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SILICON DETECTORS FOR HEP EXPERIMENTS.
- RADIATION HARDNESS -

Gunnar Lindstroem
University of Hamburg
I-st Inst. of Exp.Physics,Nuclear Metrology

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ABSTRACT

We present the transparencies of the seminar held by Professor Gunnar Lindstroem about radiation hardness of silicon detectors used in HEP-experiments. The material contains a presentation of the Hamburg University Group, the research subjects and their interest for the HEP community in view of the future experiments at LHC and HERA B. The behaviour of silicon detectors has been investigated starting with macroscopic measurements(C/V,I/V,Q/V) for detectors irradiated with protons,neutrons and pions at high fluences(10^14 part/cm2) as well as the influence of temperature, starting properties of the wafer, annealing time.
Microscopic studies(PIXE,TCT,DLTS,TSC)have been performed in order to characterise the defects.Surface damage due to high doses in electron and gamma fields are also discussed.Conclusions about the manufacturing and opperating silicon detectors in high radiation fields for a long period are of great interest for high energy physicists.

Dr. Gunnar Lindstroem, professor at Hamburg University and chief of the Nuclear Metrology Group of the First Institute of Experimental Physics in Hamburg is well known for his contributions in the field of radiation damage, hardness and hardening of the silicon detectors. During the last ten years his group has investigated systematically macroscopic and microscopic effects of neutrons, protons and pions on silicon detectors used in experiments at high energies and high fluences. Their results will be the basis of designing and operating the detectors in the experiments H1 at HERA and ATLAS at LHC.

Professor Gunnar Lindstroem is involved in the organisation of an R&D collaboration at CERN with the goal of unifying the efforts of all groups interested in LHC experiments in the study of the hardening problems of silicon detectors to be used in the future experiments.

Last time this problem has been investigated also by a group of physicists from Bucharest University, the Institute for Atomic Phisics and the Institute of Microtechnology. The activity of this group roused the interest of Dr.Gunnar Lindstroem and he accepted our invitation to spend some days in Bucharest and meet all the people interested in radiation hardness studies.

On this occasion he presented in a seminar held at the Physics Faculty on 7 th of june 1995, the contribution of his group to the radiation hardness subject. The many discussions which followed his presentation revealed the interest of our phyisicists in this field and some possibilities of participating in the next R&D collaboration. Therefore, we found useful to multiply the transparencies Dr. Lindstrom used during the seminar.

By the systematic presentation and the multiple notes included, the transparences can be used as a reference material. They do not need a final editing and the references indicated complete the less explicit parts.

Reading these transparences our collegues and students can benefit form the comprehensive presentation of the silicon detector hardness realm.

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Bucharest
7-June-95

Silicon Detectors for HEP-Experiments
– Radiation Hardness –

G. Lindström
University of Hamburg
I^st Inst. of Exp. Physics
Nuclear Metrology

- The Nuclear Metrology Group - fields of activities
- Applications in H1/HERA & ATLAS/LHC
- Si-Radiation Hardness – "Macroscopic" Measurem.
  C/V (ΔN_{eff}); I/V (α); Q/V (trapping)
  modeling; dependence on material, particle type, energy
- Operational Projections for the ATLAS-SCT (tracker)
- Si-Radiation Hardness – "Microscopic" Measurem.
  DLTS, TSC, TCT, μ-beam
  defect characterization & generation rates
  physical understanding of deterioration effects
  (→ defect engineering, hardening of initial mat.)
- Conclusions

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- The Nuclear Metrology Group at Hamburg University
  – fields of activities –

– Staff members: (8 + 1 NN)

G. Lindström[1,2]; E. Fretwurst[1,2]; C. Nickel (techn.)[1,2]; W. Hildescheim (postdoc/DESY)[2]; U. Pein (engin)[1,2]; V. Riedel[2]; M. Seidel (postdoc)[2]; S. Yousbadri (secr.)[1,2]

– PhD-students (normally 3 years) (presently): (4)
H. Feick[1]; M. Moll[1]; E. Panaro (DESY)[2]; T. Schulz[1]

– Diploma-students (< 1.5 years) (presently): (10-12)
M. Buck[2]; C. Dehn[1]; J. Gerhard[1]; M. Henkel[1]; P. Heydarpoor[1]; H. Jarck[2]; M. Krüger[2]; C. Osius[1]; P. Schlichtkörle[1]; C. Schütze[1]; Th. Ulrichmann[1]

– Fields of Activity:
Silicon Process Technology (H1-PLUG & dam. studies)
New developments, mainly Rad. Hardness[1]
operation of Si-instrumented PLUG-calorim. in H1[2]

– Collaborations:
H1/HERA; ATLAS/LHC; RD2; (RDxx)

– Joint Work with:
MPI (Munich); Uni Dortmund; PTB Braunschweig; Res. Inst. Rossendorf (Dresden); BNL Instr. Div.; PTI Ioffe Inst.; Tel Aviv Univ.

- Applications in H1/HERA and ATLAS/LHC

HERA: p-e collider, p: 800 GeV, e: 30 GeV
CM-energy: 300 GeV, Luminosity: $10^{31}\,cm^{-2}s^{-1}$
bunch crossing: 100 ns
experiments: H1 & ZEUS; future: HERA-B

why and where silicon in H1:
- HERA = asymmetric beam collider, much of energy flux goes into forward direction
- H1 has LAr-Calorimeter, additional plug-calorim. needed for hermiticity in forward direction
- silicon: only choice because of compactness
  future: also Si-instrumented μ-vertex detector

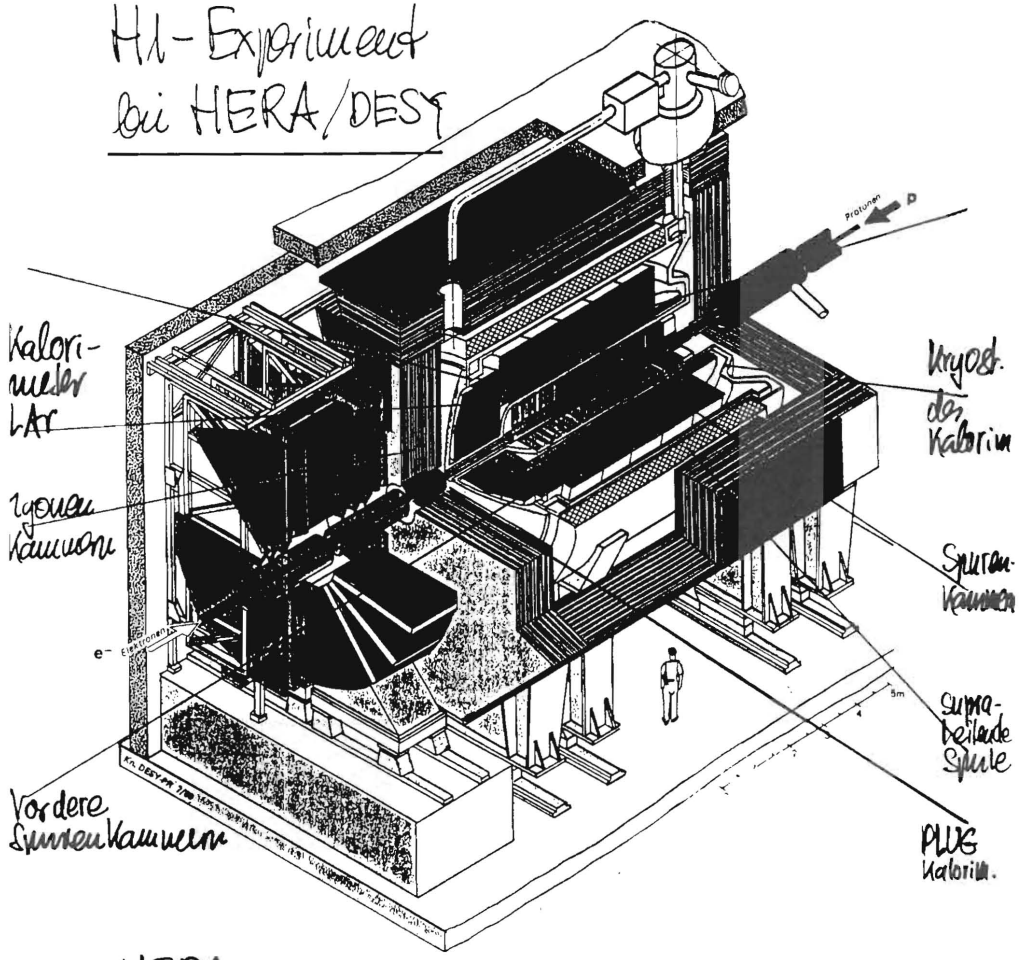
radiation problems:
- background hadrons from beam-wall / beam-gas interactions but small intensity
- synchrotron radiation, esp. during injection → surface damage

LHC: p-p collider, CM-energy 8 TeV
Luminosity $10^{34}\,cm^{-2}s^{-1}$, bunch crossing 20 ns
experiments: ATLAS & CMS, ...

why and where silicon in ATLAS:
- Inner Barrel Tracker: silicon pixels & strips only choice (fast read out, high pos. resolution)
- future: MSGC to be replaced by silicon? (very forward area: GaAs (rad. hardness))

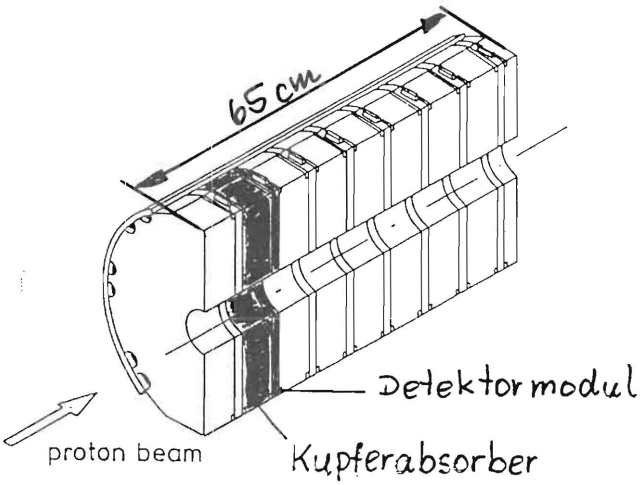
radiation problems:
- high hadronic flux from interactions mainly pions (small radii) and neutrons
- bulk damage (n, π) + surface damage ($\pi^{\pm}$)

H1-Experiment bei HERA/DESY

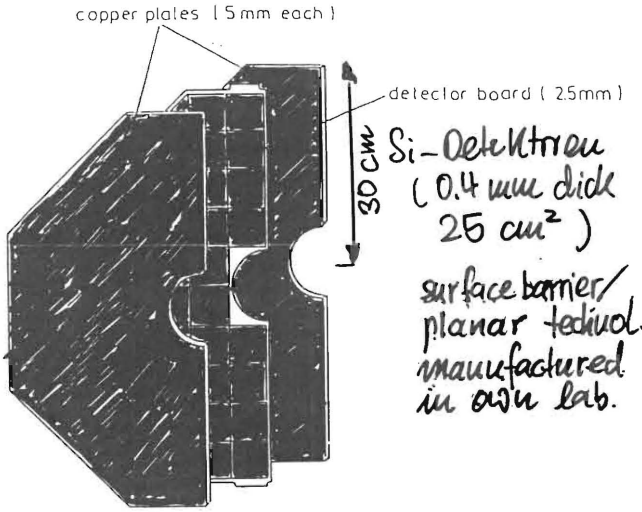


HERA:
p-e-collider
p: 800 GeV, e: 30 GeV
Schwerpunktsenergie: 300 GeV
Luminosität: $10^{31}\,cm^{-2}s^{-1}$
bunch crossing: 100 ns

H1 PLUG CALORIMETER



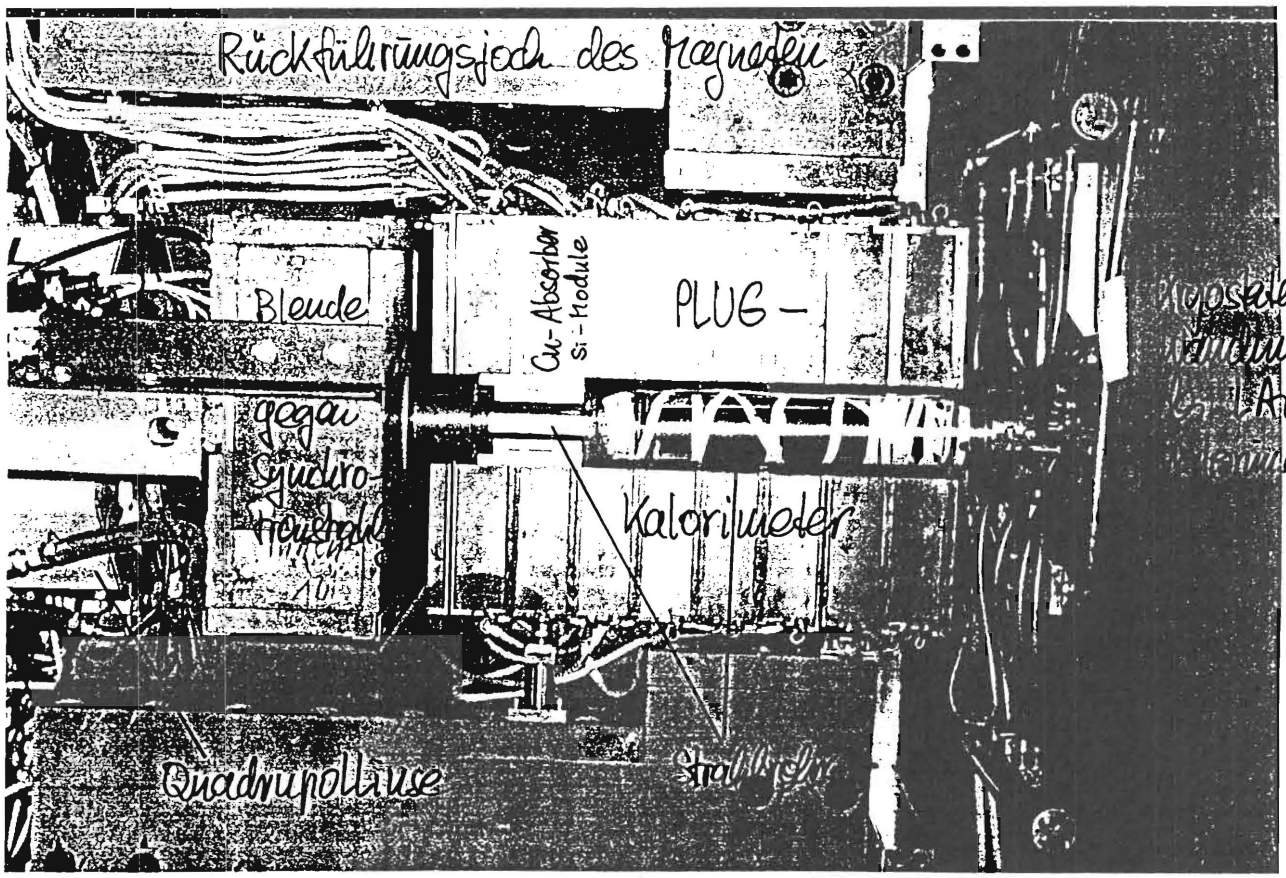
Detektormodul

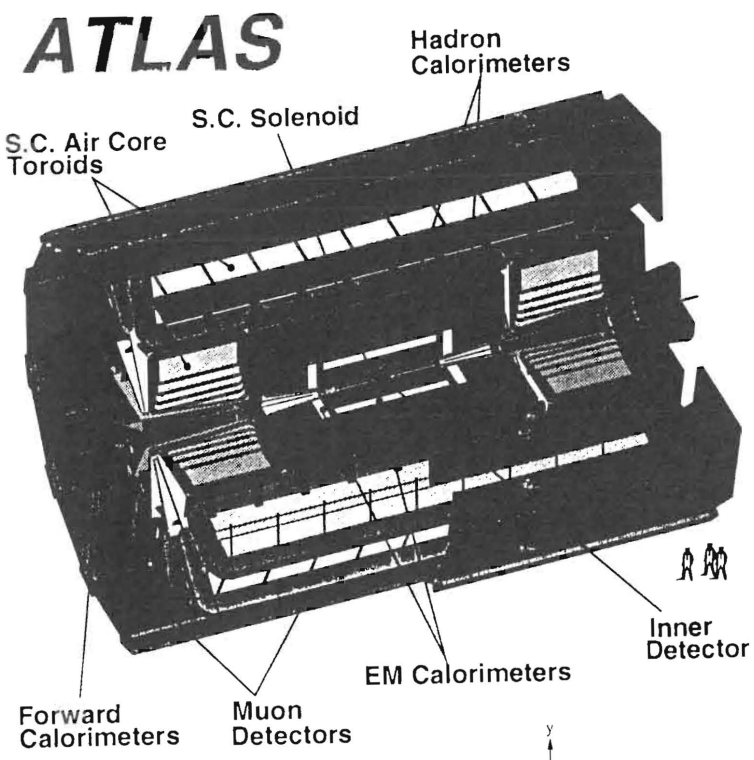


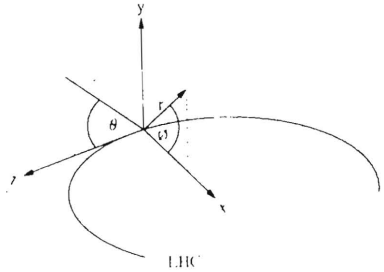
Design Parameters

radial dimensions	60 mm ≤ r ≤ 250 mm
angular range	12.5 mrad ≤ Θ ≤ 58 mrad
total length (instrumented)	65 cm = 4.3 λ
number of layers	8
layer structure	7.5 cm Cu + 400 μm Si-detector
lateral detector cell size	5 x 5 cm²
total number of electronic channels	672
number of electronic channels	336
angular resolution	4 mrad
energy resolution	≈ 150% / √E

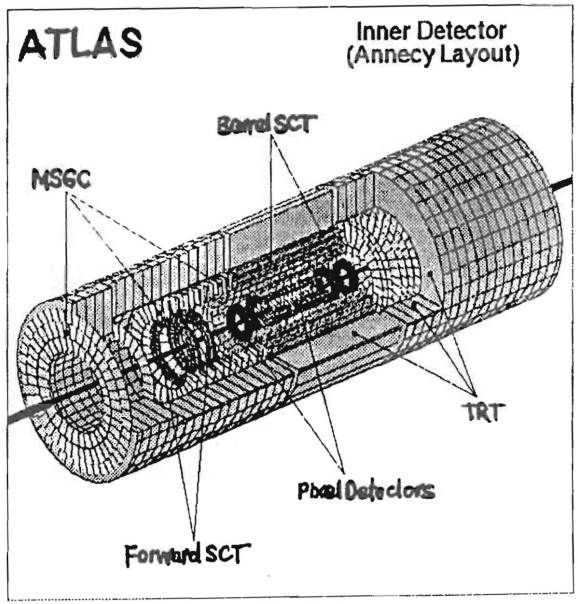
insgesamt 8 Ebenen
zus. 1.5 m² Si-Detektren
jede Ebene enthält mosaikartig 2 × 42 Detektren

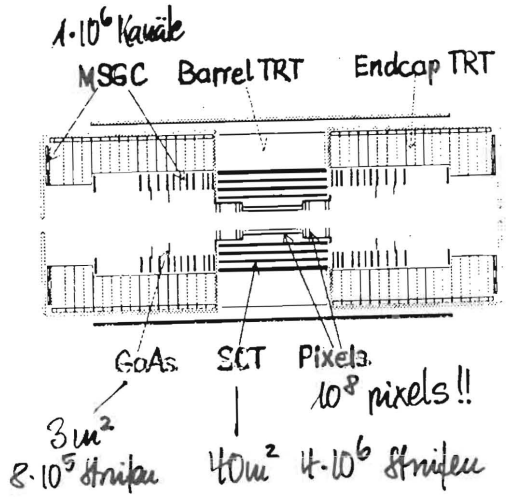






p-p-Collider LHC
8 TeV
20ns bunch crossing
10^{34} cm^{-2} s^{-1} Luminosität



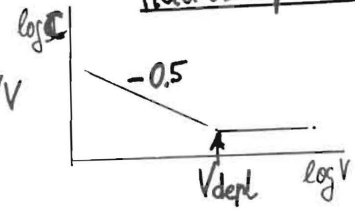


- **Radiation Hardness of Silicon Detectors**

"Macroscopic Measurements"

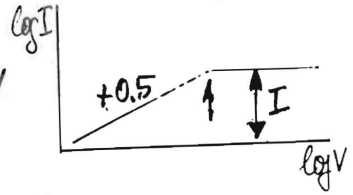
$V_{depl} = \frac{q_0 d^2}{2\varepsilon\varepsilon_0} |N_{eff}|$

– C/V



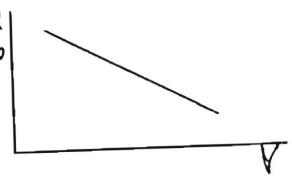
$\searrow N_{eff}(\Phi)$ bulk damage
(check also with TCT!)

– I/V



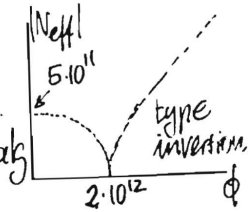
$I/V_{ol} = \alpha \cdot \Phi$ bulk damage

– Q/V



$\frac{\Delta Q}{Q_0}(\Phi)$ bulk damage
$\searrow \tau_{e,h}^{t}(\Phi)$

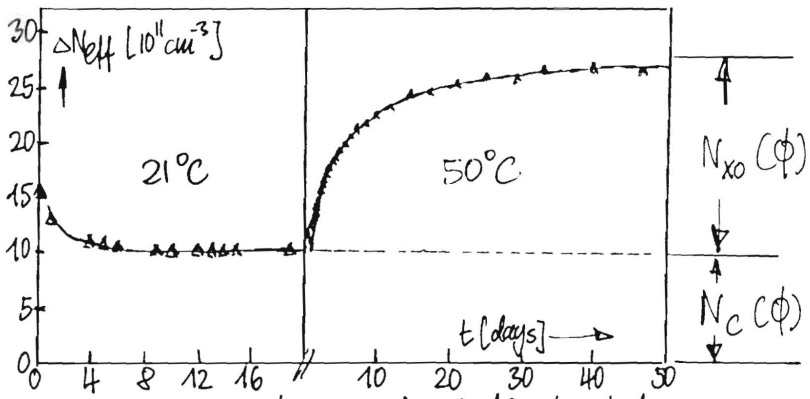
! most important:
change of N_{eff} resp. V_{depl}
type inversion & reverse anneals



- Modeling as function of fluence Φ
- Dependence on material (material characterization?)
- Dependence on particle type & energy, NIEL
- Operational Projections for the ATLAS-SCT (10 years!)

[Surface Effects: see last section]
(not discussed for RD2 14-07-95)

Long Term Annealing Effects of N_{eff} as seen in C/V-measurements



$$\Delta N_{eff} = N_C + N_{X0}\left\{1 - \frac{1}{1 + N_{X0} \cdot k \cdot t}\right\}$$

stable damage: $N_C(\Phi) = N_{C0}(1 - \exp(-c\Phi)) + g_C \cdot \Phi$
(partial donor removal) ("acceptors")

reverse annealing amplitude: $N_{X0}(\Phi) = g_Y \cdot \Phi$
(2nd order process)

$$k(T) = k_0 \cdot \exp\left(-\frac{E_a}{k_B \cdot T}\right)$$

universal activation energy describes all data at different temp.!

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Relaxation Effect, a hidden parameter in ΔNeff-measurements wrt temp. annealing

M. Moll
Diploma thesis, 94

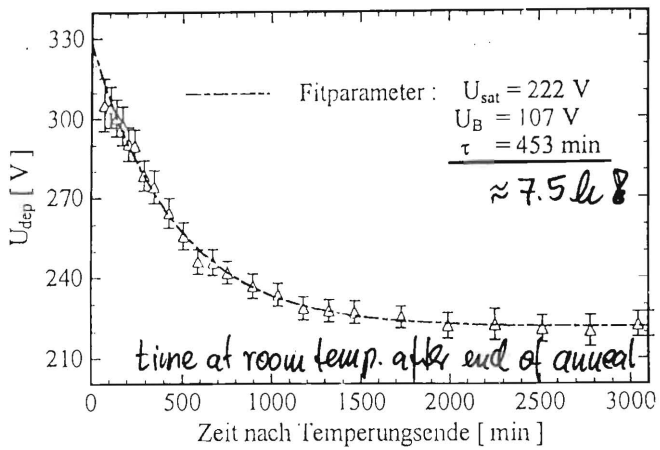

Abbildung 1.1: Abklingen der Verarmungsspannung beim isochronalen Tempern des Detektors 932G19 nach der 117°C Temperung.

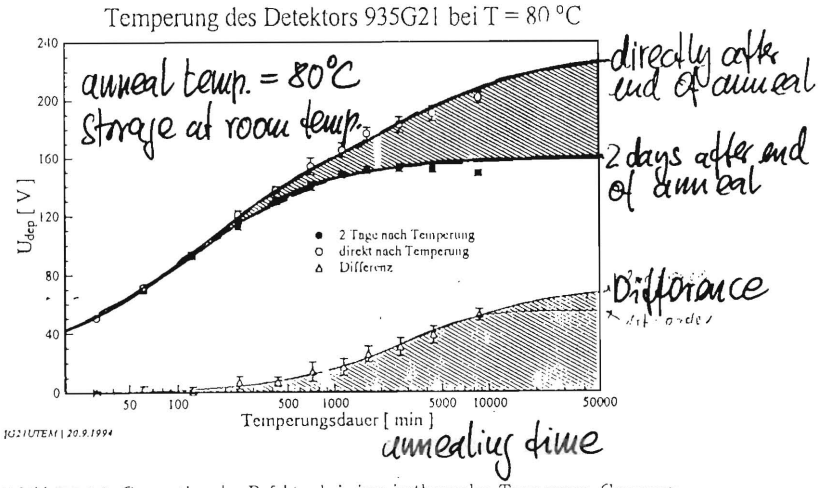

Abbildung 1.2: Generation des Defektes bei einer isothermalen Temperung. Gemessen wurde bei 10 kHz. Detektor : 935G21.

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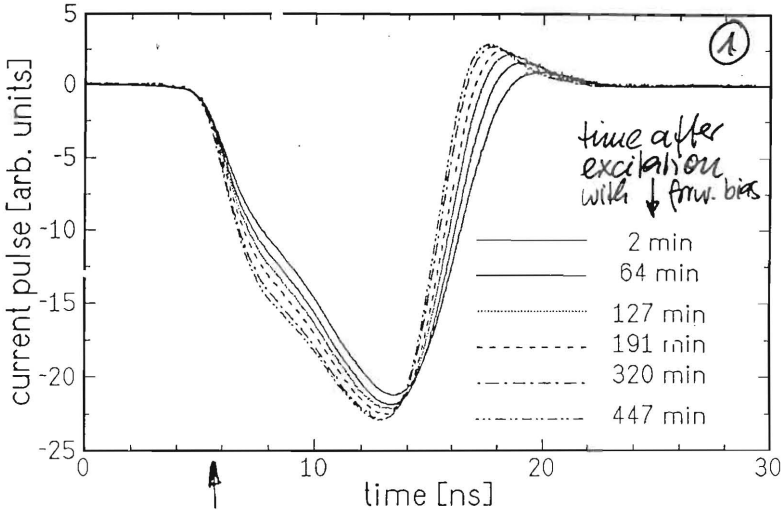
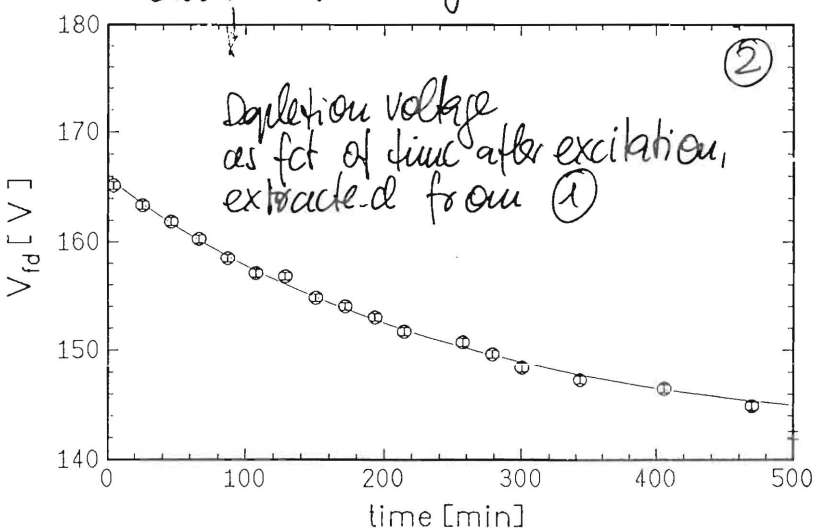
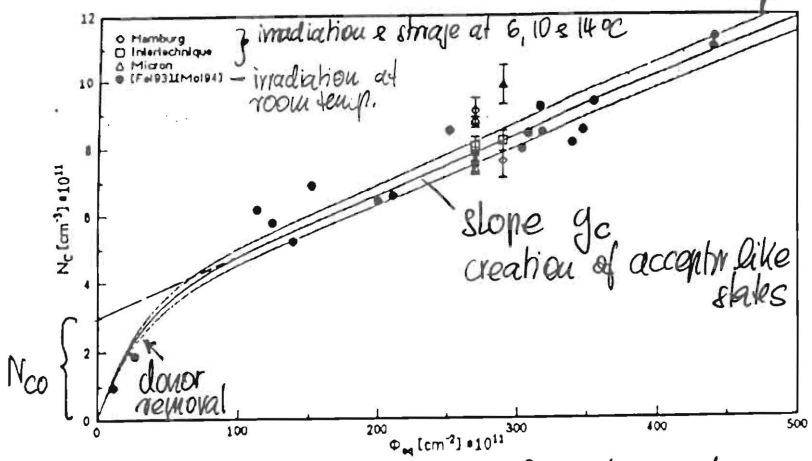
Relaxation of bistable defect measured with TCT-method



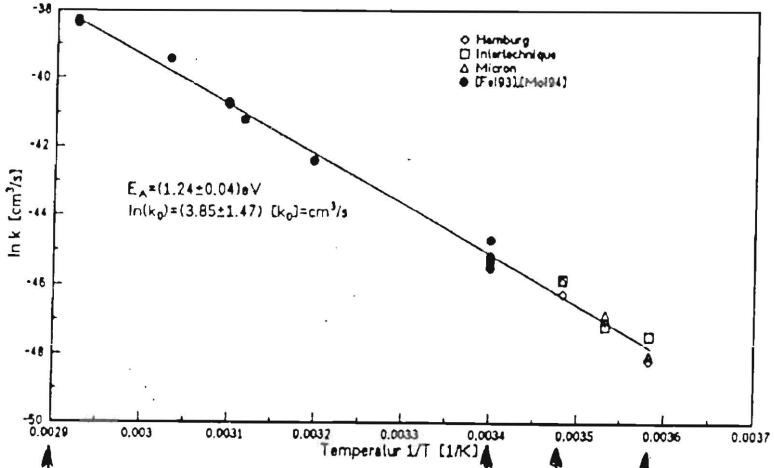
Detector 937G01, $\Phi_{eq.} = 1.9 \cdot 10^{13}$ n/cm²
Isochronal Annealing 50–100 °C Δt = 5°C



Effects of irradiation and storage at lower temperatures



No temperature effect in formation of stable defects $N_c = N_{c0}(1-\exp(-c\Phi)) + g_c \cdot \Phi$



72°C 20°C 14°C 6°C

Temperature dependence of rate constant k for reverse annealing is well described by simple activation energy!

B. Hamburg Group only! Dedicated investigation avoiding systematic errors

Material Dependence: Experimental Setup

Devices	Manufacturer	Type	d [µm]	N_{eff0} [10^{12} cm^{-3}]
935	Hamburg	surface b.	330	0.45
936	Hamburg	surface b.	300	-0.58
934	Hamburg	surface b.	505	0.44
BRBI	Tesla	ion impl.	375	2.5
MI	MPI München	ion impl.	280	1.4

p-type thick 'low' resistivity

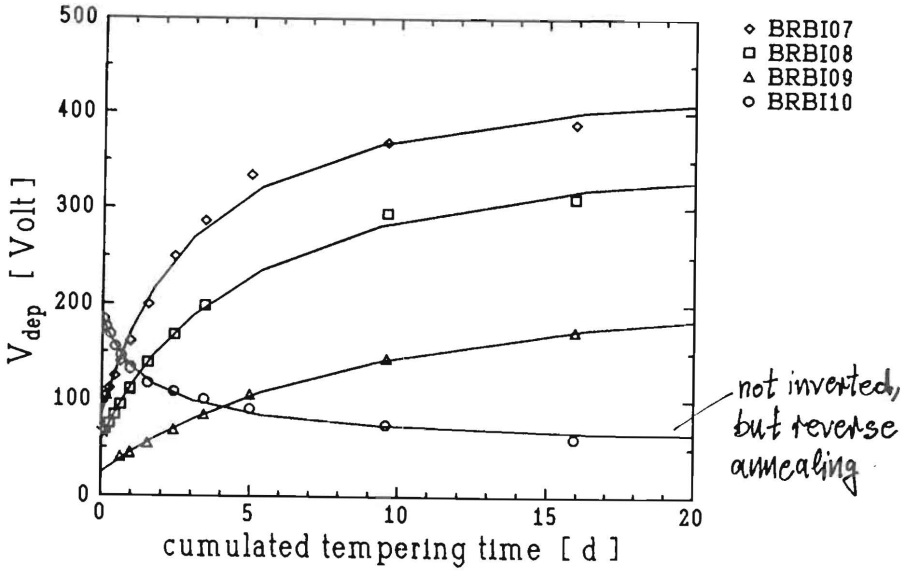
All devices irradiated at the PTB Braunschweig with 6.2 MeV neutrons

Fluences in the range 1.0 ... 8.0·10^{13} $\frac{n}{cm^2}$

At least 4 samples per material type

Similar annealing study at ≈ 50°C for all devices, 10...20 annealing steps

Isothermal Annealing Curves



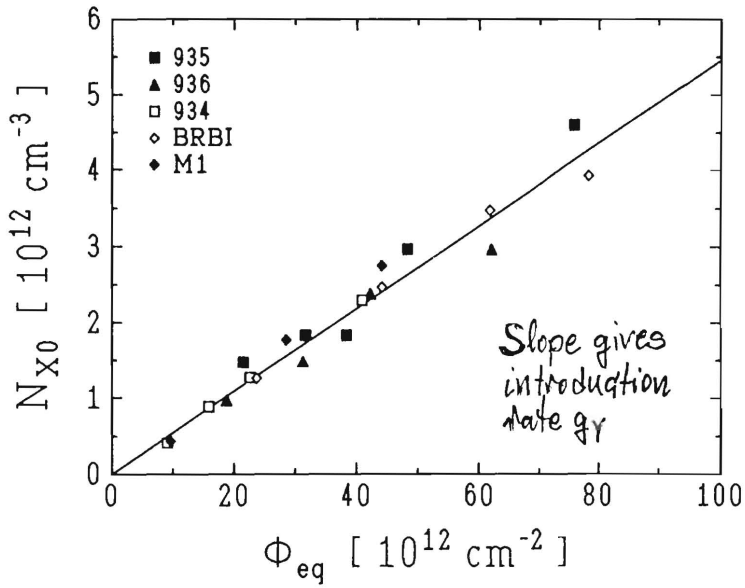
Each annealing curve gives a set of optimized fit parameters,

Stable damage: $N_G(\Phi)$

Reverse annealing amplitude: $N_{X0}(\Phi)$

Rate constant: $k(50C)$

Material Dependence of the Reverse Annealing Amplitude

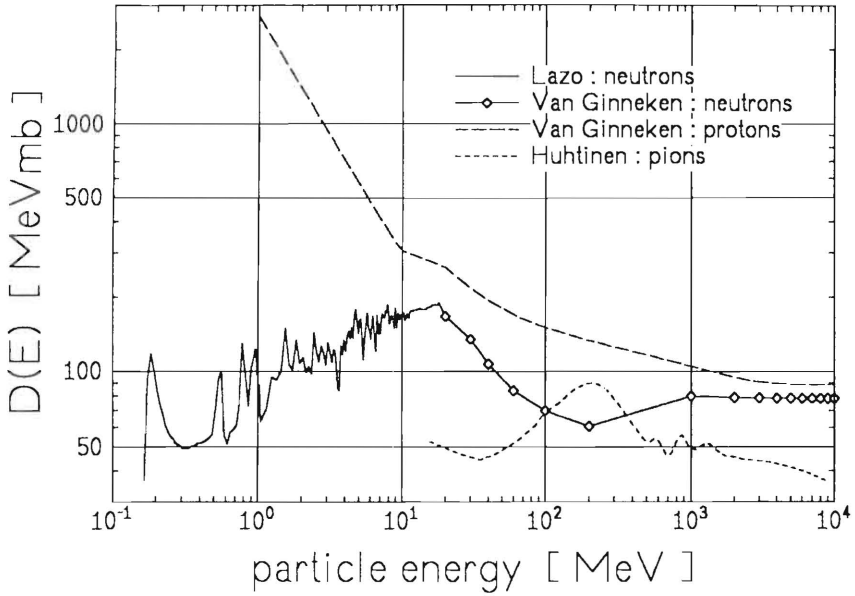


Introduction Rates

Devices	N_{eff0} [10^{12} cm^{-3}]	g_Y [10^{-2} cm^{-1}]
935	0.45	5.9
936	-0.58	5.1
934	0.44	5.3
BRBI	2.5	5.4
M1	1.4	5.6

No significant dependence within experimental error

NIEL Hypothesis



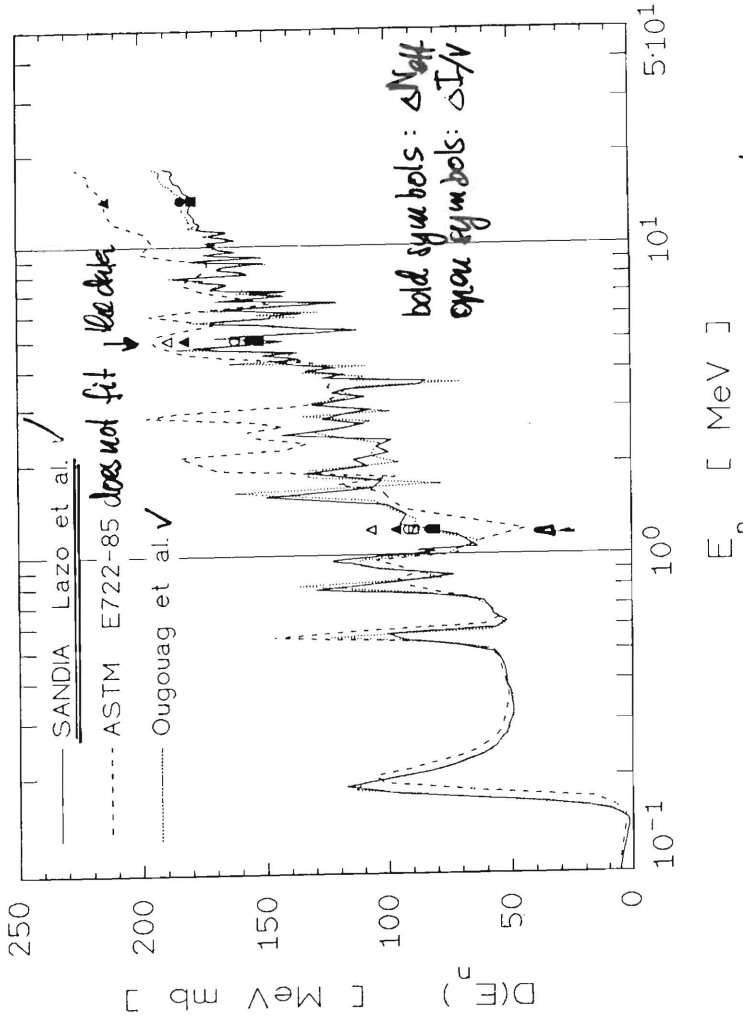
Bulk damage effects scale linearly with the total displacement energy ~ D(E)
(Non Ionizing Energy Loss)

Equivalent fluence

$$\Phi_{eq} = \int dE\, \phi(E) \cdot \frac{\int dE\, \phi(E) \cdot D(E)}{95\,\mathrm{MeVmb} \int dE\, \phi(E)} =: \Phi \cdot \varkappa$$

Source	Particle	Reaction	T [MeV]	κ
TB Be	neutron	Be(d,n)	6.2	1.53
ERN PS	proton	Beam	24000	0.93
SI236	pion	Beam	236	0.93

aracteristics of the Radiation Sources compared in the study



Comparison of different displacement cross section functions with exp. values obtained from monoenergetic neutron irradiation all results normalised to $E_n = 14.1$ MeV

Discussion

	neutrons (global fit)	protons (global fit)	pions (global fit)
g_C [10-2 cm-1]	2.5 (1.8)	1.5 (1.2)	2.5 (2.5)
g_Y [10-2 cm-1]	5.9 (4.6)	4.2 (5.8)	7.5 (7.5)
α_∞ [10-17 Acm-1]	4.7 (2.9)	2.7 (2.2)	5.0 (5.0)
g_C/α_∞ [arb]	0.53 (0.62)	0.56 (0.55)	0.50 (0.50)
g_Y/α_∞ [arb]	1.26 (1.59)	1.56 (2.64)	1.50 (1.50)

ummary of equivalent 1 MeV damage constants found for neutrons, rotons, and pions (Wafer 935).

Damage function and/or NIEL hypothesis may be incorrect

Ratio of introduction Rates is independent of the damage function and fluence calibration

g_C/α_∞ similar for all particles

g_Y/α_∞ neutrons lower

⇒ Weak evidence that NIEL hypothesis does not apply (E-Distribution of recoil atoms)

• Operational Projections for the ATLAS SCT-Tracker

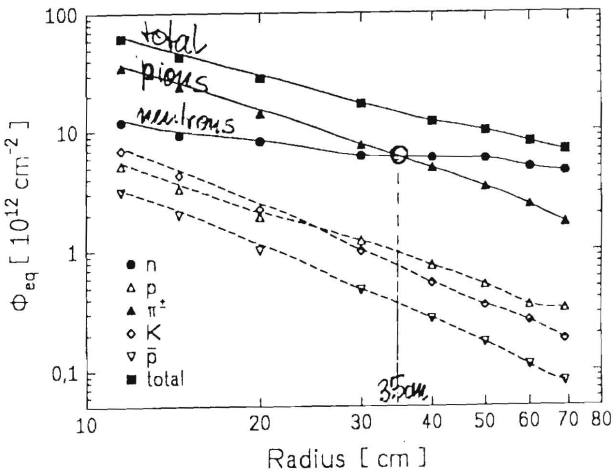
Flux Calculations

Single TRT design configuration B, p-p cross section 71mb, Luminosity 10^{34} cm^{-2}s^{-1}, running time 10^7 s per year (G. Gorfine, G. Taylor ATLAS-INDET-NO-030)

- Normalization to 1 MeV neutrons with damage functions given above
- Simulation includes Integrated Forward Calorimeter (private communication G. Gorfine)

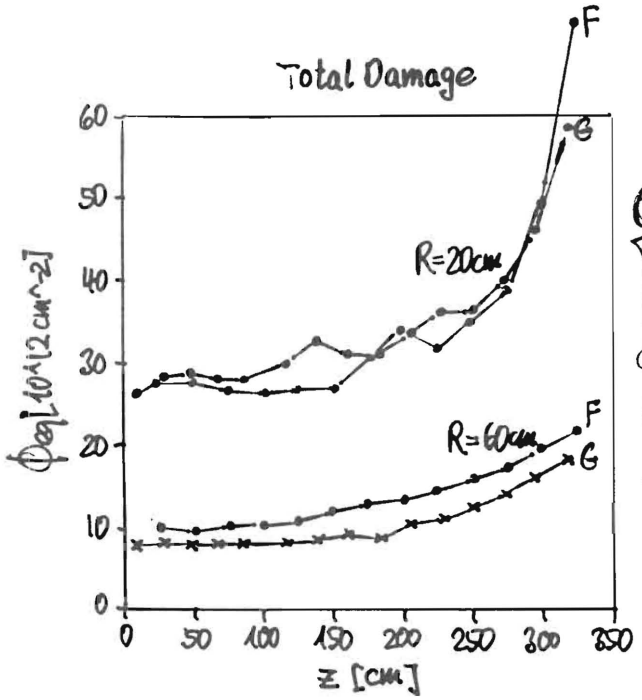
Annual Equivalent Damage [cm^{-2}]

Radius	Region	Neutron	Proton	Pion	Kaon	Anti p	Total	Charged
11.5	SI1	1.2E+13	5.2E+12	3.5E+13	7.0E+12	3.1E+12	6.2E+13	5.03E13
14.5	SI2	9.3E+12	3.3E+12	2.4E+13	4.3E+12	2.0E+12	4.3E+13	3.36E13
20	SI3	8.2E+12	1.9E+12	1.4E+13	2.2E+12	1.0E+12	2.8E+13	1.91E13
30	SI4	6.2E+12	1.2E+12	7.6E+12	9.9E+11	4.7E+11	1.7E+13	1.03E13
40	SI5	6.0E+12	7.5E+11	4.9E+12	5.4E+11	2.7E+11	1.2E+13	6.46E12
50	SI6	5.9E+12	5.2E+11	3.4E+12	3.5E+11	1.7E+11	1.0E+13	4.44E12
60	SI7	5.0E+12	3.5E+11	2.4E+12	2.6E+11	1.1E+11	8.1E+12	3.12E12
69	SI8	4.6E+12	3.3E+11	1.7E+12	1.8E+11	8.0E+10	6.9E+12	2.29E12



Simulations

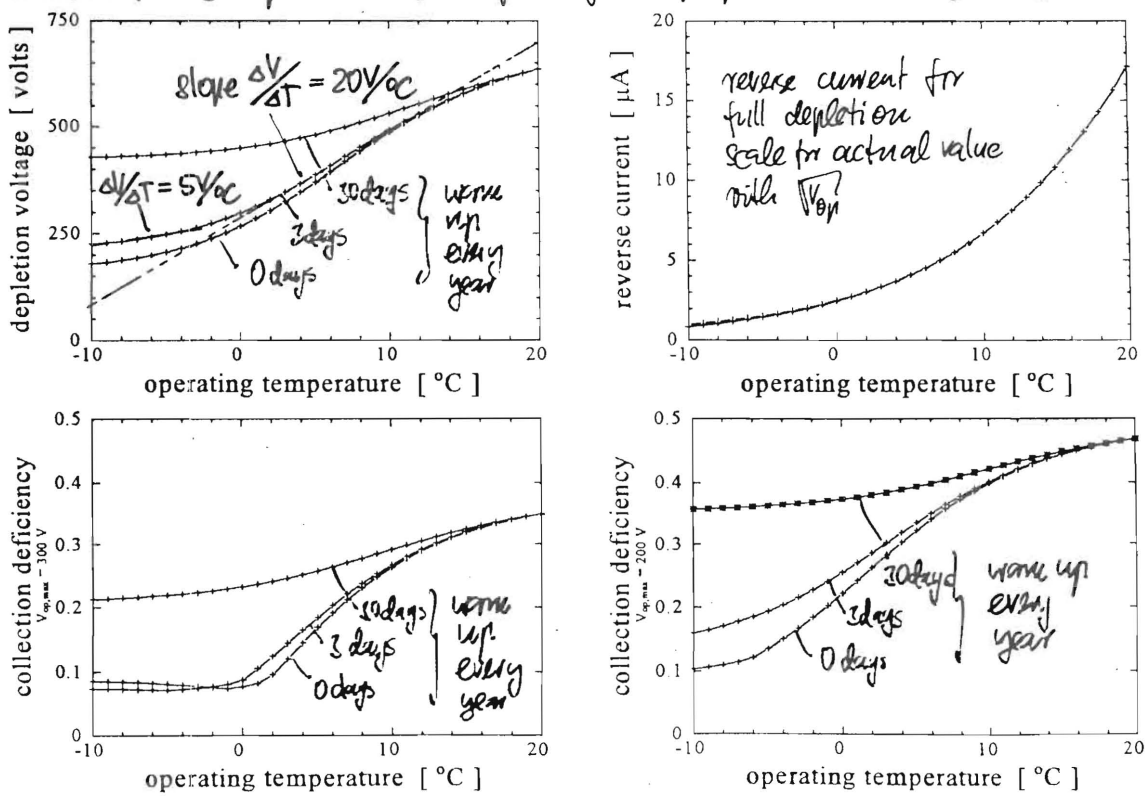
Neutron Fluences	:	Neutron Damage Constants
Charged Hadron Fluences	:	Pion Damage Constants
Luminosity	:	3 years at 10^{33} cm^{-2}s^{-1} followed by (B= 2T) 7 years at 10^{34} cm^{-2}s^{-1}
Active Area	:	pixels (11.5 cm...20 cm) -> 50 μm × 300 μm; strips (30 cm...69 cm) -> 12 cm × 112.5 μm
Warm Up	:	no, 3 days and 1 month

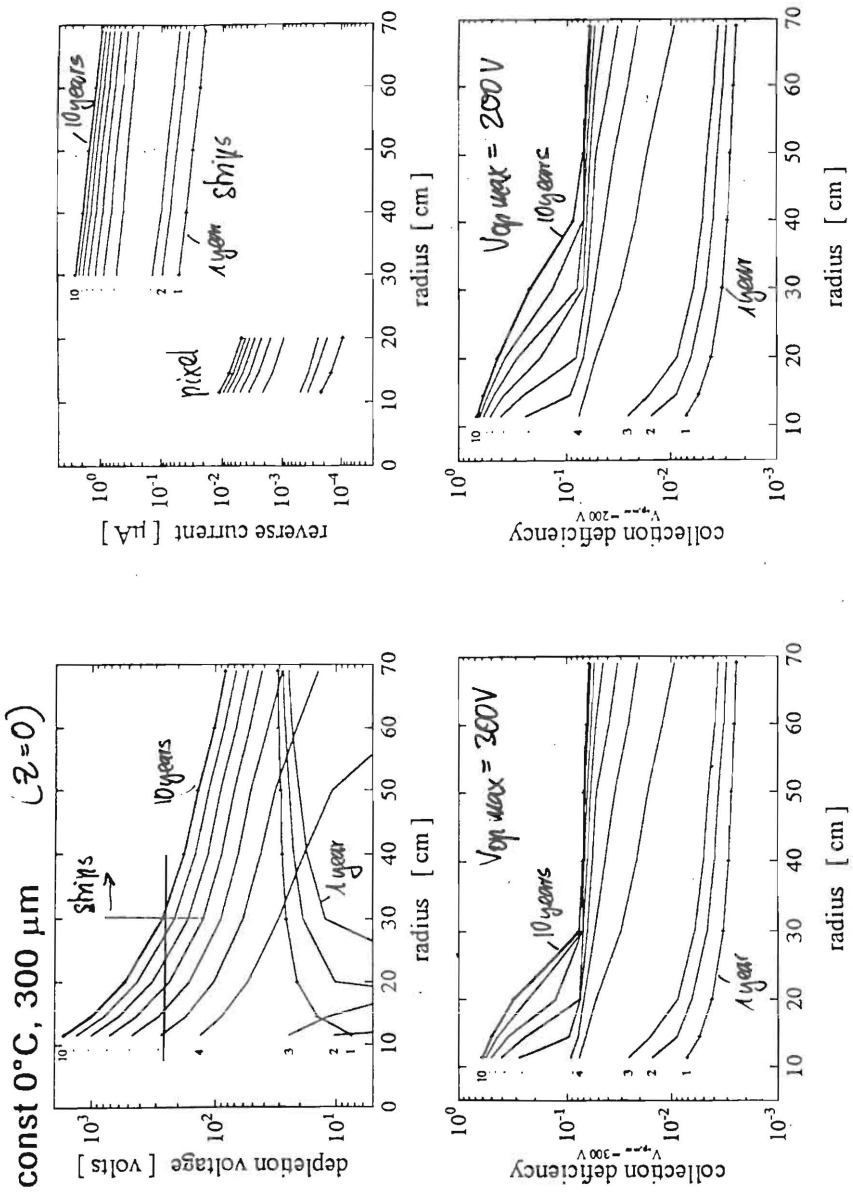


Comparison of Total Damage per LHC-year ($L=10^{34}$) calculated by
G. Gorfine — G
A. Ferrari — F

Remarks : Gorfine : single TRT + IFC, $\sigma = 71$ mb, n : Lazo
Ferrari : Technical Proposal, $\sigma = 80$ mb, n : ASTM

30 cm, 300 μm (strip detectors) after 10 year of operation : (z = 0)

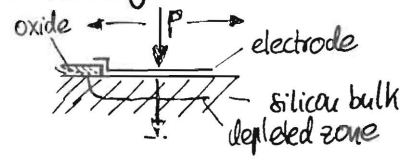




G. Lindström
RD2 meeting, Dortmund 14-07-95

Radiation Hardness of Silicon Detectors
"Microscopic Measurements"

- **Scanning proton micro-beam** (normally used for PIXE)



p-beam $\phi < 1\,\mu m$
current reduced to single proton counting
measured: energy in depleted zone, 2dim. scan
applications: depth profiles, esp. lateral extensions

- **TCT** time resolved current transient measurements

current transient of charge generated with ultrashort laser pulse (1ns infrared) measured with high time resolution using 1 GHz digital oscilloscope
$i(t) \rightsquigarrow E(x)$ electric field distrib., many applic.

- **DLTS** deep level transient spectroscopy

FFT-C-DLTS (fast Fourier transform capacitance transients)
dechanging of traps filled by initial pulse
defect characterization: energy, cross section, concentration
powerful tool, but limited to $N_{Trap} \ll N_{Doping}$ (small ϕ)
future: I-DLTS and laser induced DLTS

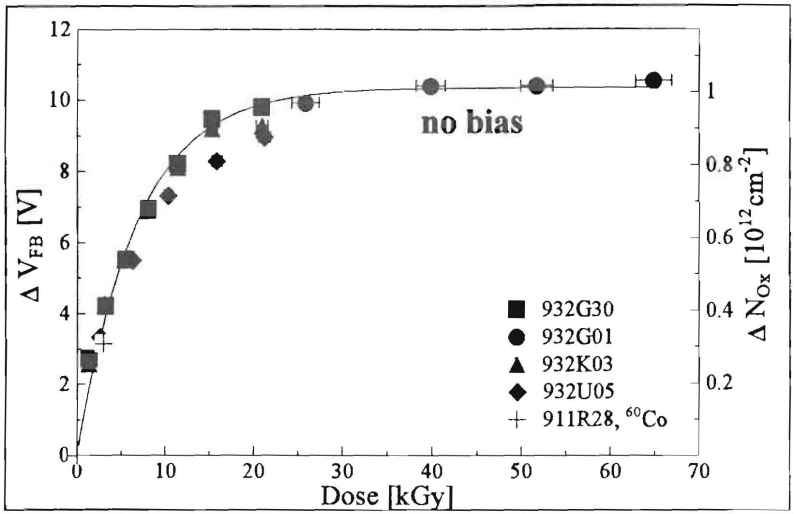
- **TSC** temperature stimulated current

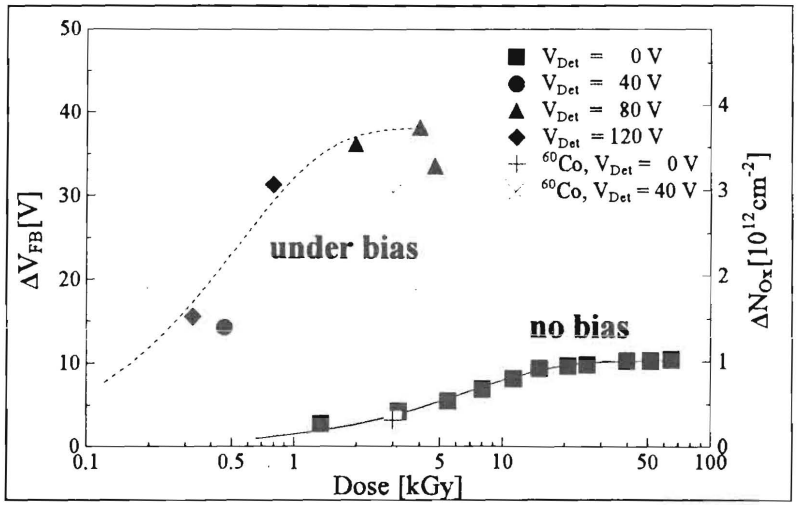
defect characterization as for DLTS
but no limitations wrt N_{Trap} (also meas. for high ϕ)
more difficult to analyse than DLTS
DLTS: differential method, TSC: integral effect

For DLTS and TSC:
liquid N_2 and He-cryostates available.

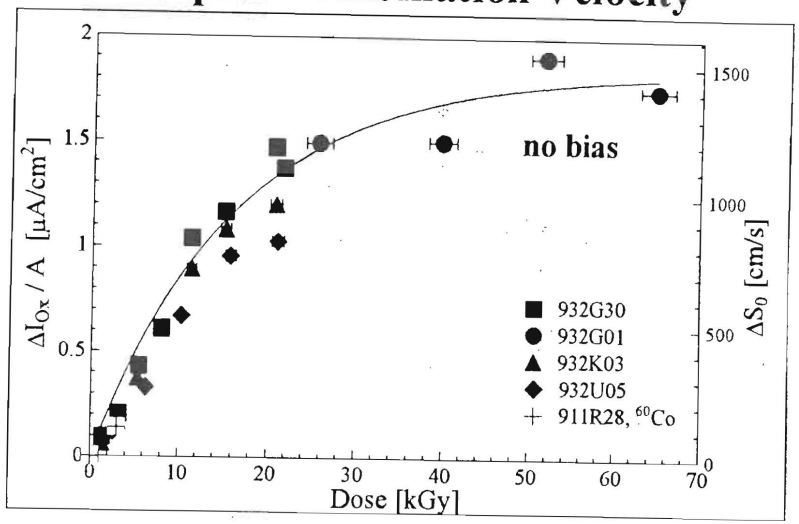
- Study of Surface Effects due to Ionizing Radiation

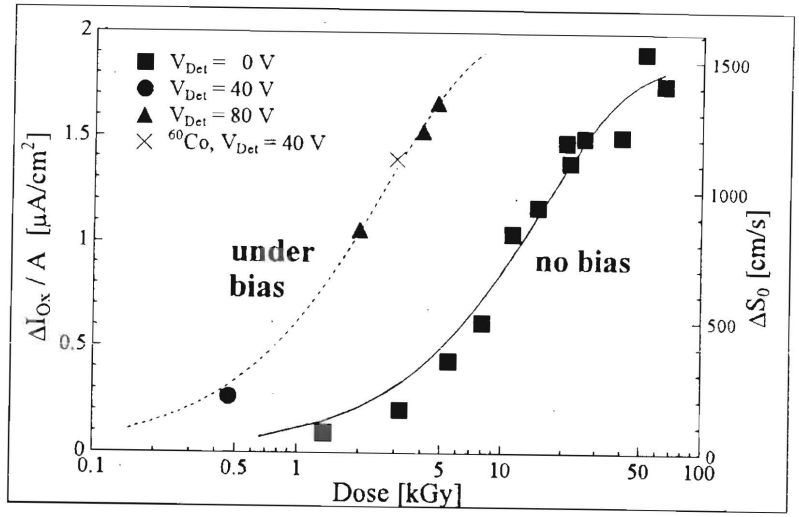
Increase of Flatband Voltage resp. Oxide Charge



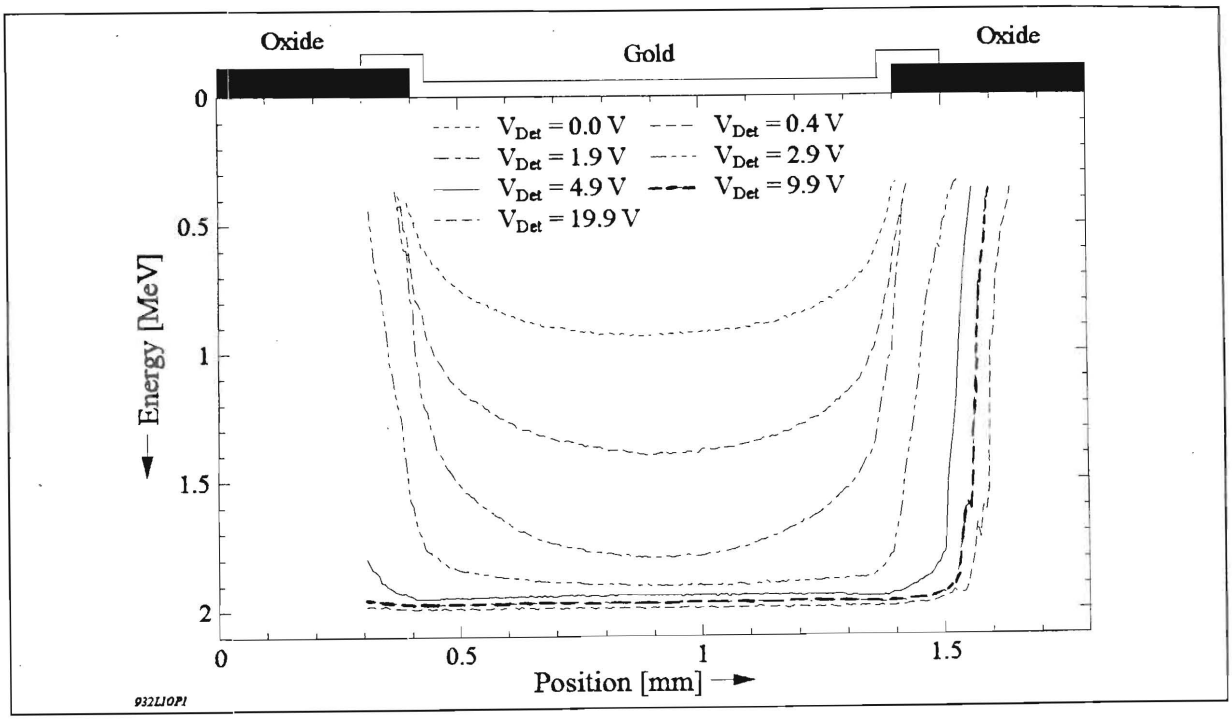


Increase of Surface Generation Current resp. Recombination Velocity

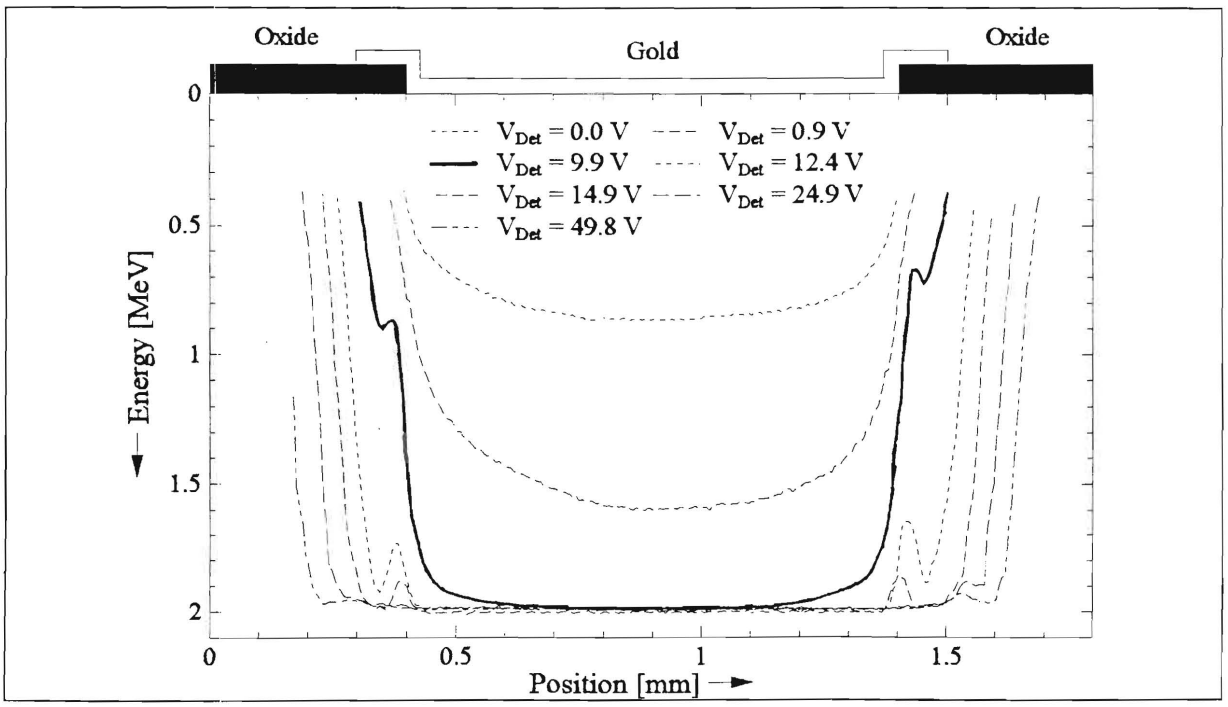




Before Irradiation



After Irradiation: 2 kGy , V = 0 V



7 ① Scanning proton micro beam

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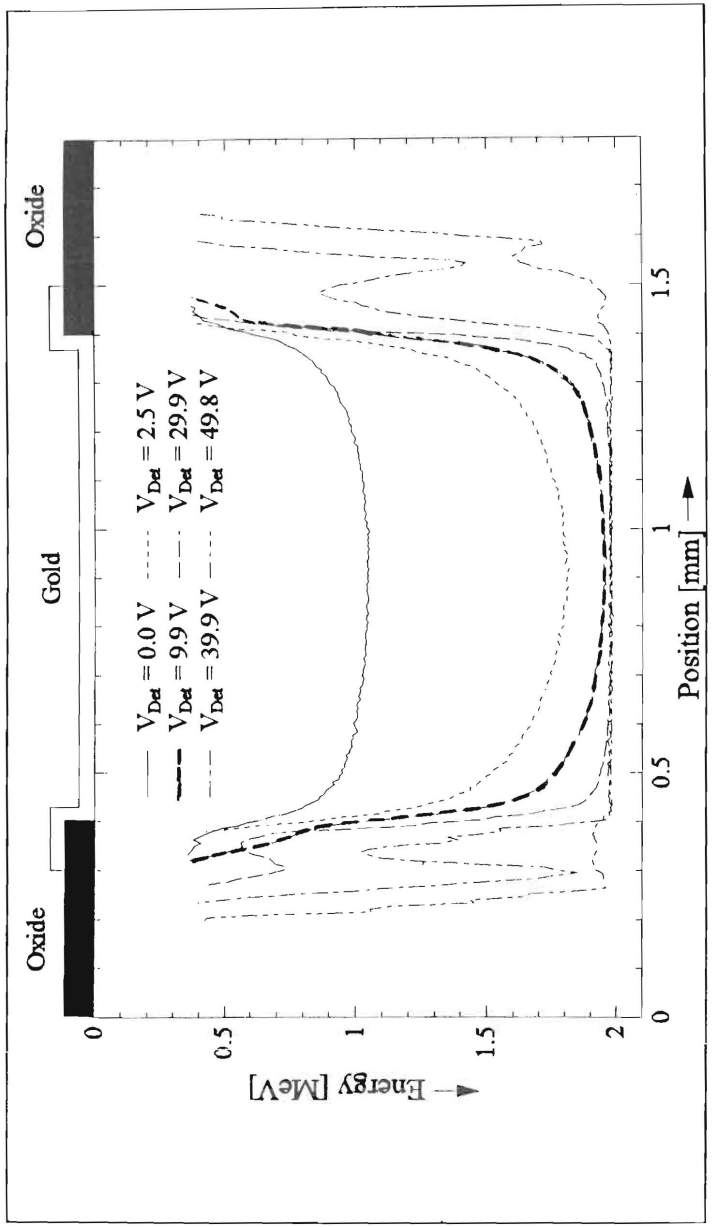
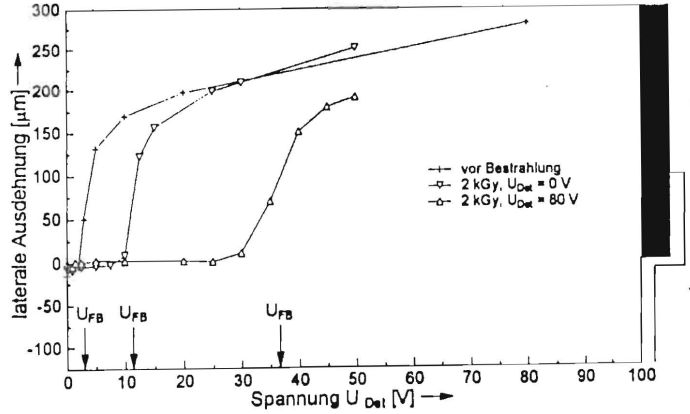
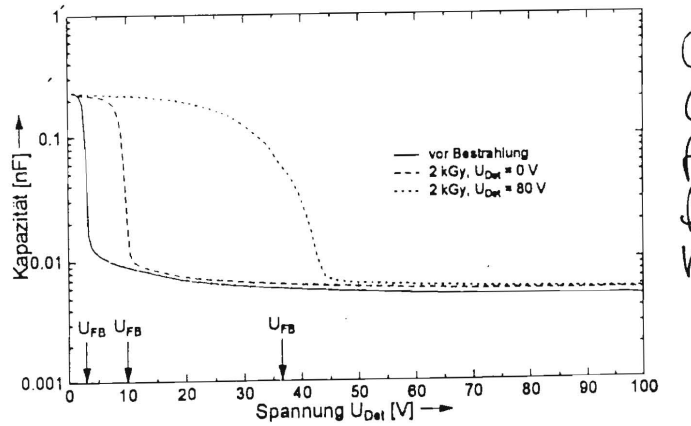
After Irradiation: 2 kGy, V= 80 V





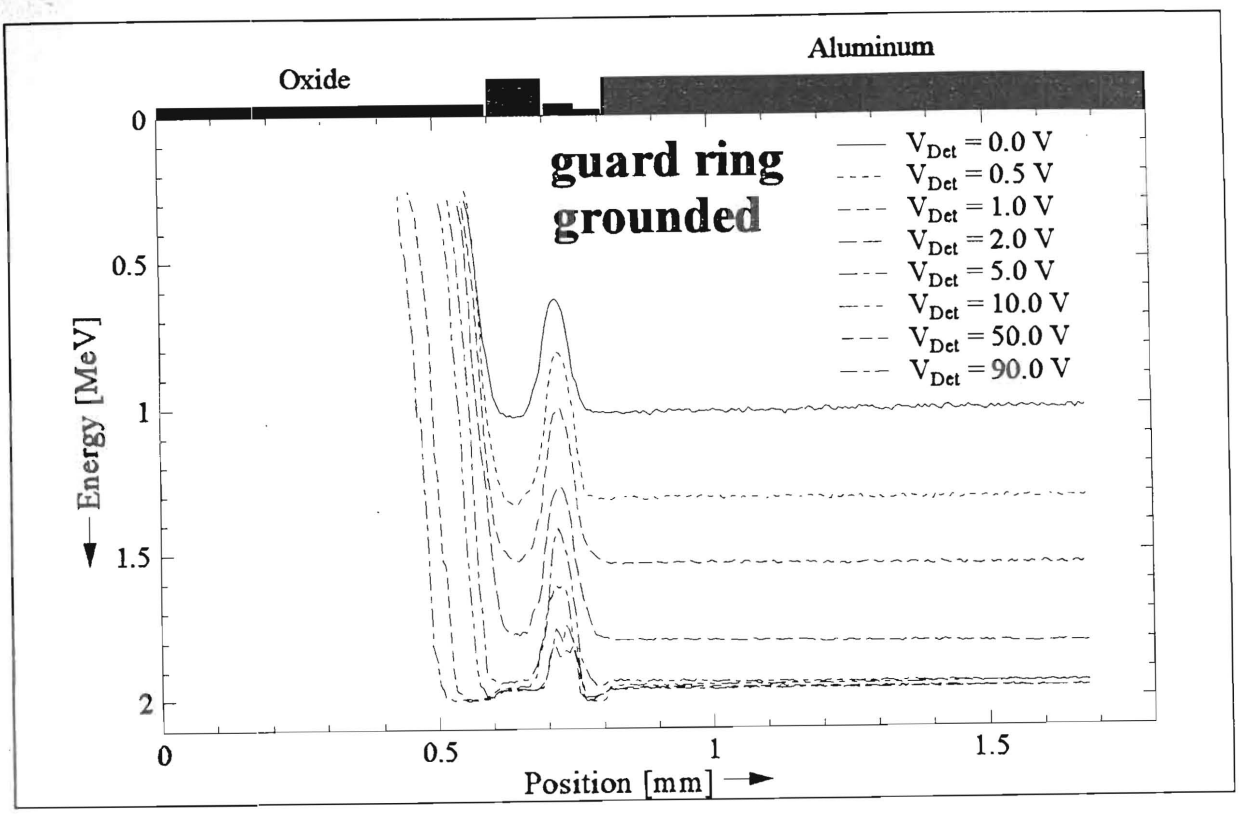
lateral extension of electric field below front electrode measured with p-µbeam

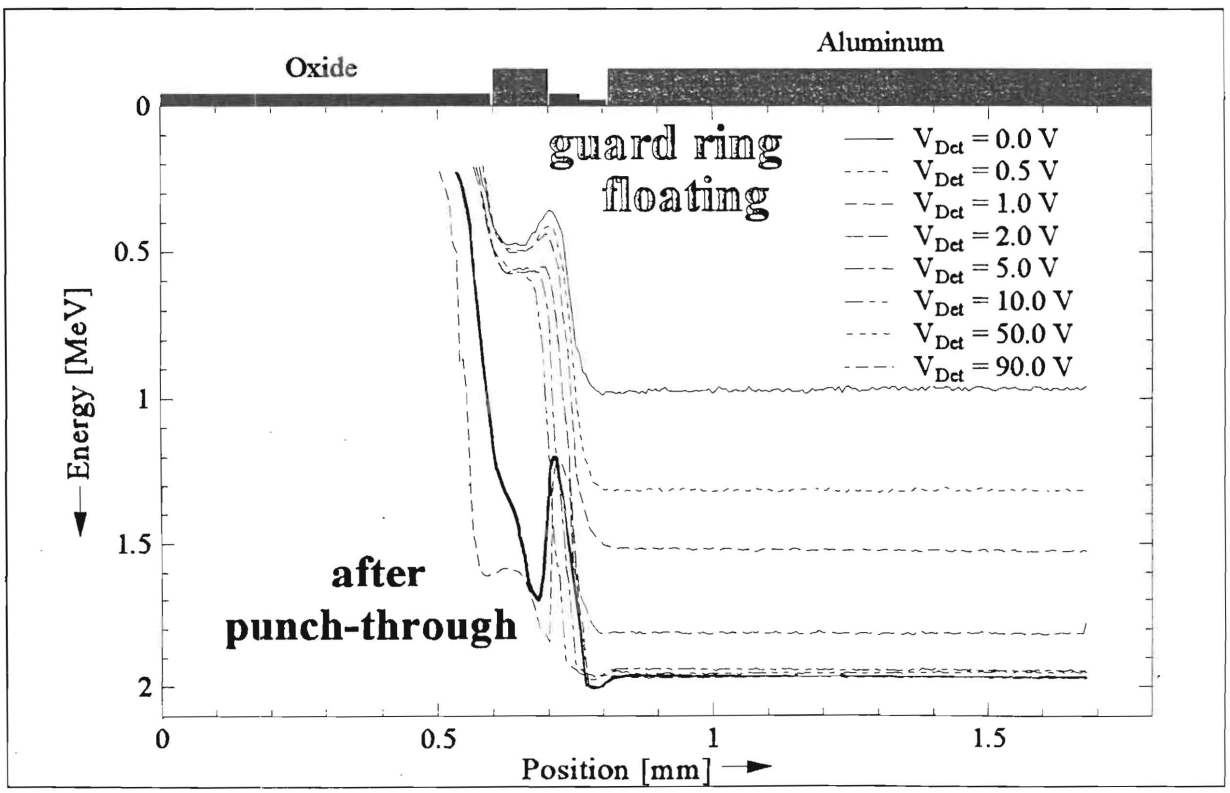
Abbildung 7-17: Laterale Ausdehnung der Verarmungszone in elektronenbestrahlten Detektoren.



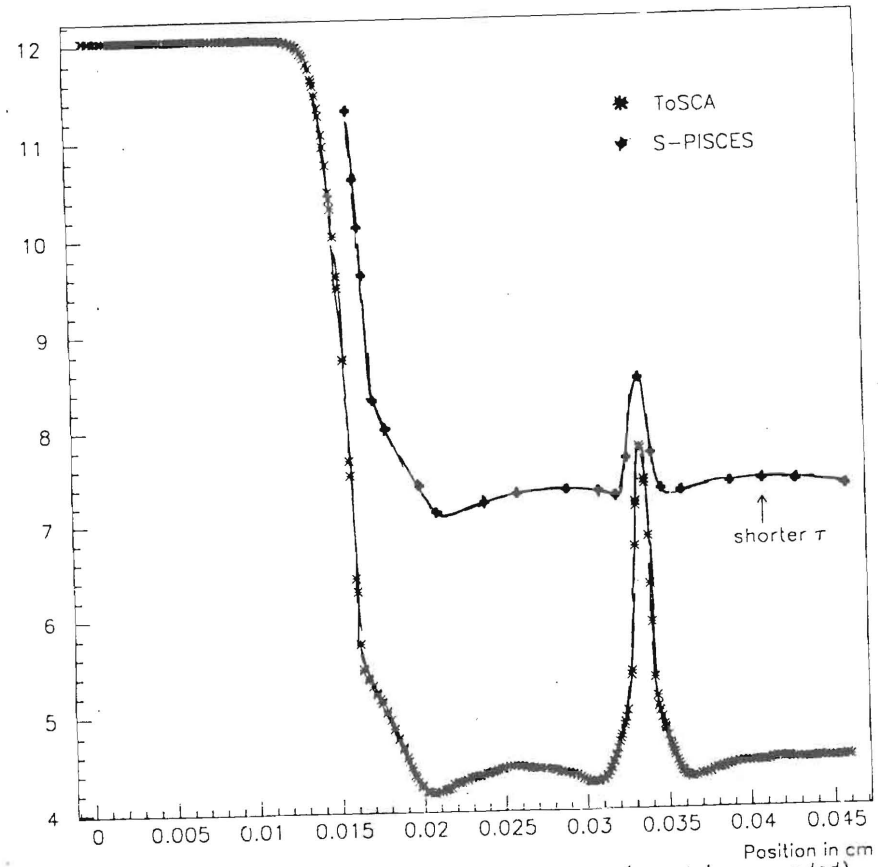
Conventional C/V-measurem. for extracting flat band voltage

Abbildung 7-18: Kapazitäts-Spannungs-Charakteristiken (lineare Spannungsskala) der mit dem Protonenmikrostrahl untersuchten Oberflächensperrschicht-Detektoren. Die Flachbandspannungen sind in Übereinstimmung mit den aus der lateralen Ausdehnung der Verarmungszone bestimmten Werten.


Oxide
Aluminum
guard ring grounded
V_{Det} = 0.0 V
V_{Det} = 0.5 V
V_{Det} = 1.0 V
V_{Det} = 2.0 V
V_{Det} = 5.0 V
V_{Det} = 10.0 V
V_{Det} = 50.0 V
V_{Det} = 90.0 V
Energy [MeV]
0
0.5
1
1.5
2
0
0.5
1
1.5
Position [mm]


Oxide
Aluminum
guard ring floating
V_{Det} = 0.0 V
V_{Det} = 0.5 V
V_{Det} = 1.0 V
V_{Det} = 2.0 V
V_{Det} = 5.0 V
V_{Det} = 10.0 V
V_{Det} = 50.0 V
V_{Det} = 90.0 V
after punch-through
Energy [MeV]
0
0.5
1
1.5
2
0
0.5
1
1.5
Position [mm]

33



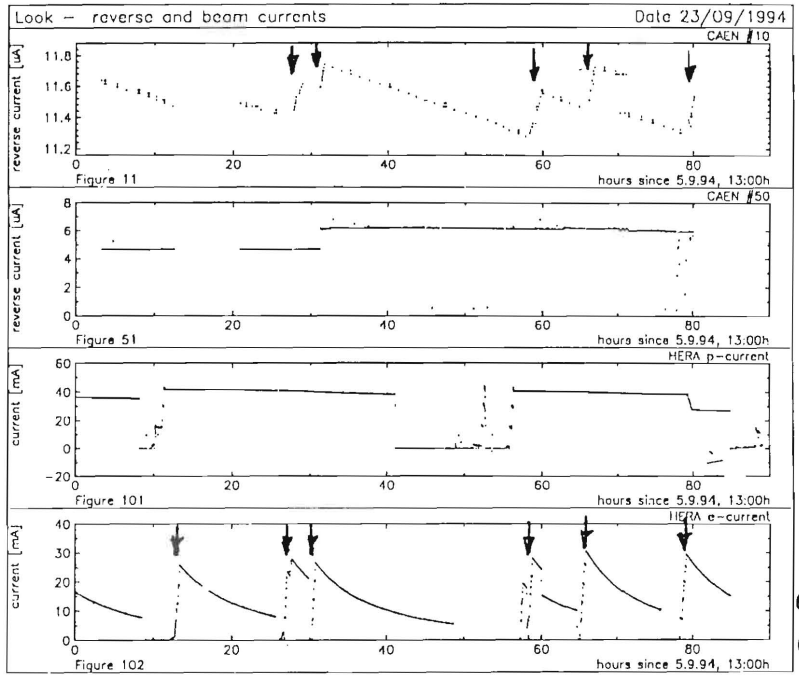
Profil of Electron Concentration at Depth of 10 μm (guard ring grounded)

34

H. Krüger, W. Hildesheim
H. Seidel

HERA - RUN-PERIOD - 1994

Performance of PLUG-calorim. detectors in H1



PLUG detector reverse current

HERA e-beam current

Figure 18: correlation in time of reverse currents and beam currents

Also: dramatic increase of flat band voltage from a few volts to ≈ 50 Volts !!

Ionizing dose measured with glass dosimeters (≳ 30 kGy) was low: ≈ 20-30 Gy for innermost radii decreasing rapidly to ≈ 1 Gy for larger distances to beam pipe.

Ionizing dose calculated from reverse current increase: leads to integrated dose (total run period) Φ

$$20\ \text{kRad} \approx \Phi \lesssim \underbrace{200\ \text{kRad}}_{\text{more likely}}$$

i.e. $\Phi \approx 2\ \text{kGy}$ at least off by a factor of 100 wrt glass dosim.

but energy dose ≲ 30 kGy !!

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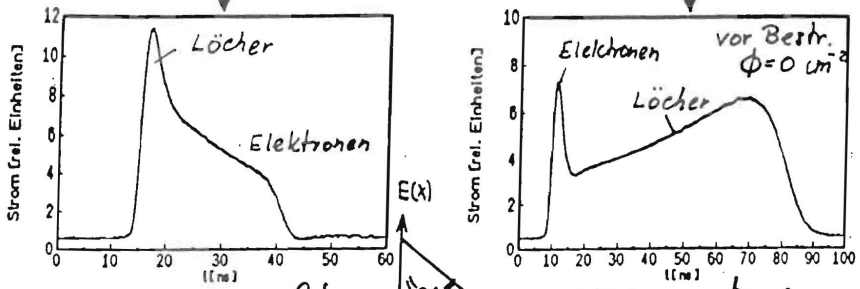
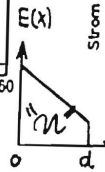
- TCT as tool for studying internal field distrib.

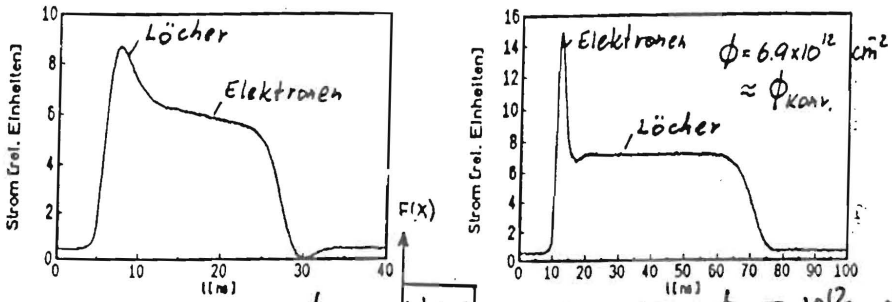
Änderung der Stromimpulsform durch Betrahlung (GaAs-Laser, 820nm

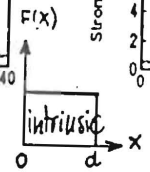
Frontelektrode ↓ Rückelektrode ↓



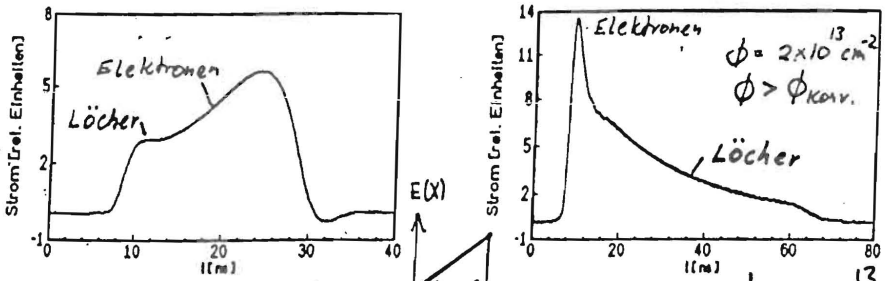


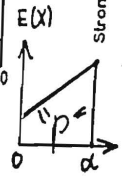
before — conversion $\phi = 0$





at — conversion $\phi = 7 \cdot 10^{12}\ cm^{-2}$





after — conversion $\phi = 2 \cdot 10^{13}\ cm^{-2}$

TCP-2

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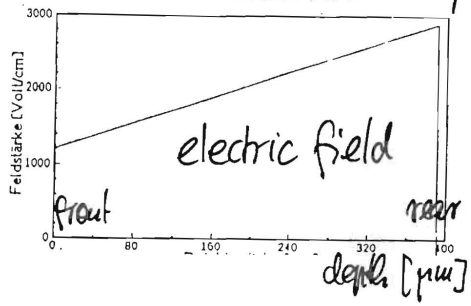
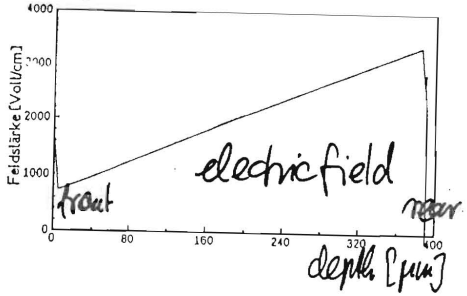
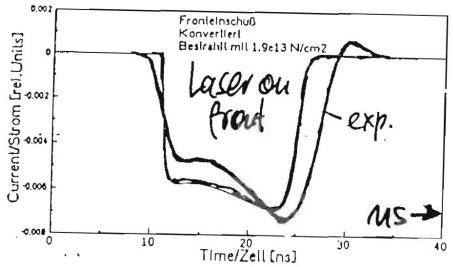
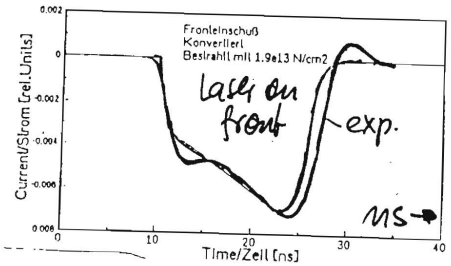
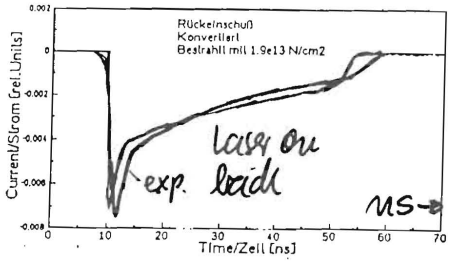
Experimental and theoretical current pulse shapes for 2 detectors converted to p-type after $1.9 \cdot 10^{13}\ n/cm^2$

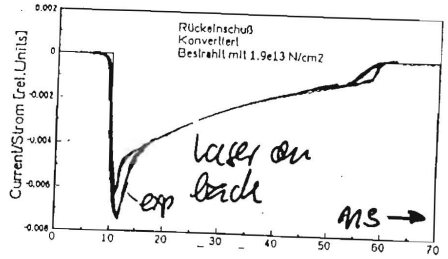








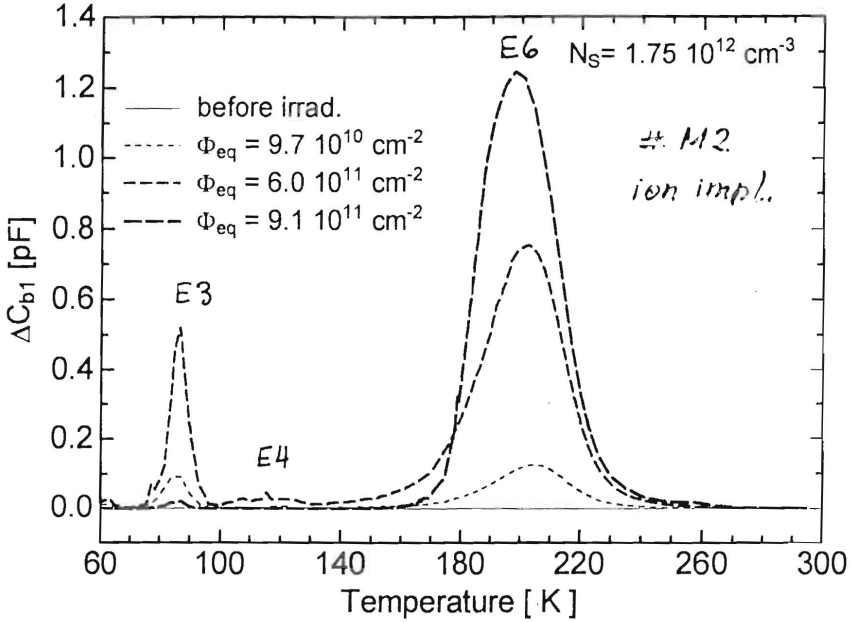




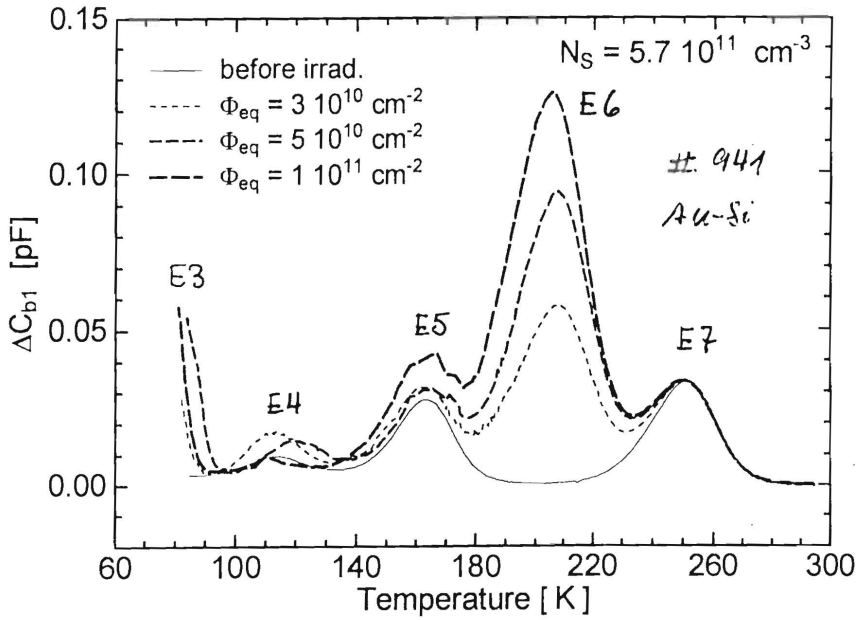
— experimental
— theoretical

Defect levels in neutron irradiated detectors

– DLTS measurements



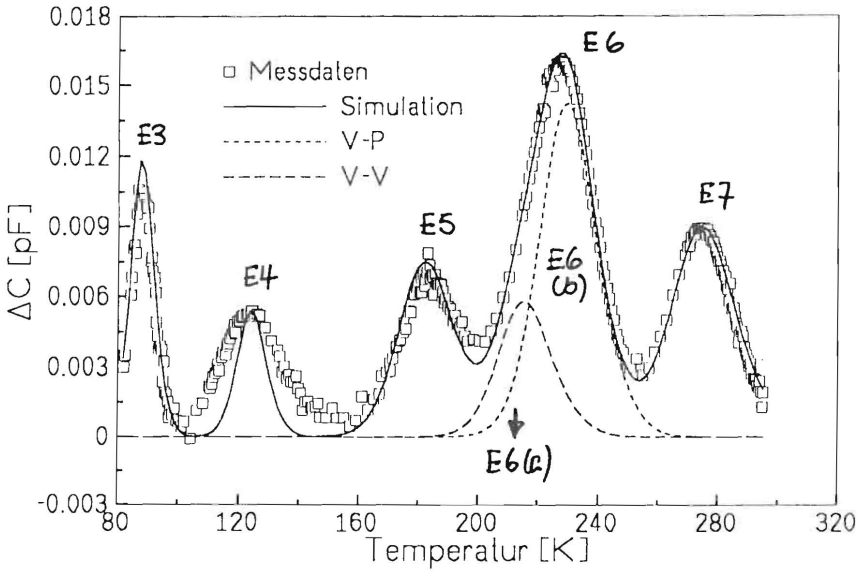
Defect label	Identification	ΔE [eV]
E3	A-center (VO), C_iC_s ?	0.18
E4	$V_2^=$	0.22
E6	V_2^- + E-center (VP) ?	0.42 + 0.39



ΔE [eV]	defect label	rad. induced	Identification
0.17	E3	yes	A-center + (C_iC_s)
(0.22)	E4	partly	$V_2^=$ + unknown
0.26	E5	no	unknown
0.42+0.39	E6	yes	V_2^- + E-center
0.53	E7	no	unknown

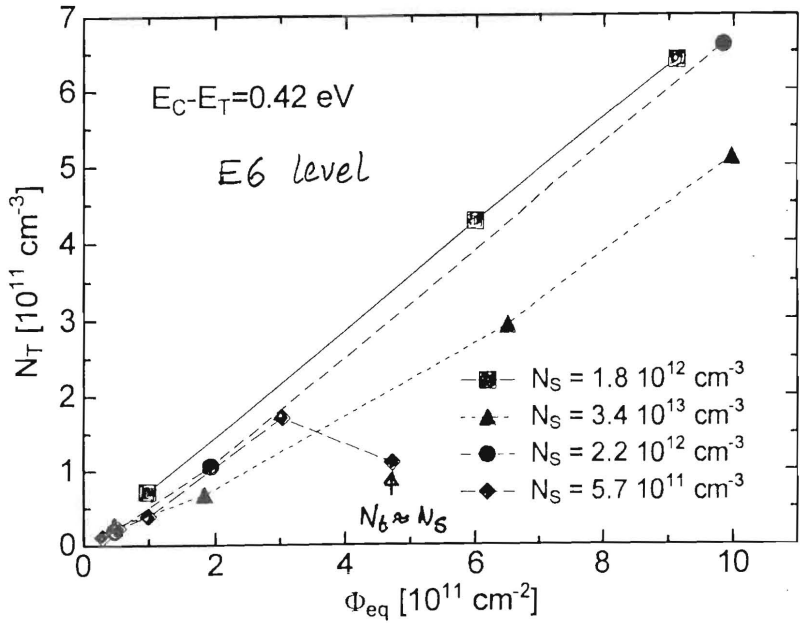
Analysis of the 0.42 eV level

wafer #941, 7000Ωcm



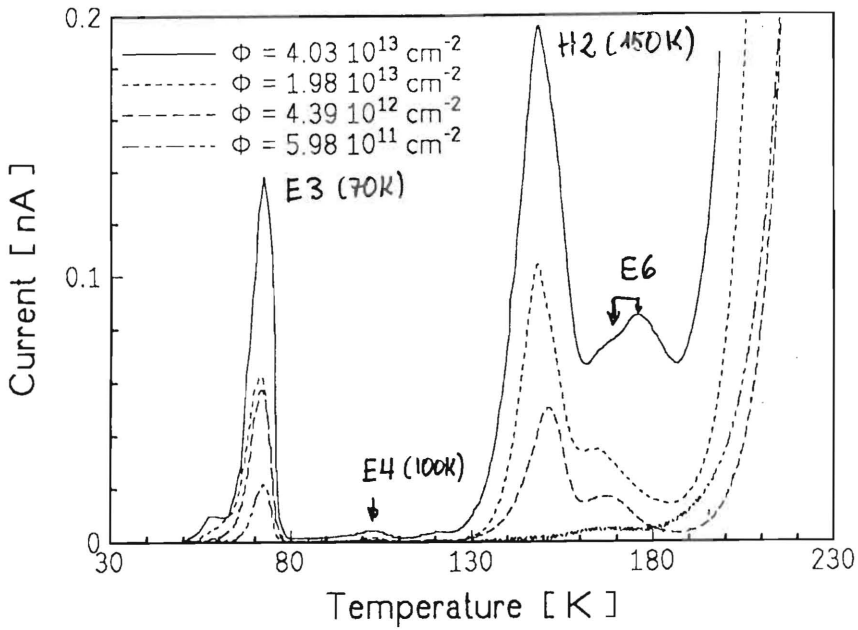
defect label	$E_c - E_t$ /eV	σ_n /cm²
E6 (a)	0.39	$1 \cdot 10^{-15}$
E6 (b)	0.42	$1 \cdot 10^{-15}$

Defect concentration versus fluence



	wafer	resistivity/Ωcm	generation rate/cm⁻¹
◆	#941	7000	0.6
■	#H2	2000	0.7
●	#93A	2000	0.7
▲	#938	100	0.5

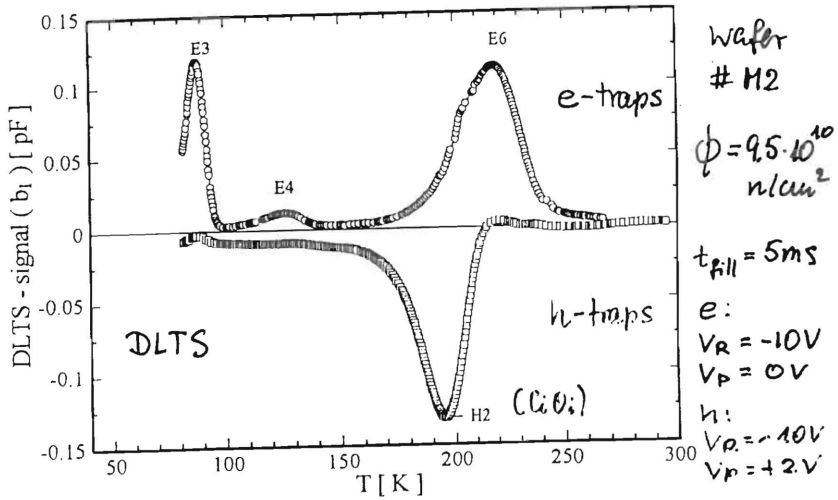
TSC measurements

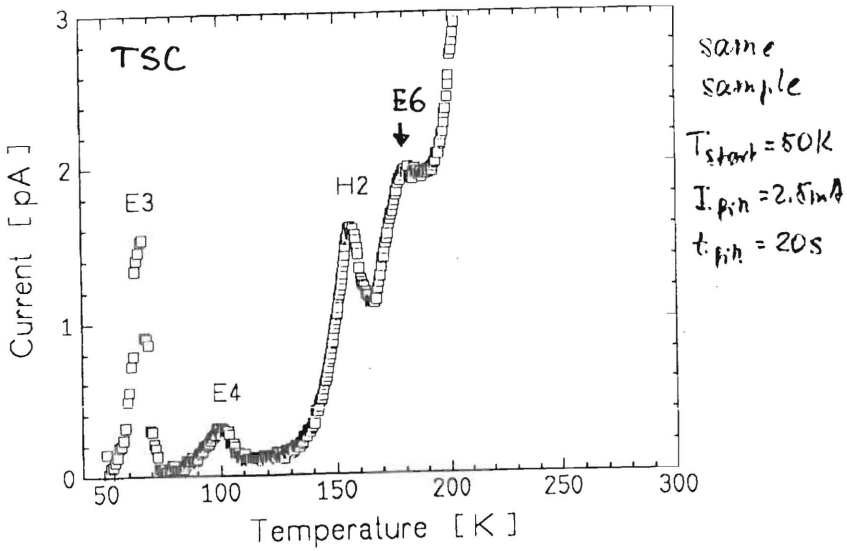


wafer #M2, ion implanted

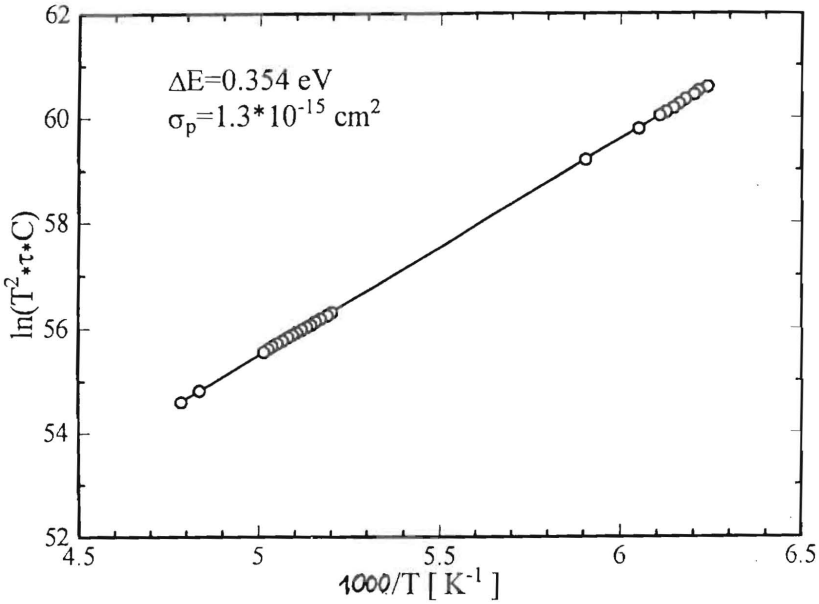
start temperature : 50 K
filling current : 2.5 mA
filling time : 20s

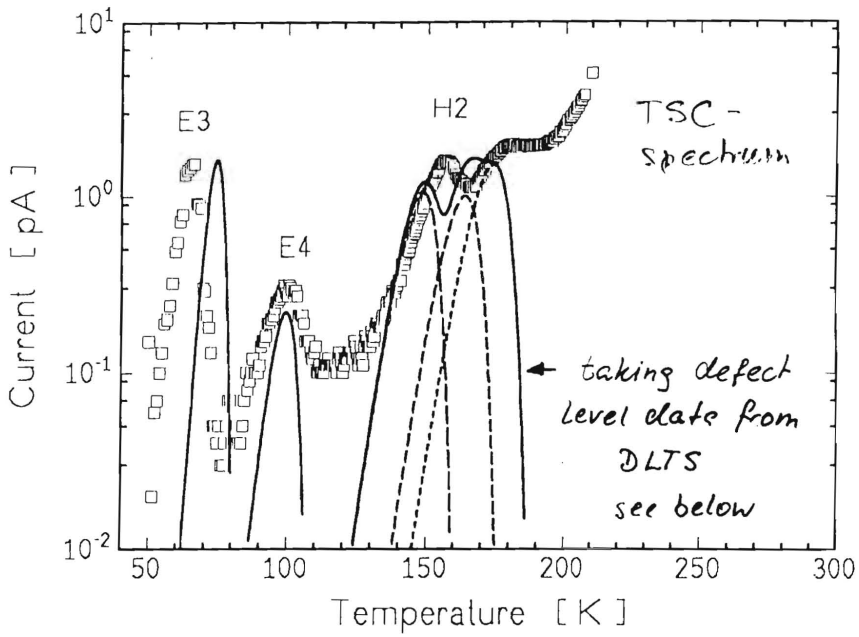
Comparison of DLTS -and TSC-measurements





Arrhenius plot of the H2 DLTS-peak

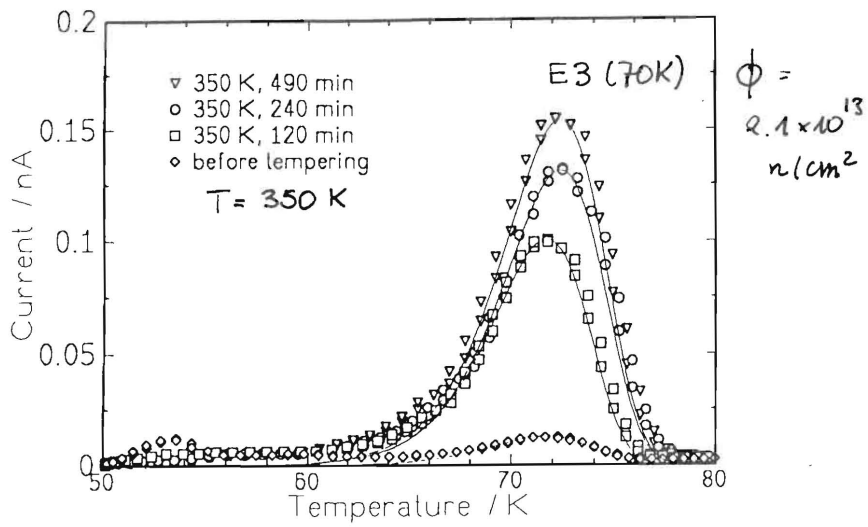


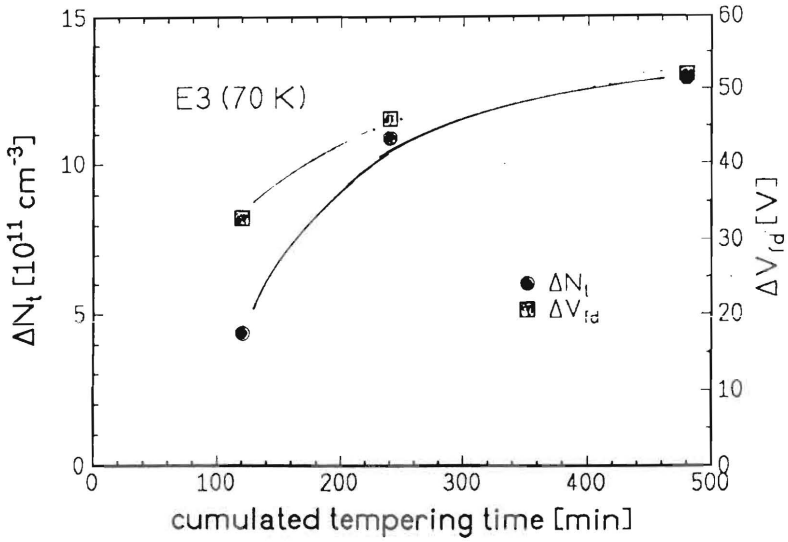


Fit-parameter

label	ΔE [eV]	σ [cm^2]	N_t [cm^{-3}]
E3	0.179	$2.90\ 10^{-14}$	$1.69\ 10^{10}$
E4	0.21	$1.62\ 10^{-16}$	$4.66\ 10^{9}$
H2	0.34	$3.18\ 10^{-16}$	$5.0\ 10^{10}$
E6a	0.39	$1.00\ 10^{-15}$	$5.0\ 10^{10}$
E6b	0.42	$1.20\ 10^{-15}$	$8.0\ 10^{10}$

Effect of isothermal heat treatment





- Summary

  - Macroscopic Effects of Bulk Damage in Silicon Detectors have been systematically studied for n, p and pion-irradiation. Results are in reasonable agreement with those of other groups (global fit: see Elba, Olaysen). Special care has been taken to exclude "hidden" parameters and to ensure reliability of results for material, particle and energy depend. (see Elman 95).

    Most important effect: Type inversion and reverse annealing of N_{eff}, leading to high operating voltages and thus limiting the operability for extended periods (10 years necessary for LHC). Detectors have to be cooled in order to keep reverse current low (power dissipation, S/N-ratio), avoiding long warm up periods since this will lead to activation of frozen reverse annealing.

  - Modelling and parametrization of effects as function of fluence, annealing time and temperature is reliable now, 2nd-order approach to reverse annealing of N_{eff} deduced by many measurements.

    Problems: With respect to available displacement cross sections, NIEL hypothesis only appr. valid. However work necessary to better understand differences between neutrons, protons, pions. complicated nature of defect dynamics (clusters) and primary interaction could be responsible.

- microscopic, i.e. physical, understanding of bulk damage much less systematically studied. In our studies we used conventional C-DLTS but with fast Fourier transform analysis. One temp. scan is thus producing all needed data.
  The analysis is relatively easy and leads to consistent results (exp. peaks as compared to simulations) several defects in irradiated and mod. mat. have been identified.
  Most prominent defects: A-center (V-O), V-V⁻ and E-center (V-P), introduction rates measured.
  Problems: limitation to $N_{Trap} \ll N_{shallow\ dopants}$
  Future plans: modification to laser induced I-DLTS

  Results using TSC in good agreement with DLTS
  No restriction with resp. to N_{Trap} but analysis more complicated.

! Correlation between microscopic measurements and macroscopic behaviour yet to be established

- TCT and p-μbeam have been demonstrated to be powerful tools for bulk and surface damage studies. Device modelling promising.

  Future plans: RDxx - a joint coordinated study of silicon radiation hardness combining all powerful groups
  Approach:
  Physical understanding → macroscopic features
  Bulk: Hardening by def. engineering

Recent publications from the Hamburg group

1. CERN Detector R&D Collaboration RD2
   S.J. Bates et al.
   The Design and Function of a Radiation Tolerant Silicon Tracker for an LHC Experiment
   Nucl. Phys. Proc. Suppl. B32 (1993) 250

2. H.W. Kraner, E. Fretwurst and Z. Li
   The Use fo the Signal Current Pulse Shape to Study the Internal Electric Field Profile and Trapping Effects in Neutron Damaged Silcion Detectors
   Contr. to VIth European Symposium on Semiconductor Detectors, Milano/Italy, February 1992
   Nucl. Instr. & Meth. A326 (1993) 350

3. E. Fretwurst, N. Claussen, N. Croitoru, G. Lindström, B. Papendick, U. Pein, H. Schatz, T. Schulz and R. Wunstorf
   Radiation Hardness of Silicon Detectors for Future Colliders
   Nucl. Instr. & Meth. in Phys. Res. A326 (1993) 357

4. CERN Detector R&D Collaboration RD2
   F. Anghinolfi et al.
   Neutron Irradiation of Silicon Diodes at Temperatures of +20°C and -20°C
   Nucl. Instr. & Meth. in Phys. Res. A326 (1993) 365

5. CERN Detector R&D Collaboration RD2
   E. Fretwurst, H. Feick, M. Glaser, C. Gössling, E.H.M. Heijne, A. Hess, F. Lemeilleur, G. Lindström, K.H. Mählmann, A. Rolf, T. Schulz and C. Soave
   Reverse Annealing of the Effective Impurity Concentration and Long Term Operational Scenario for Silicon Detectors in Future Collider Experiments
   Nucl. Instr. & Meth. in Phys. Res. A342 (1994) 119

6. CERN Detector R&D Collaboration RD2
   T. Schulz et al.
   Recent Results of Radiation Damage Studies in Silicon
   Nucl. Instr. & Meth. in Phys. Res. A344 (1994) 228

7. T. Schulz, H. Feick, E. Fretwurst, G. Lindström, M. Moll and K.H. Mählmann
   Long Term Reverse Annealing in Silicon Detectors
   IEEE Trans. Nucl. Sci. 41,4 (1994) 791

8. CERN Detector R&D Collaboration RD2
   R. Bonino et al.
   Electronics and readout of a large area silicon detector for LHC
   Nucl. Instr. & Meth. in Phys. Res. A344 (1994) 185

9. CERN Detector R&D Collaboration RD2
   A. Chilingarov et al.
   Some Recent Results of the Silicon Detector Radiation Damage Study by RD2 Collaboration
   Submitted to the Proceedings of the 6th Pisa Meeting on Advanced Detectors (1994),
   to be published in Nucl. Instr. & Meth. in Phys. Res. A (1995)

10. CERN Detector R&D Collaboration RD2 and RD20
    H. Feick et al.
    Radiation Studies and Operational Projections for Silicon in the ATLAS Inner Detector
    Submitted to the Proceedings of the 6th Pisa Meeting on Advanced Detectors (1994),
    to be published in Nucl. Instr. & Meth. in Phys. Res. A (1995)

11. M. Moll, H. Feick, E. Fretwurst, G. Lindström and T. Schulz
    Observation of a bistabile defect generated and activated by heat treatments in irradiated high resistivity silicon detectors
    Submitted to the Proceedings of the 4th Inf. Conf. on Advanced Technology and Particle Physics, Como 1994,
    to be published in Nucl. Phys. Proc. Suppl. B (1995)

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