

32nd RD50 Worskhop, Hamburg, 4-6. June 2018

Symposium in Honor of Dr.Eckhart Fretwurst



A brief history of the RD50 Collaboration

... in perspective of RD50 Hamburg team ..

Michael Moll

CERN, Geneva, Switzerland



- ... out of my perspective (198x - 1999)

- ...remember,

I was still a young student in Hamburg

so, from the outside things might have looked different

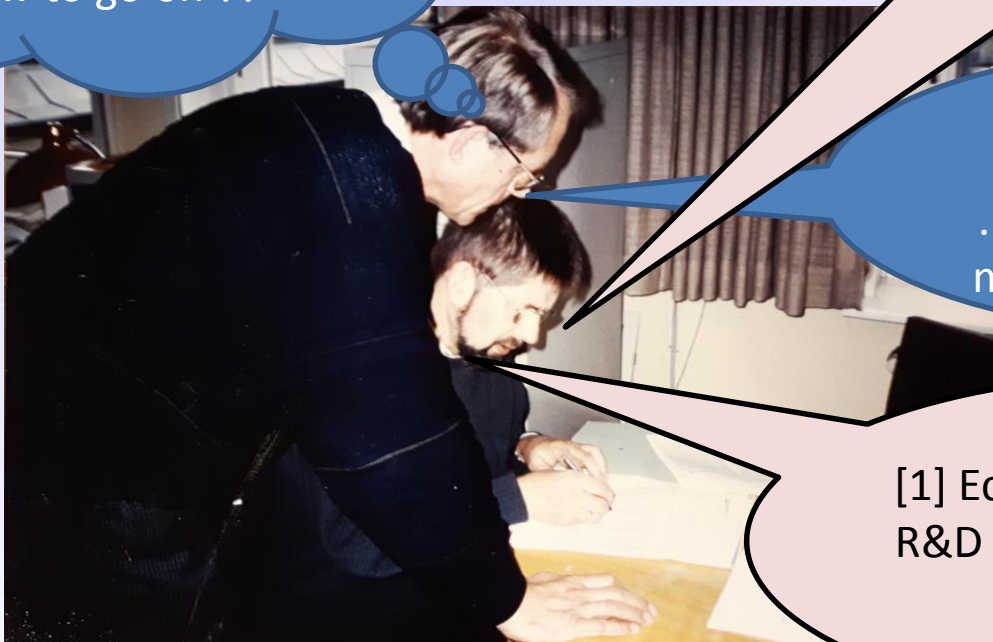
- Potentially like this: Jungiusstrasse, Hamburg, maybe rainy afternoon, around 198x.

[4] Hmm, I wonder who will teach and supervise all those students, help them if they don't know how to go on ??

[3] Eckhart, don't worry! We will build a team with lots of students.

[2] Good idea! Let's get started. ..but who will do all the measurements Gunnar?

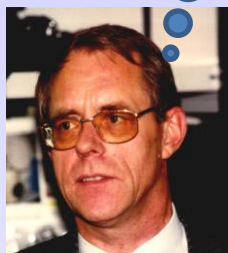
[1] Eckhart, we need to start R&D on radiation damage in silicon detectors.



- ..and the next step potentially like this: equipping the lab.

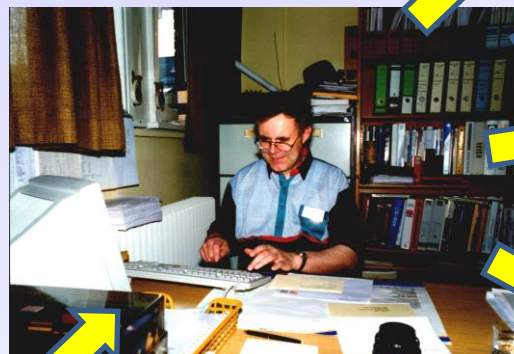
How to get the data?

How to equip the lab?



Uuuweeee

Kein Problem!



1997 Neutron irradiations at the PTB Braunschweig
“...lets switch off the radiation monitors, they make too much noise...”



Portable freezer
... liquid nitrogen all around
.. open transport in the trunk of our car

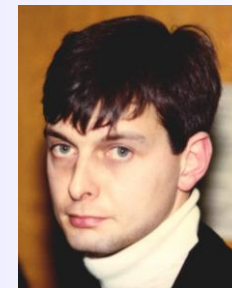
- ...working on the “Hamburg Model” 1987 - 2001

Systematische Untersuchungen zur Strahlenresistenz von Silizium-Detektoren für die Verwendung in Hochenergiephysik-Experimenten

Renate Wunstorf 1992

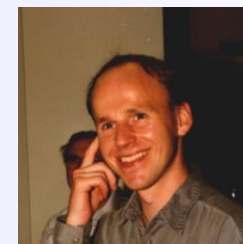


Investigation on the Long Term Behaviour of Damage Effects and Corresponding Defects in Detector Grade Silicon after Neutron Irradiation



Torsten Schulz 1992

Radiation Tolerance of Silicon Particle Detectors for High-Energy Physics Experiments



Henning Feick 1997

Radiation Damage in Silicon Particle Detectors

– microscopic defects and macroscopic properties –

Michael Moll 1999

Microscopic Investigations on various Silicon Materials Irradiated with different Particles with the DLTS Method



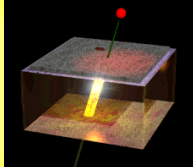
Look at that smile, I certainly had a good time!



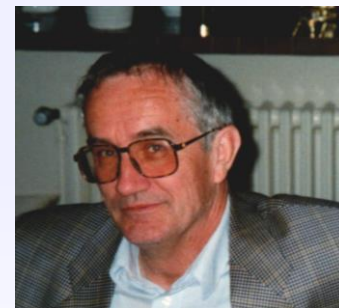
Martin Kuhnke 2001



... and many, many diploma students.



- Thank you Eckhart, thank you Gunnar and all the Nukleare Messtechnik team for the great years in Hamburg!



1999 ..inspiring visitors

- “Karin is not around,
let’s have a cigarette before we continue.”



- ...o.k. lets try again from another perspective:
How did RD50 start?

- R&D on radiation damage
- RD2 – formed 1990
- RD48 – The ROSE Collaboration (1995-2000)
- 23-24.10.2000 6th ROSE Workshop
 - Last RD48 Workshop, discussions how to continue are starting.....

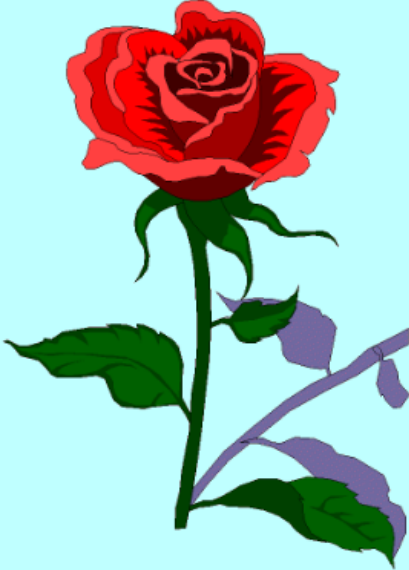
The ROSE Collaboration
CERN - RD48

ROSE
Research and development
On Silicon for future Experiments

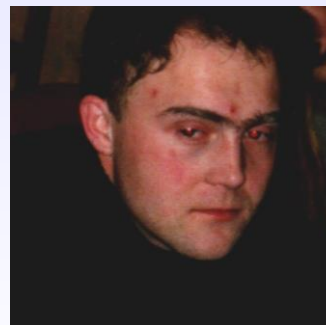
RD48 Spokespersons:
Dr. Francois Lemeilleur
Prof. Dr. Dr. hc. Gunnar Lindström
Prof. Dr. Stephen J. Watts

ROSE representative at CERN:
Dr. Michael Moll

[About ROSE](#)



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

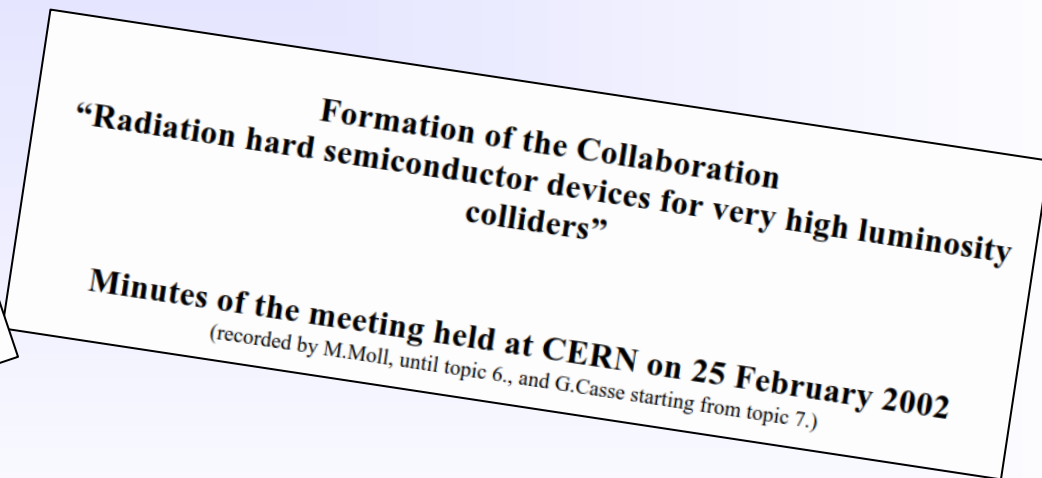
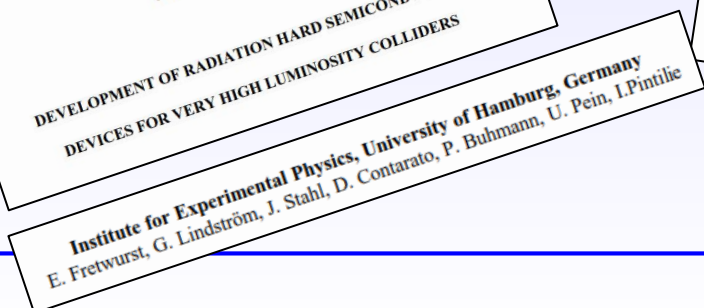




2001/2002: The RD50 story begins



- 28-31 November 2001 “1st Workshop on Radiation hard semiconductor devices for very high luminosity colliders” [100 participants]
- 15 February 2002: Proposal submitted to the LHCC
[proposal drivers & editors: C. Da Via, M.Moll, C.Joram,]
- 25 February 2002: Formation of the Collaboration
47 members: 45 Institutes and 2 Industrial Partners
 -and the first official role within the collaboration goes to:
 - Collaboration Board Chair: **Dr.Eckhart Fretwurst**
 - Spokespersons: Mara Bruzzi (Florence) and Claude Leroy (Montreal)
- 14/15 March 2002: Discussion of Proposal in LHCC closed session
- 15/16 May 2002: Proposal presented to the LHCC (open session)
- 30 May 2002: Proposal approved by Research Board and project defined as RD50



- **30 May 2002 : Research Board approves the proposal**
 - ..following the recommendation of the LHCC (Large Hadron Collider Committee)

MINUTES OF THE 159th MEETING OF THE RESEARCH BOARD
HELD ON THURSDAY, 30 May 2002

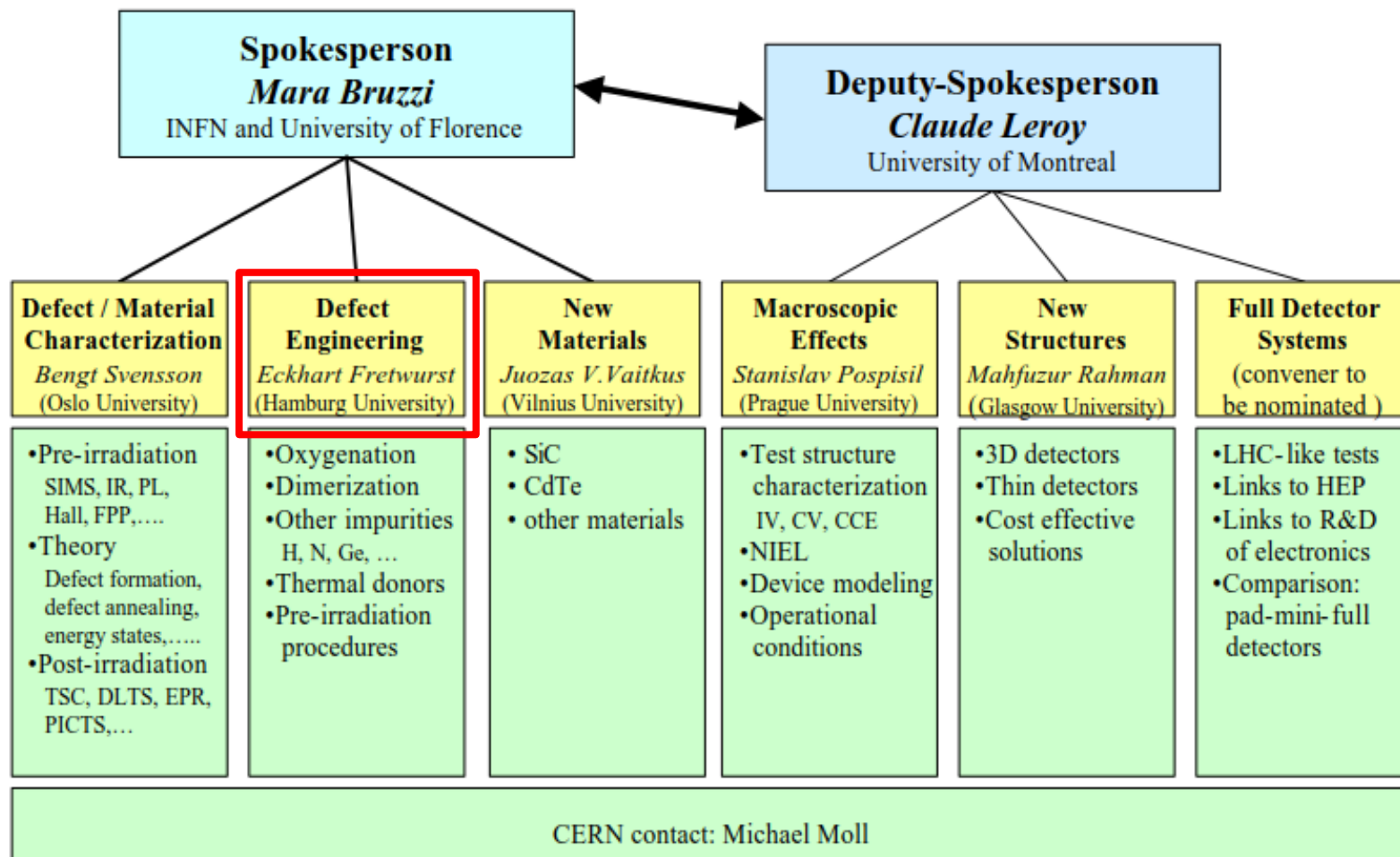
3. **REPORTS AND MATTERS ARISING FROM THE LHCC MEETING OF
15-16 MAY 2002**

M. Calvetti reported on the 58th meeting of the LHCC. 3

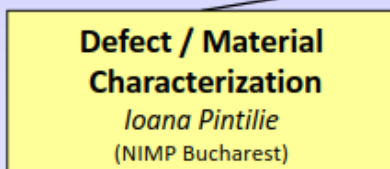
He also described a new R&D proposal [10] that intends to develop semiconductor devices that could operate at hadron collider luminosities as high as $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. The LHCC estimated that the proposed programme of research is sound and therefore recommended approval of this proposal with the proviso that the collaboration presents a clearer organizational structure. The Research Board **concurred** with this recommendation. The new R&D project will be known as **RD50**.

In the ensuing discussion on semiconductor R&D Schlatter pointed out that, whereas CERN resources was wished for, these were not available.

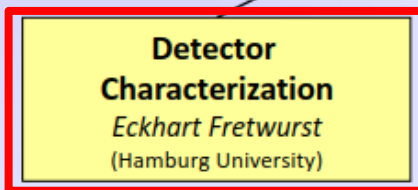
Born in times of strong funding concerns for the LHC construction; guideline at CERN :
“O.k, you can spend some time on R&D, but don’t ask for resources and don’t take any visible role in an R&D collaboration”



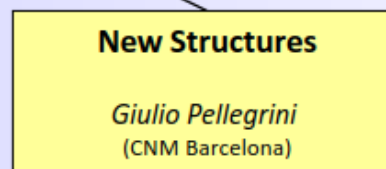
LHCC presentation: May 2002



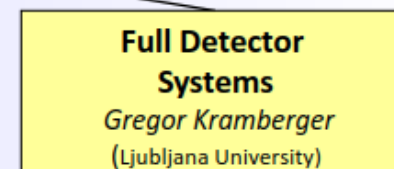
- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC,
- SIMS, SR, ...
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects



- Characterization of test structures (IV, CV, CCE, TCT,..)
- Development and testing of defect engineered devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD simulations



- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- LGAD: Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS
- LGAD (S.Hidalgo)
- HVCMOS (E. Vilella)
- Slim Edges (V.Fadeyev)



- LHC-like tests
- Links to HEP(LHC upgrade, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibava)
- Comparison:
 - pad-mini-full detectors
 - different producers
- Radiation Damage in HEP detectors
- Timing detectors
- Test beams (M.Bomben & G.Casse)

*Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
 CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder & GLIMOS: M.Moll & M.Glaser (EP-DT)*

- 2002: n-in-p segmented sensors: not mentioned in proposal
- 2004: First “very encouraging” results on p-type strip sensors presented

RD50 n-in-p microstrip detectors LHCC 2005

RD50 n-in-p microstrip detector LHCC 2006

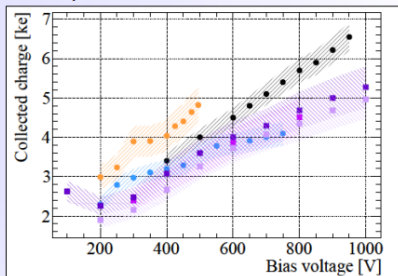
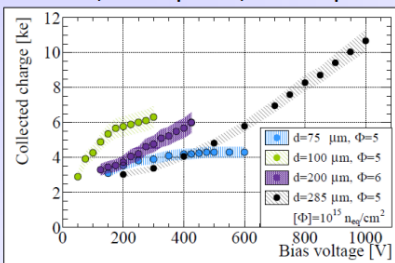
n-in-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- n-in-p microstrip detectors on p-type FZ (280 μ m thick, 80 μ m pitch, 18 μ m implant)
- Detectors read-out with 40MHz



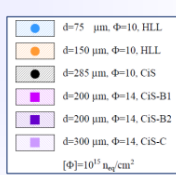
RD50 Thin p-type pixel sensors

- Thin FZ p-type pixel sensors: 75 to 300 μ m with 450 μ m edge (MPI/CIS/VTT)
- ATLAS FE14, 25 MeV protons, 800 MeV protons, neutrons, data obtained with beta source



- Detectors irradiated with $5 \times 10^{15} n_{eq}/cm^2$
- 100 μ m thick sensors give more charge than 75 μ m thick sensors, both saturate with voltage
- 200 μ m thick sensors give more charge than 300 μ m thick sensors at moderate voltage
- Beam tests show 97-99% hit efficiency (thickness tested 100 -200 μ m, 500V)

- Detectors irradiated up to $1.4 \times 10^{16} n_{eq}/cm^2$
- Sensor modules still functional (even if in homogeneously irradiated)



LHCC 2015

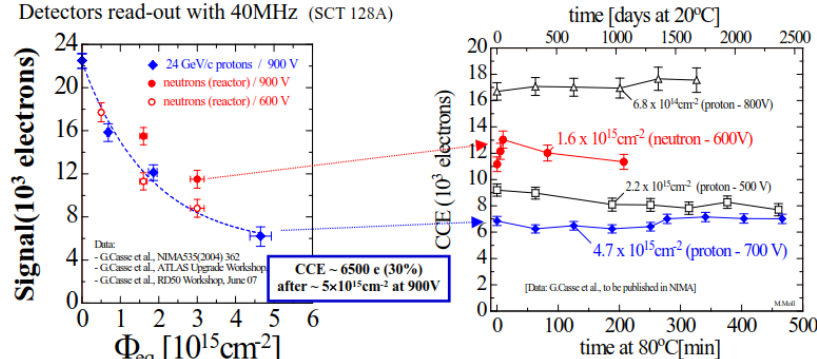
hen, 25th RD50 Workshop Nov. 2014

RD50 Annealing of p-type sensors LHCC 2005

RD50 n-in-p microstrip detectors LHCC 2007

n-in-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- n-in-p microstrip p-type FZ detectors (Micron, 280 or 300 μ m thick, 80 μ m pitch, 18 μ m implant)
- Detectors read-out with 40MHz (SCT 128A)



- n-in-p sensors are now strongly considered for ATLAS upgrade (previously p-in-n was used)

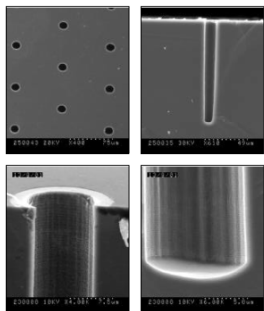
- no reverse annealing visible in CCE measurements for neutron and proton irradiated detectors

Mara Bruzzi and Michael Moll on behalf of the RD50 CERN Collaboration – LHCC, November 21, 2007 -9-

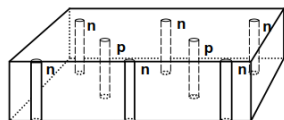
Today: For HL-LHC upgrades the trackers and the pixel will be based on n-on-p technology!

Device Engineering: 3D detectors

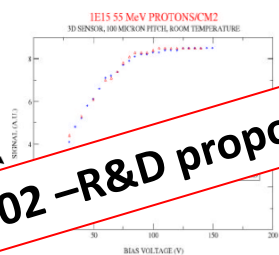
p^+ and n^+ polysilicon electrodes in narrow columns along the detector thickness.
Depletion depth develops laterally - Typical electrode distances: 50-100 μm .
Very fast collection times, low full depletion voltages ($\sim 10\text{V}$), full charge collection over the 300 μm detector active thickness



Size up to $\sim 1\text{cm}^2$



First radiation hardness tests after 10^{15} cm^{-2} 55MeV protons (measured with IR LED)



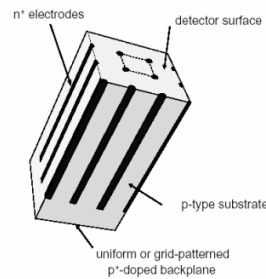
2002 - R&D proposal

R. Bates, 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders, CERN, November 2001.

LHCC 15 May 2002 M. Bruzzi

16

RD50 3D Detectors: New Architecture



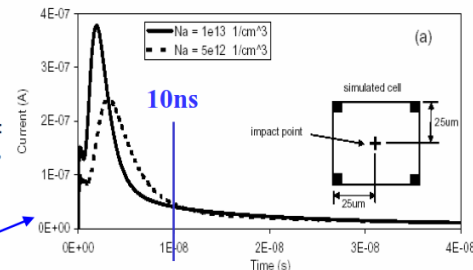
- Simplified 3D architecture**
 - n^+ columns in p-type
 - operation similar to standard
- Simplified process**
 - hole etching and doping only done once
 - no wafer bonding technology needed

Fabrication planned for 2005

- INFN/Trento funded project: collaboration between IRST, Trento and CNM Barcelona

Simulation

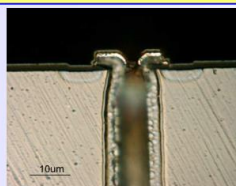
- CCE within $< 10\text{ ns}$
- worst case shown (hit in middle of cell)



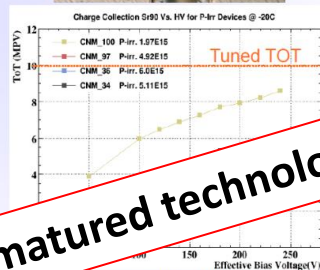
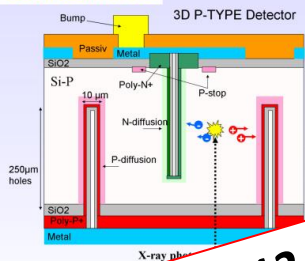
C. Piemonte et al. Presented at STD05, June 04, Hiroshima, in press on Nucl. Instrum. Meth. A. -14-

New structures: 3D sensors

- 3D sensors: Mastering the technology (CNM-Barcelona, FBK-Trento)**
- Reproducible, reliable results before and after irradiation



Double sided 3D



2012 - matured technology

G.Casse and M.Moll, RD50 Status Report, June 2012 -16-



May 2014 - ATLAS IBL installed
...3D detectors are operating in the LHC

Many tools and characterization techniques developed by RD50 ... examples

RD50 Edge-TCT to Study Fields

- **Edge-TCT: Illuminate sensor from the side**
- **Scan across detector thickness**
- **Measure charge and induced current as function of depth**
- **Reconstruct electric field**

- **Expectation**
 - Significant electric field only in depleted silicon
 - Charge generated in undepleted part of detector is lost
 - Field not easy to probe but recently became accessible using Edge-TCT

Labels in diagram: Laser (1060 nm, 100 ps pulse, 200 Hz - 1 MHz repetition), scanning direction, y=0, y=W, T = -20°C, HV, Micro AM-1309, 1.5 GHz scope, n+ implant (all connected to HV), p bulk, drift direction electrons, FWHM = 8 μm, drift direction holes, p+ implant, NOT TO SCALE!

[G. Kramberger, 17th RD50 Workshop, Nov. 2010]

LHCC 2011 : edge-TCT

RD50 Charge collection and velocity profiles

RD50 Micron p-type sensor

CHARGE COLLECTION PROFILE

VELOCITY PROFILE

Equations: $I(y, t) \propto v_e + v_h$, $Q(y) = \int_0^{25ns} I(y, t) dt$, $\langle Q \rangle \propto Q = \int_0^{25ns} I(y, t) dt$

Legend for bias voltages: $V_{bias} = 200V, 120V, 70V, 30V, 20V, 10V, 0V$

[G. Kramberger, 17th RD50 Workshop, Nov. 2010]

RD50 TPA – Two Photon Absorption

- Investigation on a new technique for sensor characterization (TPA – TCT)
- Deposition of charge at specific position in detector
- Laser: $\lambda \sim 1300$ nm; $P \sim 50$ -100 μ J; $\Delta T \sim 240$ fs
- Proof of principle achieved:

Two Photon absorption: 2-Photon, Specimen focal plane, Confocal (1-Photon)

Diode Displacement

80 x $n_{index_Si} \sim 280 \mu m$

Carga calculada del Scan vertical-Diodo W9F9-TPA-V=500

• r spot size $\rightarrow 1\sigma - 0.8 \mu m$ & $2\sigma - 3.4 \mu m$
 • z spot size $\rightarrow 1\sigma - 13 \mu m$ & $2\sigma - 60 \mu m$

[L.Vila, 25th RD50 Workshop, CERN, November 2014] G.Casse and M.Moll, RD50 Status Report, June 2015 -21-

LHCC 2015 : TPA-TCT

..spin offs

ALIBAVA SYSTEMS

Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273-275 (2016) 2563-2565

ALIBAVA Silicon Microstrip Readout System for Educational Purposes

particulars, advanced measurement

home products support technical library tutorials references faq contact

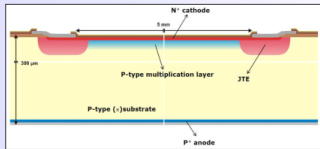
Born out of RD50 “charge multiplication studies”

RD50 First production of low gain diodes

- Diodes with implemented multiplication layer (deep p+ implant)

- Following APD concept

$n^{++} - p^{+} - p - p^{+}$ structure



- Gain of ~10 before irradiation

- Spectra are Landau spectra (⁹⁰Sr)

- Gain reduces with irradiation

- Dropping to about 1.5 after 2e15 n/cm². Why? Boron removal in p-type layer

- Current and noise scale as expected with multiplication

- Characterization with alpha's (Am-241)



[G.Kramberger, 22nd RD50 Workshop, Albuquerque, June 2013]

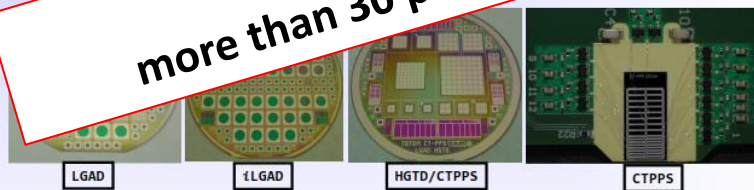
G.Casse and M.Moll, RD50 Status Report, June 2013 -12-

2013 : first time presented to LHCC

RD50 LGAD within RD50 Collaboration

- 2010: LGAD activities started with CNM project
- 2012: First 4 inch wafer, 300 µm thick, LGAD
- 2014: First 200 µm thick LGAD. First Gallium Process
- 2015: First PiN on 6 inch wafer. First Inverse L
- 2016: First 50 µm thick LGAD for T
- 2017: First LGAD
- 2018: First 35 µm thick LGAD

2010 - 2018 : more than 30 production runs



- FBK, Trento: 1st batch of LGAD in 2016, 2nd in 2017 (processed, being characterized)
- p-side and n-side segmentation, pixel, strip, AC coupling, ... (see Annex)
- Today: CNM Spain, FBK Italy and HPK Japan produced LGAD's (3 suppliers)

[C. Pellegrini et al. "Low Gain Avalanche Detectors (LGAD) Update 2016]

G.Casse and M.Moll, RD50 Status Report, May 2017 -18-

RD50 LGAD for Timing Applications

- LHC experiments starting to implement/plan on Si based timing detectors with RD50 technology

- CTPPS – CMS-TOTEM Precision Proton Spectrometer

- Installed in 2016 YETS in two Roman pots two planes of segmented LGAD

- Time resolution measured by CTPPS (at high voltage!)
 - 45 µm LGAD on SOI – 1.7 mm²
 - 27ps single device; 16 ps with 3 layers (@ 230 V)

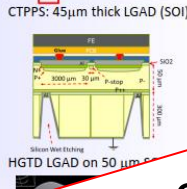
- ATLAS AFP - Forward Proton

- 30 ps up to 3x10¹⁴ n_{eq}/cm²
- 57 ps at 10¹³ n_{eq}/cm² (@ 620 V)

- ATLAS HGTD - High Granularity Timing Detector

- CMS Timing layer

- Planning for hermetic timing detector for phase II;
- CB approved a full coverage eta 0 – 3 timing layer for MIPs crystals in the barrel and LGAD as baseline in the endcap
- Expect: 10¹⁴ n_{eq}/cm² to 10¹⁵ n_{eq}/cm²; 9m² (tentative: 40-50µm thick, 1x3)

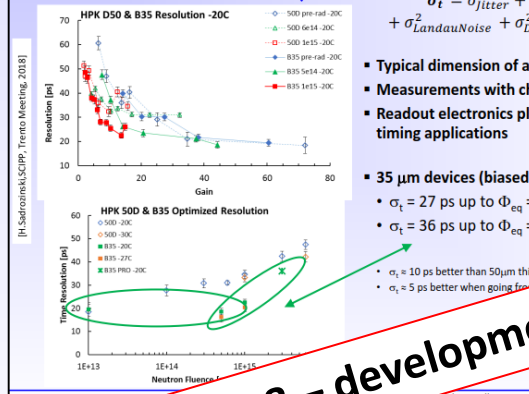


G.Casse and M.Moll, RD50 Status Report, May 2017 -19-

LHCC 2017 – going into experiments

RD50 LGADs for precision timing

- LGADs with thickness of 50 or 35 µm



$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{LandauNoise}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{ADC}}^2$$

- Typical dimension of active region ≈ 1mm²
- Measurements with charged particles
- Readout electronics plays major role in timing applications

- 35 µm devices (biased up to 500V):

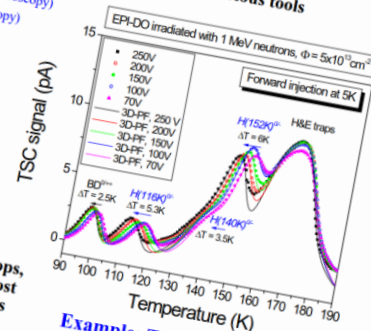
- σ_t = 27 ps up to Φ_{eq} = 10¹⁵cm⁻²
- σ_t = 36 ps up to Φ_{eq} = 3·10¹⁵cm⁻²
- σ_t = 10 ps better than 50µm thick device
- σ_t = 5 ps better when going for

LHCC 2018 – development in full swing

- Very strong impact from the Hamburg and Bucharest teams
 - .. see following presentation of Ioana Pintilie

WODEAN

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G.Lindstrom, Hamburg)
 - **Aim:** Identify defects responsible for Trapping, Leakage Current, Change of N_{eff} available inside the RD50 network
 - **Method:** Defect Analysis on identical samples performed with the various tools
 - 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 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

LHCC 2008



1999

- and many more success stories (simulations, models, sensor designs,....)
 - ... sorry, for not being able to show them all

- Development of the **p-type silicon** strip and pixel technology
- Double column **3D detectors** and first industrialization at CNM and FBK
- Convincing demonstration of the performance of **planar segmented sensors** to the maximum fluences anticipated for the HL-LHC ($3 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$)
- Extensive evaluation of **defect engineered Silicon** and other semiconductor materials
- Observation and explanation of **charge multiplication** in highly irradiated sensors operated at high voltage
- Design and production of **LGAD (Low Gain Avalanche Detectors)** for 4D tracking
- Development of **several unique characterization methods** and systems for sensor and material analyses: Transient Current Technique (TCT), Edge-TCT, Two Photon Absorption (TPA)-TCT, Alivaba readout system and standardized measurement and analyses procedures, partly now marketed through spin-off companies
- **Defect characterization**: identification of defects responsible for the degradation of various detectors parameters defining the state of the art in the corresponding solid state community
- Data collection and **development of damage parameters/models** essential for sensor design (TCAD parameters) and for planning the running scenarios of LHC experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise,....)
- **Close links to the LHC experiments (upgrades and operation)**

- RD50 produced long articles: Eckhart consumed 3 pages for the title and abstract

Recent advancements in the development of radiation hard semiconductor detectors for S-LHC

E. Fretwurst^{a,*}, J. Adey^b, A. Al-Ajili^c, G. Alfieri^d, P.P. Allport^e, M. Artuso^f, S. Assouak^g, B.S. Avset^h, L. Barabashⁱ, A. Barcz^j, R. Bates^c, S.F. Biagi^c, G.M. Bilei^k, D. Bisello^l, A. Blue^c, A. Blumenau^b, V. Boisvert^m, G. Bollaⁿ,

...plus typo:
S-LHC (Super – LHC)
....became
HL-LHC (High Lumi – LHC)

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Nuclear Instruments and Methods in Physics Research A 552 (2005) 7–19

Recent advancements in the development of radiation hard semiconductor detectors for S-LHC

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8

E. Fretwurst et al. / Nuclear Instruments and Methods in Physics Research A 552 (2005) 7–19

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9

E. Fretwurst et al. / Nuclear Instruments and Methods in Physics Research A 552 (2005) 7–19

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The CERN RD50 collaboration

Abstract

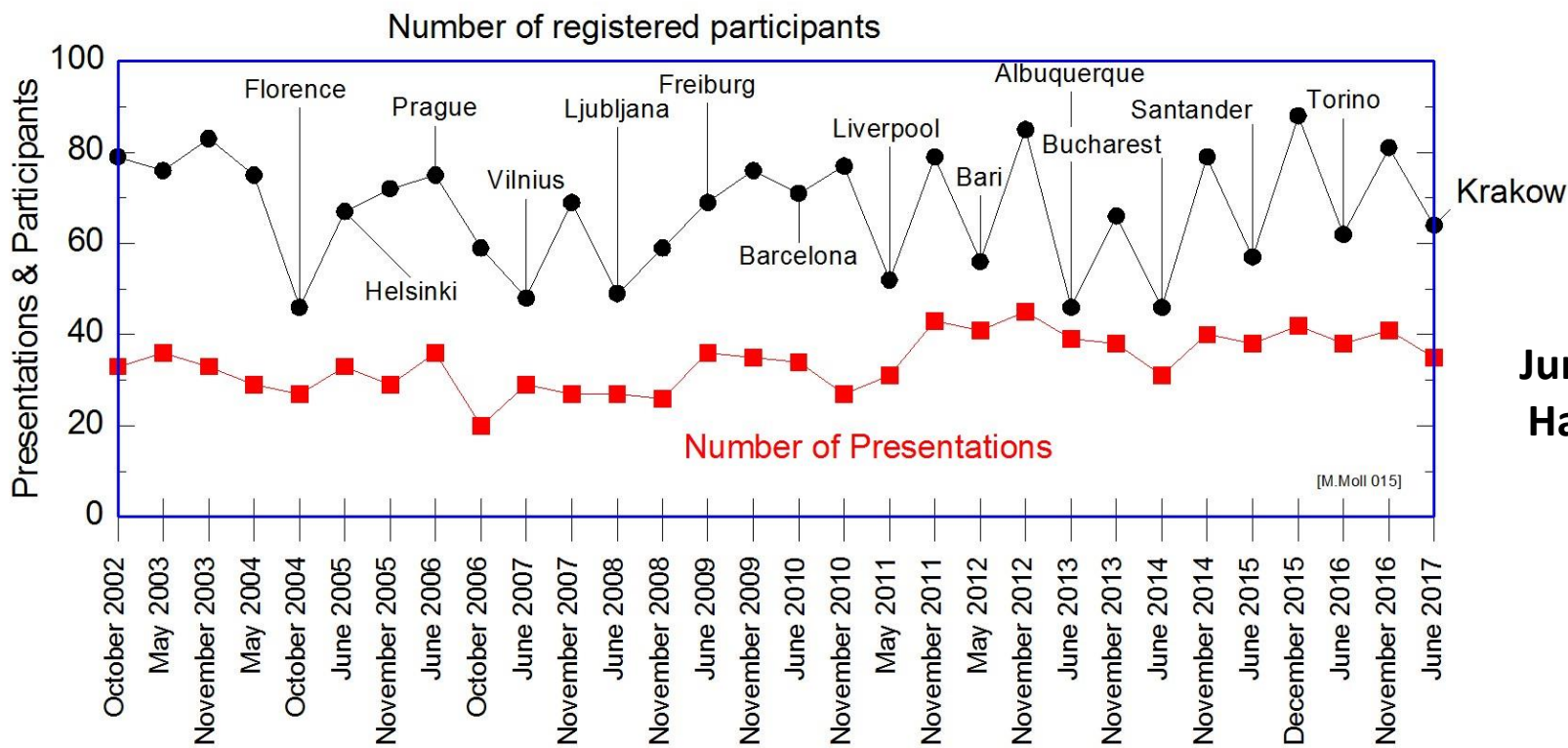
The proposed luminosity upgrade of the Large Hadron Collider (LHC) at CERN will demand the innermost layers of the vertex detectors to sustain fluences of about 10^{16} hadrons/cm². Due to the high multiplicity of tracks, the required spatial resolution and the extremely harsh radiation field new detector concepts and semiconductor materials have to be explored for a possible solution of this challenge. The CERN RD50 collaboration "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" has started in 2002 an R&D program for the development of detector technologies that will fulfill the requirements of the S-LHC. Different strategies are followed by RD50 to improve the radiation tolerance. These include the development of defect engineered silicon like Caschrahlak, epitaxial and oxygen-enriched silicon and of other semiconductor materials like SiC and GaN as well as extensive studies of the microscopic defects responsible for the degradation of irradiated sensors. Further, with 3D, Semi-3D and thin device new detector concepts have been evaluated. These and other recent advancements of the RD50 collaboration are presented and discussed.

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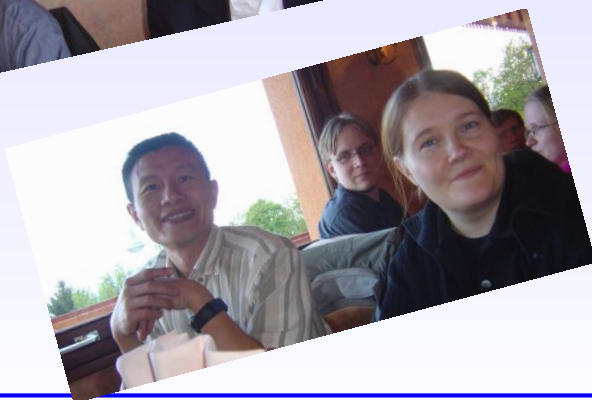
Keywords: Radiation damage; Semiconductor detectors; Defect engineering; Super-LHC

PACS: 29.40.Gg; 29.40.Wg; 61.82.Fg

- 2 Workshops per year: One at CERN in November and one outside in summer
- The R&D highlights of the year 😊 ..and a lot of fun.

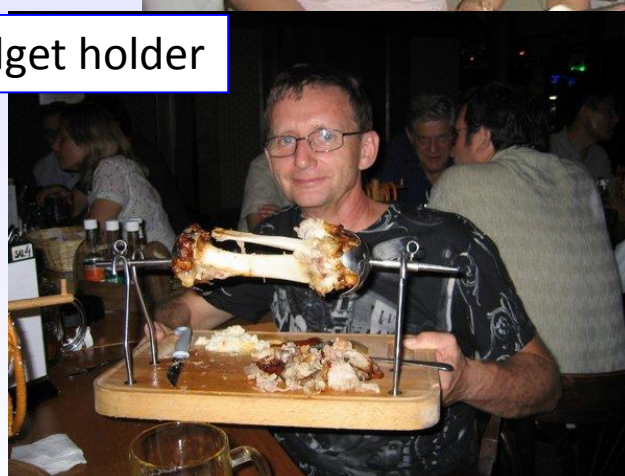


**June 2018
Hamburg**





.. RD50 budget holder





.. with cake and press conference at the Center of Europe









- **RD50: 59 institutes and 345 members...**

... forming a *COLLABORATION!*

The RD50 community brings together:
solid state physicists; device physicists;
experts of radiation-matter interactions;
high energy physicists; electronics system designers;
ASICs designers; sensor foundries.

This community has learned to work towards common goals developing methods, tools and standards that are world reference for the domain.

This vast expertise is an unsurpassed basis for continuing research towards sensor solution for future challenges.

- **5 year work plan submitted to LHCC on 31.May 2018**
 -just in time for the 1.6.2018 (...a special day, Eckhart's Birthday, see next slide).



<https://cds.cern.ch/record/2320882/files/LHCC-SR-007.pdf>

80 years
Happy Birthday Eckhart
and
many thanks for your
outstanding contribution to RD50
... in science and in management

P.S.: We count on your contribution for the future