A Submicron InGaAs/InP Heterojunction Bipolar Transistor with f_t of 238GHz*

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Abstract: A non-micro-air-bridge InP-based heterojunction bipolar transistor (HBT) is fabricated. A very small emitter side etching (<100nm) is developed and makes a submicron InP-based HBT possible. The current gain cutoff frequency is as high as 238GHz for the submicron HBT with an emitter area of 0.8μm×15μm due to the reduction of emitter width. A base-collector over-etching technology is developed, resulting in a reduction of base-collector junction area and an increase in the maximum oscillation frequency. A very high Kirk current density of 3.1mA/μm^2 is obtained. To the best of our knowledge, the current gain cutoff frequency is the highest among three-terminal devices in China and the Kirk current density is also the highest in HBTs reported in China. This is very helpful for the application of HBTs in ultra high-speed circuits.

Key words: InP; heterojunction bipolar transistor; planarization; high frequency
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1 Introduction

InP-based HBTs have been extensively studied in recent years. Compared with SiGe/Si HBTs, InGaAs/InP HBTs have much better high frequency performances due to lower lattice mismatch between InGaAs and InP, larger band discontinuity between emitter and base, lower base contact resistance, and higher saturation velocity of electrons in the collector, and so on. The collector current density needs to be maximized to improve the speed of circuits[1]. A method to increase the collector current density is to decrease the emitter width. To increase the high frequency performances of HBTs, the emitter width decreases further and the active region becomes smaller. A submicron HBT is necessary for analog circuits working at W-band and higher frequencies and mixed-signal circuits at very high speed[2,3]. To develop submicron HBT, the parasitics must be considered carefully. Yu *et al*. developed double and single μ-air bridge technologies to reduce the parasitics[4]. The current gain cutoff frequency (f_t) could reach 147GHz for the double μ-air bridge HBT and 178GHz for the single μ-air bridge HBT. This indicates that the reduction of the μ-air bridge can reduce the parasitics and increase f_t. However, this technology is not suitable for submicron HBT fabrication because the alignment of the aligner can not meet the requirement and an air bridge with such a small connection is not reliable. Recently, we developed a layout to avoid using both emitter and base μ-air bridges. A recorded current gain cutoff frequency was as high as 210GHz when the emitter size is 1.4μm × 15μm[5]. The submicron emitter width can further improve the high frequency performances. To develop a submicron HBT, the most important things are the submicron photolithography and a very small emitter under etching. However, there is no report on the submicron InP-based HBT and there is also no report on the Kirk current density of InP-based HBTs in China so far. In this paper, we mainly concentrate on solving the small emitter under-etching and submicron photolithography. An HBT with the width of the emitter as small as 0.8μm has been fabricated successfully, and f_t reaches as high as 238GHz and a very high Kirk current density of 3.1mA/μm^2 has been obtained. Both the f_t and the Kirk current density are the best recorded values in China.

2 Device fabrication

The HBT layers were grown by gas source molecular beam epitaxy (GSMBE) on semi-insulating InP substrate. The band diagram of the layer structure is shown in Fig. 1. The layer structure of the HBT consists of a 300nm InP (Si: 3×10^{19} cm^{-3}) and a 50nm

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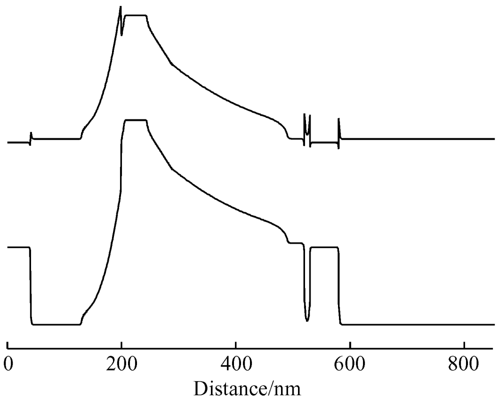

Fig.1　Band diagram of the InGaAs/InP HBT

$In_{0.53}Ga_{0.47}As$ subcollector (Si: $3\times10^{19}cm^{-3}$), a 10nm InP etch stop layer (Si: $1.5\times10^{19}cm^{-3}$) and a 30nm $In_{0.53}Ga_{0.47}As$ (Si: $1\times10^{19}cm^{-3}$), a 245nm InGaAs collector (Si: $1\times10^{16}cm^{-3}$), a 40nm InGaAs base layer (Be: $3\times10^{19}cm^{-3}$), a 5nm InGaAs (unintentionally doped) to avoid the Be diffusion, a 60nm InP emitter (Si: $3\times10^{17}cm^{-3}$), a 90nm InP (Si: $3\times10^{19}cm^{-3}$), and a 40nm $In_{0.53}Ga_{0.47}As$ cap layer (Si: $3\times10^{19}cm^{-3}$). The HBTs were fabricated by contact-mode photolithography, conventional wet etching, and metal deposition with 3-mesa design. Non-alloyed Ti/Pt/Au is used as n- and p-type Ohmic contacts. InP was etched by a HCl-based etchant, and InGaAs was etched by a H_3PO_4-based etchant. The planarization of the device was done by polyimide, which allows the contact connections with pads without a micro-air bridge to avoid the micro-air-bridge-related parasitics. After the planarization, the dielectric film is etched back to expose the emitter contact and base and collector posts. Figure 2(a) shows a photograph of the HBT. The emitter area is $0.8\mu m\times15\mu m$. The emitter contact and the base and collector posts are all higher than the dielectric film. The emitter contact and posts are connected with the outside pads through a thick Au film. There are several advantages in this structure: first, the emitter area can be made very small; second, the parasitics related to the emitter and base contacts are reduced; third, the thermal heat generated can be easily dissipated through the emitter pad.

Figure 2(b) shows the cross-section of the HBT. In the current process, we mainly optimize the photolithography and the emitter under etching to develop the submicron HBT process. Figure 2(b) shows that the undercut of the emitter is less than 100nm. The base and collector are deeply etched to decrease the base-collector area. The DC and RF characteristics of the HBTs were measured by an HP 4515B semiconductor parameter analyzer and an HP 8510C vector network analyzer, respectively.

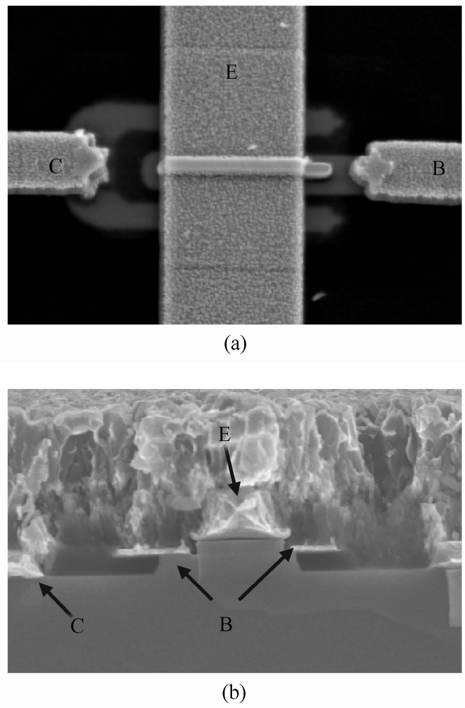

Fig.2　(a) Photograph of the submicron InGaAs/InP HBT after dielectric planarization; (b) Cross-section of the submicron HBT　E, B, and C are the connections of emitter, base, and collector.

3　Results and discussion

The DC measurement of the submicron HBT shows that the current gain is more than 100 and the breakdown voltage is 3.2V. Figure 3 shows $|h_{21}|$ and the maximum stable gain/maximum available gain (MSG/MAG) as a function of the measured frequency at the collector-emitter junction voltage V_{CE} = 1.1V and base current I_B = 0.2mA. Under these conditions, the collector current, I_C, is 23.8mA, making the DC current gain of the device more than 110. The DC current gain of 110 is a very high value for the emitter area of $0.8\mu m\times15\mu m$, indicating good processing control. The slopes of the two guidelines in Fig.3 are −20 dB/decade, thus f_t = 238GHz and f_{max} =

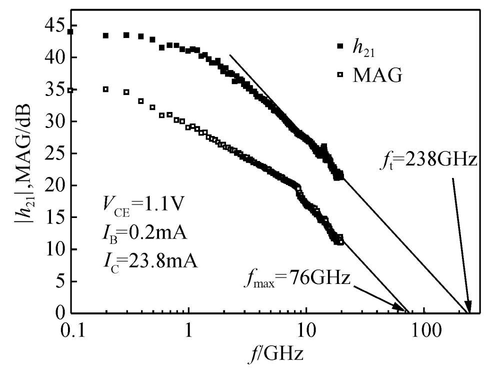

Fig.3　$|h_{21}|$ and MSG/MAG as a function of frequency at V_{CE} = 1.1V and I_B = 0.2mA

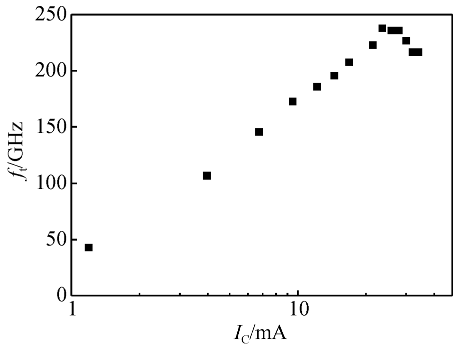

Fig. 4 f_t as a function of I_C

76GHz can be extrapolated. f_t of the submicron HBT is larger than that of the HBT with 1.4μm × 15μm[5], indicating the superiority of the small emitter size. The f_t is even higher than that of the InGaAs/InP HBT with the Be doped base developed by transferred-substrate technology[8]. To the best our knowledge, the f_t is the highest in China.

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

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

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

where 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 are the thickness of the base, D_n are the electron diffusion coefficient in the base, X_{dep} is the depletion layer thickness of the collector, ν is the coefficient of the base transmit time ($\nu = 2$ 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 is the resistances of the emitter and collector contacts, respectively and r_B is the resistance of the base.

Our previous work showed that the lower f_{max} is due to the large contact resistances and the large specific sheet resistance. Compared with the results in Ref. [5], the maximum oscillation frequency increases by 35%. We believe that the increase in f_{max} is mainly due to the reduction of C_{BC}. The deep undercut base and collector etching is developed, as shown in Fig. 2 (b). This decreases the base-collector junction area and decreases C_{BC}. The f_{max} is thus increased by the reduction of C_{BC}.

Another advantage of the submicron HBT is the high Kirk current density. Figure 4 shows f_t as a function of I_C for the submicron HBT. This figure shows that f_t increases linearly with an increase in the logarithm of I_C. From Eq. (1), the increase actually reflects the first term in the bracket on the right side. However, f_t decreases with an increase in I_C when I_C is larger than 28mA. This effect is not indicated in Eq. (1) and is due to the Kirk effect[7]. The carriers injected from the emitter-base junction go through the base and are collected by the collector. The carrier density in the collector increases as I_C increases. When the carrier density is larger than the collector doping density, the slope sign of the electric field in the collector changes. The electric field of the collector at the base side can reach zero when the collector current increases further. The corresponding current density is the Kirk current density. If the collector current increases, the electric field of the collector is positive and the base region will extend into the collector. Because the carriers go through the base by diffusion and the diffusivity is typically very small in a highly doped base, the extension of the base thus increases the transient time of the carriers in the base. f_t decreases accordingly. The Kirk current is the maximum operation current of HBTs in the circuits. To increase the speed of the circuit, the Kirk current should be as high as possible. In addition, f_t increases before the collector current reaches the Kirk current, as seen in Eq. (1). Thus the increase of Kirk current can also result in an increase in f_t. If we consider the undercut of the emitter, the real emitter area is 0.6μm × 15μm. The Kirk current density is thus as high as 3.1mA/μm^2, which is a very high value.

4 Conclusion

In summary, non-micro-air-bridge processing of InGaAs/InP HBT has been successfully demonstrated. A very small emitter side etching (<100nm) has been developed and makes a submicron InP-based HBT possible. The recorded current gain cutoff frequency of 238GHz has been obtained for the submicron HBT with an emitter area of 0.8μm × 15μm and the maximum oscillation frequency is increased to 76GHz, which benefits from the base-collector over-etching technology. A very high Kirk current density of 3.1mA/μm^2 has been demonstrated. These results indicate the advantages of our layout design and the improvement of our process.

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截止频率为 238GHz 的亚微米 InGaAs/InP 异质结双极晶体管*

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摘要： 研制成功了一种无微空气桥的亚微米 InP 基异质结双极晶体管(HBT).发展了小于 100nm 的发射极侧向腐蚀工艺,实现了亚微米的 InP 基 HBT.发射极宽度的减小有效提高了频率特性,发射极面积为 0.8μm×15μm 的 HBT 的电流增益截止频率达到了 238GHz.发展了基极-集电极的侧向过腐蚀工艺,有效减小了结面积,提高了最大振荡频率. Kirk 电流密度达到了 3.1mA/μm^2.据我们所知,电流增益截止频率是目前国内三端器件中最高的,Kirk 电流密度是国内报道的 HBT 中最高的.这对于 HBT 器件在超高速电路中的应用具有十分重要的意义.

关键词： InP；异质结构双极晶体管；平坦化；高频

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