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Characterisation of a Thin Fully Depleted SOI Pixel Sensor with Soft X-ray Radiation

Marco Battaglia [a,b,*], Dario Bisello [c], Richard Celestre [a], Devis Contarato [a], Peter Denes [a], Serena Mattiazzo [c], Craig Tindall [a]

[a] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[b] *Santa Cruz Institute of Particle Physics, University of California at Santa Cruz, CA 95064, USA*
[c] *Dipartimento di Fisica, Universitá di Padova and INFN, Sezione di Padova, I-35131 Padova, Italy*

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ABSTRACT

This paper presents the results of the characterisation of a back-illuminated pixel sensor manufactured in Silicon-on-Insulator technology on a high-resistivity substrate with soft X-rays. The sensor is thinned and a low energy phosphorus implantation is performed on the back-plane. The response to X-rays from 2.12 to 8.6 keV is evaluated with fluorescence radiation at the LBNL Advanced Light Source.

1. Introduction

The availability of the Lapis Semiconductor (former OKI Semiconductor) Silicon-on-Insulator (SOI) process with an handle wafer of moderate resistivity and contacts through the buried oxide layer has enabled significant R&D on monolithic Si pixel sensors for charged particle tracking and imaging. The SOI technology has a number of potential advantages compared to bulk CMOS processes for the fabrication of pixel sensors. Past the first proof of principle of beam particle detection with an SOI pixel sensor [1], the R&D had to solve the back-gating effect, which limited the practical depletion voltage and thus the depleted thickness. The use of a buried p-well (BPW) to protect the CMOS electronics from the potential on the handle wafer in the sensor substrate has successfully solved this problem and SOI pixels have demonstrated full functionality up to 90 V and above [2–4], corresponding to a depleted thicknesses $\geq 130\,\mu$m. An SOI pixel sensor is potentially well suited for applications in X-ray imaging and Ref. [5] discusses tests of a prototype chip for application in hard X-ray imaging spectroscopy on future astronomical satellites. The availability of a pixellated sensor with large quantum efficiency for soft X-rays and low-energy electrons, small pixels, fast readout and moderate energy resolution opens up a broad field of potential imaging applications. In this paper we present the results of the characterisation of an SOI pixel sensor with soft X-rays in back-illumination. For this application the sensor is thinned to 70 μm, to ensure full depletion, and the back-plane post-processed to create a thin entrance window. Results obtained with the same thin, back-processed SOI sensor on an high energy hadron beam to study its performance in particle vertex tracking for accelerator particle physics are presented in a companion paper [6].

2. Sensor back-plane post-processing

The "SOImager-2" pixel sensor prototype has simple 3T analog pixels arrayed on a 13.75 μm pitch. It has been designed at LBNL and produced in the OKI 0.2 μm SOI process. The *n*-type handle wafer is of Czochralski (CZ) type and has a nominal resistivity of 700 Ω cm and buried oxide thickness of 200 nm. This chip has already been characterised both in the lab with laser beams of different wavelengths and on a beam-line at the CERN SPS using 200 GeV π^-. These tests demonstrated that pixel cells with BPW extending below either the diode or the transistors are not affected by the back-gating effect up to voltages ≥ 70 V. The cluster signal-to-noise ratio for minimum ionising particles was measured to be 55, the particle detection efficiency ≥ 0.98 and the single point resolution $1.12 \pm 0.03\,\mu$m, for $V_d \geq 50$ V [4].

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* Corresponding author at: Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.
E-mail address: MBattaglia@lbl.gov (M. Battaglia).

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These sensors have a breakdown voltage of ~130 V, which prevents the full depletion of their 260 μm full thickness, as provided by the foundry. Therefore, a set of sensor chips has been back-thinned to 70 μm using a commercial grinding technique [7], which has been already successfully employed for back-thinning CMOS Active Pixel Sensors [8]. After thinning, the sensor leakage current increases by more than one order of magnitude, due to the defects generated on the back-plane by the grinding process.

The thinned sensors are post-processed to create a thin entrance window on the back-plane and anneal the crystal damage from the thinning. A thin phosphor layer is implanted at 33 keV using a cold process at $-160\,^{\circ}$C. The dose is adjusted to obtain an amorphous layer of Si, which favours crystal re-growth. After phosphor implant the chip is annealed at 500 °C for 10 min in Nitrogen atmosphere. The thickness of the phosphor layer is measured using spreading resistance analysis (SRA) on a chip. The result is shown in Fig. 1 and indicates that the phosphor layer extends to a depth of $\simeq 0.4$ μm from the back-plane surface, with the highest concentration in the first 0.2 μm.

This process provides the sensors with a thin entrance window on the back-plane ensuring in principle good sensitivity to X-rays down to ~1.5 keV and to electrons down to ~9 keV. After back-plane post-processing the leakage current is reduced to values comparable to, or lower than, those obtained on un-processed chips [6] and the sensors are functional with a total single pixel noise of $95 \pm 6\ e^-$ ENC, which is consistent with that of $83 \pm 8\ e^-$ measured on thick, un-processed sensors, and can be fully depleted.

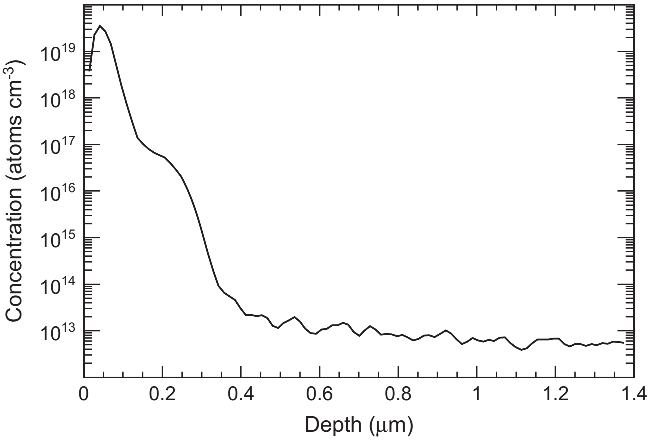

Fig. 1. Phosphor concentration profile on the back-plane from SRA of a post-processed sensor chip.

3. Experimental set-up and results

The data acquisition of the SOI sensor is performed with the setup discussed in Refs. [4,9]. Most of the measurements reported here have been performed with the chip clocked at 6.25 MHz, corresponding to a read-out time of 160 ns per pixel. Data sparsification is performed on-line in the DAQ PC using a custom `Root`-based [10] program. The matrix of pedestal subtracted data is scanned for seed pixels with signal exceeding a preset threshold in noise units. For each seed, the 7×7 pixel matrix centred around the seed position is selected and stored on file. Signal clusters are reconstructed off-line by applying a double threshold method on the matrix of pixels selected around a candidate cluster seed. Clusters are required to have a seed pixel with a signal-to-noise ratio, S/N, of at least 5.0 and the neighbouring pixels with a S/N in excess of 2.5.

First the sensor is tested in the laboratory using 2-ns-long pulses of a 980 nm laser collimated to a $\simeq 5$ μm spot on the pixel back-plane. The number of pixels accepted in a cluster, N_{pixels}, and the ratio of the signal on the seed pixel to the total signal in the cluster measure the spread of the signal charge and the inter-pixel coupling. Fig. 2 shows the pixel multiplicity in the clusters and the ratio of the signal on the seed pixel to the total signal in the cluster as a function of V_d. The thinned sensor becomes fully depleted at $\simeq 40$ V. We observe that both the pixel multiplicity in the clusters, N_{pixels}, and the ratio of the seed to cluster charge, PHR, approach a plateau with average values of $N_{\text{pixels}} = 2.16 \pm 0.03$ and $\text{PHR} = 0.93 \pm 0.01$, above $V_d \simeq 40$ V. The full depletion value is confirmed by $C{-}V$ curves [6].

The quantum efficiency for X-rays is studied on data collected at the beam-line 5.3.1 of the Advanced Light Source (ALS) at LBNL for various values of the photon energy and sensor depletion voltage V_d. The thin, post-processed SOI sensor has been exposed to fluorescence radiation excited in various metal foils, with energy in the range $2.1 < E < 8.6$ keV. The synchrotron radiation beam from a bending magnet is selected in energy through a monochromator to obtain a 12 keV monochromatic beam. This beam is sent on a target metal foil at a 45° incidence angle. A computer-controlled movable stage holds multiple foils, making possible to select different target materials remotely. The target and the detector are placed into a vacuum enclosure in order to minimise the absorption of soft X-rays in air at the lower energies (below 4 keV) and mounted in back-illumination configuration. The angle between the beam and the SOI sensor is 90°. The energy spectrum and the fluorescence radiation intensity are monitored using a spectrometer consisting of a Si drift detector [11] with a FWHM resolution of 130 eV at 5.9 keV. This is installed at a 30° angle w.r.t. the incoming beam. The elements

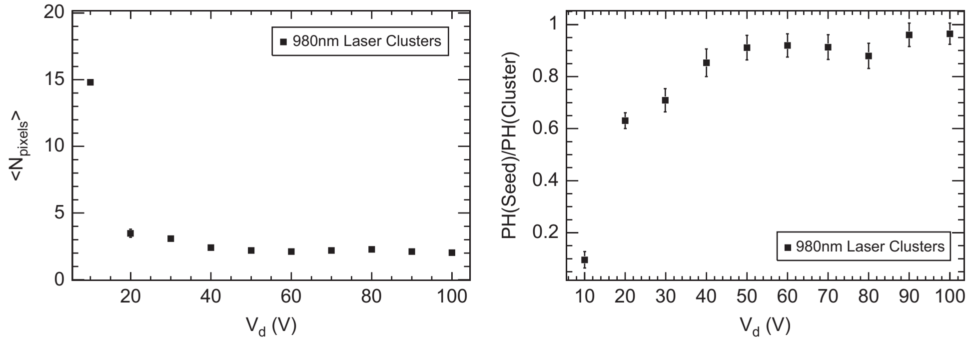

Fig. 2. Average number of pixels in signal clusters and fraction of the total signal in the cluster carried by the seed pixel for 980 nm laser pulses in back-illumination configuration as a function of the depletion voltage, V_d.