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Development of 3D Detectors for Very High Luminosity Colliders

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On behalf of the CERN-RD50 Collaboration

Abstract

3D solid state detectors have very promising characteristics for particle trackers in harsh radiation environments such as the expected after the proposed luminosity upgrade of the Large Hadron Collider at CERN. Different 3D technologies, including single- and double- type column and full 3D detectors, are being evaluated by the CERN RD50 collaboration. In this review the most recent work will be presented and discussed.

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***Abstract*–3D solid state detectors have very promising characteristics for particle trackers in harsh radiation environments such as the expected after the proposed luminosity upgrade of the Large Hadron Collider at CERN. Different 3D technologies, including single- and double- type column and full 3D detectors, are being evaluated by the CERN RD50 collaboration. In this review the most recent work will be presented and discussed.**

I. INTRODUCTION

THE CERN RD50 collaboration, "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" [1], was created in 2002 with the objective to develop solid state detectors capable of operating in extreme radiation environments like the Super-LHC facility (SLHC). The innermost layers of the vertex detectors in the SLHC will have to withstand fluences of about 10^{16} hadrons/cm^2. Present vertex detectors, relying on highly segmented silicon sensors, are designed to survive fast hadron fluences of about 10^{15} cm^{-2}. Semiconductor detectors also seem to be the best option for vertex sensors in the next generation of colliders, provided that their radiation hardness can be significantly improved.

The "new structures" group within RD50 is investigating new detector designs in order to find a solution to this challenge, and 3D detectors are very promising candidates.

3D solid-state radiation sensors were proposed in 1995 by S. Parker *et al.* [2]. These structures consist of arrays of p- and n-type electrode columns that penetrate into the detector bulk, instead of being implanted on the wafer surface like in standard planar semiconductor detectors. As a consequence of this geometry, the depletion region grows laterally between the electrodes, and the electrons and holes created by ionizing radiation move parallel to the wafer surface when they are being collected. Thus, the maximum drift and depletion distances are set by the electrode spacing (50 to 100 μm) rather than by the detector thickness (typically ~ 300 μm). Consequently, 3D detectors are expected to have very short collection times, which should counteract the charge trapping caused by high levels of radiation damage.

The fabrication of 3D detectors presents many technological challenges. One of the main difficulties is to integrate the etching and doping of the n^+ and p^+ columnar electrodes into the fabrication sequence. Several different approaches are being pursued by groups in RD50 to address this problem. These include: single column, double sided column and full 3D detector technologies.

II. SINGLE-TYPE COLUMN 3D DETECTORS

With the aim of simplifying the manufacturing process of the 3D detectors, FBK-irst (Trento, Italy) have proposed a modified 3D detector architecture, Single-Type Column 3D (STC-3D) [3]. This design has columnar electrodes of only one doping type, so the column etching and doping steps are performed just once. Also, the electrodes do not go all the way through the wafer, which simplifies the processing further, since the initial bonding and final removal of a support wafer are not required. The ohmic contact is achieved by a uniform implant at the back surface of the wafer, which makes the process single-sided.

Electrical simulations of the carrier dynamics show that the electrons generated by the incident radiation drift to the nearest column and are collected, while the holes have to drift across the full substrate thickness to the backplane. Thus, the read out signal shows a fast peak due to electrons and a long tail due to the slow drift of holes, and the complete charge collection is relatively slow. Another drawback of this structure is that when the volume between columns is fully depleted, the electric field in this region cannot be increased further. Fast charge collection is essential to counteract charge trapping, so STC-3D detectors are not expected to be radiation hard. For a device fabricated on a 500 μm substrate and biased to 40 V, the peak of the simulated signal pulse will arrive at the read-out electrode in 2.5 ns, 92% of the charge will be collected in 15 ns and 97% in 36 ns [4].

The fabrication of the first set of STC-3D devices was carried out at FBK-irst in collaboration with CNM (Barcelona, Spain), who provided the DRIE (Deep Reactive Ion Etching) hole etching for the electrodes. The devices were fabricated on standard FZ (500 μm thick) and MCz (300 μm) p-type silicon wafers. The intercolumn pitch is 80 or 100 μm, the column diameter is 10 μm and the column depth is 150 μm. The wafers include pad and strip-like 3D detectors, planar diodes and other test structures [5], [6].

The electrical characterization of the 3D pad diodes with 80 μm pitch shows that the volume between the columns is depleted at low bias (~ 10 V), and that the leakage current is low (< 3 pA/column for the FZ detectors [4]). After irradiation with neutrons to a fluence of 5×10^{14} n_{eq}/cm^2, the lateral depletion voltage is 40 V [7].

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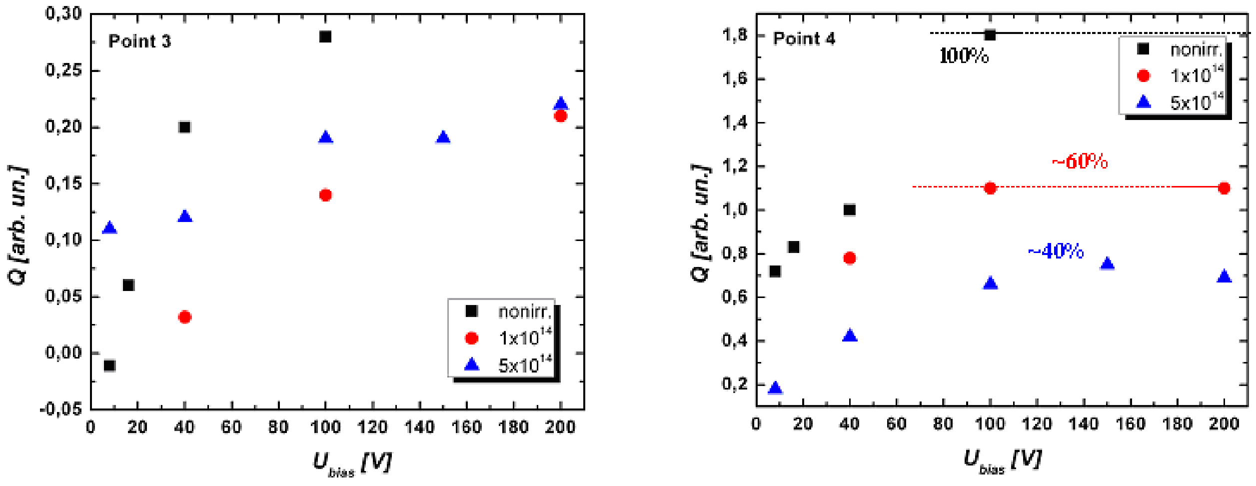


a) b)

Fig. 1. Charge collection efficiency of a STC-3D strip device measured by integrating the transient current generated by an IR laser over 25 ns. The laser beam position is a) next to the strip; b) in the mid-strip area. The irradiation fluence, in 1 MeV neutrons, is shown in the legend [7].

Charge collection efficiency tests have been performed with β particles on non-irradiated pad [4], [8], [9] and strip detectors [9]. In all cases the shaping time was >100 ns, long enough to avoid the ballistic deficit of the charge, even at low voltages when charge collection is slower. The results show the voltage dependence of the charge collection and confirm the two-stage depletion model predicted by simulations: first, the depleted region grows laterally from the n+ electrodes until the region between the columns is fully depleted, and then it progresses towards the back contact like in a planar device. Another interesting feature is that these devices have non-zero charge collection at 0 V, due to the depleted region already present around the columns in the unbiased device.

Position sensitive multi-channel TCT measurements have been carried out at the Jozef Stefan Institute (Ljubljana, Slovenia) on STC-3D strip detectors, before and after irradiation with neutrons up to a fluence of 5×10^{14} n_{eq}/cm^2. A pulsed infrared laser, which simulates the interaction of minimum ionizing particles, was scanned over the detector surface. The position resolution of the laser was 0.5 µm and its FWHM ~ 7 µm. The devices tested were DC coupled STC-3D strip detectors, with a strip pitch of 80 µm and p-spray insulation. Three neighboring strips were wirebonded to the readout electronics and the induced current pulse was measured for each position of the incident laser beam. The other strips were left floating. The experiments were carried out at a controlled temperature of 10°C.

The TCT tests of non-irradiated detectors [10] confirm the pulse shape (fast rise and long tail) predicted by the above described simulations of the carrier dynamics. The signal induced on the adjacent strips is much larger than in the planar strip detectors, and this could be used to increase the position resolution.

The charge collection efficiency (CCE) was estimated by integrating the transient current over 25 ns. As expected, the STC-3D detectors are not well suited for applications that require high charge collection after irradiation. The results show a significant loss of efficiency for interaction points close to the strips: CCE is 60% for 10^{14} n_{eq}/cm^2 and 40% for 5×10^{14} n_{eq}/cm^2. This is due to the ballistic deficit and trapping caused by the slow drift of holes. The CCE is even lower in the mid-strip region where there is a saddle in the electric field [7], [11]. Fig. 1 shows the CCE as a function of the bias voltage and the fluence for a laser focused next to a strip and in the interstrip area.

At the University of Freiburg (Germany) similar tests with infrared laser pulses on short STC-3D strip detectors have been performed [12], [13]. The signal was read out using fast ATLAS SCT front-end electronics with a shaping time of 20 ns. The laser spot size was 5 µm.

The laser tests of detectors where the surface is insulated with a p-spray show a 25% drop in the collected charge in the region between the strips due to the “saddle” in the electric field, as can be seen in Fig. 2.

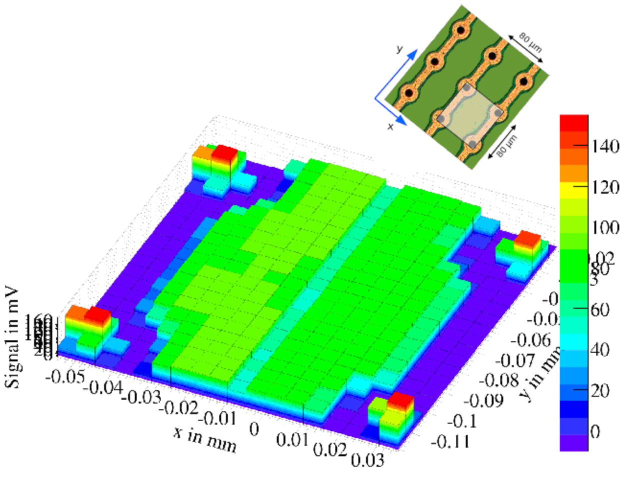
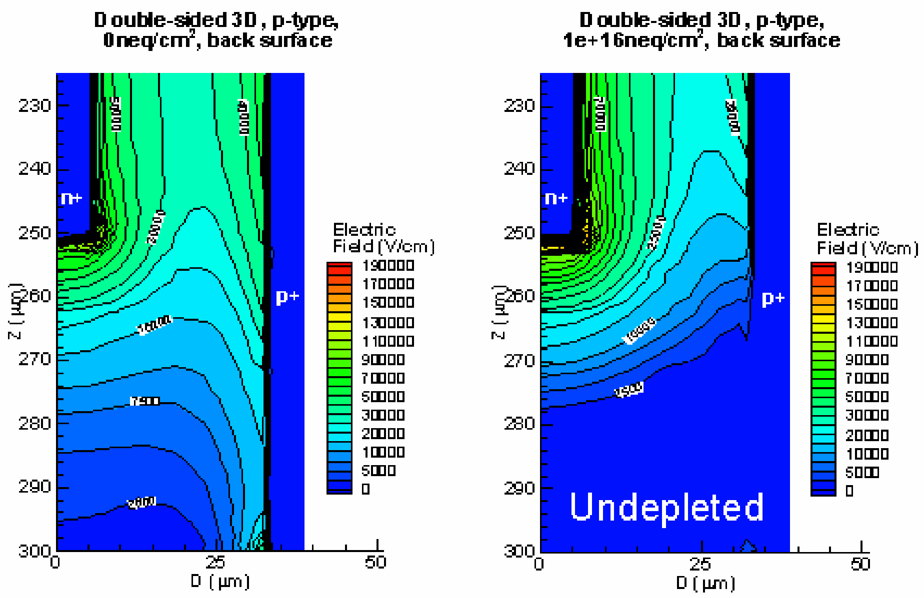


Fig. 2. Result of a 2D scan over a STC-3D detector at a bias voltage of 80 V. The columnar electrodes are at the corners of figure. The metal layers running along each strip reflect the laser, meaning that no signal is seen in these regions. The signal measured in the region between the strips shows a 25% drop.



a) b)

Fig. 3. Electric field distribution at the back surface of a double-sided 3D detector with pixel size 55 μm by 55 μm a) unirradiated and b) irradiated with 10^{16} n_{eq}/cm^2. The substrate thickness is 300 μm and the columns are 250 μm deep. The back surface is covered with oxide and metal layers. The bias voltage is 100 V.

In addition, the detectors where the strips are isolated with p-stops have charge collection problems between the electrodes in the vicinity of the p-stop surface isolation scheme. This can be attributed to a low field region created by the p-stop [12]. After an irradiation with 26 MeV protons up to an equivalent fluence of 9×10^{14} n_{eq}/cm^2 the detectors are still operational, with a lateral depletion voltage of 100 V. At this fluence the CCE shows a 15% reduction with respect to the non irradiated device in the vicinity of the strips and a 50% drop in the p-stop area between the strips [13].

Absolute charge collection efficiency measurements with a β source set-up and ATLAS-SCT electronics have also been carried out at the University of Freiburg [14]. The STC-3D detectors show low noise levels, comparable to ATLAS SCT inner modules. The signal to noise ratio of the devices irradiated with 26 MeV protons to 9×10^{14} n_{eq}/cm^2 is ~ 12 for an FZ detector at a bias voltage of 300 V and ~ 13 for a CZ detector at a bias voltage of 500 V.

There is a new variation of the STC-3D structure developed at BNL [15], where the ohmic contact is fabricated on the same side of the substrate as the column etching. This type of STC-3D device is a true one-sided detector, since the back side is simply covered by silicon dioxide (without any processing) and is left floating during the device operation. The first prototype detectors, with stripixel configuration [16], have been fabricated on FZ p-type Si wafers with 300 μm thickness and about 10 kΩ·cm resistivity. The n^+ columns, about 240 μm deep, were etched by CNM using a deep reactive ion etcher. The planar processing steps, which include ion implantations and two-metal layers, were completed at BNL. CCE testing of the sensors is underway.

III. DOUBLE-SIDED 3D DETECTORS

CNM (Centro Nacional de Microelectronica, Spain) have proposed [17] a "Double-Sided" 3D detector that has both n- and p-type columns, as in a full 3D detector. However, the holes of one doping type are etched from the front side of the wafer, and the holes of the other type are etched from the back side. This avoids the difficulty of etching and doping the two different kinds of holes on the same side of the wafer. Furthermore, the columns do not pass through the full thickness of the substrate, which makes the devices more resistant to mechanical stress than full 3D detectors, and makes the use of a carrier wafer unnecessary if active edges are not needed. Moreover, the contacts with the bias electrodes are located on the back side, so this structure is easier to connect to the readout electronics than a conventional 3D detector, which has both sets of contacts on the front.

The electrical performance of the proposed devices has been simulated at the University of Glasgow with the finite-element simulation package ISE-TCAD [18]. The simulations show that the area between the columns in a double-sided 3D detector depletes very quickly, with the depletion region growing cylindrically outwards the electrodes like in a standard 3D detector. However, there are low electric field regions around the front and back surfaces of the detector that deplete more slowly (see Fig. 3a), but full depletion is reached at voltages lower than 10 V for typical doping concentrations.

In the area where the columns overlap, i.e. throughout most of the device, the electric field pattern matches that of a full 3D detector and charge collection is fast because the charge carriers drift horizontally. In the low electric field regions the charge carriers are collected more slowly,

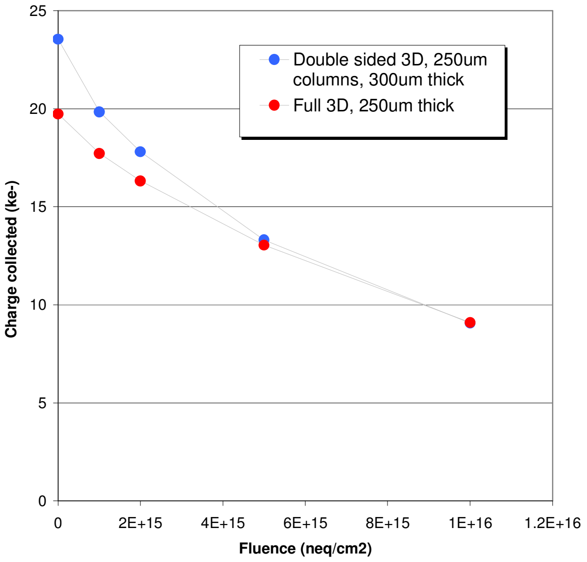


Fig. 4. Average charge collection in a standard and a double-sided 3D detector. Both devices have 250μm columns; the double-sided detector has a 300μm-thick substrate. The pixel is 55 μm by 55 μm, and the bias voltage is 100V.

increasing the full collection time. For instance, in a double sided detector with 250 μm columns and 300 μm substrate it takes 0.75 ns to collect 90% of the charge but 2.5 ns to collect 99%. This is still much faster than a conventional planar detector which takes 10–20 ns. Increasing the length of the columns reduces the size of the low-field regions and for 290 μm the detector gives the same collection speed as a full 3D sensor.

The behavior of the double-sided 3D after irradiation to SLHC levels has been simulated in Glasgow [19], [20], using the 3-level trap model proposed by the University of Perugia [21]. Some of the carrier cross sections in the Perugia model have been modified to match experimental trapping times.

As can be seen in Fig. 3b, after heavy irradiation the back surface of the sensor will not will be depleted for voltages as high as 100 V, which will result in a loss of collection efficiency.

Fig. 4 shows the average charge collection, simulated by flooding the pixel with uniform charge, of a double sided and a full 3D detector with Medipix2 geometry (pixel size 55 μm by 55 μm). Both detectors use 250 μm columns. The double-sided 3D has higher charge collection at low fluences due to the greater substrate thickness. However, at high fluences, the charge deposited underneath or above the not fully penetrating columns is lost due to the low electric field and the results match those of the standard 3D with columns of the same size.

A first run of 3D pixel and strip detectors with double-sided geometry has been processed at CNM on n- type silicon. The wafer layout contains 3D detectors with Medipix2, ATLAS pixel and Pilatus geometry, simple pad and strip-like 3D detectors and test structures. The fabrication has just finished, and the devices will be distributed to RD50 collaborators for electrical and charge collection characterization before and after irradiation to SLHC levels.

The double sided approach is also being investigated by FBK-irst (Trento). A first run on n-type wafers, containing double sided 3D pads, strips and ALICE and Medipix1 pixel detectors, has been produced. The first results of the characterisation of the pad detectors show low depletion voltages and leakage currents (~ 10 V, < 3.5 nA/cm^2), and breakdown voltages higher than 100 V [22]. A second set of p-type silicon wafers, with 3D ATLAS and CMS pixel detectors, is currently being processed at FBK-irst.

A different double-type column detector in which the columns are not etched all the way through the substrate has been proposed [15]. Unlike in the double-sided 3D the electrodes are etched from the same side of the wafer, giving true one-sided processing. The performance of this structure has been studied by simulations [15], [23]. The electric field and charge collection properties are good and comparable to those of a full 3D, except in the area at the bottom of the electrodes. The CCE can be improved by increasing the bias voltage, but this improvement is limited by the saturation velocity of the carriers and the electric breakdown of the device. It can also be significantly improved by reducing the electrode spacing although this is limited by the increase of the dead volume of the columns.

IV. FULL 3D DETECTORS

The University of Glasgow have entered into a commercial development programme with IceMOS Technology Ltd. [24], a MEMS fabrication company based in Northern Ireland, to make full 3D detectors. This is a joint project between Glasgow and the Diamond Light Source Synchrotron [25] to produce 3D detectors for X-ray imaging applications. 3D detectors are potentially interesting for synchrotron imaging due to their reduced charge sharing that improves the signal to noise ratio, their small dead area, and the possibility to use thicker substrates to detect higher energy X-rays while maintaining a good performance. Some of the fabricated detectors will also be used for radiation hardness studies within the RD50 collaboration.

The full 3D devices fabricated in IceMOS are 250 μm thick and have p^+ and n^+ columns of 10 μm diameter fabricated on high resistivity n-type silicon. The key steps of the fabrication of these devices are outlined in Fig. 5. No support wafer is required. Instead, a thick (500 μm) wafer is used for the fabrication. After a first oxidation, a set of electrodes is etched with an inductively coupled plasma etch tool to a depth of 250 μm and filled with n^+-doped polysilicon (Fig. 5a). Then, the polysilicon is removed and the oxide etched, and the second set of electrodes, p^+, is processed in the same way, also from the front surface (Fig. 5b). Next, the back side of the wafer is polished with a chemical mechanical polishing processing tool to expose the electrodes. The front surface is also planarised, leaving an unpatterned 250 μm wafer with p^+ and n^+ doped polysilicon columns going all the way through the substrate (Fig. 5c). Next, the field oxide is thermally grown, and the fabrication ends with the standard steps for contact opening, metallisation and passivation. The final device is shown in Fig. 5d.

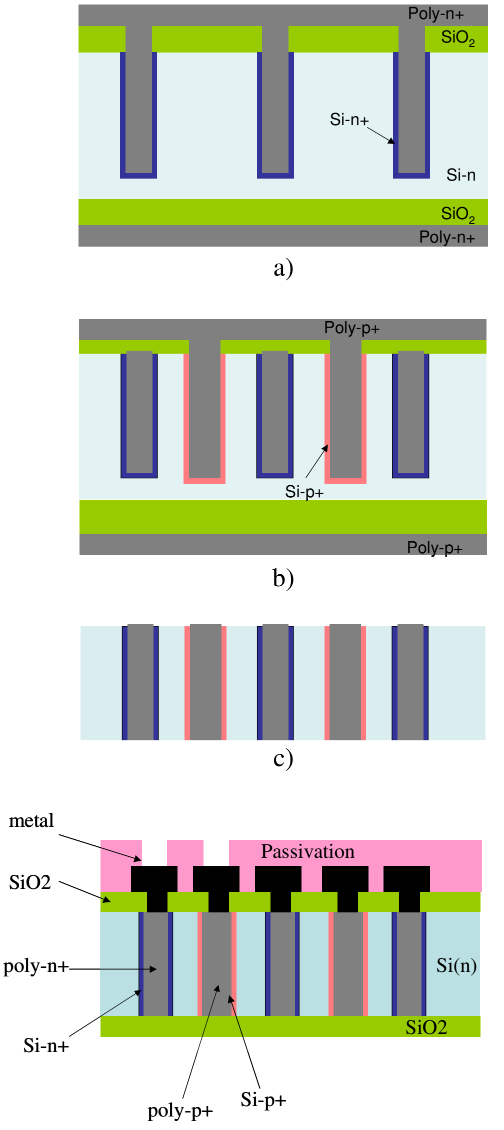


Fig. 5. Key steps of the fabrication of the Glasgow/Diamond full 3D detectors: a) n^+ electrodes; b) p^+ electrodes; c) front and back planarisation; d) final device.

To simplify the fabrication process, the contacts with both the p^+ and n^+ electrodes are located on the on the front side of the wafer, so all the biasing (n+) electrodes are connected with rerouting metal lines on the front surface.

The detectors have been designed at the University of Glasgow. The wafer layout includes pixel detectors (Medipix2, Pilatus2), pads and microstrip detectors that will be coupled to LHC electronics for their characterization.

V. CONCLUSIONS

The CERN-RD50 collaboration is investigating the 3D detector technology as a possible solution for tracking detectors at the innermost layers of the SLHC experiments.

A first approach, aimed to understand the technology and operation of the 3D devices, has been the single-type column 3D structure. STC-3D detectors with different configurations have been fabricated on FZ and CZ p-type substrates and tested. These devices present full lateral depletion at voltages lower than 10 V and planar-diode like depletion afterwards. Infrared laser tests on microstrip STC-3D sensors show variations in the signal produced as a function of the interaction point due to the inhomogeneity of the electric field along the detector surface. After irradiation with neutrons to a fluence of 5×10^{14} n_{eq}/cm^2 the charge collected with an integration time of 25 ns decreases substantially due to the ballistic deficit and trapping of holes. However, absolute charge collection measurements with ATLAS SCT readout and a β source show that after an irradiation with protons to a fluence of 10^{15} n_{eq}/cm^2 the sensors still have low noise levels, comparable to the shown by ATLAS SCT modules, and a reasonably good signal to noise ratio of ~ 12.

An alternative structure, the double-sided 3D detector, has also been proposed. The simulation studies of these devices predict a charge collection efficiency comparable to the shown by a full 3D sensor, even after heavy irradiation. The first fabricated double-sided detectors present good electrical characteristics, with low leakage currents and high breakdown voltages. The devices will be subjected to further electrical and charge collection characterization using discrete amplifiers and ASICs, including LHC speed electronics.

The production of a set of full 3D detectors is currently ongoing.

REFERENCES

[1] http://rd50.web.cern.ch/rd50/

[2] S. Parker, C. J. Kenney and J. Segal, “3D – A proposed new architecture for solid-state radiation detectors”, *Nucl. Instr. and Meth. A*, vol. 395, no. 3, pp. 328–343, Aug. 1997.

[3] C. Piemonte, M. Boscardin, G. –F. Dalla Betta, S. Ronchin and N. Zorzi, “Development of 3D detectors featuring columnar electrodes of the same doping type”, *Nucl. Instr. and Meth. A*, vol. 541, no. 1–2, pp. 441–448, Apr. 2005.

[4] C. Fleta, D. Pennicard, R. Bates, C. Parkes, G. Pellegrini, M. Lozano, V. Wright, M. Boscardin, G.-F. Dalla Betta, C. Piemonte, A. Pozza, S. Ronchin and N. Zorzi, “Simulation and test of 3D silicon radiation detectors”, *Nucl. Instr. and Meth. A*, vol. 579, no. 2, pp. 642–647, Sep. 2007.

[5] S. Ronchin, M. Boscardin, C. Piemonte, A. Pozza, N. Zorzi, G.-F. Dalla Betta, L. Bosisio and G. Pellegrini, “Fabrication of 3D detectors with columnar electrodes of the same doping type”, *Nucl. Instr. and Meth. A*, vol. 573, no. 1–2, pp. 224–227, Apr. 2007.

[6] A. Pozza, M. Boscardin, L. Bosisio, G.-F. Dalla Betta, C. Piemonte, S. Ronchin and N. Zorzi, “First electrical characterization of 3D detectors with electrodes of the same doping type”, *Nucl. Instr. and Meth. A*, vol. 570, no. 2, pp. 317–321, Jan. 2007.

[7] G. Kramberger, V. Cindro, J. Langus, I. Mandić, M. Mikuž, M. Zavrtanik, M. Boscardin, G.-F. Dalla Betta, C. Piemonte, A. Pozza, S. Ronchin and N. Zorzi, “Position sensitive TCT studies of irradiated 3D-sct sensors”, 10th RD50 Workshop, Vilnius (Lithuania), 3–6 June 2007, available online at http://rd50.web.cern.ch/rd50/

[8] M. Boscardin, L. Bosisio, M. Bruzzi, G.-F. Dalla Betta, C. Piemonte, A. Pozza, S. Ronchin, C. Tosi, N. Zorzi, “Characterization of 3D-stc detectors fabricated at ITC-irst”, *Nucl. Instr. and Meth. A*, vol. 572, no. 1, pp. 284–286, Mar. 2007.

[9] M. Scaringella, A. Polyakov, H.F.-W. Sadrozinski, M. Bruzzi, C. Tosi, M. Boscardin, C. Piemonte, A. Pozza, S. Ronchin, N. Zorzi and G.-F. Dalla Betta, “Charge collection measurements in single-type column 3D sensors”, *Nucl. Instr. and Meth. A*, vol. 579, no. 2, pp. 638–641, Sep. 2007.

[10] V. Cindro, G. Kramberger, J. Langus, I. Mandić, M. Mikuž, M. Zavrtanik, M. Boscardin, G.-F. Dalla Betta, C. Piemonte, A. Pozza, S. Ronchin and N. Zorzi, “Position Sensitive TCT Measurements with 3D-stc detectors”, 8th RD50 Workshop, Prague (Czech Republic), 25–28 June 2006, available online at http://rd50.web.cern.ch/rd50/

[11] M. Zavrtanik, V. Cindro, G. Kramberger, J. Langus, I. Mandi, M. Mikuz, C. Piamonte, M. Boscardin, G.-F. Dalla Betta, S. Ronchin, N. Zorzi and A. Pozza, “Position sensitive TCT evaluation of irradiated 3D-stc detectors”, these proceedings.

[12] T. Ehrich, S. Kuhn, M. Boscardin, G.-F. Dalla Betta, S. Eckert, K. Jakobs, M. Maaßen, U. Parzefall, C. Piemonte, A. Pozza, S. Ronchin and N. Zorzi, “Laser characterisation of a 3D single-type column p-type prototype module read out with ATLAS SCT electronics”, to be published in *Nucl. Instr. and Meth. A*.

[13] S. Eckert, T. Ehrich, K. Jakobs, S. Kuhn, U. Parzefall, M. Boscardin, C. Piemonte and S. Ronchin, “Signal and charge collection efficiency of a p-type STC 3D-detector irradiated to sLHC-fluences, read out with 40 MHz”, *Nucl. Instr. and Meth. A*, vol. 581, no. 1–2, pp. 322–325, Oct. 2007.

[14] S. Kuehn, G.-F. Dalla Betta, S. Eckert, K. Jakobs, U. Parzefall, A. Pozza, A. Zoboli and N. Zorzi, “Short strips for the sLHC: a p-type silicon microstrip detector in 3D-technology”, these proceedings.

[15] Z. Li, W. Chen, Y.H. Guo, D. Lissauer, D. Lynn, V. Radeka, M. Lozano and G. Pellegrini, “Development, simulation and processing of new 3d Si detectors”, to be published in *Nucl. Instr. and Meth. A*.

[16] Z. Li, “Novel silicon stripixel detector: concept, simulation, design and fabrication”, *Nucl. Instr. and Meth. A*, vol. 518, no. 3, pp. 738–753, Feb. 2004.

[17] G. Pellegrini, F. Campabadal, M. Lozano, J.M. Rafi, M. Ullan, R. Bates, C. Fleta and D. Pennicard, “Double sided 3D detector technologies at CNM-IMB”, *Nuclear Science Symposium Conference Record, 2006. IEEE* , vol. 2, pp. 1248–1252, Oct. 29 2006-Nov. 1 2006.

[18] D. Pennicard, G. Pellegrini, M. Lozano, R. Bates, C. Parkes, V. O'Shea and V. Wright, “Simulation results from double-sided 3-D detectors”, *IEEE Trans. Nucl. Sci.*, vol. 54, no. 4, pp.1435-1443, Aug. 2007.

[19] D. Pennicard, “Simulation results from double-sided and standard 3D detectors”, 10th RD50 Workshop, Vilnius (Lithuania), 3–6 June 2007, available online at http://rd50.web.cern.ch/rd50/

[20] D. Pennicard, “Simulations of 3D detectors with radiation damage up to $10^{16} n_{eq}/cm^2$”, ATLAS 3D Sensors R&D meeting, CERN, 2 July 2007, available online at http://indico.cern.ch/conferenceDisplay.py?confId=17797

[21] M. Petasecca, F. Moscatelli, D. Passeri and G.U. Pignatel, “Numerical simulation of radiation damage effects in p-type and n-type FZ silicon detectors”, *IEEE Trans. Nucl. Sci.*, vol. 53, no. 5, pp. 2971–2976, Oct. 2006.

[22] G.-F. Dalla Betta, M. Boscardin, L. Bosisio, C. Piemonte, A. Pozza, S. Ronchin, A. Zoboli and N. Zorzi, “New developments on 3D detectors at IRST”, these proceedings.

[23] T. Palviainen and Z. Li, “Full 3D simulations of BNL silicon 3D detectors and comparisons with other types of 3D detectors”, 10th RD50 Workshop, Vilnius (Lithuania), 3–6 June 2007, available online at http://rd50.web.cern.ch/rd50/

[24] http://www.icemostech.com/

[25] http://www.diamond.ac.uk/