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COMPARATIVE STUDY OF IV-CHARACTERISTICS OF PIN DIODE AT DIFFERENT DOPING CONCENTRATIONS FOR DIFFERENT SEMICONDUCTOR MATERIALS USING TCAD

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ABSTRACT

For the purpose of designing and selection the optimal device for a particular application, device and circuit engineers has to analyze the between competing devices. This article presents a comparative study of current voltage characteristics for PIN diodes. Three different sets of doping concentrations are studied for each of the five different material PiN diodes. The PiN diode is simulated using V-TCAD software. For the same diode structure effects of different doping on different materials are studied and VI characteristics are plotted based on simulated results. The change in doping concentration resulted in almost negligible change in threshold voltage. Whereas large increase in current is obtained for increase in doping concentrations.

KEYWORDS: Pin Diode, I-V Characteristics, Doping Concentration, Semiconductor Material, VTCAD

INTRODUCTION

For the purpose of designing and selection the optimal device for a particular application, device and circuit engineers has to analyze the between competing devices. A PIN diode is different from a normal diode because it consists of a wide, undoped intrinsic semiconductor region between the p and n type semiconductor region. The p-type and n-type regions are heavily doped so as to form ohomiccontacts . Due to this PiN diodes are not used as rectifiers [1]. Instead, PiN diodes are extensively used as attenuators, photodetectors, fast electronic switches. The main use of PiNdiodes are in high voltage power applications. In the last decade PIN diode materials have been evolved from the commonly used semiconductor materials like Ge and Si to various other semiconductor materials. SiC came into being the most potential candidate and later other amorphous form of SiC came into use [2,3,4]. The two mainly used amorphous forms of SiC that are used are SiC-H4 and SiC-3C. Previous works based on SiC based PiN diodes have shown a strong potential for use in high-speed and high-voltage power electronics operations at high temperature compared to that of Si PiN diodes. Switching performance of 4H–SiC diode is superior to the ultrafast Si diodes [5,6]. Another commonly used material InP is also considered in the simulation for it is used for PiN photo-detector applications.

Devices of different structures and materials can be simulated with VTCAD. Also it provides options for changing concentration of the simulated device for the purpose of studying them.

This article presents a comparative study of current voltage characteristics for PIN diodes. Three different sets of doping concentrations are studied for each of the five different material PiN diodes. The PiN diode is simulated using

V-TCAD software in the view of studying the effects of different doping on different materials on the same PiN diode structure and to plot their VI characteristics are based on simulated results.

Structure & Operation of Pin Diode

A PIN diode is a diode with a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region. The p-type and n-type regions are typically heavily doped because they are used for ohmic contacts. The wide intrinsic region is in contrast to an ordinary PN diode. The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode), but it makes the PIN diode suitable for attenuators, fast switches, photo detectors, and high voltage power electronics applications.

A PiN diode operates under what is known as high-level injection. In other words, the intrinsic "i" region is flooded with charge carriers from the "p" and "n" regions. Its function can be likened to filling up a water bucket with a hole on the side. Once the water reaches the hole's level it will begin to pour out. Similarly, the diode will conduct current once the flooded electrons and holes reach an equilibrium point, where the number of electrons is equal to the number of holes in the intrinsic region. When the diode is forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic level carrier concentration. Due to this high level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from P to N region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

A PiN diode obeys the standard diode equation for low frequency signals. At higher frequencies, the diode looks like an almost perfect (very linear, even for large signals) resistor. There is a lot of stored charge in the intrinsic region. At low frequencies, the charge can be removed and the diode turns off. At higher frequencies, there is not enough time to remove the charge, so the diode never turns off. The PIN diode has a poor reverse recovery time.

The high-frequency resistance is inversely proportional to the DC bias current through the diode. A PIN diode, suitably biased, therefore acts as a variable resistor. This high-frequency resistance may vary over a wide range (from 0.1 ohm to 10 kΩ in some cases the useful range is smaller, though).

The wide intrinsic region also means the diode will have a low capacitance when reverse biased.

In a PiN diode, the depletion region exists almost completely within the intrinsic region. This depletion region is much larger than in a PN diode, and almost constant size, independent of the reverse bias applied to the diode. This increases the volume where electron-hole pairs can be generated by an incident photon. Some photodetector devices, such as PiN photodiodes and phototransistors (in which the base-collector junction is a PiN diode), use a PiN junction in their construction.

The diode design has some design tradeoffs. Increasing the dimensions of the intrinsic region (and its stored charge) allows the diode to look like a resistor at lower frequencies. It adversely affects the time needed to turn off the diode and its shunt capacitance. PiN diodes will be tailored for a particular use. The 2D structure, 3D Structure and Biasing of PiN Diode are shown in Figure bellow.

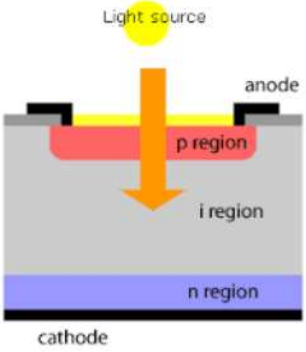


Figure 1: 2D Structure of Pin Diode

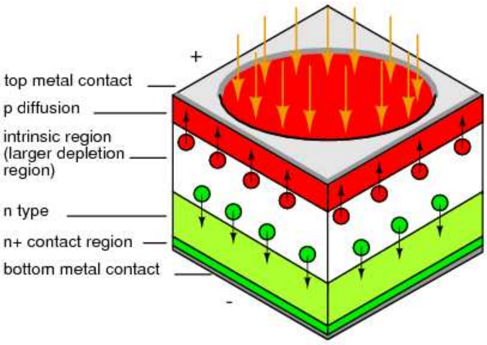


Figure 2: 3D Structure of Pin Diode

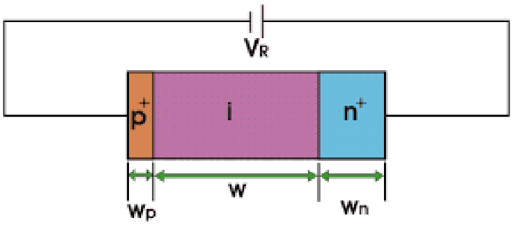


Figure 3: Biasing of a Pin Diode

Device Simulation Using VTCAD

Using V-TCAD software the PiN diode is simulated. The PiN diode consists of highly doped n+ and p+ layers, and a lightly doped p− buffer layer separating the p+ contact layer from the intrinsic region. The p+, p- ,i and n+ region thicknesses considered in this simulation is 80nm, 70nm, 600nm and 300nm respectively . The final simulated device structure is shown in Figure 4. Three different concentration sets are considered for each material as shown in table I.

Table 1: Doping Concentration and Thickness Specifications of the Simulated Device

Layer Name	Thickness (Nm)	Doping Concentration Set 1 (Cm^{-3})	Doping Concentration Set 2 (Cm^{-3})	Doping Concentration Set 3 (Cm^{-3})
P+	80	10^{18}	10^{20}	10^{22}
P-	70	$3x10^{16}$	$3x10^{18}$	$3x10^{20}$
I	600	-	-	-
N+	300	10^{18}	10^{20}	10^{22}

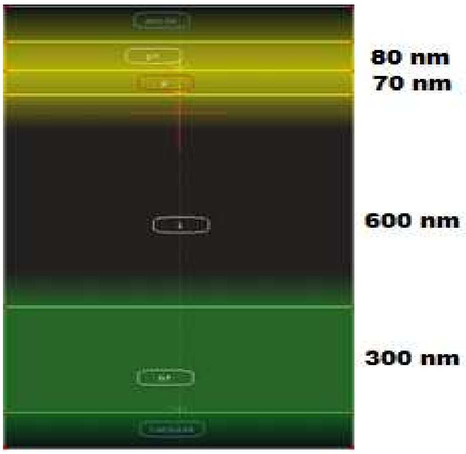


Figure 5: Simulated Pin Diode Structure Using VTCAD

Result Analysis

Five different materials namely Silicon (Si), Germanium (Ge), Silicon Carbide Tri Carbide (SiC-3C), Silicon Carbide Tetra Hydride (SiC-4H) and Indium Phosphide (InP) are chosen for the simulation purpose. For each material three concentration sets (except for InP, where only two concentration sets are taken into account) are considered and the current voltage data is obtained in each case. Finally the IV characteristics in each case is plotted for the purpose of comparison.

	Current (A)		
Vapp (V)	SET 1(181618)	SET 2 (201820)	SET 3 (222022)
0	-2.78E-16	-5.77E-16	7.44E-14
0.5	2.22E-11	1.10E-11	1.07E-11
1	0.000510757	5.47E-05	2.79E-05
1.5	0.0122844	0.363169	0.749869
2	0.0247814	1.07949	2.73535
2.5	0.0322335	1.68467	4.60266
3	0.0352898	2.1428	6.09004
3.5	0.0363847	2.46383	7.22668
4	0.0368303	2.68393	8.0909
4.5	0.0370471	2.8378	8.75192
5	0.0371696	2.94915	9.25934

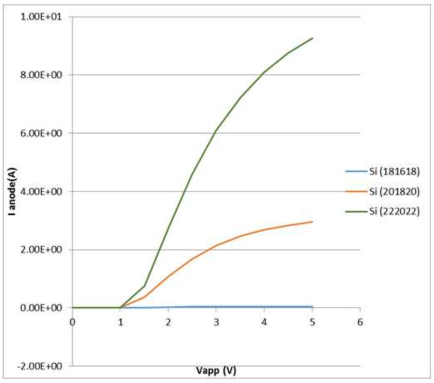


Figure 6: I–V Characteristics of Si Pin Diode at Different Concentrations

	Current (A)		
Vapp (V)	SET 1 (181618)	SET 2 (201820)	SET 3 (222022)
0	-1.95E-16	1.01E-14	-1.29E-13
0.5	4.09E-05	1.95E-06	8.96E-07
1	0.00927328	0.0535986	0.416831
1.5	0.0224832	0.211722	2.31007
2	0.0310454	0.390851	4.23643
2.5	0.0348236	0.570876	5.79813
3	0.0361889	0.744396	6.99931
3.5	0.03673	0.907455	7.91311
4	0.0369868	1.0575	8.61206
4.5	0.0371299	1.19258	9.14832
5	0.0372205	1.31118	9.56211

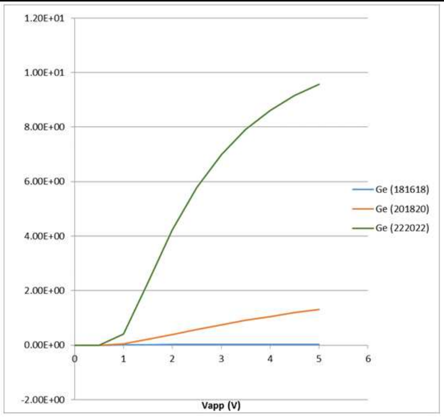


Figure 7: I-V Plots for Ge Based Pin Diode for Three Different Sets of Doping Concentrations

	Current (A)		
Vapp (V)	SET 1 (181618)	SET 2 (201820)	SET 3 (222022)
0	-5.01E-15	7.26E-17	1.10E-13
0.5	-1.64E-17	-1.09E-16	1.52E-13
1	-2.93E-17	-1.52E-16	1.29E-13
1.5	-3.03E-17	-1.54E-16	1.01E-13
2	1.02E-14	9.86E-15	1.33E-13
2.5	2.27E-08	2.36E-09	1.92E-09
3	0.00379316	0.0110106	0.02725
3.5	0.0175721	0.142833	1.48538
4	0.0282993	0.317517	3.49354
4.5	0.0337939	0.498406	5.21139
5	0.0358427	0.675175	6.55172

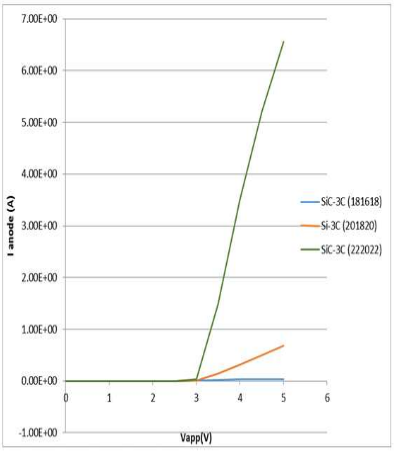


Figure 8: I-V Plots for Sic-3C Based Pin Diode for Three Different Sets of Doping Concentrations

	Current (A)		
Vapp (V)	SiC-4H (181618)	SiC-4H (201820)	SiC-4H (222022)
0	-1.91E-15	-4.82E-18	1.18E-13
0.5	-2.52E-17	-3.19E-16	5.99E-14
1	-3.62E-17	-3.15E-16	7.53E-14
1.5	-2.88E-17	7.16E-17	5.57E-14
2	-2.32E-17	-6.95E-17	8.27E-14
2.5	4.03E-13	1.98E-13	2.63E-13
3	3.72E-05	4.81E-07	2.03E-07
3.5	0.00533284	0.0214225	0.0736142
4	0.0112136	0.0668753	0.274193
4.5	0.0154508	0.110777	0.484301
5	0.0186584	0.152527	0.694334

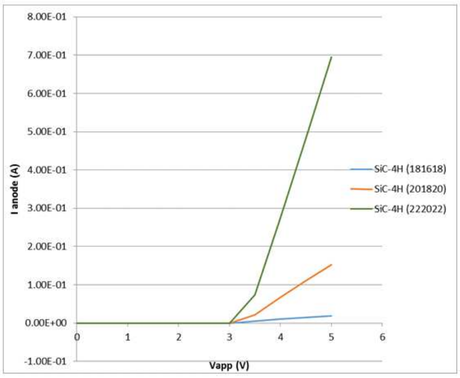
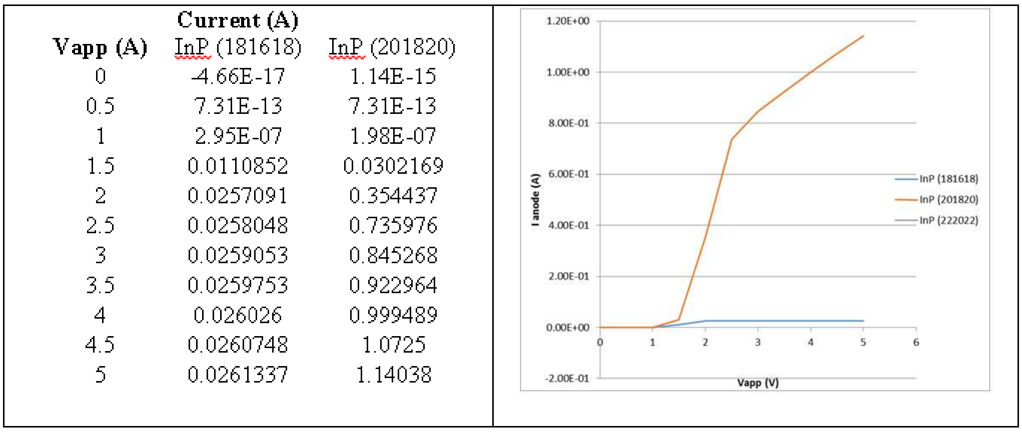
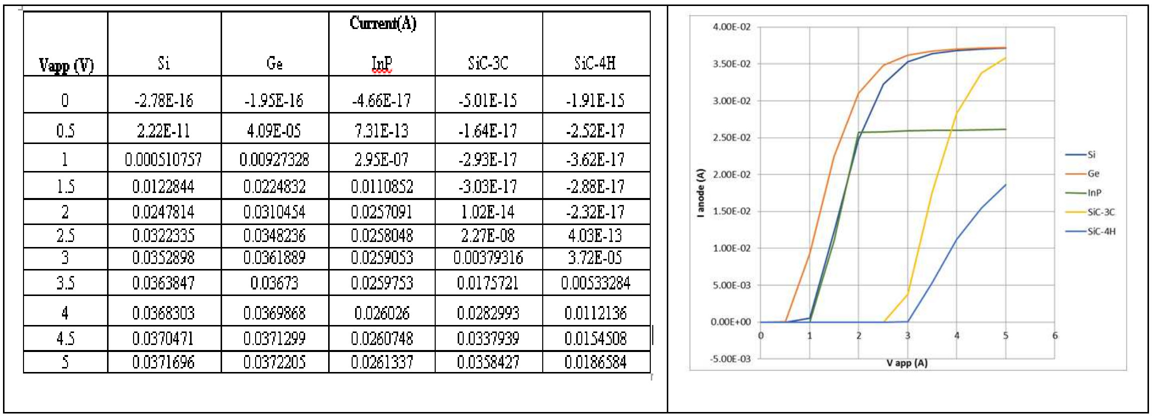


Figure 9: I-V Plots for Sic-4H Based Pin Diode for Three Different Sets of Doping Concentrations



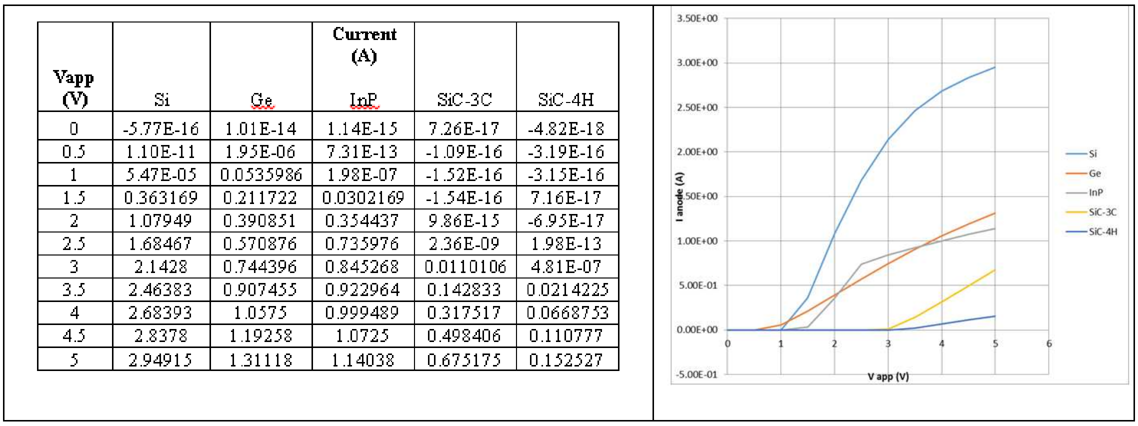
	Current (A)	
Vapp (A)	InP (181618)	InP (201820)
0	-4.66E-17	1.14E-15
0.5	7.31E-13	7.31E-13
1	2.95E-07	1.98E-07
1.5	0.0110852	0.0302169
2	0.0257091	0.354437
2.5	0.0258048	0.735976
3	0.0259053	0.845268
3.5	0.0259753	0.922964
4	0.026026	0.999489
4.5	0.0260748	1.0725
5	0.0261337	1.14038

Figure 10: IV Plots for INP Based Pin Diode for Three Different Sets of Doping Concentrations



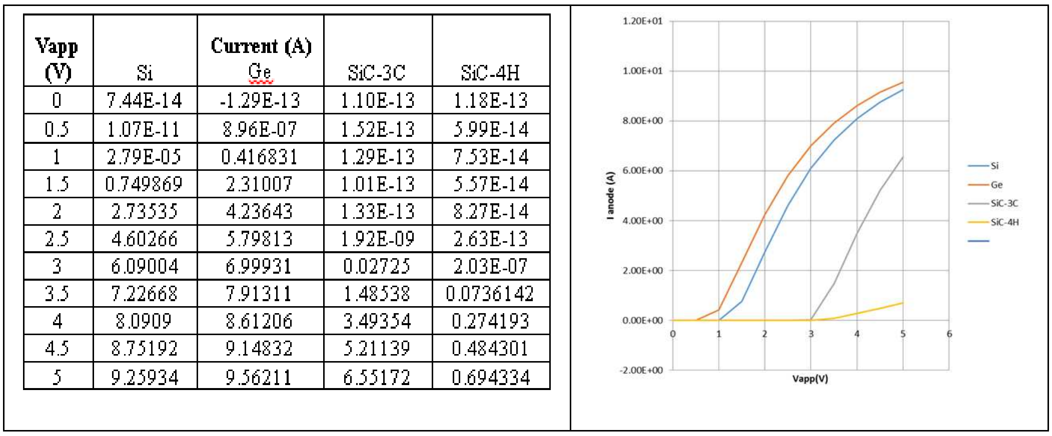
			Current(A)		
Vapp (V)	Si	Ge	InP	SiC-3C	SiC-4H
0	-2.78E-16	-1.95E-16	-4.66E-17	-5.01E-15	-1.91E-15
0.5	2.22E-11	4.09E-05	7.31E-13	-1.64E-17	-2.52E-17
1	0.000510757	0.00927328	2.95E-07	-2.93E-17	-3.62E-17
1.5	0.0122844	0.0224832	0.0110852	-3.03E-17	-2.88E-17
2	0.0247814	0.0310454	0.0257091	1.02E-14	-2.32E-17
2.5	0.0322335	0.0348236	0.0258048	2.27E-08	4.03E-13
3	0.0352898	0.0361889	0.0259053	0.00379316	3.72E-05
3.5	0.0363847	0.03673	0.0259753	0.0175721	0.00533284
4	0.0368303	0.0369868	0.026026	0.0282993	0.0112136
4.5	0.0370471	0.0371299	0.0260748	0.0337939	0.0154508
5	0.0371696	0.0372205	0.0261337	0.0358427	0.0186584

Figure 11: IV Plots for Pin Diodes for Doping Concentrations SET 1



			Current (A)		
Vapp (V)	Si	Ge	InP	SiC-3C	SiC-4H
0	-5.77E-16	1.01E-14	1.14E-15	7.26E-17	-4.82E-18
0.5	1.10E-11	1.95E-06	7.31E-13	-1.09E-16	-3.19E-16
1	5.47E-05	0.0535986	1.98E-07	-1.52E-16	-3.15E-16
1.5	0.363169	0.211722	0.0302169	-1.54E-16	7.16E-17
2	1.07949	0.390851	0.354437	9.86E-15	-6.95E-17
2.5	1.68467	0.570876	0.735976	2.36E-09	1.98E-13
3	2.1428	0.744396	0.845268	0.0110106	4.81E-07
3.5	2.46383	0.907455	0.922964	0.142833	0.0214225
4	2.68393	1.0575	0.999489	0.317517	0.0668753
4.5	2.8378	1.19258	1.0725	0.498406	0.110777
5	2.94915	1.31118	1.14038	0.675175	0.152527

Figure 12: IV Plots for Pin Diodes for Doping Concentrations SET 2



Vapp (V)		Current (A)		
	Si	Ge	SiC-3C	SiC-4H
0	7.44E-14	-1.29E-13	1.10E-13	1.18E-13
0.5	1.07E-11	8.96E-07	1.52E-13	5.99E-14
1	2.79E-05	0.416831	1.29E-13	7.53E-14
1.5	0.749869	2.31007	1.01E-13	5.57E-14
2	2.73535	4.23643	1.33E-13	8.27E-14
2.5	4.60266	5.79813	1.92E-09	2.63E-13
3	6.09004	6.99931	0.02725	2.03E-07
3.5	7.22668	7.91311	1.48538	0.0736142
4	8.0909	8.61206	3.49354	0.274193
4.5	8.75192	9.14832	5.21139	0.484301
5	9.25934	9.56211	6.55172	0.694334

Figure 13: IV Plots for Pin Diodes for Doping Concentrations SET 3

Table 2: Pin Diode on Voltages and Anode Currents for Doping Concentration SET 1

Material	On Voltage (V)	Anode Current (A) At 5V
Ge	0.5	0.0355
Si	1	0.0355
SiC-3C	2.8	0.035
SiC-4H	3	0.019
InP	1.2	0.026

Table 3: Pin Diode on Voltages and Anode Current for Doping Concentration SET 2

Material	on Voltage (V)	Anode Current (A) At 5v
Ge	0.8	1.3
Si	1	2.9
SiC-3C	2.7	0.68
SiC-4H	3.2	0.15
InP	1.4	1.15

Table 4: Pin Diode on Voltages and Anode Current for Doping Concentration SET 3

Material	on Voltage (V)	Anode Current (A) At 5V
Ge	0.8	9.5
Si	1	9.5
SiC-3C	3	6.5
SiC-4H	3.2	0.7

CONCLUSIONS

The ON voltage or the threshold voltage remains almost same for each material for change in doping concentrations. Thus the ON voltage is only material dependent and independent of doping. On the other hand we can see that the anode current is highly dependent on doping. With increase in doping concentration the current largely increases for same material. The I-V plots for each of the five materials at three different sets of concentration are shown in Figure 10, 11 & 12. The corresponding values of ON voltage and current at an applied voltage of 5V for each material at three different materials is shown in tables II, III & IV. Thus a device engineer could choose the doping and material based on the results of this simulation to satisfy the requirements of ON voltage and current range.

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