A 500V, Very High Current Gain ($\beta=1517$) 4H-SiC Bipolar Darlington Transistor

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Abstract. This paper reports the demonstration of a record high current gain high voltage 4H-SiC hybrid bipolar Darlington transistor. The DC current gain of the bipolar Darlington was measured up to 1517 at $I_c=27.3A$ ($J_c=284A/cm^2$) with $V_{ce}=20V$ at room temperature, which substantially surpasses the past record of a 500V Darlington with a DC current gain of 430. The differential specific on-resistance (R_{SP_ON}) is $12.9m\Omega\cdot cm^2$ up to $I_c=25.6A$ ($J_c=267A/cm^2$) at $V_{ce}=7.0V$. This high current gain SiC Darlington has a 7.8mA leakage current at a blocking voltage of 500V. At 150°C, the Darlington still maintains a high current gain of 1015 at $I_c=20.3A$ ($J_c=211A/cm^2$), $V_{ce}=20V$, and a low leakage current of 6.5mA at 500V. The Darlington's R_{SP_ON} is increased to $19.0m\Omega\cdot cm^2$ at I_c up to 16.4A ($J_c=171A/cm^2$) at $V_{ce}=6.5V$ at 150°C. An inductively-loaded half-bridge switching measurement (320V-50A) at RT and 150°C is also reported.

Introduction

4H-SiC has been exploited for high temperature and high power applications since late 1980's due to its high critical field and large bandgap. 4H-SiC power bipolar junction transistors (BJTs) are gaining more and more interest in the recent years[1,2,3], partly because BJTs are free of gate oxide problems and have the potential to achieve a low on-state voltage at high current density. The main disadvantage of SiC BJTs, however, is the low current gain or the high base driving current requirement. Bipolar Darlington transistor can drastically reduce the base current requirement but at the expense of increased forward voltage drop (V_F), making Darlington transistor attractive only at a relatively high voltage region. Among the best results of earlier efforts are: (i) a hybrid Darlington of 500V, $>200A/cm^2$ ($>23A$) at $V_{CE}=6.4V$ with a DC current gain of 430 at $J_c\sim 200A/cm^2$ [4], (ii) a monolithic 4H-SiC Darlington of 0.3A at $V_{CE}=7.5V$ with a corresponding DC current gain $\beta\sim 40$ at $J_c \geq 50A/cm^2$ [5], and (iii) a hybrid Darlington of 1800V, 3.9A(278A/cm²) at $V_{CE}=6.3V$ with a maximum AC current gain of 500 (Estimated DC current gain is 367)[6]. This paper reports a Darlington transistor with a drastically increased current gain of $\beta > 1517$ (measurement set-up limited) at $I_c=27.3A$ ($J_c=284A/cm^2$).

Device Design and Fabrication

The 4H-SiC BJT driving transistor (active area= $1.2mm^2$) and output transistors (active area= $9.6mm^2$) were fabricated on the same chip. The 4H-SiC wafer was purchased from Cree Inc. The emitter was formed by heavily-doped n-type epi-layer, with a thickness of $0.7\mu m$. The base was a $0.8\mu m$ p-type epi-layer with a concentration of $3.0\times 10^{17}cm^{-3}$. The collector was formed by a $12\mu m$ drift layer with n-type doping of $6.0\times 10^{15}cm^{-3}$ and the n⁺-type 4H-SiC substrate. The emitter mesa was formed by inductively coupled plasma etching, and the mesa depth was $0.82\mu m$. The base implanted region has a $5\mu m$ spacing to the emitter mesa edge. The base implantation was done by aluminum and carbon co-implantation at room temperature, and the implanted sample was annealed at 1550°C for 30 minutes in Ar. The devices were isolated by a mesa etching of $\sim 1.4\mu m$ into the drift layer. Device passivation included 2 hours wet thermal oxidation at 1100°C, 1 hour Ar

annealing at 1100°C, 3 hours low-temperature wet-oxygen re-anneal at 950°C, as well as PECVD deposited 250nm SiO₂ and 250nm Si₃N₄. Al-free Ohmic contacts (200nm Ti covered by 200nm TiN) were sputtered on both emitter and base. AlTi(20nm)/Ni(700nm) bi-layer was used as the collector contact metal. All the contacts were annealed in hydrogen and nitrogen forming gas for 8 minutes at 1050°C. After the Ohmic contact formation, a thick layer of PECVD SiO₂ (410nm) and Si₃N₄ (250nm) was deposited for insulation between the overlay metals. The final overlay metals were Ti(50nm) and Au(1.5μm) on the emitter and base, Ni(100nm) and Au(700nm) on the collector.

After characterization on each BJT cells on the chip, the sample was then die mounted into a multi-pin metal package and ribbon-bonded. One BJT cell was used as the driving transistor(T1), and 8 other cells were used to form the output transistor(T2). The hybrid 4H-SiC bipolar Darlington transistor containing a monolithic multi-cell BJT chip was completed by connecting the emitter pin of the driving transistor(T1) to the base pin of the output transistor(T2) which contains 8 BJT cells in parallel. Fig.1 shows the formation of the hybrid Darlington transistor.

Fig.1. Formation of a Darlington transistor.

Characterization and Discussion

The high performance driver BJT I-V curves are shown in Fig.2. The peak current gain was 47 at $I_{C1}=4.7\text{A}$ ($J_{C1}=392\text{A/cm}^2$) and $V_{CE1}=10\text{V}$ at room temperature. The specific on-resistance (R_{SP_ON}) was $9.4\text{m}\Omega\cdot\text{cm}^2$ at $I_{C1}=6.36\text{A}$ ($J_{C1}=530\text{A/cm}^2$) and $V_{CE1}=5.0\text{V}$. Fig.3 shows the I-V characteristics of the output transistor. The peak DC current gain was 44 at $I_{C2}=35\text{A}$ ($J_{C2}=366\text{A/cm}^2$) and $V_{CE2}=10\text{V}$. The R_{SP_ON} was $10.5\text{m}\Omega\cdot\text{cm}^2$ for current up to $I_{C2}=55.1\text{A}$ ($J_{C2}=574\text{A/cm}^2$) and $V_{CE2}=6.0\text{V}$.

Fig.2. I-V characteristics of the driver BJT(T1). Fig.3. I-V characteristics of the output BJT(T2).

The hybrid BJT Darlington transistor's RT and 150°C I-V characteristics are shown in Fig.4. A record high DC current gain of 1517 was obtained at room temperature at $I_{C2}=27.3\text{A}$ ($J_{C2}\sim 284\text{A/cm}^2$) at $V_{CE2}=20\text{V}$, which is the highest high voltage SiC BJT Darlington current gain reported to date. The gain could be even higher at higher collector current level, as evidenced by the current gain curves shown in Fig.5(a) and (b), but the measurement was at present limited by the instrument. Fig.4(a) shows the Darlington has a differential R_{SP_ON} of $12.9\text{m}\Omega\cdot\text{cm}^2$ for current up to $I_{C2}=25.6\text{A}$.

($J_{C2} \sim 267 \text{ A/cm}^2$) at $V_{CE2} = 7.0 \text{ V}$. The current gain decreased at elevated temperatures, but still maintained a high gain of 1015 at $I_C = 20.3 \text{ A}$ ($J_{C2} \sim 211 \text{ A/cm}^2$) at 150°C . The differential R_{SP_ON} increased to $19.0 \text{ m}\Omega\text{-cm}^2$ up to $I_C = 16.4 \text{ A}$ ($J_{C2} \sim 171 \text{ A/cm}^2$) at $V_{CE2} = 6.5 \text{ V}$ at 150°C . The open base blocking performance was measured up to $V_{CEO} = 500 \text{ V}$ at room temperature with a leakage current of 7.8 mA . At 150°C , the leakage current was 6.5 mA at $V_{CEO} = 500 \text{ V}$. Fig.5 shows the DC current gain versus the collector current level at $V_{ce} = 10 \text{ V}$ for the driver BJT, the output transistor and the BJT Darlington transistors, respectively.

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

The switching properties of this high power hybrid Darlington transistor has also been tested in an inductively-loaded half-bridge inverter with a SiC MPS (Merged-PiN-Schottky) serving as the freewheeling diode. A 1 mH inductor load was used to simulate an induction electric motor. Fig.6 shows switching waveforms at room temperature and at 150°C , with a bus voltage of 320 V and a switching current of 50 A . Results showed that the collector current (I_C) had a turn-on rise time of $0.16 \mu\text{s}$ at both room temperature and 150°C , and a turn-off fall time of $0.15 \mu\text{s}$ at room temperature and $0.13 \mu\text{s}$ at 150°C . At room temperature, the turn-on switching energy loss was 5.68 mJ , while the turn-off energy loss was 3.15 mJ . Two different working modes of the Darlington transistor can be clearly distinguished from Fig.6. At room temperature, the Darlington worked in saturation mode with both base-emitter and base-collector junctions forward-biased which explains the high

Fig.5. Current gain at different collector current levels.

base current. While at 150°C, due to the reduced current gain, the same base bias voltage kept the Darlington working in active region where base-collector junction was still reverse biased. In this desired mode of operation, the base current required to switch 50A was less than 0.05A. Compared to the single stage 4H-SiC BJTs, the base driving current is much less for the Darlington BJT, which substantially lowers the base driving requirement. However, as shown by the long V_{CE} falling time, better base drive circuit design is needed and device parasitic RC time should be reduced in order to achieve a better switching performance.

Summary

A record high current gain ($\beta=1517$) was demonstrated for a high power(500V-27A) SiC hybrid bipolar Darlington transistor. At room temperature, the DC current gain was measured up to 1517 at $J_{C2}\sim 284\text{A}/\text{cm}^2$. And a very high current gain of 1015 was still maintained at $J_{C2}\sim 211\text{A}/\text{cm}^2$ at 150°C. The Darlington blocked 500V both at room temperature and at 150°C, and the differential R_{SP_ON} was $12.9\text{m}\Omega\cdot\text{cm}^2$ and $19.0\text{m}\Omega\cdot\text{cm}^2$ at room temperature and 150°C, respectively. Inductively-loaded half-bridge inverter switching at 320V-50A was demonstrated with the Darlington in active mode showing a base driving current $< 0.05\text{A}$.

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Fig.6 Half-bridge inverter switching waveforms for 4H-SiC Darlington BJT using SiC MPS freewheeling diode. The load was a 1mH inductor.