4H-SiC Power Bipolar Junction Transistor with a Very Low Specific On-resistance of 2.9 mΩ.cm^2

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Abstract— This paper reports a newly achieved best result on the specific on-resistance (Rsp,on) of power 4H-SiC bipolar junction transistors (BJT). A 4H-SiC BJT based on a 12 um drift-layer shows a record low specific-on resistance of only 2.9 mΩ.cm^2, with an open base collector-to-emitter blocking voltage (Vceo) of 757 V, and a current gain of 18.8. The active area of this 4H-SiC BJT is 0.61 mm^2, and it has a fully inter-digitated design. This high performance 4H-SiC BJT conducts up to 5.24 A at a forward voltage drop of V_{CE} = 2.5 V, corresponding to a low Rsp_on of 2.9 mΩ.cm^2 up to Jc=859 A/cm^2. This is the lowest specific on-resistance ever reported for high power 4H-SiC BJTs.

Index Terms—Silicon carbide, bipolar junction transistors (BJTs), power transistors

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I. INTRODUCTION

Silicon Carbide electronic devices have got more and more attentions recently due to its wide band-gap material properties and fast-maturing technologies. 4H-SiC (Eg=3.26 eV) bipolar junction transistor (BJT) is an important switching device for high power and high temperature applications, which is an intrinsically normally-off device, does not have the gate oxide problems and conducts higher current with low forward voltage drop. For a power 4H-SiC BJT device, high blocking voltage [1], low on-state resistance and high current gain [2,3] are desirable for better efficiency. The most recently reported high power 4H-SiC BJTs with a low specific on-resistance (Rsp,on) include (i) a Vceo = 1400 V, 17 A BJT showing a current gain of 14 and an R_{SP_ON} of 5.3 $m\Omega \cdot cm^2$ [4]; (ii) a Vceo = 1450 V BJT with a current gain of 14 and an R_{SP_ON} of 5.4 $m\Omega \cdot cm^2$ [5]; (iii) a 1000 V BJT with a current gain of 40 and an R_{SP_ON} of 6.0 $m\Omega \cdot cm^2$ [6]; (iv) a 1677 V, 5.7 $m\Omega \cdot cm^2$ 4H-SiC BJT with a current gain of 7.1 [7]; (v) a 1600 V-20 A 4H-SiC BJT with Rsp,on=4.5 $m\Omega \cdot cm^2$ and a current gain of 40 [8]; (vi) a 3200 V, 10 A 4H-SiC BJT with a current gain of 44 and a specific on-resistance of 8.1 $m\Omega \cdot cm^2$ [9]; (vii) a 1836V, 4.7 $m\Omega \cdot cm^2$ 4H-SiC BJT with a current gain of 8.8 [10]. This paper reports a newly developed 4H-SiC BJT with a record low specific on-resistance (R_{SP_ON}) of only 2.9 $m\Omega \cdot cm^2$ up to Jc = 859 A/cm^2 , a high blocking voltage V_B (Vceo) of 757 V and a good DC current gain(Ic/Ib) of 18.8.

II. DEVICE DESIGN AND FABRICATION

Fig.1 shows a simplified cross-sectional view of the 4H-SiC BJT structure. The 4H-SiC wafer was purchased from Cree Inc. Three epi-layers are grown on the 8^o off-axis n-type

4H-SiC substrate. The top n^+ epi-layer of 0.8 μm is heavily doped to about 2×10^{19} cm^{-3} to serve as the emitter. The base p-type epi-layer is 1.0 μm thick and is doped to 4.1×10^{17} cm^{-3}. The collector drift layer of 12 μm is lightly-doped to 8.5×10^{15} cm^{-3}. The fabrication process starts from the dry-etching of the emitter fingers by inductively coupled plasma (ICP) etching in a gas mixture of freon and oxygen at an etching rate of 70-80 nm/min. The emitter finger width is 10 um and the etching depth is 1.0 μm. The p-type epi-layer was exposed in the base trench and the JTE region. To achieve better base ohmic contact, a 3 um-wide region in the center of the 13 um-wide base trench was implanted at room temperature with carbon and aluminum co-implantation [11], which consists of C ions of $4x10^{14}$ cm^{-2} at 28keV, $5.2x10^{14}$ cm^{-2} at 60 keV, and $1.1x10^{14}$ cm^{-2} at 75 keV plus Al ions of $3.6x10^{14}$ cm^{-2} at 50 keV and $7.5x10^{14}$ cm^{-2} at 100 keV. The spacing between the implanted base region and the emitter mesa edge (BE-spacing) is 5 μm. The ion-implantation activation annealing was done at 1550^oC for 30 min in Ar ambient. Device edge termination applied a single step JTE of 150 μm-wide based on an ion-implanted p-layer and the base epi-layer. The isolation between each device is served by a mesa etching of ~1.5 μm into the drift layer. Surface passivation was first done by a regular wet thermal oxidation for 2 hours at 1100^oC followed by a one-hour Ar annealing at 1100^oC, then the sample was re-annealed in wet-oxygen for 3 hours at 950^oC. After the thermal oxidation, 500 nm SiO_2 and 250 nm Si_3N_4 were deposited by PECVD to seal the thermal passivation layer. Device contact windows were opened by ICP etching and wet-etching, Ni/AlTi/Ni was sputtered on the base contact region, Ni was sputtered on the emitter contact region and the collector. The Ohmic contact annealing was carried out at 1000^oC for 5 minutes in Argon forming gas (5% H_2 in Ar) by using a rapid thermal

processing (RTP) system. After Ohmic contact formation, about 3 um Al/AlTi was sputtered and wet-etched to form a thick overlay metal on the base and emitter fingers to improve the voltage and current distribution. Then, 1.4 μm multi-layer of SiO_2 and Si_3N_4 were deposited by PECVD to cover all the sample surface. The contact windows for the base bonding pad, the emitter bonding pad and the emitter fingers were opened by ICP, and over 0.5 um Ti / Au were deposited. Fig.2 shows a photo of the fabricated 4H-SiC BJT device. The 4H-SiC BJT device has a footprint of 1.2 mm × 1.4 mm including the bonding pads and the JTE region. This BJT device contains 37 emitter fingers and 38 base fingers in a fully inter-digitated geometry. The finger length is 728 μm, and the width of the emitter mesa and base trench are 10 μm and 13 μm, respectively. Excluding the bonding pads and the edge termination region, the device active area is 0.61 mm^2.

III. Experimental Results and Discussions

Measured from the on-chip TLM (transmission line model) structure, the emitter n-type specific contact resistance and n^+ emitter layer sheet resistance are 1.1×10^{-5} $\Omega\cdot cm^2$ and 147 Ω, respectively, while the p-type specific contact resistance and p-base sheet resistance are 2.6×10^{-2} $\Omega\cdot cm^2$ and 33 kΩ, respectively.

The device DC I-V characteristics were measured mainly by Tektronix 371A curve tracer. Fig. 3 shows the I-V characteristics of a single 4H-SiC BJT cell at room temperature. This BJT device conducts 5.24 A collector current (Jc = 859 A/cm^2) at a forward voltage drop of 2.5 V, corresponding to a specific on- resistance of only 2.9 $m\Omega\cdot cm^2$. This is so far the lowest specific on-resistance ever reported for 4H-SiC bipolar

transistors. The maximum collector current was measured up to 8.2 A (Jc = 1344 A/cm^2) and is actually limited by the capability of Tektronix 371A curve tracer. The DC current gain is 18.8 at Ic=3.75 A (Jc=615 A/cm2) and Vce=4.6 V. The open base blocking voltage (Vceo) was measured up to 757 V with 231 μA leakage current in Fluorinert.

The key to achieving this record low specific on-resistance is biasing the base-emitter junction uniformly so that each part of the active area works homogeneously. Therefore, the base overlay metal plays a critical role, which carries the base current from the bonding pad to the end of each base fingers. We reported two similar 4H-SiC BJTs before [7,10] with nearly same active area. The 5.7 mΩ·cm^2 BJT device [7] has 0.4 um Ti/Au as the base overlay metal, and its base contact region is as wide as 11 um. We pointed out in that paper that the BE junction needs to be more uniformly biased. Therefore, in the following batch of our 4H-SiC BJT study, we put down about 2.1 um AlTi/Mo as the base overlay metal, and reduced the pitch from 33 um to 22 um. That BJT device shows an absolute specific on-resistance of 4.7 mΩ·cm^2 and a differential specific on-resistance of only 3.9 mΩ·cm^2 [10]. But the current gain of the both previous BJTs is only about 7.1 and 8.8, which requires large base current to be distributed across the whole device active area, thus even thicker base metal might be needed. In the 4H-SiC BJT reported in this paper, we successfully got the current gain (Ic/Ib) as high as 18.8, which significantly reduces the required base driving current, and we still put down 3.0 um Al/AlTi as the base overlay metal. Hence we have successfully achieved this record low specific on-resistance of only 2.9 mΩ·cm^2. Fig.4 shows the forward I-V characteristics of the base-emitter (BE) junctions of this 2.9 mΩ·cm^2 BJT device and the earlier 4.7 mΩ·cm^2 BJT device. Clearly, we could see a big improvement on the BE

junction forward I-V characteristics, and we believe it leads to a more uniformly-biased BE junctions across the whole device area.

It has been proved that the current gain of 4H-SiC BJTs is more determined by the epi-layer growth process rather than the device fabrication process [3,6,7,8,9,12]. On a similar 4H-SiC BJT wafer we fabricated before, the current gain was about 24.8 [12]. The blocking performance (Vceo=757V) on this 4H-SiC BJT only reaches about half of its theoretical value, which is due to the excessive SiC consumption in the JTE region during the thermal oxidation process.

IV. SUMMARY

A 4H-SiC power BJT with a record low specific on-resistance of 2.9 $m\Omega \cdot cm^2$ has been demonstrated based on a drift layer of 12 μm doped to 8.5×10^{15} cm^{-3}. The blocking voltage V_B (Vceo) is 757 V, and the current gain is 18.8. The uniform biasing of base-emitter junction across the whole device active area is the key to achieving this best result on the specific on-resistance.

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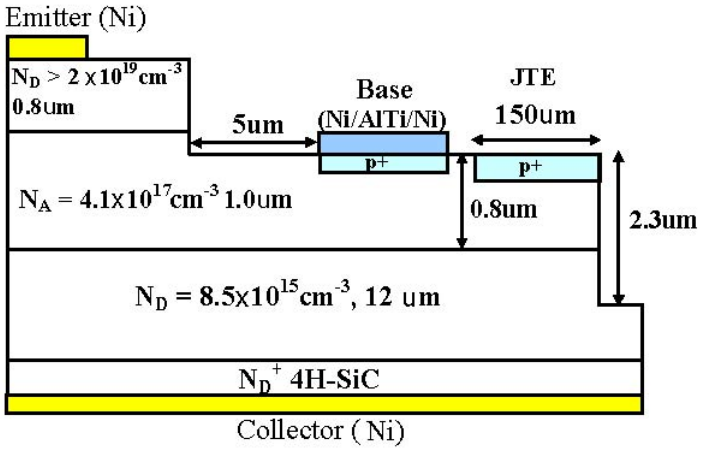
Emitter (Ni)
$N_D > 2 \times 10^{19} cm^{-3}$
0.8um
5um
Base
(Ni/AlTi/Ni)
JTE
150um
p+
p+
$N_A = 4.1 \times 10^{17} cm^{-3}$ 1.0um
0.8um
2.3um
$N_D = 8.5 \times 10^{15} cm^{-3}$, 12 um
N_D^+ 4H-SiC
Collector (Ni)

Fig.1

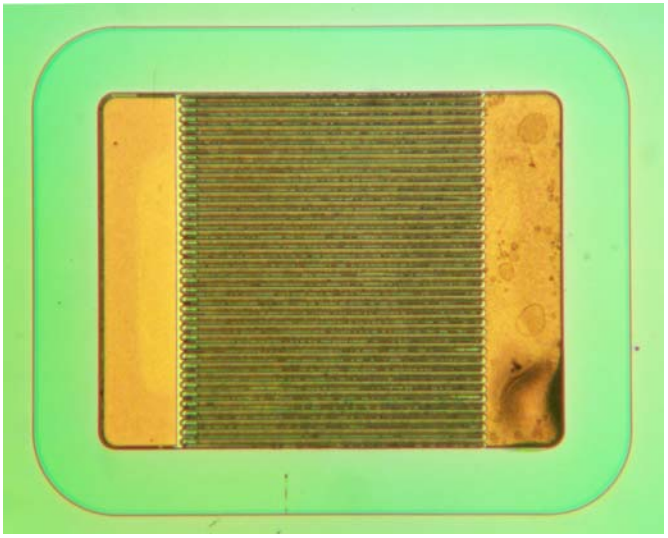

Fig.2

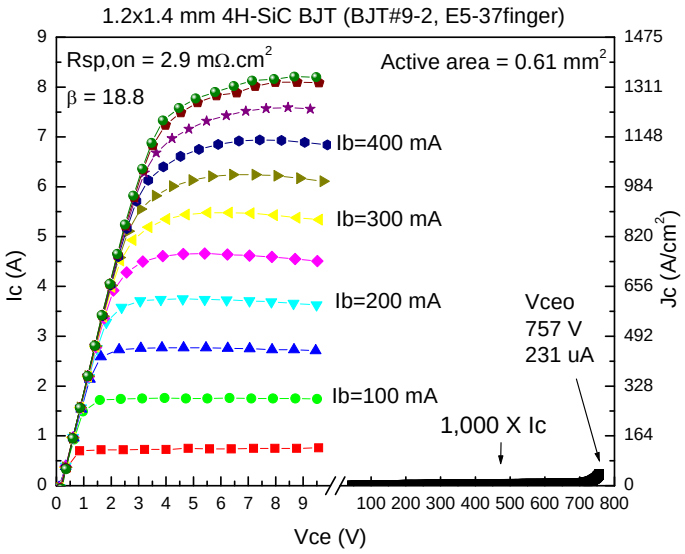
1.2x1.4 mm 4H-SiC BJT (BJT#9-2, E5-37finger)
Rsp,on = 2.9 mΩ.cm2
Active area = 0.61 mm2
β = 18.8
Ib=400 mA
Ib=300 mA
Ib=200 mA
Ib=100 mA
Vceo
757 V
231 uA
1,000 X Ic
Ic (A)
Jc (A/cm2)
Vce (V)
0 1 2 3 4 5 6 7 8 9
100 200 300 400 500 600 700 800
0 164 328 492 656 820 984 1148 1311 1475

Fig.3

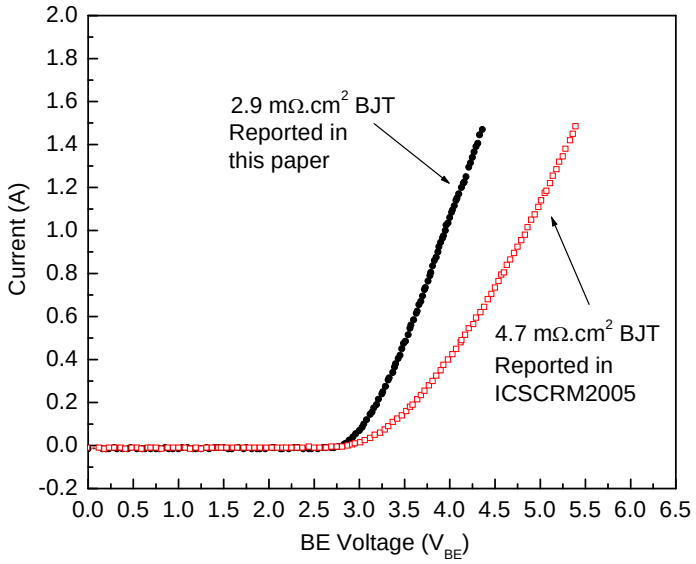
2.9 mΩ.cm2 BJT
Reported in
this paper
4.7 mΩ.cm2 BJT
Reported in
ICSCRM2005
Current (A)
BE Voltage (VBE)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5

Fig.4

FIGURE CAPTIONS

Fig. 1. Cross sectional view of the 4H-SiC BJT device

Fig. 2. Photo of a fabricated 4H-SiC BJT.

Fig. 3. I-V characteristics of the 4H-SiC BJT.

Fig. 4. Forward I-V characteristics of the base-emitter junction.

References:

[1] J. Zhang, J. H. Zhao, P. Alexandrov and T. Burke, “Demonstration of first 9.2 KV 4H-SiC bipolar junction transistor”, in IEE Electronics Letters, Vol.40, pp1381-1382, 2004.

[2] C.-F. Huang and J. A. Cooper, Jr., “High current gain 4H-SiC NPN Bipolar Junction Transistors,” IEEE Electron Device Lett., vol.24, pp.396-398, Jun. 2003.

[3] J. Zhang**,** P. Alexandrov, and J. H. Zhao, “High Power(500 V-70 A) and High Gain(44-47) 4H-SiC Bipolar Junction Transistors”, in *Materials Science Forum*, Vol. 457-460, pp1149-1152, 2004.

[4] A. Agarwal, S. H. Ryu, C. Capell, J. Richmond, J. Palmour, H. Bartlow, P. Chow, S. Scozzie, W. Tipton, S. Baynes and K. Jones, “SiC BJT technology for power switching and RF applications.” in *Materials Science Forum,* vol. 457-460, pp.1141-1144, 2004.

[5] A. Agarwal, S. H. Ryu, J. Richmond, C. Capell, J. W. Palmar, S. Balachandran, T. P. Chow, B. Geil, S. Bayne, C. Scozzie and K. A. Jones, “Recent progress in SiC bipolar junction transistors”, in *IEEE Int. Symp. On Power Semicondctor Devices and IC’s (ISPSD) 2004*, pp. 361-364.

[6] S. Krishnaswami, A. Agarwal, C. Capell, J. Richmond, S.H. Ryu, J. Palmar, S. Balachandran, T. P. Chow, S. Bayne, B. Geil, K. A. Jones and C. Scozzie, “1000 V-30 A SiC bipolar junction transistors and integrated darlington pairs”, in *Materials Science Forum* Vol. 483-485, pp901-904, 2005.

[7] Jianhui Zhang, Petre Alexandrov, Jian H. Zhao and Terry Burke, “1677 V, 5.7 $m\Omega.cm^2$ 4H-SiC BJTs”, in IEEE Electron Device Letters, Vol. 26, pp188-190, 2005.

[8] Anant K. Agarwal, Sumi Krishnaswami, James Richmond, Craig Capell, Sei-Hyung Ryu, John W. Palmour, Santosh Balachandran, T. Paul Chow, Stephen Bayne, Bruce Geil, Charles Scozzie and Kenneth A. Jones, "Evolution of the 1600 V, 20 A, SiC bipolar junction transistors", in Proc. Of 17th international symposium on power semiconductor devices & IC's (ISPSD), pp271-274, 2005.

[9] Sumi Krishnaswami, Anant Agarwal, James Richmond, Craig Capell, Sei-Hyung Ryu, John Palmour, Bruce Geil, Dimosthenis Katsis, and Charles Scozzie, "High temperature characterization of 4H-SiC bipolar junction transistors", in ICSCRM 2005.

[10] Jianhui Zhang, Jian Wu, Petre Alexandrov, Terry Burke, Kuang Sheng and Jian H. Zhao, "1836 V, 4.7 mΩ.cm^2 high power 4H-SiC bipolar junction transistor", in ICSCRM 2005.

[11] Kiyoshi Tone and Jian H. Zhao, "A comparative study of C plus Al coimplantation and Al implantation in 4H- and 6H-SiC", in *IEEE Transanctions on Electron Devices*, Vol. 46, No. 3, pp612-619, 1999.

[12] J. H. Zhao, J. Zhang, P. Alexandrov, X. Li, and T. Burke, "A High Voltage (1,750 V) and High Current Gain (β= 24.8) 4H-SiC Bipolar Junction Transistor Using a Thin (12 μm) Drift Layer", in *Materials Science Forum*, Vol. 457-460, pp1173-1176, 2004.