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A GALLIUM PHOSPHIDE HIGH-TEMPERATURE BIPOLAR JUNCTION TRANSISTOR*

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SUMMARY

Preliminary results are reported on the development of a high-temperature (>350°C) gallium phosphide bipolar junction transistor (BJT) for geothermal and other energy applications. This four-layer $p^+n^-pp^+$ structure was formed by liquid phase epitaxy using a supercooling technique to insure uniform nucleation of the thin layers. Magnesium was used as the p-type dopant to avoid excessive out-diffusion into the lightly doped base. By appropriate choice of electrodes, the device may also be driven as an n-channel junction field-effect transistor.

The gallium phosphide BJT is observed to have a common-emitter current gain peaking in the range of 6-10 (for temperatures from 20°C to 400°C) and a room-temperature, punchthrough-limited, collector-emitter breakdown voltage of approximately -6V. Other parameters of interest include an f_T = 400 KHz (at 20°C) and a collector base leakage current = -200 μA (at 350°C).

The initial design suffers from a series resistance problem which limits the transistor's usefulness at high temperatures. This is not a fundamental material limit, and second generation structures are presently in process which will alleviate this problem as well as improve the device's output resistance and breakdown voltage.

INTRODUCTION

Recent successful operation[1] of gallium phosphide high-temperature diodes at temperatures and times exceeding 300°C and 1000 hours respectively, has prompted the development of a gallium phosphide bipolar junction transistor (BJT) for geothermal and other energy applications. Using contacting and epitaxial growth technologies similar to the diodes of Ref. 1, a prototype, four-layer $p^+n^-pp^+$ structure has been successfully fabricated and evaluated at temperatures up to 440°C. The processing sequence and device characteristics of the GaP BJT, as well as suggested improvements and predicted characteristics will be discussed.

FABRICATION

The structure of the prototype GaP transistor is shown in Fig. 1. This all-epitaxial device incorporates a double-base stripe geometry, a mesa-isolated emitter region, and a saw-isolated collector region. Important structural information is summarized in Table I below. By appropriate connection of electrodes, the device may also be driven as an n-channel junction field-effect transistor (JFET).

TABLE I

Emitter acceptor concentration	$2.x10^{18}cm^{-3}$
Emitter thickness	0.9 μm
Emitter-Base junction area	$4.6x10^{-4}cm^2$
Base donor concentration	$2.x10^{16}cm^{-3}$
Base thickness	1.1 μm
Epitaxial collector acceptor concentration	$1.5x10^{17}/cm^{-3}$
Epitaxial collector thickness	4 μm
Collector-Base junction area	$4.x10^{-3}cm^2$
Substrate acceptor concentration	$1.x10^{18}cm^{-3}$

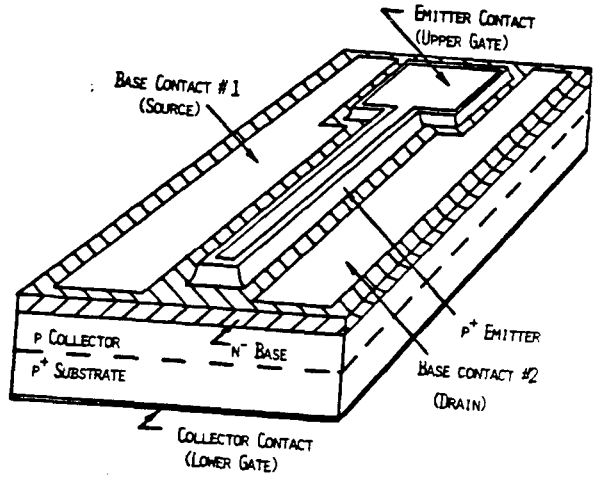

Figure 1. Structure of a prototype GaP high-temperature bipolar junction transistor (BJT) with a mesa-etched emitter, chip size 500x750 μm. The device may also be driven as an n-channel junction field-effect transistor (JFET) where the base region serves as the channel and the emitter and collector regions function as upper and lower gates, respectively.

The device of Fig. 1 is fabricated from a 3-layer p^+n^-p structure prepared by liquid phase epitaxy (LPE) on a p^+ substrate. The graphite sliding boat assembly used to grow these layers is shown in Fig. 2. Non-volatile Mg is used as the p-type dopant to avoid vapor-phase contamination of the lightly doped n-type growth solution. A pre-bake under flowing purified H_2 in position 2a is used to remove residual oxygen from the growth solutions before addition of the Mg dopant. After addition of Mg, the system is raised to the growth temperature (850°C) and held for ~2 hrs. to allow saturation of the solution with phosphorus (Fig. 2b). Growth is initiated by quickly decreasing the system temperature by 15°C, causing each solution to become correspondingly supercooled. The slider is then translated to bring the GaP substrate in contact with the first supercooled solution, as in Fig. 2c. Due to the supercooling, nucleation immediately occurs on the substrate, leading to epitaxial growth. Subsequent translation of the slider brings the substrate in contact with the other growth solutions for the completion of the multilayer structure.

*This work sponsored by the U. S. Department of Energy (D.O.E.) under Contract DE-AC04-76-DP00789.

†A U. S. Department of Energy facility.

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By adjusting the amount of supercooling and the duration of contact between substrate and growth solution, layer thicknesses as small as 0.2 μm can be controlled. Interface planarity, as delineated by staining in $1HF:1H_2O_2$, is excellent, owing to the supercooling technique, which avoids nonuniform nucleation and island growth.

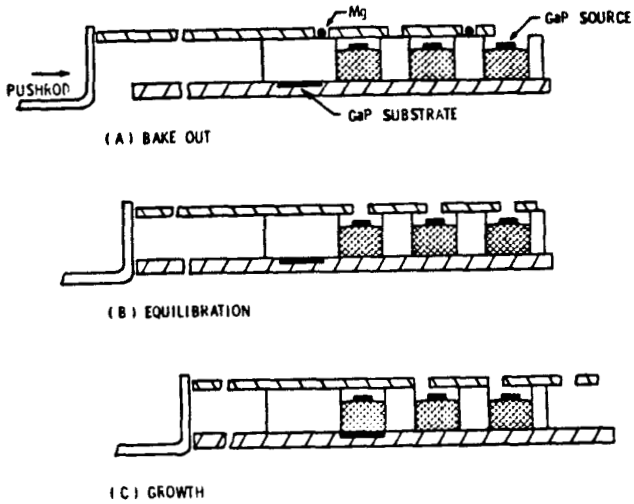

Figure 2. Graphite sliding boat assembly used for liquid phase epitaxial growth of the three active layers of the GaP BJT.

Once the resistivity and thickness of all three active layers are defined by LPE, the processing sequence of Fig. 3 is implemented to uncover the base and contact all three regions. The first step (Fig. 3a) involves definition of a thermally evaporated Au-Be/Au emitter metalization by a single-step optical lift-off process.[2] Next, 300 nm of plasma-enhanced CVD Si-N is deposited and patterned to serve as a masking material for the GaP etchant. The emitter mesa is then formed (Fig. 3b) by chemically removing unwanted p^+ material in a $K_3Fe(CN)_6$ (0.5 molar): KOH (1.0 molar) solution at 17°C. Without agitation this mixture etches p-type GaP at 80 ± 8 nm/min. The Au-Ge/Ni/Au base metalization is then defined (Fig. 3c) by deposition through a shadow mask. After thermal evaporation of the Au-Be/Au collector metalization on the back of the wafer, the contacts are annealed at 500°C for 15 min in H_2. Individual transistors are then formed (Fig. 3d) by sawing the wafer into dice with a high-speed diamond-impregnated saw. The transistors are then mounted in ceramic headers using a silver loaded polyimide adhesive and contact is made using thermocompression-bonded, 1.0 mil Au wire. This packaging technique is unsatisfactory for life testing, however, as the polyimide adhesive is known to fail[3] after extended use at or above 300°C.

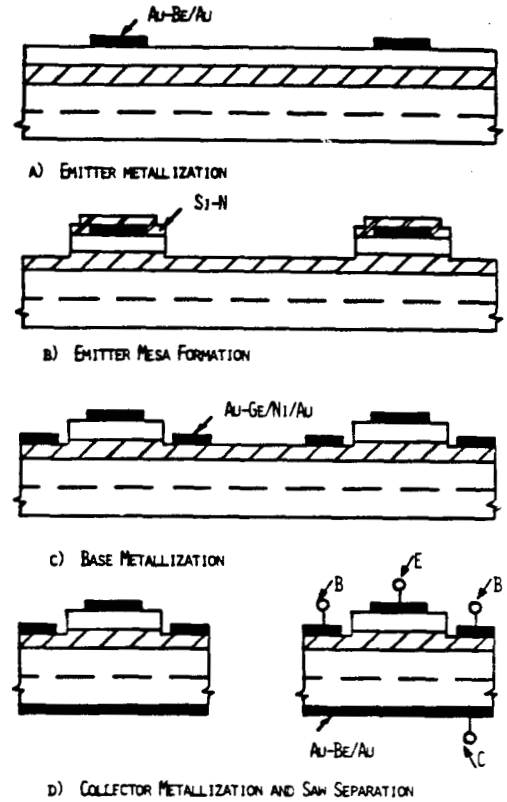

Figure 3. Processing sequence for the prototype GaP BJT

DEVICE EVALUATION AND DISCUSSION

The GaP transistor described above was evaluated in both the bipolar and JFET modes. Common-emitter output characteristics of the device at 20°C and 350°C are shown in Fig. 4. The transistor is observed to have a common-emitter current gain (at 20°C or 350°C) peaking in the range of 6-10 and a room temperature, punchthrough-limited, collector-emitter breakdown voltage of approximately -6V. Other parameters of interest for this device include an f_T = 400 KHz (20°C) and a collector-base leakage current = - 200 μA (T = 350°C, V_{CB} = -4V). A simple amplifier constructed from this transistor produced power gains of: 16dB at 20°C and 350°C; 12.5 dB at 400°C; and 2.2dB at 440°C.

Operated as a JFET the transistor had a double-gate pinchoff voltage = 1.8V (20°C) and a common-source transconductance = 120 μS (20°C). No extended life tests have been performed on these structures to date.

The low value of the common-source transconductance and the degradation of the common-emitter output characteristics at high-temperature are both due to excessive series resistance in the lightly doped n-type region of the initial design. In the JFET mode, this resistance appears in series with the source and drain. This seriously degrades the JFET properties as any voltage drop across the source resistance appears as negative feedback on the gate.

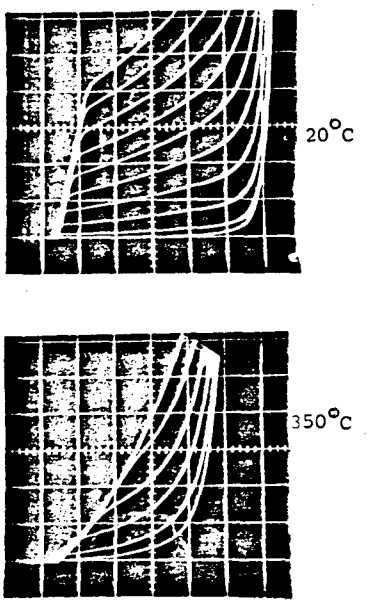

Figure 4. Common-emitter output characteristics of the GaP BJT at 20°C and 350°C. (I_C = -0.5mA/div, V_{CE} = -1V/div, ΔI_B = -0.05mA/step. The curves are inverted for clarity).

In the bipolar mode the resistance of the n-type region appears as a parasitic base resistance. The voltage drop developed across this resistance by the base current causes a decrease in the effective emitter area of the device. This effect is accentuated by the transistors' low value of current gain. The effective emitter area in turn modulates the effective collector and emitter resistances. As hole and electron mobilities decrease at high temperature, all series resistances increase and the common-emitter output characteristics appear to collapse from the saturation side.

Looking at this effect in a different way, Fig. 5 shows common-emitter, a. c. current gain as a function of collector current and temperature. The current gain below the Kirk effect[4] limit stays relatively constant with temperature whereas the peak in the current gain decreases. The important point to note from Fig. 5 is that the poor high-temperature properties of the device are limited by the series resistance of our rather crude initial geometry and not be any fundamental materials limit.

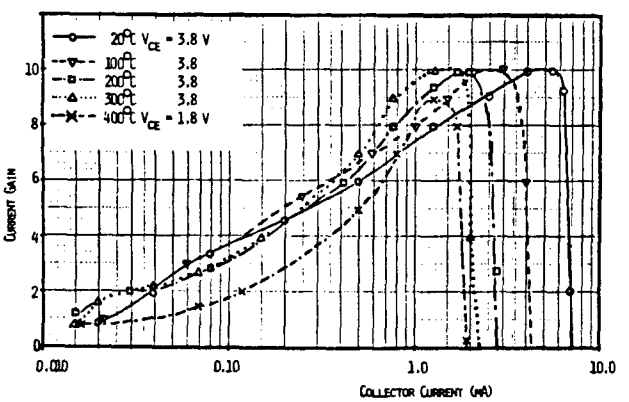

Figure 5. Common-emitter current gain vs. collector current and temperature for the GaP BJT.

An improved structure presently in process which addresses some of these problems is shown in Fig. 6. This device utilizes selective thinning of the base region and a metallorganic CVD deposited emitter to determine active device areas. A thicker inactive base region with an optimized doping concentration should decrease base resistance, increase the collector-emitter breakdown voltage and increase the output resistance. An etched rather than sawn termination of the collector-base junction should reduce collector-base leakage at high-temperatures. Utilizing improved structures such as the one shown in Fig. 6, a GaP device operating for periods in excess of 1000 hours at 400°C is expected in the near future.

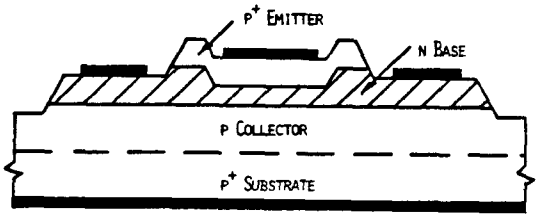

Figure 6. An improved GaP BJT incorporating a selectively thinned base region, an emitter region deposited by metallorganic CVD, and an etch-terminated collector-base junction.

CONCLUSION

Preliminary results have been reported on the development of a GaP bipolar junction transistor for geothermal and other high-temperature applications. A fabrication sequence for the transistor as well as device characteristics have been described. A series resistance problem with the initial design has been identified and suggestions have been made for improved structures.

The authors wish to thank T. A. Plut J. B. Snelling, and R. Chavez for their expert assistance in the preparation and measurement of these samples.

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