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Energy monitoring of high dose ion implantation in semiconductors via photocurrent measurement

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ABSTRACT

In this work we present an easy to apply method for the in-line energy monitoring of ion implantation in semiconductor industry. The method is based on the light induced generation of electron–hole pairs in silicon semiconductors due to the internal photoelectric effect. Herein, the generation rate of electron–hole pairs decreases with increasing depth. Therefore, the position of the depletion layer, where electrons and holes are separated in a pn junction, has a strong influence on generated photocurrents. The photocurrents were extracted from the *I*–*V* curve of illuminated wafers. We used silicon wafers of low n-type doping as raw material. In a Design of Experiments (DoE) a p-type dopant was implanted into the raw material with different doses and energies. The experimental results demonstrate that photocurrent measurements are capable of monitoring the acceleration energy of ions in implantation processes.

1. Introduction

In today's state of the art silicon microchip fabrication the control of the ion implantation process is a crucial step for the correct adjustment of device parameters. Important tuneable implantation process parameters are the dose, the energy and the tilt angle of incident dopants striking the wafer surface. Traditionally, ion implantation monitoring is performed by using sheet resistance measurement techniques and the thermal wave (TW) modulated optical reflectance method [1–3]. Both techniques are very sensitive to dose variations and therefore suitable for dose monitoring. They are less sensitive to energy variations and therefore not used for energy monitoring.

Contrarily, our presented method is based on the measurement of the photocurrent generated inside the depletion layer of a pn junction. The position of this depletion layer is mainly controlled by the implantation energy, rather than by the dose. Therefore, the photocurrents are much more sensitive to energy variations than to dose variations and suitable for energy monitoring.

We demonstrate our method by photocurrent measurements for several Boron implantations in lightly Phosphorus doped silicon wafers. The results are compared with software simulations and with in-line sheet resistance measurements. Finally, the results are evaluated in terms of the dependence of photocurrent and sheet resistance on the implantation energy and dose.

2. Concept, experiment and results

2.1. Theoretical background

We use Phosphorus doped silicon wafers and a process with Boron implantations for our investigations.

The equivalent circuit, that is considered for presented method, consists of a photon or light-induced current generator $I_{ph,}$ a diode, a series resistor r_s, and a shunt resistor r_{sh} (see Fig. 1). The dashed part to the left is the wafer and the part to the right is the current generator from the power supply. The current I through this power supply is given by [4]:

$$I = I_{ph} - I_0\left(\exp\left(\frac{q(V+Ir_s)}{nkT}\right)-1\right) - \frac{V+Ir_s}{r_{sh}} \tag{1}$$

where I_0 is the saturation current, kT/q is the thermal voltage (= 0.0259 V at 300 K), n is the ideality factor and V is the voltage generated by the power supply. A typical measured current–voltage curve with and without light illumination is shown in Fig. 2.

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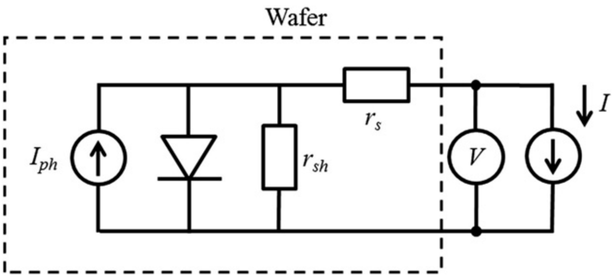

Fig. 1. Representative circuit for measured wafers.

Under short-circuit conditions, where $I = I_{sc}$ and $V = 0$, Eq. (1) becomes

$$I_{sc} = I_{ph} - I_0\left(\exp\left(\frac{q(I_{sc}r_s)}{nkT}\right) - 1\right) - \frac{I_{sc}r_s}{r_{sh}} \tag{2}$$

The short-circuit current I_{sc} at $V = 0$ is also shown in Fig. 2.

For $I_0 \approx 10^{-6}$ A, $r_s < 100$ Ω, $r_{sh} \approx 10$ kΩ, $n \approx 2$ and $T = 300$ K, are extracted from a typical measured current–voltage characteristic, Eq. (2) reduces to

$$I_{sc} \approx I_{ph}$$

The photocurrent is given by

$$I_{ph} = qA\int_0^W G(x)CP(x)dx \tag{3}$$

where A is the illuminated surface area, W is the thickness of the wafer, $G(x)$ is the generation rate of electron–hole pairs and $CP(x)$ is the collection probability. The collection probability of carriers generated in the depletion region is one as the electron–hole pairs are quickly swept apart by the electric field and are collected. Away from the junction, the collection probability drops depending on the diffusion length and the surface recombination velocity [5]. Therefore, the non-uniform collection probability will cause a dependence of the light-generated current on the position of the pn-junction and thus on the implantation energy. This dependence is schematically illustrated in Fig. 3 according to [5].

2.2. Design of experiments

Lightly Phosphorus doped (~$3 * 10^{14}$ cm^{-3}) silicon wafers were processed for various implantation energies and implantation doses of Boron dopants resulting in a large-area pn junction (see Table 1). High implantation doses were chosen for both, the front side and the back side of the wafer, to reduce the Schottky contact between tip or chuck and wafer surface and to minimize influences of the depletion width variations due to implanted doping concentration. The energy and dose range is typical for standard CMOS high current implants (e.g. used for S/D doping). Further, the Boron implants in ⟨1 0 0⟩ silicon were conducted at an angle of 7° tilt and 27° twist with respect to the silicon surface in an effort to minimize channeling effects in the silicon crystal.

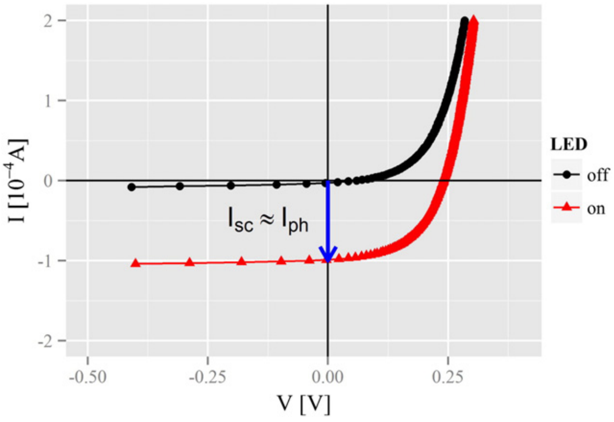

Fig. 2. Typical *I*–*V* curve of investigated wafers with and without light illumination.

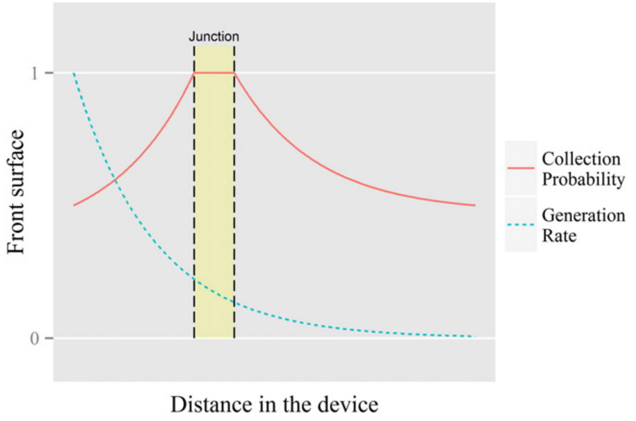

Fig. 3. Schematic of the generation rate and the collection probability of light-generated carriers.

Table 1
Wafers for various implantation energies, implantation doses and Rapid Thermal Annealing (RTA) conditions. The results of in-line sheet resistance (R_S) measurements based on 49 data points for each wafer are also included.

Wafer	Energy (keV)	Dose (cm^{-2})	RTP 1125 °C (s)	R_S mean (Ω/□)	R_S sigma [%]
1	40	1.0E+15	5	96.6	0.38
2	50	1.0E+15	5	95.4	0.48
3	80	1.0E+15	5	94.7	0.77
4	40	2.0E+15	5	49.9	0.53
5	50	2.0E+15	5	49.5	0.79
6	80	2.0E+15	5	49.5	0.81
7	40	5.0E+15	5	22.2	1.9
8	50	5.0E+15	5	21.6	1.4
9	80	5.0E+15	5	21.3	1.2
10	40	1.0E+15	10	97.2	0.63
11	50	1.0E+15	10	95.9	0.91
12	80	1.0E+15	10	94.3	1.4
13	40	2.0E+15	10	50.1	0.57
14	50	2.0E+15	10	49.5	0.72
15	80	2.0E+15	10	49.3	0.86
16	40	5.0E+15	10	22	0.87
17	50	5.0E+15	10	21.4	0.93
18	80	5.0E+15	10	21	0.76

The implantation process is followed by a Rapid Thermal Annealing (RTA) process step of 5 s or 10 s at 1125 °C. The high temperature was chosen to ensure complete healing of lattice defects plus complete activation of all Boron dopants resulting in a small sheet resistance (see column RS in Table 1). Two different times for the activation process were chosen in order to investigate the possible influence on subsequent measurements of the sheet resistance and the photocurrent. For the doses and ions used only partial amorphisation takes place, and is completely removed during the RTA step.

The resulting doping profiles were simulated by TSUPREM-4. They are shown for three different energies in Fig. 4 and for three different doses in Fig. 5, profiles after 5 s RTA.

Obviously, the projected range R_p of the Boron dopants (i.e. peak of maximum concentration) and the junction depth are mainly controlled by the implantation energy. An overview of the simulated R_p and junction depths is given in Table 2.