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Research Article

Proton Irradiations on SJ HV Power MOSFETs to Realize Fast Diode Devices

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This paper studies the effects of proton irradiations on Super Junction High Voltage power MOSFETs to realize transistors with fast diode. Experiments were performed on a sample of 600 V power MOSFETs and achieved results were compared to standard irradiated devices by electrons.

1. Introduction

In many modern applications and, in particular, when using full bridge converters, intrinsic diode of HV power MOSFET is even utilized to free wheel the current in the circuit without using any other external component [1–7]. Intrinsic diode of a power MOSFET is implemented by considering the body-drain junction of the same device. In fact, when the device is switched off and the transistor is polarized in reverse mode, the current flows from the source to the drain terminals working in third quadrant configuration. In such operating conditions, intrinsic diode needs to guarantee particular performances and features. In particular, diode needs to be fast in order to reduce switching losses when operating switching frequencies increase. A diode becomes fast when charges moved during rapid variation of V_{ds} against time are quite low as shown in Figure 1. In fact, in the example shown in Figure 1, MOSFET is rapidly switched off. When V_{ds} increases, drain current decreases down to negative values because charges stored in the body-drain junction need to be discharged. Standard devices (red curve) reach the lowest peak of drain current (I_{rm}) because the charge stored in the junction (Q_{std}) is higher than fast devices (green curve). That turns in a higher time to discharge (t_{rr}) and, thus, it makes the devices slower during commutation. To improve the performances of intrinsic diode, special processes need to be implemented. The typical action consists in the irradiation of the body-drain junction by energetic electrons in order to create suitable damage in the reticle. Such damage introduces deep energetic level traps in the silicon band-gap. Such traps capture the carriers lowering the quantity of charges moved during the fast transition from on to off states as described above. Typical irradiation doses are in the range of 5–50 MRad when considering power MOSFETs. Afterwards, a thermal process needs to be implemented in order to activate the traps. However, irradiation by considering electrons can bring issues related, for example, to the quality of gate oxide. In fact, interface traps states can be created increasing drain-source leakage current.

Recently, a new technique was implemented to realize devices with fast diodes based on proton irradiation. In fact, protons can be introduced in the body-drain junction of a power MOSFET's structure only concentrating the effect on the body-drain border junction differently from the electrons which are implanted on the entire structure.

2. Protons Irradiation, Experiment Setup, and Test Vehicles

A series of experiments were implemented by changing the dose of protons irradiation and acting on thermal process to evaluate the best solution and to compare the results with the standard electron irradiation process. The tests were performed by considering a tandem accelerator with protons at energies in the ranges of some MeV useful to

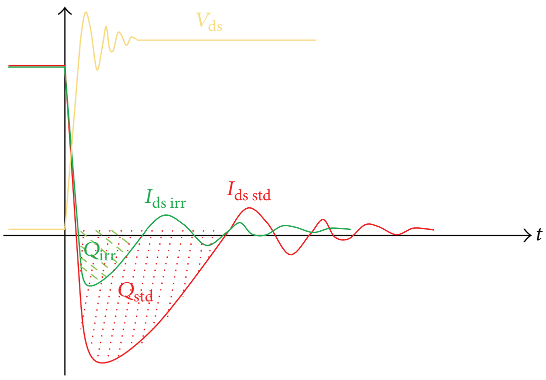

FIGURE 1: Example of commutation of the intrinsic diode and comparison with a fast diode.

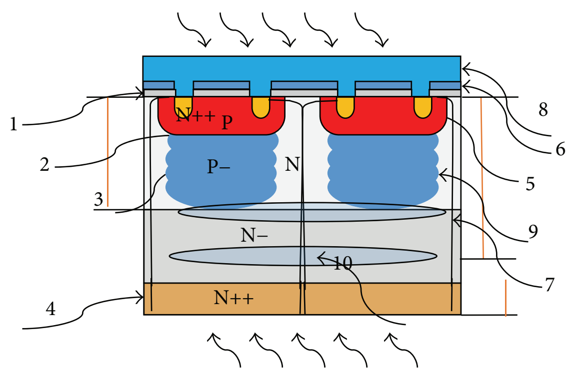

FIGURE 2: Example of cross section of a Super Junction HV power MOSFET. (1) Gate planar oxide; (2) body region; (3) EPY drift region; (4) back-drain contact; (5) source well-source contact; (6) polysilicon; (7) current flow; (8) metal; (9) drain column; and (10) region to be damaged by proton.

TABLE 1: Main characteristics of test vehicle.

Device type	SJ HV power MOSFETs used		
	BV_{dss} [V]	I_d continuous @ 25°C [A]	V_{th} [V]
n-ch	600	35	4

reach the depth inside of body-drain junction of the devices. The irradiation has been performed in air where at 1 cm of distance is located the wafer under test. Wafers were mounted on a frame connected to a precise step by step motor utilized to move it. To perform these experiments, a family of SJ HV power MOSFETs of 600 V was considered (see in Table 1 the peculiarities of the adopted test vehicle). Typical cross section of a Super Junction device is shown in Figure 2 where the depth of implant is even highlighted.

Irradiation of protons was implemented either in the front or in the back side of the wafer considered, reaching different depths in the region included between the body-drain junction and the same epitaxial layer under the pillars. Based on simulation activity, it was established that fluency of protons on the silicon needs to be in the range of 10^{11} cm^{-2} and $5 * 10^{12}$ cm^{-2} in order to compare with effects of electrons in silicon. It is necessary to observe that protons' irradiation

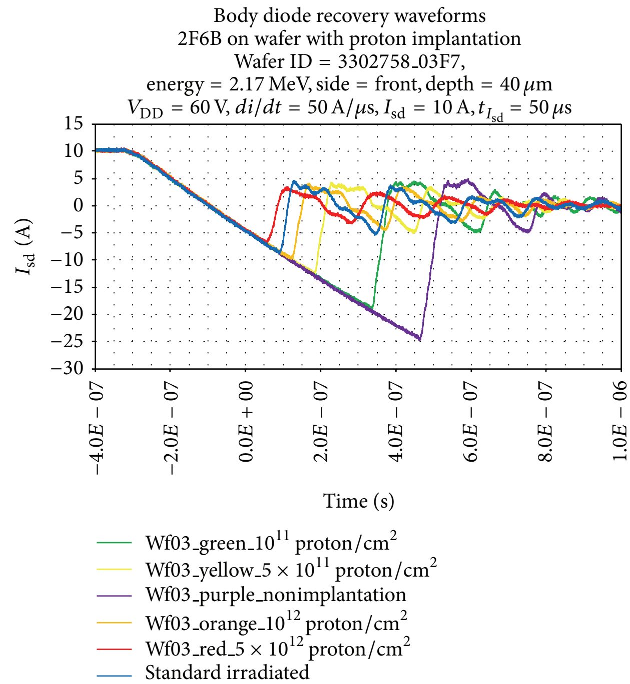

FIGURE 3: Example referred to data of Table 3.

implies a certain tail of damage along the initial path of the trajectory that could affect the electrical performances of the devices. For example, if the implantation is performed by the top of the wafer, the tail of damage involves essentially the first micrometers of silicon layers in the top of the die. Such vacancies could even affect the reliability of the gate oxide. These considerations will be more evident after studying the experimental results on the wafer irradiated on the front of the wafers. After the proton implantations, wafers under tests were thermally treated in furnaces and, afterwards, they finished the process (back end). Before packaging the dices, wafers were tested to evaluate the performances in terms of t_{rr} (diode recovery time), Q_{rr} (diode recovery charge), and I_{rm} (reverse peak current during the recovery time of diode). Figure 3 and Tables 2, 3, 4, and 5 report the data when a polarization which equals 60 V is applied.

As it is possible to see from the above data, by increasing proton dose I_{rm}, t_{rr}, and Q_{rr} decrease and the diode switching performances improve. However, results are different if compared to several trials and with standard irradiated devices with electrons. In fact, considering the devices irradiated around the body-drain junction with a concentration of 10^{12} cm^{-2}, Q_{rr} is comparable to standard irradiated transistors. Instead, considering devices with an implanted dose of $5 * 10^{12}$ cm^{-2}, Q_{rr} is lower than standard irradiated transistors. Considering devices irradiated in the epitaxial region with a concentration of $5 * 10^{12}$ cm^{-2}, Q_{rr} is quite similar to standard one. It is necessary to highlight that when the dose increases, a lowering of breakdown voltage is observed together with an increasing of drain-source leakage currents. Such results are more evident when dice implanted from the top are considered. This phenomenon can be explained taking into

Table 2: Main results on wafer bench—implantation on the front EPI layer.

Dose [cm^{-2}]	SJ HV power MOSFETs results			
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]	BV_{dss} [V]
$5 * 10^{12}$	5.1	120	354	500
$1 * 10^{12}$	9.2	189	936	610
$5 * 10^{11}$	11.5	237	1466	650
$1 * 10^{11}$	21.1	400	4475	680
No irradiation	29.6	534	7582	680
Std. electrons	8.7	184	877	660

Table 3: Main results on wafer bench—implantation on the front body-drain junction.

Dose [cm^{-2}]	SJ HV power MOSFETs results			
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]	BV_{dss} [V]
$5 * 10^{12}$	6.7	180	602	460
$1 * 10^{12}$	9.7	242	1176	570
$5 * 10^{11}$	12.5	308	1926	630
$1 * 10^{11}$	19.1	474	4524	670
No irradiation	29.6	534	7582	680
Std. electrons	8.7	184	877	660

Table 4: Main results on wafer bench—implantation on the back body-drain junction.

Dose [cm^{-2}]	SJ HV power MOSFETs results			
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]	BV_{dss} [V]
$5 * 10^{12}$	7.7	194	747	490
$1 * 10^{12}$	10.9	271	1475	600
$5 * 10^{11}$	14.1	343	2421	640
$1 * 10^{11}$	17.3	427	3692	680
No irradiation	29.6	534	7582	680
Std. electrons	8.7	184	877	660

account that tails of the damage, located near the body-drain junction, change the charges balance inside the space charge region.

Comparable results can be achieved by considering packaged devices when current is switched off at around 27 A (different operating condition compared to the previous test). In Tables 6–9 and Figures 4, 5, 6, and 7 data regarding dynamic measurements of packaged devices are shown.

3. Conclusions

This paper has analyzed the effects on SJ HV power MOSFETs of proton irradiations to realize intrinsic "fast diode" components. Intrinsic diode needs to be fast in order to decrease switching losses and to increase operating switching frequencies without any issue related to *dV/dt*. In order to improve the performances of intrinsic diode, typical action consists in the irradiation of the body-drain junction by energetic electrons. Electronic irradiations can sometimes bring issues related, for example, to the quality of gate oxide

Table 5: Main results on wafer bench—implantation on the back EPI layer.

Dose [cm^{-2}]	SJ HV power MOSFETs results			
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]	BV_{dss} [V]
$5 * 10^{12}$	9.5	232	1108	630
$1 * 10^{12}$	11.9	282	1678	660
$5 * 10^{11}$	13.5	335	2262	670
$1 * 10^{11}$	19.1	477	4550	680
No irradiation	29.6	534	7582	680
Std. electrons	8.7	184	877	660

Table 6: Main results on packaged power MOSFETs—implantation on the front EPY layer.

Dose [cm^{-2}]	SJ HV power MOSFETs results		
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]
$5 * 10^{12}$	13	162	1180
$1 * 10^{12}$	18	203	1870
$5 * 10^{11}$	24	267	3460
$1 * 10^{11}$	36	448	8612
Std. electrons	18	180	1800

Table 7: Main results on packaged power MOSFETs—implantation on the front body-drain border.

Dose [cm^{-2}]	SJ HV power MOSFETs results		
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]
$5 * 10^{12}$	10	116	630
$1 * 10^{12}$	19	233	2370
$5 * 10^{11}$	23	254	3133
$1 * 10^{11}$	35	414	7626
Std. electrons	18	180	1800

Table 8: Main results on packaged power MOSFETs—implantation on the back body-drain border.

Dose [cm^{-2}]	SJ HV power MOSFETs results		
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]
$5 * 10^{12}$	18	190	1756
$1 * 10^{12}$	20	228	2410
$5 * 10^{11}$	26	286	4056
$1 * 10^{11}$	34	406	7400
Std. electrons	18	180	1800

Table 9: Main results on packaged power MOSFETs—implantation on the back EPY layer.

Dose [cm^{-2}]	SJ HV power MOSFETs results		
	I_{rm} [A]	t_{rr} [ns]	Q_{rr} [nC]
$5 * 10^{12}$	19	205	2058
$1 * 10^{12}$	23	253	3110
$5 * 10^{11}$	27	290	4200
$1 * 10^{11}$	35	431	8330
Std. electrons	18	180	1800

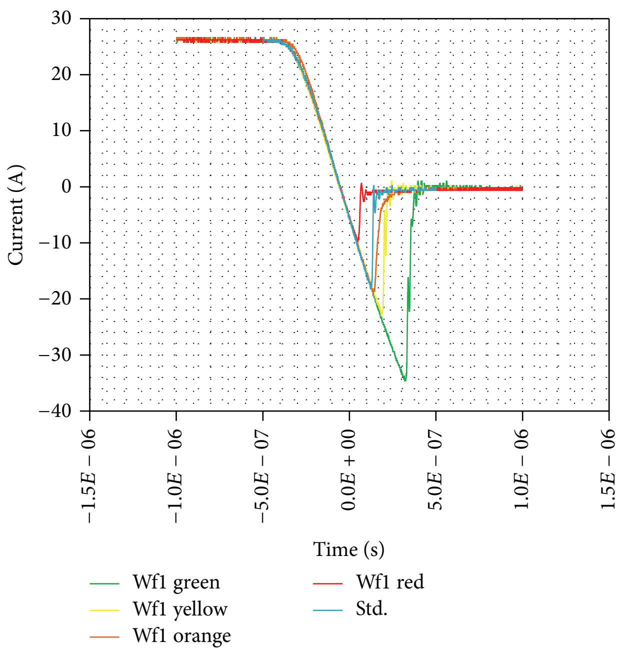

FIGURE 4: Example referred to data of Table 6.

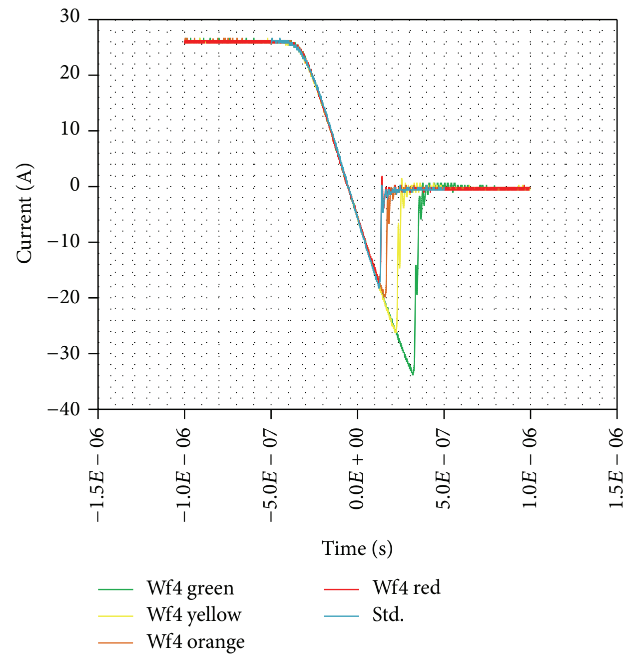

FIGURE 6: Example referred to data of Table 8.

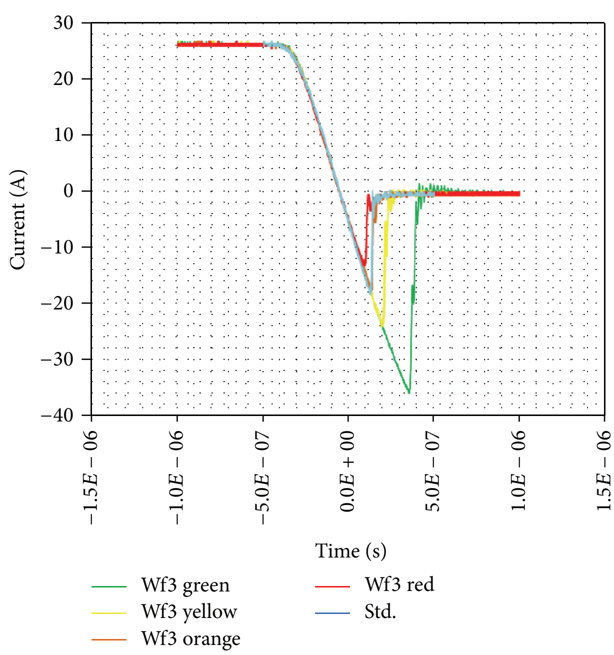

FIGURE 5: Example referred to data of Table 7.

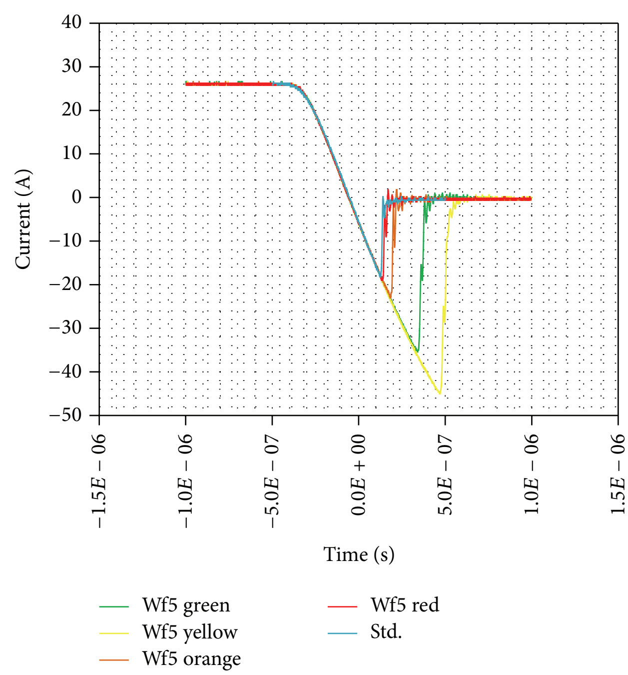

FIGURE 7: Example referred to data of Table 9.

because they are spread out in the entire wafer volume. Instead, protons are localized in a specific part of the die and, in particular, in the epitaxial layer slightly below the body-drain junction. A series of experiments was performed by considering a suitable proton irradiator on samples of Super Junction High Voltage power MOSFETs with a breakdown voltage of 600 V. Irradiations with protons were implemented either in the front or in the back side of the wafers with projected range in the region between the body-drain junction and the same epitaxial layer under the pillars. Based on simulations, it was established that fluency of protons on the silicon needs to be in the range of 10^{11} cm^{-2} and $5 * 10^{12}$ cm^{-2} to compare with effects of electrons irradiation on silicon. After the proton implantations, wafers under tests were thermally treated by considering dedicated process flow. Therefore, several measurements were performed either considering tested dice on wafers or considering static and dynamic characterizations after the packaging. Experimental results show that I_{rm}, t_{rr}, and Q_{rr} decrease by increasing proton doses. However, it is necessary to highlight that when the dose increases, a lowering of breakdown voltage is observed together with an increasing of drain-source leakage currents.

Therefore, it is possible to assume that the best trial, in terms of reverse recovery performance, was the one with protons implanted on the back side with a dose of $5 * 10^{12}\ \mathrm{cm}^{-2}$. Nevertheless, breakdown voltage degradation implies that a more optimized solution still has to be found by investigating different doses combined with thermal annealing process fine tuning, just to improve $Q_{\mathrm{rr}}/t_{\mathrm{rr}}$ performances without BV degradation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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