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Analysis and Comparison of the Breakdown Performance of Semi-Insulator and Dielectric Passivated Si Strip Detectors

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Abstract

The harsh radiation environment in future high-energy physics (HEP) experiments like LHC provides a challenging task to the performance of Si microstrip detectors. Normal operating condition for silicon detectors in HEP experiments are in most cases not as favourable as for experiments in nuclear physics. In HEP experiments the detector may be exposed to moisture and other adverse atmospheric environment. It is therefore utmost important to protect the sensitive surfaces against such poisonous effects. These instabilities can be nearly eliminated and the performance of Si detectors can be improved by implementing suitably passivated metal-overhang structures. This paper presents the influence of the relative permittivity of the passivant on the breakdown performance of the Si detectors using computer simulations. The semi-insulator and the dielectric passivated metal-overhang structures are compared under optimal conditions. The influence of various parameters such as passivation layer thickness, junction depth, metal-overhang width and fixed oxide charge on the junction breakdown voltage of these structures is extensively studied. The results presented in this work clearly demonstrate the superiority of the metal-overhang structure design employing semi-insulator passivated structures over dielectric passivated ones in realizing a given breakdown voltage.

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1. Introduction

Silicon microstrip detectors are going to play a crucial role in next generation collider experiments in high-energy physics (HEP) like LHC: their exploitation in future colliders, however, requires in-depth investigations of their long-term behaviour. For optimum performance it is crucial to achieve the maximum breakdown voltage for Si detectors operated at very high bias due to extremely hostile radiation environment of next generation experiments such as LHC [1]. Numerous techniques have been used during the last 25 years to improve the voltage handling capability of high voltage and power devices, with the intention to attain the near-ideal breakdown of a plane junction. All these methods rely either on a local change of doping or on electrostatic induction. A representative of the latter group, which minimizes dead wafer space and increases breakdown voltage, is the so-called "metal-overhang" technique [2-4]. This technique has an additional advantage of guarding the junction against environmental influences and oxide charges since it keeps the oxide surface at the fixed potential [2]. The extended electrode over the oxide, i.e., metal-overhang "relaxes" the corner electric field of the implant-strip and shifts the highest field point to the overhang edge, which is located inside the SiO_2 . However, the occurrence of breakdown within the oxide is not of much concern at the operational biases due to its much higher breakdown critical electric fields.

The electrical behaviour of a silicon microstrip detector can be influenced during operation by surface contamination, high humidity and surface moisture [5]. For example, it has been found that the reverse current and breakdown voltage change drastically, sometimes hours after biasing a seemingly good detector. A severe contamination of the surface (e.g. by touching it with fingers) may lead to increase of surface leakage current. For unprotected p^+ - n junction devices, under dry or vacuum condition, positive surface charges at the Si-SiO_2 interface are fully effective and an accumulation layer under the oxide is created. This may lead to very high electric field densities at the edge of the p^+ implantation (junction edge) and to a breakdown at voltages much lower than needed for full depletion of the detector. In the other extreme case, when the negative charges collect on the oxide surface due to the exposure of uncovered oxide surface to high humidity, an inversion layer under the oxide is developed. This leads to an extension of the depletion zone towards the edge of the detector; the reverse current can increase by an order of magnitude due to electron-hole pair generation. It is thus crucial to control surface contamination for long term stabilization of fully depleted $\text{p}^+/\text{n}^-/\text{n}^+$ silicon detector. This is achieved by depositing the final passivation layer over oxide of the silicon detector. The passivation layer also provides protection against humidity and obviates surface arcing.

Dielectric was commonly used as a surface passivant [6] for this purpose. Since its introduction, semi-insulators (SIPOS [7-10] and SinSIN [11]) have gained a lot of interest in view of their application as a surface passivation material for high-voltage Si devices.

No work has been done to correlate the breakdown voltage of the dielectric and semi-insulator passivated structures with the various physical and geometrical parameters viz., junction depth (X_j), oxide thickness (t_{ox}), width of the metal-overhang (W_{MO}), and in particular the oxide charge, which for detectors is relatively important and becomes more so as a result of ionizing radiation damage. Such a comprehensive analysis would be invaluable for detector optimization. In our recent work [4], a TCAD-based study was described, analyzing the breakdown performance of the unpassivated metal-overhang structure. The

purpose of the present paper is to extend the concepts of metal-overhang technique to the comparison of the breakdown voltage of the dielectric and semi-insulating passivated structure and also to provide the design guidelines for achieving the maximum realizable breakdown voltage by taking into account an exhaustive set of design parameters on these structures. The adoption of T-CAD tools provides the physical interpretation of the several interesting phenomena, thus, allowing for evaluating device sensitivity to most design parameters.

In our earlier works [4, 13, 14], the simulator has been validated against experimental data on guard rings and unpassivated metal-overhang structure. Here, the computed breakdown voltage was compared with the experimental data on the dielectric and semi-insulator passivated structures ([9] & [15]). From the close agreement of the simulated values with the experimental data, it can be concluded that the numerical simulation of the field distribution and avalanche generation is sufficiently accurate.

In section 2, the layout of the device simulated and the basic features of the simulation environment are described. In section 3, simulation results are presented and the comparison of the simulation with the experimental data is provided in section 4. Finally, the conclusions are presented in section 5.

2. Device Structure and Simulation Technique

The values of the parameters like detector orientation, strip-width, strip-pitch, device depth and substrate resistivity used in the present simulations lie within the acceptable limits of PreShower Detector (PSD) group at CERN [16].

A cross-section of the simulated device structure analyzed in the present work, shown in Fig.1, consists of a two-strip subset of a single-sided micro-strip array with metal-overhang. The structure is symmetric around the center of the device so only one half of the cross-section of each of the strip had to be taken into account. Such a detector is built on an n-type, 4K-cm ($N_B \sim 1 \times 10^{12}/\text{cm}^3$), 300 μm thick and [111] oriented Si wafer. The p^+ strips doping profile is Gaussian with a peak surface concentration of $5 \times 10^{19}/\text{cm}^3$. The p^+ -n junction is assumed to be cylindrical at its edge with the lateral curvature equal to 0.8 times the vertical junction depth. Depletion is achieved by positive biasing the back ohmic contact. Al electrode extending over the thicker oxide, which covers the interstrip gap, acts as a metal-overhang. The passivation layer used in this structure is either a dielectric or a semi-insulator. Surface damage can be taken into account by properly characterizing the oxide-trapped charge and the surface recombination centers. For the sake of simplicity, it is assumed that all the trapped charges are located at the Si-SiO₂ interface. This typically results in an equivalent surface charge density (Q_F) of the order of $3 \times 10^{11}/\text{cm}^2$ for the non-radiated detector with moderately good oxides, whereas the amount of trapped charge is expected to saturate at $1.0 \times 10^{12}/\text{cm}^2$, even under heavy irradiation condition, for the [111] Si orientation used in detector fabrication.

Figure1: Cross-sectional schematic of two-strip subset of a Si strip detector with metal-overhang.

For the structure shown here (Fig.1), there exist two peaks in the electric field distribution in the Si substrate: one situated near the curved portion of the junction ('A') and the second near the metal-overhang edge ('B'). In all the simulations, we consider the ideal condition where the detector is free from localized defects and the breakdown occurs either at the junction curvature or at the metal-overhang edge.

The analysis of the breakdown performance of the above-mentioned device structure is performed using TMA-MEDICI [12]. TMA-MEDICI is a general-purpose two-dimensional semiconductor device simulation program, which solves the Poisson and current continuity equations on a triangular mesh, and includes carrier generation by impact ionization. The physical models used were Shockley-Read-Hall and Auger recombination, with concentration and field dependent mobility. To avoid the ambiguity in the ionization integral, the impact ionization model was used. Current boundary conditions are imposed on the floating guard rings and homogeneous (reflecting) Neumann boundary conditions on the non-contacted outer edges of the structure. The ohmic contacts on the backside and diode on the front side are implemented by Dirichlet boundary conditions. To accurately predict junction breakdown voltage (V_{BD}), junction curvature effects causing higher electric fields at the device corners are included in the program.

The semi-insulator effect as a passivant is simulated with a linear potential distribution along the field oxide-passivation layer interface. Therefore, the solution to the Laplace equation in the passivation layer becomes redundant. In contrast, for the metal-overhang structure passivated with dielectric, the Laplace equation is solved within the passivation layer also. The qualitative information provided by the simulation leads to a deeper understanding of the

device and highlights the important parameters.

3. Simulation Results

In this section, the influence of the various parameters such as field oxide thickness (t_{OX}), junction depth (X_J), the metal-overhang width (W_{MO}), thickness of the passivant layer (t_{pass}), and the surface charge density (Q_F) on the breakdown voltage of semi-insulator passivated metal-overhang Si strip detector is systematically analyzed. These are compared with the unpassivated and dielectric passivated structures.

3.1 Effect of field oxide thickness (t_{OX}) and junction depth (X_J)

In the two-dimensional computer simulation studies on high voltage Si strip detectors involving metal-overhang structure reported in the literature [3, 4], the dielectric medium was invariably taken to be air. However, in practice, a high-voltage device equipped with metal-overhang should be protected by a suitable passivant to obviate surface arcing [17]. To study the influence of different passivants on V_{BD} , Fig.2 shows the plot of breakdown voltage as a function of t_{OX} for different passivants: two dielectrics ($\epsilon_{die}=3.9$ and $\epsilon_{die}=7.5$), a semi-insulator and also when the device is unpassivated ($\epsilon_{die}=1$). The qualitative nature of the curve is same in all the cases; V_{BD} increases with increasing t_{OX} , attains a maximum value corresponding to certain $t_{OX(OPT)}$ and then decreases with further increase in t_{OX} . For the region $t_{OX} < t_{OX(OPT)}$, breakdown occurs at the metal-overhang edge ('B' in Fig.1), whereas for $t_{OX} > t_{OX(OPT)}$, it takes place at the junction curvature ('A' in Fig.1). For $t_{OX} = t_{OX(OPT)}$, electric field distribution is such that the breakdown simultaneously occurs at the two edges, and we get the maximum breakdown voltage.

Figure 2: V_{BD} vs. t_{OX} with different passivants for $X_J=0.2\mu m$.

It can be seen from Fig.2 that the metal-overhang edge breakdown which takes place for $t_{OX} < t_{OX(OPT)}$ is very sensitive to the variation in ϵ_{die} , whereas the breakdown voltage for $t_{OX} > t_{OX(OPT)}$ is almost insensitive to changes in ϵ_{die} . For example, in the region $t_{OX} < t_{OX(OPT)}$, V_{BD} corresponding to $\epsilon_{die}=3.9$ is considerably higher than that for $\epsilon_{die}=1.0$, thus demonstrating that ϵ_{die} plays an important role in determining V_{BD} . It can also be seen that the V_{BD} for $\epsilon_{die}=7.5$ is greater than V_{BD} for $\epsilon_{die}=3.9$, indicating that the breakdown voltage increases with increasing ϵ_{die} . Also, it is clear from Fig.2 that the breakdown voltage obtained for the semi-insulator passivated structure is significantly greater than that achieved using the dielectric passivation for all values of t_{OX} . In order to understand this behaviour, the equipotential contours for the different cases are plotted in Fig.3(a)-(d). A careful observation of the potential distribution reveals that the equipotential contours spread out more in the dielectric medium when the ϵ_{die} is larger, thus, relaxing the potential crowding near the metal-overhang. Consequently, for a given voltage the electric field in Si bulk decreases resulting in higher V_{BD} for large ϵ_{die} . Comparing the potential contours of the dielectric and semi-insulator passivated structures, it can be seen that the semi-insulator layer linearizes the potential inside the field oxide, alleviating the potential crowding at the metal-overhang edge. Thus, the peak electric field at the metal-overhang edge is tremendously reduced and the voltage handling capability of the device is drastically improved.

This can be better appreciated by looking at the electric field distribution plot within the Si substrate (Fig.4(a)-(d)). It is clear that at a given bias, the peak electric field amplitude at the metal-overhang edge decreases as the ϵ_{die} of the dielectric passivant layer increases. In fact, for the semi-insulator passivated structure, field crowding at the metal-overhang is completely eliminated due to the efficient potential contours spreading and hence the breakdown voltage obtained for semi-insulator passivated structure is maximum.

Further, it is clear from Fig.2 that the $t_{OX(OPT)}$, required to accomplish maximum breakdown voltage, is lower if ϵ_{die} of the passivant layer is larger. Thus, higher values of ϵ_{die} allows for reduction in t_{OX} required for attaining a given breakdown voltage. It is seen from Fig.2 that the $t_{OX(OPT)}$ is still lower for the semi-insulator passivated structure than for the dielectric passivated one. Thus, it is clear that a given V_{BD} can be achieved at a lesser t_{OX} if larger ϵ_{die} is used, and at a still lower t_{OX} if a semi-insulator is used.

Figure 3: Potential distribution near the surface at breakdown for $X_J=0.2\mu\text{m}$ in the region $t_{OX} < t_{OX(OPT)}$ for (a) $\epsilon_{\text{die}}=1.0$, (b) $\epsilon_{\text{die}}=3.9$, (c) $\epsilon_{\text{die}}=7.5$ and (d) semi-insulator passivated structure.

To study the effect of junction depth (X_J) on the breakdown voltage for different passivants, we show in Fig.2 and Fig.5(a)-(c) the variation of V_{BD} vs. t_{OX} for different values of X_J . It is known that when X_J increases, the electric field crowding at the junction curvature decreases due to decrease in flux per unit area leading to increase in V_{BD} .

Figure 5(a): Breakdown voltage vs. field oxide thickness with different passivants for $X_J = 1.0 \mu\text{m}$.

Figure 5(b): Breakdown voltage vs. field oxide thickness with different passivants for $X_J = 3.5 \mu\text{m}$.

Figure 5(c): Breakdown voltage vs. field oxide thickness with different passivants for $X_J=15.0\mu\text{m}$.

A qualitatively similar behaviour is observed when the junction depth is increased, as shown in the plots (Fig.5(a)-(c)). Increasing the junction depth results, however, in an increase in the breakdown voltage for all the passivants. In the region $t_{OX} > t_{OX(OPT)}$, a given variation in the field oxide thickness effects a larger change in the field crowding, and hence the breakdown voltage, for a shallow junction than for a deep junction. This is because of the stronger coupling of the positive space charge and the negative charge on the metal-overhang for a shallow junction. It can be seen from Fig.5(d) that for the junctions as deep as $15\mu\text{m}$, V_{BD} is almost constant in the region $t_{OX} > t_{OX(OPT)}$ for all passivants.

Fig.6(a) & (b) depict an important feature of the semi-insulator passivated structure. As can be seen that the optimal oxide thickness (Fig.6(a)) and the maximum breakdown voltage (Fig.6(b)) increases with increase in junction depth for dielectric passivated structure, whereas the maximum breakdown voltage obtained under the optimal conditions for the semi-insulator passivated structure is nearly constant over a wide range of junction depth (Fig.6(b)). Specifically, V_{BD} changes by a marginal 4% for a semi-insulator passivated structure, whereas it changes by as much as 27% for a dielectric passivated structure ($\epsilon_{die} = 7.5$), when the junction depth is increased from $1.0\mu\text{m}$ to $15\mu\text{m}$. This aspect of the semi-insulator makes it an extremely important passivant for developing high-voltage Si detector with relatively shallow junctions. Also, it is clear from Fig.6(a) that for all junction depths, the optimal oxide thickness for the semi-insulator passivated structure is less than that of the dielectric passivated structure.

Figure 6: (a) Optimal oxide thickness vs. junction depth and (b) maximum breakdown voltage (for $t_{OX} = t_{OX(OPT)}$) vs. junction depth for the semi-insulator and dielectric passivated structure.

3.2 Effect of metal-overhang width (W_{MO})

The influence of the metal-overhang extension on the V_{BD} of the semi-insulator and dielectric passivated metal-overhang structure is compared in Fig.7.

Figure 7: Breakdown voltage vs. field oxide thickness with different metal-overhang widths for the semi-insulator and dielectric ($\epsilon_{die}=3.9$) passivated structure.

At a first glance, the effect of increasing the extension of the metal contact enhances the V_{BD} for both the cases due to the flattening of the equipotential lines near the junction edge. However, the increase in V_{BD} with W_{MO} for dielectric passivated structure is large as compared to semi-insulator passivated structure for all values of t_{OX} . The figure also shows that for any given value of the metal-overhang width, the V_{BD} for the semi-insulator passivated structure is greater than that for the dielectric passivated structure.

It can be seen from Fig.8(a) that for the dielectric passivated Si strip detector, the optimum oxide thickness increases with increase in metal-overhang extension, attains a maximum value and then decreases with further increase in W_{MO} .

The maximum V_{BD} (Fig.8(b)) obtained under the optimal condition increases continuously with increase in W_{MO} . Ideally, an infinite metal-overhang extension is required to maximize its advantage for high-voltage devices. However, in Si strip detectors, strip-pitch becomes a limiting factor for extending the overhang beyond a certain value and in fact, noise associated to the strip capacitance also increases with an increase in overhang width. Here, the semi-insulator passivated structure offers a decisive advantage over its dielectric counterpart because for such structures the maximum breakdown voltage obtained and also the optimal oxide thickness required for accomplishing it remain practically constant over a wide variation in metal-overhang.

Figure 8(a): Optimal oxide thickness vs. metal-overhang width for the semi-insulator and dielectric passivated structure.

Figure 8(b): Maximum breakdown voltage (for $t_{OX} = t_{OX(OPT)}$) vs. metal-overhang width for the semi-insulator and dielectric passivated structure.

3.3 Effect of passivation layer thickness (t_{pass})

Fig.9 shows the variation of V_{BD} with t_{pass} for different passivants. It can be seen that for dielectric passivated structure, V_{BD} increases with increase in t_{pass} , however, this increase is gradual for higher values of t_{pass} . The effect of increasing t_{pass} significantly increases the spreading of equipotential lines along the surface of the device, reduces the electric field crowding and hence increases the V_{BD} . Whereas, for semi-insulator passivated structure, V_{BD} remains independent of t_{pass} .

Figure 9: Breakdown voltage vs. passivation layer thickness for different passivants.

3.4 Effect of surface charge density (Q_F)

The SiO₂-embedded positive charge layer causes a thin electron accumulation layer to build up at the Si-SiO₂ surface. This results in a reduction of the depletion width, increasing the electric field in the Si close to the Si-SiO₂ interface, eventually causing an avalanche breakdown in that region at much smaller voltages. Results for the breakdown voltage as a function of surface charge density are plotted in Fig.10(a)-(c) for three cases, i.e., $t_{\text{OX}} < t_{\text{OX(OPT)}}$, $t_{\text{OX}} = t_{\text{OX(OPT)}}$ and $t_{\text{OX}} > t_{\text{OX(OPT)}}$ respectively. In the region $t_{\text{OX}} < t_{\text{OX(OPT)}}$, the effect of increasing oxide charge results in the reduction of V_{BD} for dielectric passivated structures (Fig.10(a)).

Figure 10: Breakdown voltage as a function of surface charge density with different passivants for (a) $t_{OX} < t_{OX(OPT)}$, (b) $t_{OX} = t_{OX(OPT)}$, (c) $t_{OX} > t_{OX(OPT)}$.

The potential distribution at a bias of 500 volt for a dielectric passivated structure ($\epsilon_{\text{die}}=7.5$) is shown in Fig.11(a)-(c).

Figure 11: Potential distribution near the surface at $V_{\text{bias}}=500$ volt for a dielectric ($\epsilon_{\text{die}}=7.5$) passivated structure with different Q_F in the region $t_{\text{OX}} < t_{\text{OX(OPT)}}$ ($W_N=300$ microns, $X_J=0.2$ microns, $W_{\text{MO}}=30$ microns).

It is clear that the avalanche is located under the overhang edge for $Q_F=3 \times 10^{11}/\text{cm}^2$. This situation is strongly modified by the increase in surface charge. As the oxide charge is increased to $\sim 6.5 \times 10^{11}/\text{cm}^2$ and beyond, the field strength increases both at the junction and under the overhang edge. However, in the same region, i.e., $t_{OX} < t_{OX(OPT)}$, Fig.10(a) shows that the semi-insulator passivated structure remains totally insensitive to the surface charge for the same variation of Q_F , thus showing its superiority over the dielectric passivated structure. A similar behaviour is also observed for the case when $t_{OX} = t_{OX(OPT)}$ (Fig.10(b)). Here also, only a marginal decrease in the value of the computed V_{BD} is found with increasing oxide charge, thus indicating that the semi-insulator structure offers nearly total-immunity against the surface charge for $t_{OX} \leq t_{OX(OPT)}$, which is again an outstanding attribute of semi-insulator passivated structures in adverse radiation conditions.

However, the situation is different for $t_{OX} > t_{OX(OPT)}$ (Fig10(c)), when the breakdown occurs at the junction edge, the simulation results indicate that the breakdown voltage assumes almost the same value after $Q_F=4.0 \times 10^{11}/\text{cm}^2$ for all the dielectric passivated structures. In fact, the V_{BD} for the semi-insulator passivated structure also overlaps with that of the dielectric passivated structure after $Q_F=6.5 \times 10^{11}/\text{cm}^2$. Thus, in the region $t_{OX} > t_{OX(OPT)}$ and for large values of Q_F , V_{BD} of the device is mainly governed by Q_F irrespective of the type of passivant used. From the above discussion, it is clear that in order to make full use of the passivant properties of the semi-insulator, the field oxide thickness used in the fabrication of the Si strip detectors, should be kept less than or equal to its optimal value.

4. Comparison with experimental work

In order to support the simulation analysis performed for the passivated structures, the simulator has been calibrated against the experimental data [9 & 15]. For clarity, cross-sections of the structures given in these references are shown in Fig.12(a) [9] and Fig.12(b) [15]. The results are given in Table1 along with the information on salient device parameters. A very good agreement between the experiments and simulations is found, thus validating our present effort.

5. Conclusions

In this paper, the application of the 2-D device simulation to the analysis and comparison of the dielectric and semi-insulator passivated metal-overhang structure has been described. By analyzing simulation results, influences of all the salient physical and geometrical parameters on these structures have been elaborated.

It is demonstrated that higher values of relative permittivity (ϵ_{die}) of the passivant dielectric play an important role in determining V_{BD} , and results in an increase in breakdown voltage as compared to the unpassivated detector. Also, V_{BD} increases with an increase in ϵ_{die} in the region $t_{OX} < t_{OX(OPT)}$ for dielectric passivated structures. However, semi-insulator passivated structure results in still higher values of V_{BD} for all values of t_{OX} due to the better distribution of equipotential lines under the same conditions. It is found that the optimal oxide thickness decreases with increase in ϵ_{die} for dielectric passivated structure and for the semi-insulator passivated structure, the decrease is still greater. For semi-insulator passivated structure, the

maximum breakdown voltage achieved for the optimal field oxide thickness remains fairly constant over a wide variation in the junction depth. Thus, the present study shows that the semi-insulator passivated structures allow for a design of Si strip detectors with shallow junctions and thinner oxides, reducing dead layer and making the detectors more suitable for high-energy physics experiments.

Also, for semi-insulator passivated structures, the maximum V_{BD} obtained under the optimal conditions is found to be independent of the overhang width. The small values of metal-overhang would help in the design of high voltage and low noise Si strip detector, since increasing the metal extension results in higher interstrip capacitance and hence the noise associated with it. V_{BD} of semi-insulator passivated structure is also found to be independent of t_{pass} , whereas that of dielectric passivated structure increases with increase in t_{pass} .

Another very important feature of the semi-insulator passivated structure is the nearly constant breakdown voltage for a wide variation in Q_F for $t_{OX} \leq t_{OX(OPT)}$, this establishes its supremacy and offers an extremely important design flexibility when realizing high-voltage junctions for Si strip detector. Thus, the present study shows that semi-insulator passivated structures are attractive for achieving high breakdown voltages of Si strip detectors.

Figure 12: Cross-sections of the structures simulated for experimental verification. (a) corresponds to structure given in Ref.[9] and (b) is for Ref.[15]. Figures are not to scale.

Table1: Comparison of the simulation results with the experimental work.

Resistivity (ρ) (Ω -cm)	Collector-base junction	t_{OX} (μm)	Field plate- stop channel distance (ΔL) (μm)	Present simulation result (P) (volt)	Exp.data (E) (volt)	(P-E)/P
60 (Ref.[9])	14 μm ($Q_F=3 \times 10^{11}$ /cm ²)	1.25	60	830	880	-6%
			110	1005	1045	-4%
			210	1080	1065	1%
75 (Ref.[9])	14 μm ($Q_F=3 \times 10^{11}$ /cm ²)	1.25	80	1170	1150	2%
			110	1200	1245	-4%
			210	1540	1500	3%

ρ (Ω - cm)	X_J (μm)	Semi-insulator (SIPOS) passivated				Nitride passivated			
		Q_F ($\times 10^{11}$) (/cm ²)	V_{BD} (P) (volt)	V_{BD} (E) (volt)	(P-E)/P	Q_F ($\times 10^{11}$) (/cm ²)	V_{BD} (P) (volt)	V_{BD} (E) (volt)	(P-E)/P
50 (Ref. [15])	70 ($t_{OX}=1$ μm)	0.5	1260	1200	5%	0.75	1115	1190	-6%
		1.0	1305	1390	-6%	2	1440	1420	1%
		4.5	1530	1500	2%	3.4	1560	1630	-4%

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