

Zhang BJT paper Nov04 to accompany OPSEC review.

"1677V, 5.7 mohm.cm² 4H-SiC Bipolar Junction Transistors"

Summary:

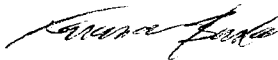
This paper reports an improved silicon carbide power transistor design. The voltage is appropriate for Army applications, but the current reported is too low (5 amperes) for the power required for hybrid electric vehicles. It is about a kilowatt, in practical operation. Theoretically, the current can be increased, when improved material becomes available.

This work was partially supported by a TACOM SBIR by United Silicon Carbide, Inc. The SBIR work is to improve the design of power transistors made from this novel semiconductor material. The contractor did this by optimized the electrical contacts to the transistor base region. This resulted in demonstration of a lower conduction-loss, high-voltage silicon carbide transistor (BJT) device. This is an important result, because lower conduction loss improves operating efficiency, and is a critical performance parameter for power devices.

The conduction loss is measured by specific on-state resistance. The specific on-state resistance achieved and reported in this paper is the best reported for these devices (SiC BJT) in this voltage range (1700V). It is better than previous reports by about 30%. This is the voltage level required for high power Army hybrid electric applications that use a 600-1000 volt dc bus (not stated in the paper). The improved design is supported by the capability to effectively block this high voltage level (1677V).

The improved contact to the base is the result of improved base electrode geometry and device processing and fabrication. Specifically, improved metallization and optimized co-implantation. The device high-voltage performance is supported by optimized passivation and junction termination design.

Terence Burke //s// 10November04



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1677V, 5.7 mΩ.cm² 4H-SiC Bipolar Junction Transistors

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Abstract— This paper reports the development of high power 4H-SiC bipolar junction transistors (BJT) with both high blocking voltage and low specific on-resistance (R_{sp_on}). A single BJT cell with an active area of 0.61 mm² blocks up to $V_{ceo} = 1677$ V and conducts up to 3.2 A ($J_c = 525$ A/cm²) at a forward voltage drop of $V_{CE} = 3.0$ V, corresponding to a R_{sp_on} of 5.7 mΩ.cm². In 4H-SiC BJT research, this BJT set a record high value of V_{BR}^2 / R_{SP_ON} of 500 MW/cm².

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

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I. INTRODUCTION

4H-SiC is a promising material for high power and high temperature applications. 4H-SiC BJTs are free of gate oxide problems and can handle high current with low forward voltage drop compared to SiC MOSFET. The first high power 4H-SiC BJTs were presented in a conference in June 2000[1,2] and published in a journal in August 2000[3]. Up to date, the reported high power 4H-SiC BJTs includes (i) a 1800V BJT with a current gain of 20, and a specific on-resistance (R_{SP_ON}) of $10.8 \text{ m}\Omega\cdot\text{cm}^2$ by using a drift layer of $20\mu\text{m}$ doped to $2.5\times 10^{15} \text{ cm}^{-3}$ [4]; (ii) a BJT with $V_{ceo} > 3200 \text{ V}$ showing a (R_{SP_ON}) of $78 \text{ m}\Omega\cdot\text{cm}^2$ and a current gain of 15 by using a drift layer of $50\mu\text{m}$ doped to $8\times 10^{14} \text{ cm}^{-3}$ [5]; (iii) a 1.8KV, 17A BJT with a $\beta = 11$ and an R_{SP_ON} of $8 \text{ m}\Omega\cdot\text{cm}^2$ at $J_C=256 \text{ A/cm}^2$ based on a $15\mu\text{m}$, $4.4\times 10^{15}\text{cm}^{-3}$ drift layer[6]; (iv) a 480V BJT with a $\beta = 38$ at $J_C=114 \text{ A/cm}^2$ and an R_{SP_ON} of $14 \text{ m}\Omega\cdot\text{cm}^2$ based on a $12\mu\text{m}$, $6\times 10^{15}\text{cm}^{-3}$ doped drift layer [7]; (v) a 500V BJT based on a $20\mu\text{m}$, $2.4\times 10^{15}\text{cm}^{-3}$ doped drift layer, showing current gain of 55 and an R_{SP_ON} of $26 \text{ m}\Omega\cdot\text{cm}^2$ [8]; (vi) a $V_{ceo} > 1\text{KV}$ 4H-SiC BJT based on a $12\mu\text{m}$, $6\times 10^{15}\text{cm}^{-3}$ doped drift layer, showing an R_{SP_ON} of $17 \text{ m}\Omega\cdot\text{cm}^2$ [9]; (vii) a $V_{ceo} > 858 \text{ V}$ BJT based on a $12\mu\text{m}$, $6\times 10^{15}\text{cm}^{-3}$ doped drift layer, showing a current gain of 47 and an R_{SP_ON} of $8.7 \text{ m}\Omega\cdot\text{cm}^2$ [10]. (viii) a $V_{ceo} > 1750 \text{ V}$ BJT based on a $12\mu\text{m}$, $8.5\times 10^{15}\text{cm}^{-3}$ doped drift layer, showing a current gain of 24.8 and an R_{SP_ON} of $8.4 \text{ m}\Omega\cdot\text{cm}^2$ [11]. (ix) a $V_{ceo} = 1400 \text{ V}$ BJT based on a $15\mu\text{m}$, $4.4\times 10^{15} \text{ cm}^{-3}$ doped drift layer, showing a current gain of 14 and an R_{SP_ON} of $5.3 \text{ m}\Omega\cdot\text{cm}^2$ [12]. Because there is a trade off in the blocking voltage and the specific on-resistance in power BJTs, blocking voltage can be increased by increasing the drift layer thickness which leads to a

higher on-state resistance. It is important to develop power BJTs capable of simultaneously high blocking voltage and low specific on-resistance. V_{BR}^2 / R_{SP_ON} is a commonly used parameter to evaluate switching devices. This paper reports a newly developed 4H-SiC BJT demonstrating a blocking voltage of $V_{ceo} = 1677$ V and an $R_{SP_ON} = 5.7$ m Ω ·cm² up to $J_c = 525$ A/cm². It has a record high V_{BR}^2 / R_{SP_ON} value of 500 MW/cm².

II. DEVICE DESIGN AND FABRICATION

A simplified cross-sectional view of the 4H-SiC BJT structure is shown in Fig.1. The 4H-SiC wafer was purchased from Cree Inc. Four epi-layers are grown on the 8° off-axis n-type 4H-SiC substrate. The top n⁺ epi-layer of 0.8 μ m is heavily doped to 1.3×10^{19} cm⁻³ to serve as the emitter. The base p-type epi-layer is 1.0 μ m thick and is doped to 2.9×10^{17} cm⁻³. The collector drift layer of 15 μ m is lightly-doped to 5.5×10^{15} cm⁻³. A n-type buffer layer of 1.0 μ m, doped to 2.0×10^{18} cm⁻³ grown directly on a heavily doped n-type 4H-SiC substrate. The emitter mesa was defined 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 mesa etching depth was 1.1 μ m. The base contact region was implanted at room temperature with carbon and aluminum co-implantation, which consists of C ions of 4×10^{14} cm⁻² at 28keV, 5.2×10^{14} cm⁻² at 60 keV, and 1.1×10^{14} cm⁻² at 75 keV plus Al ions of 3.6×10^{14} cm⁻² at 50 keV and 7.5×10^{14} cm⁻² at 100 keV. The designed spacing between the implanted base region and the emitter mesa edge (BE-spacing) is 4 μ m. The ion-implantation activation annealing was done at 1550°C for 30 min in Ar ambient. A single step JTE of 160 μ m wide based on the existing 0.7 μ m p-type base epi-layer is applied for the edge

termination. The isolation between each device is served by a mesa etching of $\sim 1.4\mu\text{m}$ into the drift layer. As wet-oxygen low-temperature re-oxidation has been shown to reduce SiO_2/SiC interface defect density, the samples were re-annealed in wet-oxygen for 3 hours at 950°C after a regular wet thermal oxidation for 2 hours at 1100°C followed by a one-hour Ar annealing at 1100°C . After the thermal oxidation, 500 nm SiO_2 and 250nm Si_3N_4 were deposited by PECVD to seal the thermal passivation layer. Base contact metals are sputtered Ni/AlTi/Ni sandwich layer, emitter and collector both have Ni as the contact metal. The Ohmic contact annealing was carried out at 1050°C for 5 minutes in Argon forming gas (5% H_2 in Ar) protection by using a rapid thermal processing (RTP) system. After Ohmic contact formation, 400 nm Ti/Au was put on base contact metals to improve the voltage and current distribution on base fingers. Then, 1.1 μm SiO_2 and 250nm Si_3N_4 were deposited by PECVD as the insulator between the overlay metals. The base and emitter contact windows were opened by ICP, and a multi-layer of AlTi / Ti / Au were deposited and patterned to form the base and emitter bonding pads, the total emitter metal thickness is about 4.5 μm . The collector overlay metal is 450 nm Ti/Au on the substrate. The device was then diced and packaged through die-mounting and gold ribbon bonding. Fig. 2 shows the two-dimensional CAD graph of a fabricated 4H-SiC BJT device. The device footprint is $1.2\text{ mm} \times 1.4\text{ mm}$. Each device contains 25 emitter fingers and 26 base fingers in an interdigitated geometry. The finger length is 728 μm , and the width of the emitter mesa and base trench are 14 μm and 19 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 $4.9 \times 10^{-6} \Omega \cdot \text{cm}^2$ and 219Ω , respectively, while the p-type specific contact resistance and p-base sheet resistance are $9.3 \times 10^{-4} \Omega \cdot \text{cm}^2$ and $49 \text{ k}\Omega$, respectively.

The device DC I-V characteristics was measured mainly by Tektronix 371A curve tracer.

Fig. 3 is the room temperature I-V characteristics of a single BJT cell, showing a peak DC current gain of 7.1 at $I_c = 1.42 \text{ A}$ ($J_c = 233 \text{ A/cm}^2$) and $V_{ce} = 10 \text{ V}$. The maximum collector current was measured up to 4.87 A ($J_c = 798 \text{ A/cm}^2$), and the specific on-resistance is $5.7 \text{ m}\Omega \cdot \text{cm}^2$ up to $I_c = 3.2 \text{ A}$ ($J_c = 525 \text{ A/cm}^2$) at $V_{ce} = 3.0 \text{ V}$. The open base blocking voltage (V_{ceo}) was measured up to 1677 V with 81 uA leakage current in Fluorinert.

This single cell BJT capable of blocking 1677 V and showing a low specific on-resistance of $5.7 \text{ m}\Omega \cdot \text{cm}^2$ up to $J_c = 525 \text{ A/cm}^2$ at a forward voltage drop of 3.0 V is among the best 4H-SiC BJTs reported to date considering high blocking voltage and low specific on-resistance. Comparing to our 4H-SiC BJTs fabricated before [10, 11], we believe that the improved base contact is the key factor to achieve such a low specific on-resistance. First of all, the Ni/AlTi/Ni base contact gives much better specific contact resistance, which is more than two orders of magnitude lower than the results from using Ti/TiN. Secondly, this reported 4H-SiC BJT has the base metal finger width of 11 um and the length of 728 um , metal thickness is about 750 nm , and all the base fingers directly connected to the base bonding pad which has 4.8 um metal thickness. The BJTs we reported before has 3 um wide, 1186 um long base metal fingers with the metal

thickness of about 400 nm, and the fingers connect to the base bonding pad through two 22 μm wide, 1 mm long rails. When BJT works at ON state, base-emitter junction needs to be forward biased, and because BJT is a current control device, a significant base current is also needed to maintain the forward bias. If the base electrode couldn't provide enough voltage and current to all the base-emitter junctions, the device is only partially working at ON state, hence, the actual active area is less than expected and the device shows a much larger specific on-resistance.

The current gain of this BJT device is 7 at $J_c = 233 \text{ A/cm}^2$, which is due to a thicker base epi-layer and a smaller BE-spacing of 4 μm .

IV. SUMMARY

A high voltage BJT capable of blocking 1677 V and showing a low specific on-resistance of $5.7 \text{ m}\Omega\cdot\text{cm}^2$ has been demonstrated in 4H-SiC using a drift layer of 15 μm doped to $5.5 \times 10^{15} \text{ cm}^{-3}$. This BJT achieves a record high value of V_{BR}^2 / R_{SP_ON} of 500 MW/cm^2 in 4H-SiC power BJT study.

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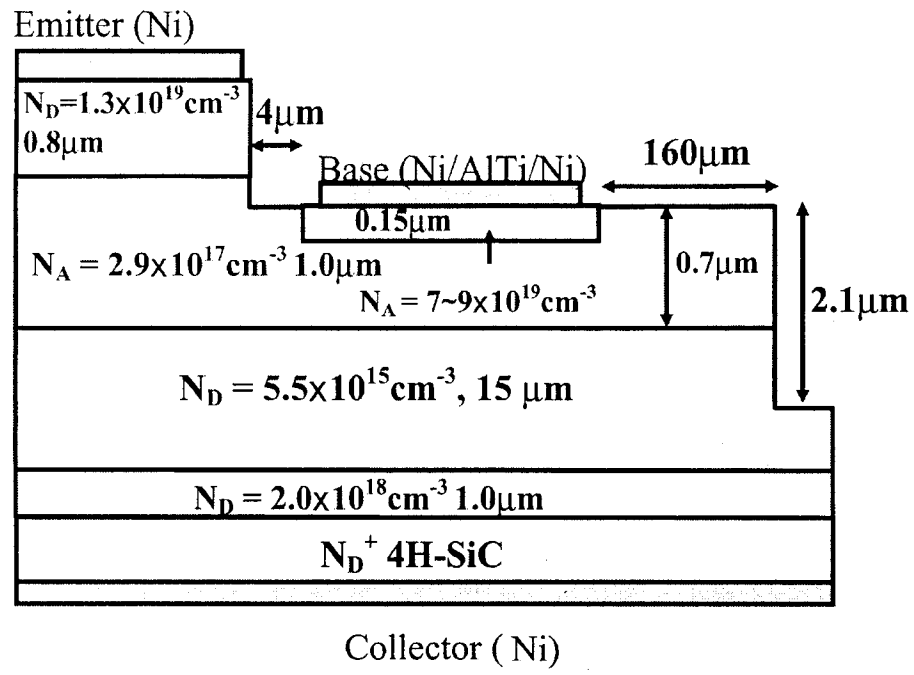


Fig.1.

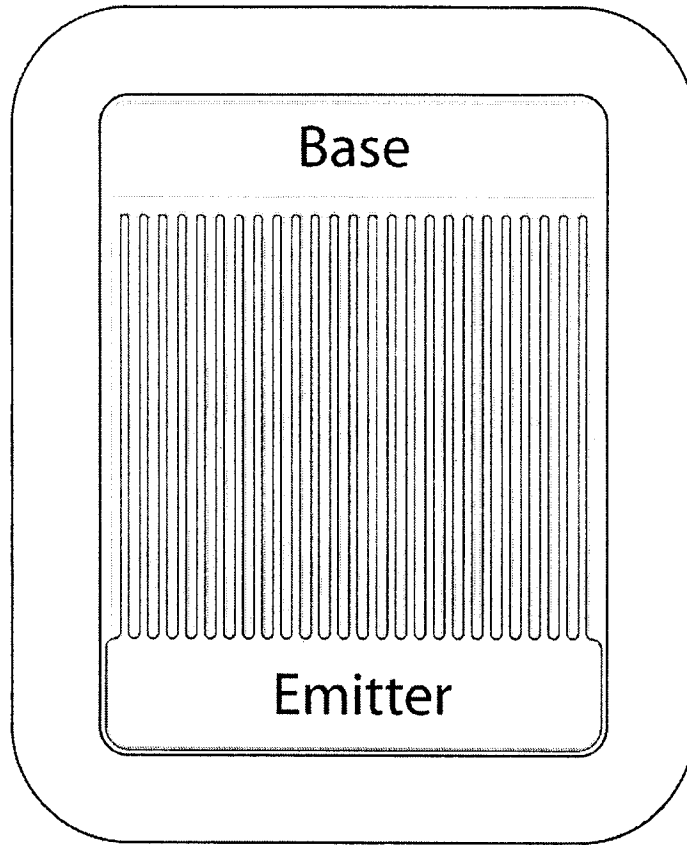


Fig. 2.

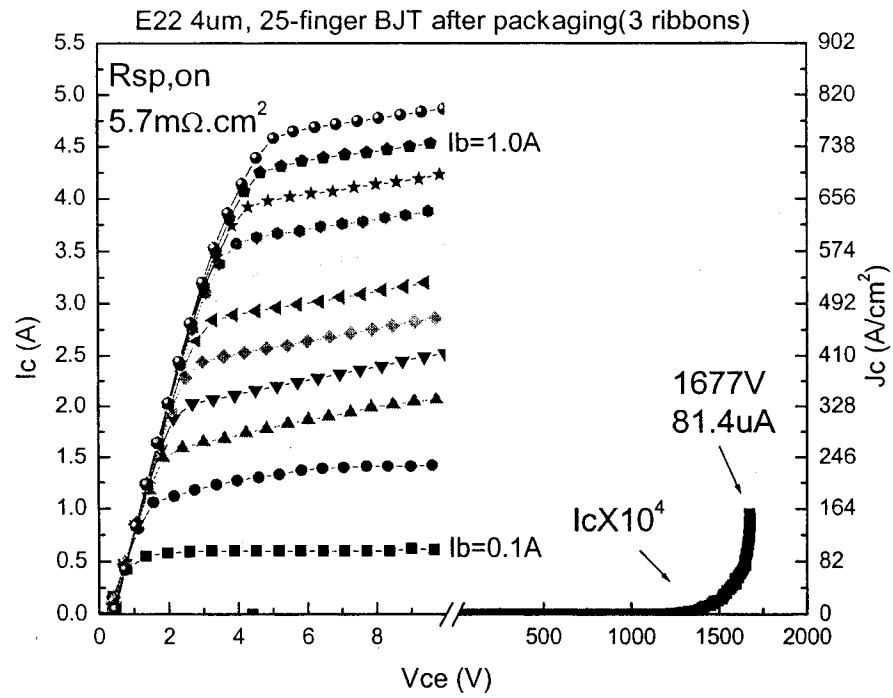


Fig.3.

FIGURE CAPTIONS

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

Fig. 2. Top view of the 4H-SiC BJT device.

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

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