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SiC polytypes and doping nature effects on electrical properties of ZnO-SiC Schottky diodes

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Abstract
Electrical properties of ZnO/SiC Schottky diodes with two SiC polytypes and N and P doping are investigated. Characterization was performed through I–V and C–V–f measurements. Schottky barrier height (Φ_b), ideality factor (n), and series resistance (R_s) were extracted from forward I–V characteristics. (Φ_b), carrier's concentrations (N_d-N_a) and (R_s) frequency dependence were extracted from C–V–f characteristics. The extracted n values suggest that current transport is dominated by interface generation-recombination and/or barrier tunneling mechanisms. When changing SiC polytypes, the rectifying ratio of ZnO/n-4HSiC is found to be twice that of ZnO/n-6HSiC. A change in doping nature gave a leakage current ratio of 40 between ZnO/p-4HSiC and ZnO/n- 4HSiC. These results indicate that ZnO/p-4HSiC diodes have a complex current transport compared to diodes on n-type SiC. From I-V measurements, barrier height values are 0.63eV, 0.65eV and 0.71 eV for heterojunction grown on n-6HSiC, n-4HSiC and p-4HSiC, respectively. C-V measurements gave higher values indicating the importance of interface density of states. N_{ss} values at 1MHz frequency are 4.54×10^{11} eV^{-1} cm^{-2}, 3×10^{12} eV^{-1} cm^{-2} and 8.13×10^{10} eV^{-1} cm^{-2} for ZnO/n-6HSiC, ZnO/n-4HSiC and ZnO/p-4HSiC, respectively. Results indicate the importance of SiC polytypes and its doping nature.

Keywords: ZnO/SiC; SiC polytypes; I–V characteristics; C–V-f measurements; Electrical properties.

1. Introduction

Silicon Carbide (SiC) is a promising semiconductor material for electronic power applications. Among its properties, there are its high electric field strength, high electron drift velocity, high thermal conductivity, radiation and harsh ambient endurance, high melting point that lead to significant advantages for power switching devices. It grows in many different polytypes, but the most studied are the 3C, 4H, and 6H SiC [1,2]. On the other hand, ZnO has a direct wide band gap (3.37 eV), large exciton binding energy and piezoelectric properties. These properties make ZnO a strong candidate for applications in solar cell development, photodiodes, and surface acoustic wave devices and so on [3,4].

To date, little has been done on this combination of materials. SiC is a good candidate for use as substrate for ZnO nanostructure growth in many applications. SiC and ZnO have the same wurtzite crystal symmetry and relatively small lattice mismatch ($\approx$5%) [5]. Ataev et al. [6] were the first to report on the fabrication of ZnO/p-6HSiC heterostructures by chemical vapor deposition, which presented poor current–voltage characteristics. A decade ago, Alivov et al. [7, 8] reported on the growth of ZnO/p-6HSiC heterostructures diodes by plasma-assisted molecular-beam epitaxy (MBE). In the same time, Yuen et al. [9] demonstrated the possibility to fabricate ZnO: Al/p-4HSiC heterojunction light-emitting diodes (LEDs) by a filtered cathodic vacuum arc technique. More recently, Y.T. Shih et al. [10] used atomic layer deposition to fabricate ZnO/p-4HSiC and n–ZnO/i–ZnO/p-4HSiC heterojunction LEDs.

A number of process methodologies have been developed for the fabrication of reproducible high quality Schottky contacts with SiC nanostructures, but controversies remain with regard to Schottky barrier height and ideality factor of SiC Schottky contacts [11,13]. Deviations in barrier heights and ideality factor have been attributed to effects of asymmetric contacts and influence of interfacial layers and/or surface states [14,15]. Schottky barrier height depends not only on work function of metal but also on pinning of Fermi level by surface states, image force lowering of barrier, field penetration and existence of an interfacial insulating layer. These effects change absolute current value at low bias values by lowering Schottky barrier [18].

Schottky devices can be used to evaluate different semiconductor parameters, including carrier density profile, Schottky barrier height, and band gap discontinuity. Capacitance and conductance measurements can provide important information about interface state energy distribution in Schottky diodes. In ideal case, these measurements are frequency independent, but this is often not the case because of the presence of interface states at metal-semiconductor interface [16,18].

This paper reports on the effects of polytypes and doping nature on electrical properties of ZnO/ n-6HSiC, ZnO/n-4HSiC and ZnO/p-4HSiC based Schottky diodes. Various measurements such as current-voltage (I-V), capacitance-voltage-frequency (C-V-f) and conductance-frequency (Gp/ ω) are used. Parameters studied are ideality factor (n), series resistance (R_s), barrier height (φ_b) and interface states density (N_{ss}). These were calculated using Cheung, Lien and Hill-Coleman [19] methods.

2. Sample details

All fabrication steps [20] were done in clean room (class 1000) using metal-oxide-semiconductor (MOS) grade chemicals. 4H-SiC and 6H-SiC wafers (Si terminated) were provided by Cree Research Corporation. In both cases, the epitaxial layer had a doping of $5x10^{15}cm^{-3}$ and its thickness was 4.9 µm. The epitaxial layer was grown 8°9 off-axes for 4HSiC and 3°22 off-axes for 6HSiC. Total wafer thickness was 421 µm for 4HSiC and 382 µm for 6HSiC. After cleaning of substrates by a modified RCA process, a large area backside electrical contact was obtained by thermal evaporation of 99.9% pure Al (thickness of 200 nm) and Ni (thickness of 50 nm), respectively. These electrical contacts were deposited by vacuum thermal evaporation at a base pressure below 10^{-6} Torr using a BOC Edwards 306 system. After evaporation, the contacts were annealed in vacuum for 5 min, at 900°C to form Ohmic contact to bottom of SiC bulk substrate [21, 22]. These SiC substrates with backside electrical contact were loaded in a thermal evaporator for evaporation of 99.99% ZnO powder through a metal mask. A 120 nm thick ZnO disc was deposited onto SiC epitaxial layer. Fig.1 shows a schematic diagram of Ni/Al/SiC/ZnO heterojunction diode structure including layer thicknesses. Schottky contacts were formed at ZnO/SiC doped epilayer [23, 24].

Current-voltage (I–V) measurements were carried out using an Agilent precision semiconductor parameters analyzer (4156C). The capacitance–voltage–frequency (C-V-f) and conductance –voltage–frequency (G-V-f) measurements were carried out with an Agilent LCR meter (4980A).

3. Current-voltage measurements

After fabrication of Schottky diodes, first step is to measure their current-voltage (I-V) characteristics that provide immediate information about quality and suitability of diodes. I-V curves may be described by thermionic emission model, with a series resistance R_s [25], according to equation (1).

$$I = Is\left[\exp\left(\frac{q(V - IR_s)}{nkT}\right) - 1\right] \quad (1)$$

Where q is electronic charge, V is applied voltage, k is Boltzmann constant, (n) is ideality factor, (Is) is saturation current, and (T) is absolute temperature in Kelvin. The values of (n) and (Is) are determined from experimental data. Saturation Current (Is) is given by:

$$I_s = AA^{**}T^2 \exp\left(\frac{-q\phi_B}{kT}\right) \quad (2)$$

Where ϕ_B is barrier height, A is diode area and A** is Richardson’s constant theoretically taken as

$$A^{**} = \frac{4\pi qk^2 m^*}{h^2} = 32Acm^{-2}K^{-2}$$ ($m^*=0.28m_0$, for ZnO and $A=0.0314cm^2$) [26].

Typical I-V characteristics of Schottky diodes are shown in Fig.2. On Fig.2.a, one observes that ZnO/n-4HSiC can pass more current than ZnO/n-6HSiC. This is attributed to its higher vertical a-axis electron mobility [27]. On the other hand, forward bias behavior of I–V characteristics of these devices is approximately similar for both SiC polytypes. Exponential behavior of current at low forward voltages indicates a thermionic emission current transport behavior. This exponential dependency at lower voltages range can be attributed to a depletion region formation between ZnO and SiC [28].

On Fig.2.b, leakage current of ZnO/p-4HSiC Schottky diode is twice larger than that of ZnO/n-4HSiC. The increase in reverse current with reverse bias-voltage has been attributed to direct tunneling- effect or defect-assisted tunneling especially for higher reverse voltage-bias values [29]. Turn-on voltages are 1.15 V and 0.75 V, respectively, indicating a difference in space charge width and interface states distribution. Band gap (Eg) of ZnO is 3.3 eV and that of 4HSiC is 3.23 eV. Hence, for ZnO/4HSiC conduction band offset (ΔEc) is 0.3 eV and valance band offset (ΔEv) is 0.4 eV. ΔEv has a higher value than ΔEc and electron injection from ZnO to n-4HSiC will be larger than hole injection from p-4HSiC to ZnO [30].

Fig.3 shows current density-voltage (J-V) characteristics of ZnO-SiC. According to thermionic emission theory, the J–V characteristic of the Schottky diode is described by equation:

$$J(V) = J_0 \exp(\frac{qV_d}{nkT})\left[1-\exp(\frac{-qV_d}{kT})\right] \quad (3)$$

Where J_0 is the saturation current density given by:

$$J_0 = A^{**}T^2 \exp(\frac{-q\phi_b}{kT}) \quad (4)$$

J_0 is deduced from the straight line intercept of Ln (J)-V curve. Ideality factor (n) of Schottky barrier is an important parameter that indicates perfection of metal-semiconductor junction. It is determined from slope of semi log J-V characteristics in exponential region and given by:

$$n = \beta \frac{dV}{d(\ln J)} \qquad \text{With} \qquad \beta = q/kT \quad (5)$$

Barrier height is an electrostatic barrier to charge transfer across metal/semiconductor interface. φ_b can be written as:

$$\phi_b = \frac{1}{\beta}\ln(\frac{A^{**}T^2}{J_o}) \quad (6)$$

When $V \succ\succ 3kT/q$, equation (3) becomes:

$$J = A^{**}T^2 \exp(\frac{-q\phi_B}{kT})\exp(\frac{qV}{nkT}) \quad (7)$$

There are four mechanisms that contribute to current transport across a metal -semiconductor interface: (i) thermionic emission over potential barrier, (ii)quantum-mechanical tunneling of carriers through potential barrier, (iii) carrier recombination in depletion region and (iv) carrier recombination in neutral region of semiconductor [31]. For wide band gap semiconductor materials such as SiC, the dominant contribution to current transport comes from thermionic emission (TE) of electron over barrier and tunneling of electrons through the barrier. If SiC material of Schottky contacts is not heavily doped and the operating temperature is not very low, thermionic emission (TE) term will be dominant. The tunneling term will only be significant if SiC is heavily doped or the device is operating under low temperature or is blocking high reverse voltage. Carrier recombination in depletion region may dominate in case of a higher density of states at the metal-semiconductor interface.

LnJ-V characteristics of Fig.3.a show a difference in rectifying behavior between n-4HSiC and n-6HSiC heterojunctions. From insight of Fig.3.a, ZnO/n-4HSiC calculated rectifying ratio (forward to reverse current ratio, I_F/I_R) is found to be twice that of ZnO/n-6HSiC. Reverse current density is about $1.39*10^{-5}$ A/cm^2 for ZnO/n-4HSiC and $6.74*10^{-5}$ A/cm^2 for ZnO/n-6HSiC. Devices exhibited very good rectification ratio, substantially low leakage current and indicate formation of rectifying behavior between ZnO and n-type SiC with a noticeable superiority for 4HSiC substrates. These values are better than values previously reported, where more sophisticated and expensive techniques were used [6,9].

In Fig.3.b, ln J–V characteristics show doping nature effects on Schottky diodes. P type characteristics are different from those of N type. At a reverse bias of -5 V, leakage current ratio between ZnO/p-4HSiC and ZnO/n-4HSiC is 40. Calculated saturation current for ZnO/n -4HSiC is $9.663x10^{-7}$ A/cm^2 and for ZnO/p -4HSiC is $9.384x10^{-8}$ A/cm^2 giving a ratio of 10.Among these two heterostructures, the one on p-4HSiC substrate has a higher leakage current .These results indicate that heavy doping of p-4HSiC makes tunneling current more probable [32]. Heterojunction diodes fabricated from ZnO grown on n-4HSiC exhibited more stable rectification characteristics and higher I_F/I_R value.

Fig.3.b inset shows forward current of Schottky diodes that tends to saturate at bias voltages above 0.7V and 1.25V for N type and P type, respectively. This relatively low forward current in P type is attributed to higher series resistance. A high value of series resistance reduces mobility of electrons and holes.

Cheung method [33] was applied to evaluate series resistance R_s and ideality factor n using a modified equation (7):

$$dV/d(\ln J) = R_s AJ + nkT/q \quad (8)$$

$$H(J) = V - n(kT/q)\ln(J/(A^{**}T^2)) \quad (9)$$

With $\quad H(J) = R_s AJ + n\phi_B \quad (10)$

Fig.4 shows experimental dV/d(lnJ) versus J and H(J) versus I plots for ZnO/ SiC based Schottky diodes. Equation (8) gives a straight line for J-V data in forward bias. Thus, n and R_S values are derived from intercept and slope of dV/d(lnJ) versus J plots. These values are shown in table 1. A plot of H(J) versus J will also lead to a straight line with y-axis intercept equal to $n\phi_b$. Substitution using deduced n value into Equation (10) gives ϕ_b. Slope of H(J) versus J determines R_S that can be compared with value obtained from dV/d(lnJ) versus J.

The ideality factor, as estimated from equation (1), was found to be >4 suggesting that the mechanism of transport is not thermionic emission only. Other mechanisms of current transport such as generation - recombination in space charge region and/or barrier tunneling [34, 35] exist. All these forms of current can be interface defects assisted. n values were found to be 6.32, 6.70, and 4.67 for ZnO deposited respectively on n-6HSiC, n-4HSiC and p-4HSiC; in good agreement with results reported by Felix et al.[11].
SiC polytypes affect ideality factor with that of ZnO/n-6HSiC smaller than that of ZnO/n-4HSiC. This difference can be ascribed to interface dipoles or specific interface structures. Defects induced during elaboration at interface ZnO/substrate are known to result from reactions between the metal and carbon face of SiC crystal [36].
Calculated barrier height values are 0.63eV, 0.65eV and 0.71 eV for heterojunctions grown on n-6HSiC, n-4HSiC and p-4HSiC, respectively. The small difference in barrier high value between devices with different polytypes can be attributed to difference in band gap between 6H-SiC and 4H-SiC substrate which is about 3 eV and 3.2eV, respectively [28].
Doping nature has an effect on barrier height, which decreases from 0.71eV to 0.65 eV when passing from P type to N type Schottky diodes. Electron tunneling traps localized in interfacial layer close to p-4HSiC surface are known to increase φ_b. Increase in ideality factor from 4.67 to 6.70 is also associated with surface states and/or carrier generation transport near interface [11].
Series resistance is a very important parameter in Schottky diodes. It is the sum of contact resistance and semiconductor device resistance in direction of current flow. A plot of dV/dLn (J) versus J is linear and from slope we deduce values of series resistance. R_s values obtained for ZnO grown on n-6HSiC, n-4HSiC and p-4HSiC, are 205.5Ω, 15.50Ω and 12.8KΩ respectively. These values are lower than those reported by Felix et al. [11]. Series resistance can also be determined from H(J) versus J plots, Fig. 4. For ZnO deposited on n-6HSiC, n-4HSiC and p-4HSiC, series resistance of devices are respectively 218.5Ω, 14.5Ω and 14.8KΩ. These values of R_s are in good agreement with those obtained from dV/dLn (J) versus J plots. R_s for P type is higher than N type because barrier to holes injection is higher compared to that of electrons. ZnO/n-6HSiC had a higher R_s than ZnO/n-4HSiC devices. This can be attributed to carriers' removal effect, mobility change and/or reduction in free carriers' concentrations [37, 33].
4. Capacitance-voltage Measurements
Plotting inverse squared junction capacitance against applied reverse voltage of ZnO/SiC Schottky contacts is used to find built in potential (V_{bi}), barrier height (φ_{b0}) and carrier concentration (N_D), equation (11) and Fig.5.

$$1/C^2 = 2(V_{bi} - V)/(A^2 q N_D \varepsilon) \quad (11)$$

N_D is deduced from slope and V_{bi} from intercept.

$$N_D = 2/(q\varepsilon_s A^2)\left[1/(d(1/C^2)/dV)\right] \quad (12)$$

Where $\varepsilon_s = 9\varepsilon_0$ is permittivity [38], A is Schottky contact area, V_{bi} is built in potential, and N_D is carrier concentration. $N_C=2(2\pi m^*kT/h^2)^{3/2}=4.8\times10^{18}cm^{-3}$ is conduction band density of states at T =300 K. V_0, x-intercept, is related to build in potential V_{bi} by:

$$V_{bi} = V_0 + kT/q \quad (13)$$

Barrier height ϕ_{b0} is given by:

$$\phi_{b0} = V_{bi} + kT/q \ln(N_C/N_D) \quad (14)$$

Density of states in conduction band edge is given by:

$$N_C = 2((2m^*kT)^{\frac{3}{2}}/h^3 \quad (15)$$

Where h is plank constant.

Carriers concentrations and ϕ_{b0} were calculated from above equations and are shown in Table 2.
Capacitance–voltage measurements were made at high frequency (1 MHz) to reduce interface state charges contribution to capacitance. There is a difference between barrier height values extracted from J–V and C–V measurements inTable1 and Table 2, respectively.
Barrier height obtained from C–V measurements is comparatively larger than barrier heights obtained from J–V measurements. Difference is attributed to interface effects [39,40]. Indeed, current in J–V measurement is dominated by current flowing through low barrier height region. In C–V measurements, barrier height is influenced by distribution of charge at depletion region boundary. This charge distribution follows weighted arithmetic average of barrier height inhomogeneity. Hence, capacitance is insensitive to potential fluctuations on a length scale of less than space-charge width and therefore C–V method averages over whole area [40].
Slope of ($1/C^2$) versus V gives carrier concentration (Nd-Na), while intercept gives built-in potential (V_{bi}). Values of V_{bi} and N_d are 0.825 V and $0.53\text{x}10^{+15}$(cm^{-3}) for ZnO/n-6HSiC, and 1.05V and $0.50\text{x}10^{+15}$(cm^{-3}) for ZnO/n-4HSiC. For ZnO/p-4HSiC, V_{bi} and N_a are 0. 675V and $23.4\text{x}10^{+15}$ (cm^{-3}), respectively. These N_d and N_a values are in good agreement with data provided for SiC substrate.
Difference in barrier heights between ZnO/n-6HSiC and ZnO/n-4HSiC is about 0.22 eV, which corresponds to difference between their respective band gaps. Barrier height is generally higher for ZnO/n-4HSiC than for ZnO/n-6HSiC, due to interface state density. Barrier height is found to be around 0.9372 eV for ZnO/n-6HSiC and 1.1638 eV, For ZnO/n-4HSiC respectively, indicating a strong Fermi-level pinning for ZnO/n-6HSiC. Interface states density was estimated to be of $4.54*10^{11}eV^{-1}cm^{-2}$ for ZnO/n-6HSiC. Barrier height of N type Schottky diodes was twice higher than P type. This is attributed to big difference in surface states densities.
Other effects that may be affecting Schottky barrier height can be revealed by studying forward capacitance–voltage and conductance–voltage as function of frequency (from 1 MHz to 10 kHz). Fig.6 shows C–V–f characteristics of ZnO/n-6HSiC, ZnO/n- 4HSiC and ZnO/p-4HSiC Schottky diodes. Diode capacitance is quasi-independent of frequency at low voltages up to 0.5 V for N type 6HSiC and 0.25 V for 4HSiC.
Measured capacitance of Schottky diodes changed with bias voltage and frequency. Such dependency is related to Schottky barrier heights, impurity levels and high series resistances.
Capacitance value decreases with increasing frequency for all structures. It exhibits a peak at positive voltage for N type SiC and at negative voltage for P type SiC. This peak has been related to interface states in band gap and series resistance [41]. Capacitance peaks changed with an increase in interface state density occupancy that is more and more activated when decreasing frequency. Series resistance can also affect the height of peak capacitance [42].
From Fig.6 , one can see that the doping effect has lead to a 5 times higher peak for N type SiC than P type SiC, while a difference in polytypes has lead to a 2 times higher peak for 4HSiC than 6HSiC. These results reflect differences in interface states densities or traps densities between ZnO/n- 4HSiC, ZnO/p-4HSiC and ZnO/n-6HSiC Schottky diodes.
Fig.7 shows measured G/ω–V characteristics of ZnO/SiC Schottky diodes, measured at various frequencies at room temperature.
One can see that conductance of Schottky diode ZnO/n-6HSiC, ZnO/n-4HSiC is different from that of ZnO/p-4HSiC. As expected, conductance increases with increasing positive voltage for ZnO/n-type SiC and with increasing negative voltage for ZnO/p-type SiC. It decreases with increasing frequency in all cases due to increasing deactivation of interface states responsible for capture and emission of carriers.
To show dependence of interface states density on frequency, Hill–Coleman [19] used:

$$Nss = 2/(qA)(G_m/\omega)_{\max}/((G_m/\omega)_{\max}/C_{ox})^2 + (1 - C_m/C_{ox})^2 \quad (16)$$

Where A is contact area of diode, ω is angular frequency, C_m and $(G_m/\omega)_{max}$ are maximum measured capacitance and conductance and C_{ox} is native insulator layer capacitance given by [43, 45]:

$$C_{ox} = C_m\left[1 + \left(\frac{G_m}{\omega C_m}\right)^2\right] = \frac{\varepsilon_i \varepsilon_0 A}{\delta} \quad (17)$$

δ is thickness of native interfacial insulator layer.

Fig.8. shows density of interface states versus frequency. N_{ss} values for ZnO/n-6HSiC are lower than ZnO/n-4HSiC. Such behavior can be ascribed to a thicker oxide layer at ZnO/n-6HSiC interface than at ZnO/n-4HSiC interface. This is due to a difference in interface dangling bonds between 6HSiC and 4HSiC surfaces.

N_{ss} values for ZnO/p-4HSiC are lower than ZnO/n-4HSiC. Since interface states play a very important role in current flow mechanism in electronic devices, one may conclude that carrier's recombination will be important in ZnO/n-4HSiC leading to I-V characteristics dominated by recombination. This is in good agreement with calculated n values. High N_{ss} values are known to affect series resistance [46]. To show this effect, series resistance R_s is being plotted using maximum measured values of capacitance C_m and conductance G_m [43,41] according to:

$$Rs = Gm / (Gm^2 + \omega^2 Cm^2) \quad (18)$$

Fig.9 shows series resistance changes with frequency for ZnO/6HSiC, ZnO/ n-4HSiC and ZnO/p-4HSiC Schottky diodes. For N type devices, series resistance peak decreases with higher frequencies and slightly shifts with greater voltages. Opposite behavior is seen to happen for P type devices. Since series resistance is also related to charge behavior at interface, above changes suggest that interface states are behind such behavior with frequency [47,48]. High value of series resistance at low frequencies is due to an excess capacitance. Decrease in peak intensity indicates interface states non response to alternating current. Above 800 kHz, peak disappears completely. Peak intensity may be taken as a measure of active interface states density and carriers mobility.

5-Conclusion

Electrical properties of ZnO/SiC Schottky diodes with two SiC polytypes and two doping natures are investigated using I–V, C–V–f and Gp/ω -V–f measurements. Parameters of interest are Schottky barrier height (ϕ_b), ideality factor (n), series resistance (R_s), carriers concentrations (N_d, N_a) and interface states density (N_{ss}). Current through ZnO/n-4HSiC is higher than that through ZnO/n-6HSiC because of its higher vertical a-axis electron mobility. Rectifying ratio (IF/IR), from ZnO/n-4HSiC is found to be twice that of ZnO/n-6HSiC. Devices exhibited very good rectification ratio, substantially low leakage current and indicate formation of excellent diodes between ZnO and n-type SiC with a noticeable superiority for 4HSiC substrates.

The small difference in barrier high from the J–V value between devices with different polytypes can be attributed to difference in band gap between 6H-SiC and 4H-SiC substrate which is about 3 eV and 3.2eV, respectively. Barrier height obtained from the C–V measurement is comparatively larger than barrier heights obtained from J–V measurements. Difference is attributed to interface effects. Barrier height is found to be around 0.9372 eV for ZnO/n-6HSiC and 1.1638 eV, For ZnO/n-4HSiC respectively. Interface states density was estimated to be $4.54*10^{11} eV^{-1} cm^{-2}$ for ZnO/n-6HSiC. Difference in barrier heights between ZnO/n-6HSiC and ZnO/n-4HSiC is about 0.22 eV, which corresponds to difference between their respective band gaps.

Series resistance determined from H(J) versus J plots are in good agreement with those obtained from dV/dLn(J) versus J plots. ZnO/n-6HSiC had a higher series resistance than ZnO/n-4HSiC devices. This can be attributed to carriers' removal effect, mobility change and/or reduction in free carriers 'concentrations.

N_{ss} values for ZnO/n-6HSiC are lower than ZnO/n-4HSiC. Such behavior can be ascribed to a thicker oxide layer at ZnO/n-6HSiC interface than at ZnO/n-4HSiC interface. This is due to a difference in interface dangling bonds between 6HSiC and 4HSiC surfaces.

From doping nature leakage current ratio between ZnO/p-4HSiC and ZnO/n- 4HSiC is 40. Among two heterostructures, the one on p-4HSiC substrate has a higher leakage current. These results indicate that heavy doping nature of p-4HSiC makes current tunneling more probable. Heterojunction diode fabricated from ZnO grown on n-4HSiC exhibited more stable rectification characteristics and higher IF/IR value. Doping nature has an effect on barrier height, which decreases from 0.71eV to 0.65 eV when passing from P type to N type Schottky diodes. Electron tunneling traps localized in interfacial layer close to p-4HSiC surface are known to increase. Barrier height of N type Schottky diodes was twice higher than P type. This is attributed to big difference in surface states densities. Series resistance for P type is higher than N type because barrier to holes injection is higher compared to that of electrons.

Nss values for ZnO/p-4HSiC are lower than ZnO/n-4HSiC. Since interface states play a very important role in current flow mechanism in electronic devices, one may conclude that carrier's recombination will be important in ZnO/n-4HSiC leading to I-V characteristics dominated by recombination.
Measured capacitance of Schottky diodes ZnO/ SiC changed with bias voltage and frequency. It is found that doping effect has lead to a 5 times higher peak for N type SiC than P type SiC, while a difference in polytypes has lead to a 2 times higher peak for 4HSiC than 6H SiC. These results reflect differences in interface states densities or traps densities between ZnO/n- 4H SiC, ZnO/p- 4H SiC and ZnO/n-6HSiC Schottky diodes.
One can see that conductance of Schottky diode ZnO/n-6HSiC, ZnO/n-4HSiC is very different from that of ZnO/p-4HSiC. As expected, conductance increases with increasing positive voltage for ZnO/n-type SiC and with increasing negative voltage for ZnO/p-type SiC. It decreases with increasing frequency in all cases due to increasing deactivation of interface states responsible for capture and emission of carriers.
Series resistance changes with frequency for ZnO/ 6HSiC, ZnO/ n-4HSiC and ZnO/p-4HSiC Schottky diodes. For N type devices, series resistance peak decreases with higher frequencies and slightly shifts with greater voltages. Opposite behavior is seen to happen for P type devices. Since series resistance is also related to charge behavior at interface, above changes suggest that interface states are behind such behavior with frequency. High value of series resistance at low frequencies is due to an excess capacitance. Decrease in peak intensity indicates interface states non response to alternating current. Above 800 kHz, peak disappears completely. Peak intensity may be taken as a measure of active interface states density and carriers mobility.

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Figure.1. Schematic diagram of Ni/Al/SiC/ZnO heterojunction.
Figure.2. Current-voltage characteristics of investigated SiC-ZnO Schottky diodes.**(a)** Effect of polytype structure. **(b)** Effect of doping nature.
Figure.3. Logarithmic plots of J-V characteristics of ZnO-SiC. **(a)** Effect of polytype structure. **(b)** Effect of doping nature.
Figure.4. dV/dln (J) vs.J and H (J) vs. J plots of ZnO-SiC. **(a)** Effect of polytype structure. **(b)** Effect of doping nature.
Figure.5. Typical ($1/C^2$–V) of ZnO-SiC. **(a)** Effect of polytype structure. **(b)** Effect of doping nature.
Figure.6. Forward capacitance–voltage-frequency characteristics for ZnO-SiC. **(a)** ZnO/n-6HSiC, **(b)** ZnO/n-4HSiC and **(c)** ZnO/p-4HSiC.
Figure.7. G/ω–V characteristics of ZnO-SiC.(a)ZnO/n-6HSiC, **(b)** ZnO/n-4HSiC and **(c)** ZnO/p-4HSiC
Figure.8. Interface states density versus frequency for ZnO-SiC Schottky diodes.**(a)** Effect of polytype structure. **(b)** Effect of doping nature.
Figure.9. Frequency behavior of Rs–V-f Schottky diodes**.(a)**ZnO/n-6HSiC, **(b)** ZnO/n-4HSiC and **(c)** ZnO/p-4HSiC

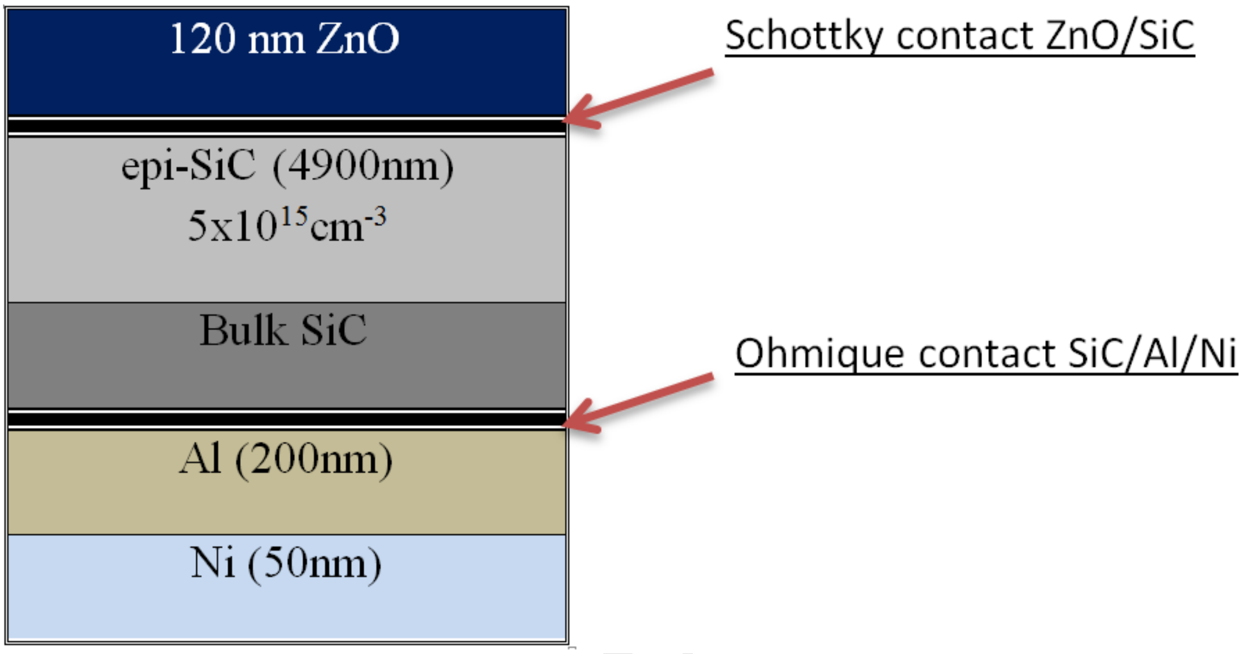

120 nm ZnO
epi-SiC (4900nm)
5x10^15cm^-3
Bulk SiC
Al (200nm)
Ni (50nm)
Schottky contact ZnO/SiC
Ohmique contact SiC/Al/Ni

Figure 1

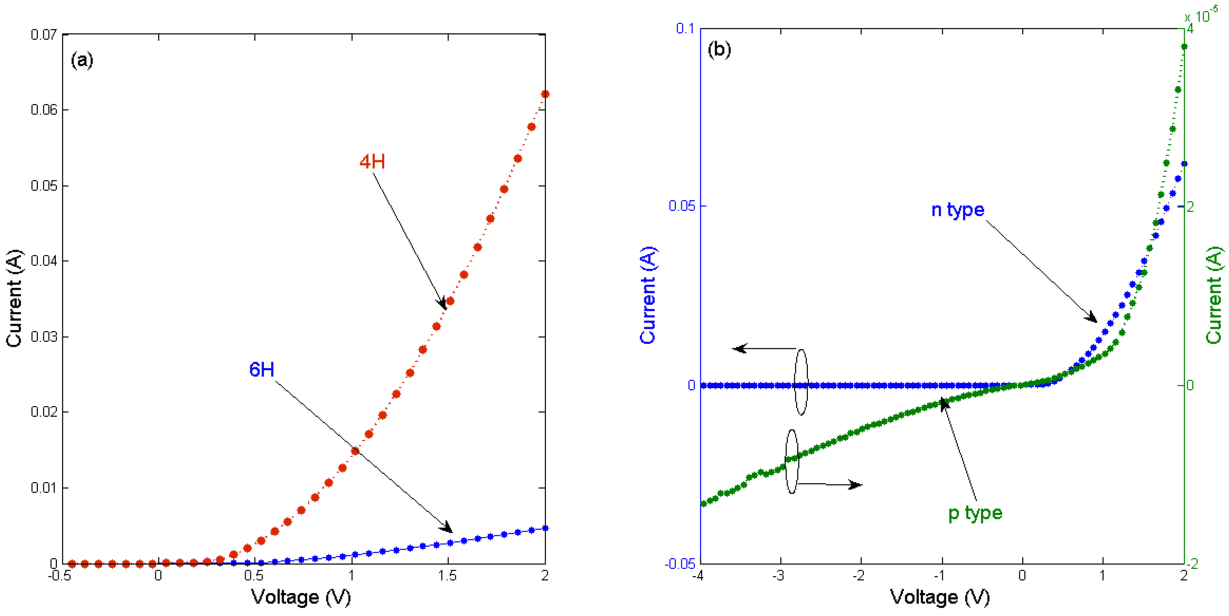
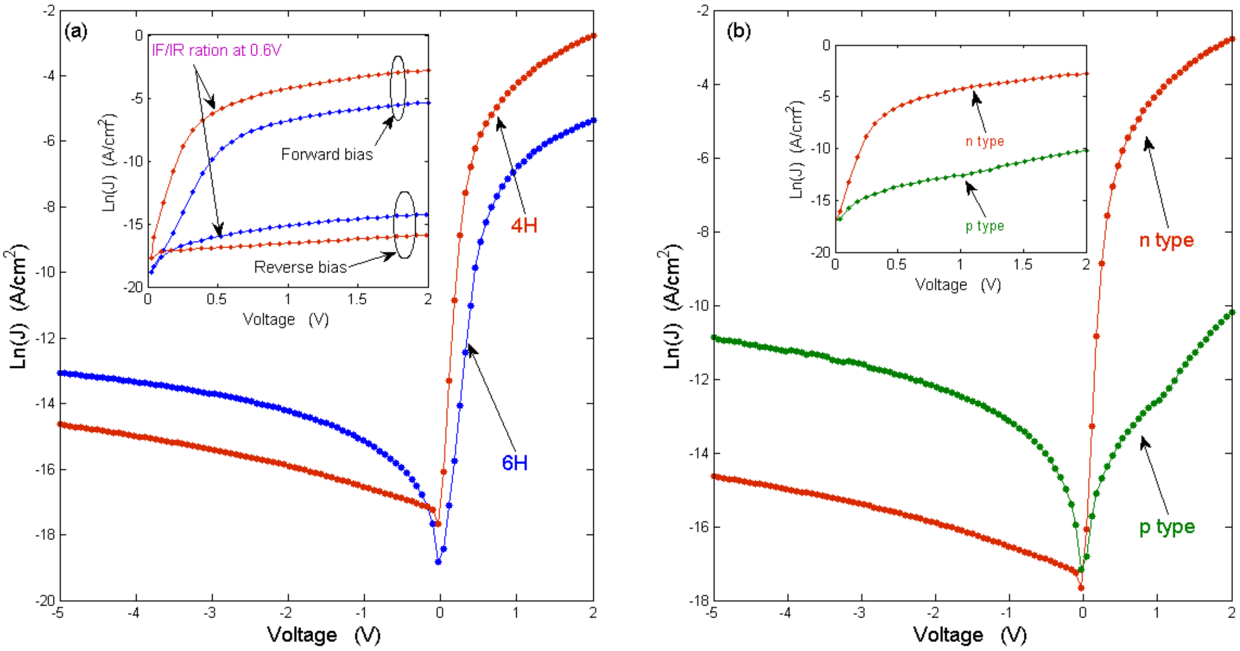

(a)
4H
6H
Current (A)
Voltage (V)
(b)
n type
p type
Current (A)
Current (A)
x 10^-5
Voltage (V)

Figure 2



(a)
IF/IR ration at 0.6V
Forward bias
Reverse bias
Ln(J) (A/cm^2)
Voltage (V)
4H
6H
(b)
n type
p type

Figure 3

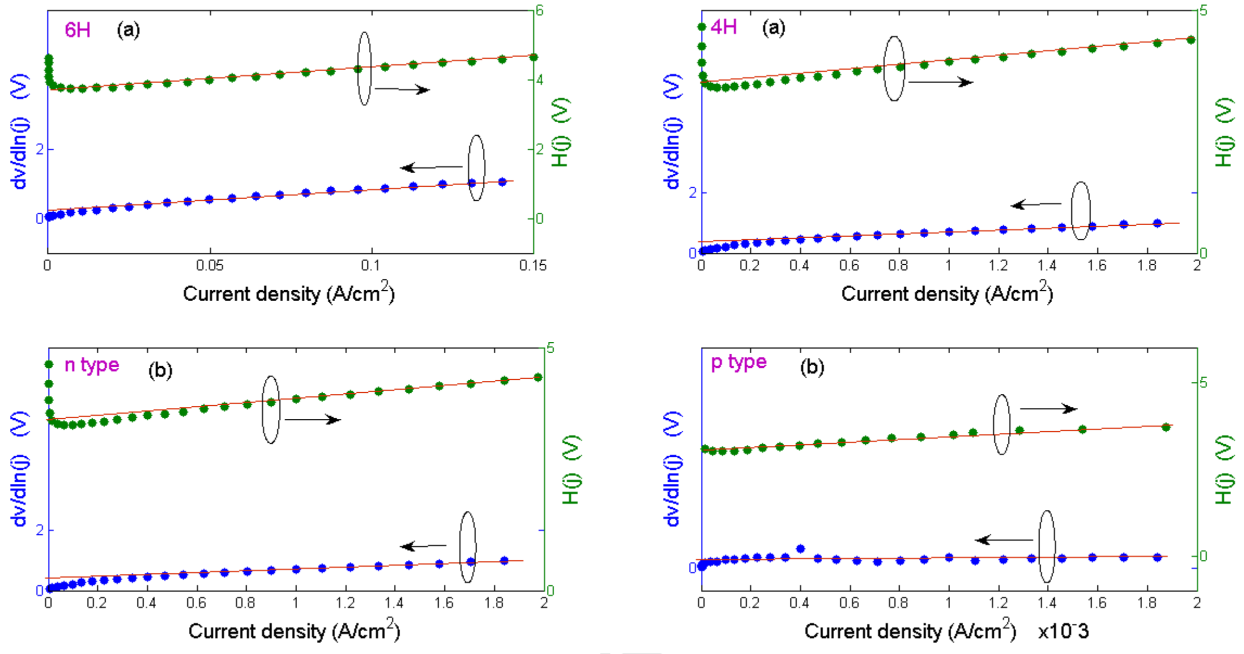

6H (a)
dv/dln(j) (V)
H(j) (V)
Current density (A/cm^2)
4H (a)
n type (b)
p type (b)
x10-3

Figure 4

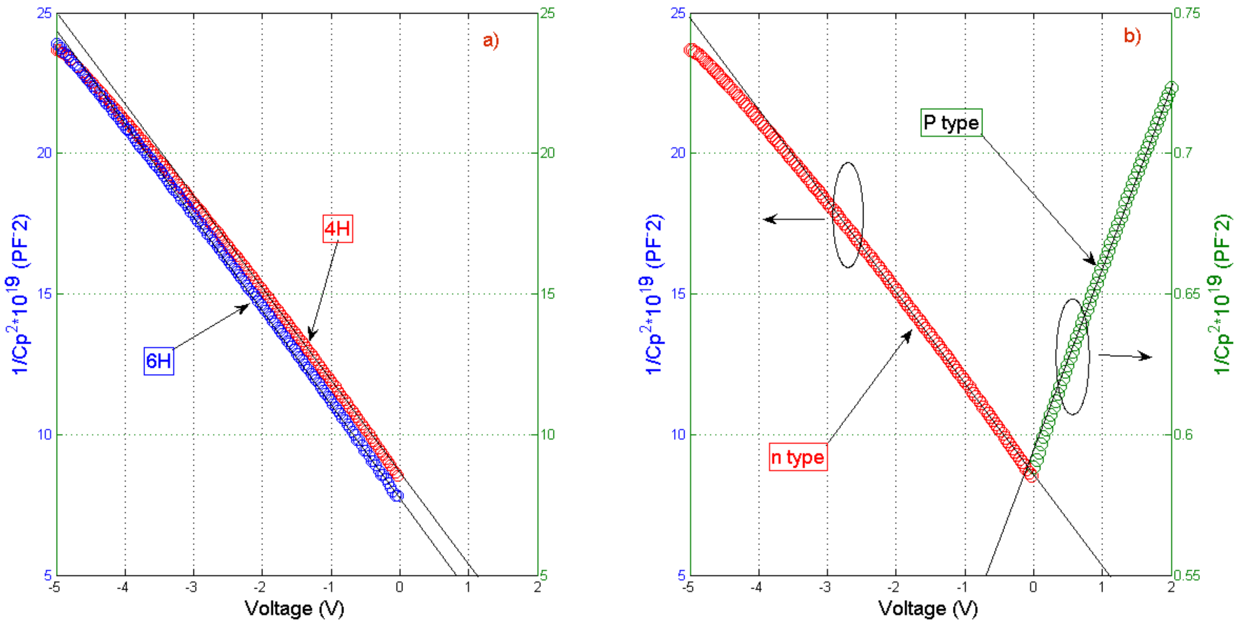
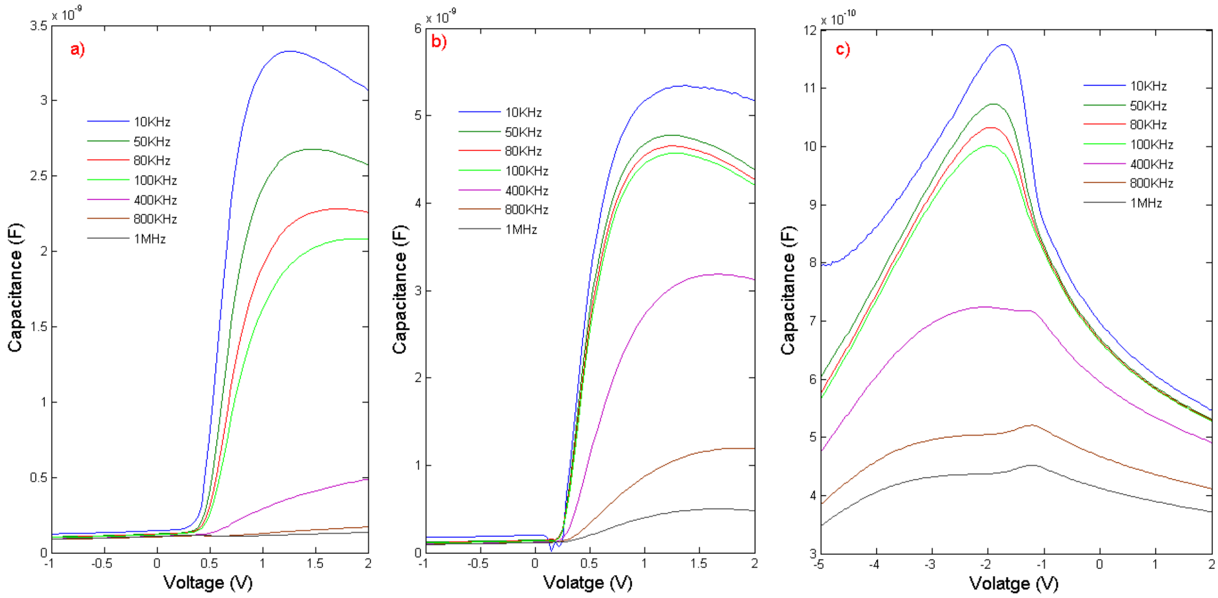
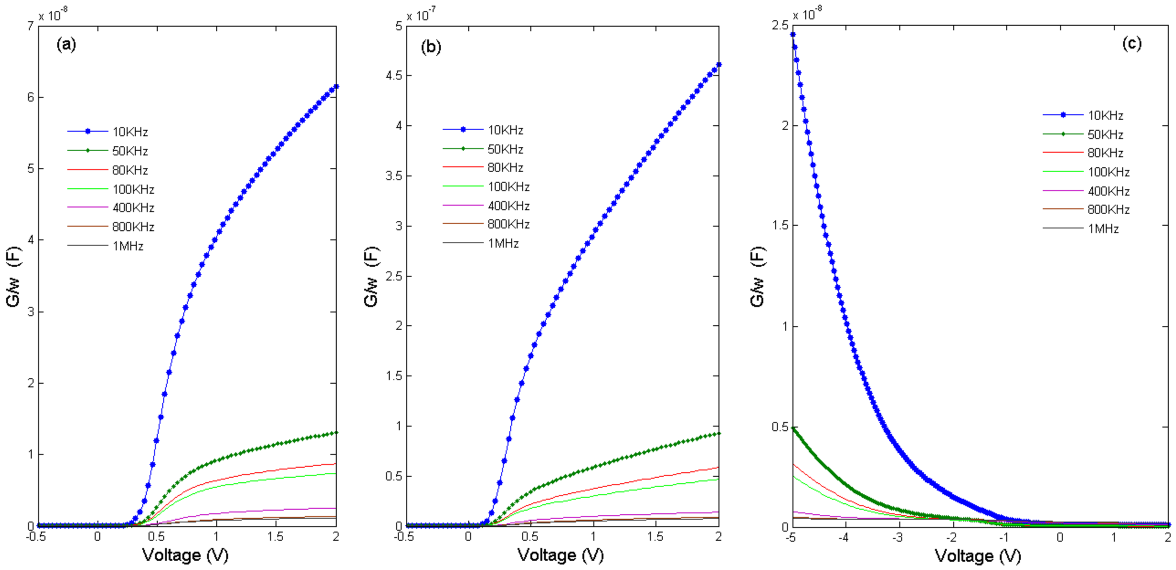

a)
4H
6H
1/Cp^2*10^19 (PF^-2)
Voltage (V)
b)
P type
n type
1/Cp^2*10^19 (PF^-2)
Voltage (V)

Figure 5



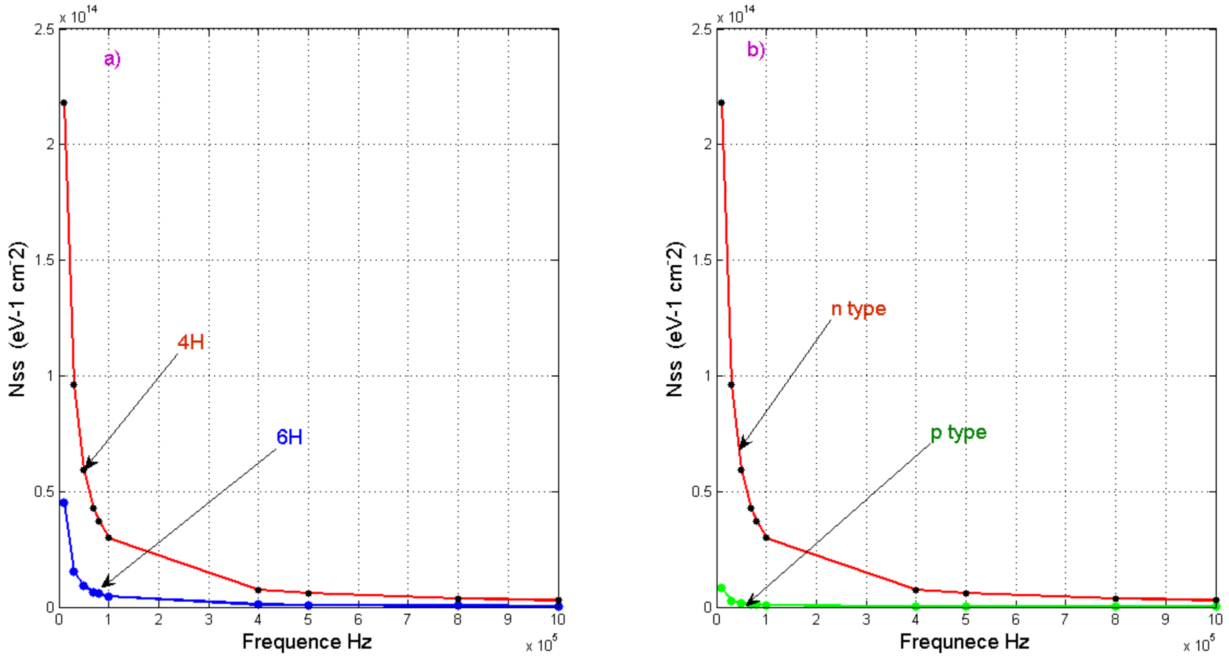
a)
b)
c)
Capacitance (F)
Voltage (V)
Volatge (V)
x 10^-9
x 10^-10
10KHz
50KHz
80KHz
100KHz
400KHz
800KHz
1MHz

Figure 6



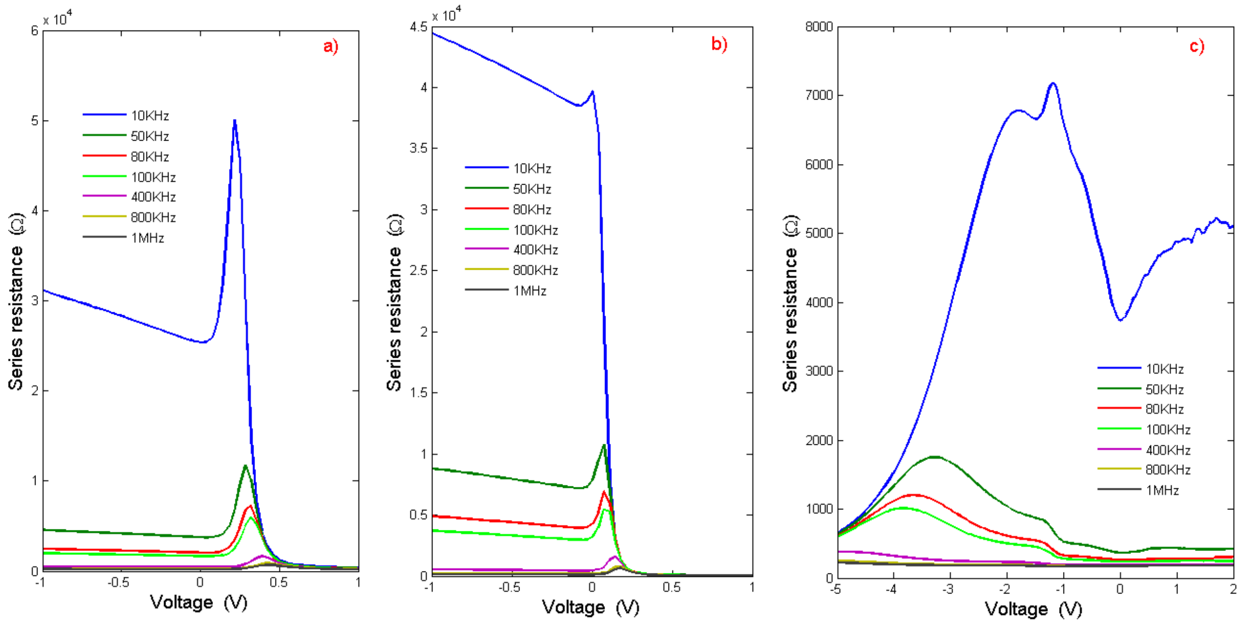
(a)
(b)
(c)
10KHz
50KHz
80KHz
100KHz
400KHz
800KHz
1MHz
G/w (F)
Voltage (V)

Figure 7



a)
b)
Nss (eV-1 cm-2)
x 10^14
4H
6H
n type
p type
Frequence Hz
Frequnece Hz
x 10^5

Figure 8



a)
x 10^4
Series resistance (Ω)
Voltage (V)
10KHz
50KHz
80KHz
100KHz
400KHz
800KHz
1MHz
b)
c)

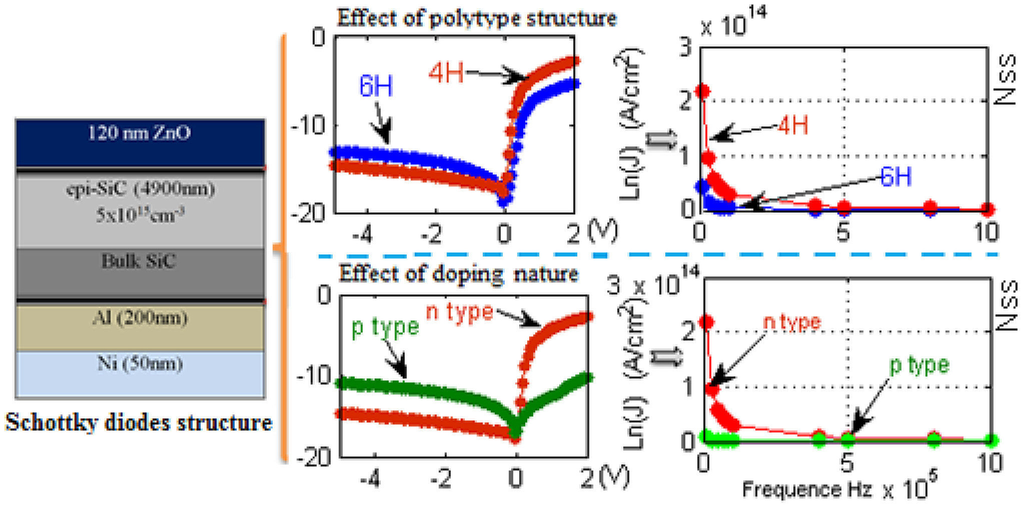
Figure 9

Table 1.Experimental barrier height (φ_b), current saturation (Js), series resistance (Rs) and ideality factor (n) determined from I-V characteristics

Table 2.Experimental barrier height (φ_{b0}) and carrier Concentration (N_D, N_A) determined from C-V characteristics.

Sample	ideality factor (n)	φ_b (eV) (J-V)	Rs dV/dLn(J)-J (Ω)	Rs H(J)-J (Ω)	Js(A/cm^2) Current saturation
ZnO/n-6HSiC	6.32	0.63	205.5	218.5	2.102x10^{-6}
ZnO/n-4HSiC	6.70	0.65	15.5	14.5	9.663x10^{-7}
ZnO/p-4HSiC	4.67	0.71	12800	14800	9.384x10^{-8}

Sample	Carrier concentration N_D-N_A (cm^{-3})	φ_{b0} (eV) C-V
ZnO/n-6HSiC	0.53956x10^{+15}	0.9372
ZnO/n-4HSiC	0.50692x10^{+15}	1.1638
ZnO/p-4HSiC	23.4 x10^{+15}	0.8230



Graphical abstract

Highlights

- ZnO/SiC diodes have mixed thermionic and defect states assisted current transport.
- C-V measurements indicate the importance of density of states.
- The Rectifying ratio from ZnO/n-4HSiC is found to be twice that of ZnO/n-6HSiC.
- C–V–f results confirm the presence of a native interfacial insulator.
- The effective Schottky barrier height was enhanced by the insulator layer.