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HIGH CURRENT, MULTI-FINGER InGaAs/InP HETEROSTRUCTURE BIPOLAR TRANSISTOR WITH f_t OF 176GHz

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Abstract: To meet the requirements of millimeter wave circuits for high-current and high cutoff-frequency devices, a compact 4-finger InGaAs/InP single heterostructure bipolar transistor(HBT) was designed and fabricated successfully by using planarization technology. The results show that the width of the emitter fingers is as small as 1μm, the high Kirk current of 4-finger HBT reaches 110mA, and the current gain cutoff frequency is as high as 176GHz. The device is promising on the applications in the medium-power circuits operating at millimeter-wave range.

Key words: InP; heterostructure bipolar transistor; high current; high frequency
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一种 f_t 为 176GHz、大电流多指结构的 InGaAs/InP 异质结双极晶体管

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摘要:针对毫米波电路对大电流、高截止频率器件的要求,利用平坦化技术,设计并制作成功了结构紧凑的四指合成 InGaAs/InP 异质结双极晶体管.实验结果表明发射极的宽度可减小到 1μm. Kirk 电流可达到 110mA,电流增益截止频率达到 176GHz.这种器件有望在中等功率的毫米波电路中有所应用.

关 键 词:InP;异质结双极晶体管;高电流;高频

Introduction

InGaAs/InP heterostructure bipolar transistors (HBTs) have been studied extensively in recent years due to their excellent material properties. InGaAs/InP HBTs have been widely used to fabricate the power amplifiers working at millimeter band and the high-speed mixed-signal integrated circuits[1,2]. The operating frequency of the power amplifier fabricated by InGaAs/InP HBTs reaches as high as 200GHz[1]. The operating frequency of the frequency divider is more than 150GHz, which is the highest among all the technologies[2]. In a power amplifier, the output power and the cutoff frequency are the critical figures of the merit of a device. The output power is proportional to the current of the device. To increase the current of HBT, two methods are adopted: one is to increase the Kirk current density of a HBT (Kirk current is the maximum operating current for HBT), the other is to increase the total emitter length of the device. The Kirk current density is increased by optimizing the HBT structure and decreasing the emitter width. However, a too long

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emitter of HBT will cause the degradation of the HBT due to the severe ununiform current along the emitter[3]. A solution is to make a multi-finger HBT. In a poor designed topology of a multi-finger HBT, the interaction between the fingers causes a significant decrease in the cutoff frequency and makes a large decrease in the Kirk current[4]. The topology of a multi-finger HBT is thus very important to increase the total current and high frequency performances. The cutoff frequency is related to the emitter width. When the emitter width decreases, the cutoff frequency increases. However, it is difficult to fabricate the HBTs with emitter width less than 1μm because the small emitter is very difficult to connect and the side etching is difficult to control. We recently developed a planarization process, in which the narrow emitter can be connected easily[5]. In that paper, a 1.4μm emitter has been demonstrated.

In this paper, we report a topology of a multi-finger InGaAs/InP HBT. The width of each emitter decreased to 1μm by the careful control of the side etching of the emitter. The Kirk current was more than 110mA and the Kirk current density was about 2.3 mA/μm^2. The current gain cutoff frequency was as high as 176GHz.

1 InGaAs/InP HBT structure and fabrication

The HBT structure was grown by Gas Source Molecular Beam Epitaxy (GSMBE) on semi-insulating InP substrate. The structure is the same as that we reported previously[5]. The schematic diagram of the structure is shown in Fig. 1. The HBTs were fabricated by contact-mode photolithography, conventional wet etching and metal deposition with 3-mesa design. The process can be found in more detail in Ref. [5]. Fig. 2 shows a photograph of HBT before the pad metal is deposited. The nominal emitter width of each finger is 1μm, the length of each emitter is 15μm. The total emitter length is then 60μm. The DC and RF characteristics of the HBTs were measured by HP 4515B semiconductor parameter analyzer and HP 8510C vector network analyzer, respectively.

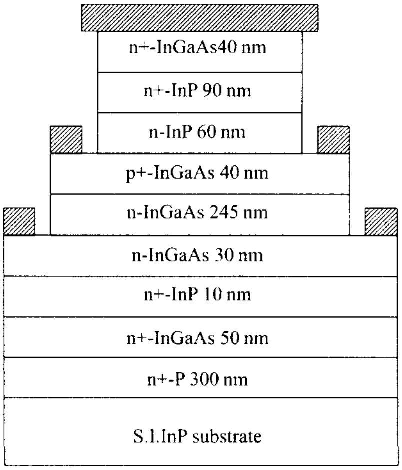

Fig. 1 The schematic diagram of InGaAs/InP HBT layer structure
图1 InGaAs/InP HBT结构示意图

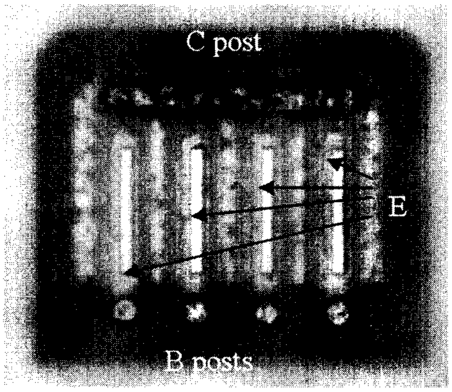

Fig. 2 Photograph of the four-finger HBT after planarization and etched back
图2 平坦化和回刻后的四指HBT照片

2 Results and discussion

DC characteristics of the multi-finger HBT are very much like those reported in Ref. [5] except that the current can be much higher. The breakdown voltage is 3.3V, which is the same as that in Ref. [5]. Here we concentrate on the RF performances of the HBT. The RF performances of the four-finger HBT were measured by vector network analyzer. The measured S parameters were de-embedded using Open and Short structures. The de-embedded S parameters were then converted into $|h_{21}|$ and unilateral power gain, U. Theoretically, $|h_{21}|$ and U roll off with increasing the frequency at a slope of −20 dB/decade at high frequencies[6]. The current gain cutoff frequency (f_t)

and the maximum oscillation frequency (f_{max}) are extrapolated from $|h_{21}|$ and U, using the -20 dB/decade slope to find out the frequencies when $|h_{21}|$ and U roll off to unity. Fig. 3 shows $|h_{21}|$ as a function of the frequency. Here, $V_{CE} = 1.1$ V, $I_B = 0.72$mA, the corresponding $I_C = 91.3$mA. The DC current gain is thus 127. $|h_{21}|$ is more than 35dB gain at low frequency. It then decreases with an increase in the frequency. f_t of 176GHz can be extrapolated from the $|h_{21}|$ curve, using the guide line with the -20dB/decade slope. f_t is lower than that of the single-finger HBT reported in Ref[5]. Fig. 3 also shows U as a function of the frequency. U is about 30dB at low frequency. It then decreases with an increase in the frequency. f_{max} of 54GHz can be obtained from the -20dB/decade slope line. f_{max} is almost the same as that of the single-finger HBT reported in Ref. [5].

f_t and f_{max} can be expressed as follows[6]

$$f_t = \frac{1}{2\pi}\left[\frac{nkT}{qI_C}(C_{BE} + C_{BC}) + \frac{X_B^2}{vD_n} + \frac{X_{dep}}{2v_{sat}} + (R_E + R_C)C_{BC}\right]^{-1}, \qquad (1)$$

$$f_{max} = \sqrt{f_t/(8\pi r_B C_{BC})}, \qquad (2)$$

here, n is the ideality factor of collector current, k is the Boltzmann's constant, T is the temperature of the device, q is the electric charge, I_C is the collector current, C_{BE} and C_{BC} are the capacitors of the base-emitter and base-collector junctions, respectively, X_B is the thickness of the base, D_n is the electron diffusion coefficient in the base, X_{dep} is the depletion layer thickness of the collector, v is the coefficient of the base transmit time ($v = 2$ in the case of non-grading composition and doping in the base), v_{sat} is the saturation velocity of electrons in the collector, R_E and R_C are the resistances of the emitter and collector contacts and r_B is the resistance of the base. f_t of the four-finger HBT is smaller than that of the single-finger HBT. The difference in f_t between the four-and single-finger HBTs may be caused by the reduction of the collector current density. The contact resistances (R_E, R_C and r_B) of a four-finger HBT are a quarter of those of a single-finger HBT. However, the associated junction capacitances of a four-finger HBT increase by 4 times. If the current density decreases, the first term in the bracket on the right side of Eq. (1) increases, while the left three terms keep constant. The current density of the four-finger HBT at the measurement point is smaller than that in Ref. [5]. Thus f_t should be smaller than that of the single-finger HBT. As we can see from Eq. (2), f_{max} is related to C_{BC} and r_B. The product of C_{BC} and r_B of four-and single-finger HBTs should be the same, as analyzed above. r_B is related to the base sheet resistance and the base specific contact resistivity[5]. The base sheet resistance and base specific contact resistivity are 2184Ω/□ and $2.4 \times 10^{-5}\Omega \cdot cm^2$, which are large values and may be caused by the low activation rate of the p doping in the base. The low f_{max} is mainly due to the high base sheet resistance and the high specific contact resistance, which is the same reason as that in Ref. [5].

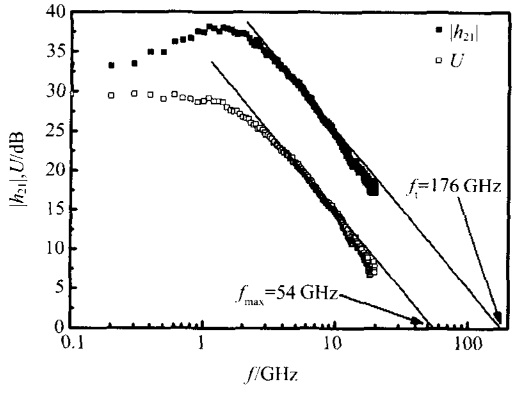

Fig. 3　$|h_{21}|$ and U as a function of the frequency f
图 3　$|h_{21}|$ 和 U 与测量频率 f 关系曲线

The slope of $|h_{21}|$ should be -20dB/decade at high frequencies for HBT. However, $|h_{21}|$ decreases faster than -20dB/decade when the frequency is larger than 10GHz, as shown in Fig. 2. This may be due to the de-embedding process. The de-embedding process eliminates the effects of the parasitics of the pads. Fig. 4 compares $|h_{21}|$ as a function of the frequency before and after de-embedding. We can see that $|h_{21}|$ is almost the same before and after de-embedding when the frequency is less than 4GHz. This indicates that at low frequency, the effect of the pad-related parasitics on the S parameters is negligible. However, the difference of $|h_{21}|$ between before and after de-embedding increases with increasing the frequency when the frequency is larger than 4GHz. Fur-

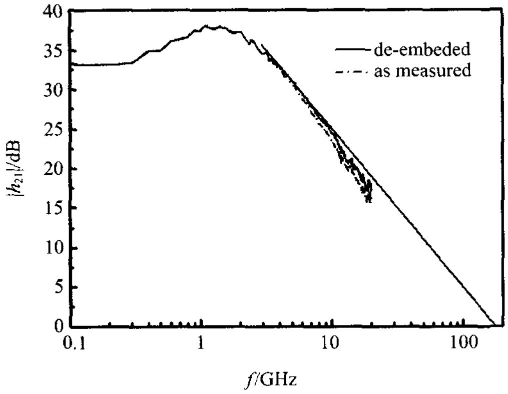

Fig. 4 $|h_{21}|$ as a function of the frequency before and after de-embedding
图4 去嵌化前后$|h_{21}|$与测量频率的关系曲线

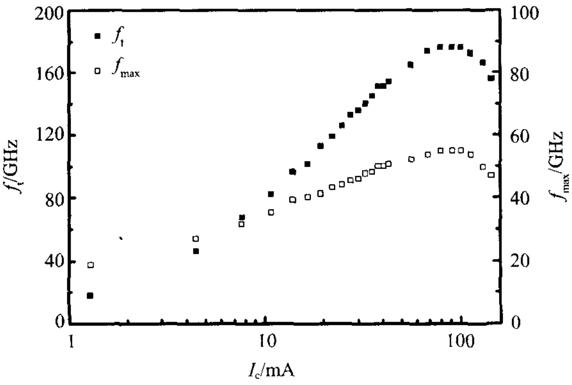

Fig. 5 f_t and f_{max} as a function of the collector current I_c
图5 f_t和f_{max}与集电极电流I_c的关系曲线

thermore, $|h_{21}|$ before de-embedding decreases even faster than that after de-embedding. The similar phenomenon has been reported by Lee et al[7]. In their case, both $|h_{21}|$ and U deviate from the -20dB/decade slope line at high frequencies. In our case, the de-embedding makes the slope closer to the -20dB/decade and makes f_t increase by 12GHz. However, the slope of $|h_{21}|$ is still smaller than -20dB/decade. The smaller slope thus indicates that the S parameters are under de-embedded and that the actual f_t should be larger than 176GHz.

Fig. 5 shows f_t and f_{max} as a function of the collector current. Both f_t and f_{max} first increase with an increase in the collector current, they then decrease with increasing the collector current. From Eq. (1), f_t should increase monotonously with an increase in I_C. The decrease in f_t is due to the Kirk effect[4]. In the circuit design, Kirk current is the maximum operating current. Thus the Kirk current should be as high as possible. The Kirk current of our HBT is more than 110mA, which is almost four times that of single-finger HBT in Ref. [5]. Considering the undercut of the emitter, which is 0.1μm on each side, the total area of the emitter is 48μm^2. The Kirk current density is then more than 2.3mA/μm^2. This is a very high value. The high Kirk current density means that the effect between fingers of the HBT is small. This may benefit from the topology. In the structure, the emitter fingers are directly contacted through a wide metal strip, so the thermal dissipates more easily. This decreases the interaction between the fingers of the HBT and results in a high Kirk current density.

3 Conclusions

A multi-finger InGaAs/InP HBT with very high frequency and very high Kirk current density has been demonstrated. The current gain cutoff frequency is more than 176GHz and the maximum oscillation frequency is more than 54GHz. The Kirk current density reaches more than 2.3mA/μm^2. The device is very promising on the applications in millimeter wave circuits.

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