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High Voltage GaN Schottky Rectifiers

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Abstract

Mesa and planar GaN Schottky diode rectifiers with reverse breakdown voltages (V_{RB}) up to 550V and >2000V, respectively, have been fabricated. The on-state resistance, R_{ON}, was $6m\Omega\cdot cm^2$ and $0.8\Omega cm^2$, respectively, producing figure-of-merit values for $(V_{RB})^2/R_{ON}$ in the range 5-48 $MW\cdot cm^{-2}$. At low biases the reverse leakage current was proportional to the size of the rectifying contact perimeter, while at high biases the current was proportional to the area of this contact. These results suggest that at low reverse biases, the leakage is dominated by the surface component, while at higher biases the bulk component dominates. On-state voltages were 3.5V for the 550V diodes and ≥15 for the 2kV diodes. Reverse recovery times were <0.2µsec for devices switched from a forward current density of ~$500A\cdot cm^{-2}$ to a reverse bias of 100V.

Introduction

Wide bandgap diode rectifiers are attractive devices for a range of high power, high temperature applications, including solid-state drives for heavy motors, pulsed power for electric vehicles or ships, drive trains for electric automobiles and utilities transmission and distribution.(1) To date, most effort has been focussed on SiC and a full range of power devices including thyristors, insulated gate bipolar transistors, metal oxide semiconductor field effect transistors and pin and Schottky rectifiers, has been reported.(2-13) The GaN materials systems is also attractive for ultra high power electronic devices because of its wide bandgap and excellent transport properties.(13,14) A potential disadvantage for thick, carrier-modulated devices is the low minority carrier lifetime, but for unipolar devices GaN has the potential for higher switching speed and larger standoff voltage than SiC. Efforts to fabricate high power GaN devices are in their infancy and there have been reports of simple Schottky rectifiers with reverse breakdown voltage (V_{RB}) in the range 350-450V.(15,16) While pin rectifiers would be expected to have larger blocking voltages, the Schottky rectifiers are attractive for their faster switching speed and lower forward voltage drop.

In this paper we report on the fabrication of mesa and planar GaN Schottky diode rectifiers. We have found that mesa structures formed by dry etching can have similar V_{RB} values to planar diodes provided the dry etch damage is removed by annealing or wet etch clean-up. The mesa diodes have lower specific on-resistances because ohmic contacts can be formed on a heavily doped GaN layer below the undoped standoff layer.

Experimental

Two different types of GaN were grown on c-plane sapphire substrates by Metal Organic Chemical Vapor Deposition using trimethylgallium and ammonia as the precursors. For structures intended for vertical depletion, a 1μm thick n^+ ($3x10^{18}$ cm^{-3}, Si doped) contact layer was grown in a low temperature GaN buffer and then followed with either 4 or 11μm of undoped ($n \sim 2x10^{16}$ cm^{-3}) GaN. For structures intended for lateral depletion, a 3μm thick resistive ($n<10^{15}$ cm^{-3}) active region was grown on a low temperature buffer.

The mesas were formed by Cl_2/Ar Inductively Coupled Plasma etching (300W source power, 40W rf chuck power, corresponding to a dc self-bias of –85V) at a rate of 1100Å·min^{-1}, using a photoresist mask. The samples were annealed at ~800°C to remove dry etch damage.(17) Ohmic contacts were formed by lift-off of e-beam evaporated Ti/Al, subsequently annealed at 750°C for 20 secs under N_2. The rectifying contacts with diameter 60-1100μm were formed by lift-off of e-beam evaporated Pt/Au.

On the lateral diodes, n^+ contact regions were formed by implantation of Si^+ followed by annealing at 1150°C for 10 secs under N_2. The GaN was protected by a dielectric encapsulant during the annealing step. The ohmic and rectifying contacts were formed as described above. Schematics of the two different structures are shown in Figure 1. The current-voltage (I-V) characteristics were recorded on a HP 4145A parameter analyzer.

Results and Discussion

(a) Mesa Diodes

A typical I-V characteristic for the 11μm undoped depletion layer diodes is shown in

Figure 2. The V_{RB} for these devices was 550V at 25°C, with typical V_F's of 3-5V (100Å·cm^{-2}). The specific on-resistance was in the range 6-10 mΩ·cm^2, leading to a figure-of-merit $(V_{RB})^2/R_{ON}$ of 48 MW·cm^{-2}. The breakdown voltage is approximately a factor of 3 lower than the theoretical maximum value for this doping and thickness. Secondary Ion Mass Spectrometry showed that the main background impurities present were O (~9x10^{17} cm^{-3}), C (~10^{17} cm^{-3}), Si (4x10^{17} cm^{-3}) and H (3x10^{18} cm^{-3}). While O and Si can produce shallow donor states, it is clear that these impurities have only fractional electrical activation. The surfaces of the material were relatively smooth with root-mean-square roughness of ~0.2nm (1x1μm^2) and 1.5nm (10x10m^2). Cross-sectional transmission electron microscopy (TEM) views of the structure are shown in Figure 3. The threading dislocation density at the top surface was ~10^8- cm^{-2}, typical of high quality, heteroepitaxial GaN.

For the 4μm thick active region structure, the room temperature V_{RB} was 356V, with typical V_F's of 3-5V (100Å·cm^{-2}). The specific on-resistance of these devices was 28 mΩ·cm^2, leading to a value of $(V_{RB})^2/R_{ON}$ of 42 MW·cm^{-2}. Once again the breakdown voltage was approximately a factor of 3 lower than the theoretical maximum value. In these diodes we observed a negative temperature coefficient for V_{RB}, with a value of –0.92 V·K^{-1} in the range 25-50°C and 0.17 VK^{-1} in the range 50-150°C. If impact ionization were the cause of breakdown, one would expect to observe a positive temperature coefficient for V_{RB}, as has been reported for GaN heterostructure field effect transistors and p^+pn^+ diodes.(18,20) In analogy with some reports from some SiC Schottky diodes with negative V_{RB} temperature coefficients, we believe the breakdown mechanism in our diodes is defect-assisted tunnelling through surface or bulk states.(10)

Figure 4 shows the reverse current density in the 4μm active layer diodes at a low bias (15V) and a bias approximately half of V_{RB} (i.e. 150V). For the low bias condition the current density scales as the perimeter/area ratio, while at the high bias condition the current density is constant with this ratio. This data indicates that at low biases the surface perimeter currents are the dominant contribution, while at higher biases the current is proportional to contact area indicating that bulk leakage is dominant. In SiC devices it has been reported that increases in leakage current in the voltage range approximately half the V_{RB} of the diodes are due to the presence of this interfacial layer (typically as oxide) between the rectifying contact and the semiconductor. This oxide can sustain a voltage drop, but is thin enough for carrier tunnelling.(6) Figure 5 shows reverse recovery current transient waveforms from a diode switched from a forward current density of $500\text{A}\cdot\text{cm}^{-2}$ to a reverse voltage of 100V. The recovery time is <0.2μsec, similar to values reported for SiC rectifiers.(6)

In all wide bandgap diode rectifiers (both SiC and the GaN reported here), the magnitude of the reverse leakage currents are generally 1-2 orders higher than the theoretical values based on image-force lowering of the Schottky barrier.(6) Our GaN diodes have slightly higher reverse leakage relative to SiC devices at the same biases, which probably reflects the earlier stage of maturity of the former.

(b) Lateral, Planar Diodes

Figure 6 shows a room temperature I-V characteristic from the 3μm thick structure. The V_{RB} was >2000V (the limit of our test setup), with a best V_F of 15V (more typically 50-60V). The specific on-resistance was $0.8\Omega\text{cm}^2$ producing a $(V_{RB})^2/R_{ON}$ value of $>15\ \text{MW}\cdot\text{cm}^{-2}$. For this structure we believe the depletion is lateral, because for the larger thickness and doping a vertical device would breakdown at ~1000V. TEM cross-sections of the structure showed a threading dislocation density of ~3×10^8 cm^{-2}, typical of high quality GaN of this thickness.

To place the results in context, Figure 7 shows a plot of specific on-resistance for Schottky diode rectifiers as a function of breakdown voltage. The lines are theoretical values for Si, 4H-SiC, 6H-SiC and GaN and the points are experimental values for SiC and GaN devices.(2-6,10,13,15,16) Note that the 356V and 2kV diodes reported here essentially fit on the line expected for perfect Si devices, but the 550V diode has clearly superior performance to Si. However there is still significant improvement required before GaN matches the reported performance of SiC Schottky rectifiers.

Summary and Conclusions

The main conclusions of our study can be summarized as follows:

(i) Mesa diodes with V_{RB} equal to planar diodes, but with improved R_{ON} values, have been fabricated in GaN using Cl_2/Ar dry etching, followed by annealing to remove the plasma damage.

(ii) V_{RB} values up to 550V with figure-of-merit 48 MW·cm^{-2} have been achieved on mesa diodes fabricated on thick (12μm total) MOCVD GaN.

(iii) V_{RB} values >2 kV have been achieved in lateral diodes fabricated on resistive GaN grown by MOVCD.

(iv) For the mesa diodes, the V_{RB} values are approximately a factor of three lower than the theoretical maximum for GaN based on avalanche breakdown. Similarly, the reverse leakage currents are several orders of magnitude higher than the theoretical values.

(v) At low reverse biases, the leakage current is dominated by contributions from the surface, while at higher biases bulk leakage dominates.

Acknowledgments

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Figure Captions

Figure 1. Schematic of mesa and planar GaN diodes.

Figure 2. I-V characteristic at 25°C from mesa diode with 11μm thick blocking layer.

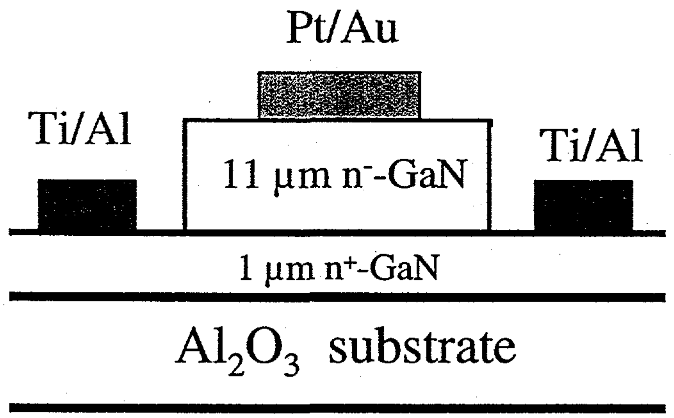
Figure 3. TEM cross-sections of the MOCVD-grown structure with 11μm thick blocking layer.

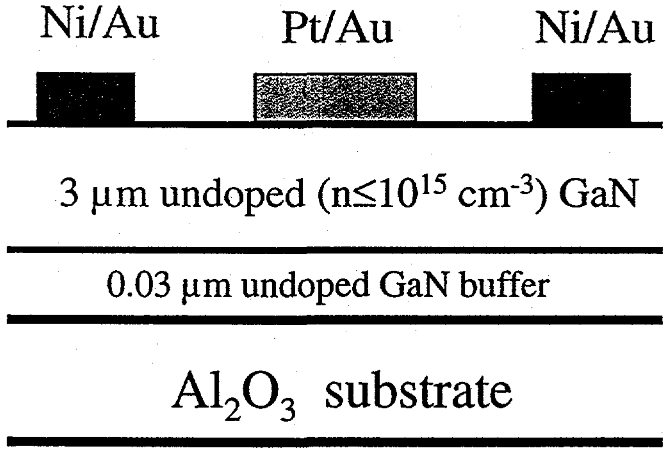
Figure 4. Reverse current density in GaN mesa diodes (4μm thick blocking layer) as a function of perimeter-to-area ratio, at two different reverse biases.

Figure 5. Reverse recovery current transient waveform measured for GaN rectifier (550μm diameter) at 25°C. The device was switched from a forward current density of $500\text{A}\cdot\text{cm}^{-2}$ to a reverse voltage of 100V.

Figure 6. I-V characteristic at 25°C from planar diode with 3μm thick blocking layer.

Figure 7. Specific on-resistance versus blocking voltage for SiC and GaN Schottky diode rectifiers. The performance limits of Si, SiC and GaN devices are shown by the solid lines.


Pt/Au
Ti/Al
11 μm n⁻-GaN
Ti/Al
1 μm n⁺-GaN
Al₂O₃ substrate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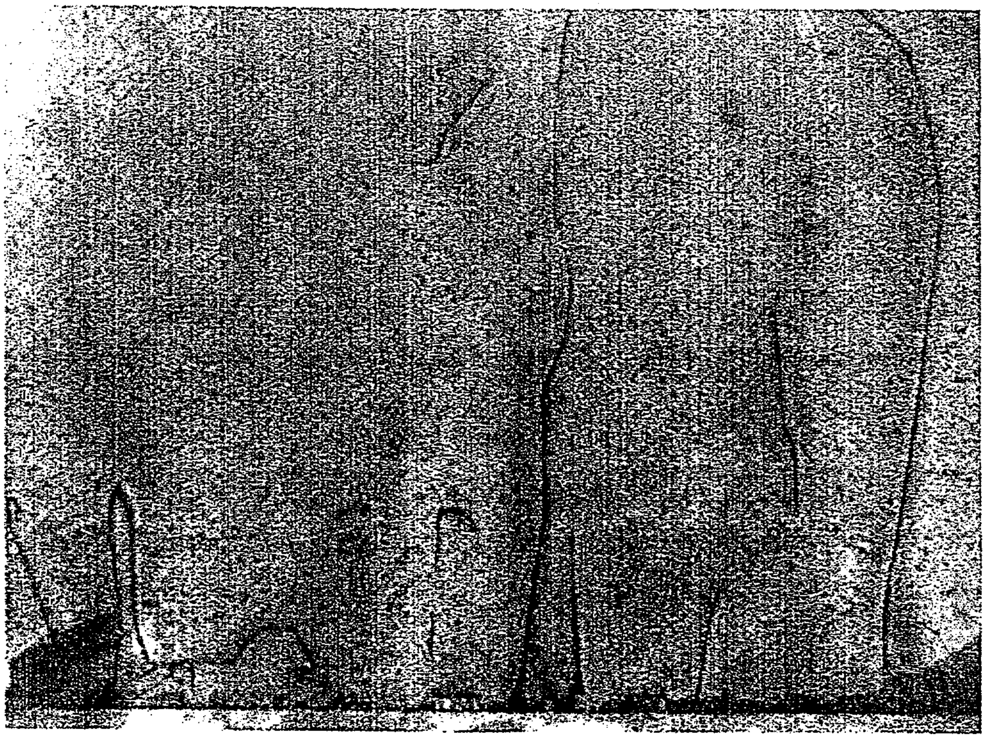

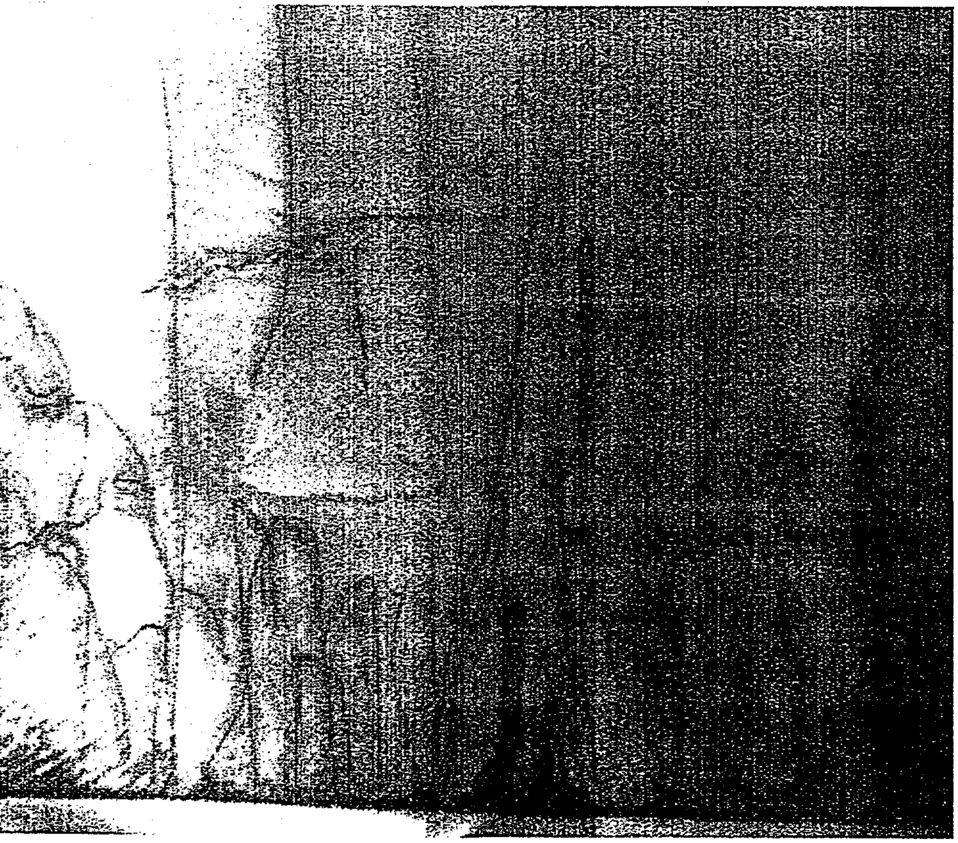

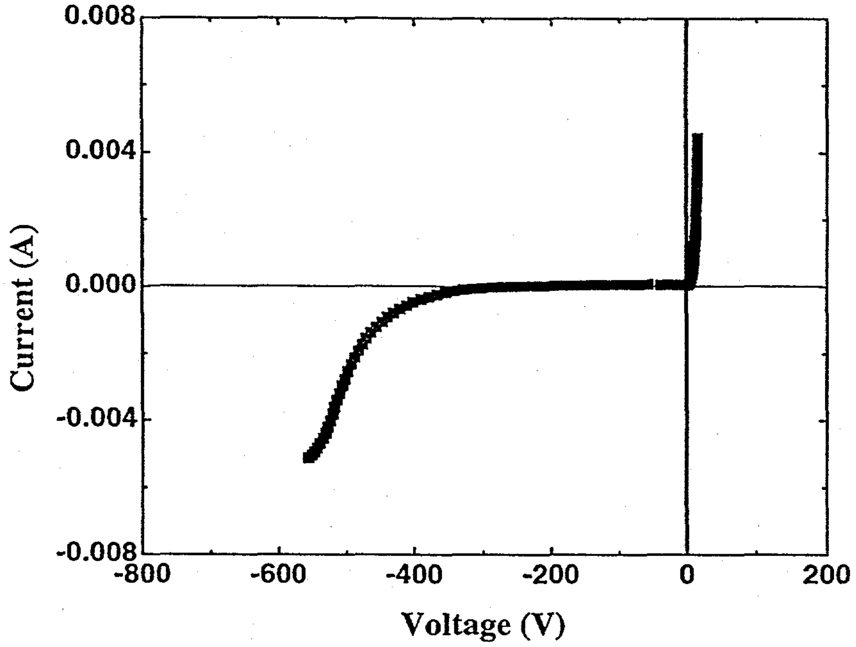
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0.004
0.000
-0.004
-0.008
Current (A)
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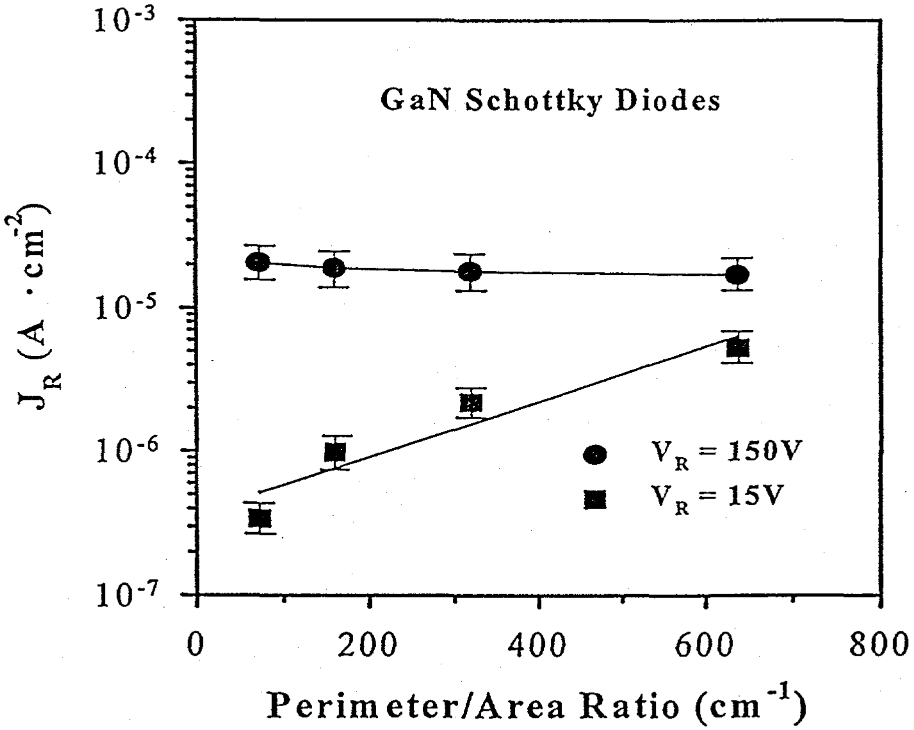
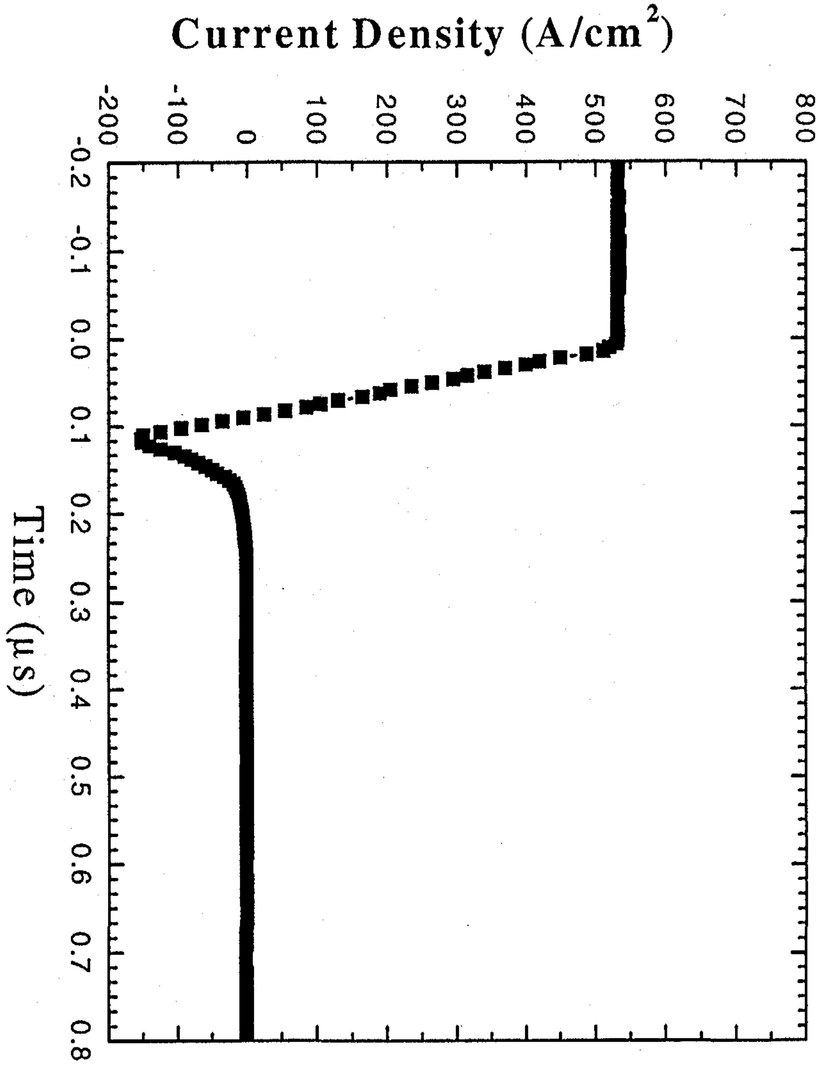
-600
-400
-200
0
200
Voltage (V)


GaN Schottky Diodes
J_R (A · cm^{-2})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
200
400
600
800
Perimeter/Area Ratio (cm^{-1})
● V_R = 150V
■ V_R = 15V


Current Density (A/cm^2)
-200
-100
0
100
200
300
400
500
600
700
800
Time (µs)
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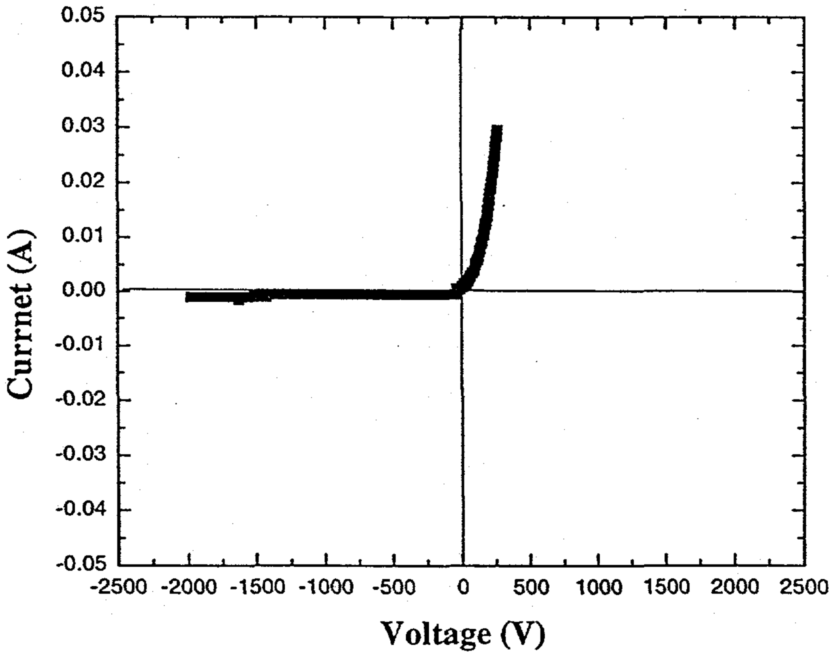
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8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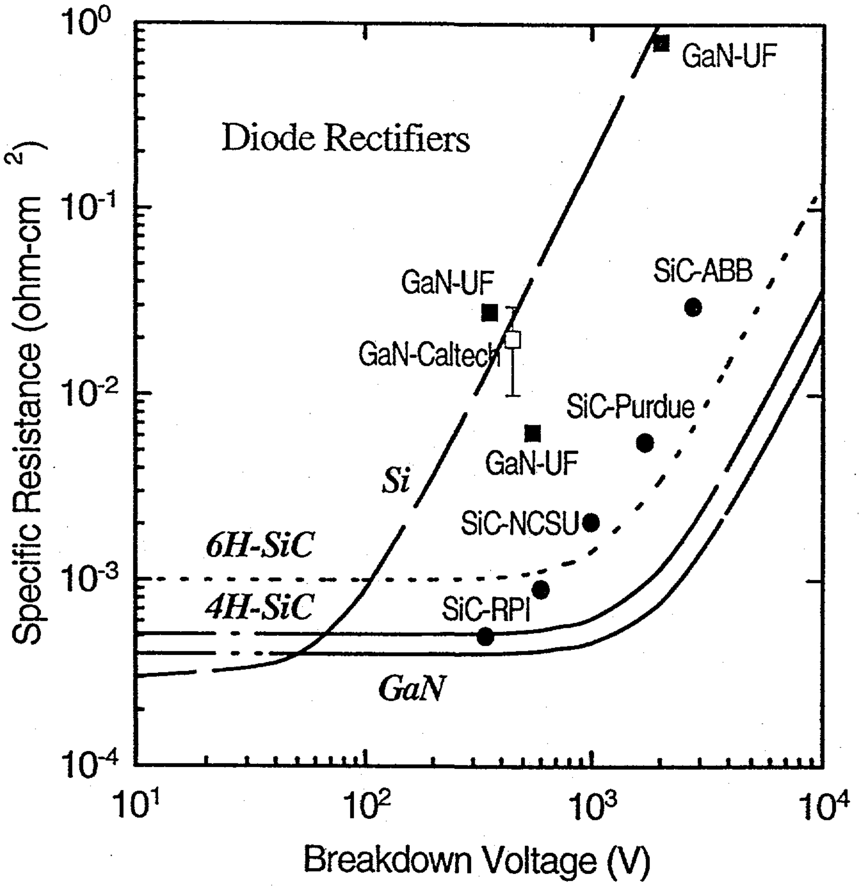
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
Currnet (A)
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500
Voltage (V)


Diode Rectifiers
Specific Resistance (ohm-cm 2)
Breakdown Voltage (V)
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10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
10^4
GaN-UF
GaN-UF
GaN-Caltech
GaN-UF
SiC-ABB
SiC-Purdue
SiC-NCSU
SiC-RPI
Si
6H-SiC
4H-SiC
GaN