# High breakdown voltage InGaAs/InP double heterojunction bipolar transistors with $f_{max} = 256$ GHz and $BV_{CEO} = 8.3$ V

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**Abstract:** An InGaAs/InP DHBT with an InGaAsP composite collector is designed and fabricated using triple mesa structural and planarization technology. All processes are on 3-inch wafers. The DHBT with an emitter area of $1 \times 15$ $\mu$m$^2$ exhibits a current cutoff frequency $f_t = 170$ GHz and a maximum oscillation frequency $f_{max} = 256$ GHz. The breakdown voltage is 8.3 V, which is to our knowledge the highest $BV_{CEO}$ ever reported for InGaAs/InP DHBTs in China with comparable high frequency performances. The high speed InGaAs/InP DHBTs with high breakdown voltage are promising for voltage-controlled oscillator and mixer applications at W band or even higher frequencies.

**Key words:** InP; double heterojunction bipolar transistor; planarization

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## 1. Introduction

Although InP SHBTs have demonstrated good microwave characteristics, the low breakdown voltage and high thermal resistance of the InGaAs collector have limited their applications in millimeter or sub-millimeter wave monolithic ICs and wide dynamic mixed signal circuits. The collector of the InGaAs/InP DHBT is InP, which has a wide gap and high thermal conductivity, these characteristics lead to the much higher breakdown voltage and lower thermal resistance of InP DHBT as compared with InP SHBT. However, there is a conduction band spike between the base and collector for the type I InGaAs/InP DHBT, the spike must be removed otherwise the device performance will be severely degraded[1]. Various composite collector structures have been proposed to overcome this problem[2−4].

In this work, a composite collector with an InGaAs spacer and an InGaAsP quaternary layer was used to eliminate the conduction band spike between the base and the collector. The InGaAs/InP DHBTs were fabricated with a triple mesa process and a benzocyclobutene (BCB) planarization technique. The DHBTs in this process have an emitter area of $1 \times 15$ $\mu$m$^2$ and show cutoff frequencies $f_t$ of 170 GHz and $f_{max}$ of 256 GHz, while maintaining a high break down voltage of more than 8 V.

## 2. Growth and fabrication

The layer structure of the InGaAs/InP DHBTs was grown by molecular-beam epitaxy on a 3-inch semi-insulating InP substrate. The layer sequence is shown in Fig. 1. The DHBT structure includes an InGaAs cap layer (200 nm, $3 \times 10^{19}$ cm$^{-3}$), an InP emitter (200 nm, $2 \times 10^{17}$ cm$^{-3}$), a carbon-doped InGaAs base (50 nm, $3 \times 10^{19}$ cm$^{-3}$) and a compositionally step-graded InGaAs/InGaAsP/InP collector (200 nm, $1 \times 10^{16}$ cm$^{-3}$). A composite collector with an InGaAs spacer and an InGaAsP quaternary layer was used to eliminate the conduction band spike at the B-C interface and thus the collector current blocking effect was minimized[2].

In contrast to most recent reports in China[5, 6], the InP DHBTs in this work were fabricated using standard manufacturing techniques such as i-line stepper lithography and selective dry/wet etching, etc. All InP DHBT processes were on 3-inch wafers. The InP DHBTs were fabricated with conventional wet etching and metal deposition with a triple mesa design. Non-alloyed ohmic Ti/Pt/Au was used as the n-type ohmic contacts and Pt/Ti/Pt/Au was used as a p-type contact. After device isolation, BCB was used for device passivation and planarization. Subsequently, an RIE etch-back step was performed to expose the tops of the device contacts and then the first-level metal was deposited to form the probe pads.

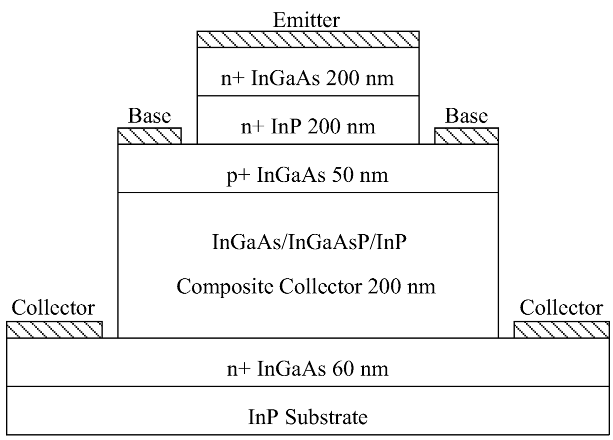


Fig. 1. Layer structure of the InGaAs/InP DHBT.

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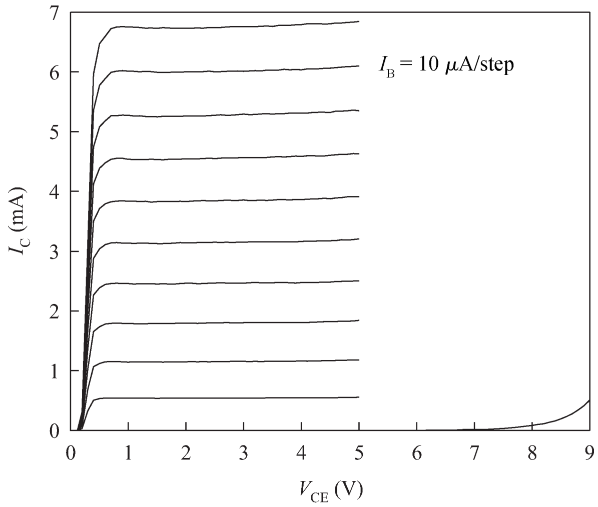


Fig. 2. Typical common-emitter $I$–$V$ curves of a 1 × 15 $\mu$m$^2$ InP DHBT device.

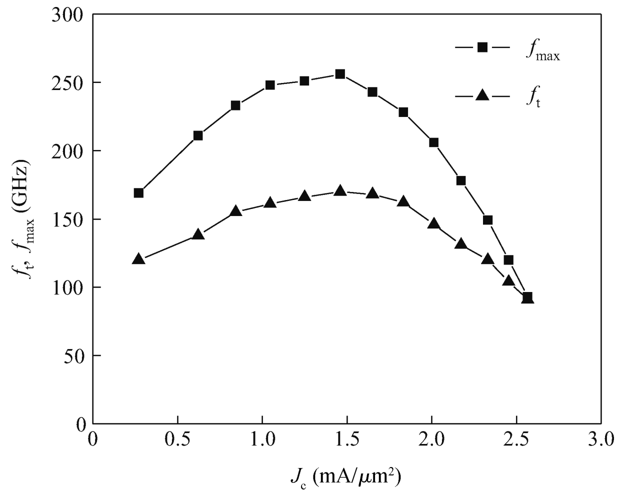


Fig. 4. Variation of $f_t$ and $f_{max}$ versus $J_c$ for the DHBT with emitter area of 1 × 15 $\mu$m$^2$ at $V_{CE}$ = 2.0 V.

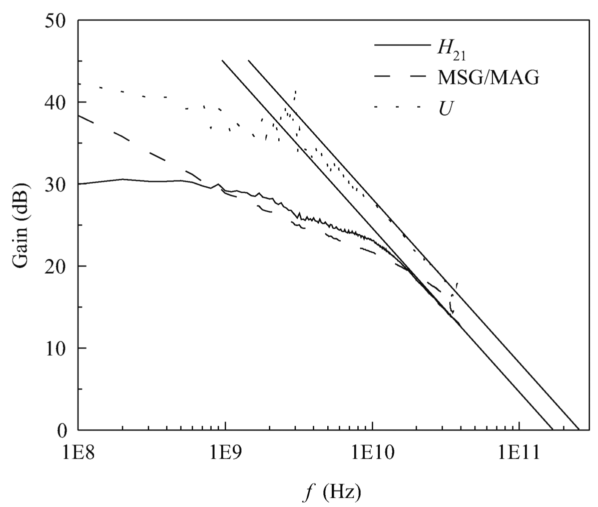


Fig. 3. $H_{21}$, MSG/MAG and $U$ of the DHBT with emitter area of 1 × 15 $\mu$m$^2$ at $V_{CE}$ = 2.0 V and $I_C$ = 22 mA.

## 3. Measurements and results

The InP DHBTs were measured on-wafer at room temperature. The DC characteristics of the InP DHBTs were measured by an Agilent 1500A semiconductor parameter analyzer. The common-emitter $I$–$V$ characteristics of the DHBT with an emitter area of 1 × 15 $\mu$m$^2$ are shown in Fig. 2. The offset voltage is 0.15 V and the knee voltage is about 0.5 V. The small knee voltage and sharp rising current indicate that the current blocking effect is successfully suppressed with the composite collector[7]. The typical current gain is more than 60. The common-emitter breakdown voltage is 8.3 V, which is defined at a current density of $J_c$ = 10 $\mu$A/$\mu$m$^2$. To our knowledge, the common-emitter breakdown voltage is the highest in InGaAs/InP DHBT in China with comparable high frequency performance[5, 8].

100 MHz to 40 GHz measurements were carried out using an HP8510C VNA, which was calibrated using standard short-open-load-through (SOLT) standards. On-wafer open and short pad structures identical to those used by the devices were used to de-embed the pad parasitics. Figure 3 shows the current gain ($H_{21}$), maximum stable gain/maximum available gain (MSG/MAG) and Mason's unilateral gain ($U$) as a function of the frequency at the collector–emitter junction voltage $V_{CE}$ = 2.0 V and the collector current $I_C$ = 22 mA. Extrapolating at –20 dB/decade, $f_t$ and $f_{max}$ are 170 GHz and 256 GHz, respectively. Figure 4 shows the variation of the $f_t$ and $f_{max}$ as a function of the collector current density at a collector–emitter voltage of 2.0 V. The decrease of $f_t$ at a high collector density is due to the Kirk effect, and thus the corresponding Kirk current density of 1.5 mA/$\mu$m$^2$ can be derived.

## 4. Conclusion

In summary, InGaAs/InP DHBTs have been designed and fabricated using standard manufacturing techniques on 3-inch wafers. Devices with an emitter area of 1 × 15 $\mu$m$^2$ show cutoff frequencies $f_t$ of 170 GHz and $f_{max}$ of 256 GHz, while maintaining a high break down voltage ($BV_{CEO}$) of more than 8 V, which is to our knowledge the highest $BV_{CEO}$ ever reported for InGaAs/InP DHBTs in China with comparable high frequency performance. The high speed InGaAs/InP DHBTs with a high breakdown voltage are suitable for voltage-controlled oscillators and mixers at W-band or even higher frequencies.

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