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# Study of surface properties of ATLAS12 strip sensors and their radiation resistance

M. Mikestikova [s,*], P.P. Allport [a], M. Baca [a], J. Broughton [a], A. Chisholm [a], K. Nikolopoulos [a], S. Pyatt [a], J.P. Thomas [a], J.A. Wilson [a], J. Kierstead [b], P. Kuczewski [b], D. Lynn [b], L.B.A. Hommels [c], M. Ullan [d], I. Bloch [e], I.M. Gregor [e], K. Tackmann [e], M. Hauser [f], K. Jakobs [f], S. Kuehn [f], K. Mahboubi [f], R. Mori [f], U. Parzefall [f], A. Clark [g], D. Ferrere [g], S. Gonzalez Sevilla [g], J. Ashby [h], A. Blue [h], R. Bates [h], C. Buttar [h], F. Doherty [h], T. McMullen [h], F. McEwan [h], V. O'Shea [h], S. Kamada [i], K. Yamamura [i], Y. Ikegami [j], K. Nakamura [j], Y. Takubo [j], Y. Unno [j], R. Takashima [k], A. Chilingarov [l], H. Fox [l], A.A. Affolder [m], G. Casse [m], P. Dervan [m], D. Forshaw [m,l], A. Greenall [m], S. Wonsak [m], M. Wormald [m], V. Cindro [n], G. Kramberger [n], I. Mandić [n], M. Mikuž [n], I. Gorelov [o], M. Hoeferkamp [o], P. Palni [o], S. Seidel [o], A. Taylor [o], K. Toms [o], R. Wang [o], N.P. Hessey [p], N. Valencic [p], K. Hanagaki [q,j], Z. Dolezal [r], P. Kodys [r], J. Bohm [s], J. Stastny [s], A. Bevan [t], G. Beck [t], C. Milke [u], M. Domingo [u], V. Fadeyev [u], Z. Galloway [u], D. Hibbard-Lubow [u], Z. Liang [u], H.F.-W. Sadrozinski [u], A. Seiden [u], K. To [u], R. French [v], P. Hodgson [v], H. Marin-Reyes [v], K. Parker [v], O. Jinnouchi [w], K. Hara [x,y], K. Sato [x,y], M. Hagihara [x], S. Iwabuchi [x], J. Bernabeu [z], J.V. Civera [z], C. Garcia [z], C. Lacasta [z], S. Marti i Garcia [z], D. Rodriguez [z], D. Santoyo [z], C. Solaz [z], U. Soldevila [z]

[a] *School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[b] *Brookhaven National Laboratory, Physics Department and Instrumentation Division, Upton, NY 11973-5000, USA*
[c] *Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[d] *Centro Nacional de Microelectronica (IMB-CNM, CSIC), Campus UAB-Bellaterra, 08193 Barcelona, Spain*
[e] *DESY, Notkestrasse 85, 22607 Hamburg, Germany*
[f] *Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, D-79104 Freiburg, Germany*
[g] *DPNC, University of Geneva, 24, Quai Ernest-Ansermet, CH-1211 Geneve 4, Switzerland*
[h] *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[i] *Solid State Div., Hamamatsu Photonics K.K., 1126-1, Ichino-cho, Higashi-ku, Hamamatsu-shi, Shizuoka 435-8558, Japan*
[j] *Institute of Particle and Nuclear Study, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan*
[k] *Department of Science Education, Kyoto University of Education, Kyoto 612-8522, Japan*
[l] *Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom*
[m] *Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Oxford St., Liverpool L69 7ZE, United Kingdom*
[n] *Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
[o] *Department of Physics and Astronomy, University of New Mexico, MSC07 4220, 1919 Lomas Blvd. NE, Albuquerque, NM 87131, USA*
[p] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[q] *Department of Physics, Osaka University, Machikaneyama-cho 1-1, Toyonaka-shi, Osaka 560-0043, Japan*
[r] *Charles University in Prague, Faculty of Mathematics and Physics, V Holesovickach 2, Prague 8, Czech Republic*
[s] *Academy of Sciences of the Czech Republic, Institute of Physics, Na Slovance 2, 18221 Prague 8, Czech Republic*
[t] *School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, United Kingdom*
[u] *Santa Cruz Institute for Particle Physics (SCIPP), University of California, Santa Cruz, CA 95064, USA*
[v] *Department of Physics and Astronomy, The University of Sheffield, Hicks Building, Hounsfield Road, S3 7RH Sheffield, United Kingdom*
[w] *Institute of Science and Engineering, Tokyo Institute of Technology, Ookayama 2-12-1, Meguro-ku, Tokyo 152-8551, Japan*
[x] *Institute of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8751, Japan*
[y] *Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan*
[z] *IFIC/CSIC-UVEG, Ed. Inst. Investigacion, PO Box 22085, 46071 Valencia, Spain*

* Corresponding author.
*E-mail address:* mikestik@fzu.cz (M. Mikestikova).

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ABSTRACT

A radiation hard $n^+$-in-$p$ micro-strip sensor for the use in the Upgrade of the strip tracker of the ATLAS experiment at the High Luminosity Large Hadron Collider (HL-LHC) has been developed by the "ATLAS ITk Strip Sensor collaboration" and produced by Hamamatsu Photonics.

Surface properties of different types of end-cap and barrel miniature sensors of the latest sensor design ATLAS12 have been studied before and after irradiation. The tested barrel sensors vary in "punch-through protection" (PTP) structure, and the end-cap sensors, whose stereo-strips differ in fan geometry, in strip pitch and in edge strip ganging options. Sensors have been irradiated with proton fluences of up to $1 \times 10^{16}$ $n_{eq}/cm^2$, by reactor neutron fluence of $1 \times 10^{15}$ $n_{eq}/cm^2$ and by gamma rays from $^{60}$Co up to dose of 1 MGy. The main goal of the present study is to characterize the leakage current for micro-discharge breakdown voltage estimation, the inter-strip resistance and capacitance, the bias resistance and the effectiveness of PTP structures as a function of bias voltage and fluence. It has been verified that the ATLAS12 sensors have high breakdown voltage well above the operational voltage which implies that different geometries of sensors do not influence their stability. The inter-strip isolation is a strong function of irradiation fluence, however the sensor performance is acceptable in the expected range for HL-LHC. New gated PTP structure exhibits low PTP onset voltage and sharp cut-off of effective resistance even at the highest tested radiation fluence. The inter-strip capacitance complies with the technical specification required before irradiation and no radiation-induced degradation was observed. A summary of ATLAS12 sensors tests is presented including a comparison of results from different irradiation sites. The measured characteristics are compared with the previous prototype of the sensor design, ATLAS07.



## 1. Introduction

The Phase-II upgrade of the Large Hadron Collider (LHC) to the higher luminosity ($5 \times 10^{34}\,cm^{-2}\,s^{-1}$) machine, called the High Luminosity-LHC (HL-LHC) [1], will require replacement of the entire current ATLAS Inner Detector with a new all-silicon tracker containing new type and design of silicon sensors. It will have pixel sensors at the inner radii surrounded by micro-strips. As currently planned, the micro-strip detector in the upgraded Inner Tracker (ITk) [2,3] will consist of 2 barrel layers of "short" strips (length 23.8 mm), 2 barrel layers of "long" strips (length 47.8 mm) and seven end-cap discs on each side. The end-cap strips length varies from 15 mm to 60 mm depending on the radius. The strip length is chosen so as to maintain the average hit occupancy to be less than 1% at the expected maximum instantaneous luminosity. The maximum hit occupancy is limited by the bandwidth of the read-out system.

Strip sensors in the ITk will be exposed to charged particles, neutrons and gammas. The predicted maximum fluence and ionizing dose [4] for the integrated luminosity of 3000 $fb^{-1}$ in the strip barrels is $5.3 \times 10^{14}$ 1-MeV neutron equivalent $(n_{eq})/cm^2$ and 216 kGy for the short strips in the layer 1, and in the strip end-caps $8.1 \times 10^{14}$ $n_{eq}/cm^2$ and 288 kGy in the inner regions of the outermost disk at a distance of 300 cm from interaction point. The estimates stated above have no safety factors applied. Such a high fluence of particles and ionizing dose causes bulk and surface damage to the sensors. In this study the miniature sensors were irradiated by protons, neutrons and gammas from $^{60}$Co source. Protons and neutrons displace silicon atoms via non-ionizing energy losses, which results in point and cluster defects in the bulk. In addition protons ionize both the Si bulk and the insulating layer ($SiO_2$). The latter causes the accumulation of positive charges and traps in the $SiO_2$ and at the Si-$SiO_2$ interface that leads to deterioration of the sensor surface. The gamma irradiation is usually used to study the oxide/interface damage separately from the bulk damage. However, gamma rays from $^{60}$Co source are absorbed in the sensor mainly through Compton scattering and the scattered Compton electrons have high enough energy (hundreds of keV) to produce point defects in the Si bulk. The surface damage is expected to influence the breakdown voltage, the inter-electrode isolation and capacitance.

The current ATLAS Semi-Conductor Tracker is based on single-sided type of micro-strip sensors made with $p$-strips implanted on $n$-type silicon bulk ($p$-in-$n$). $n^+$-in-$p$ type sensors, which are much more radiation hard [5,6], are being considered for use in the HL-LHC trackers. This type of sensor has much faster response as it collects electrons instead of holes. It also has no radiation induced type inversion and therefore it always depletes from the segmented side that allows sensor operation in partially depleted mode. This is particularly useful after high radiation fluencies when the full depletion voltage becomes higher. However, $n^+$-in-$p$ strip sensors need additional strip isolation.

A large area $n^+$-in-$p$ silicon sensor for the use in ITk has been developed by the ATLAS ITk Strip Sensor Collaboration [7,8] and produced by Hamamatsu Photonics (HPK) [9] in a 6-inch (150 mm) wafer. Besides the large sensor (9.75 cm × 9.75 cm), the wafer also includes sets of miniature sensors, which are used for irradiation studies. The sensors were irradiated by different particles, energies and doses and were distributed for extensive test to many institutions of the collaboration for studies of sensor properties that have received up to double maximal fluence predicted in ITk.

The samples for the surface irradiation study presented in this paper are the barrel and end-cap (EC) miniature strip sensors of the latest sensor design, called ATLAS12 [8] which was developed from ATLAS07 design [7]. The surface properties before and after ionizing radiation up to the proton fluence of $1 \times 10^{16}$ $n_{eq}/cm^2$, neutron fluence $1 \times 10^{15}$ $n_{eq}/cm^2$ and gamma dose of up to 1 MGy were evaluated. The tests include measurements of the inter-strip capacitance and resistance as a function of fluence, and the inter-strip resistance as a function of bias, temperature and annealing time. The effectiveness of different types of punch-through protection structures was tested with DC voltage scan method.

Some of the surface studies with previous design ATLAS07 were reported in Ref. [10] to maximal fluence of $1.5 \times 10^{13}$ $n_{eq}/cm^2$. The bulk damage of latest design ATLAS12 is presented in Ref. [11] for barrel and in Ref. [12] for end-cap sensors.

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