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RF characterization of InP double heterojunction bipolar transistors on a flexible substrate under bending conditions

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Abstract: This letter presents the fabrication of InP double heterojunction bipolar transistors (DHBTs) on a 3-inch flexible substrate with various thickness values of the benzocyclobutene (BCB) adhesive bonding layer, the corresponding thermal resistance of the InP DHBT on flexible substrate is also measured and calculated. InP DHBT on a flexible substrate with 100 nm BCB obtains cut-off frequency f_T = 358 GHz and maximum oscillation frequency f_{MAX} = 530 GHz. Moreover, the frequency performance of the InP DHBT on flexible substrates at different bending radii are compared. It is shown that the bending strain has little effect on the frequency characteristics (less than 8.5%), and these bending tests prove that InP DHBT has feasible flexibility.

Key words: InP DHBT; thermal resistance; radio frequency; bending

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1. Introduction

Flexible electronics have unique advantages of flexibility, ductility and portability, which have wide application prospects in communication information, energy, medical and other fields[1−6]. However, the future application of high frequency communication and wireless internet of things puts forward higher requirements on the frequency of flexible electrons. The current traditional flexible electronic devices and circuits cannot meet the requirements of larger bandwidth and higher speed, because these flexible electronic devices have low carrier mobility and saturation speed in a higher frequency range[7−9]. As a result, high performance RF transistors and circuits with higher speeds and frequencies are in great demand.

At present, various types of flexible electronic materials and devices have been developed and applied, such as graphene/carbon transistor, GaAs HBT/HEMT, Si MOSFET, etc., all of which have their own unique advantages and application fields[10−17]. We have reported a fabrication method for transferring InP DHBTs onto a flexible substrate using benzocyclobutene (BCB) bonding technology lately. The flexible substrate InP DHBT device has the cut off frequency f_T = 337 GHz and oscillation frequency f_{MAX} = 485 GHz[18]. In this paper, we continue to present an optimized process of the BCB adhesive layer between InP DHBT and the flexible substrate, which can operate at higher cut off frequency f_T = 358 GHz and oscillation frequency f_{MAX} = 530 GHz, the thermal resistance (R_{th}) of InP DHBT on flexible substrate is estimated. In addition, the RF performance under different bending radii is also compared.

2. Fabrication process

The process of fabricating InP DHBT devices on flexible substrate has been reported in previous work with identical device geometry[18], while the standard 0.5 μm process is used for InP DHBT devices. Fig. 1 shows a schematic diagram of InP DHBT devices on flexible substrate.

The BCB adhesive layer is sandwiched between InP DHBTs layers and flexible substrate, the thermal conductivity of BCB is 0.3, and InP is 68 W/(m·K), the flexible substrate material used in this letter is boron nitride (BN) composite polymer material, which has a thermal conductivity greater than 8 W/(m·K). Considering the BCB having low thermal conductivity, it is necessary to evaluate the different thickness of BCB adhesive layer which affect the RF and I–V performances of InP DHBT.

The BCB adhesive layer is spun onto two groups of 3-

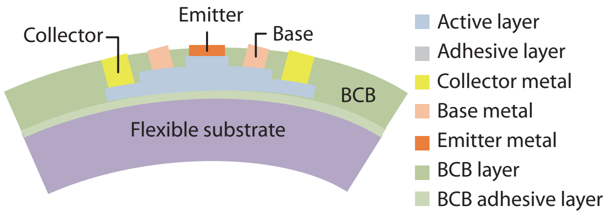

Fig. 1. (Color online) The schematic diagram of InP DHBT device on flexible substrate.

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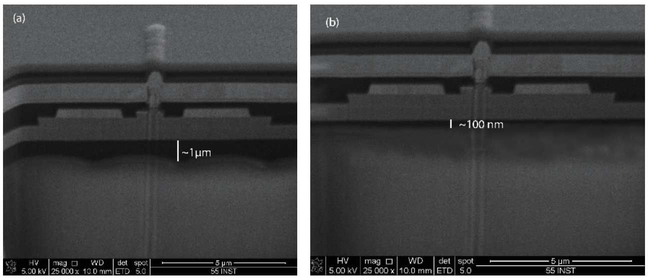

Fig. 2. (a) FIB cross-sectional image of InP DHBT device on flexible substrate with 1 μm BCB. (b) FIB cross-sectional image of InP DHBT device on flexible substrate with 100 nm BCB.

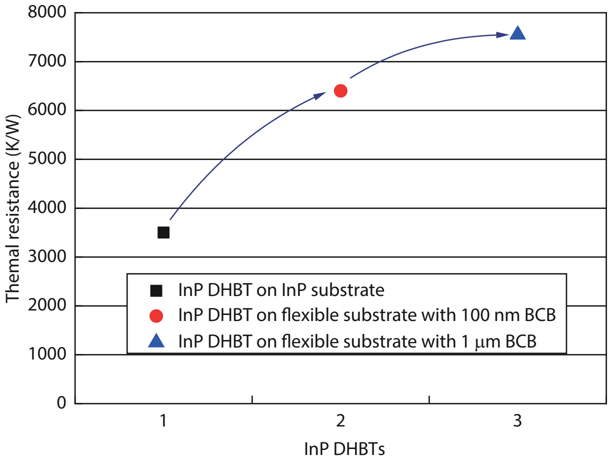

Fig. 3. (Color online) Experimental and calculated R_{th} for InP DHBT and flexible substrate InP DHBT.

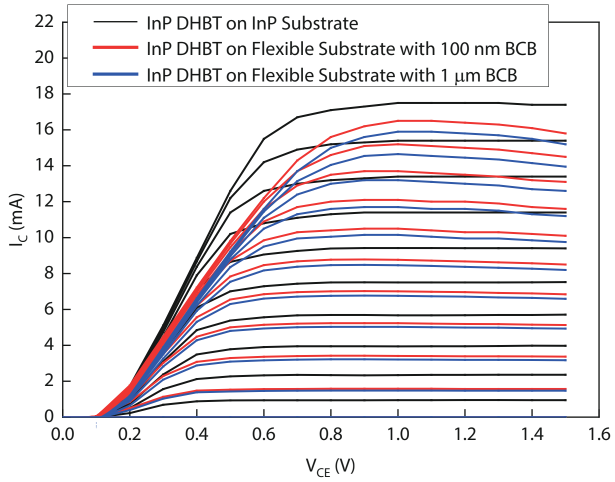

Fig. 4. (Color online) The corresponding I_C– V_{CE} of InP DHBT and flexible substrate InP DHBT.

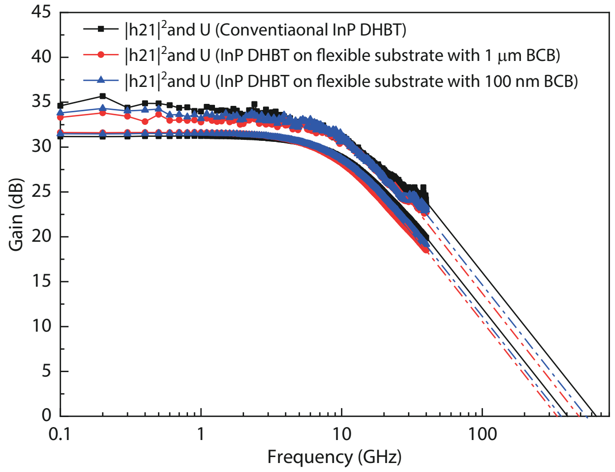

Fig. 5. (Color online) Mason's unilateral gain U and $|h_{21}|^2$ as a function of frequency measured the InP DHBT and flexible substrate InP DHBT.

inch flexible substrates with BCB thickness of 100 nm and 1 μm, respectively. After the InP DHBT device is bonded to the flexible substrate, the BCB thickness under the InP DHBT device is measured by the focused ion beam (FIB), as shown in Figs. 2(a) and 2(b), which shows the FIB image of InP DHBT on the flexible substrate, the thickness of BCB can be measured separately.

3. Results and discussions

To make a heat dissipation evaluation of InP DHBT device on flexible substrate, thermal resistance (R_{th}) of InP DHBT was measured. A large output current leads to an increasing amount of self-heating. Fig. 3 shows the calculated and experimental R_{th} of fabricated InP DHBT with the emitter area of A_E = 0.5 × 5 μm^2. The current gain and emitter-base voltage vary with temperature to evaluate thermal resistance of the device, R_{th} is expressed by the following relation[19]:

$$R_{th} = \frac{1}{\phi}\frac{\Delta V_{be}}{P_{diss}}. \qquad (1)$$

The ϕ is a thermo-electrical coefficient expressed from Gummel plots with different testing temperatures, V_{be} is the base-emitter voltage for a constant collector current, the ϕ can be expressed as $\Delta V_{be} = \phi \cdot \Delta T$, the ΔT in junction temperature versus the backplate temperature for a certain power P_{diss} dissipated in the InP DHBT. And the P_{diss} dissipated power variation with $P_{diss} = \Delta V_{ce} \cdot I_c$. The measured ϕ is about 0.84 mV/K of InP DHBT device. The measured R_{th} of a conventional InP DHBT device on the InP substrate is 3505 K/W, while the InP DHBT device on a flexible substrate with 100 nm BCB exhibits R_{th} of 6410 K/W, which is about an 82.8% increase. And the InP DHBT device on a flexible substrate with 1 μm BCB exhibits R_{th} of 7550 K/W, which is attributed to the low thermal conductivity of flexible substrate and BCB.

I–*V* measurements of flexible substrate InP DHBT devices were performed on a semiconductor wafer probe, Fig. 4 shows the common emitter I_C–V_{CE} characteristics of flexible substrate InP DHBT devices with two different thickness of BCB. It can be confirmed that the I_C–V_{CE} characteristics of InP DHBT devices with different BCB thicknesses are degraded to a certain extent, and the BCB with the thickness of 1 μm is degraded more seriously, this result corresponds to an increase in thermal resistance.

The RF performance of flexible substrate InP DHBTs are measured by vector network analyzer, which using off-wafer line-line-reflect-match calibration, at the same time, the device pads are de-embedded with open/short calibration structures[20–23]. Fig. 5 shows the InP DHBT short-circuit current gain $|h_{21}|^2$ and Mason's unilateral gain U on frequency function, when the V_{CE} = 1.5 V and collector current I_C = 15 mA. Using extrapolation of U and $|h_{21}|^2$ with a –20 dB/dec roll-off yields method, which shows the cut off frequency f_T = 395 GHz, the maximum oscillation frequency f_{MAX} = 630 GHz

Table 1. Comparison of the f_T and f_{MAX} with other previous reported flexible transistors.

Device	f_T (GHz)	f_{MAX} (GHz)	Ref.
Graphene transistor	198	28.2	[13]
InAs MOSFET	105	22.9	[15]
InGaAs/InAlAs HEMT	160	290	[17]
GaAs HBT	37.5	6.9	[24]
GaN HEMT	60	115	[25]
SOI CMOS	150	160	[26]
Si MOFET	5	38	[27]
InP DHBT	337	485	[18]
InP DHBT	358	530	This Work

of the InP DHBT on InP substrate. For the flexible substrate InP DHBT with 100 nm BCB, the cut off frequency f_T and maximum oscillation f_{MAX} are 358 and 530 GHz respectively.

The RF performance f_T and f_{MAX} of the flexible substrate InP DHBT device in this paper are compared with the performance of other flexible transistors reported previously in Refs. [13, 15, 17, 18, 24–27], as shown in Table 1. Our work shows the highest RF frequency performance of flexible devices to date, besides confirms the potential of flexible substrate InP DHBT for high frequency applications.

At the same time, in order to explore the influence of flexible substrate bending on the high-frequency performance of InP DHBT devices, the 3-inch flexible substrate InP DHBT is pasted on curved glass with a certain bending radius[28–30]. The bending degree of flexible substrate depends on the bending radius of curved glass, as shown in Fig. 6(a). Three different bending radii of 70, 30 and 15 mm are set to measure the high frequency performance of the flexible substrate InP DHBT. Figs. 6(b) and 6(c) show a comparison of the frequency characteristics of InP DHBT at these three bending radii. It is observed that a decrease in the bending radii leads to a slight degradation of the device's high-frequency performance, although in a case there is a small increase in f_T as the bending increases. The f_T and f_{MAX} of the device in the bent state are reduced by about 8.5% compared with that in the flat state. The performance of InP DHBT devices decreases slightly under different bending states, which may be related to strain, it affects the carrier mobility and other properties of InP DHBT.

4. Conclusion

A standard 0.5 μm process of InP DHBT is fabricated on 3-inch flexible substrate using epitaxial lift-off and BCB adhesive bonding techniques. Different thickness values of BCB adhesive bonding layer and the corresponding thermal resistance are investigated, besides high cut-off frequency f_T = 358 GHz and maximum oscillation f_{MAX} = 530 GHz are obtained. Moreover, the RF performance under different bending radii is also compared, and the results show that the RF performance of the flexible InP DHBT is less affected by bending strain. These results further confirm the possibility that flexible InP DHBT will be used in flexible RF circuits.

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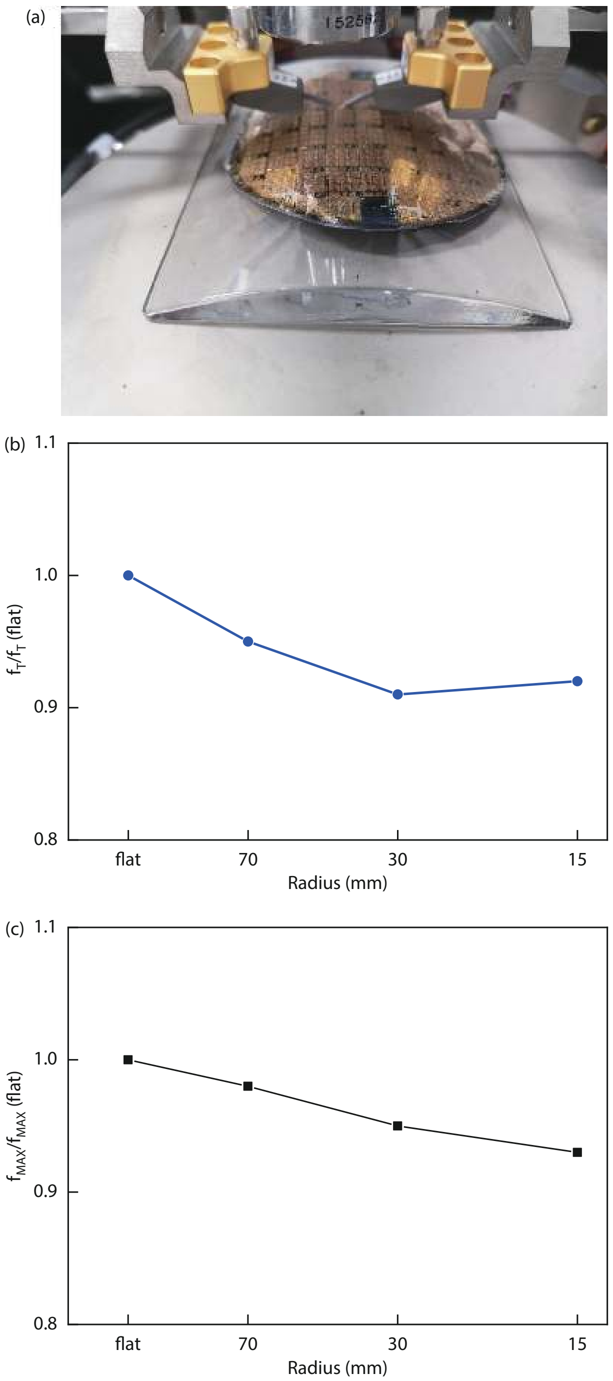

Fig. 6. (Color online) (a) Photographs of InP DHBT on flexible substrate under bending conditions on test bench. The InP DHBT frequency performance under different bending radii: (b) f_T/f_T(flat), (c) f_{MAX}/f_{MAX}(flat).

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