Radiation Damage in Bipolar Transistors Caused by Thermal Neutrons

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INTRODUCTION

- important fraction of neutrons in radiation fields in experiments at high luminosity hadron colliders (LHC) have thermal energies

→ neutron fluence in ATLAS SCT after 10 years:

all neutrons : $4 \cdot 10^{14}$ n/cm^2

thermal neutrons: $2 \cdot 10^{14}$ n/cm^2

- fast neutrons (E > 100 keV) cause bulk damage by knocking Si atoms out of crystal lattice

- thermal neutrons cause bulk damage by triggering nuclear reactions in which energetic fragments are released

→ in pure silicon effect small compared to fast neutrons

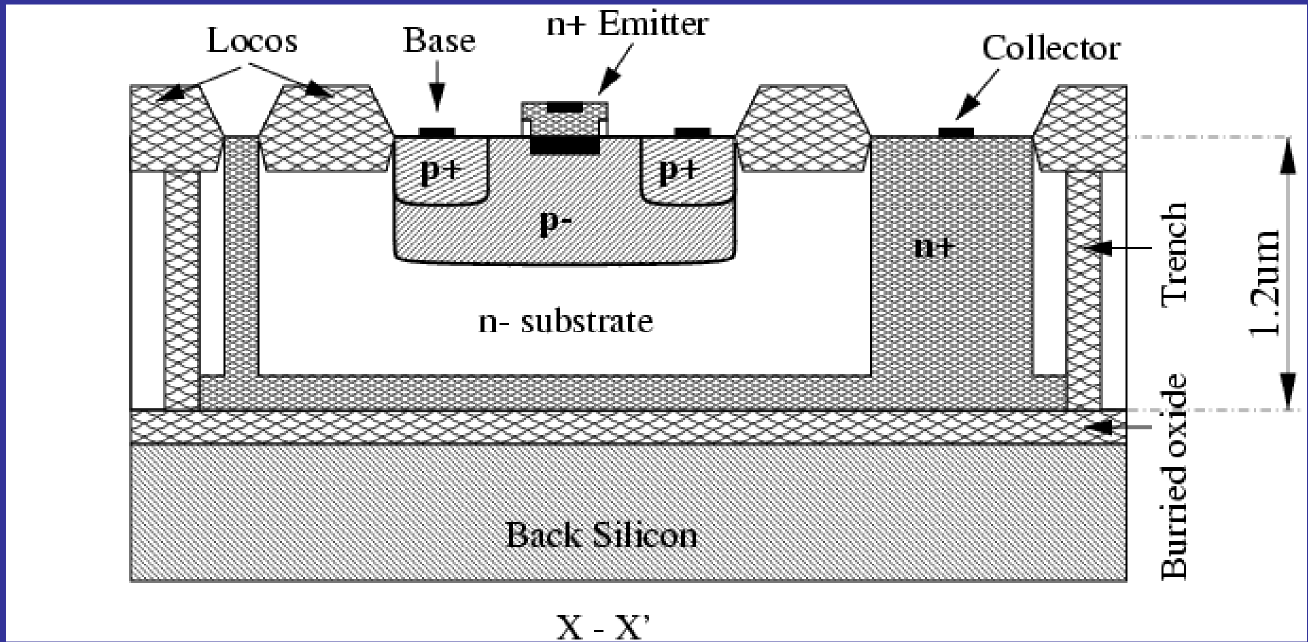
- in p-type silicon B is used as dopant
- effect of thermal neutrons enhanced by neutron capture on boron:

$$^{10}B + {}^{1}n \longrightarrow {}^{7}Li + {}^{4}\alpha + \gamma \quad \text{(2.3 MeV released)}$$

  - large cross section $\sigma \sim 3400$ barn

- Li and α have range of ~ 5 µm
  - large damage close to highly doped regions
  - potentially dangerous in integrated bipolar transistors

- cross section of *npn* bipolar transistor



- fragments from boron reaction in p+ regions can cause bulk damage in the base
- similar effect has already been measured in pnp transistors: *IEEE TNS Vol. 20 (1973) pp 274-279*

IRRADIATIONS

- DMILL *npn* transistors of the same design as used in ATLAS-SCT front-end ASIC were irradiated in reactor in Ljubljana

- irradiations were done at two sites in the reactor:

1. channel F19 inside the reactor core:
   - fast neutrons (E > 100 keV), contributing to NIEL
   - thermal neutrons

$$\Phi_{equivalent}/\Phi_{thermal} \sim 0.6$$

⇨ irradiations inside Cd shield: **fast neutrons only!**

2. Dry Chamber: 1 m of graphite between the core and the DC
   - thermal neutrons only

     $\Phi_{equivalent}/\Phi_{thermal} < 0.03$

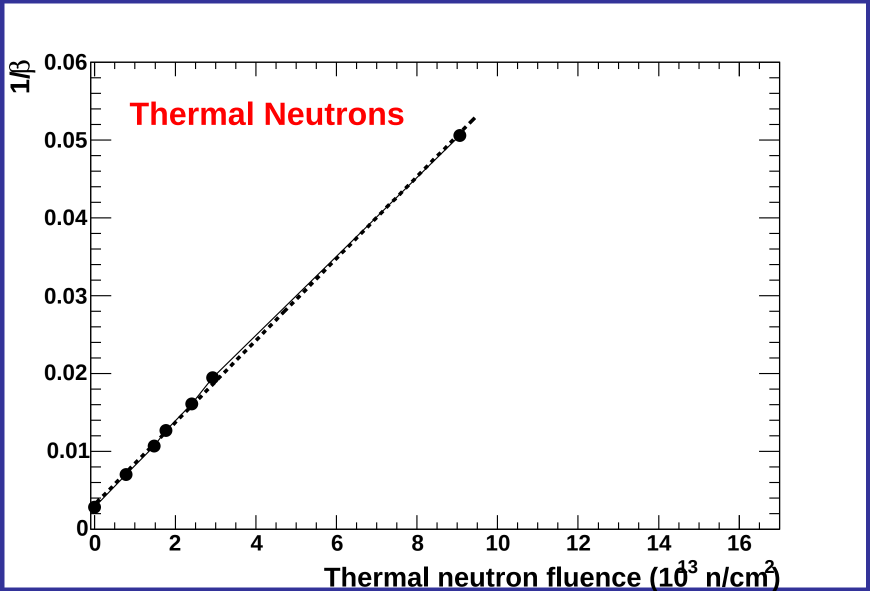
Common emitter current gain factor $\beta = I_{collector}/I_{base}$

measured as a function of neutron fluence

1/β vs. thermal neutron fluence

Dry Chamber:

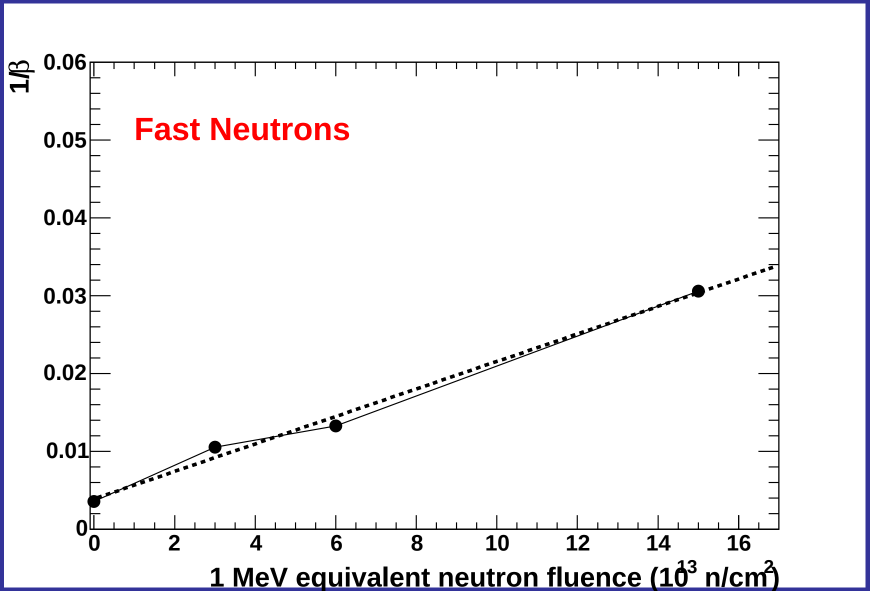
$$\Delta 1/\beta = k_{thermal} \cdot \Phi_{thermal}$$



1/β vs. 1 MeV equivalent neutron fluence delivered by fast neutrons

F19, Cd shield:

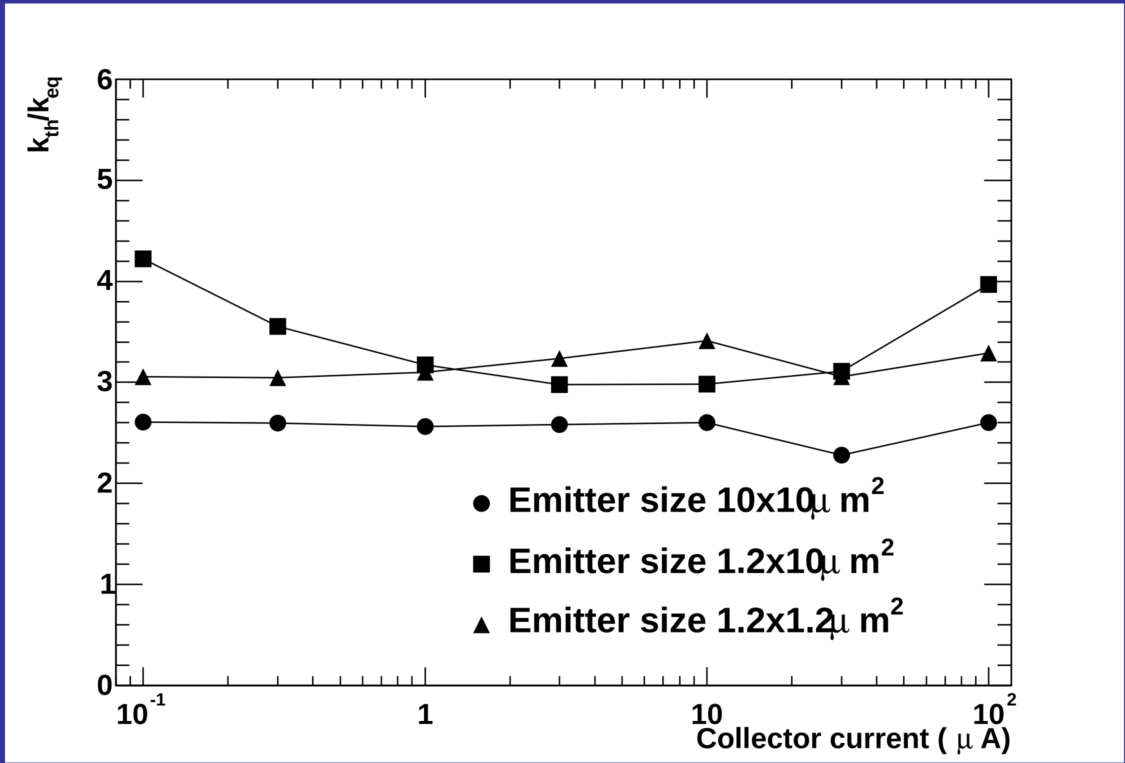
$$\Delta 1/\beta = k_{eq} \cdot \Phi_{eq}$$



Large damage caused by thermal neutrons!

- thermal: $\Delta 1/\beta = k_{thermal} \cdot \Phi_{thermal}$
- 1 MeV equivalent, delivered by fast: $\Delta 1/\beta = k_{eq} \cdot \Phi_{eq}$

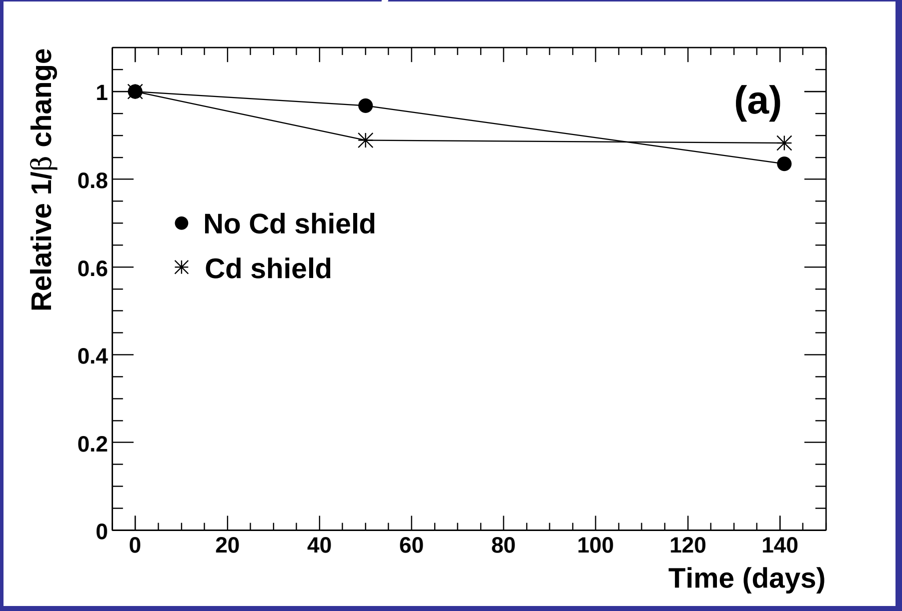
$$k_{thermal}/k_{eq} \sim 3$$



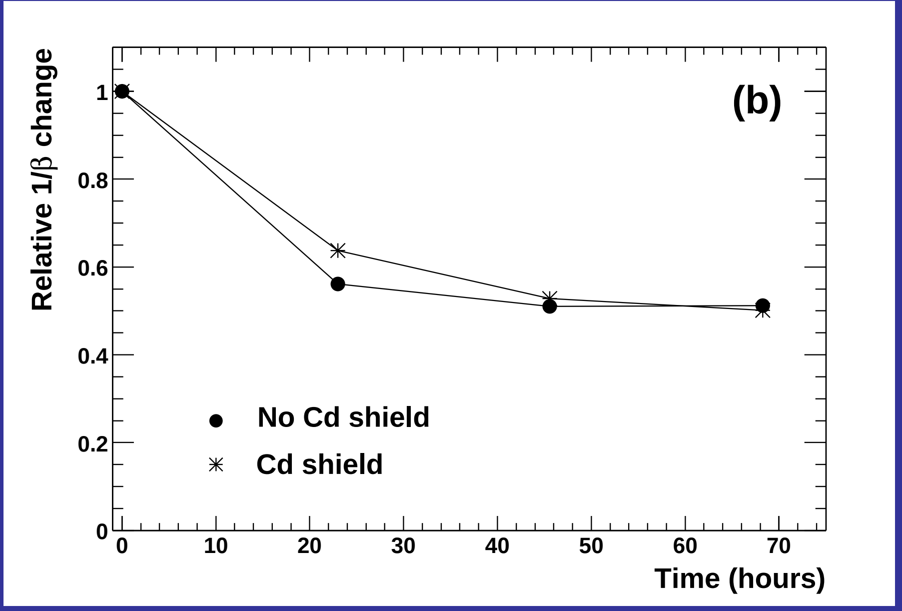
ANNEALING

- annealing was measured on samples irradiated in
  - F19 no Cd shield (fast + thermal neutrons)
  - F19 with Cd shield

140 days at RT



70 hours at 160°C

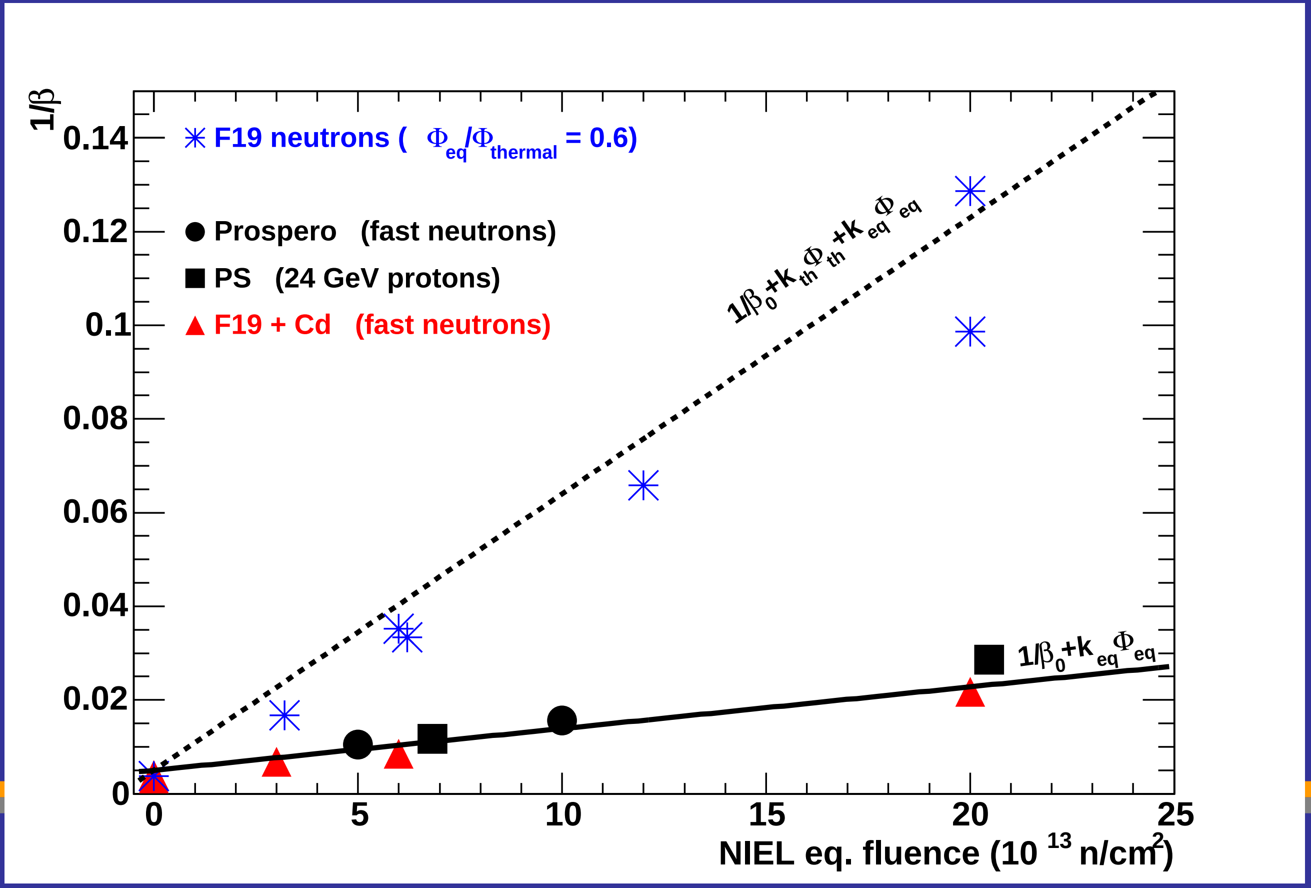


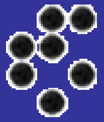
Similar annealing for both samples!

Comparison with other irradiations

- if no thermal neutrons: NIEL scaling of Δ 1/β OK
- if thermal neutron present:

$$\Delta 1/\beta \sim k_{thermal} \cdot \Phi_{thermal} + k_{eq} \cdot \Phi_{eq}$$





CONCLUSIONS

- large beta degradation caused by thermal neutrons measured in DMILL *npn* transistors $k_{thermal} = 3 \cdot k_{eq}$

- thermal and fast neutrons cause similar kind of damage
  → thermal neutron capture on boron, damage caused by fragments

- if thermal and fast neutrons present in the radiation field, as is the case in ATLAS inner detector, damage can be estimated with:

$$\Delta 1/\beta \sim k_{thermal} \cdot \Phi_{thermal} + k_{eq} \cdot \Phi_{eq}$$

- support doping of neutron shield with B or Li