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Determination of the p-spray profile for n^+p silicon sensors using a MOSFET

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ABSTRACT

The standard technique to electrically isolate the n^+ implants of segmented silicon sensors fabricated on high-ohmic p-type silicon are p^+-implants. Although the knowledge of the p^+-implant dose and of the doping profile is highly relevant for the understanding and optimisation of sensors, this information is usually not available from the vendors, and methods to obtain it are highly welcome. The paper presents methods to obtain this information from circular MOSFETs fabricated as test structures on the same wafer as the sensors. Two circular MOSFETs, one with and one without a p^+-implant under the gate, are used for this study. They were produced on Magnetic Czochralski silicon doped with $\approx 3.5\times10^{12}$ cm^{-2} of boron and $\langle 100 \rangle$ crystal orientation. The drain–source current as function of gate voltage for different back-side voltages is measured at a drain–source voltage of 50 mV in the linear MOSFET region, and the values of threshold voltage and mobility extracted using the standard MOSFET formulae. To determine the bulk doping, the implantation dose and profile from the data, two methods are used, which give compatible results. The doping profile, which varies between 3.5×10^{12} cm^{-3} and 2×10^{15} cm^{-3} for the MOSFET with p^+-implant, is determined down to a distance of a fraction of a μm from the Si-SiO$_2$ interface. The method of extracting the doping profiles is verified using data from a TCAD simulation of the two MOSFETs. The details of the methods and of the problems encountered are discussed.

1. Introduction

In segmented n^+p silicon sensors positive charges in the SiO$_2$ close to the Si–SiO$_2$ interface can cause an electron accumulation layer, which essentially shortens the n^+ implants of the electrodes. The positive oxide charges are the result of the growing of the SiO$_2$ on the Si. Radiation damage due to ionising radiation typically further increases the density of positive oxide charges. A p^+ implantation, either over the entire wafer (p-spray) or as strips (p-stop) or a combination of both is frequently used to isolate the n^+ electrodes [1–4]. In most cases the implantation dose and the following thermal activation process is not communicated by the vendor. However, the knowledge of the value and of the density profile of active acceptors is required to understand and simulate the performance of the sensors. This is particularly relevant if the sensors are operated in a high radiation field, like at the CERN LHC or the European X-ray Free-Electron Laser, EuXFEL. Therefore, reliable methods for determining the profile of active acceptors are highly desirable. For electronics applications a number of methods, both destructive and non-destructive, are readily available. An overview can be found in Ref. [5]. Given the high resistivity of several kΩ cm of the silicon used for detector fabrication, the applicability and accuracy of the different methods has to be evaluated.

In this paper we use current–voltage measurements in the linear region of one circular n MOSFET with and a second one without a p-spray implant, to determine the value and the profile of the p-spray implants. In addition, the electron mobilities in the inversion layer at the Si–SiO$_2$ interface as function of the electric field normal to the interface for the two MOSFETs are determined. The MOSFETs have been fabricated by Hamamatsu [6] on ∼4 kΩ cm p-type silicon together with test sensors for the *CMS HPK Campaign* [7–9] of the CMS Collaboration working at the CERN LHC. For a verification of the method, data from TCAD simulations of the two MOSFETs are analyzed with the same software as the experimental data. The paper presents the problems encountered using the standard methods of the MOSFET analysis developed for electronics and how some of them could be overcome. More information on the measurements and the analysis can be found in [10].

2. MOSFETs investigated and measurement setup

The MOSFETs were fabricated on Magnetic Czochralski p-type silicon with the crystal orientation $\langle 100 \rangle$. Fig. 1(a) shows a cross section of the circular MOSFET without p-spray implant. The thickness of the Si

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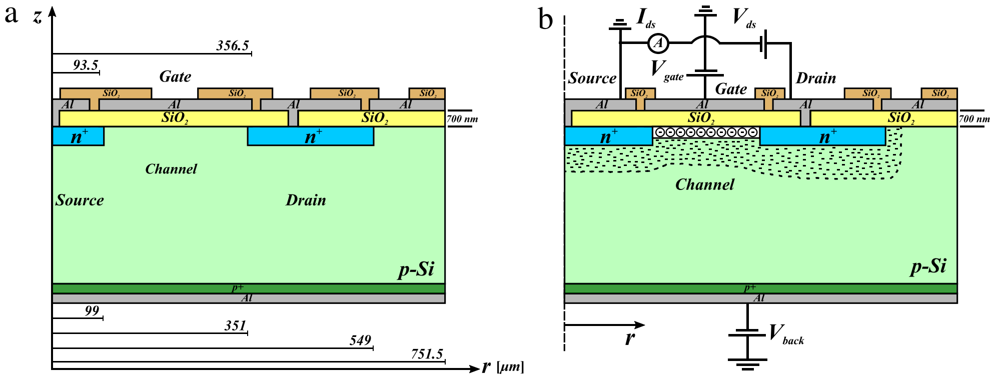

Fig. 1. (a) Schematic cross section of the MOSFET. The dimensions are taken from the GDS files of the photomask and (b) measurement setup.

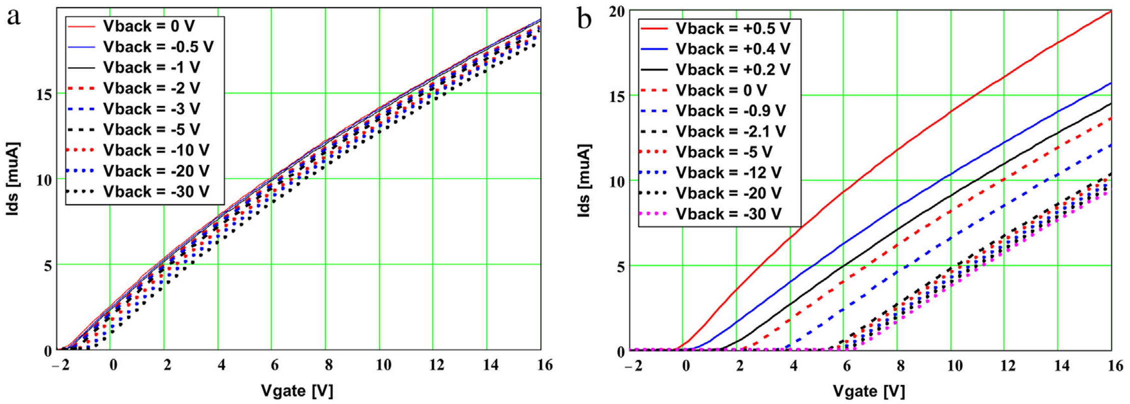

Fig. 2. Measured $I_{ds}(V_{gate})$ at $V_{ds} = 50\,\text{mV}$ for the MOSFET (a) M200P and (b) M200Y.

is approximately 200 μm. The Si-bulk dopant density, derived from the $C-V$ measurement of pad diodes is $CN_{bulk} = (3.3 \pm 0.3) \times 10^{12}$ cm^{-3}, where the spread of the measured depletion voltage from different samples and the uncertainty of the effective silicon thickness contribute about equally to the uncertainty. Here and in the following we use CN for the volume dopant concentration with units [cm^{-3}] and N for the area dopant concentration with units [cm^{-2}]. The maximum dopant densities of the n^+ implants of source and drain and of the p^+ back contact are approximately 10^{19} cm^{-3}, and the junction depths are about 2 μm. The oxide thickness, determined using capacitance measurements on MOS capacitors, is $t_{ox} = 700 \pm 5$ nm. The metal overlaps of the gate over the n^+ implants are estimated to be about 4 μm.

Following the nomenclature of the *CMS HPK Campaign* the MOSFET without p-spray implant is called **M200P**, and the MOSFET with p-spray implant **M200Y**.

Fig. 1(b) shows the biasing scheme for the MOSFET measurements, which were made on a probe station at approximately 20 °C in ambient atmosphere. The source was put on ground potential. The drain was biased at $V_{ds} = 50$ mV, and the drain–source current I_{ds} was measured using a Keithley 6487 PicoAmmeter/Voltage source. The backside voltage V_{back} was set manually in the range 0 to −30 V for the M200P, and from +0.5 to −30 V for the M200Y. As the extracted value of the doping concentration is very sensitive to the exact value of V_{back}, this voltage has been recorded with an accuracy at the 1 mV level, which is more precise than the setting accuracy of the voltage source. For a given value of V_{back}, V_{gate} was ramped from −6 to +16 V and I_{ds} recorded. It was verified that the results for ramping V_{gate} up and down are compatible.

3. Data analysis and results

3.1. MOSFET parameters extracted from the $I_{ds}(V_{gate})$ measurements

Fig. 2 shows a selection of the $I_{ds}(V_{gate}, V_{back})$ results. For the M200Y measurements and $V_{back} > 0.3$ V, the p^+n junctions of source and drain approach forward biasing and the diffusion current contributes significantly to I_{ds}. Therefore for these data the I_{ds} current measured at $V_{gate} = -6$ V has been subtracted. Comparing the results of M200Y, the MOSFET with p-spray implant, to the ones of M200P, the MOSFET without p-spray implant, one notices: For $V_{back} \lesssim -2$ V, apart from a shift of V_{gate} by about 7 V, the curves and their spacings with V_{back} are similar, and for $V_{back} \gtrsim -2$ V, the spacings remain approximately constant for M200P, but increase rapidly for M200Y. These differences are caused by the p-spray implant, as will be shown in Section 3.2. In addition, the shapes of all curves are similar with the exception of the M200Y measurement at $V_{back} = 0.5$ V. This difference can be described by a change of the electron mobility at the Si–SiO$_2$ interface.

To extract the MOSFET parameters, the standard formula for an n-MOSFET in the linear region, adapted for the circular geometry, is used [11–13]:

$$I_{ds} \approx \frac{W}{L} \cdot \mu_e \cdot C_{ox} \cdot (V_{gate} - V_{th}) \cdot V_{ds}. \tag{1}$$

The width-over-length ratio for the circular MOSFET is given by $W/L = 2\pi/\ln(r_2/r_1) = 4.964$, with r_1 the outer radius of the source-implant, and r_2 the inner radius of the drain-implant. The value of the oxide capacitance $C_{ox} = 4.933$ nF/cm^2. The mobility of the electrons is denoted by μ_e, where the following parametrisation of its dependence on V_{gate} and V_{th} has been used [5]:

$$\mu_e = \mu_0 \cdot \frac{1}{1 + \frac{V_{gate} - V_{th}}{V_{1/2}}}, \tag{2}$$