Characterization of the Polysilicon Resistor in Silicon Strip Sensors for ATLAS Inner Tracker as a Function of Temperature, Pre- And Post-Irradiation

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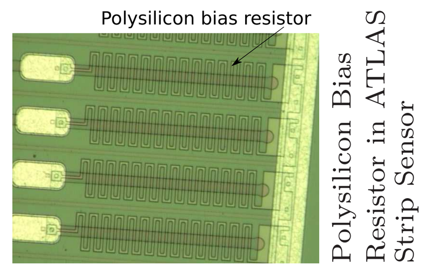
Introduction

The high luminosity upgrade of the Large Hadron Collider, foreseen to start in 2029, requires the replacement of the ATLAS Inner Detector with a new all-silicon Inner Tracker (ITk). Radiation hard n^+-in-p micro-strip sensors were developed by the ATLAS ITk strip collaboration and are produced by Hamamatsu Photonics K.K. The active area of ITk strip sensor is delimited by the n-implant bias ring, which is connected to each individual n^+ implant strip by a polysilicon bias resistor. The total resistance of the polysilicon bias resistor should be within a specified range to keep all the strips at the same potential, isolate individual strips well and keep the noise acceptably small due to the resistance.



Polysilicon Bias Resistor in ATLAS Strip Sensor

Motivation

While the polysilicon is a ubiquitous semiconductor material, the radiation damage and temperature dependence of its resistance is not easily predictable, especially for the tracking detector with the operational temperature significantly below the values typical for commercial microelectronics. Dependence of the resistance of polysilicon bias resistor on the temperature, as well as on the total delivered fluence and ionizing dose, was studied, both before and after irradiation by protons, neutrons, and gammas to the maximal expected fluence of $1.6 \cdot 10^{15}$ 1-MeV n_{eq}/cm^2 and ionizing dose of 0.66 MGy.

Aims And Objectives

- Determine the activation energy of the polysilicon material.
- Find a function which describes the dependence of the polysilicon bias resistance value on temperature and irradiation.

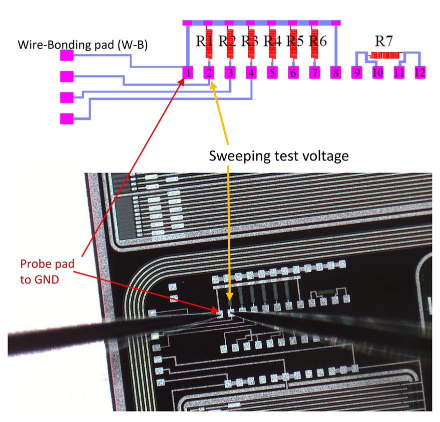
→ With the help of the extracted parameters predict the behavior of the polysilicon bias resistance in the ATLAS Inner Tracker.

For the purpose of this study 14 test chips* were irradiated by gammas from ^{60}Co source at UJP Praha, reactor neutrons at Ljubljana JSI TRIGA Reactor, 27 MeV protons at Birmingham and 70 MeV protons at CYRIC.

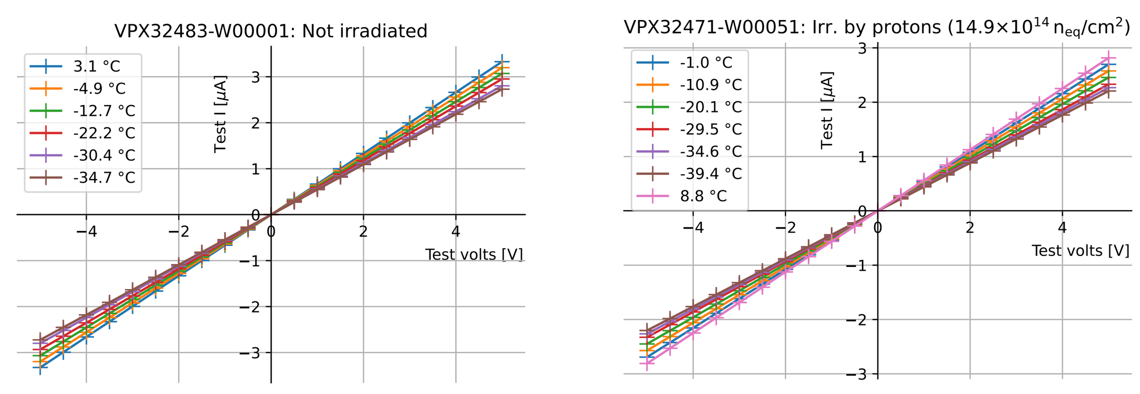
* M. Ullan et al., Nuclear Inst. and Methods in Physics Research, A 981 (2020) 164521

Measurement Procedure

- The measurement was performed on special structures called Test Chips, in temperature range between −50 °C and +25 °C.
- The bias resistance is measured by setting pad 1 to ground and performing a test voltage sweep on pads 2 to 7 while measuring the test current.



Example of Test IV Curves Measured at Different Temperatures



- The resulting bias resistance value for each temperature is calculated from the slope of measured test voltage vs test current (Test I) as $R_{\mathrm{bias}} = \left(\frac{\mathrm{d}I}{\mathrm{d}V}\right)^{-1}$.

Temperature Dependence of R_{bias} And Activation Energy of Polysilicon

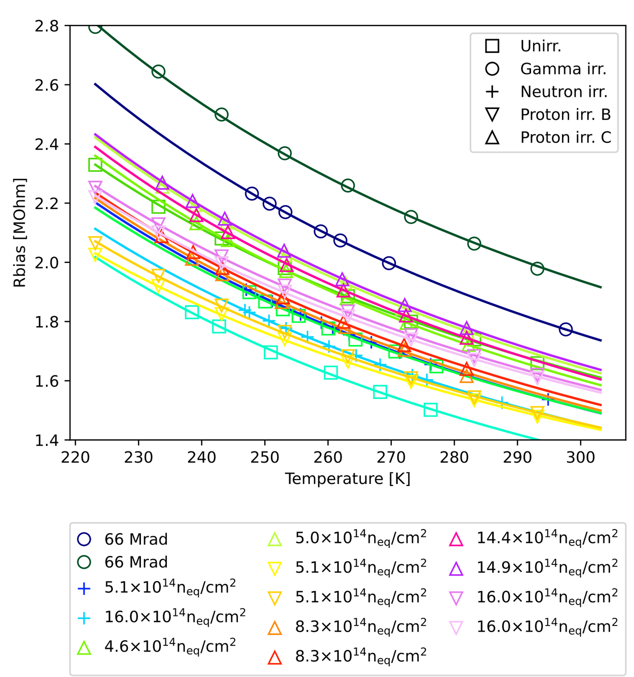
- The Rbias dependence on temperature was fitted using the exponential function:

$$R_{\mathrm{bias}}(T) = a \cdot \exp\left(\frac{b}{T}\right),$$

from which the activation energy was determined as

$$E_a = 2 \cdot k \cdot b,$$

where k is the Boltzmann constant.



Extracted activation energies

Unirradiated test chips

Test Chip	$E_a[\cdot 10^{-3}\,\mathrm{eV}]$
VPX32483-W00001	58.7 ± 1.1
VPX33426-W00082	55.6 ± 0.9
VPX34148-W00201	53.8 ± 0.6

Gamma irr. test chips

Test Chip	Dose [Mrad]	$E_a[\cdot 10^{-3}\,\mathrm{eV}]$
VPX32418-W00144	66	58.9 ± 0.2
VPX33426-W00073	66	55.7 ± 0.6

Neutron irr. test chips

Test Chip	Fluence $[\cdot 10^{14}\,n_{eq}/cm^2]$	$E_a[\cdot 10^{-3}\,\mathrm{eV}]$
VPX32421-W00371	5.1	56.9 ± 0.3
VPX32426-W00367	16	55.9 ± 0.2

Proton irr. test chips

Test Chip	Fluence $[\cdot 10^{14}\,n_{eq}/cm^2]$	$E_a[\cdot 10^{-3}\,\mathrm{eV}]$
VPX32423-W80366^C	4.57	58.0 ± 0.2
VPX32587-W00064^C	5.02	58.1 ± 0.6
VPA37915-W00314^B	5.1	50.6 ± 0.3
VPA37915-W00306^B	5.1	52.8 ± 0.4
VPA37915-W00295^C	8.34	57.0 ± 1.4
VPX37425-W00755^C	8.34	56.4 ± 0.6
VPX32425-W00317^C	14.4	58.1 ± 0.5
VPX32471-W00051^C	14.9	57.7 ± 0.3
VPA37915-W00333^B	16	53.0 ± 0.4
VPA37915-W00340^B	16	51.8 ± 0.4

^{B} Test chips irr. at Birmingham,
^{C} Test chips irr. at CYRIC

→ Average value of the activation energy is $E_a = (55.8 \pm 0.1) \cdot 10^{-3}\,\mathrm{eV}$.

→ Activation energy is independent of irradiation type.

→ Slight deviations in measured values are caused by different set-ups at testing sites.

Prediction of Temperature Development of R_{bias} for All Samples

- It has been shown that the general function describing the development of R_{bias} with temperature has the form:

$$R(T) = a \cdot \exp\left(\frac{b}{T}\right) \quad (1)$$

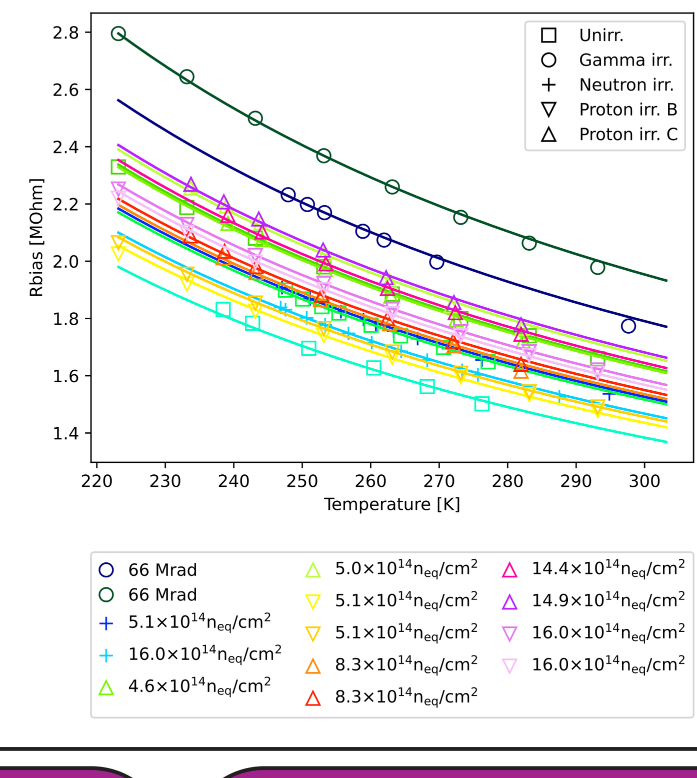
- Let us assume that b as a material constant has the same value for all samples.
- For one chosen sample we take $R_{\mathrm{bias}} = R_m$ at a temperature T_m.

→ Then from eq. (1) we get:

$$a = \frac{R_m}{\exp\left(\frac{b}{T_m}\right)} \quad (2)$$

- By inserting eq. (2) into eq. (1), we can write for all other samples:

$$R(T; T_m, R_m) = \frac{R_m}{\exp\left(\frac{b}{T_m}\right)} \exp\left(\frac{b}{T}\right) = R_m(T_m) \cdot \exp\left(\frac{b}{T} - \frac{b}{T_m}\right) \quad (3)$$

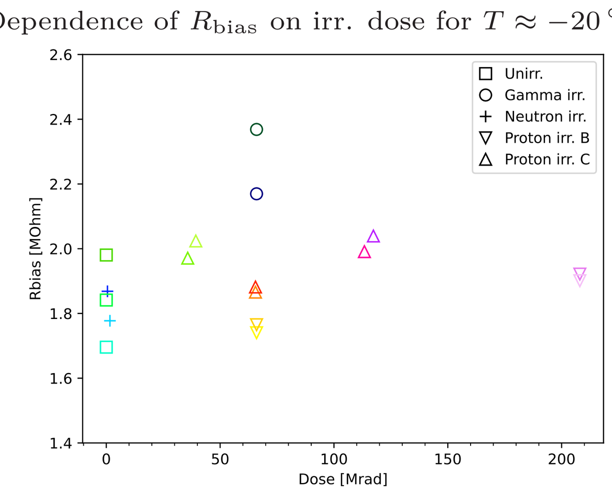


- Measured R_{bias} values of each test chip were compared with a curve obtained from the formula (3): $R(T; T_m, R_m) = R_m(T_m) \cdot \exp\left(\frac{b}{T} - \frac{b}{T_m}\right)$, where R_m is R_{bias} value of individual test chip measured at temperature T_m.
- For R_m we used the bias resistance value at temperature $T_m \approx -20\,°\mathrm{C}$.
- For the parameter b in eq. (1) we used the value $b = 312.2\,\mathrm{K}$ obtained from the fit of data measured for unirr. sensor.

→ Predicted R_{bias} development matches very well with the measured values.

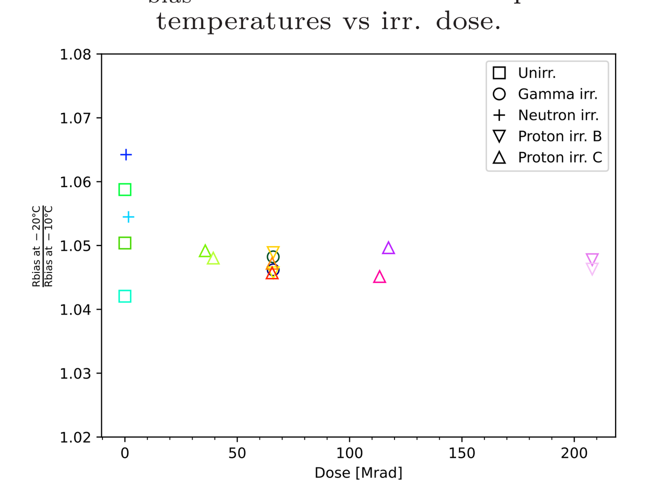
R_{bias} vs Dose

Dependence of R_{bias} on irr. dose for $T \approx -20\,°\mathrm{C}$.



- No significant change of R_{bias} values with irr. dose observed.

Ratio of two R_{bias} values of the same sample at different temperatures vs irr. dose.



- Activation energy does not change with irradiation.

Note: In case of proton irr. test chips the ionizing doses were obtained from fluences using the formula: $\mathrm{TID} = \frac{\Phi}{\kappa}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{E_p}$.
The TID in neutron irr. test chips due to secondary particles has been assessed to be 100 krad per $1 \cdot 10^{14}\,n_{eq}/cm^2$.

Conclusion

- The activation energy of polysilicon has been determined as $E_a = (55.8 \pm 0.1) \cdot 10^{-3}\,\mathrm{eV}$.
- The value of polysilicon bias resistance decreases as $\exp\left(\frac{b}{T}\right)$ with increasing temperature.
- The dependence of polysilicon bias resistance on temperature can be calculated for any sample from one measured value of bias resistance R_m at a temperature T_m using:

$$R(T; T_m, R_m) = R_m(T_m) \cdot \exp\left(\frac{b}{T} - \frac{b}{T_m}\right)$$

- For a given temperature, the value of polysilicon bias resistance does not change with fluence or TID.
- Activation energy does not depend on irradiation and particle type.

Acknowledgements

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