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High-Power High-Temperature Heterobipolar TransistorWith Gallium Nitride Emitter

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Abstract

A new heterobipolar transistor was made with the wide bandgap semicon-ductors gallium nitride (GaN) and silicon carbide (SiC). The heterojunction allows high injection efficiency, even at elevated temperatures. A record current gain of ten million was obtained at room temperature, decreasing to 100 at 535°C. An Arrhenius plot of current gain vs 1/T yields an activation energy of 0.43 eV that corresponds to the valence band barrier blocking the escape of holes from the base to the emitter. This activation energy is approximately equal to the difference of energy gaps between emitter and base. This Transistor can operate at high power without cooling. A power density of 30 KW/cm^2 was sustained.

1. Principle of Operation

A heterobipolar transistor was made by growing a GaN emitter on a commercial SiC pn junction as shown in Figure 1. [1] [2] The reason for this structure is evident from Figure 2 that shows a band diagram of this transistor while biased to amplify a signal. The electrons injected at low voltage by the n-type emitter traverse the SiC base and are collected at high voltage in the Collector. This represents a high power gain. The injection efficiency is very high because all the emitter current consists of electrons injected by the emitter and none involving holes from the base because the holes are blocked by a valence band barrier at the emitter. Furthermore, SiC being an indirect gap semiconductor, the injected electrons have a long lifetime in the base. Hence this transistor is endowed with an extremely high amplification factor. The current gain begins to degrade at high temperature when holes in the Boltzmann tail at the base can overcome the barrier and escape into the emitter.

2. Device Fabrication

To fabricate this structure, a layer of n-type GaN is grown on the p-type surface of the SiC using an MOCVD reactor. The emitter is patterned and reactively etched. Then the surfaces are metallized with chromium and aluminum. After patterning to define the emitter and base electrodes, an etching step is used. The collector contact of Cr/Al is applied over the back of the waver. The next step consists in etching a trench around each base to define each transistor and avoid having all the collector-base junctions on the chip in parallel. Figure 3 shows a cross section of the processed device. While Figure 4 is an SEM view of part of a chip. The largest emitter (lower row) measures 250 x 250 μm^2 while the smallest transistor (next row above) has a 10 x 20 μm^2 emitter surrounded by the base. Note that both emitter and base are connected to bonding pads.

3. Device Characteristics

The common base operating characteristics of the new HBT at room temperature are shown in Figure 5. They are the typical characteristics of a bipolar transistor with unit current gain. Since the emitter area is 75 x 75 μm^2, at 100 mA the current density is almost 1800 A/cm^2, which corresponds to a 30 KW/cm^2 power density. Although these are the highest values used for this device, and they are characteristic of many other devices tested, they do not represent the maximum achievable.

To measure the device characteristics at higher temperatures, the transistor was placed on a calibrated hot plate with a covering thermal shield and an aperture for the test probes to contact the emitter and base pads (Figure 6). Figure 7 shows the 520°C common base characteristics of the same device as in Figure 5. Note that the emitter current gain is still near unity though there is an increase in leakage current. The differential current gain dIc/dIb is plotted against emitter current for various temperatures in Figure 8. Note the extremely high value of differential current gain of ten million at room temperature and the fact that at 535°C the current gain of 100 is comparable to the current gain of most Si transistors at room temperature.

4. Discussion

When the log of the differential current gain of several transistors is plotted against reciprocal temperature (Arrhenius plot), one finds that it follows an exponential dependence (Figure 9). From the slope of this data the value Ea = 0.43 eV is obtained, which as expected, corresponds to the difference between the bandgaps of the GaN emitter and the SiC base. This is the activation energy for the escape of holes from the base to the emitter. This becomes evident by visualizing the energy band diagram of Figure 2 with a flat conduction band between emitter and base, i.e. maximum electron injection. In this case the valence band discontinuity equals the bandgap difference at the emitter base junction.

5. Conclusions

The new GaN/SiC heterobipolar transistor can operate at high temperatures and at high powers. Therefore it does not need special cooling means such as ventilation, liquid heat exchangers, or thermoelectric coolers. The new device will satisfy the needs of under-the-hood automotive electronics, fuel injection control in diesel engines, monitoring and controlling jet engines, and driving the electric motors that will replace the hydraulic systems in avionics and in the future hybrid and all electric automobiles.

Acknowledgments

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References

[1]J. Pankove, S. S. Chang, H. C. Lee, R. Molnar, T. D. Moustakas, B. Van Zeghbroeck. , "High-Temperature GaN/SiC Heterojunction Bipolar Transistor with High Gain", Proc. IEDM. , San Francisco, CA. Dec. , 389 (1994)

[2]S. S. Chang, J. Pankove, M. Leksono, B. Van Zeghbroeck, "500C Operation of a GaN/SiC Heterojunction Bipolar Transistor», Device Research Conference, paper IVB-5, Charlottesville, VA, June (1995)

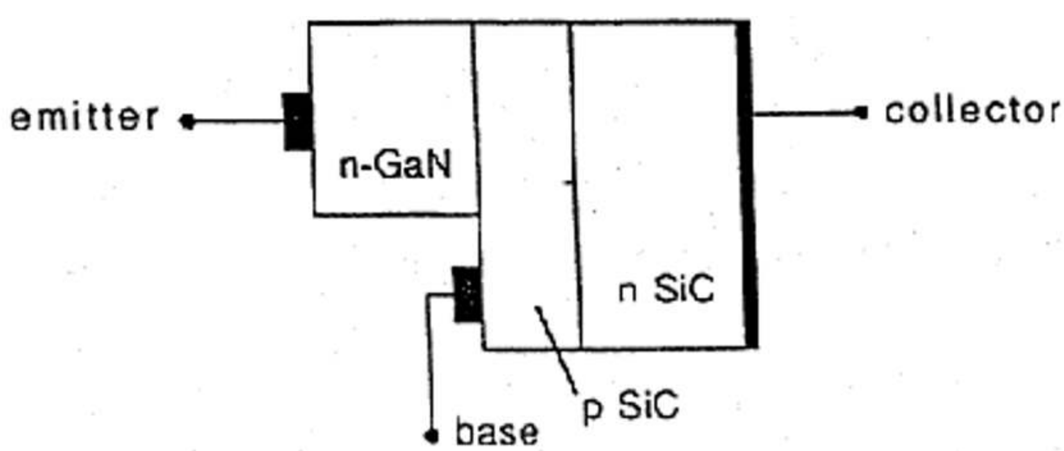

Figure 1. Schematic structure of heterobipolar transistor

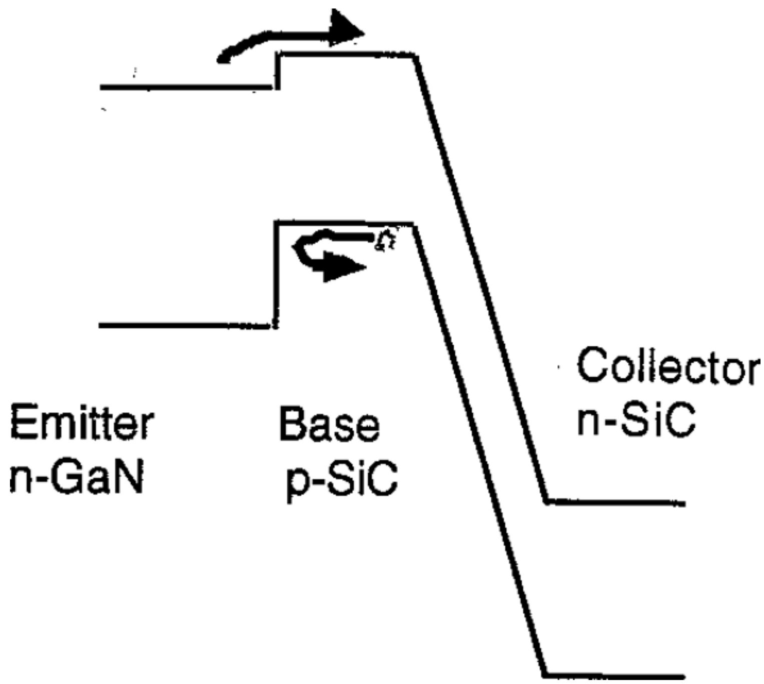

Figure 2. Energy band diagram for biased transistor showing a barrier that blocks the escape of holes from base to emitter

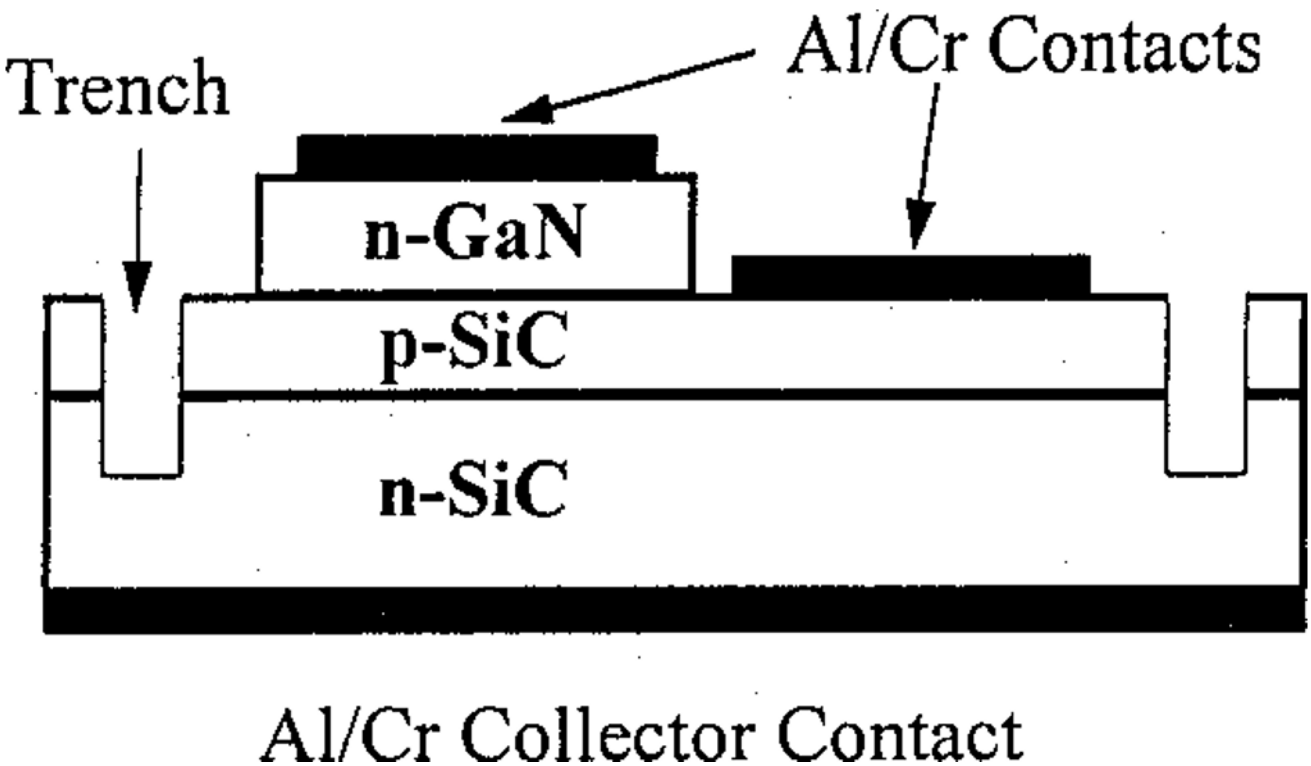

Figure 3. Cross sectional view of GaN/SiC heterojunction bipolar transistor

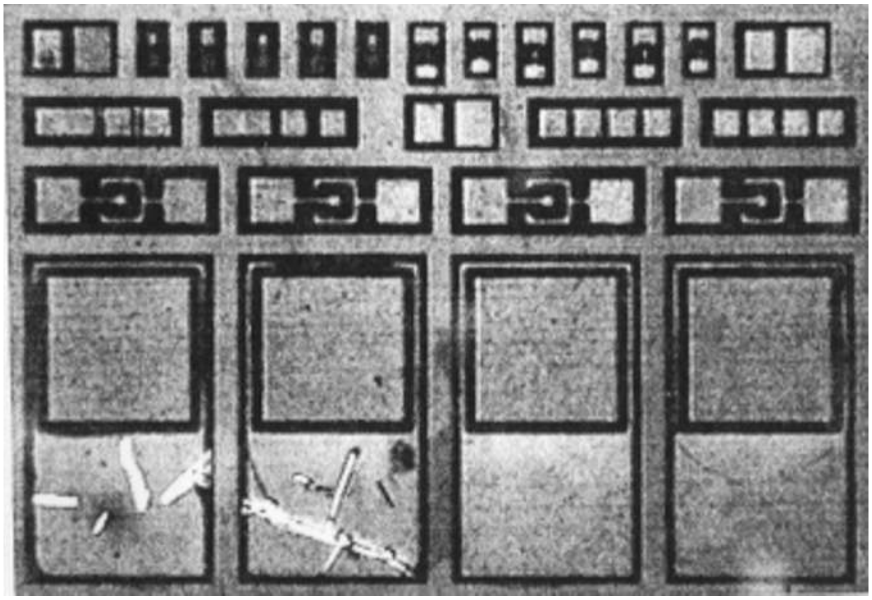

Figure 4. Scanning electron microscopy image of and small transistors on a chip

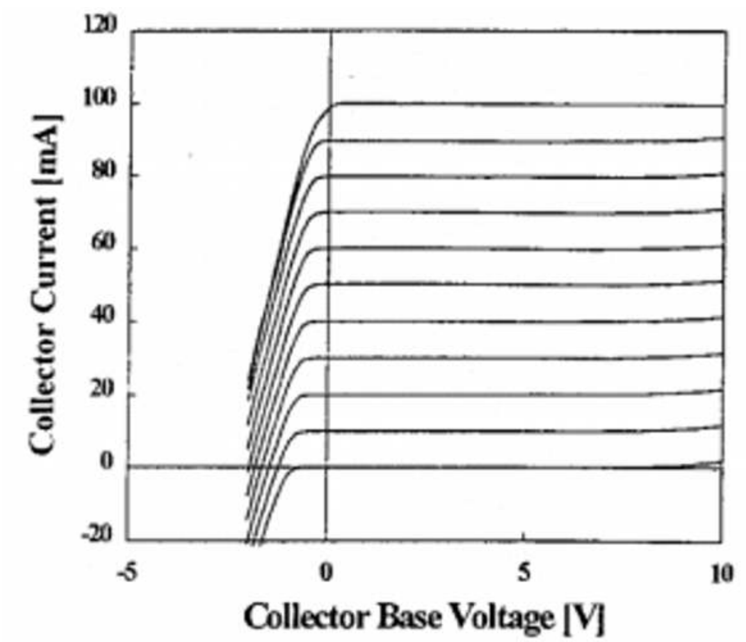

Figure 5. Common base characteristics at room temperature as the emitter current increases in 10 mA steps from 0 to 100 mA.

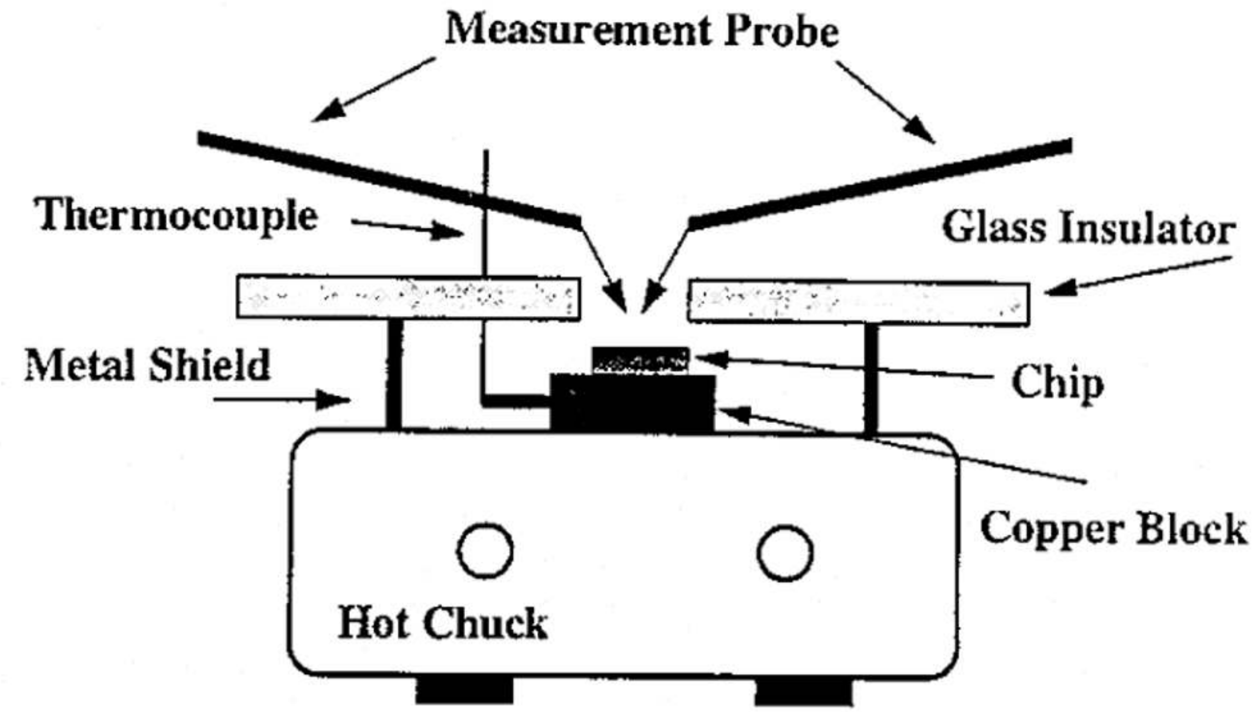

Figure 6. High temperature measurement setup.

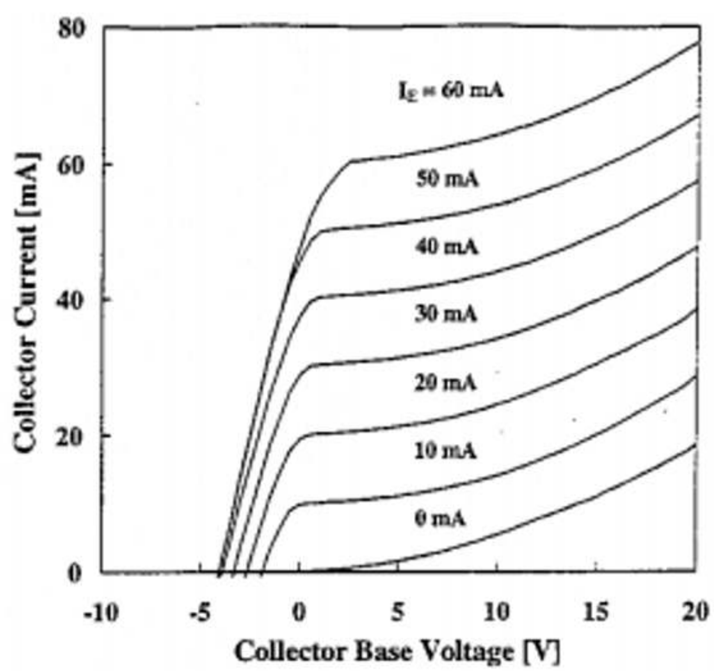

Figure 7. Common base I-V characteristics at 520

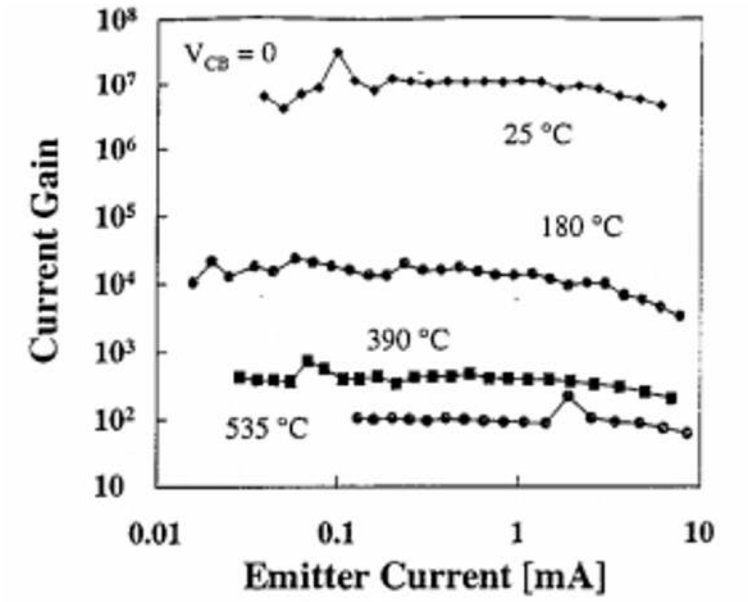

Figure 8. Current gain versus emitter current at indicated temperatures.

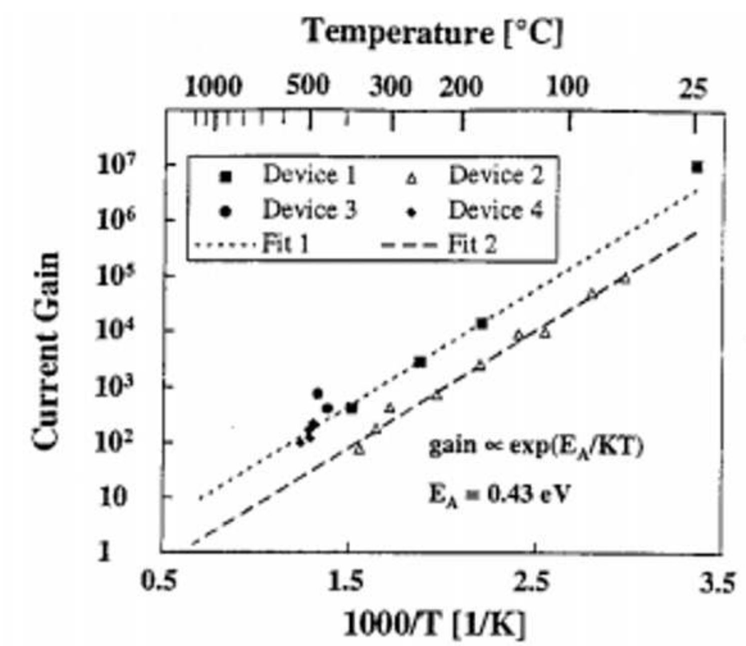

Figure 9. Current gain as a function of temperature.