Characterisation of micro-strip and pixel silicon detectors before and after hadron irradiation

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ABSTRACT: The use of segmented silicon detectors for tracking and vertexing in particle physics has grown substantially since their introduction in 1980. It is now anticipated that roughly 50,000 six inch wafers of high resistivity silicon will need to be processed into sensors to be deployed in the upgraded experiments in the future high luminosity LHC (HL-LHC) at CERN. These detectors will also face an extremely severe radiation environment, varying with distance from the interaction point. The volume of required sensors is large and their delivery is required during a relatively short time, demanding a high throughput from the chosen suppliers. The current situation internationally, in this highly specialist market, means that security of supply for large orders can therefore be an issue and bringing additional potential vendors into the field can only be an advantage. Semiconductor companies that could include planar sensors suitable for particle physics in their product lines will, however, need to prove their products meet all the stringent technical requirements. A semiconductor company with very widespread experience of producing science grade CCDs (including deep depletion devices) has adapted their CCD process to fabricate for the first time several wafers of pixel and micro-strip radiation hard sensors, suitable for future high energy physics experiments. The results of the pre-irradiation characterization of devices fabricated with different processing parameters and the measurements of charge collection properties after different hadron irradiation doses up to those anticipated for the (larger area) outer pixel layers at the high-luminosity LHC (HL-LHC) are presented and compared with results from more established particle physics suppliers.

KEYWORDS: Radiation damage to detector materials (solid state); Particle tracking detectors (Solid-state detectors); Particle detectors

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Contents

1 Introduction

The long-term international planning of particle physics includes the assumption that the LHC scientific programme should last at least as long as the highly successful Tevatron collider programme in the US, which started in 1985 and is only just now drawing to a close. The Tevatron underwent several major upgrades, finally achieving luminosities as high as 400 times its original design of 10^{30}cm^{-2}s^{-1}. The LHC is currently operating at 3.5 times the energy of the Tevatron (the same factor as that by which the Tevatron itself improved over its predecessor facility, the CERN SpṗS collider) and is planned to reach its design energy of 7 TeV on 7 TeV proton collisions before the middle of this decade. By the end of the decade the LHC is planned to be operating well above its nominal luminosity of 10^{34}cm^{-2}s^{-1} (with current operation already only a factor of 3 away from this value).

When the current LHC experiments were being designed nearly 20 years ago, it was already thought highly ambitious to design for 10 years at the unprecedented projected radiation levels of the LHC, or to accommodate much more than 20 superimposed interactions every 25 ns beam crossing. Operating conditions at the proposed High Luminosity LHC (HL-LHC) imply integrated dose and events per crossing could both go up by a factor of 10 (depending on bunch spacing and luminosity levelling). For the currently installed silicon detectors this represents an unmanageable increase on top of an already highly demanding specification, and both ATLAS and CMS anticipate the need to replace their silicon trackers for HL-LHC running.

The current area of the CMS Silicon Strip Tracker is around 200 m^2 with planned upgrades for the experiment approaching this scale again [1]. ATLAS, in contemplating an all silicon tracker with no gas-based straw tube component at high radii, is also looking at a similar area of silicon [2].

Under these circumstances it becomes important to look at all the potential vendors who could meet orders on the scale of 20,000 large area (approximately $10\,\text{cm} \times 10\,\text{cm}$) silicon sensors per experiment in a time-frame of two or so years when orders would be placed towards the second half of this decade. Part of the work described here shows results with a supplier new to particle physics silicon micro-strip detector technology, which nevertheless would bring such a capability to complement the capacity already existing internationally and which supplied the existing large area trackers of ATLAS and CMS.

2 Silicon sensors for the High-Luminosity LHC

2.1 HL-LHC radiation tolerance requirements

Starting at the beginning of the next decade, the HL-LHC programme is targeting to deliver roughly $3000\,\text{fb}^{-1}$ per experiment at close to 14 TeV centre-of-mass energy to allow the full exploration, in hadron-hadron collisions, of the TeV scale [3]. At such integrated luminosities, the expected dose in units of 1 MeV neutron equivalent integrated fluence is $6.5 \times 10^{14}\,\text{n}_{eq}\text{cm}^{-2}$, at the expected radii where strip detectors are anticipated and up to $\sim 10^{16}\,\text{n}_{eq}\text{cm}^{-2}$ in the pixels (depending on the final HL-LHC beam-pipe radius). In ATLAS the target dose is to withstand a factor of two greater than these figures, to allow for uncertainties and some additional safety factor. In the plots shown later, it is assumed that strip detectors need to withstand around $1.3 \times 10^{15}\,\text{n}_{eq}\text{cm}^{-2}$ and the pixel layers should withstand $2\text{--}3 \times 10^{16}\,\text{n}_{eq}\text{cm}^{-2}$.

2.2 Development of p-type silicon for high radiation environments

In ATLAS and the CERN RD50 R&D Collaboration [4–6], there has been considerable progress on the development of p-type silicon substrates, with a view to achieving an equivalent high radiation tolerance to that of n-in-n [7] configurations (where the read-out side is patterned on the n-implant side of a diode structure with a large area p-implant effectively on the back of the n-substrate sensor). The motivation of the n-in-n design is to exploit the more commonly available high resistivity n-type substrate material, but to cope with the inversion of the substrate type to being effectively p-type after LHC levels of irradiation [8]. This design has been successfully employed for the higher radiation regions at the LHC (ATLAS pixels, CMS pixels and LHCb VeLo) but suffers from the higher cost associated with the implicit double-sided processing. This further limits the available vendors, making the use of 150 mm wafers suitable for large area sensors an issue, if very large orders are required. The use of p-type, large area wafers opens up many possibilities, including vendors not traditionally used for particle physics.

Figures 1a and 1b show the signal at 900 V as a function of proton and neutron fluence for a wide range of different substrates [9].

The superiority of detectors with n-implant read-out (n-in-n and n-in-p) is clearly demonstrated, which is a result of the significant improvements in designs where electron collection provides the main signal component. This follows from the higher electron mobility and the reduced trapping, as well as the high field region after heavy irradiation being at the n-implant side [10].
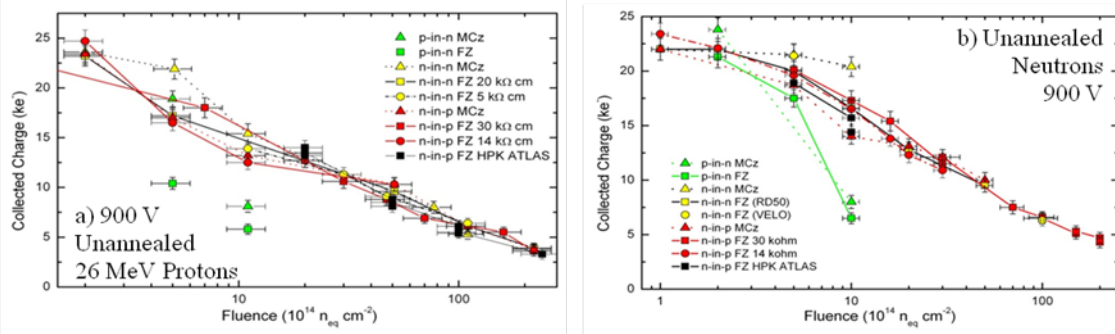
Figure 1. Signal as a function of fluence for different silicon detector types at 900 V after both a) proton and b) neutron irradiation and after non-ionising energy loss corrections to 1 MeV neutron equivalent doses.

2.3 The HL-LHC large area sensors

The current estimates for HL-LHC ATLAS tracker replacement are to require roughly $150\,\mathrm{m}^2$ of strip detector and $6\,\mathrm{m}^2$ of pixel detector [2]. The requirements for the ATLAS strip detector are discussed elsewhere in this conference [11], while much of the pixel research and development has focussed on the near-term upgrade of an Insertable B-Layer [12–15]. Options to increase the final pixel area for HL-LHC operation are under consideration, but currently this depends on requirements from simulation and better estimates of the cost.

The CMS plans include a full pixel replacement [16] this decade and then the entire tracker [1] on the same timescale as ATLAS. Clearly, even without considering other high energy physics, nuclear physics or space applications of micro-strip detectors, the expected requirements are large and major orders are expected to be placed around the same time in the latter half of this decade. It can only help to have as many potential suppliers as possible. The LHC upgrade requirements, alone, may generate requirements that approach 50,000 150 mm wafers for equipping replacement vertex detectors and trackers.

3 Evaluation of silicon detectors from a new potential micro-strip and planar pixel supplier

3.1 Sensor processing with e2v technologies plc

e2v technologies plc[1] has a long history of semiconductor device fabrication with expertise in CCD technology dating back to their first introduction in the 1970s. CCDs for scientific instruments, space & astronomy is a niche market where e2v have made considerable contributions (see for example [17]). However, the company has also made x-ray CCDs on a larger scale, giving it the production capability which matches the fabrication requirements for large area silicon sensor arrays for particle physics. Following the RD50 irradiation campaigns, for which a dedicated set of miniature detectors were designed (based on the ATLAS micro-strip and both ATLAS and CMS pixel sensor layouts) masks were designed for fabrication of devices with e2v that exactly

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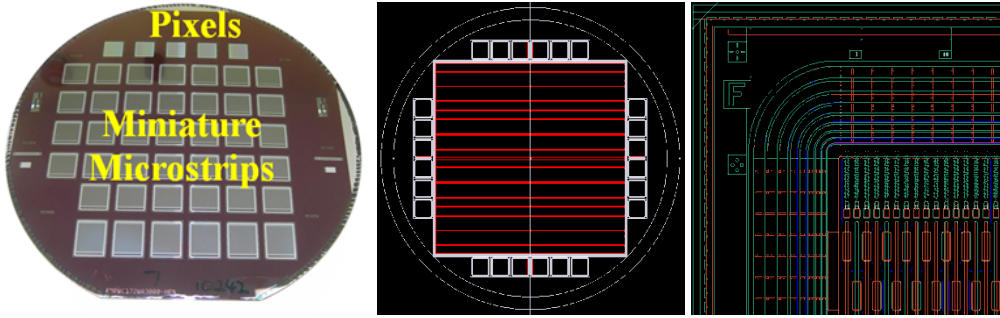
Figure 2. e2v 150 mm silicon wafer, large area sensor mask design and sensor corner detail.

matched those with which RD50 has extensive experience of pre-irradiation and post-irradiation performance. Figure 2 shows the layout of the sensors as fabricated on a 150 mm wafer.

At the time of writing the first large area sensors consistent with the needs of the ATLAS and CMS strip tracker upgrade plans are still in processing, but the results (below) with miniature sensors give good grounds for optimism in terms of yield and performance.

3.2 Charge collection studies and comparisons with established micro-strip suppliers

The ALiBaVa (Liverpool, Barcelona and Valencia) read-out based on the LHCb Beetle ASIC [18] allows detectors with strip readout to be fully characterised unirradiated, disconnected from the ASIC and taken for irradiation, and then re-measured on the same ASIC where the only differences have to be due to the received radiation dose. This removes many sources of systematic error and allows excellent calibration of the collected charge, using the well documented pre-irradiation signal generated in silicon detectors as a function of thickness. Using this approach with strip detectors produced by e2v Technologies leads to the results shown in figures 3 and 4, below. The data show the current vs voltage (IV) characteristics after doses of 2×10^{14} n_{eq}/cm^2 , 1.4×10^{15} n_{eq}/cm^2 and 4×10^{15} n_{eq}/cm^2 using the 24 GeV CERN PS to perform proton irradiations, and then using standard procedures to convert to 1 MeV neutron equivalent fluence figures. Here, and below, the irradiated samples are measured at $-20°$C, while the unirradiated characteristics are evaluated at room temperature. For comparison, the expected currents after 10 days room temperature annealing, operating at $-20°$C for 2×10^{14} n_{eq}/cm^2 and 1.4×10^{15} n_{eq}/cm^2 (assuming an α value of $3.99 \pm 0.03 \times 10^{-17}$ A cm^{-1} [19]) should be 4 μA and 22 μA, respectively, at the full depletion voltage. Given dose and annealing uncertainties and that the 1.4×10^{15} n_{eq}/cm^2 sample is only expected to be fully depleted above 1300 V, these values agree reasonably with the results presented in figure 3.

The signals in figure 4 are evaluated with a ^{90}Sr β-source, triggered by a scintillator below the sample which ensures we mainly see minimum ionising particles, as confirmed by the pre-irradiation calibration with identical electronics and read-out.

If these results are superimposed on those obtained with other manufacturers a good consistency is seen (see figures 5 and 6). However, standard CCD processing differs from that typical for micro-strip devices, and processing needs to be tuned to give the excellent high voltage characteristics demanded of devices able to be over-depleted before irradiation and operated at very high

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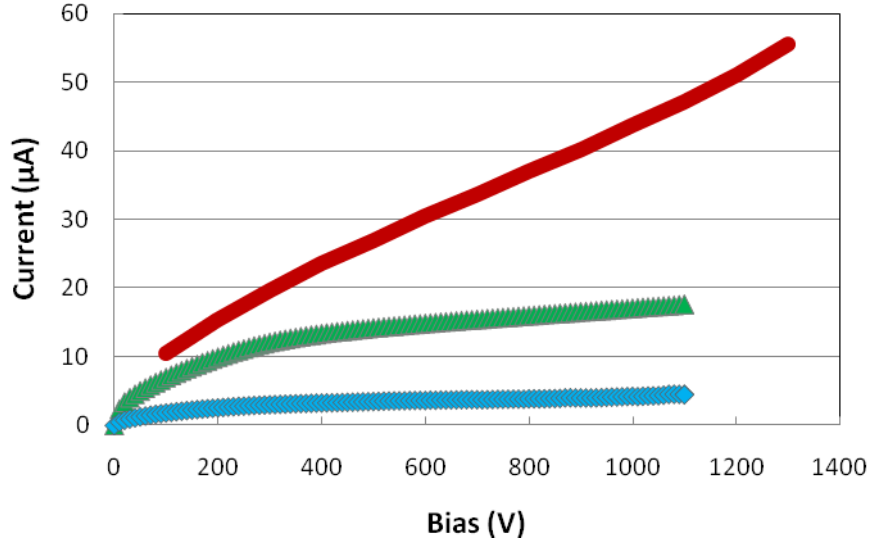
Figure 3. IV characteristics of e2v n-in-p strip sensors irradiated to $2 \times 10^{14} n_{eq}/cm^2$ (blue), $1.4 \times 10^{15} n_{eq}/cm^2$ (green) and $4 \times 10^{15}\ n_{eq}/cm^2$ (red) as a function of the applied depletion voltage.
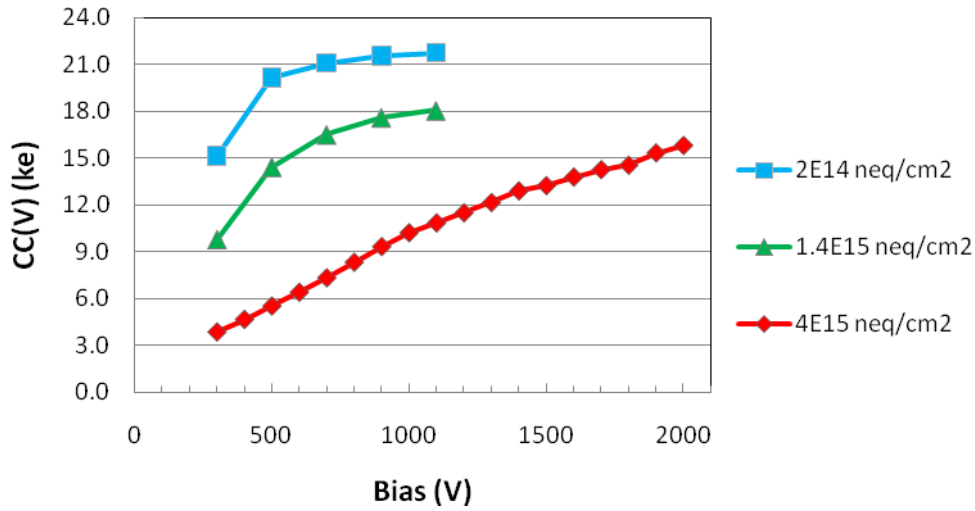

Figure 4. Charge collection characteristics of e2v n-in-p strip sensors irradiated to 2, 14 and 40×10^{14} n_{eq}/cm^2.

voltage after irradiation. It has been our past experience that after irradiation, performance differences with different manufacturers tend to be swamped by the radiation induced characteristics. However, it is traditional to try and set pre-irradiation specifications that allow a realistic quality assurance procedure to be defined with relevance to post-irradiation performance. Hence, low current operation well above depletion voltage before irradiation is often demanded, even though we expect final leakage currents to be dominated by radiation induced defects.
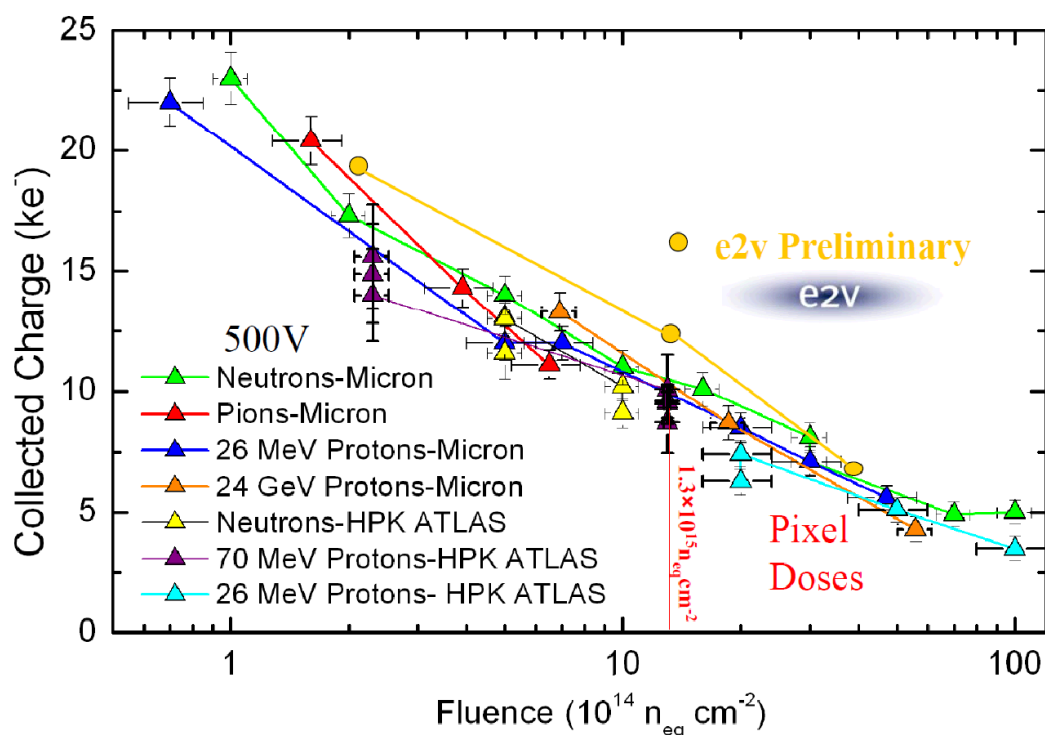
Figure 5. Signal vs fluence for e2v sensor superimposed on previously published data with other manufacturers and sources of irradiation (biased to 500 V).
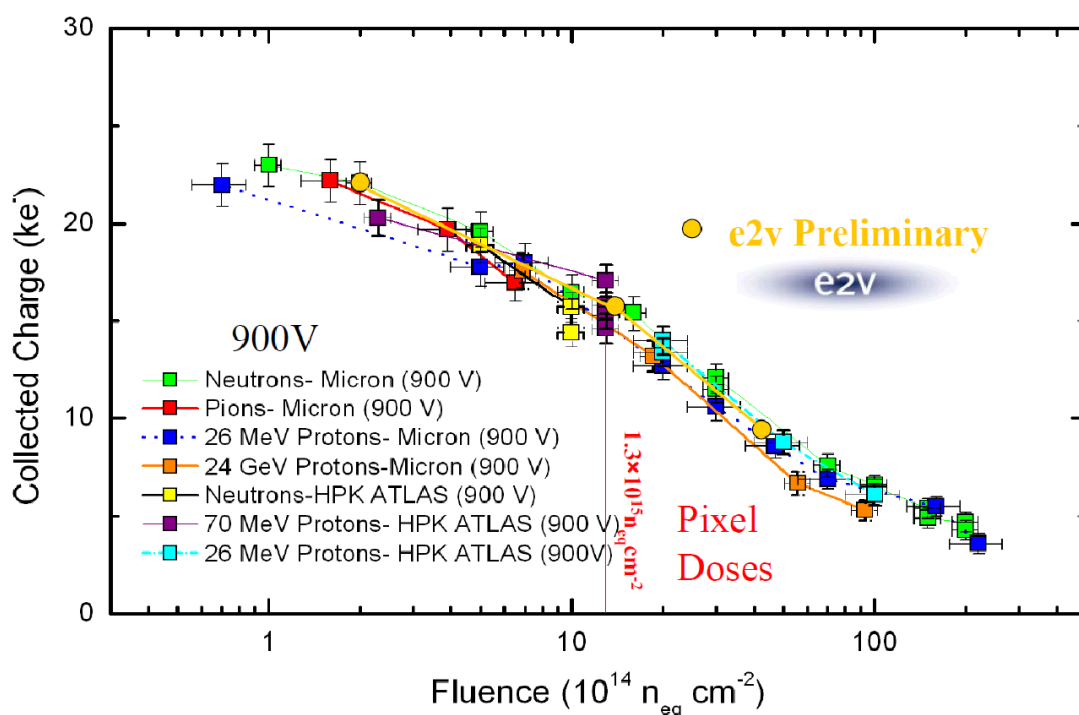
Figure 6. Signal vs fluence for e2v sensor superimposed on previously published data with other manufacturers and sources of irradiation (biased to 900 V).

3.3 Dielectric processing optimisation

The "standard" CCD process would employ a capacitive dielectric layer composed of SiO_2 and Si_3N_4. Other suppliers often use the same combination, but with different thicknesses, or even just SiO_2. The three different options explored in detail here were 300 nm of SiO_2 alone and two different composite layers: 300 nm of SiO_2 with 150 nm of Si_3N_4 and the, so called, "thin film" with 125 nm SiO_2 and 150 nm Si_3N_4. Results of pre-irradiation IV characteristics are presented in figures 7, 8 and 9; while those after 4×10^{15} n_{eq}/cm^2 are presented in figures 10, 11 and 12. As might be expected, the behavior after irradiation is much less sensitive to the processing choice than that before, but a clear indication that "all oxide" is to be preferred is seen from the data for this particular manufacturer.

The results include post-irradiation (figures 10, 11, and 12) data from both miniature strip detectors and from pixel designs consistent with the ATLAS FE-I3 ASIC production used for the current ATLAS pixel detector [20]. The thicker composite dielectric and "all oxide" perform better after irradiation while the "all oxide" even gives a large number of devices holding all the way to 1000 V before irradiation. Given the 230–260 V depletion voltage, this is a very promising result for first devices to these designs processed by a new supplier.

In addition to changes in the dielectric, various combinations of the p-spray and p-stop isolation of the n-strip implants were explored, but no major differences were found in the IV characteristics over the range of parameters studied.

4 Conclusions

The requirements of the High Luminosity LHC pose further demands on the tracker technologies already employed at the LHC, particularly in terms of required radiation hardness and granularity. In addition, constraints of cost for tracker replacement and the area of silicon required for the new micro-strip arrays will imply issues of supply and, potentially, cost. Whilst several excellent suppliers already exist, the additional security of having a further supplier with significant production capacity can only be helpful both for particle physics and other fields which use similar technologies for large area detector systems. Such a potential manufacturer has been identified and has produced very promising prototypes which perform identically after irradiation to those from existing mainstream suppliers. This offers the promise of increasing the pool of available companies which could be available to help provide the very large orders anticipated for the next generation of large area silicon trackers, including those needed for the High Luminosity LHC.
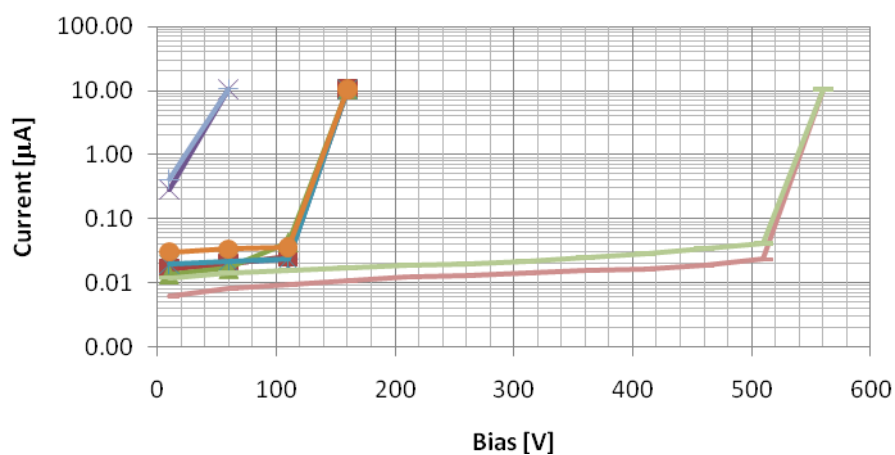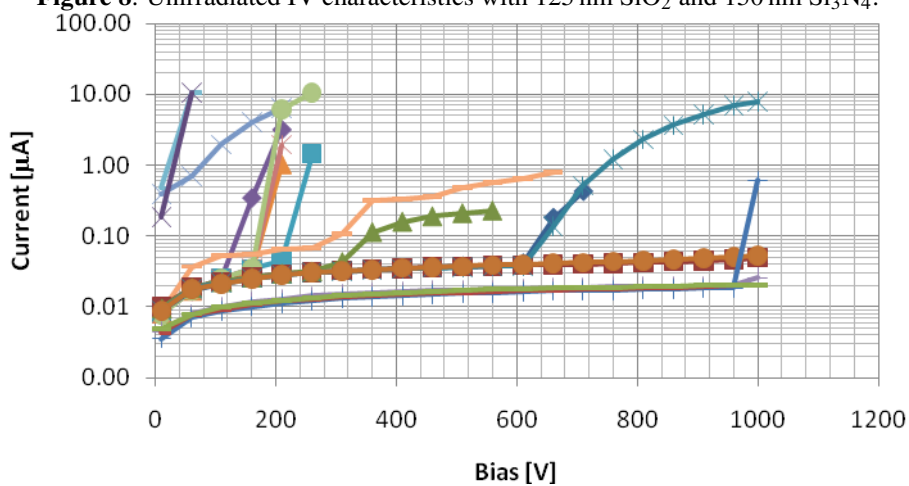
Figure 7. Unirradiated IV characteristics with 300 nm of SiO_2 and 150 nm of Si_3N_4.
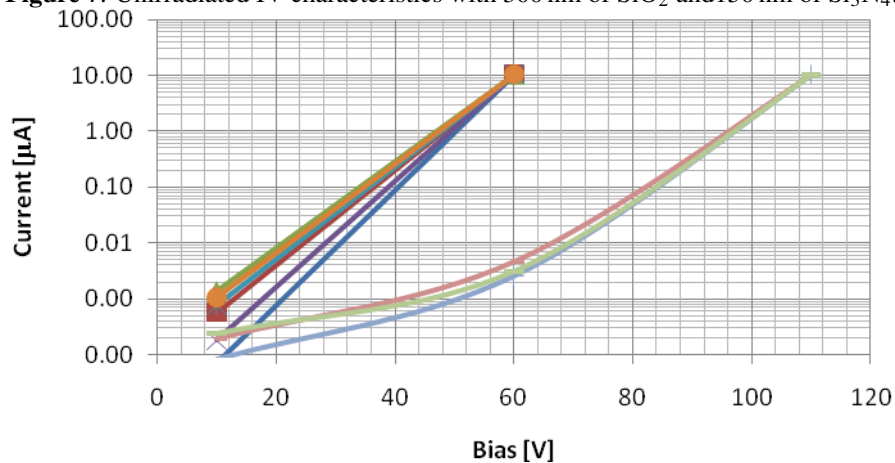
Figure 8. Unirradiated IV characteristics with 125 nm SiO_2 and 150 nm Si_3N_4.

Figure 9. Unirradiated IV characteristics with just 300 nm of SiO_2.
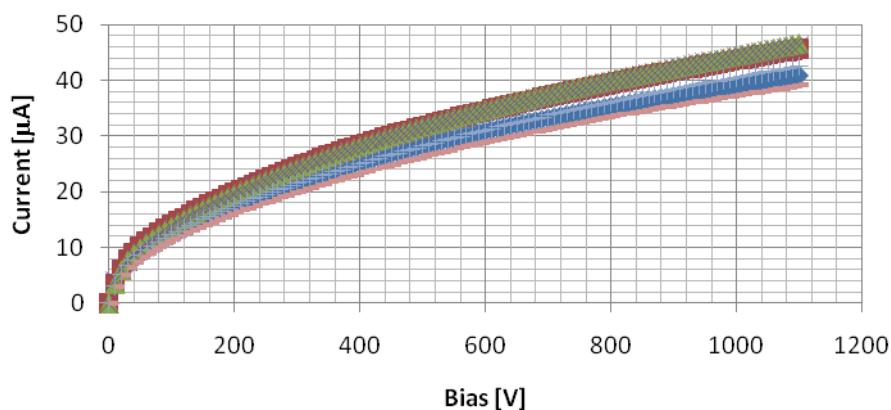
Figure 10. Irradiated IV characteristics with 300 nm of SiO_2 and 150 nm of Si_3N_4.
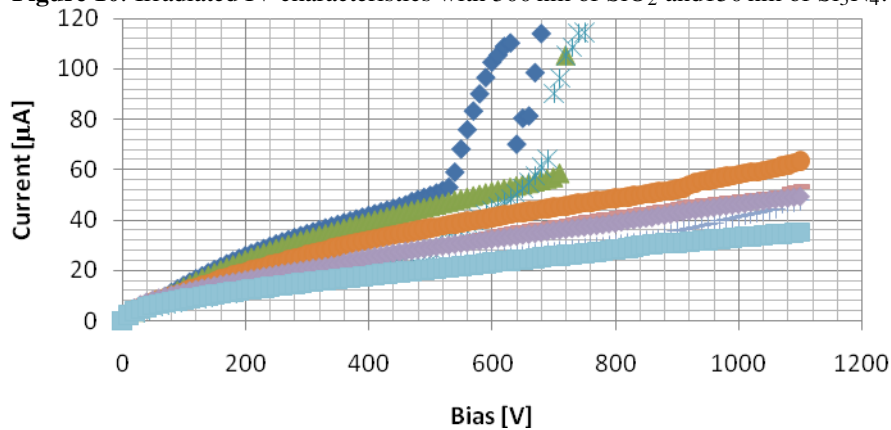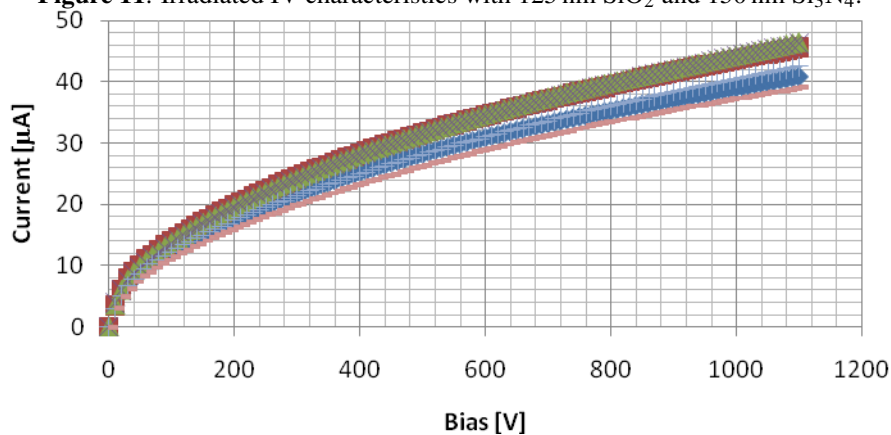

Figure 11. Irradiated IV characteristics with 125 nm SiO_2 and 150 nm Si_3N_4.

Figure 12. Irradiated IV characteristics with just 300 nm of SiO_2.

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