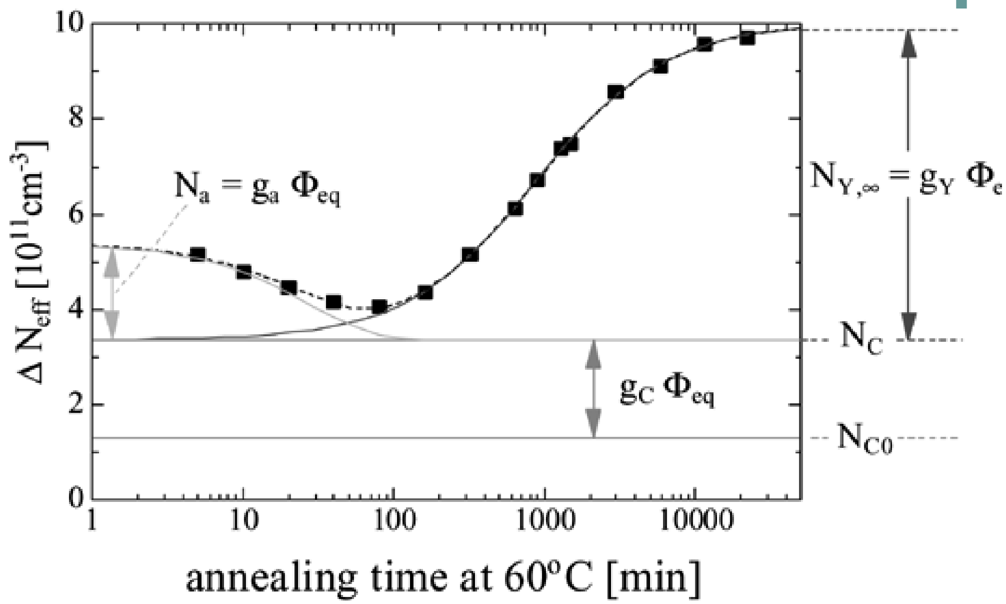
Annealing studies on Sintef sensors

Amit Roy, Daniela Bortoletto and Gino Bolla
Purdue University

Time Evolution of Radiation Induced ΔN_{eff}

Annealing behavior of radiation induced change in effective doping concentration can be described as

$\Delta N_{eff} = N_A + N_C + N_Y$



- N_A is short term beneficial annealing
- N_C is stable damage
- N_Y is reverse annealing

Study the dependence of the annealing parameters on the processing

Sensors under study

- **9 structures, fabricated by SINTEF, were irradiated, and annealed at 3 different temperatures.**

Sensor ID	Fluence (n_{eq}/cm^2)	Annealing temp (^0C)	Sensor type
W4D42	1×10^{14}	63	Oxygenated
W7P16	1×10^{14}	63	Standard
W14P16	6×10^{14}	63	Standard
W3D41	1×10^{14}	70	Oxygenated
W7P4	1×10^{14}	70	Standard
W14P13	1×10^{14}	80	Standard
W7D41	5×10^{14}	80	Standard
W4D44	5×10^{14}	80	Oxygenated
W4D46	6×10^{14}	80	Oxygenated

(green) - Diodes

(white) - Pixels

Dimensions & Initial Resistivity

Active Area

Depth (mm)	Width (mm)	Length (mm)
0.27	2.79	4.04

	V_{dep} before irradiation (V)	Corresponding resistivity (Ωcm)	Corresponding N_{eff0} (cm^{-3})
Wafer 3	148	1612	2.67×10^{12}
Wafer 4	173	1379	3.12×10^{12}
Wafer 7	143	1668	2.58×10^{12}
Wafer 14	169	1412	3.15×10^{12}

Irradiation

- **Sensors were irradiated at Indiana University Cyclotron Facility with 200 MeV proton beam. Sensors were exposed to 3 different doses**
  - **1×10^{14} proton/cm^2**
  - **5×10^{14} proton/cm^2**
  - **6×10^{14} proton/cm^2**
- **After irradiation sensors were kept at -10^{0}C at the radiation facility until they were safe for shipping. On receiving the sensors at Purdue leakage current were measured at -10^{0}C. Expected leakage at 20^{0}C was calculated by using the formula**

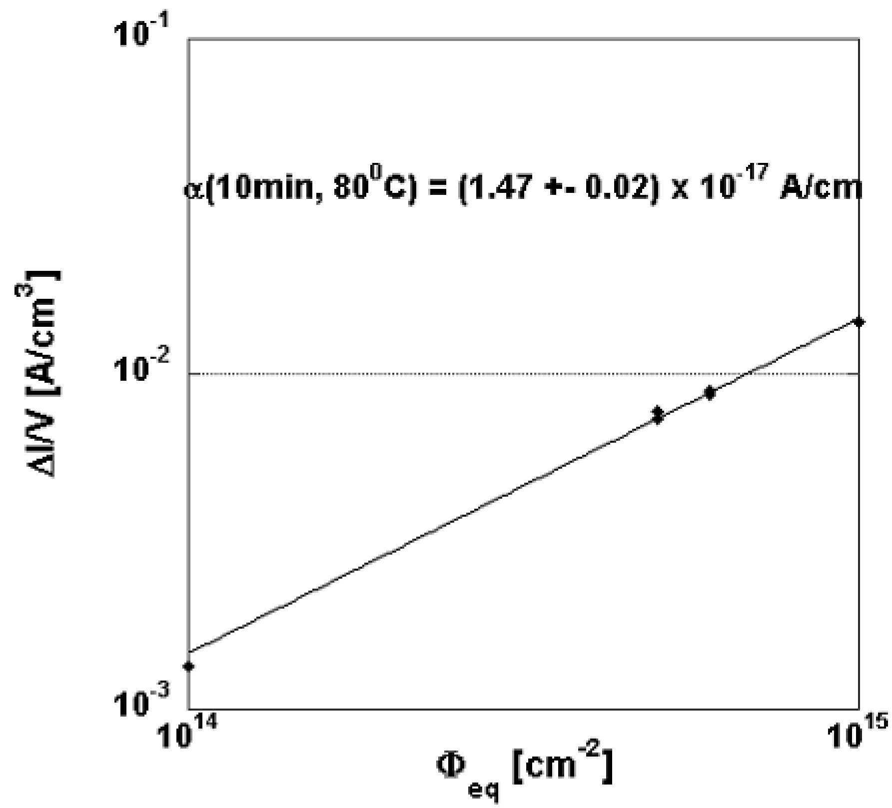
$$I(T) = I(T_0) * [T/T_0]^{2} * \exp[- E/2k_B * (1/T - 1/T_0)] \quad \text{with } E=1.2 \text{ eV}$$

Leakage Current Damage Constant

- **Radiation induced increase of leakage current**
  $\Delta I = \alpha \cdot V \cdot \Phi_{eq}$

- **Value of α after 10 minute annealing at 80^0C is $(1.47 \pm 0.02) \times 10^{-17}$ A/cm**

- **Average value of α from other experiments after 80 minute annealing at 60^0C is $(3.99 \pm 0.03) \times 10^{-17}$ A/cm**



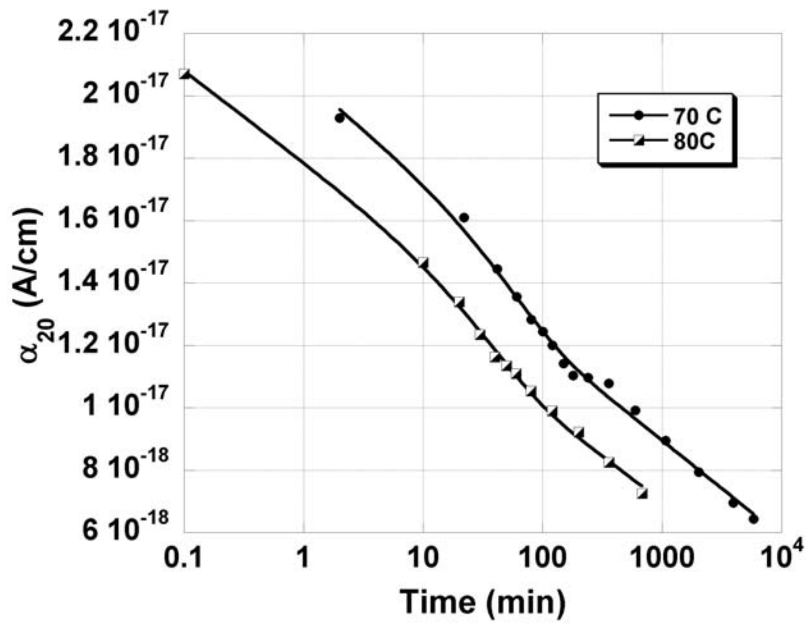
Note: ΔN_{eff} reaches it minima after 10 minute at 80^0C.

Time Evolution of α

- **The annealing of α can be described by:**

$$\alpha(t) = \alpha_I . \exp(-t/\tau_I) + \alpha_0 - \beta . \ln(t/t_0)$$

- Even after 6 years of annealing at room temperature α doesn't reach any saturation value



T_a	α_I	τ_I	α_0	β	t_0
[0C]	[10^{-18} A/cm]	[min]	[10^{-17} A/cm]	[10^{-18} A/cm]	[min]
70	2.36±0.47	58.26±13.44	1.82±0.05	1.34±0.07	1
80	2.19±0.42	39.64±6.33	1.57±0.03	1.26±0.06	1

Time Evolution Model of ΔN_{eff}

$$N_{eff} = N_{eff0} - N_{damage}(\phi, t, T)$$

$$N_{damage}(\phi, t, T) = N_c(\phi) + N_a(\phi, t, T) + N_Y(\phi, t, T)$$

$$N_c(\phi) = N_{c0}\,(1 - \exp(-c\phi)) + g_c\phi$$

for proton damage $N_{c0} = N_{eff0}$

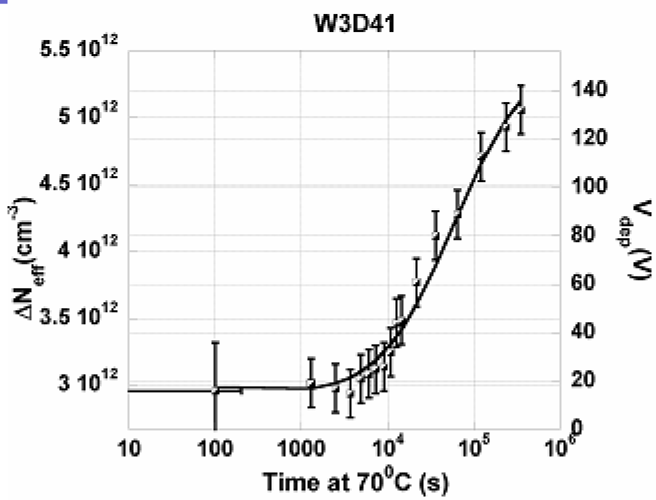
$$N_a(\phi, t, T) = g_a\phi\, \exp(-k_{a0} t\, \exp(-E_{aa}/k_B T))$$

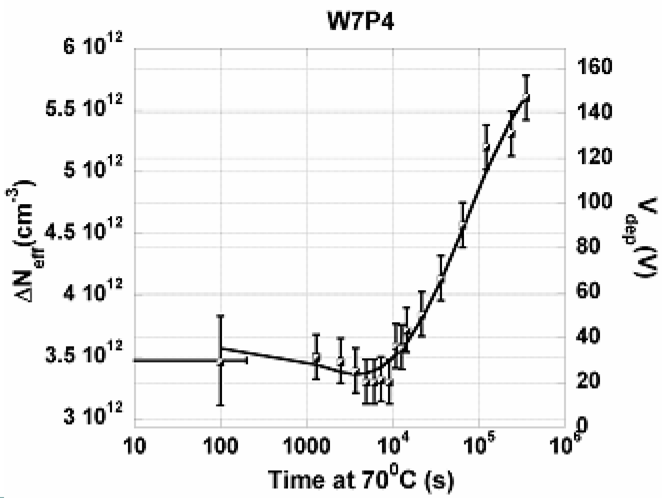
$$N_Y(\phi, t, T) = g_Y\phi\, (1 - 1/(1 + k_{Y0} t\, \exp(-E_{aY}/k_B T)))$$

$E_{aa} = 1.09$ eV
$E_{aY} = 1.33$ eV

Annealing at 70^{0}C

- Measurements were done at thermally controlled probe station. Sensors were placed on thermal chuck. The chamber was kept dry by flowing dry air.
- It takes about 5 minutes to reach the desired temperature.
- Temperature varies less than 0.1 ^{0}C once it reaches the desired value.
- Error in measuring depletion voltage is ±10V
- Error in determining exact initial time at 70^{0}C is ±100s which is equivalent to about 15 hours at room temperature.

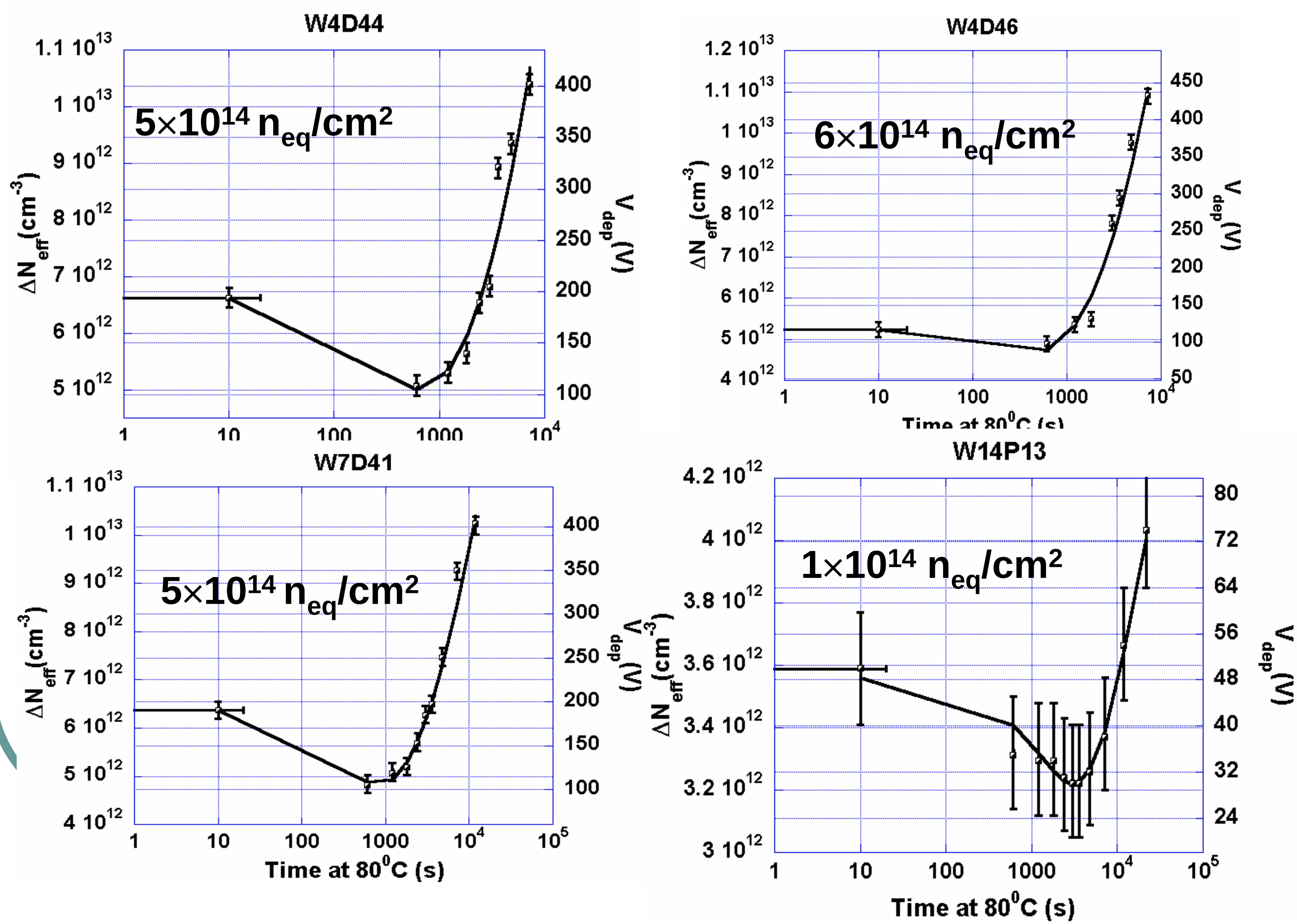




Results from Annealing at 70^0C

Fluence (n_{eq}/cm^2)	W3D41 1×10^{14}	W7P4 1×10^{14}
N_c {ϕ} [cm^{-3}]	$(2.91\pm0.18)\times10^{12}$	$(3.12\pm0.27)\times10^{12}$
g_a [cm^{-1}]	$(0.86\pm4.82)\times10^{-3}$	$(4.68\pm3.79)\times10^{-3}$
k_{a0} [s^{-1}]	$(1.11\pm12.6)\times10^{13}$	$(0.39\pm0.63)\times10^{13}$
g_Y [cm^{-1}]	$(2.59\pm0.24)\times10^{-2}$	$(3.02\pm0.28)\times10^{-2}$
k_{Y0} [s^{-1})	$(5.09\pm2.38)\times10^{14}$	$(4.04\pm2.09)\times10^{14}$

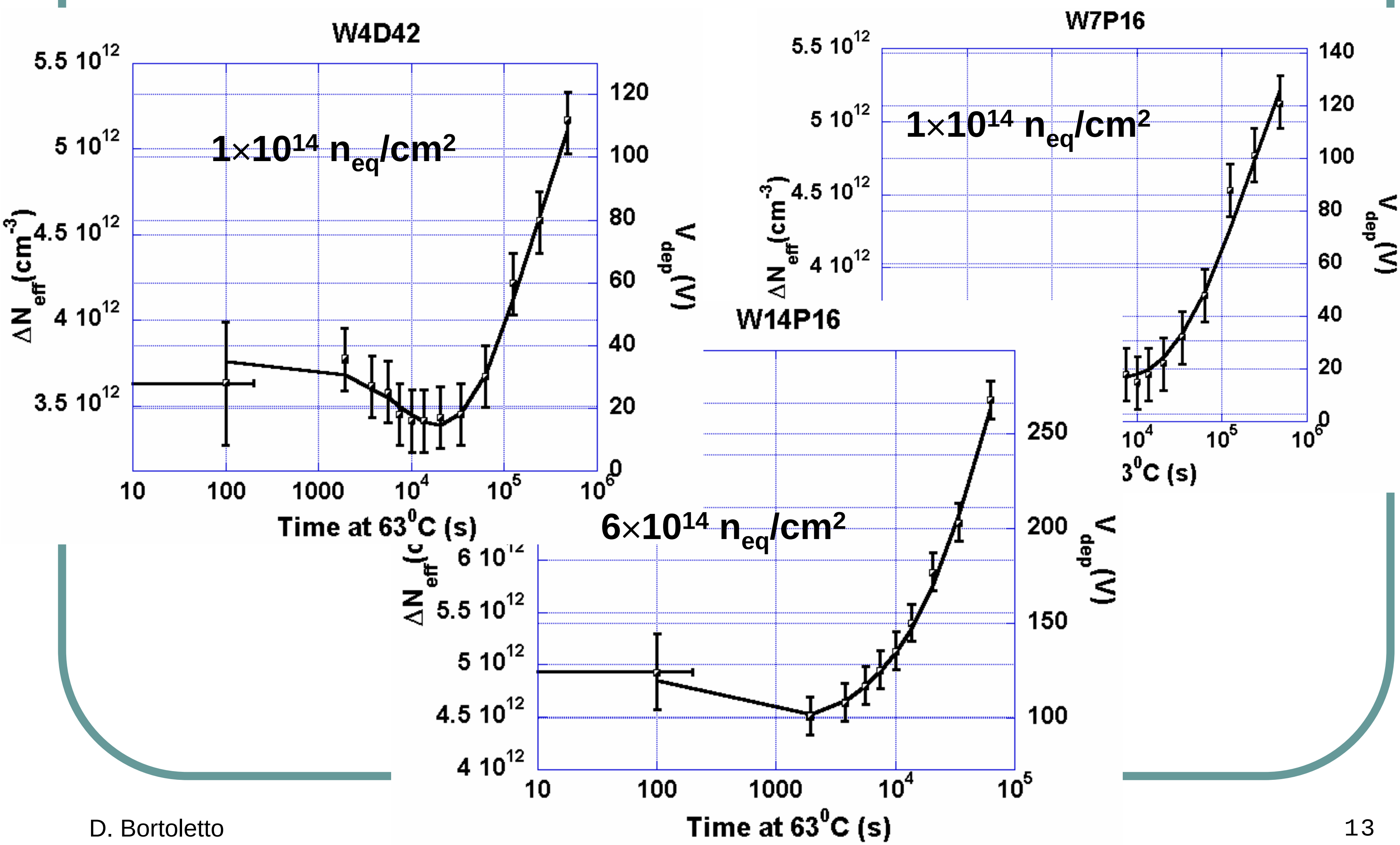
Annealing at 80^0C



Results from Annealing at 80^0C

Fluence(n_{eq}/cm^2)	W14P13 1×10^{14}	W7D41 5×10^{14}	W4D44 5×10^{14}	W4D46 6×10^{14}
N_c {ϕ} [cm^{-3}]	$(2.75\pm1.16)\times10^{12}$	$(3.69\pm2.47)\times10^{12}$	$(3.66\pm7.17)\times10^{12}$	$(3.63\pm6.35)\times10^{12}$
g_a [cm^{-1}]	$(8.18\pm11.4)\times10^{-3}$	$(5.48\pm4.97)\times10^{-3}$	$(6.08\pm14.1)\times10^{-3}$	$(2.76\pm10.7)\times10^{-3}$
k_{a0} [s^{-1}]	$(0.16\pm0.18)\times10^{13}$	$(0.79\pm1.52)\times10^{13}$	$(0.91\pm4.65)\times10^{13}$	$(1.01\pm11.5)\times10^{13}$
g_Y [cm^{-1}]	$(2.64\pm2.06)\times10^{-2}$	$(3.12\pm3.11)\times10^{-2}$	$(4.56\pm19.2)\times10^{-2}$	$(4.07\pm14.2)\times10^{-2}$
k_{Y0} [s^{-1})	$(3.56\pm11.2)\times10^{14}$	$(5.22\pm11.7)\times10^{14}$	$(5.09\pm37.2)\times10^{14}$	$(5.09\pm30.7)\times10^{14}$

Annealing at 63^0C



Results from Annealing at 63^0C

Fluence(n_{eq}/cm^2)	W4D42 1×10^{14}	W7P16 1×10^{14}	W14P16 6×10^{14}
N_c {ϕ} [cm^{-3}]	$(2.98\pm0.50)\times10^{12}$	$(3.10\pm0.31)\times10^{12}$	$(4.36\pm0.18)\times10^{12}$
g_a [cm^{-1}]	$(7.86\pm4.36)\times10^{-3}$	$(3.03\pm4.15)\times10^{-3}$	$(0.97\pm6.59)\times10^{-3}$
k_{a0} [s^{-1}]	$(0.17\pm0.14)\times10^{13}$	$(0.49\pm1.41)\times10^{13}$	$(3.74\pm11.1)\times10^{13}$
g_Y [cm^{-1}]	$(3.07\pm0.42)\times10^{-2}$	$(2.94\pm0.62)\times10^{-2}$	$(1.27\pm0.47)\times10^{-2}$
k_{Y0} [s^{-1})	$(3.59\pm2.88)\times10^{14}$	$(4.00\pm3.25)\times10^{14}$	$(8.26\pm5.44)\times10^{14}$

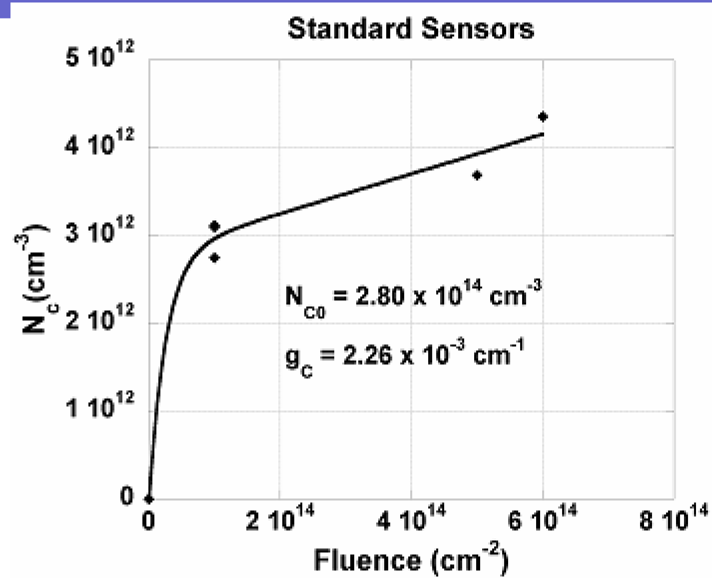
Extracting N_{c0} and g_c from $N_c(\phi)$

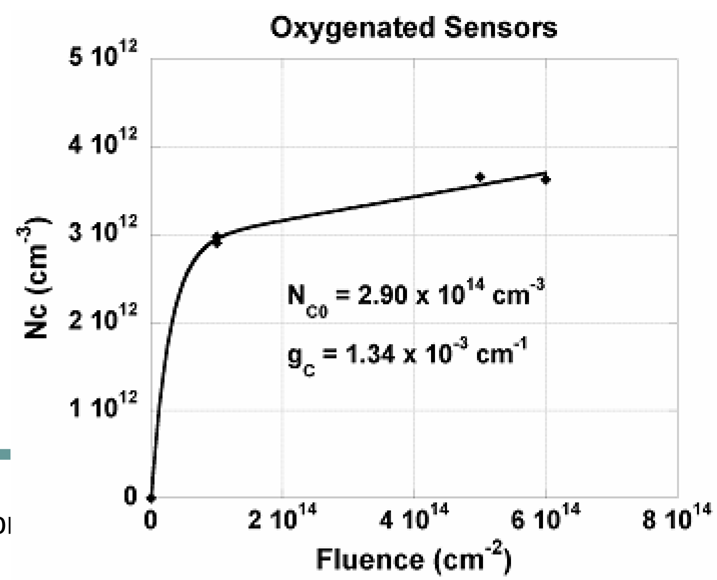
$$N_c(\phi) = N_{c0}\,(1-\exp(-c\phi)) + g_c\phi$$

- **Due to unavailability of data at low fluence it is not possible to fit $N_c(\phi)$ data and get a reliable value of c. Fortunately $N_{eff0} \times c$ has a constant value independent of initial concentration and material and it is $(10.9 \pm 0.08) \times 10^{-2}$ cm^{-1}.**

- **For oxygenated sensors $c = (3.62 \pm 0.48) \times 10^{-14}$ cm^2**

- **For standard sensors $c = (3.88 \pm 0.54) \times 10^{-14}$ cm^2**





Annealing Constants

	Purdue Oxy	Purdue Std	RD48 Oxy	RD48 Std
N_{eff0}/N_{C0}	0.96±0.08	1.00±0.12	1	1
c ($10^{-14}cm^2$)	3.62±0.48	3.88±0.54	10.9	10.9
g_c ($10^{-3}cm^{-1}$)	1.34±0.17	2.26±0.44	5.30	19.0
g_a ($10^{-3}cm^{-1}$)	4.62±9.41	4.07±6.77	14.0	18.1
k_{a0} ($10^{13}s^{-1}$)	0.17±8.86	0.19±5.08	2.38	2.38
g_Y ($10^{-2}cm^{-1}$)	2.71±11.9	2.62±1.71	7.40	6.60
k_{Y0} ($10^{14}s^{-1}$)	4.48±24.2	4.43±7.83	7.40	14.8

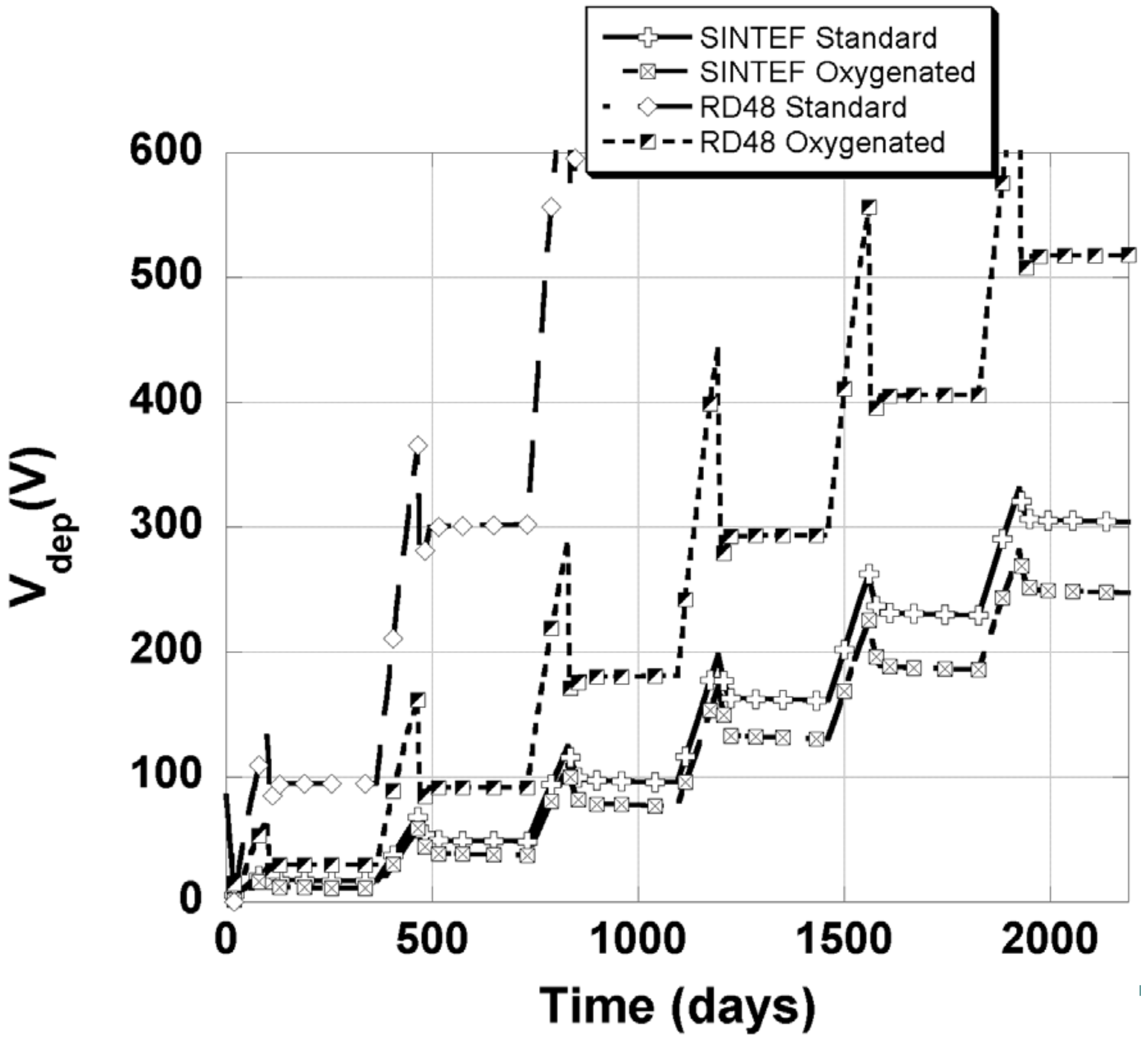
LHC Scenario

period	days	T [°C]	phi_n_eq [cm-2]	phi_p_eq [cm-2]
1	100	-7	5.22E+13	2.96E+14
2	30	20		
3	100	-7		
4	135	-7		
sum:	365		5.22E+13	2.96E+14

Projected depletion voltage is calculated using this scenario at LHC. Damage due to neutron irradiation has not been taken into account. Depletion voltage has been calculated for a sensor of 270μm thickness and with an initial depletion voltage of 85V. Projected depletion voltage will increase by 15-20% if neutron damage is taken into account.

year	lumi (1e34)
1	25.00%
2	50.00%
3	75.00%
4 onwards	100.00%

Predicted Depletion Voltage



Conclusion

- Several parameters that control the long term behavior of irradiated silicon are significantly smaller for SINTEF sensors than RD48 even if oxygenated.
- g_C, for oxygenated SINTEF is smaller than for standard Sintef sensors
- Oxygenation improves radiation hardness, but a processing has also a large impact on the radiation hardness