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DESIGN AND ANALYSIS OF NORMALLY-ON 4H-SiC VERTICAL JUNCTION FIELD EFFECT TRANSISTOR (VJFET) USING SENTAURUS TCAD SIMULATION

M. KHALID[a*], J. K. KHAN[c], G. MUSTAFA[c], M. S. AKHTAR[d],
Z. A. GILANI[a], H. M. N. UL HUDA KHAN ASGHAR[a], S. RIAZ[b], S. NASEEM[b],
[a]*Department of Physics, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan*
[e]*Centre of Excellence in Solid State Physics, University of the Punjab, Lahore-54590, Pakistan*
[c]*Department of Physics, NED University of Engineering and Technology, Karachi, 75270, Pakistan*
[d]*Department of Physics, Division of Science and Technology, University of Education, College Road, Township, Lahore, Pakistan*

This paper is intended to simulate the performance of normally-on 4H-SiC vertical junction field effect transistor (VJFET) for high voltage applications. Sentaurus TCAD simulator was used to investigate the breakdown voltages with different channel width (0.5 to 0.9 μm) under the negative bate bias. It is observed that high negative voltage is needed most likely for normally-on devices. Simulation results show that breakdown voltage decreases with increasing negative gate voltage. By combining the device geometrical parameters model fitting parameters and device physics, breakdown voltage, distribution of electric field and leakage current was observed. In addition, the effect of drift doping on the breakdown voltage is discussed in details. Moreover, drift doping dependent breakdown voltage was measured with the influence of channel width and drift layer thickness. It was observed that breakdown voltage decrease with increasing drift doping. Also for a given channel width, high breakdown voltage was found in case of high drift layer thickness. The maximum breakdown voltage approximately 11 kV was examined with drain leakage current of the order of 10^{-7} A. The novelty of the proposed design has strong correlation with already published experimental data.

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Keywords: Normally-on, Electric field, breakdown voltage, Drifts doping, Leakage current

1. Introduction

Recent research shows that SiC based semiconductor power devices has reliability to provide remarkable attention for the production of next generation high temperature and high power applications [1, 2]. Its remarkable properties, like as wide energy band gap (3.2 eV), a very high critical electric field (2MV/cm), a high thermal conductivity (4.9 W/cm.K), and very high electron saturation velocity (2×10^7 cm/s) make it very important and favorable device in all other Si based semiconductor power devices [3-5] (Alexandru et al., 2012, Abuishmais et al. 2012, Jiang et al., 2012). Recently, scientists are paying a lot of attention to gain the best performance in technology of SiC power devices for very high breakdown voltage. The unique properties of unipolar devices made it common for high voltage application devices. In general, MOSFET and JFET are considered more reliable to give high breakdown voltage as compared to bipolar devices. Unfortunatelly, the SiC MOSFET has unsolved problems such as SiO2/SiC interfacing due to gate oxide. Due to this reason SiC MOSFET has no capability to provide very high breakdown strength as compared to SiC JFETs [6-8]. A lot of work on SiC VJFET has been performed using

*Corresponding authors: khalid.mesp@gmail.com

experimentally and theoretically [9, 10]. In reported simulation work, numerous models have been developed by many authors for high temperature and high voltage application of the devices [11, 12]. its high breakdown electric field strength comparatively makes it extraordinary compound semi-conductor device for the modeling of 4H-SiC VJFET that permit to gain a very high power density for the better power conversion. For power semiconductor transistors, vertical channel has good advantage over the lateral one because of the up- gradation in the high breakdown characteristics and low leakage current. Normally, a lower channel width means that the potential barrier be entrenched with lower negative voltage to gain desirable breakdown voltage. Moreover, high channel opening depends upon additional negative biasing for full depletion for the sake of maximum breakdown voltage [13]. Formally, normally-on operation of SiC VJFET, having the drift layer thickness of 18 μm described the limiting breakdown capacity of greater than 810 V [14]. With this description, the device inhibits trade-off between the on-resistance and breakdown voltage. Furthermore, the fabricating process SiC VJFET is very predictable rather than SiC MOSFET process. In the recent times, Maralani et al. investigated the manufacturing process of SiC VJFET; the characteristic of the device is more beneficial for the analog model [15]. Veliadis et al. expressed normally-on 9 kV SiC VJFET with low leakage current and high breakdown voltage [16]. Moreover, they expressed 100 μm/6 × 10^{14} cm^{-3} model and got 13.6 kV theoretical breakdown voltages. In another article by Veliadis et al. it was recorded that very acute breakdown voltage in the breakdown voltage limit crosses with low leakage current. The limited breakdown voltage of 2055V having negative gate biasing of -33V was seen [17]. Ryu et al. granted a 12 μm drift layer with doping of 5 x 10^{15} cm^{-3} and blocking voltage of 800 V at the gate biasing of -33 V [18].

In this paper, a design of normally-on 4H-SiC VJFET has been given and modulated by the Sentaurus TCAD simulator. The Lackner model was applied to obtain breakdown voltage as well as compatibility with device geometry. The novelty of this model is to give the breakdown voltage that has 100% correlation with already reported experimental data. The mathematical simulation shows that the breakdown voltage can be calculated in the device with the inter-relation of different design parameters. The low drift doping, high drift layer thickness and lower channel width gives the high breakdown capacity.

2. Device structure

To construct device geometry before, important device parameters must be considered such as high breakdown voltage and low leakage current. These two parameters strongly depend on the selection of device geometrical dimensions with their doping profiles. The crossectional view of 4H-SiC VJFET is shown in Fig. 1. The modeling and simulation of a device is very complicated because it requires a large number of physical parameters. In order to limit the breakdown voltage, the adjustment of depletion width is very essential by the full controlled of channel width. For this aspire, the channel width is modulated by the separation of two gates in the n region. So, the broad range of channel width was built up ranging between 0.6-0.9 μm by the steps of 0.1 μm. The doping concentration of the drift layer is selected very low as 6 × 10^{14} cm^{-3} which is two orders of magnitude lower than the channel concentration as 2 × 10^{16} cm^{-3}. It has been reported that low drift doping gives the high breakdown voltage while high channel doping exhibits the normally-on behavior. As the high resistance is commanded by the drift layer thickness along with drift doping, that is more effective for the analysis of breakdown voltage. So, the drift layer thickness and doping are chosen to 0.6 to 0.9 μm, Subsequently, It has been observed that the breakdown voltage is also governed by the drift layer thickness.

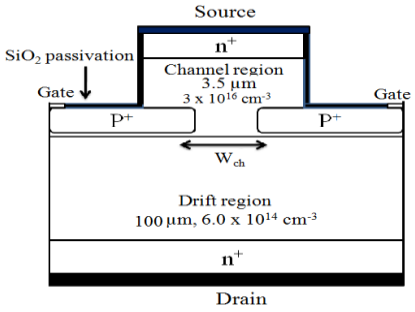

Fig. 1. Cross-sectional view of device structure.

3. Numerical simulation

The breakdown properties are simulated using physics based semiconductor device Sentaurus TCAD simulator. For scientific simulation, the device models play a vital role for the physical characteristics of the device. According to the literature, various designs for simulation of SiC JFET have been presented. The particular use of a model is a fundamental assignment not only for the designing project but also for study of the structural behavior in order to make strong correlation with the experimental work.

However, the breakdown voltage are highly related to the strength of electric field .the model by Lackner [19] for the simulation of 4H-SiC VJFET is given firstly as

$$\alpha_{n,p}(F_{ava}) = \frac{\gamma a_{n,p}}{z}\exp(-\frac{\gamma b_{n,p}}{F_{ava}}) \tag{1}$$

$$z = 1 + \frac{\gamma b_n}{F_{ava}}\exp\left(-\frac{\gamma b_n}{F_{ava}}\right) + \frac{\gamma b_p}{F_{ava}}\exp\left(-\frac{\gamma b_p}{F_{ava}}\right) \tag{2}$$

$$\gamma = \frac{\tanh(\frac{\hbar\omega_{op}}{2KT_0})}{\tanh(\frac{\hbar\omega_{op}}{2KT})} \tag{3}$$

In the above eq. a, b and $\hbar\omega_{op}$ are the fitting parameters and these values were designed from the published literature [20] is given in the Table 1. In respect of these other physicals models for device simulation of SiC VJFET are energy band gap dependent model, electrons and holes effective masses, SRH an Auger recombination model, incomplete ionization model and high field saturation design [21].

Table 1. Model fitting parameters used for simulation.

Parameter	Unit	Electron	hole
a	cm^{-1}	2.10×10^7	2.96×10^7
b	Vcm^{-1}	1.70×10^7	1.60×10^7
γ	-	1.0	1.0
$\hbar\omega_o$	meV	0.36	0.36

4. Results and discussion

Fig. 2 shows the distribution of electric field with device taken from the half cutting line from source to drain. It can be seen from the figure, the electric field has no such significant effect in the channel because of high channel doping. Overshoot in electric field was carried out at the depth of 3.5 µm which is caused by the longitudinal electric field. The maximum electric field is observed 2.6 MV/cm which is essential for the breakdown voltage of 11 kV. It can be seen from figure electric field decreases with decreasing the breakdown voltage. In addition, the electric field

decreases with depth and collapse at the interface of drift/drain. This collapse is caused by the sudden changed of doping from 10^{14} to 10^{18}. So this effect is known as punch through effect which has a contribution to enhance the breakdown capability of the proposed designed.

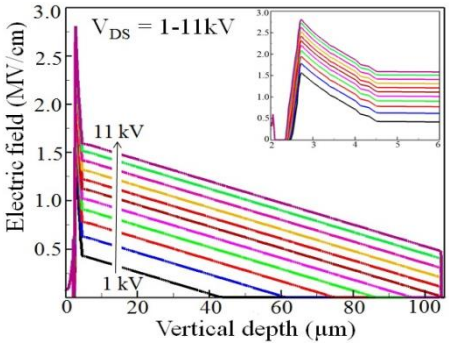

Fig. 2. Vertical depth dependent electric field distribution taken by cutting vertical half structure.

Normally-on devices have no capability to provide high breakdown voltage at zero gate bias. It is necessary to apply a negative voltage at the gate to achieve maximum electric field strength. The 2D electric field distribution was simulated using the finite element simulation for the gate voltage of -18, -14, -10 and -6 V as shown in Fig. 3. Figure shows the contour of electric field in the device near the channel. Much high potential exists at the edge of gate in case of high negative voltage. As the negative voltage shift from higher to lower there is significant reduction in electric field was observed. High electric field at the edge is highly responsible for high breakdown voltage. Furthermore, it has been observed, due to low doping in the channel there is a little effect of electric field in the channel was found.

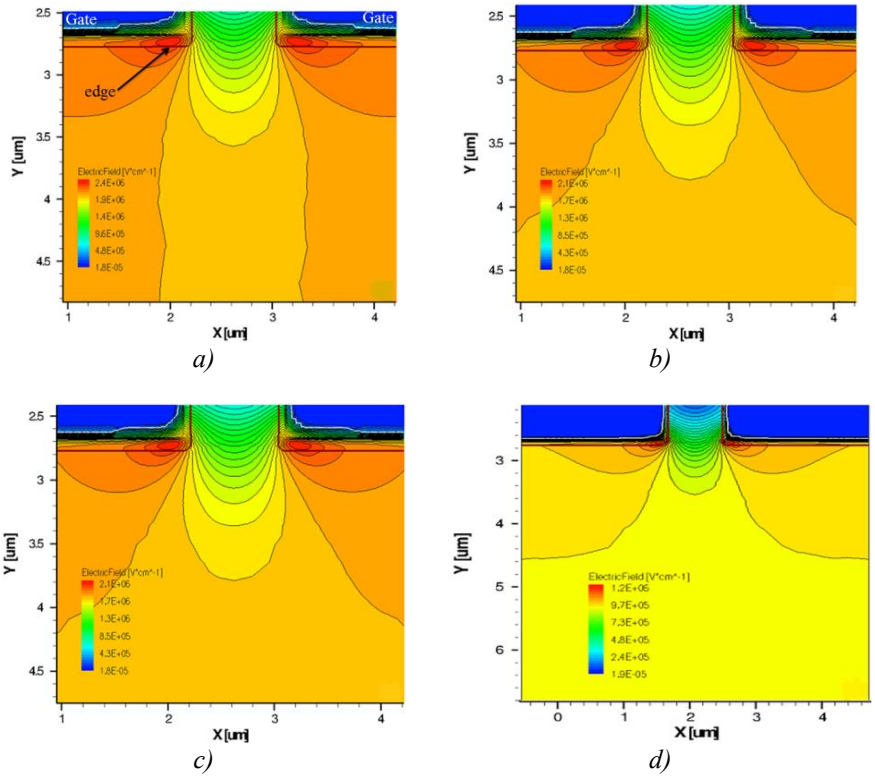

Fig. 3. 2D electric field distribution at different negative gate voltage (a) -18 V (b) -14 V (c) -10 V (d) -6 V.

We have simulated the channel width dependent breakdown voltage by different limited negative biasing of the gate. It was seen that during simulations the consequence of the breakdown was carried out when the ionization integral gives unity along the way from drain to source. For this condition, the high drain voltage is necessary to terminate the ionization process. Moreover, it was seen that the lesser negative biasing with a lower channel width gives the value of the electric field at the gate in the drift region highly contributes to the greater breakdown. Further, for wider channel opening, a high negative voltage is required at the gate for having the larger breakdown voltage. The breakdown properties for a 100 µm/6.0 x 10^{14} cm^{-3} drift doped 4H-SiC VJFET with different channel widths was examined. The influence of the channel width with their limited negative bias is shown in Fig. 4. The breakdown voltage along with leakage current extracted from the simulation is summarized in Table 1. It is notice that four different channel widths provide approximately the same breakdown voltage under the different negative applied gate voltage. At channel width of 0.6 µm, the breakdown voltage does not provide any remarkable variation at V_G <-18V. So, the maximum breakdown voltage of 11 kV can be obtained from the simulation under the negative gate voltage of -18 V. A very high breakdown voltage characteristic was examined having a drain leakage current up to the order of 10^{-7} A.

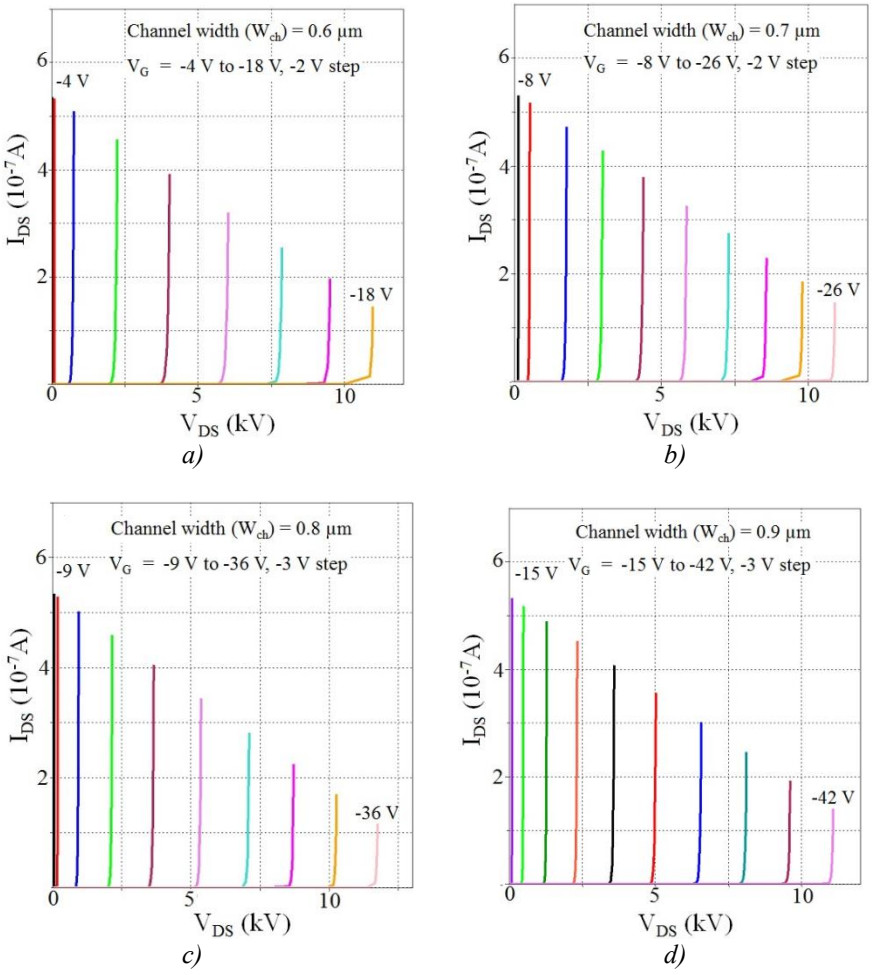

Fig. 4. Channel width dependent breakdown voltage characteristics of normally-on SiC VJFET at various negative voltages V_G (a) -4 to -18 V (b) -8 to -26 V (c) -9 to -36 V (d) -15 to -42 V.

The examined leakage current goes higher value significantly when V_G shifts from -18 V to -4 V. Moreover, the breakdown voltage goes down by decreasing the value of negative biasing in gate voltage due to the decrease in potential barrier. It is also essential to examine that the larger channel width demands more negative voltage to gain the required breakdown voltage is clearly

shown in Fig. 4 (b), (c) and (d). The breakdown voltage with leakage current extracted from the simulation is summarized in Table 2. The significant increment in the drain leakage current was estimated when a voltage shift from higher negative bias to lower negative bias. The reasons for the enhancement of drain leakage current is due to the large number of holes are recombined with the electrons. The higher breakdown voltage of 11 kV comes out with the channel widths of 0.7, 0.8 and 0.9 μm under limited negative gate bias of -26, -36 and -42 V, respectively. It is worth noting that, the device experimented by [16], had drift layer thickness of 120 μm, which has gate b ias of -32 V to achieve breakdown voltage of 9 kV. In our simulation case, for drift layer of 100 μ m under channel width of 0.7 μm requires a gate voltage of -26 V to achieve breakdown voltage of 11 KV which leads to a 18 % higher in value.

Table 2. Channel width (W_{ch}) dependent breakdown voltage (V_{BD}) and drain leakage current (I_{DS}) characteristics of normally-on SiC VJFET at various negative gate voltages (V_G).

W_{ch} = 0.6	**V_G (V)**	-18	-16	-14	-12	-10	-8	-6	-4	-2
	V_{BD} (V)	10959	9503	7869	6029	4026	2241	756	93	24
	I_{DS} (x10^{-7}) A	1.443	1.963	2.547	3.204	3.919	4.557	5.087	5.324	5.349
W_{ch} = 0.7	**V_G (V)**	-26	-24	-22	-20	-18	-16	-14	-12	-10
	V_{BD} (V)	10900	9797	8578	7290	5862	4384	3004	1784	529
	I_{DS} (x10^{-7}) A	1.464	1.858	2.293	2.753	3.264	3.791	4.284	4.720	5.168
W_{ch} = 0.8	**V_G (V)**	-36	-33	-30	-27	-24	-21	-18	-15	-12
	V_{BD} (V)	11753	10263	8717	7109	5370	3664	2165	949	194
	I_{DS} (x10^{-7}) A	1.160	1.692	2.244	2.818	3.440	4.049	4.584	5.019	5.288
W_{ch} = 0.9	**V_G (V)**	-42	-39	-36	-33	-30	-27	-24	-21	-18
	V_{BD} (V)	11074	9609	8114	6573	5019	3594	2335	1294	493
	I_{DS} (x10^{-7}) A	1.402	1.925	2.459	3.010	3.565	4.074	4.523	4.895	5.181

The higher value of breakdown voltage also precisely depends upon the two important parameters as drift layer thickness and drift doping. Normally, low drift doping and higher drift layer thickness gives the maximum breakdown voltage. Outstanding variation in the breakdown voltage relation with the drift doping modulated as shown in Fig. 5. The data extracted from the simulation is summarized in Table 3. The forecasting of breakdown voltage with mathematical simulation is constant with the results given by experimental observations.

As it is clearly shown in fig, the breakdown voltage having high value of drift layer thickness is very sensitive and gives the maximum breakdown voltage of 15 kV. It is very significant to note that the doping of drift layer changes the breakdown voltage. On the other hand, if we vary the drift doping under low drift layer conditions, it does not change the breakdown voltage. It can also be seen that with the increase in drift doping gives a decrease in breakdown voltage. In case of every channel width, the value of maximum breakdown voltage was found to be 15000 V at t_{Drift}=100 μm having low drift doping. The value of drain leakage current can be seen below than 10^{-12}A for drift layer thickness t_{Drift}=100 μm, that is of the orders of 5 when compared with t_{Drift}=20 μm. The modulating results tell that the improvement in the drift design of the SiC VJFET and the biasing conditions leads to the further improvement in the breakdown analysis.

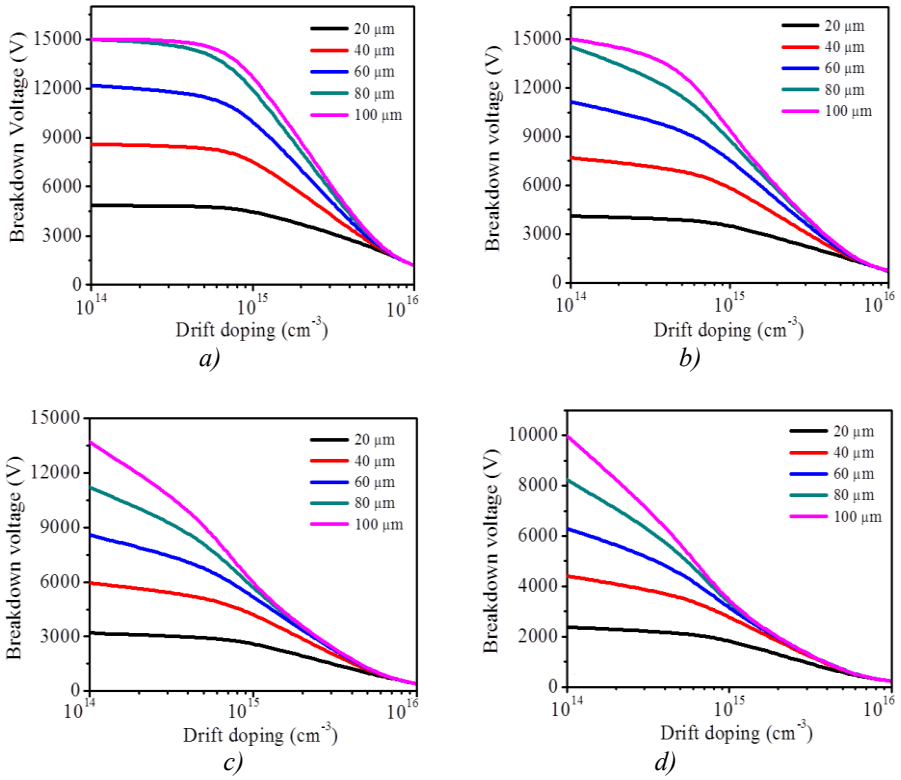

Fig. 5. Drift doping dependent breakdown voltage at various channels (a) W_{ch} = 0.6 µm (b) W_{ch} = 0.7 µm (c) W_{ch} = 0.8 µm (d) W_{ch} = 0.9 µm width under the negative gate bias of -30 V with different drift layer thickness from 20 to 100 µm.

Table 3. Drift doping dependent breakdown voltage (V_{BD}) characteristics of normally-on SiC VJFET at various channel width (W_{ch}) and drift layer thickness with applied negative voltage of V_G = -30 V.

W_{ch} (µm)	Drift doping (cm^{-3})	Drift layer thickness (µm)				
		20	40	60	80	100
		V_{BD} (V)				
W_{ch} = 0.6	**10^{14}**	4849	8606	12179	15000	15000
	10^{15}	4633	7975	10502	12378	13477
	10^{16}	1164	1164	1155	1165	1164
W_{ch} = 0.7	**10^{14}**	4119	7708	11152	14572	15000
	10^{15}	3645	6099	7743	8742	8986
	10^{16}	725	725	720	725	725
W_{ch} = 0.8	**10^{14}**	3195	5951	8575	11206	13693
	10^{15}	2720	4339	5157	5363	5371
	10^{16}	416	416	413	416	416
W_{ch} = 0.9	**10^{14}**	2383	4408	6304	8224	9988
	10^{15}	1907	2793	2927	2977	2968
	10^{16}	227	228	228	226	228

The critical value of breakdown voltage characteristics having dependence of drift doping under different channel width related to the negative biasing of V_G= -30 V is shown in Fig. The maximum breakdown voltage is not only dependent upon the drift layer thickness but also depends on the gate spacing. At smaller channel width barrier height has stronger effects resulting in a high breakdown voltage. It is clear from the figure, the channel width of 0.6 and 0.7 µm having the limited breakdown capability under low drift doping, demonstrated that the high potential barrier established. This condition also realizes the device goes into punch through. The channel width of

0.8 and 0.9 µm minimized the effect of barrier resulting in lower breakdown voltage. The simulations value shows that the breakdown voltage decreases with the increase in drift doping. For greater channel width and lower drift doping, the penetration of electric field lateral with the gate in the n drift region is small. However, if the channel widths and drift doping are lower, then the electric field compensates both laterally and drifts doping gives higher breakdown voltage.

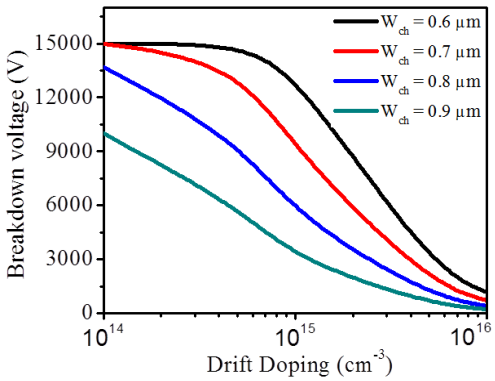

Fig. 6. Effect of drift doping with different channel with at drift layer thickness of 100 µm gate bias of -30 V.

5. Conclusions

The simulated breakdown voltages and electric field as a function of drift doping suggested that low drift doping is required to obtain the optimum breakdown voltage at a channel width of 0.6 µm. A large reduction in breakdown voltage was observed when the level of drift doping increased up to$10^{17}cm^{-3}$. It is suggested that the punch through approach is more dominant at higher breakdown voltage under limited negative gate bias. The overshoot in electric field has been analyzed at the edge of the gate attributed to the longitudinal electric field. The obtained maximum breakdown voltage of 11 kV is in good agreement with the experimental and theoretical reported value. Finally, we suggest that the Lackner is a very good predictive model for the analysis of breakdown characteristics of normally-on 4H-SiC VJFET.

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