$ higher order V

$\Rightarrow$ V -CLUSTER

- **Secondary defect generation**

Dopants : P, B

Main impurities in silicon: Carbon C_s

Oxygen O_i

Oxygen dimer: O_{2i}

$$I+C_s \rightarrow C_i \Rightarrow \begin{array}{l} C_i+C_s \rightarrow C_iC_S \\ C_i+O_i \rightarrow C_iO_i \\ C_i+P_s \rightarrow C_iP_S \end{array}$$

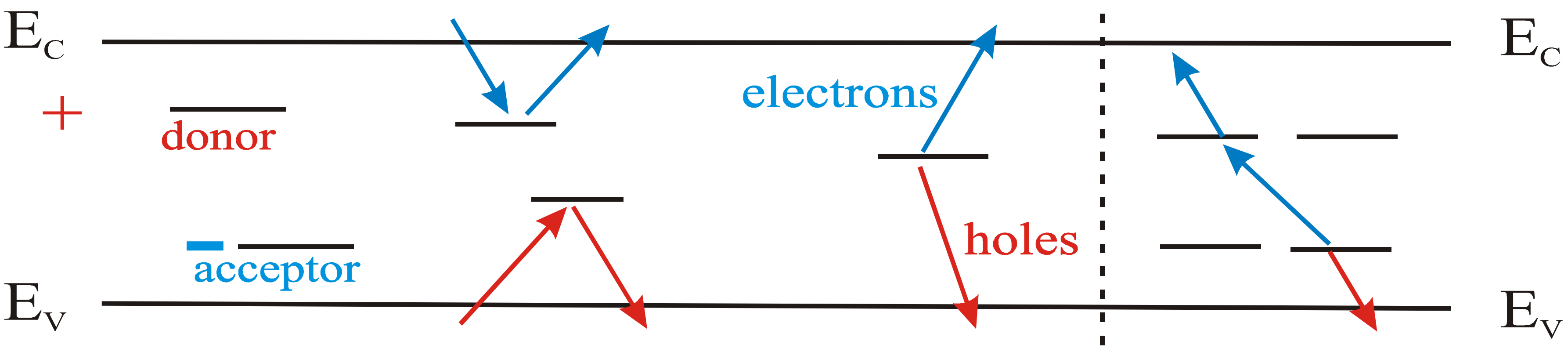
$$I + O_{2i} \rightarrow IO_{2i}$$

$$\begin{array}{l} V+V \rightarrow V_2 \\ V+O_i \rightarrow VO_i \\ V+P_s \rightarrow VP_s \end{array} \Rightarrow \begin{array}{l} V+V_2 \rightarrow V_3 \\ V+VO_i \rightarrow \underline{V_2O_i} \end{array}$$

Defects generate Macroscopic Damage

Shockley-Read-Hall statistics (standard theory)

Inter-center charge transfer model (inside clusters only)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

enhanced generation
⇒ leakage current
⇒ space charge

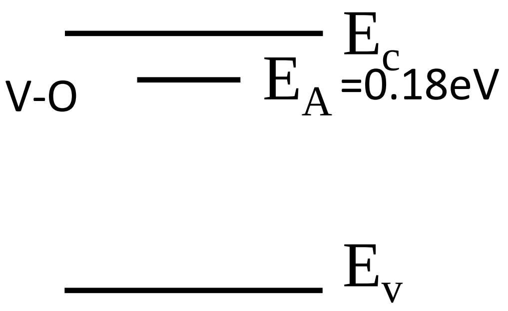
Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections ΔE : ionization energy N_t : concentration

60-70s: Solid State Physics Studies on Point Defects in irradiated Si

The A centre

oxygen-doped silicon dominant centers of vacancy capture may be isolated interstitials O_i and trapping results in the formation of the V-O centre, so-called A centre



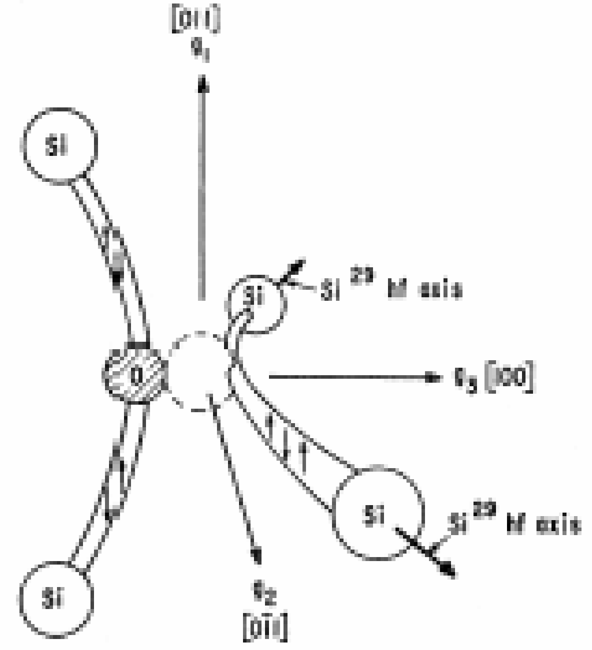


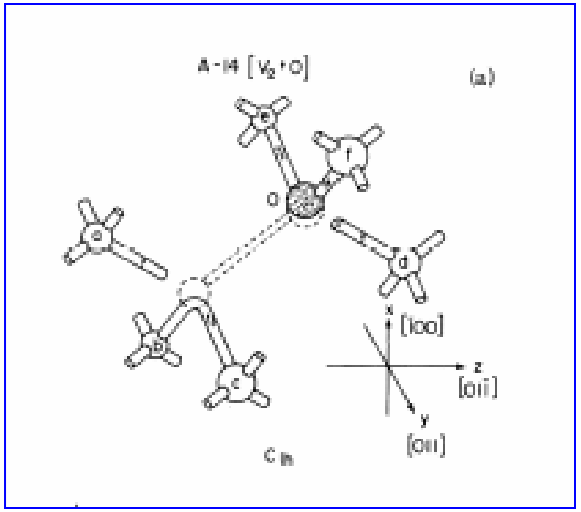
FIG. 5. Model of the *A* center as a substitutional oxygen atom. The oxygen atom bonds between two of the four neighboring silicon atoms, and the remaining two silicon atoms pull together to form a covalent bond. Spin resonance arises from an additional electron which is trapped in the Si—Si molecular bond as shown. The *g* tensor and hyperfine axes are indicated.

V-O defect (A centre)

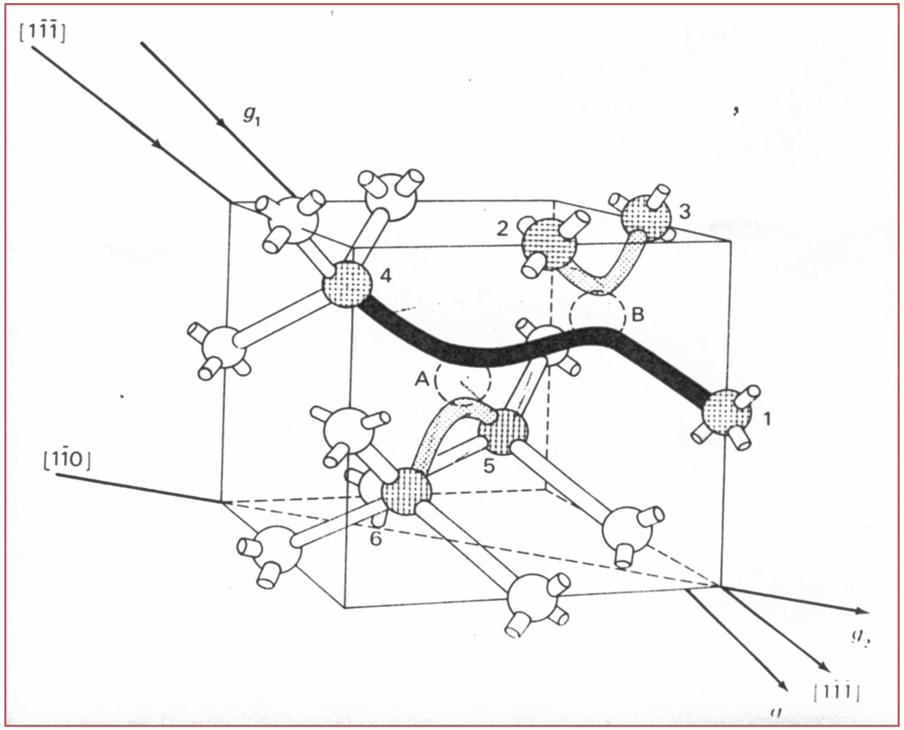
Watkins, Corbett: Phys.Rev.,121,4, (1961),1001

Si Point-defects involving more than one vacancy

Point-defects can involve more than one vacancy, creating deep levels in the Si gap: V_2, V_2O, V_3O etc..



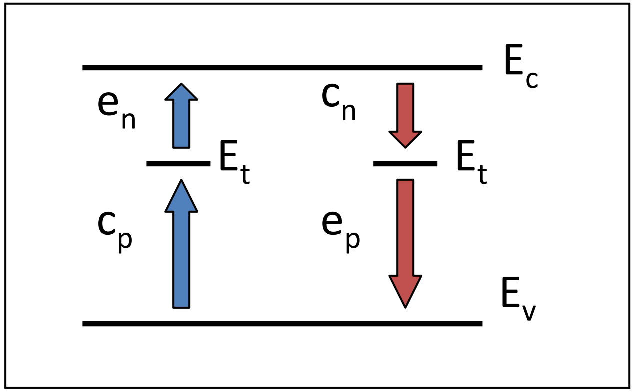
V_2O defect

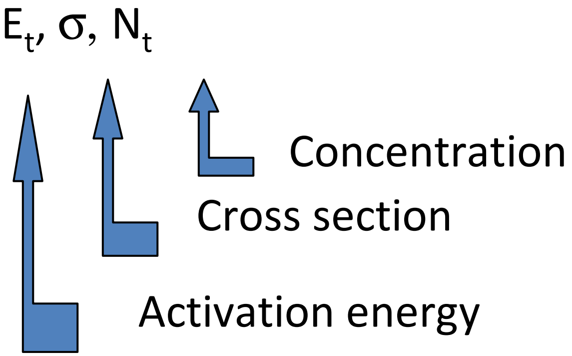


Lee, Corbett: Phys.Rev.B,13,6, (1976),2653

Divacancy V_2

Main trap parameters:




E_t, σ, N_t

Concentration

Cross section

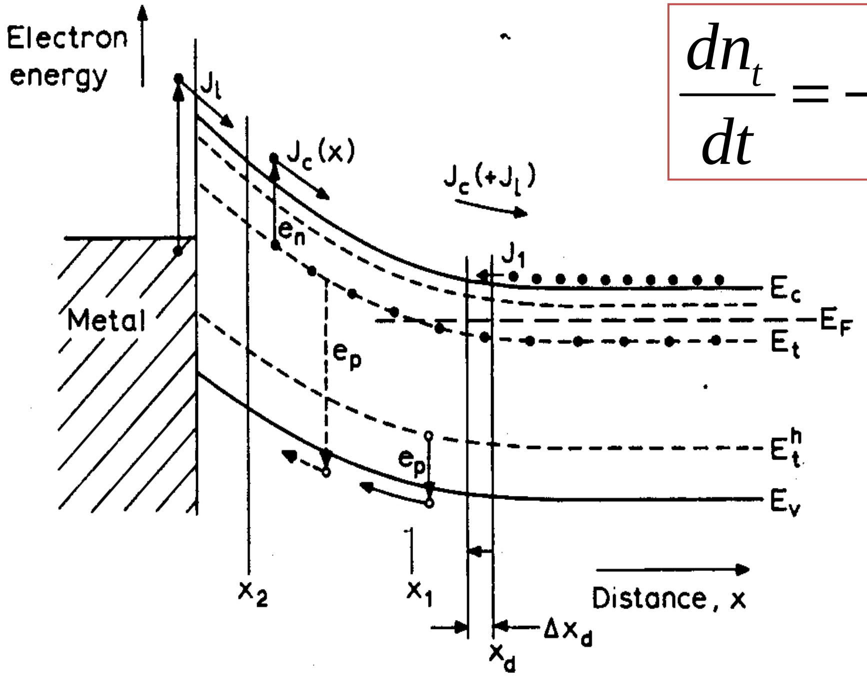
Activation energy

Emission coefficient:

$$e_n = N_c \sigma_n v_{th} \cdot e^{-\frac{E_c - E_t}{KT}}$$

Capture coefficient :

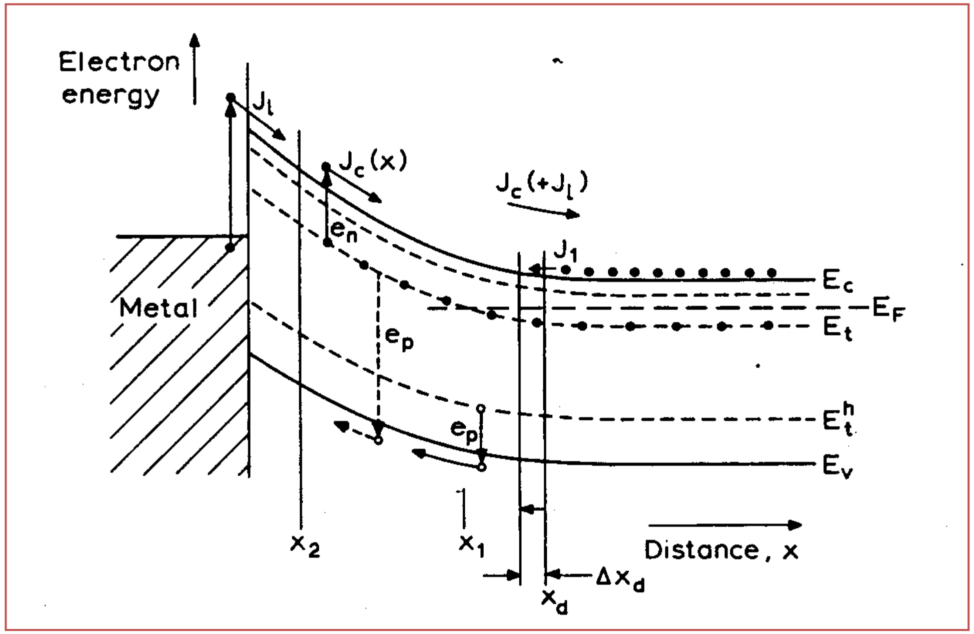
$$c_n = n\sigma_n v_{th}$$

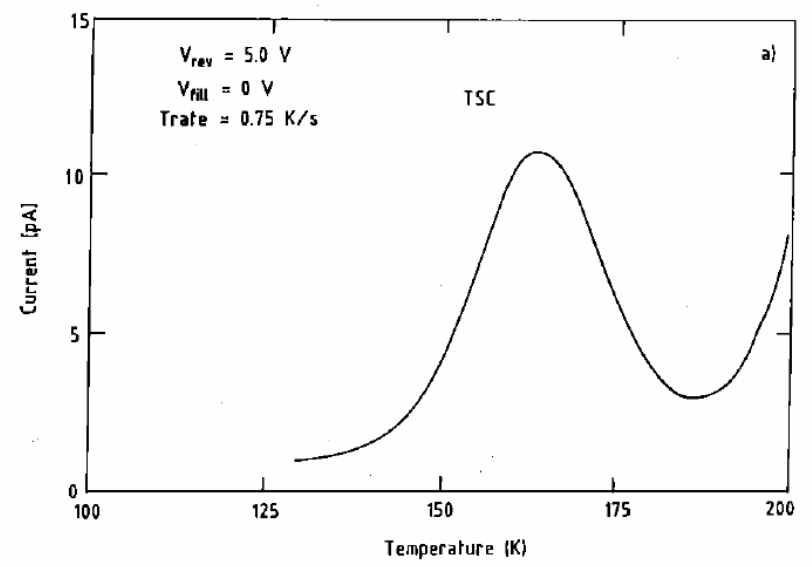


$$\frac{dn_t}{dt} = -e_n \cdot n_t$$

Mid 70s : Thermally Stimulated Currents and Deep Levels Transient Spectroscopy as valuable methods to study point defects in semiconductors

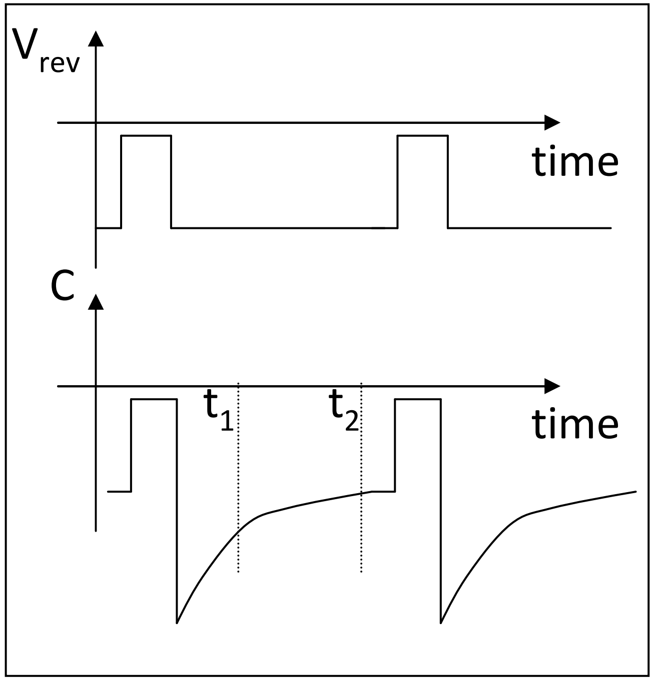
Thermally Stimulated Current TSC





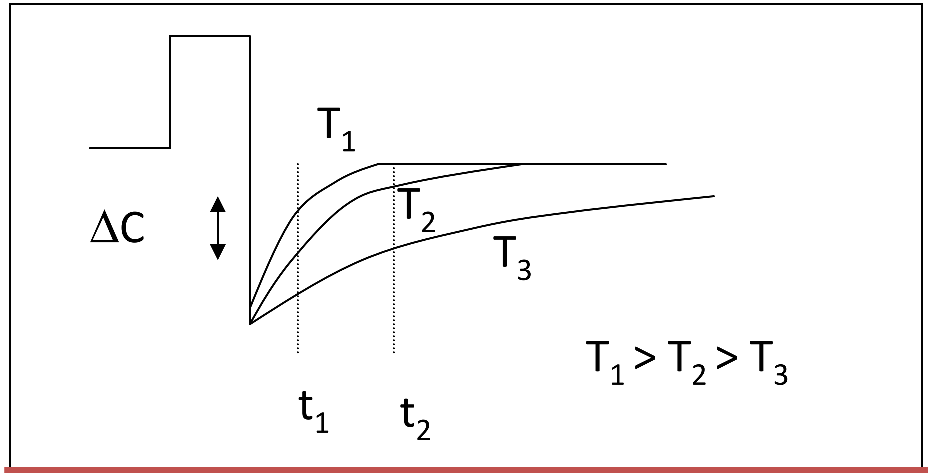
$$J_{TSC} = J_c + \frac{\partial D}{\partial t} = -\frac{1}{2} q W_d e_n n_t$$

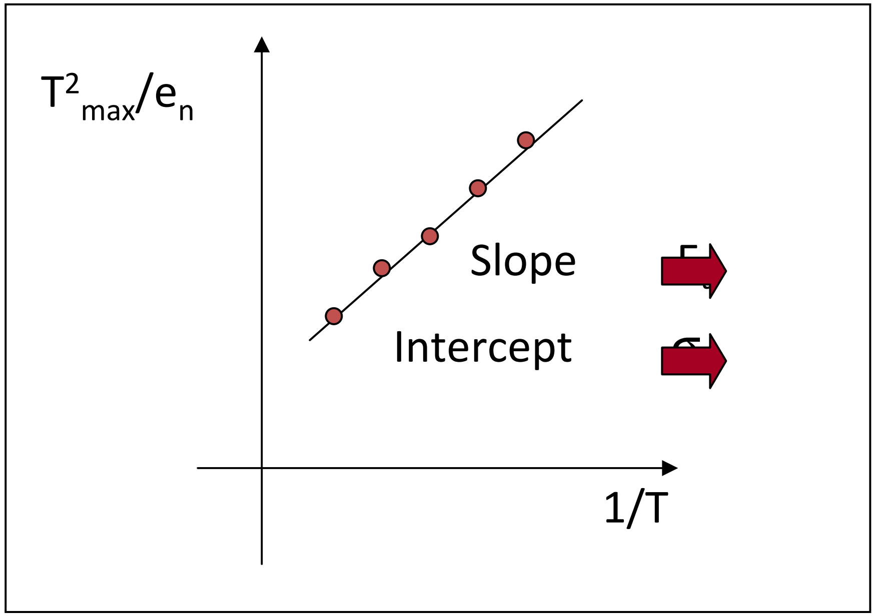
Deep Level Transient Spectroscopy DLTS



$$S = \Delta C_0 \left(e^{-e_n(T)t_1} - e^{-e_n(T)t_2} \right)$$

$$e_n(T_{\max}) = \frac{t_2 - t_1}{\ln(t_2 / t_1)} \alpha T_{\max}^2 \cdot e^{-E_t / KT_{\max}}$$





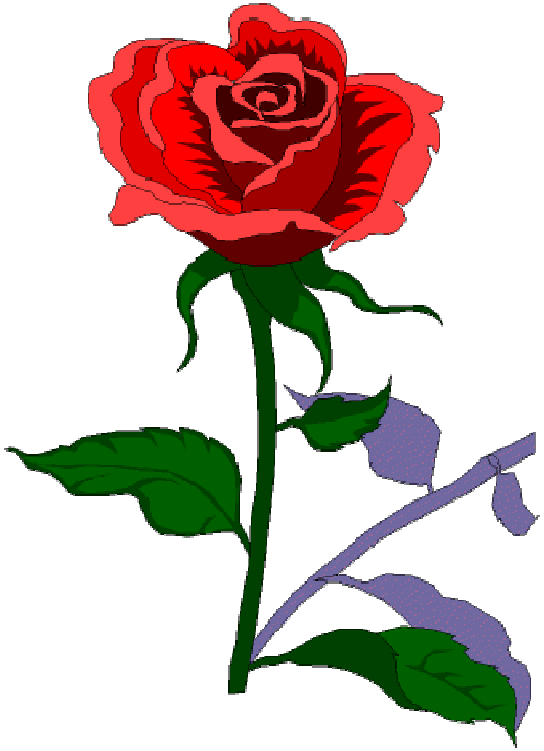
The ROSE Collaboration: 1995-2001

mid 90s: The ROSE Collaboration starts …

The ROSE Collaboration
CERN - RD48

ROSE

Research and development
On Silicon for future Experiments



RD48 Spokespersons:
Dr. Francois Lemeilleur
Prof. Dr. Dr. hc. Gunnar Lindström
Prof.Dr. Stephen J. Watts

ROSE representative at CERN:
Dr. Michael Moll

http://rd48.web.cern.ch/RD48/

The objectives of the collaboration are:

- The development of radiation hard silicon detectors that can operate beyond the limits of present devices and that ensure guaranteed operation for the whole lifetime of the LHC experimental programme.
- The outline of recommendations to experiments on the optimum silicon for detectors and quality control procedures required to ensure optimal radiation tolerance.

The ROSE Collaboration formed following the First Workshop on Radiation Hardening of Silicon Detectors at CERN in October 1995. The proposal was approved by the LHCC in June 1996.

38 international groups working on detectors for particle physics experiments at the LHC. **The Collaboration benefits from the very valuable input of solid state physicists and the expertise of silicon manufacturers**, who are also members of RD48. In addition the close involvement of Canberra, CNM, Micron and SINTEF is shown through their "Associated Company" status. Inputs are also acknowledged from the European Space Agency, IMEC, Belgium and the MPI Semiconductor Laboratory in Munich all of which are cooperating via an "Observer" status. Work at ITE and ITME (both RD48 members) has been vital for the rapid development, production and processing of various materials. More recently collaboration with ITME has resulted in high quality material characterisation**. Finally the RD48 technique for Oxygen enrichment** had been successfully transferred to CiS (Germany), Micron (Great Britain), SINTEF (Norway) and ST-Microelectronics (Italy). These manufacturers have produced dedicated ROSE test detectors and full scale detector prototypes for LHC experimental groups on oxygenated silicon.

96-97 : ATLAS/CMS Proposals of Inner Detector Technical Design report

ATLAS. Inner Detector Technical Design Report (ATLAS TDR 4-5). *CERN/LHCC/97-16 and 17*, 1997.

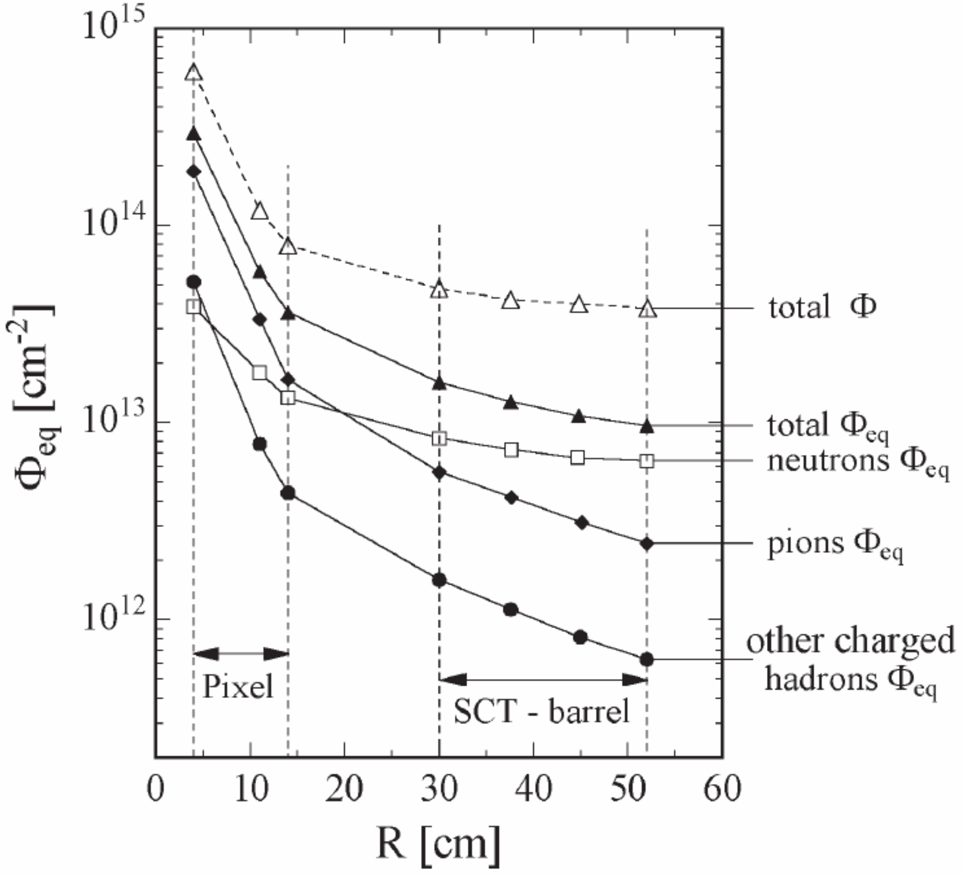


Figure 1.1: Expected particle fluences for the ATLAS detector within one operational year (10^7 s) of high luminosity ($10^{34} cm^{-2} s^{-1}$) assuming an inelastic pp interaction cross section of 80 mb [Vas97b].

Radiation Hardness improvement through Defect Engineering

- Impurities intentionally incorporated into Si may serve to getter radiation-induced vacancies to prevent them from forming the damaging V-V and related centers
- Impurities: O, Sn, N, Cl, H, etc.

One example: oxygen O:

$$V + V \rightarrow V_2$$

$$V + O \rightarrow O - V$$

Two competing processes for V

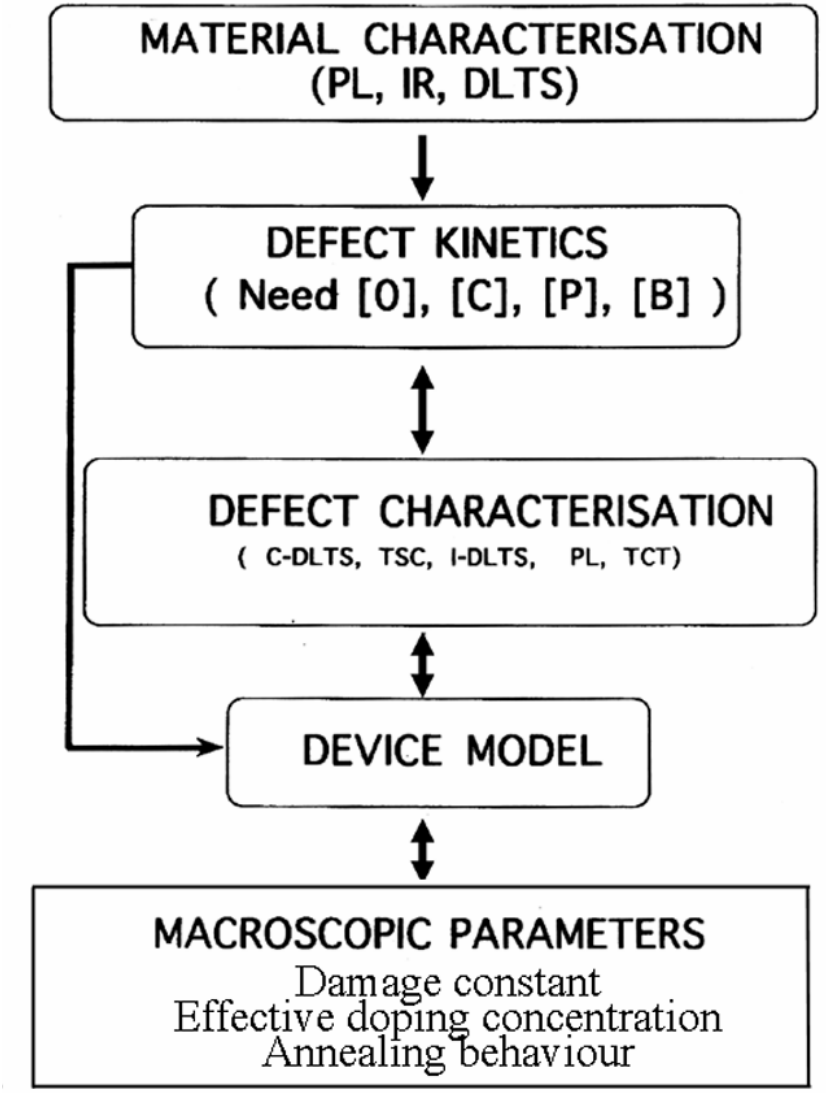
Then the rate for V_2, the most important defect for N_{eff} changes, is:

$$R_{V_2} = \frac{d[V_2]}{dt} \propto \frac{[V]}{[V]+[O]} \longrightarrow 0 \text{ if } [O] >> [V]$$

Key: impurity concentration should be much larger than that of vacancies

RD48: Defect engineering strategy

ROSE status Report/RD48, CERN/LHCC 97-39



MATERIAL CHARACTERISATION
(PL, IR, DLTS)

DEFECT KINETICS
(Need [O], [C], [P], [B])

DEFECT CHARACTERISATION
(C-DLTS, TSC, I-DLTS, PL, TCT)

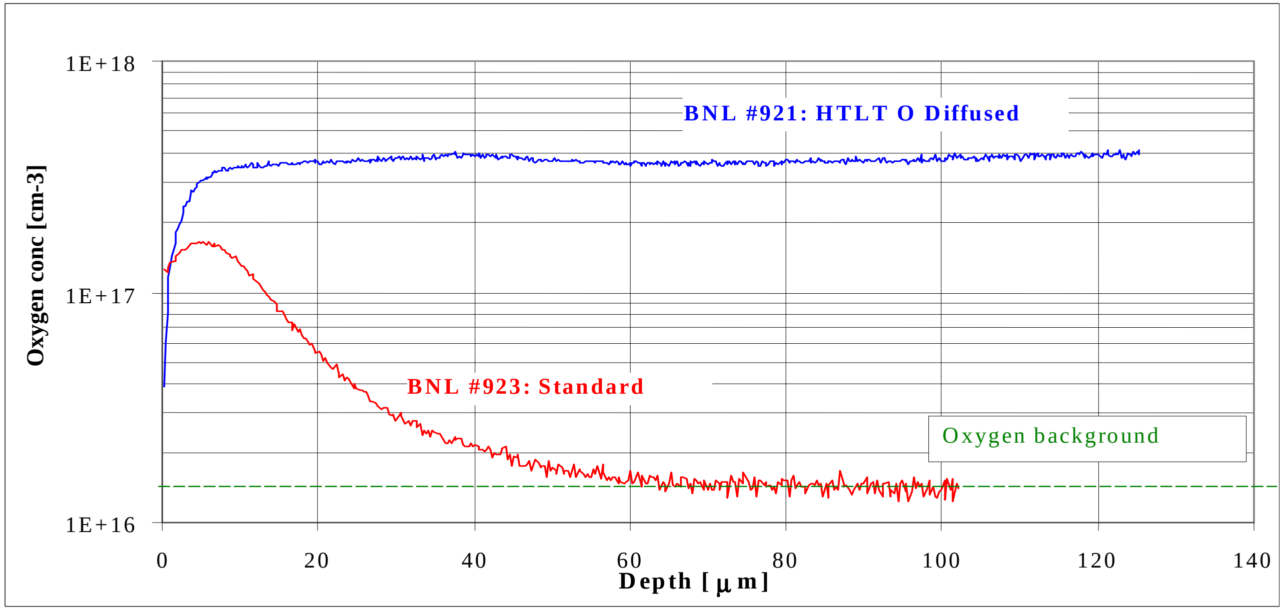
DEVICE MODEL

MACROSCOPIC PARAMETERS
Damage constant
Effective doping concentration
Annealing behaviour

Technology for Enriching Si with oxygen
(developed by BNL in the framework of RD48)

BNL's Thermal Process

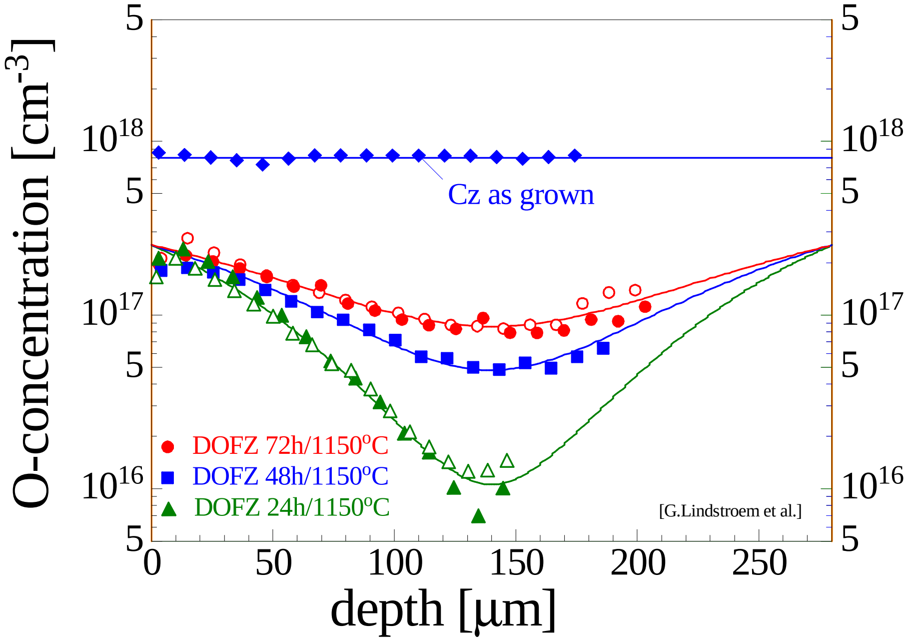
Process	Temperature (°C)	Diffusion Time (h)	Diffusion Length (μm)	Oxide Thickness (μm)
Standard	1100	6	12	0.5
HTLT O Diffusion	1200	216	155	3



Oxygen concentration in FZ, CZ and EPI: the activity of the Hamburg group

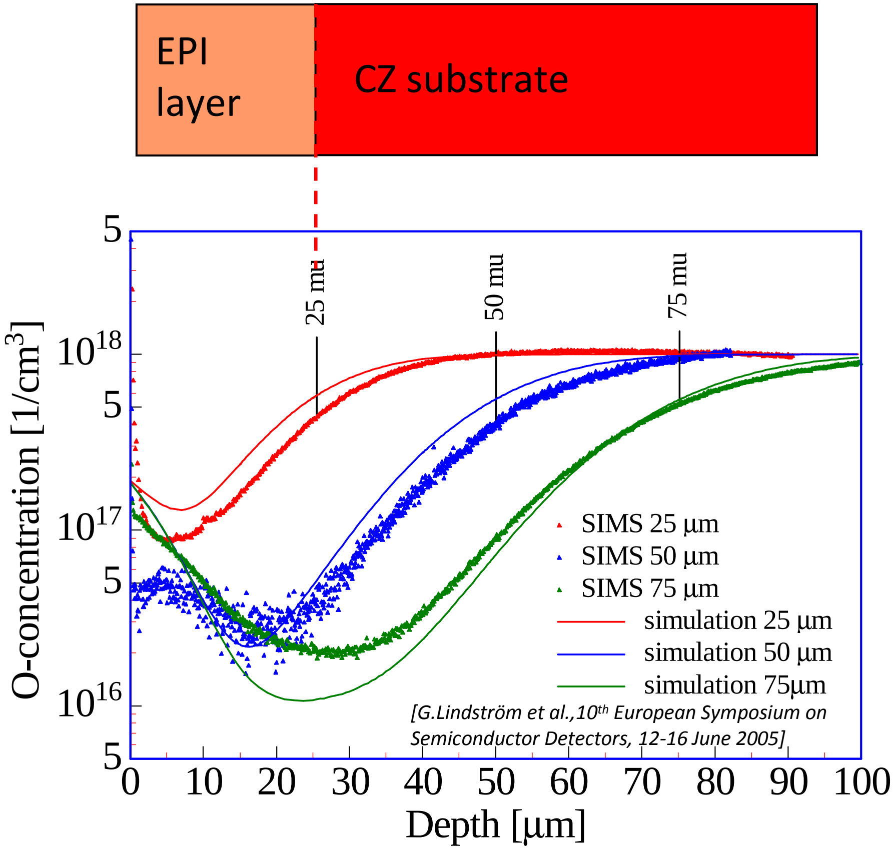
Cz and DOFZ silicon

- CZ: high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
- CZ: formation of Thermal Donors possible !



- DOFZ: inhomogeneous oxygen distribution
- DOFZ: oxygen content increasing with time at high temperature

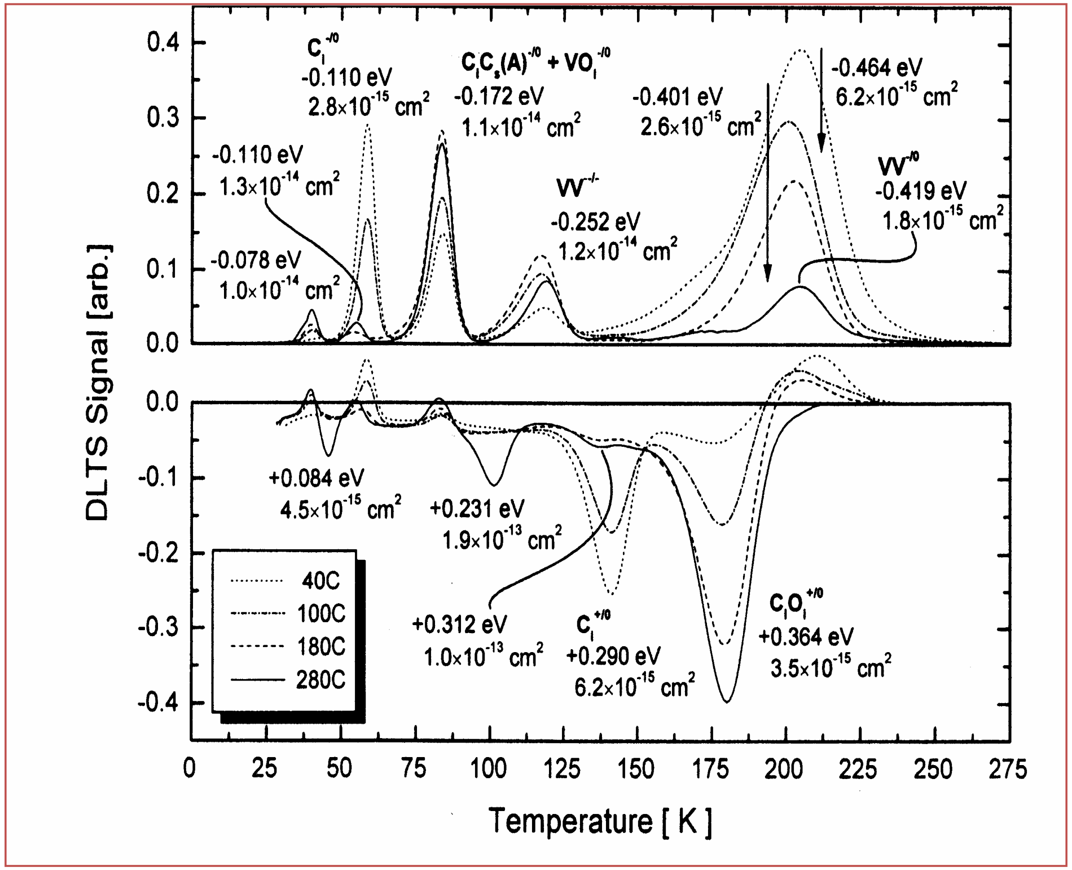
Epitaxial silicon



[G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005]

- EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production
- EPI: in-homogeneous oxygen distribution

Under the ROSE Collaboration the large amount of samples and different kind of materials allowed for a systematic analysis of microscopic and macroscopic damage in silicon irradiated with different kind of particles and fluences



DLTS - f $=10^{11}$ cm^{-2} 5.3MeV neutrons
ROSE Coll. NIM A 466 (2001) 308-326

Problem: How to normalize radiation damage from different particles?

Charged particles interact with silicon primarily by Coulomb interaction at lower energies: big part of the energy is lost due to ionization of lattice atoms. Neutrons interact only with the nucleus, by elastic scattering and nuclear interactions (Non-Ionising Energy Loss) NIEL.

Problem : **scaling of radiation damage produced by different kind of particles and energy with respect to radiation induced changes.**

NIEL hypothesis : any displacement-damage induced change in the materials scales linearly with the amount of energy imparted in displacing collisions. The portion of energy recoil deposited in form of displacement damage is depending on the recoil energy itself and can be calculated by the Lindhard partition function $P(E_r)$. NIEL can be calculated and expressed by the displacement damage cross section D(E)

NIEL - Non Ionizing Energy Loss scaling using hardness factor κ

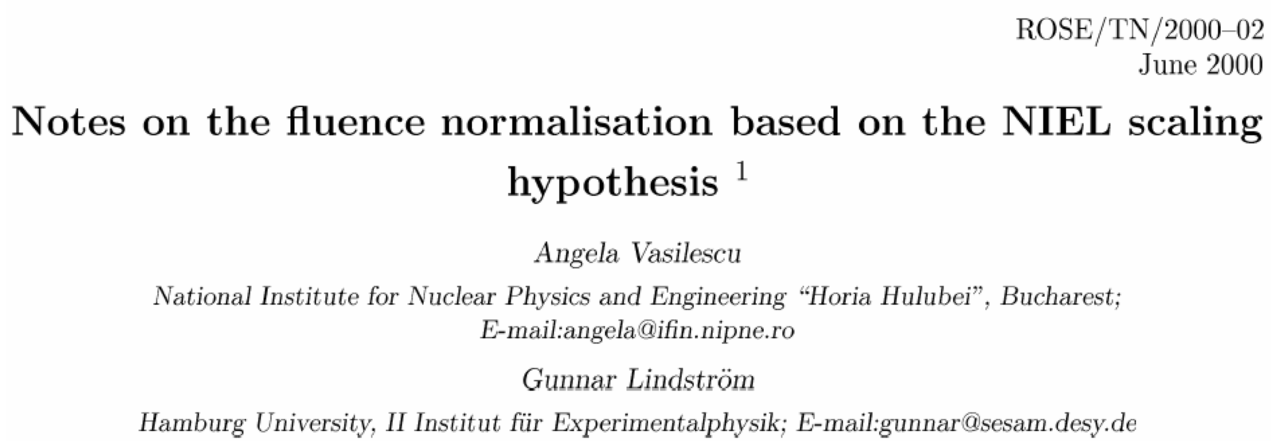
$$\boxed{\kappa = \frac{1}{D(1MeV\ neutrons)} \bullet \frac{\int D(E)\,\phi(E)\,dE}{\int \phi(E)\,dE}}$$

of **a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons**

- **E** **energy of particle**
- **D(E)** **displacement damage cross section for a certain particle at energy E**
  D(1MeV neutrons)=95 MeV·mb
- **ϕ(E)** **energy spectrum of radiation field**

The integrals are evaluated for the interval [E_{MIN},E_{MAX}], being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

G. Lindström, A. Vasilescu – Displacement Damage in Silicon, an on-line data compilation on displacement damage functions in silicon, at www.sesam.desy.de

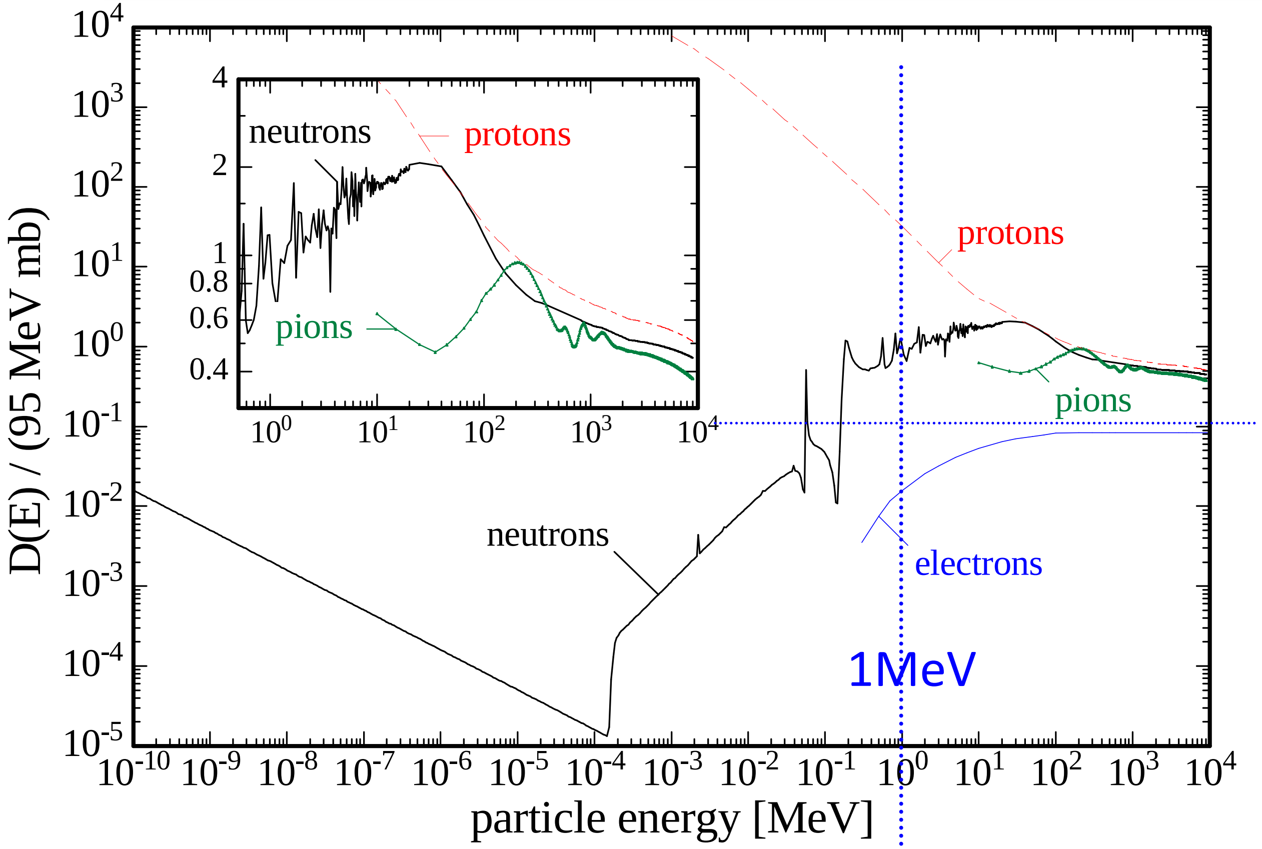


ROSE/TN/2000–02
June 2000

Notes on the fluence normalisation based on the NIEL scaling hypothesis [1]

Angela Vasilescu
National Institute for Nuclear Physics and Engineering "Horia Hulubei", Bucharest;
E-mail:angela@ifin.nipne.ro

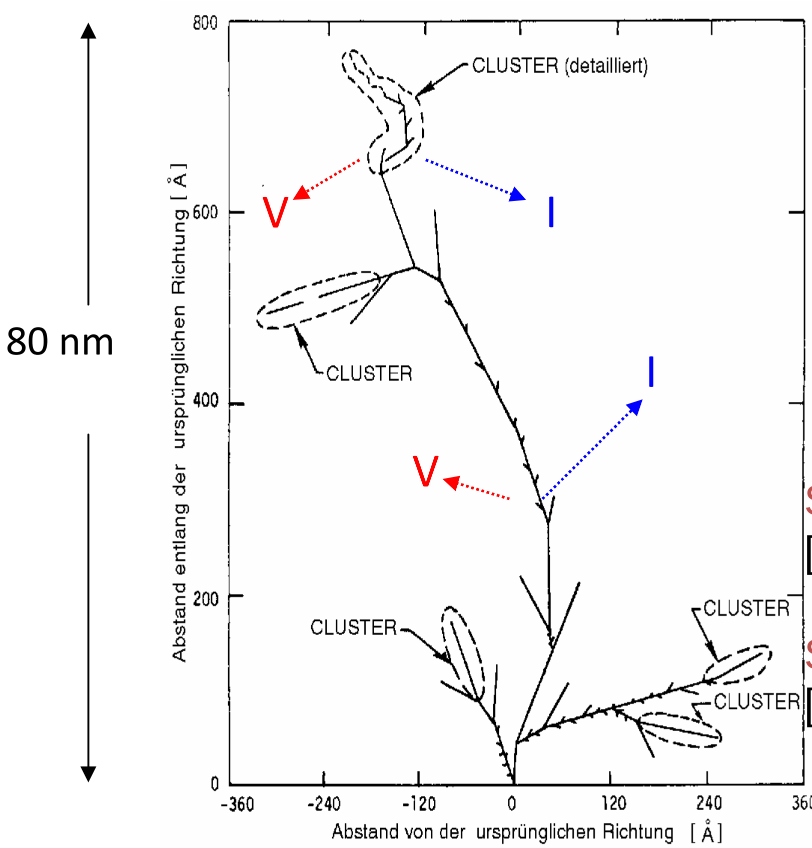
Gunnar Lindström
Hamburg University, II Institut für Experimentalphysik; E-mail:gunnar@sesam.desy.de



1 MeV neutron equivalent damage

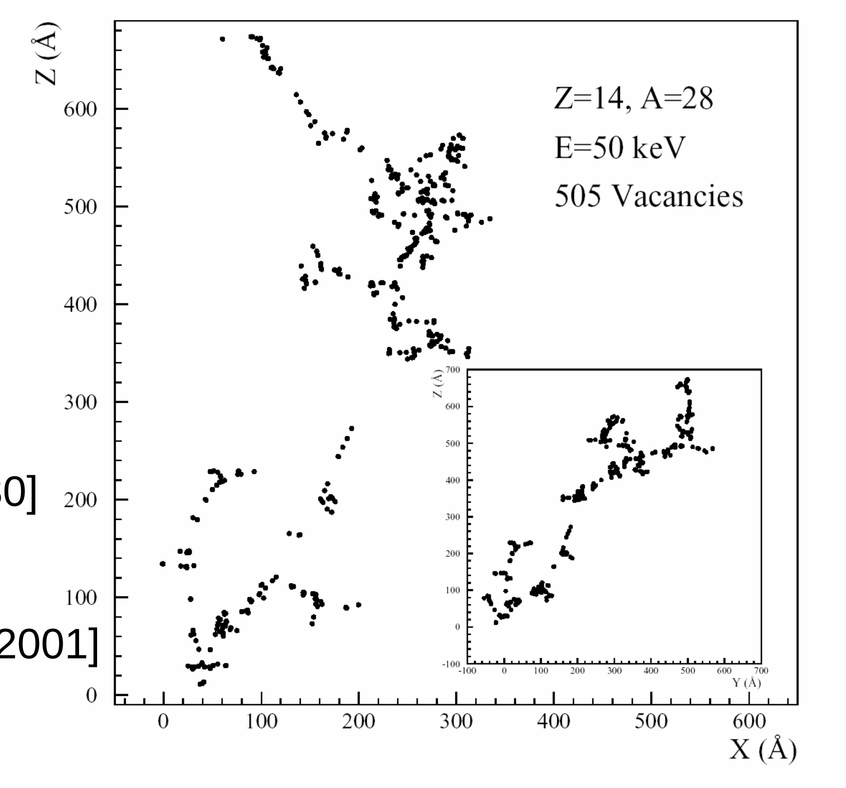
Simulation of the displacement of lattice atoms

Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):



Schematic
[Van Lint 1980]

Simulation
[M.Huhtinen 2001]



Vacancy amount and distribution depends on particle kind and energy

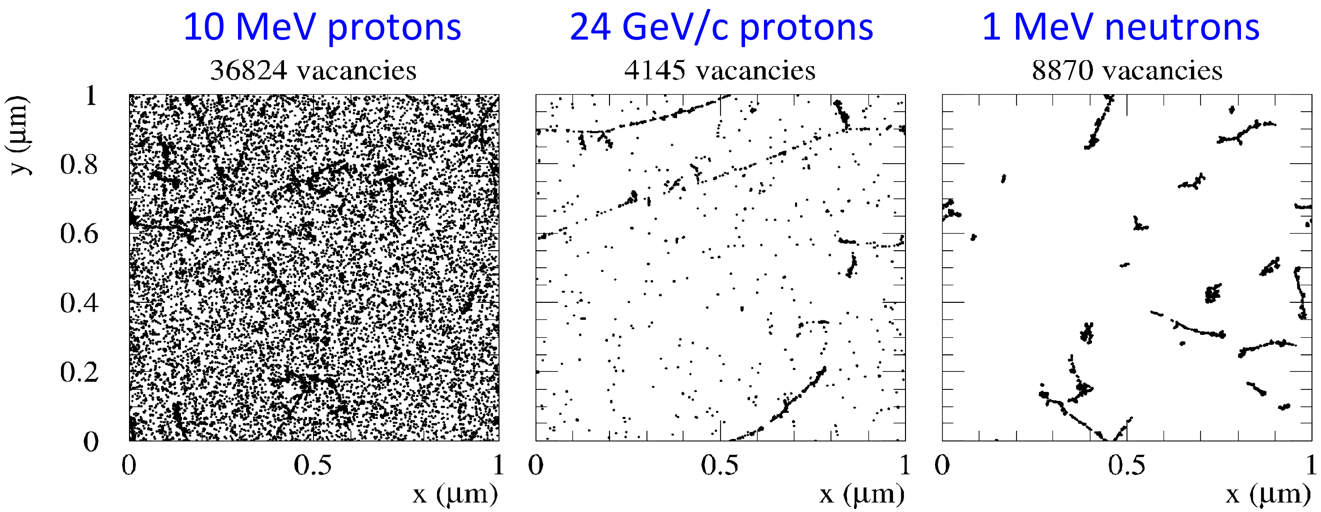
^{60}Co-gammas
- Compton Electrons with max. $E_\gamma \approx 1$ MeV (no cluster production)

Electrons
- $E_e > 255$ keV for displacement
- $E_e > 8$ MeV for cluster

Neutrons (elastic scattering)
- $E_n > 185$ eV for displacement
- $E_n > 35$ keV for cluster

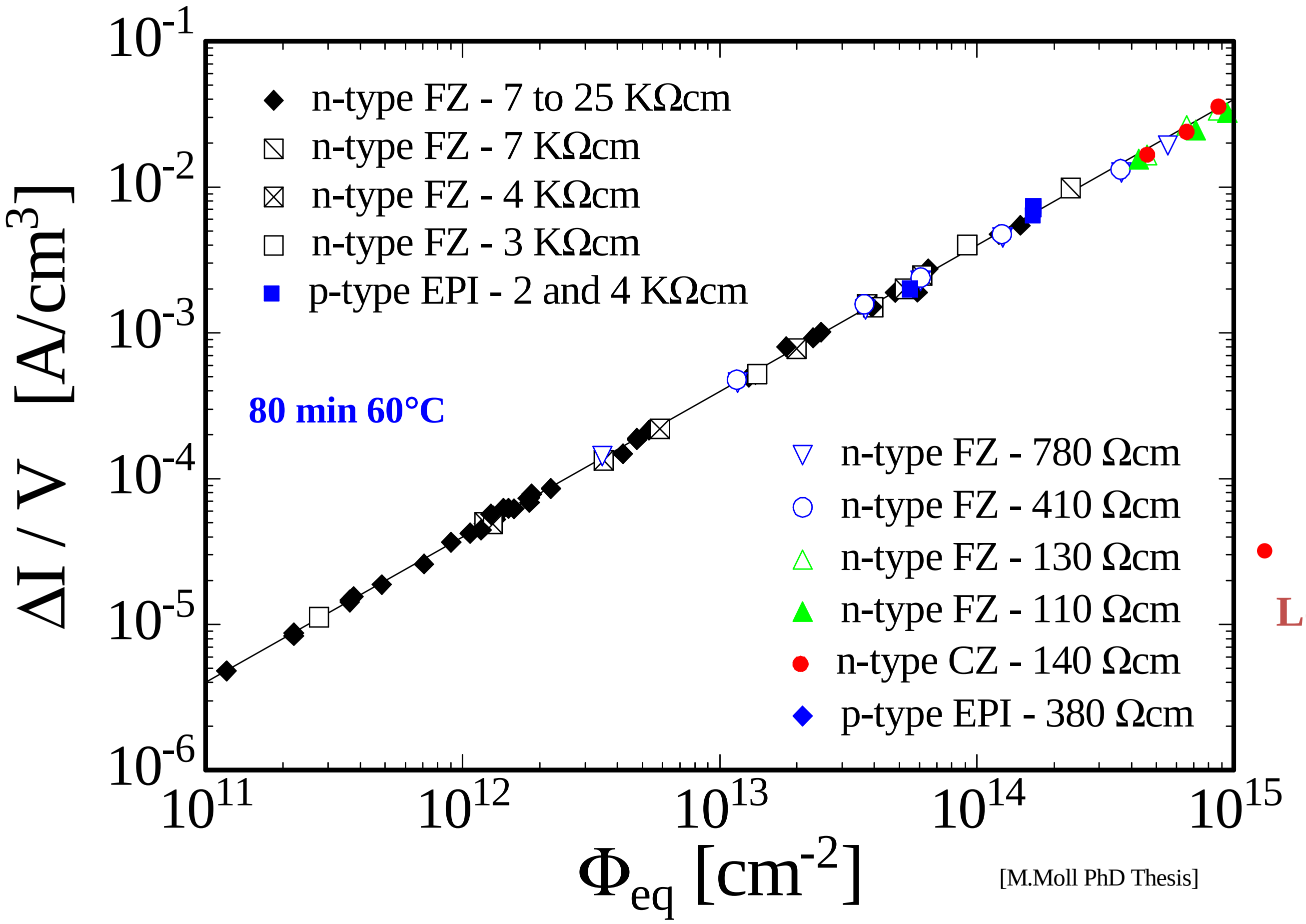
Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

Initial distribution of vacancies in (1µm)^{3}after 10^{14} particles/cm^2



[Mika Huhtinen NIMA 491(2002) 194]

Leakage Current as a function of hadron irradiation



[M.Moll PhD Thesis]

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

- **Damage parameter α**

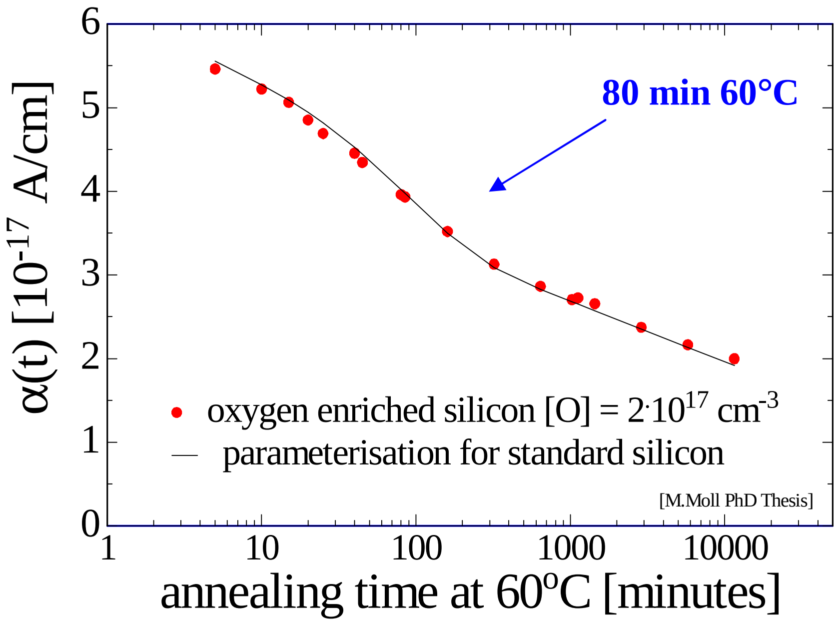
  Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

Changes with time and temperature after irradiation (annealing)

- **Leakage Current and N_{eff} (after hadron irradiation)**

…. with time (annealing):



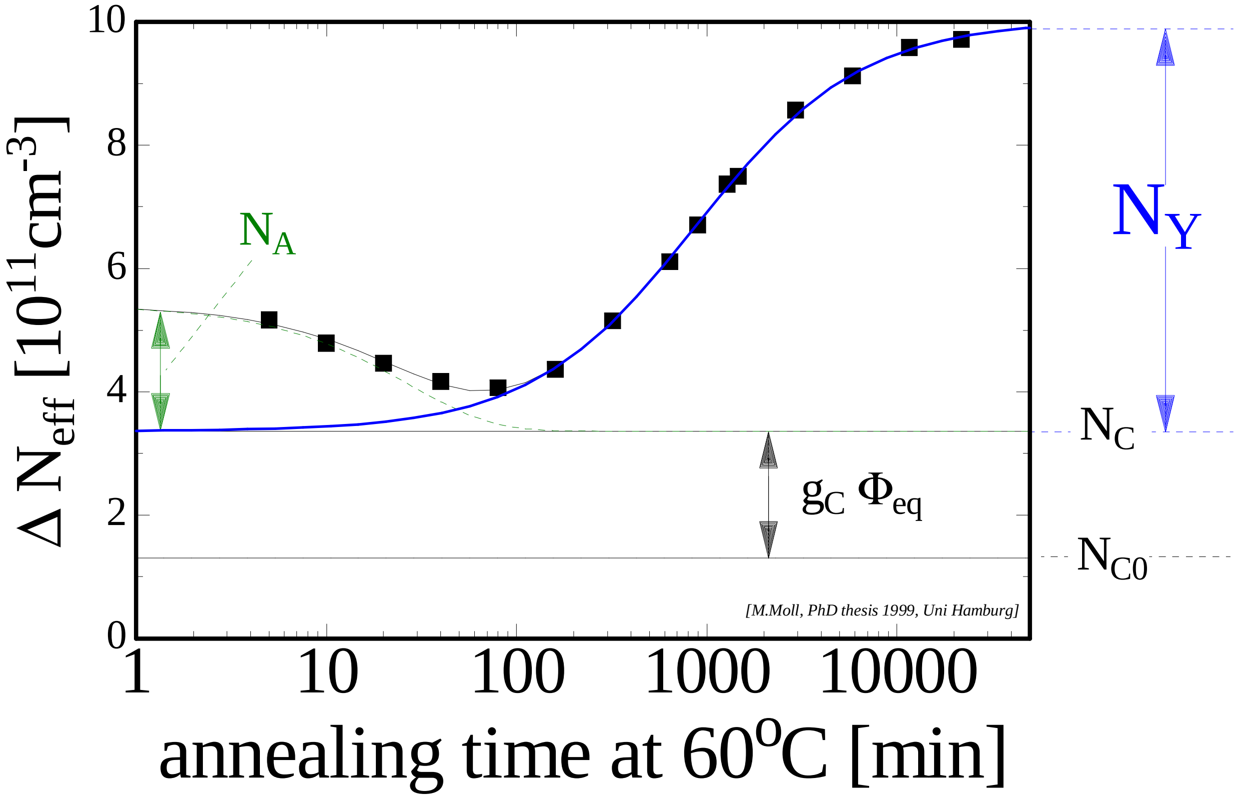
- **Leakage current decreasing in time (depending on temperature)**

$$\alpha(t) = \alpha_I \cdot exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \cdot ln\,(t/t_0)\,.$$

- **Strong temperature dependence**

- **Consequence:** **Cool detectors during operation!** **Example: *I*(-10°C) ~1/16 *I*(20°C)**

Hamburg Model on evolution of N_{eff} with annealing and time



- Short term: "Beneficial annealing" • Long term: "Reverse annealing"
  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)
  - Consequence: Detectors must be cooled even when the experiment is not running!

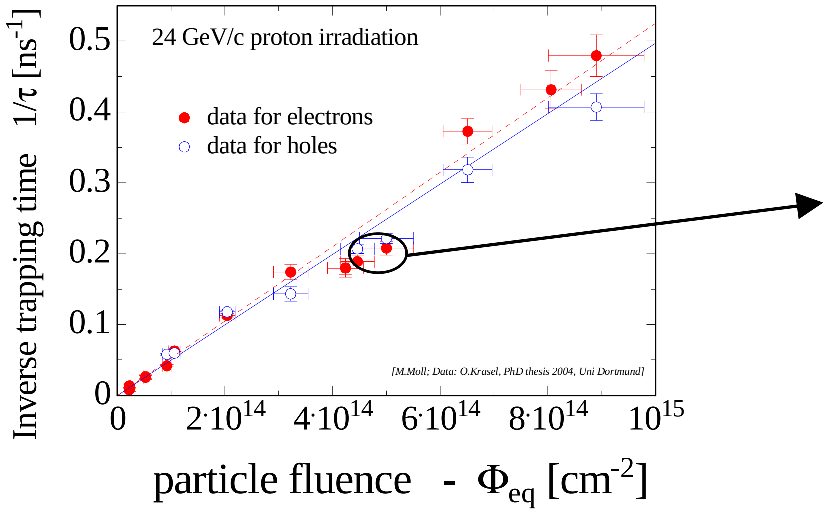
Radiation Damage – Charge carrier trapping

Deterioration of Charge Collection Efficiency (CCE) by trapping

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

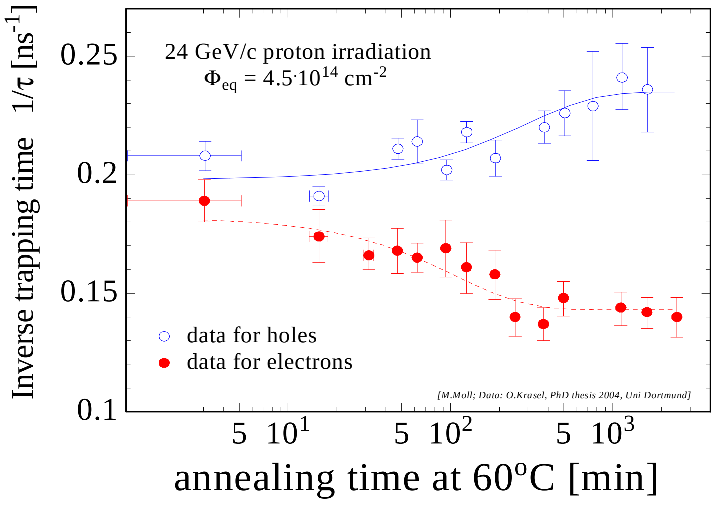
$$Q_{e,h}(t) = Q_{0e,h}\exp\left(-\frac{1}{\tau_{eff\ e,h}}\cdot t\right) \qquad \text{where:} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence



[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

….. and change with time (annealing):



[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

Charge trapping leads to very small $\lambda_{e,h}$ at $\Phi_{eq} = 10^{16}$/cm²

→

<u>Consequence:</u> Cooling does not help but: use thin detectors (~100µm) and p-type Si,

DOFZ Si : Open Problems by the end of 2001

The microscopic defects responsible of the oxygen-effect have been no clearly identified. A direct correlation has been observed between the oxygen-related defect V_2O ($E_t= E_c-0.543eV$) and the macroscopic changes of the detector properties after γ irradiation. **Systematic studies are needed to understand the microscopic mechanisms occurring for proton, neutron irradiation.**

No clear quantitative correlation between oxygen content and radiation hardness, probably due to the impact of individual processes of different manufacturers.

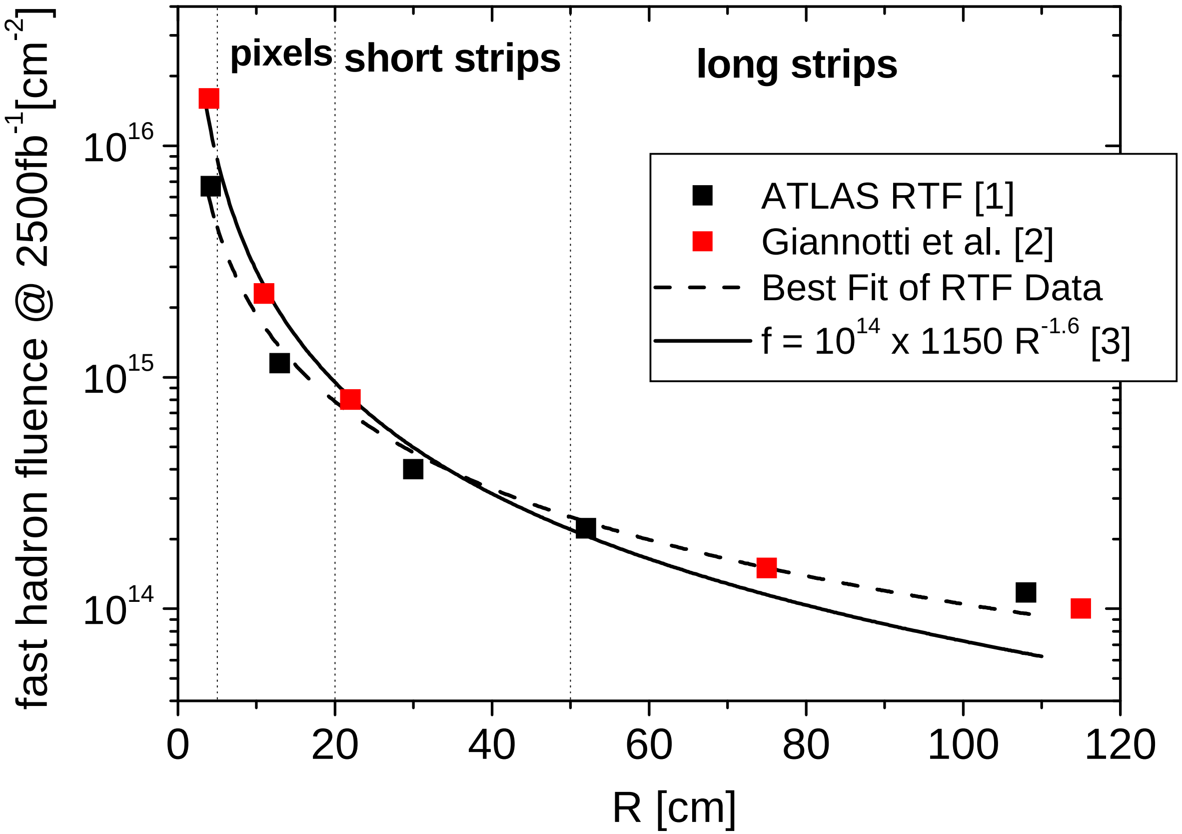
Optimization of the DOFZ process To determine the optimal process with respect to radiation hardness and cost effectiveness.

Detailed characterization of oxygenated segmented detectors More detailed investigations are needed to compare and quantify the radiation hardness properties of single pad, mini- and full segmented devices made with oxygenated Si.

High resistivity Czochralski Silicon New developments in Si manufacturing make high resistivity CZ possible. This material is cheaper than DOFZ and exhibit the same or better radiation tolerance.

Possible increase of Luminosity up to 10^{35} $cm^{-2}s^{-1}$ was suggested in 2001 (Giannotti et al.)

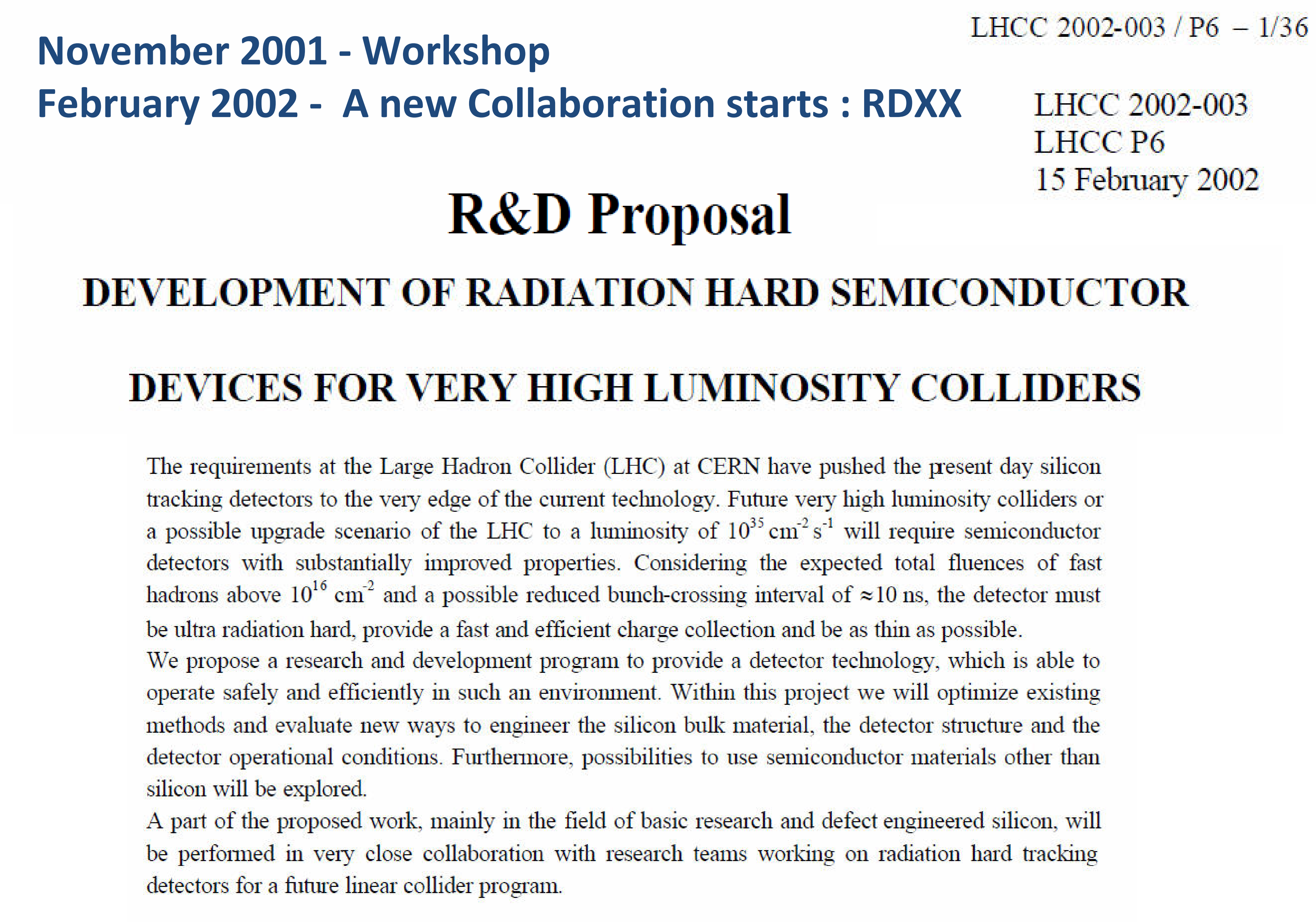
Fluences up to $1.6x10^{16}cm^{-2}$: Main constraint is the survival of the Si detector tracker to the exceptionally high fluences of fast hadrons.



The RD50 Collaboration: 2002 -

November 2001 - Workshop

February 2002 - A new Collaboration starts : RDXX



LHCC 2002-003 / P6 – 1/36

LHCC 2002-003
LHCC P6
15 February 2002

R&D Proposal

DEVELOPMENT OF RADIATION HARD SEMICONDUCTOR

DEVICES FOR VERY HIGH LUMINOSITY COLLIDERS

The requirements at the Large Hadron Collider (LHC) at CERN have pushed the present day silicon tracking detectors to the very edge of the current technology. Future very high luminosity colliders or a possible upgrade scenario of the LHC to a luminosity of 10^{35} cm^{-2} s^{-1} will require semiconductor detectors with substantially improved properties. Considering the expected total fluences of fast hadrons above 10^{16} cm^{-2} and a possible reduced bunch-crossing interval of $\approx$10 ns, the detector must be ultra radiation hard, provide a fast and efficient charge collection and be as thin as possible.

We propose a research and development program to provide a detector technology, which is able to operate safely and efficiently in such an environment. Within this project we will optimize existing methods and evaluate new ways to engineer the silicon bulk material, the detector structure and the detector operational conditions. Furthermore, possibilities to use semiconductor materials other than silicon will be explored.

A part of the proposed work, mainly in the field of basic research and defect engineered silicon, will be performed in very close collaboration with research teams working on radiation hard tracking detectors for a future linear collider program.

Referees: J.J Gomez-Cadenas – Claude Vallee

The CERN RD50 Collaboration

http://www.cern.ch/rd50

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

- formed in November 2001
- approved as RD50 by CERN June 2002
- Main objective:

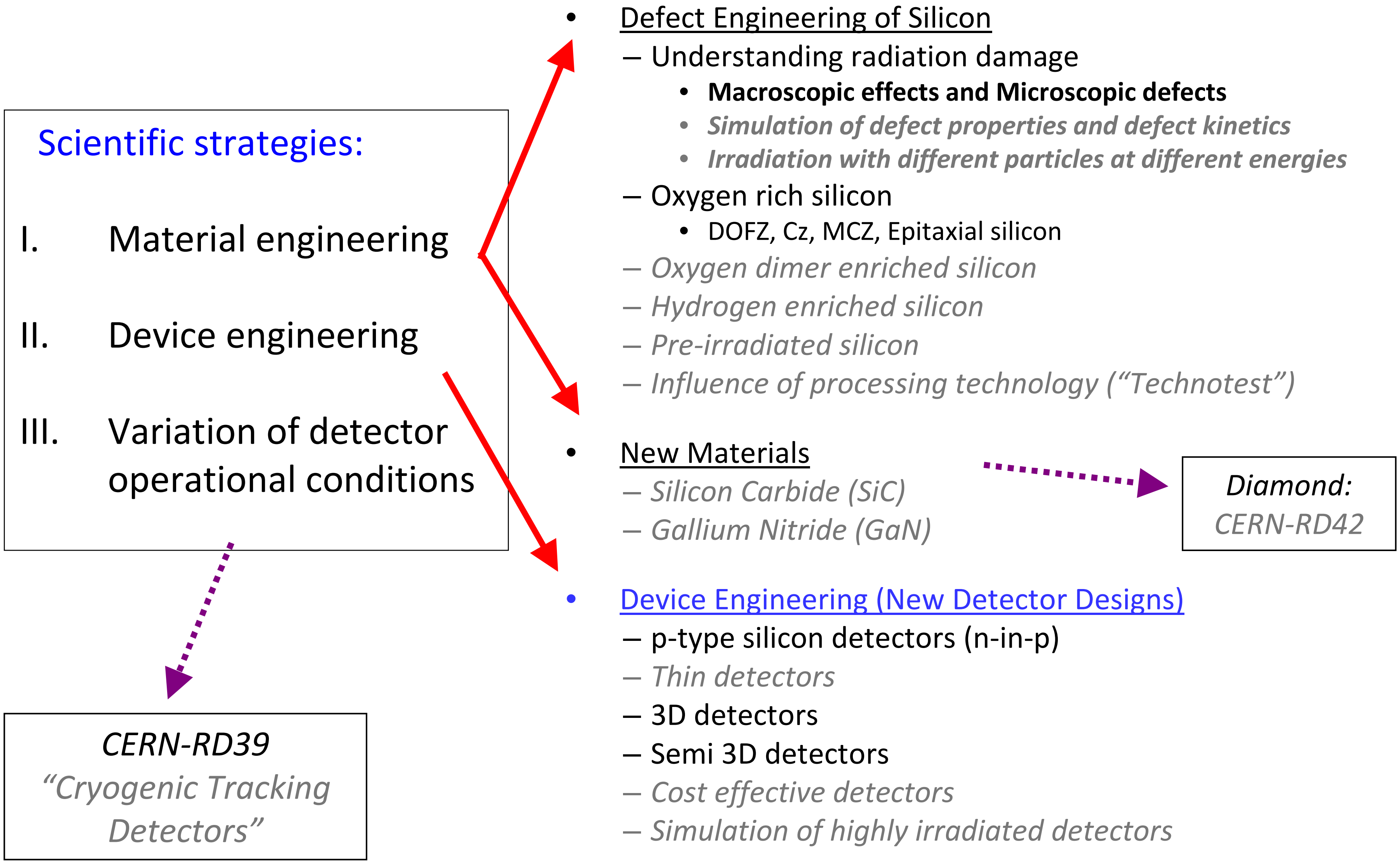
Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} $cm^{-2}s^{-1}$ (“Super-LHC”).

Challenges:
- Radiation hardness up to 10^{16} cm^{-2} required
- Fast signal collection (Going from 25ns to 10 ns bunch crossing ?)
- Low mass (reducing multiple scattering close to interaction point)
- Cost effectiveness (big surfaces have to be covered with detectors!)

- Presently 251 members from 51 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), Norway (Oslo (2x)), Poland (Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow), St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, University of Surrey), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

Approaches of RD50 to develop radiation harder tracking detectors



Scientific strategies:

I. Material engineering

II. Device engineering

III. Variation of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"

- Defect Engineering of Silicon
  - Understanding radiation damage
    - **Macroscopic effects and Microscopic defects**
    - ***Simulation of defect properties and defect kinetics***
    - ***Irradiation with different particles at different energies***
  - Oxygen rich silicon
    - DOFZ, Cz, MCZ, Epitaxial silicon
  - *Oxygen dimer enriched silicon*
  - *Hydrogen enriched silicon*
  - *Pre-irradiated silicon*
  - *Influence of processing technology ("Technotest")*
- New Materials
  - *Silicon Carbide (SiC)*
  - *Gallium Nitride (GaN)*

Diamond:
CERN-RD42

- Device Engineering (New Detector Designs)
  - p-type silicon detectors (n-in-p)
  - *Thin detectors*
  - 3D detectors
  - Semi 3D detectors
  - *Cost effective detectors*
  - *Simulation of highly irradiated detectors*

Silicon Materials under Investigation by RD50

Material	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard n- or p-type FZ	FZ	$1–7\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ, n- or p-type	DOFZ	$1–7\times10^{3}$	$\sim 1–2\times10^{17}$
Czochralski Sumitomo, Japan	Cz	$\sim 1\times10^{3}$	$\sim 8\text{-}9\times10^{17}$
Magnetic Czochralski Okmetic, Finland n,p-type	MCz	$\sim 1\times10^{3}$	$\sim 4\text{-}9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME	EPI	50 - 100	$< 1\times10^{17}$

CZ silicon:

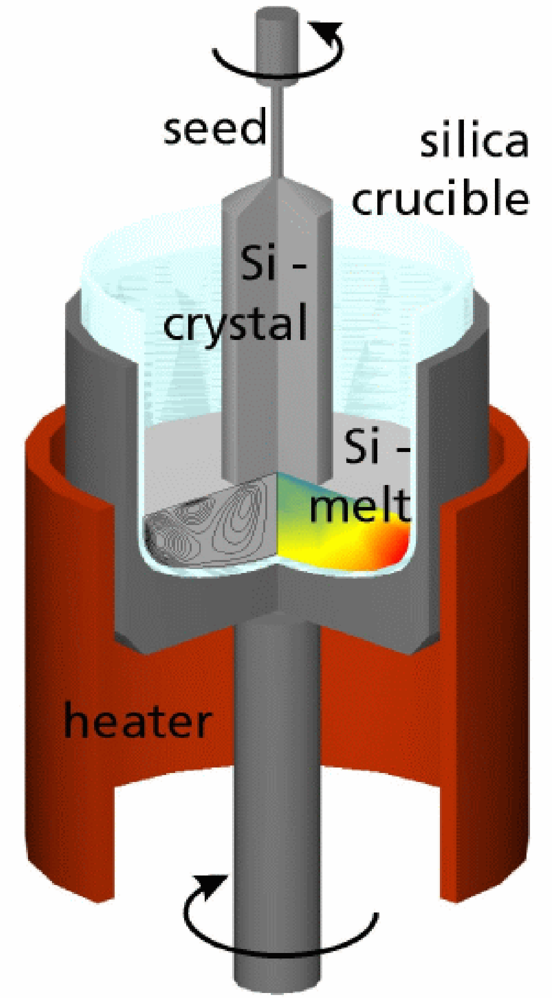
high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
formation of shallow Thermal Donors possible

Epi silicon

high O_i , O_{2i} content due to out-diffusion from the CZ substrate (inhomogeneous)
thin layers: high doping possible (low starting resistivity)

Czochralski silicon (Cz) & Epitaxial silicon (EPI)

Czochralski silicon



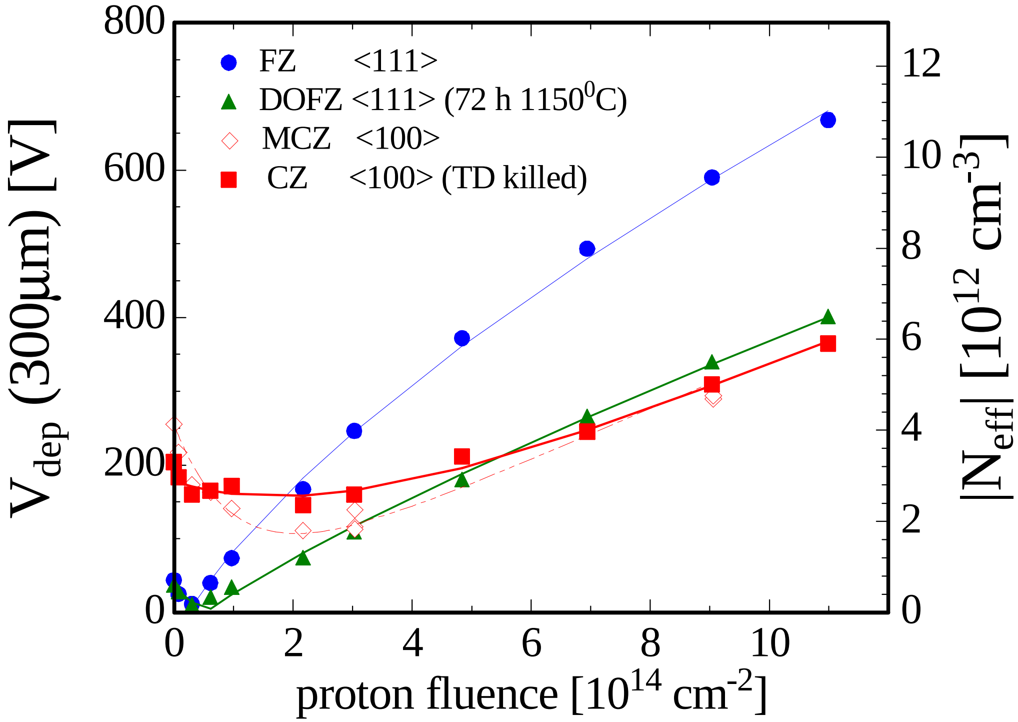
- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap)
- Recent developments (~5 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.

Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ **in-diffusion of oxygen**
- growth rate about 1µm/min
- excellent homogeneity of resistivity
- up to 150 µm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

Standard FZ, DOFZ, MCz and Cz silicon

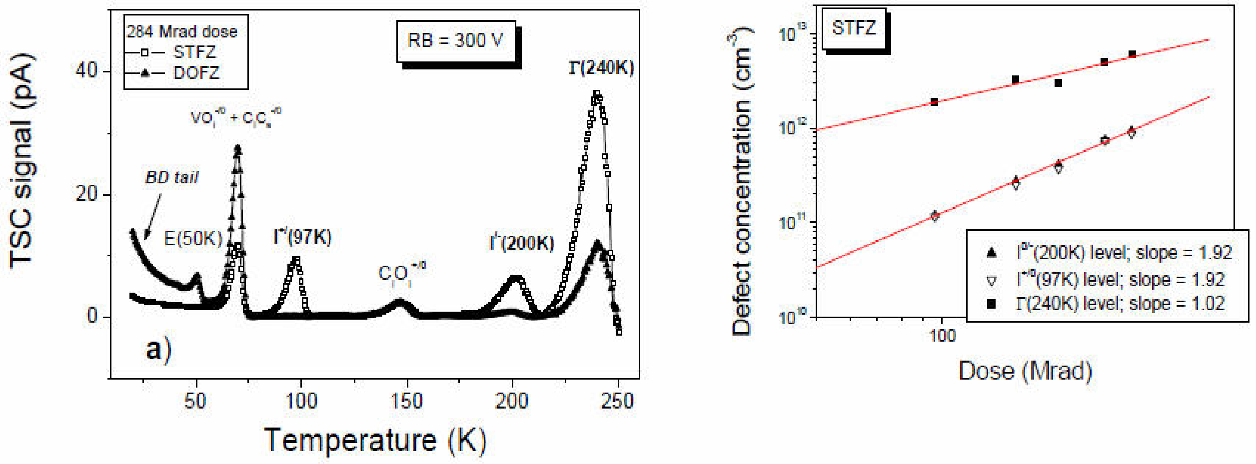
24 GeV/c proton irradiation



- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range

(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

- 2003: γ-irradiated samples For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects !



[APL, 82, 2169, March 2003]

Figure 2.: a) TSC spectra for STFZ and DOFZ; b) dose dependence of I and Γ defects.

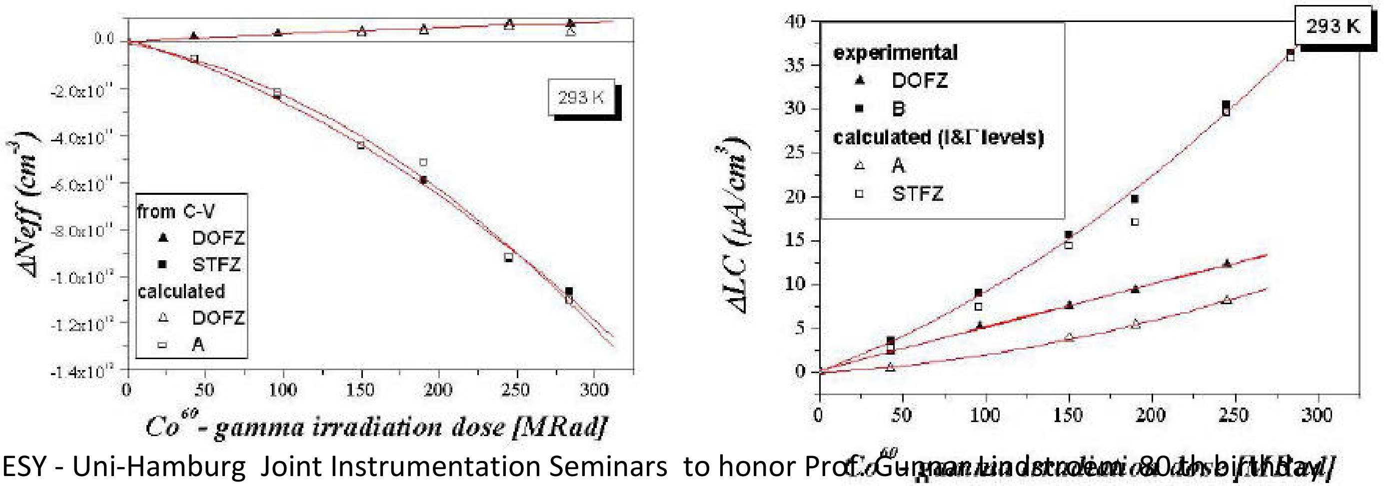


Figure 4.: The contribution of "I", "Γ" and "BD" centers to the change of the diodes properties with increasing dose.

2004- proton irradiated silicon detectors

Levels responsible for depletion voltage after 23 GeV proton irradiation:

Almost <u>independent of oxygen</u> content:

- Donor removal
- "Cluster damage" ⇒ negative charge

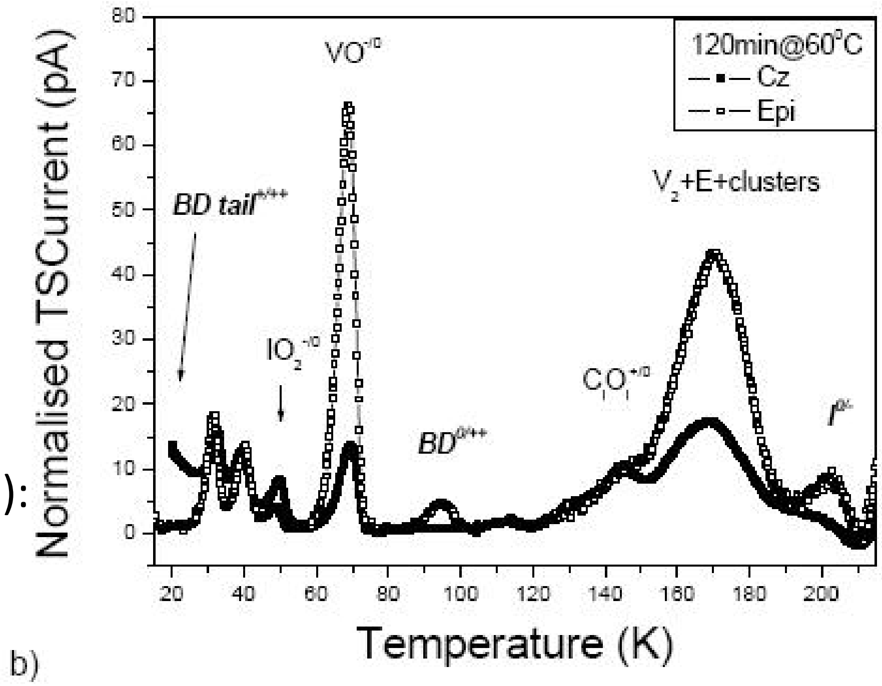
Influenced by <u>initial oxygen</u> content:

- deep acceptor level at E_C-0.54eV
  (good candidate for the V_2O defect)
  ⇒ negative charge

- Influenced by <u>initial oxygen dimer</u> content (?):

- BD-defect: bistable shallow thermal <u>donor</u>
  (formed via oxygen dimers O_{2i})
  ⇒ positive charge

[I.Pintilie, RESMDD, Oct.2004]



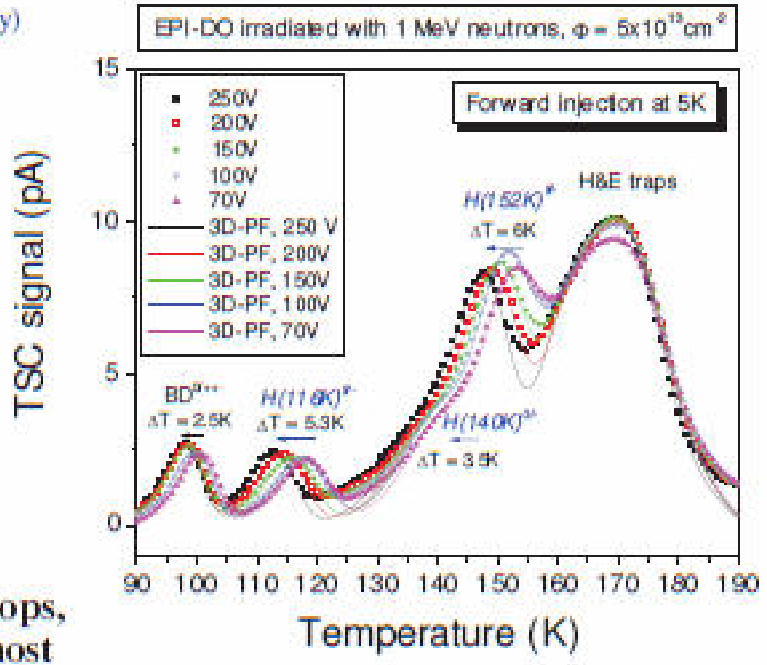
TSC after irradiation with 23 GeV protons with an equivalent fluence of 1.84×10^{14} cm^{-2} recorded on Cz and Epi material after an annealing treatment at 600C for 120 min.

WODEAN (WOrkshop on DEfect ANalysis), 1st meeting in Hamburg, 23-25 August 2006 idea triggered by Gordon Davies‘ talk at RD50, CERN, Nov. 2005 we need all available tools (not only DLTS, TSC) for thorough defect analysis and possible defect engineering

RD50 Defect Characterization - WODEAN

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G.Lindstroem, Hamburg)
  - **Aim:** Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}
  - **Method:** Defect Analysis on identical samples performed with the various tools available inside the RD50 network:
    - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
    - **I-DLTS** (Current Deep Level Transient Spectroscopy)
    - **TSC** (Thermally Stimulated Currents)
    - **PITS** (Photo Induced Transient Spectroscopy)
    - **FTIR** (Fourier Transform Infrared Spectroscopy)
    - **RL** (Recombination Lifetime Measurements)
    - **PC** (Photo Conductivity Measurements)
    - **EPR** (Electron Paramagnetic Resonance)
    - **TCT** (Transient Charge Technique)
    - **CV/IV**
  - ~ 240 samples irradiated with protons and neutrons
  - first results presented on 2007 RD50 Workshops, further analyses in 2008 and publication of most important results in in Applied Physics Letters

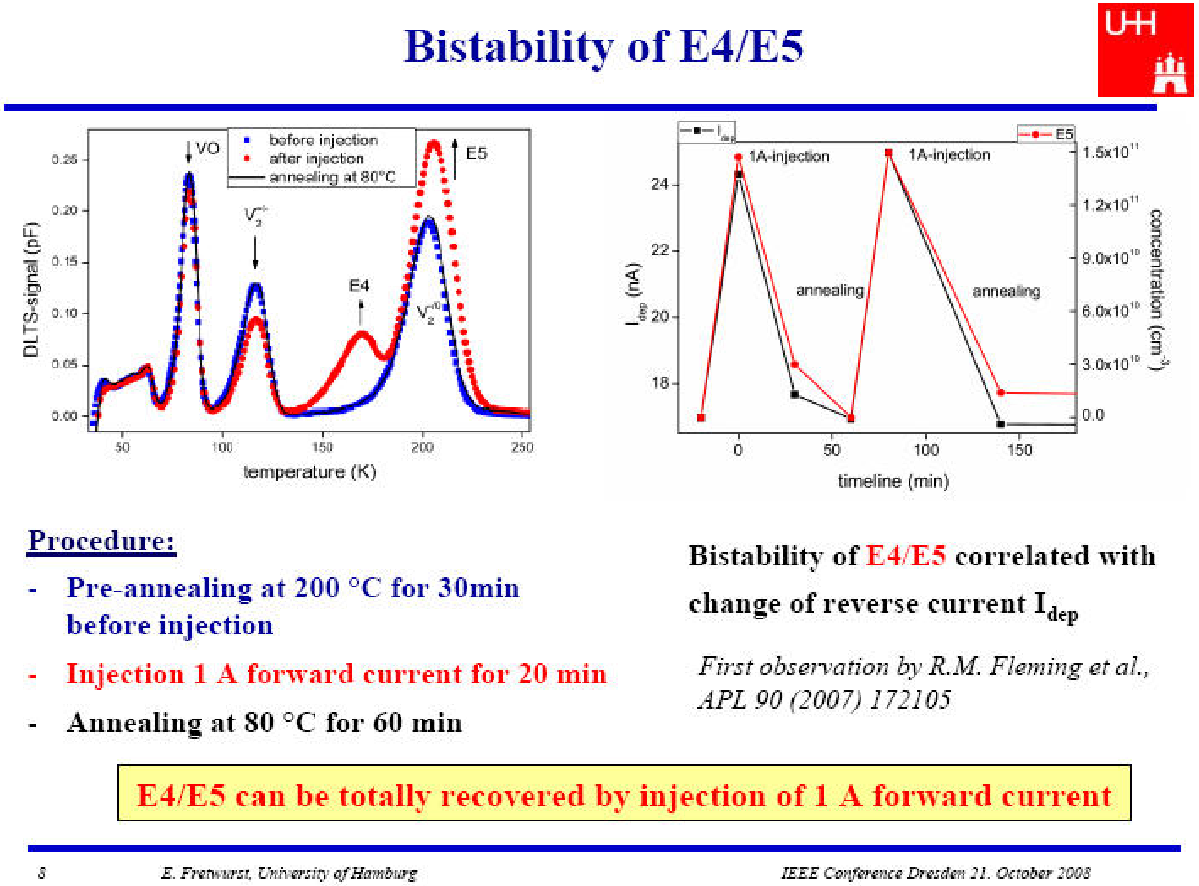
… significant impact of RD50 results on silicon solid state physics – defect identification



Example: TSC measurement on defects (acceptors) responsible for the reverse annealing

The issue of Defect Clusters in neutron irradiated silicon

Divacancy has two charge states at 0.24 and 0.43 eV corresponding to 135 K and 233 K DLTS transitions. Bistability of the $V_2^=$ peak observed after forward bias (appearance of a peak at 195K corresponding to a decrease in the shallower the shallow peak at 135 K) explained as partial filling of the level due to band bending within a cluster (R. M. Fleming et al APL, 90, 172105 2007). In 2008 The Hamburg group apply the concept to neutron irradiated silicon detectors anmd correlates defects in clusters to reverse current.



Bistability of E4/E5

Procedure:

- Pre-annealing at 200 °C for 30min before injection
- Injection 1 A forward current for 20 min
- Annealing at 80 °C for 60 min

Bistability of E4/E5 correlated with change of reverse current I_{dep}

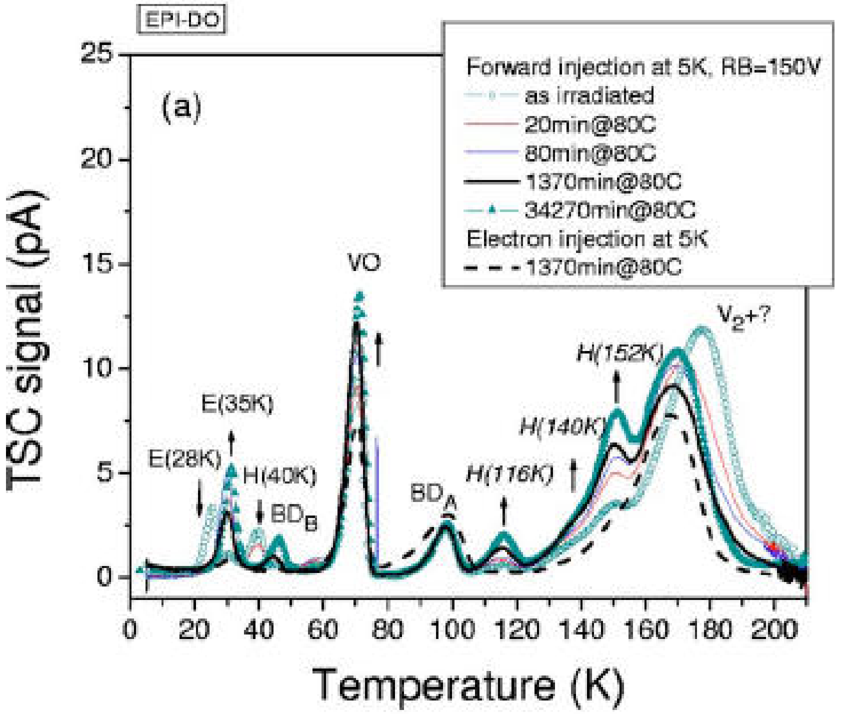
First observation by R.M. Fleming et al., APL 90 (2007) 172105

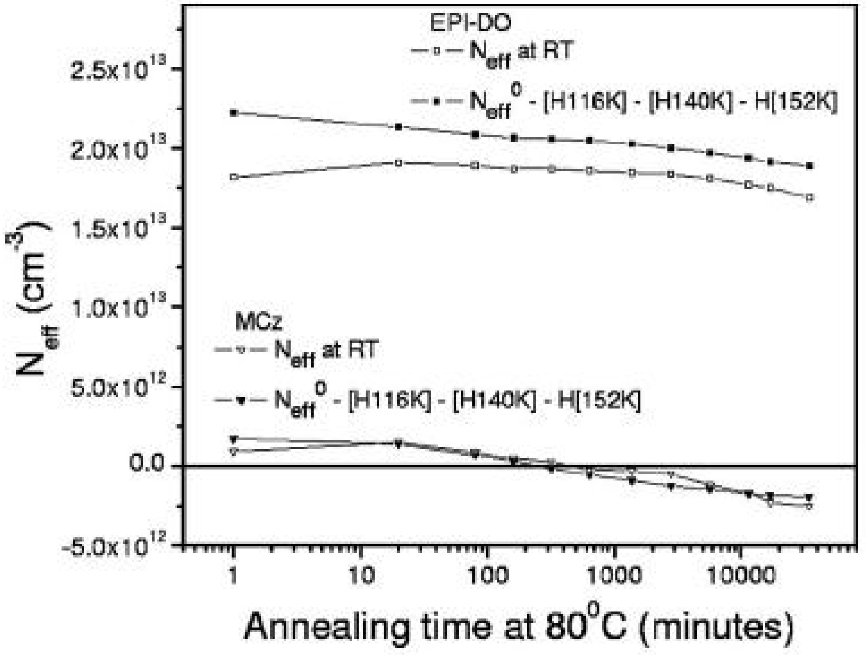
E4/E5 can be totally recovered by injection of 1 A forward current

8 *E. Fretwurst, University of Hamburg* *IEEE Conference Dresden 21. October 2008*

The issue of long term annealing: which traps ?

In 2008 the Hamburg group shows that hole traps *H*116 K, *H*140 K, and *H*152K (cluster related defects not present after γ-irradiation and observed in neutron irradiated *n*-type Si diodes during 80 °C annealing) are repsonsible of long term annealing





Hole traps concentration is in fact in agreement with Neff changes during 80 °C annealing.

I. Pintilie, E. Fretwurst, and G. Lindström, APL 92, 024101 2008

Summary from Hamburg group of defects with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
  $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm²

$E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3 \cdot 10^{-14}$ cm²
  - $\sigma p^{I} = 2.3 \cdot 10^{-14}$ cm²

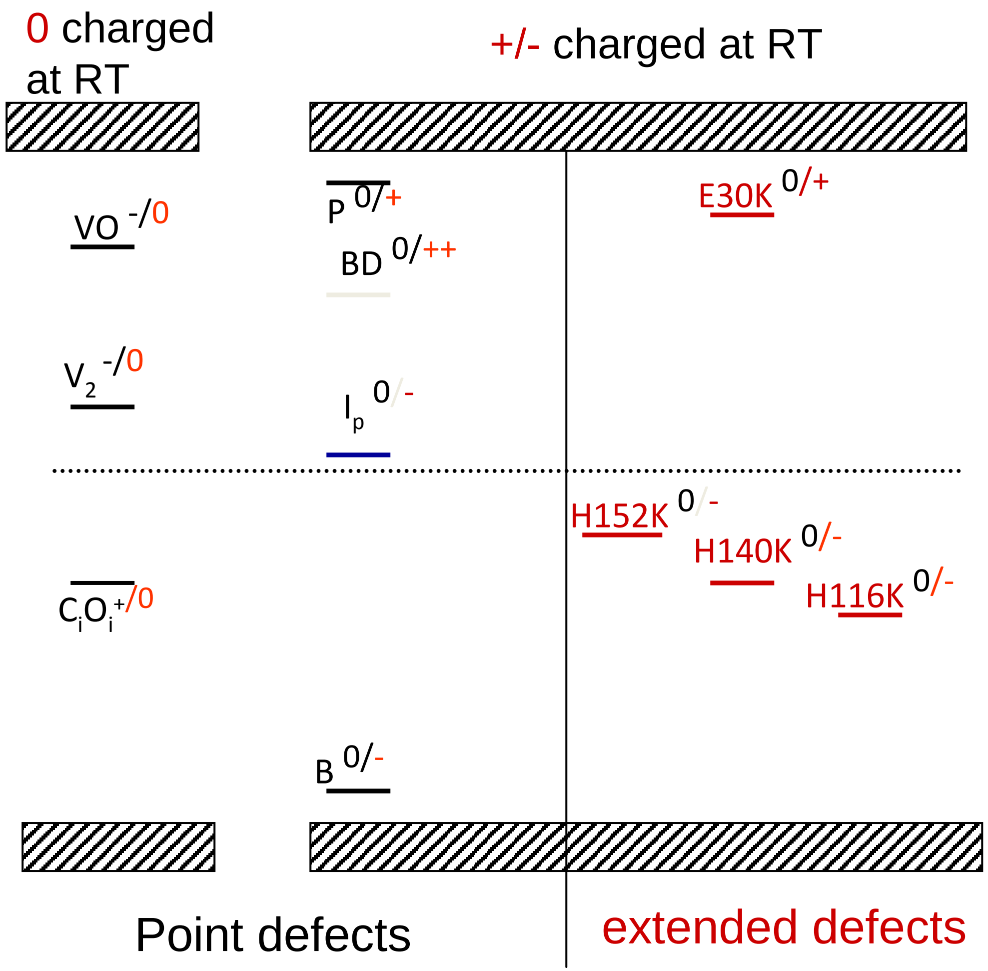
Cluster related centers

$E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm²



I.Pintilie, NSS, 21 October 2008, Dresden

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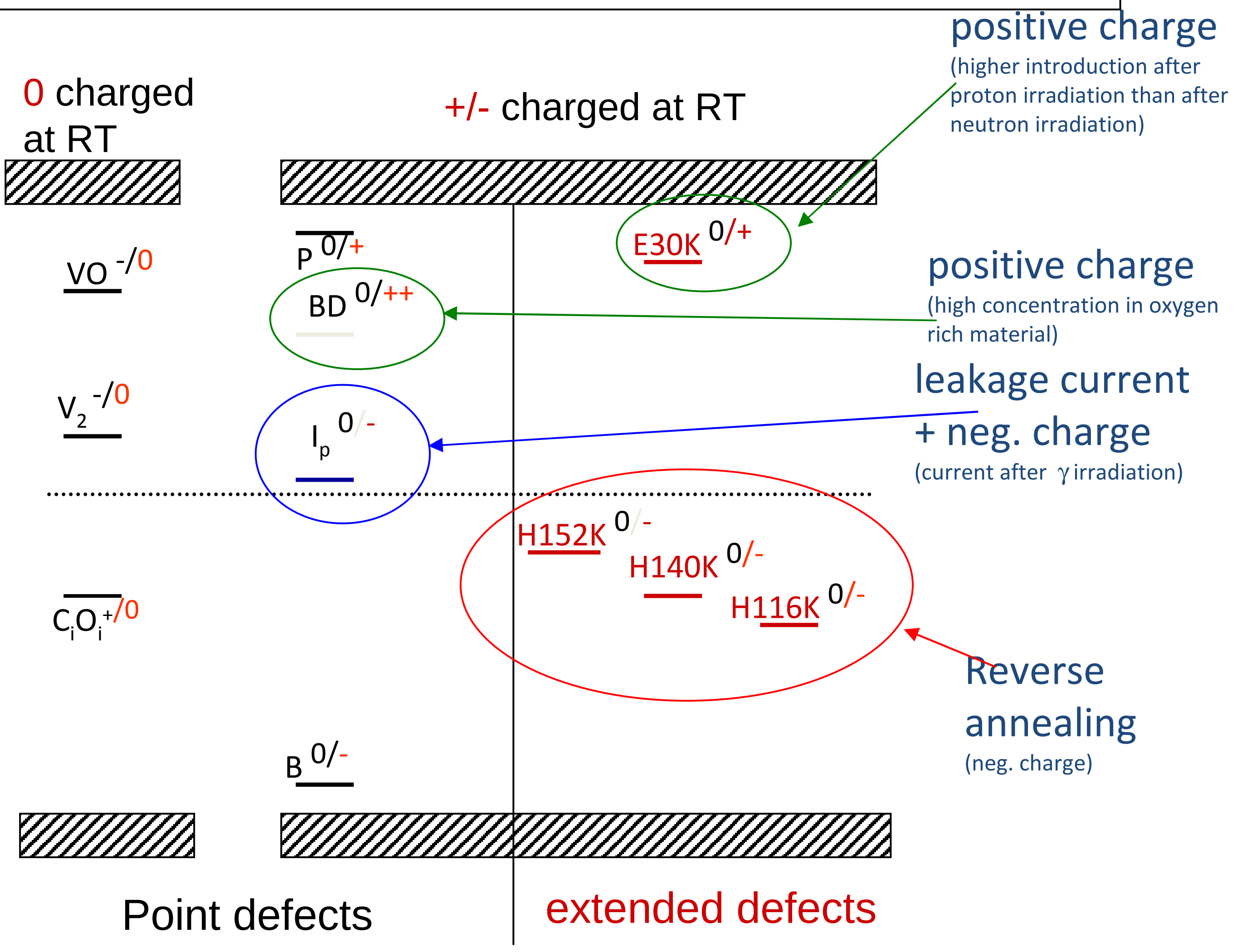


0 charged at RT

+/- charged at RT

$VO^{-/0}$

$V_2^{-/0}$

$C_iO_i^{+/0}$

$P^{0/+}$

$BD^{0/++}$

$I_p^{0/-}$

$B^{0/-}$

$E30K^{0/+}$

$H152K^{0/-}$

$H140K^{0/-}$

$H116K^{0/-}$

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

leakage current
+ neg. charge
(current after γ irradiation)

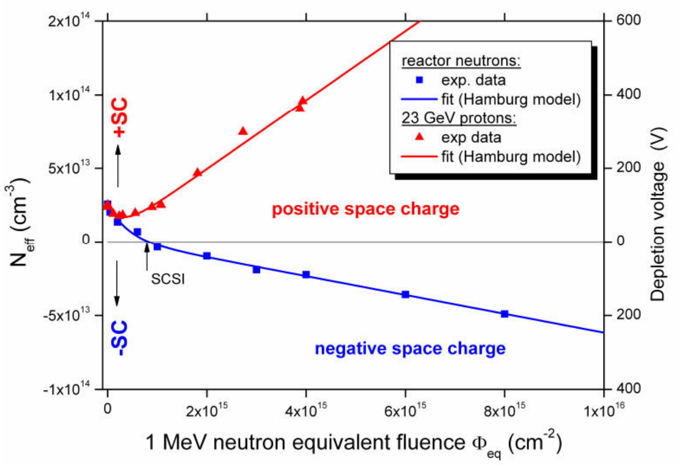
Reverse annealing
(neg. charge)

Point defects

extended defects

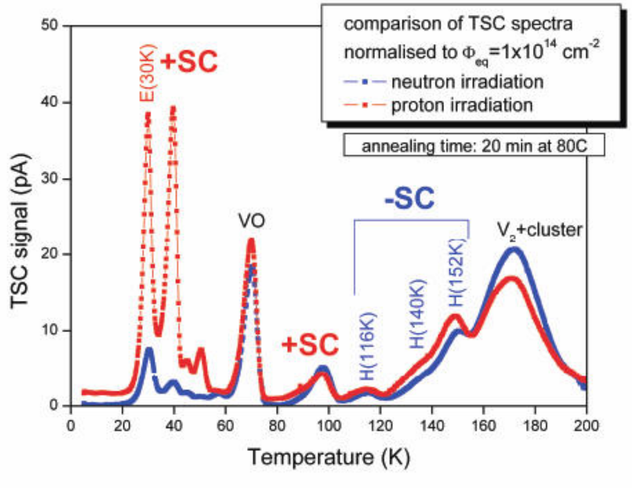
I.Pintilie, NSS, 21 October 2008, Dresden

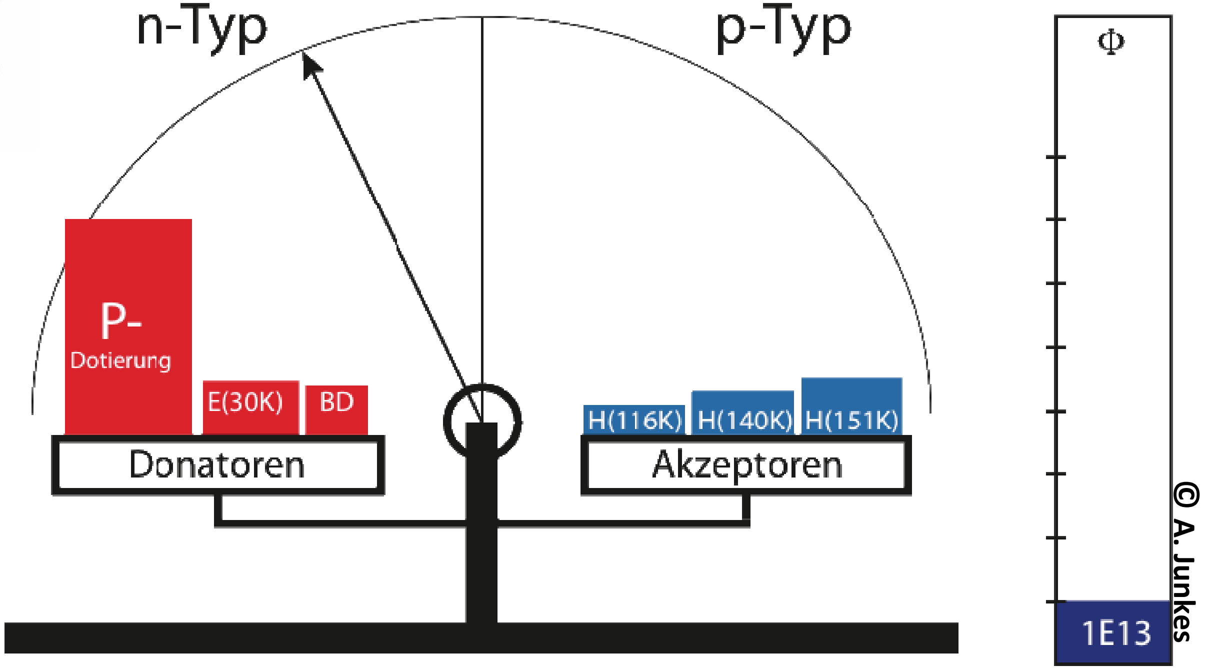
An example of application : N_{eff} changes in Epitaxial Si irradiated with neutrons



Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm***)

N_{eff}: Neutron irradiation





By A. Junkes, presented by U. Parzefal on behalf of the RD50 Collaboration, RESMDD10 , Oct. 2010, Florence

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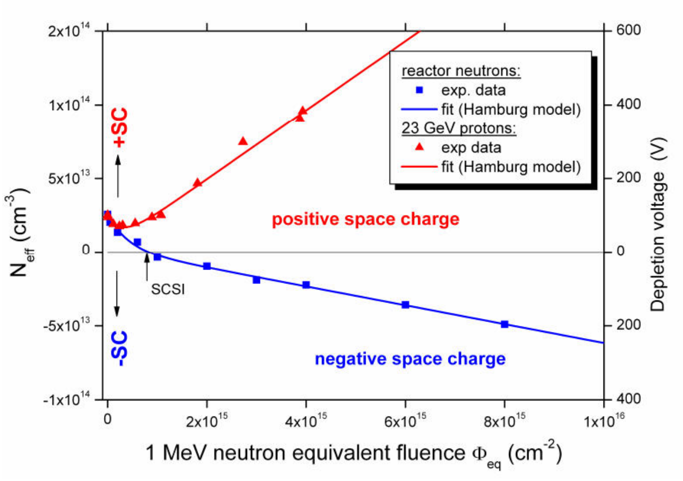

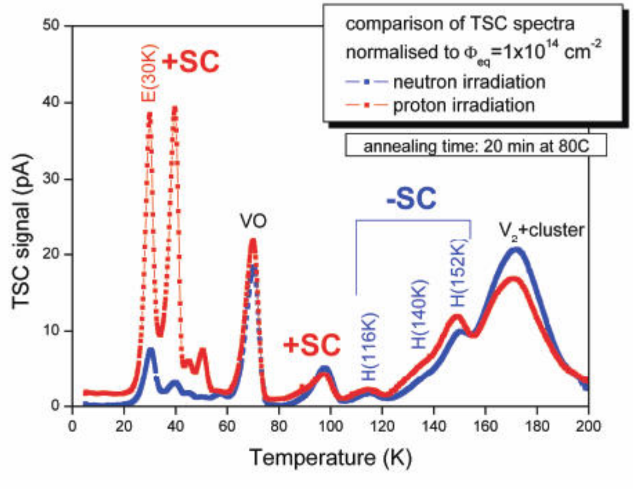

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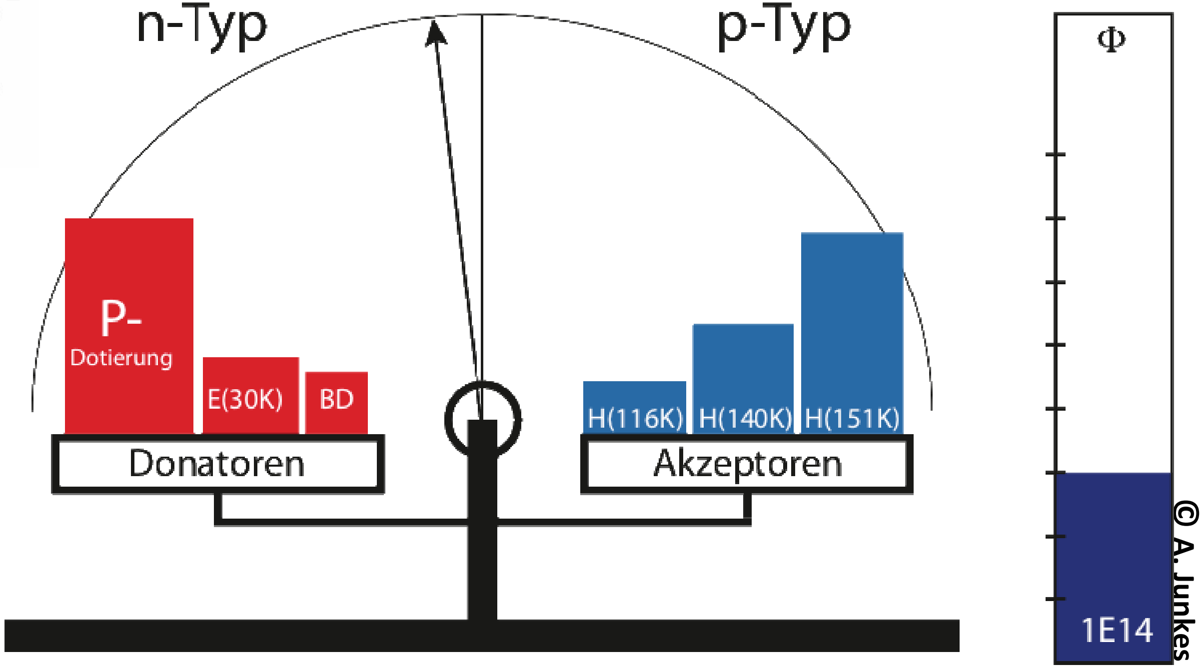

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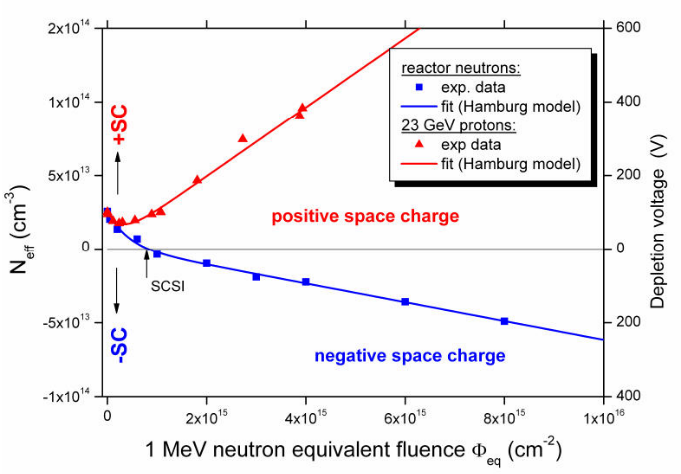

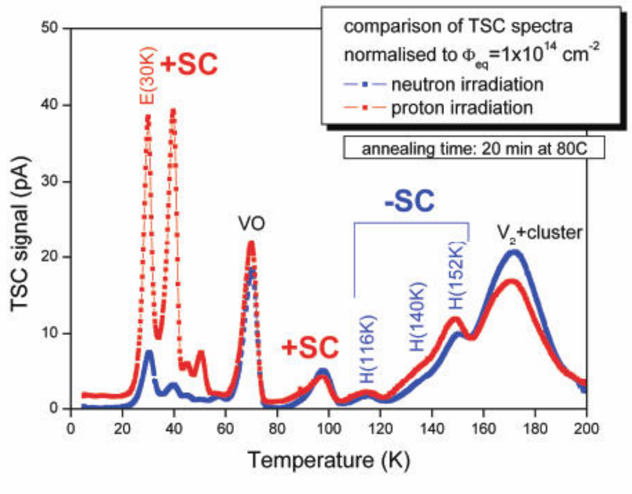

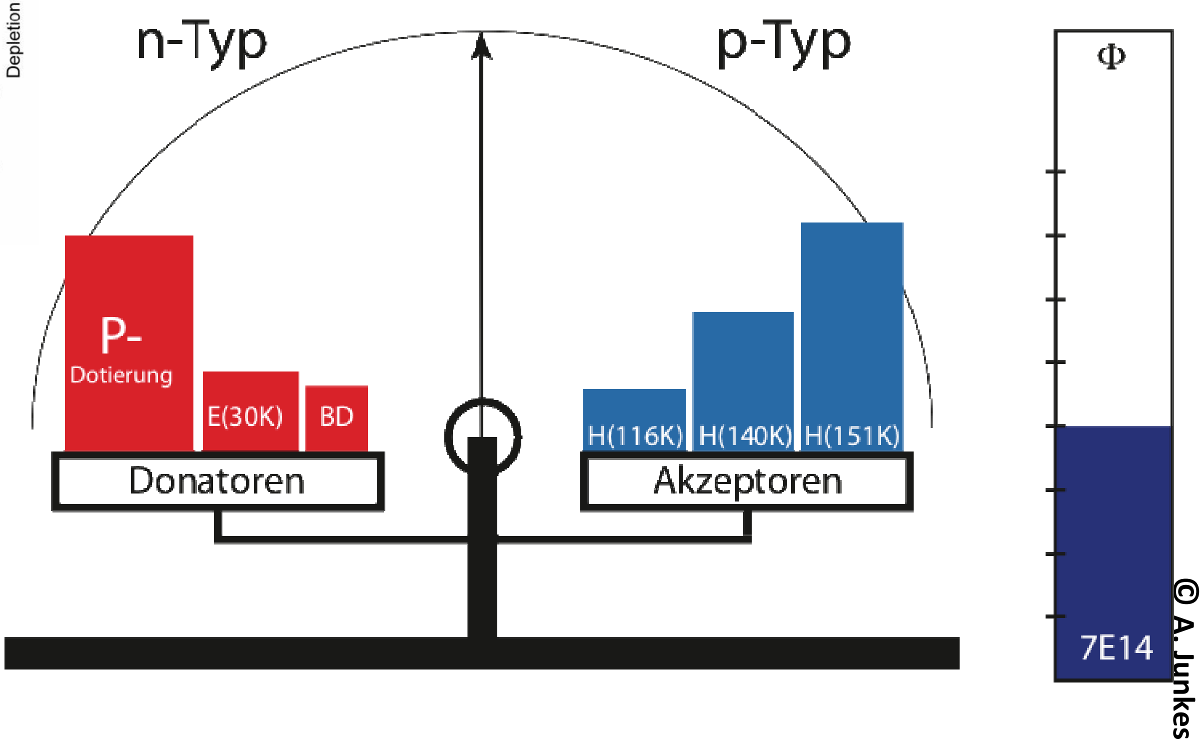

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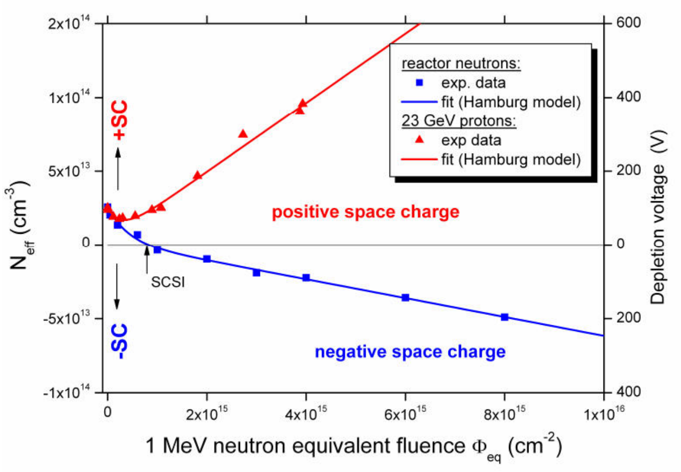
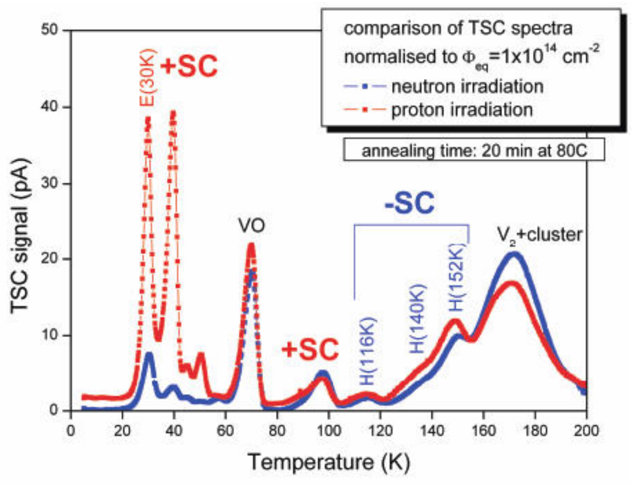
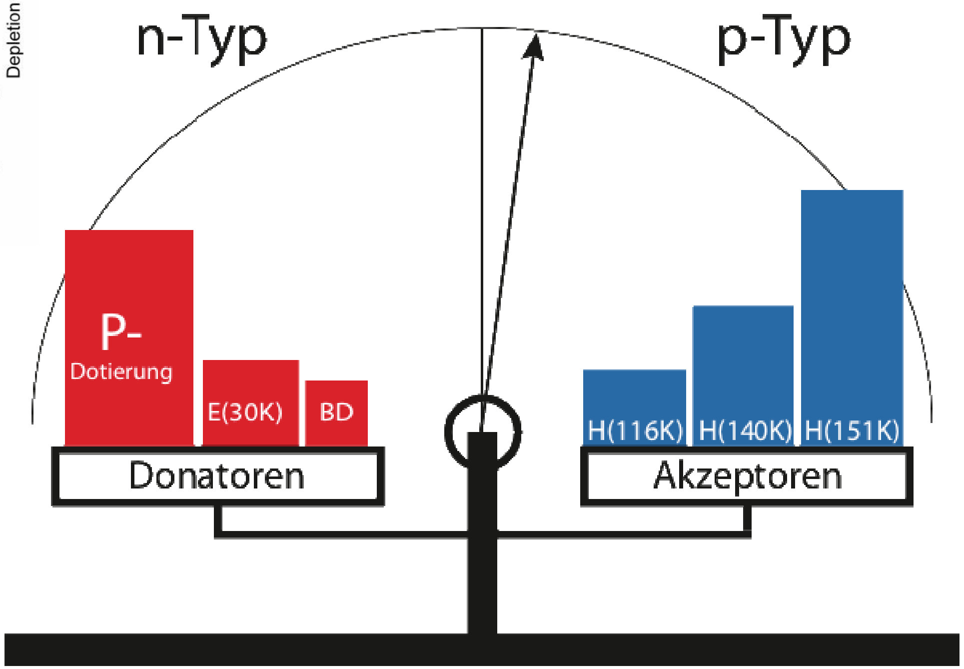
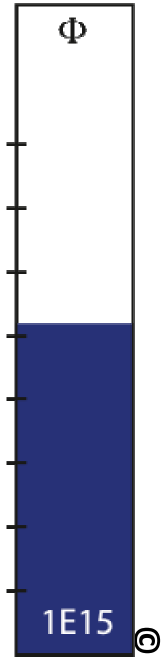




N_{eff}: Neutron irradiation





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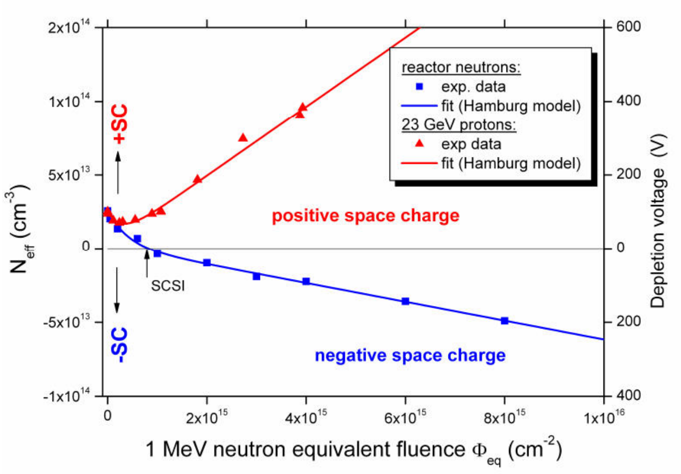

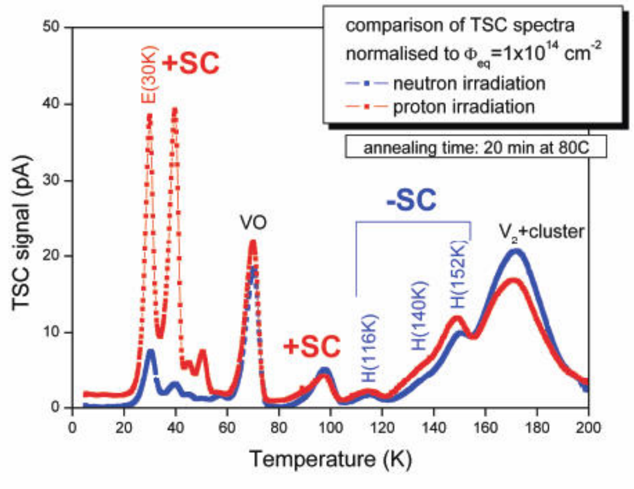

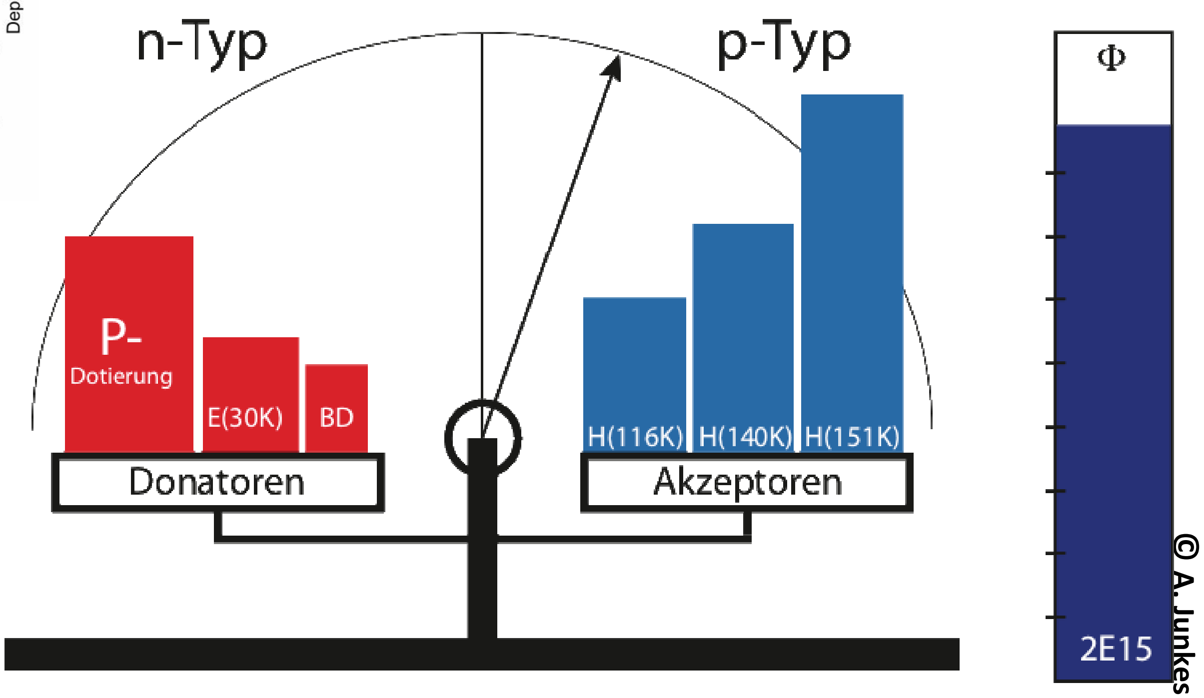

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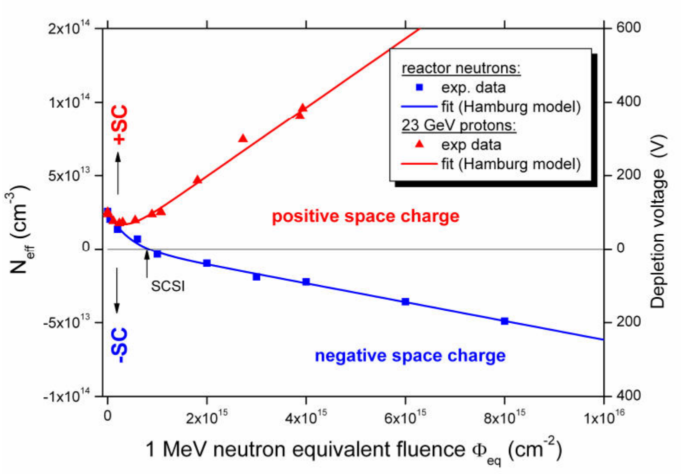

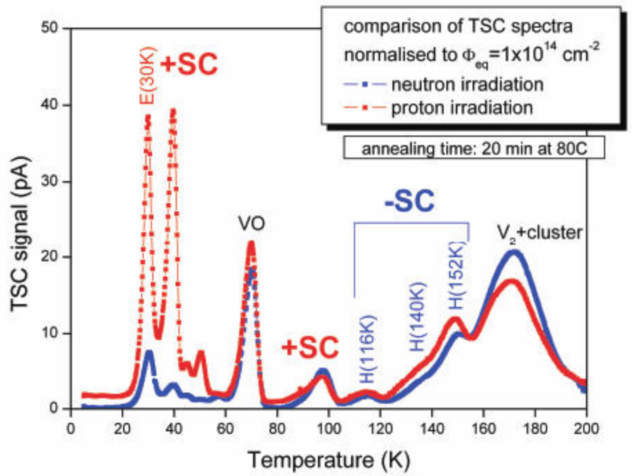

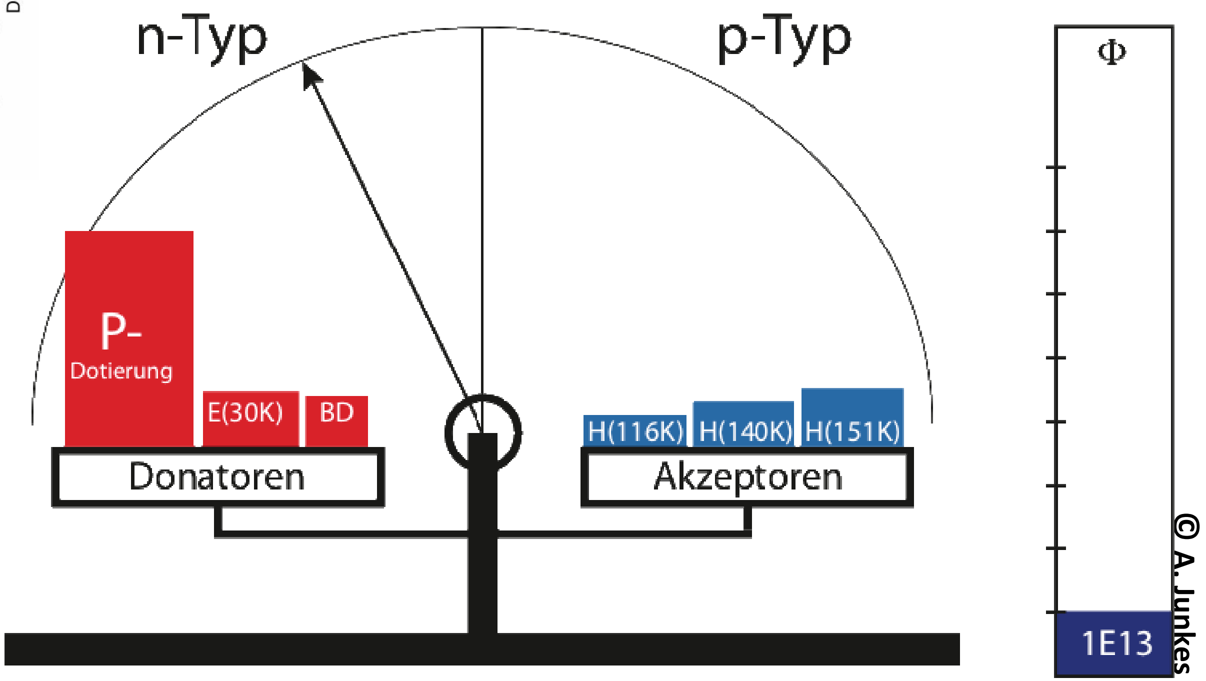

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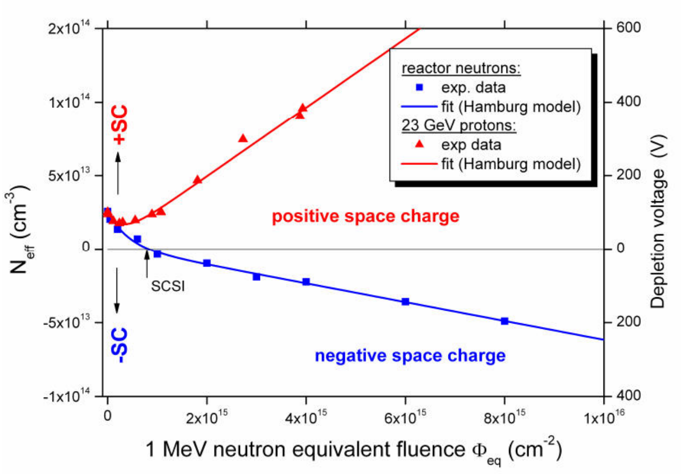
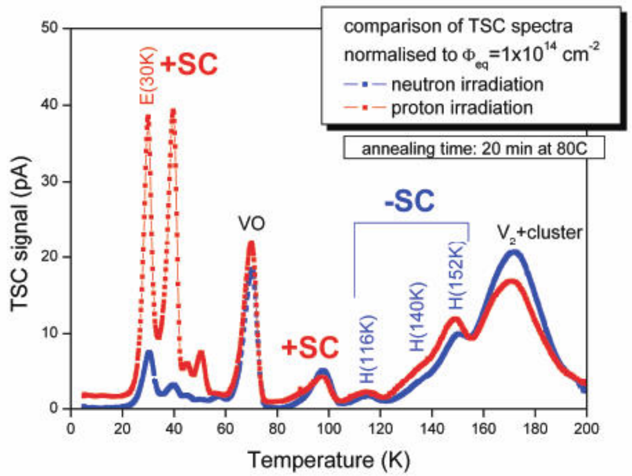
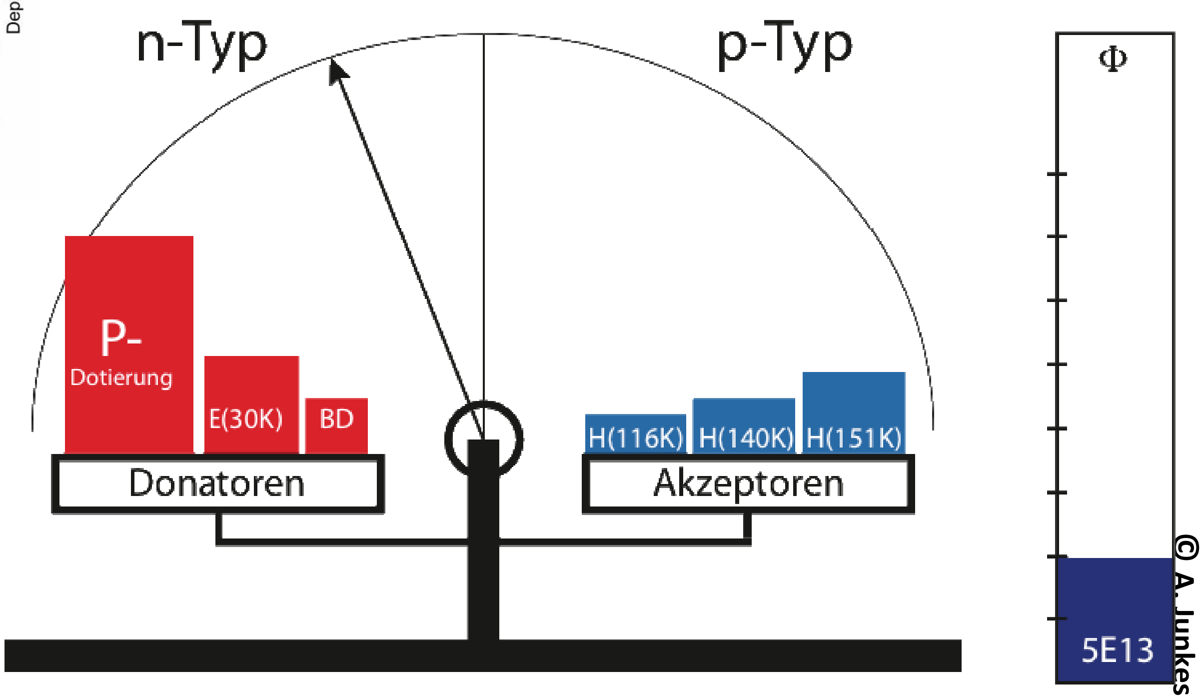


N_{eff}: proton irradiation





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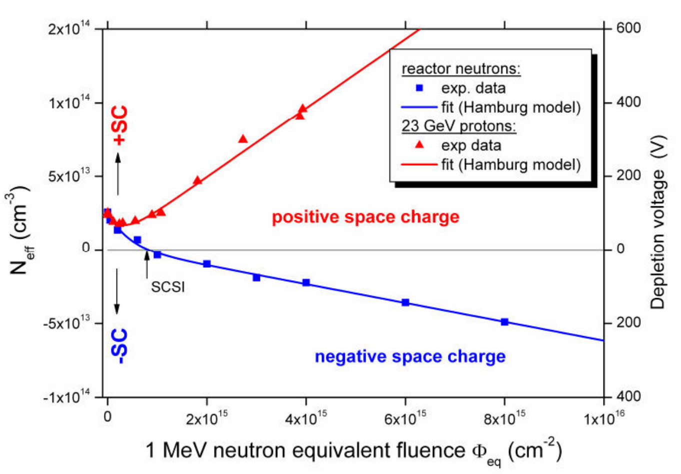

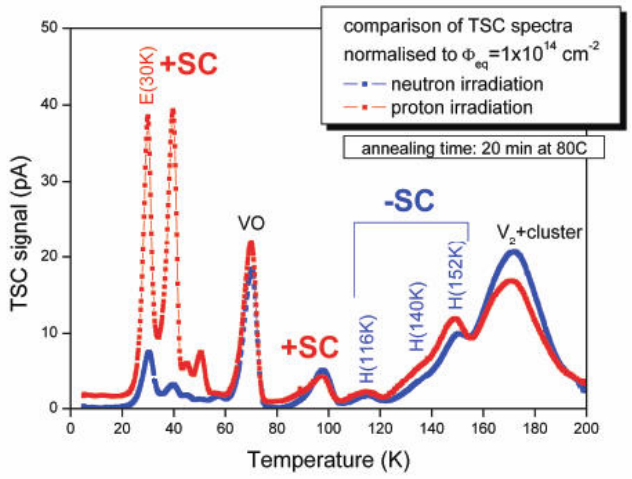

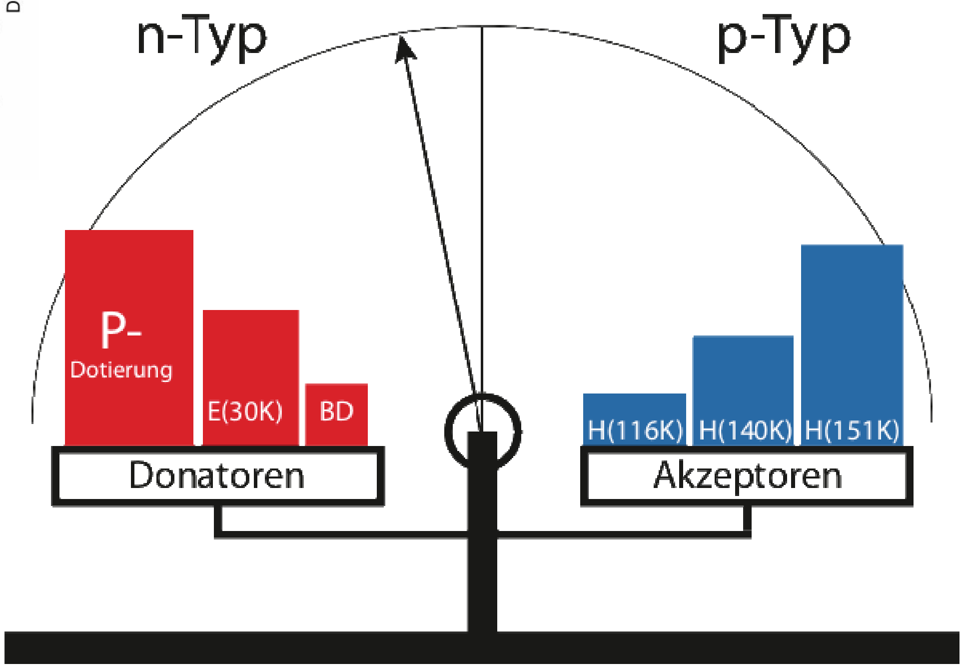

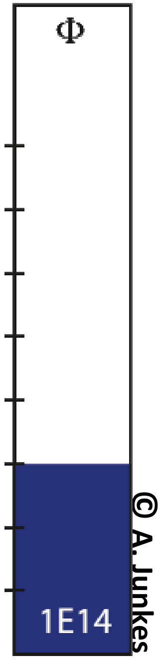

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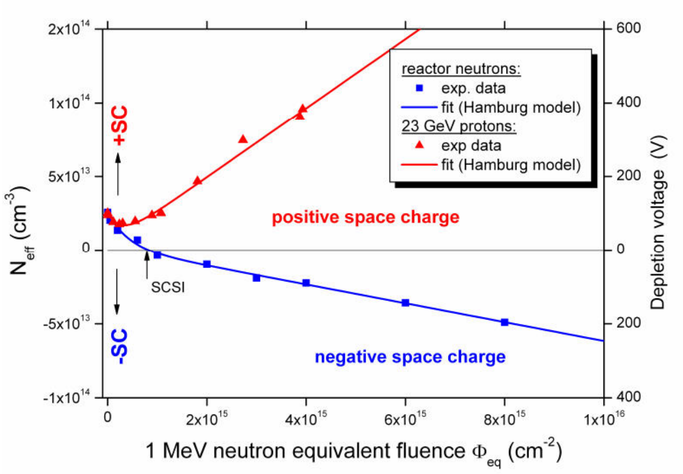

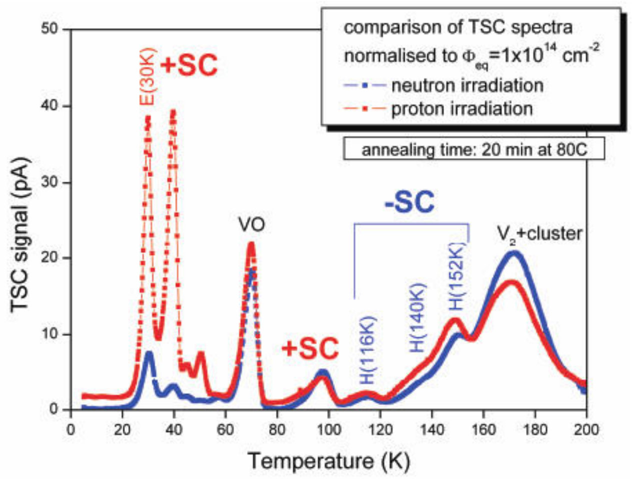

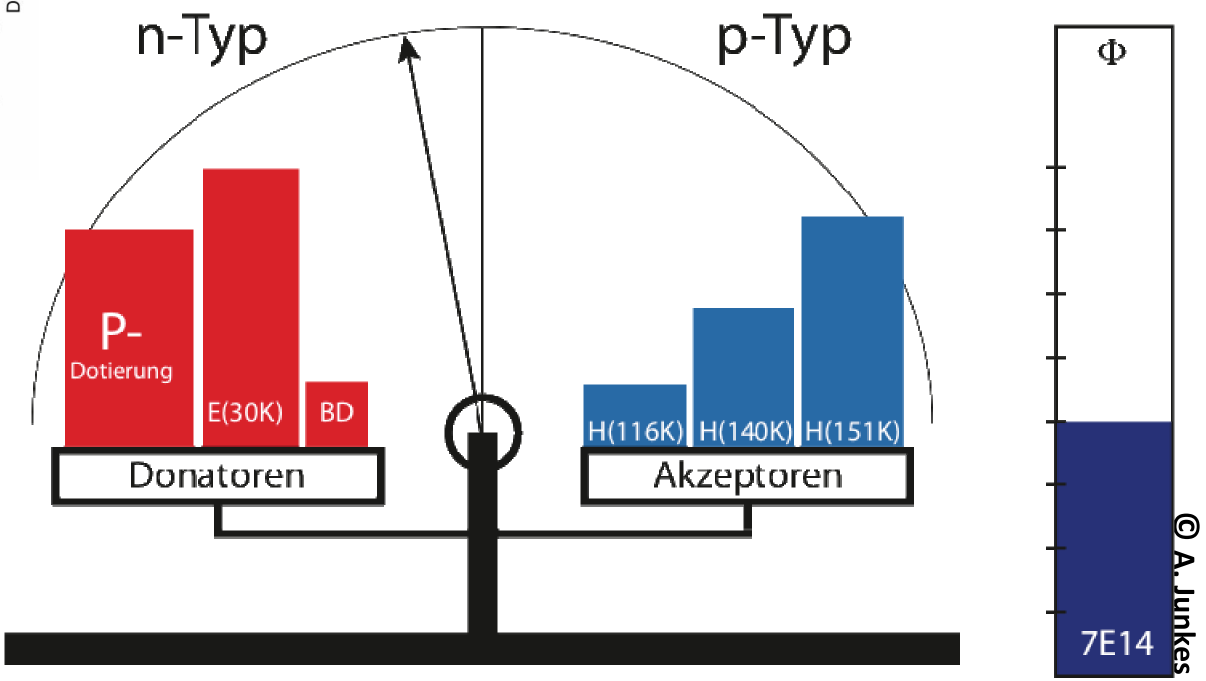

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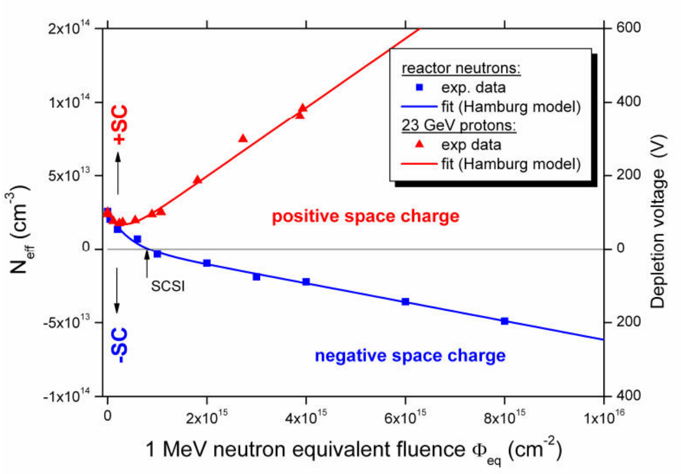

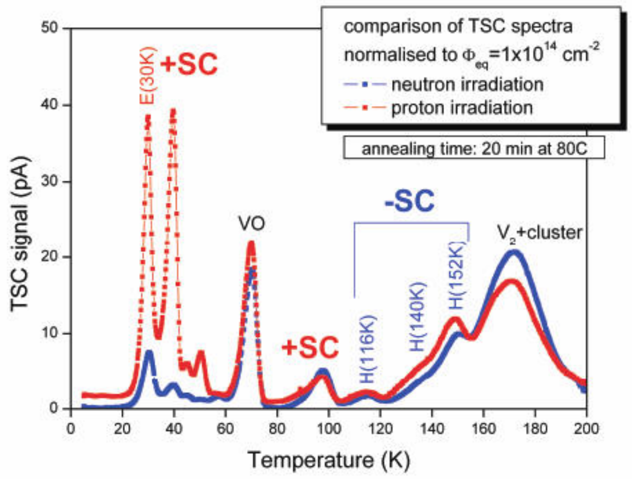

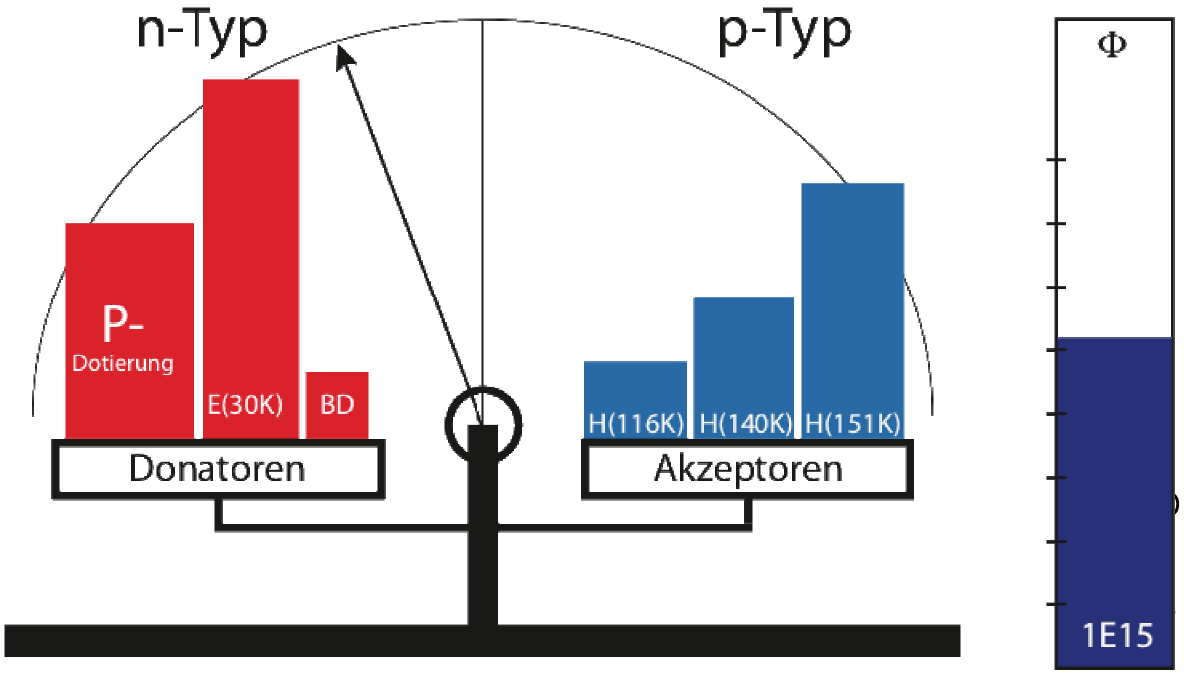

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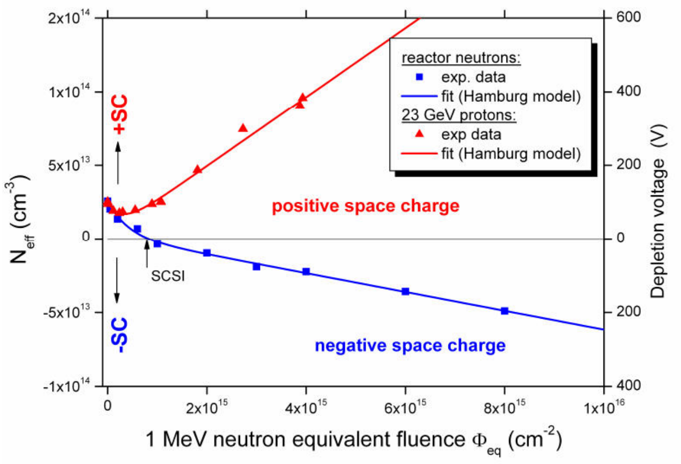

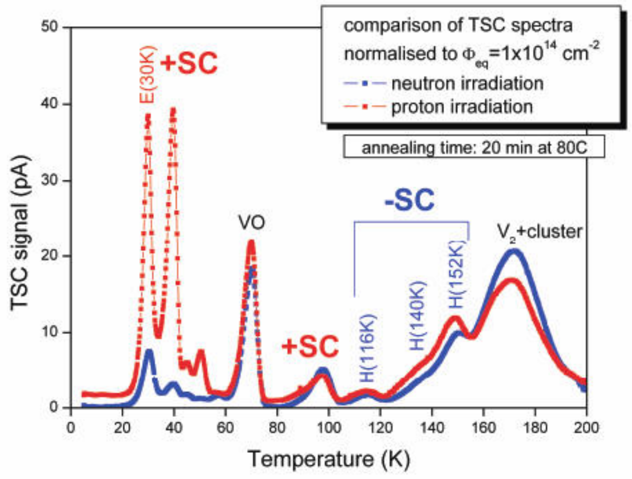

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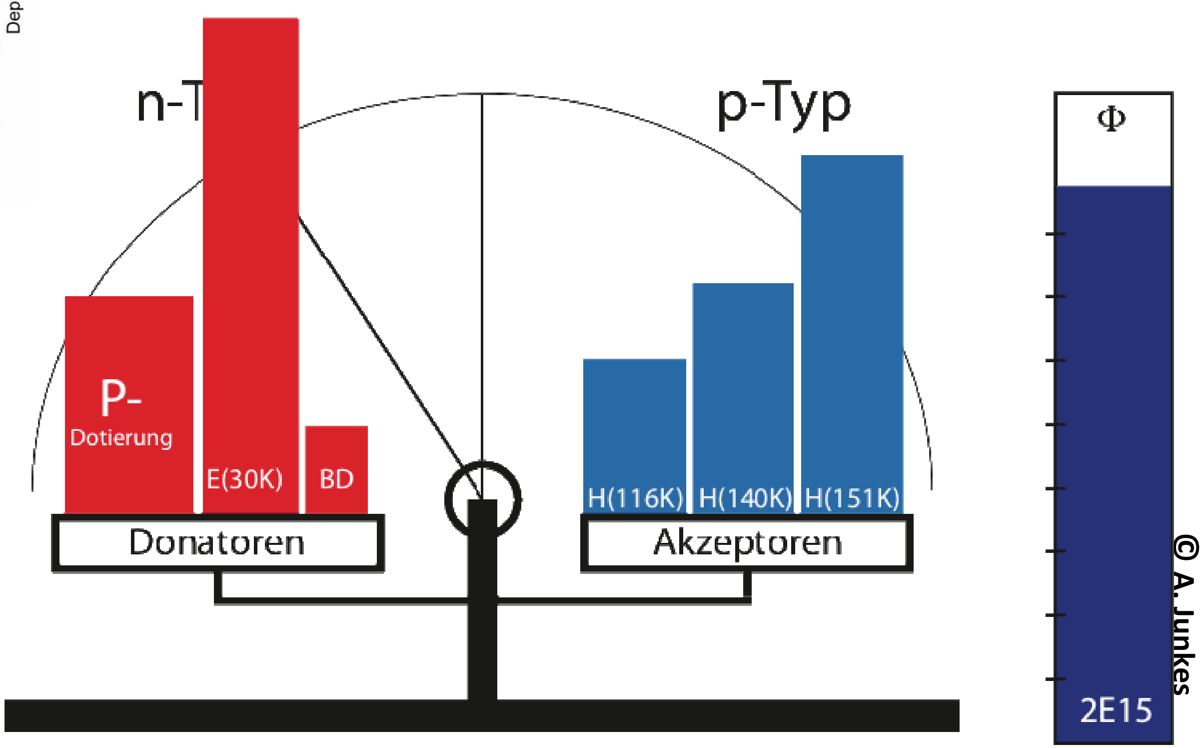

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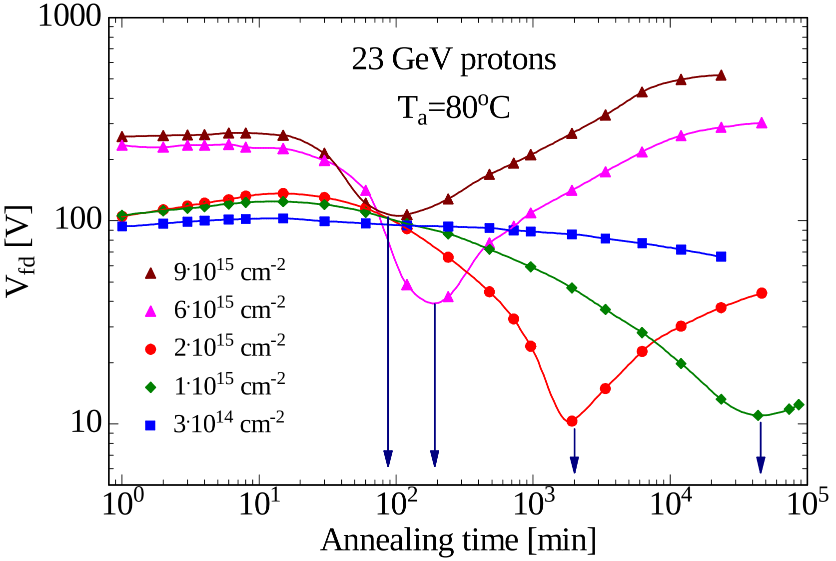
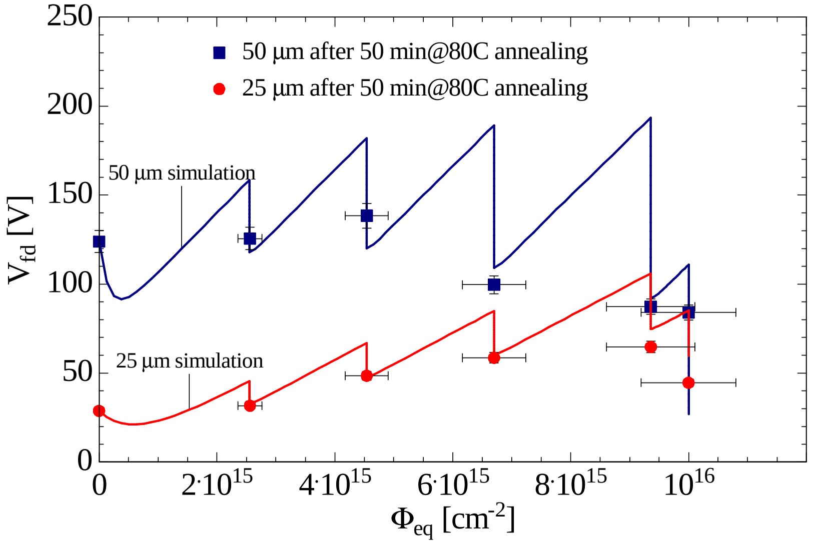
EPI Devices – No reverse Annealing





Typical annealing behavior of EPI-devices:

Inversion only(!) during annealing

(100 min @ 80C ≈ 500 days @ RT)

→EPI never inverted at RT (t < 500d), even for 10^{16}

→Parameters extracted at elevated annealing fit measurements at room temperatures very well

→Very good reproducibility and working model

(BA, constant damage, 1st order RA, 2nd order RA)

S-LHC: L=10^{35}cm^{-2}s^{-1}

Most inner pixel layer

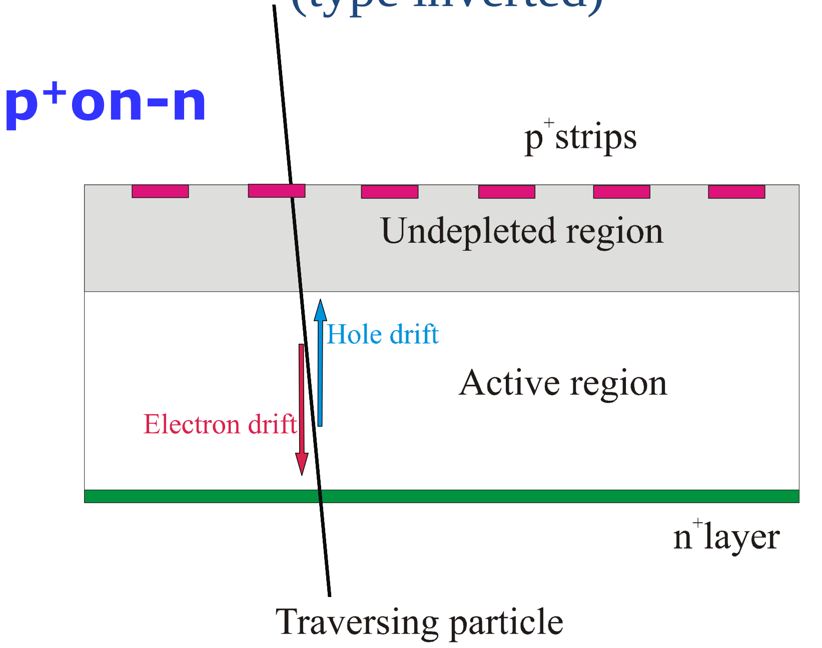
operational period per year:

100 d, -7°C, Φ = $3.48{\cdot}10^{15}$cm^{-2}

beam off period per year 265 d, +20°C

Highest Fluence Range:
Lets move to p-type !

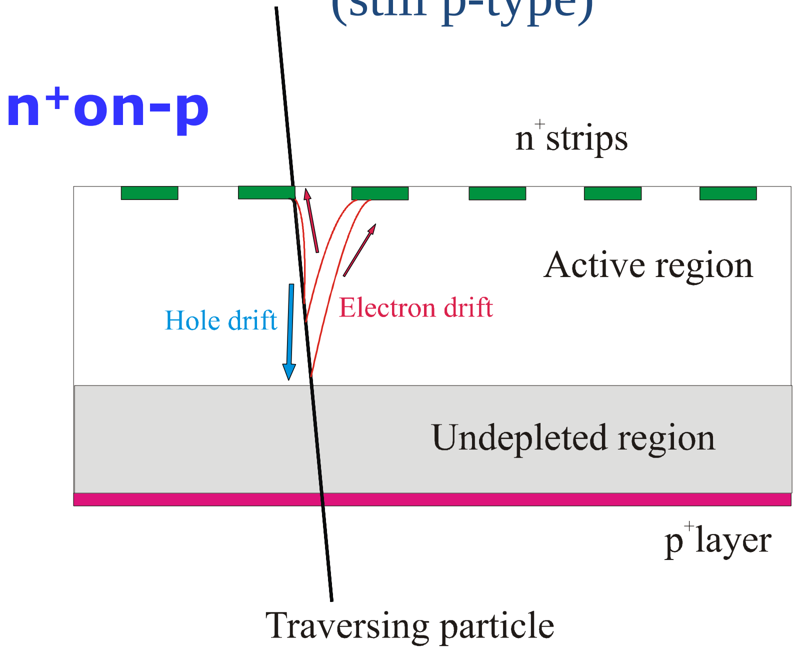
n-type silicon after high fluences:
(type inverted)



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

p-type silicon after high fluences:
(still p-type)



n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**
- **Favourable Annealing of trapping times**

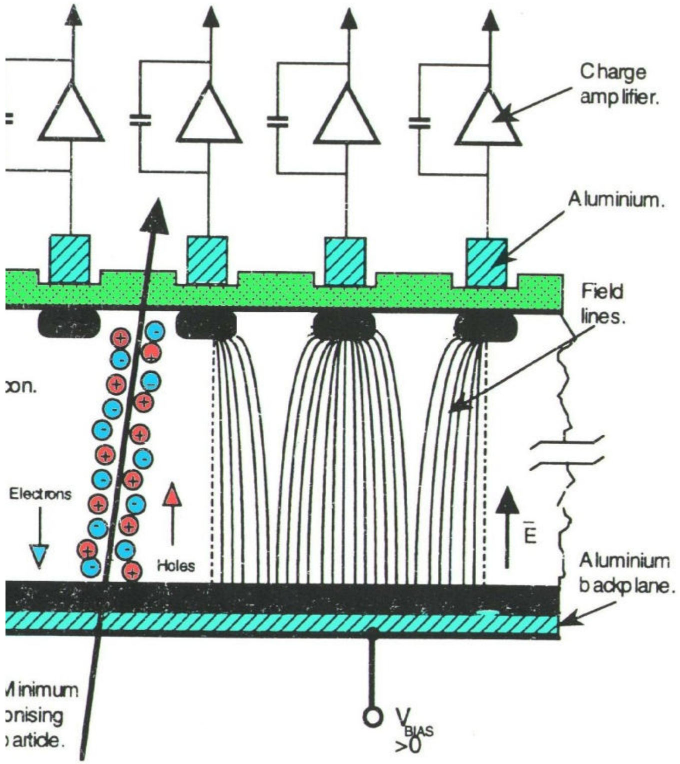
New Outcomes:
Charge Multiplication by impact ionization
Suppression of reverse Annealing

Charge Multiplication by impact ionization

Charge collected at electrodes in a semiconductor can not only be generated by ionising radiation but also by the acceleration of charge carriers by high electric fields, a phenomenon called impact ionization.

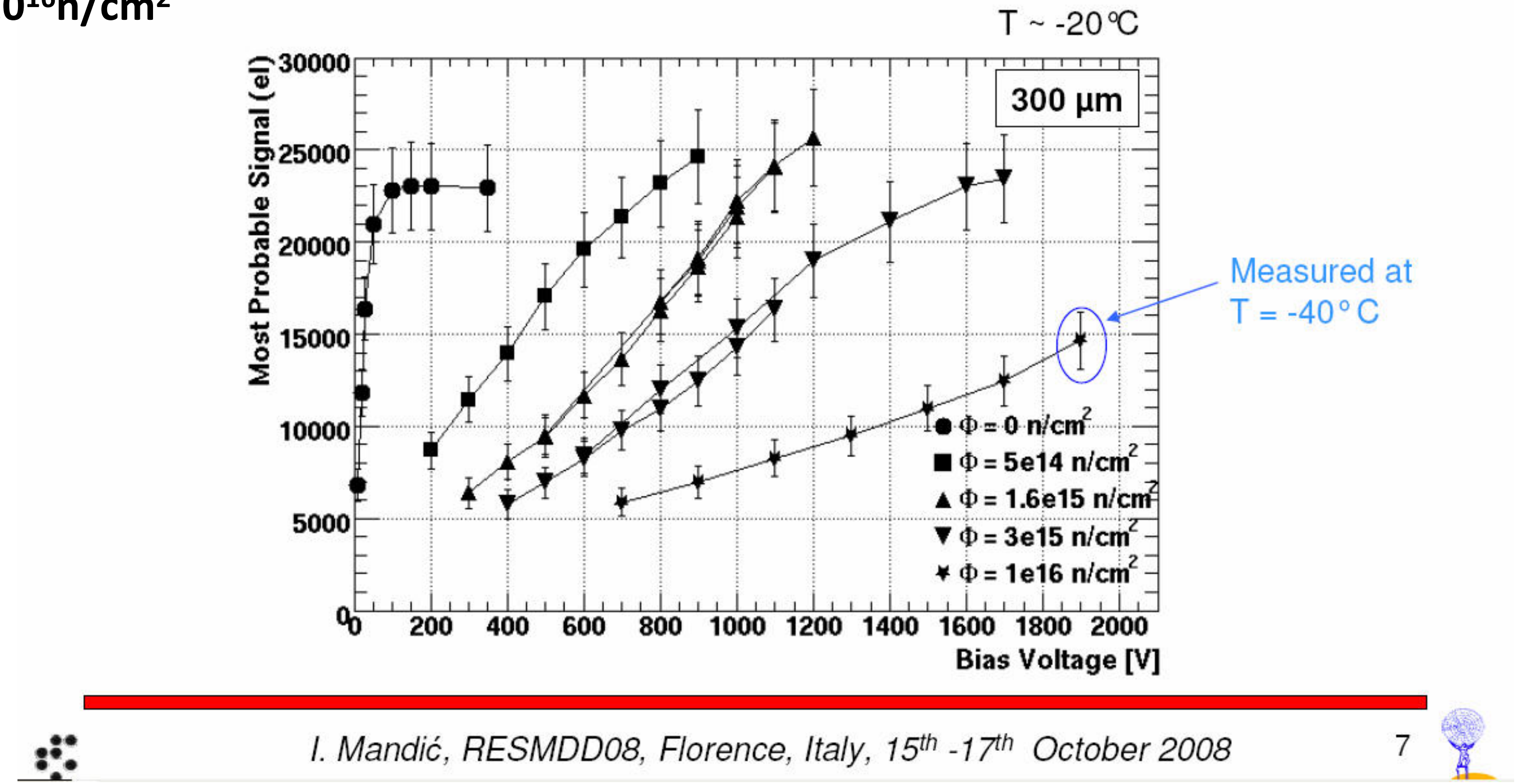
This way electrons and holes promoted in conduction/valence bands by ionising radiation (primary charge) attain enough energy to create new electron-hole pairs (secondary charge). This mechanism is also origin of current breakdown in diodes when very high reverse voltage are applied.

In a segmented device electric field is increased in the nearby of the collecting electrode due to accumulation of field lines. In irradiated devices the electric field is also enhanced by radiation induced defects.



Charge Multiplication

CCE measured with p-type Si microstrip detectors at very high fluences shows <u>evidence of a charge multiplication effect</u>: 100% CCE seen after 3x10^{15} n/cm^2, 15000 electrons after 10^{16}n/cm^2



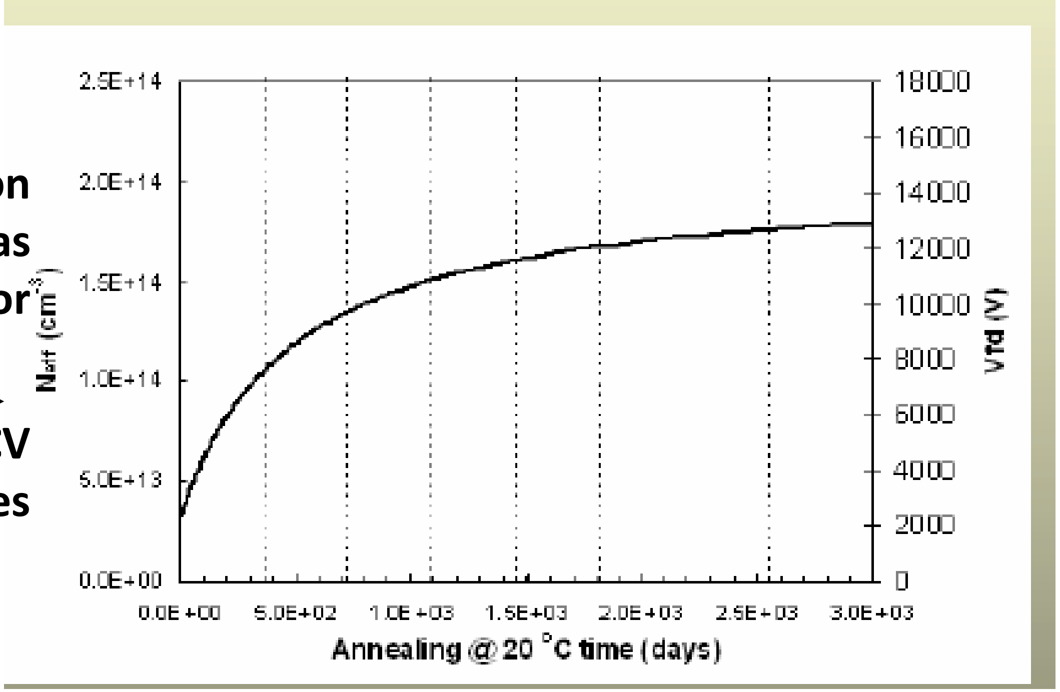
Increase of the electric field close to the strips causing impact ionization/carrier injection when high concentrations of effective acceptors are introduced at very high fluences.

Annealing of irradiated microstrip detectors

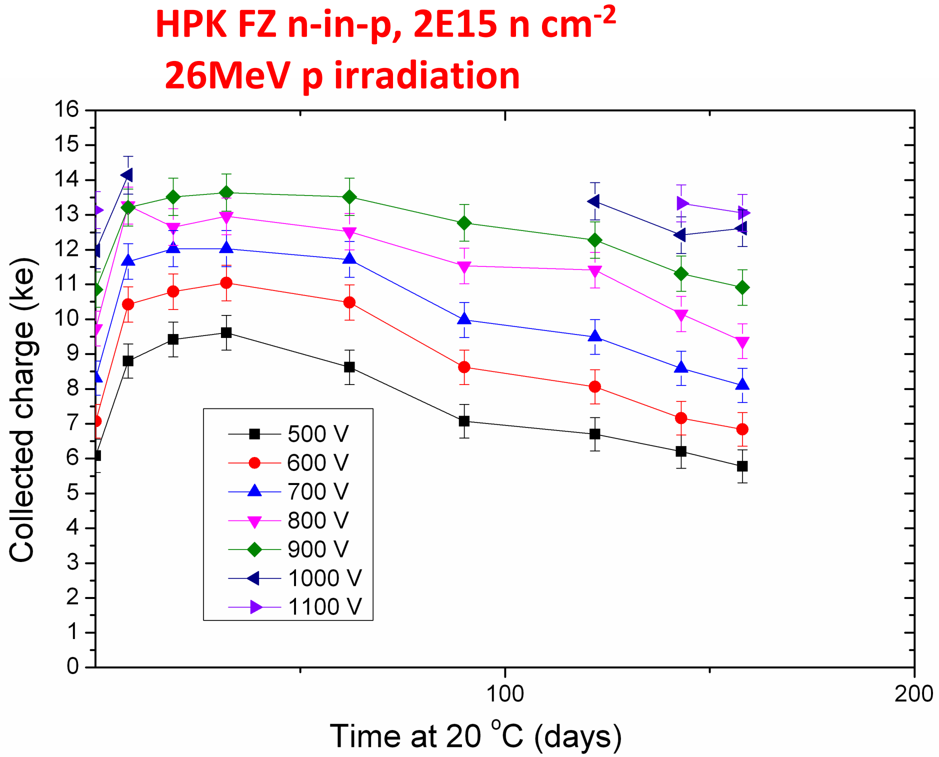
Reverse annealing in irradiated Si microstrip detectors has been always considered as a possible cause of early failure in the experiments if not controlled by mean of low temperature (not only during operations but also during maintenance/shut down periods). This was originated by accurate measurements of the annealing behavior of the full depletion voltage in diodes measured with the CV method.

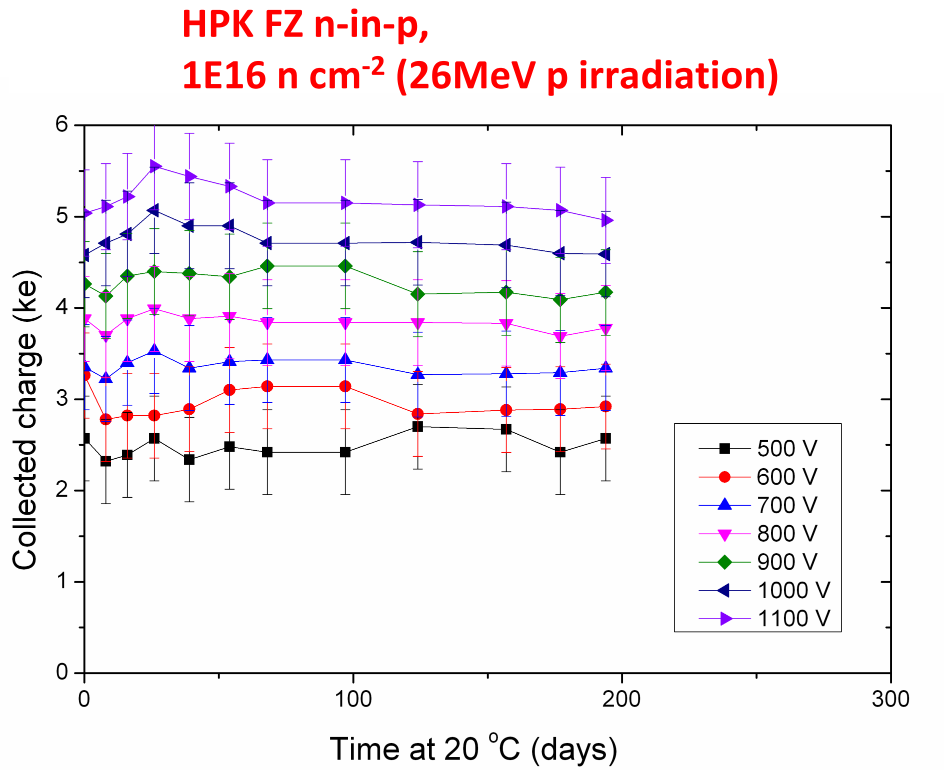
Expected changes of full depletion voltage with time after irradiation (as measured with the C-V method) for detector irradiated to 7.5 10^{15} p cm^{-2}.

Please notice that according to CV measurements the so called V_{FD} changes from <3kV to >12kV!



As a matter of fact, the annealing behaviour of the CCE measured with p-type Si microstrip detectors does not correspond to that measured by CV with diodes. No reverse annealing is visible in the CCE measurement.

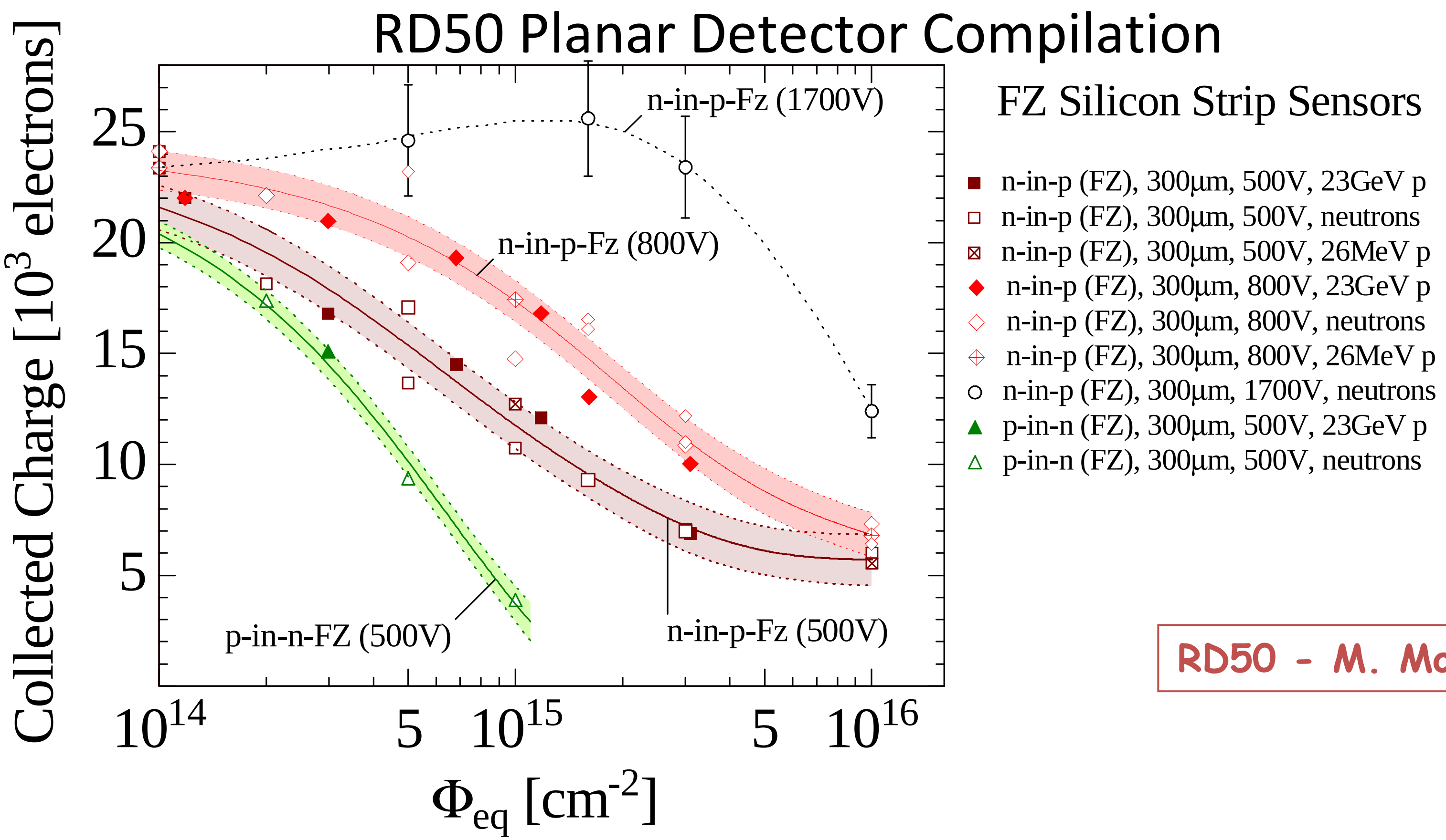

HPK FZ n-in-p, 2E15 n cm^{-2}
26MeV p irradiation


HPK FZ n-in-p,
1E16 n cm^{-2} (26MeV p irradiation)

Origin of observed behaviour :

-Charge Multiplication due to increased electric field close to strips as concentration of acceptors grows with time/temperature;

-Reduction of the effective trapping probability of electrons with annealing.

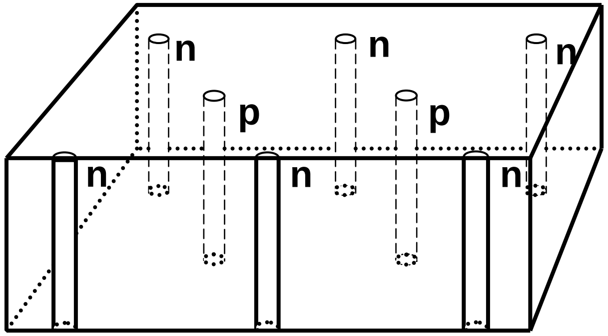


RD50 - M. Moll

- p-in-n fades away well before $10^{15}N_{eq}$
- n-in-p still gets 50% charge at $10^{16}N_{eq}$ at high bias voltages
- n-in-p benefits from charge multiplication (at high bias voltages)
- CM effect also seen for p-in-n (but less strong in partial depletion mode)
- n-in-p (n-in-n) superior material for high radiation environments

Just mentioned: 3D detectors

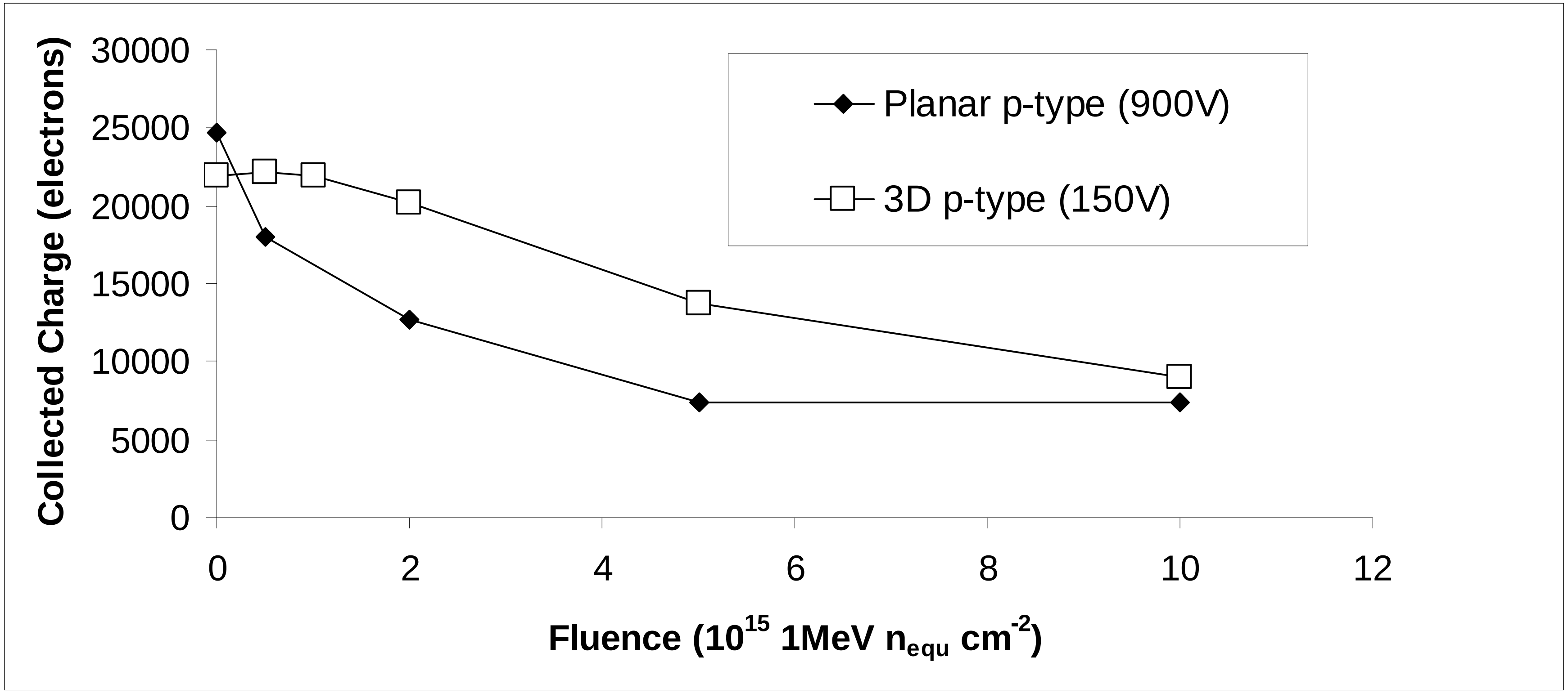
- Electrodes:
  - **narrow columns along detector thickness-"3D"**
  - **diameter:** 10μm **distance:** 50 - 100μm
- Lateral depletion:
  - **lower depletion voltage needed**
  - **thicker detectors possible**
  - **fast signal**
- Hole processing :
  - **Dry etching, Laser drilling, Photo Electro Chemical**



(Introduced by S.I. Parker et al., NIMA 395 (1997) 328)

3D vs planar detectors

Collected charge as a function of fluence. Note 3D only 150V, high bias gets increase in charge due to multiplication



Future Perspectives ….

Electron irradiation for investigating point defects against cluster concentrations at different energies – pad detectors

Study of microstrip detectors efficiency - ALIBAVA system

Investigation of plasma effects in silicon sensors for the European XFEL - Multi Channel TCT as advanced measurement setup to study segmented sensors

…..

This talk tried to give a perspective overview on the issue of radiation damage on silicon detectors for HEP, high-lighting the contributions of Gunnar Lindström and his group on this subject for the last twenty years. Indeed, the Hamburg group gave from early 90s many significant contributions to several fundamental aspects of the research on the issue of radiation damage of silicon detectors: macroscopic damage evaluation and modeling, radiation hardening technologies, radiation-induced defect understanding. Research activity of the group is still on going ...

No Conclusions but …

Happy Birthday Herr Professor !