第26卷 第8期 半 导 体 学 报 Vol.26 No.8
2005年8月 CHINESE JOURNAL OF SEMICONDUCTORS Aug.,2005

Fabrication and Simulation of an AlGaAs/GaAs Ultra-Thin Base NDR HBT*

Qi Haitao, Zhang Shilin, Guo Weilian, Liang Huilai, and Mao Luhong

(School of Electronic Information Engineering, Tianjin University, Tianjin 300072, China)

Abstract: A novel mesa ultra-thin base AlGaAs/GaAs HBT is designed and fabricated with wet chemical selective etch technique and monitor electrode technique. It has a particular and obvious voltage-controlled NDR whose PVCR is larger than 120. By use of device simulation, the cause of NDR is that increasing collector voltage makes the ultra-thin base reach through and the device transforms from a bipolar state to a bulk barrier state. In addition, the simulated cutoff frequency is about 60～80GHz.

Key words: HBT; ultra-thin base; device simulation; voltage-controlled NDR; PVCR

EEACC: 2550X; 2560J **PACC:** 7280E

CLC number: TN325⁺.3 **Document code:** A **Article ID:** 0253-4177(2005)08-1495-05

1 Introduction

In the last ten years, several types of novel high speed and high frequency negative differential resistance (NDR) devices, such as resonant tunnelling diode (RTD)[1～3] and real space transfer transistor (RSTT)[4,5], have been fabricated and widely used as multiple value logic circuits, trigger, frequency amplifier, A/D converter, and so on[6]. Application of NDR devices not only evidently improves circuit performance, but also greatly simplifies the device quantity needed in circuits and enhances integration degree. A heterojunction bipolar transistor (HBT) is a high speed and high frequency bipolar device. Because of having resolved the conflict between emission efficiency and base resistance on base doping concentration, HBT influences the development of bipolar devices greatly. If a device realizes the integration of NDR device and HBT, it will have high speed, high frequency merits derived from HBT as well as intrinsic bistability and self-latching characters from NDR. Such a device will be a new type of device of wide application.

In this paper, through special material structure and fabrication process design, a novel 8nm base AlGaAs/GaAs NDR HBT which has distinct voltage-controlled negative differential resistance character and the PVCR (peak-to-valley current rate) is bigger than 120 was fabricated successfully. The simulation results with ATLAS simulator are consistent with the experiment ones. The cause of NDR is explained to transformation from bipolar state to bulk barrier state.

2 Material structure and fabrication process

The device is designed to be a double heterojunction HBT structure and material is prepared with molecular beam eptaxial (MBE) technique in the Institute of Physics, CAS, which is shown in Fig. 1. On the semi-insulated GaAs substrate, n^+

* Project supported by the State Key Development Program for Basic Research of China (No. 2002CB311905)

Qi Haitao male, was born in 1975, PhD. He is mainly engaged in research on novel semiconductor devices and integrated technologies.

Received 15 February 2005, revised manuscript received 10 April 2005

GaAs subcollector layer, n^- AlGaAs collector layer, undoped spacer, p^+ GaAs base layer, undoped spacer, n^- AlGaAs emitter layer, and n^+ GaAs cap layer are grown in turn. The n-type dopant is Si^{4+} and the p-type dopant is Be^{2+}. During the fabrication, conventional contact photolithography, metal lift-off, and mesa isolation are used. Firstly, the GaAs cap layer and the part of AlGaAs emitter layer are etched by a low concentration $H_2SO_4/H_2O_2/H_2O$ solution. Then, the remainder AlGaAs emitter layer is etched by a high concentration HF/H_2O solution, which etches GaAs little. The emitter and collector metal are magnetron-sputtering AuGeNi/Au and the base metal is vacuum evaporation ZnAu/Au. They are alloyed together from 100 ℃ to 360 ℃ for 5min. The device is passivated using SiO_2 through PECVD. The cross-sectional view of the device is shown in Fig. 2. All the electrodes are the same size of 10μm × 20μm. The area of the base mesa is 50μm × 40μm and the area of the collector mesa is 90μm × 60μm. The key of the process is how to ensure base metal evaporating exactly on the top cap layer. In former reports, the base of the thin base HBT (10～30nm base) was commonly educed through V-type groove[7] or ion implantation[8], which are complicated and difficult to control. In this paper, monitor electrode technique is adopted, except for wet selective etch technique. Monitor electrodes are fabricated along with various electrode metals. Etching depth and quality of contact metal can be estimated through testing the electric characteristics between monitor electrodes at any moment. The detailed fabrication process is shown in Fig. 3.

n^+	GaAs	$2\times10^{18}cm^{-3}$	200nm
n^-	AlGaAs	$5\times10^{17}cm^{-3}$	200nm
Undoped	GaAs		5nm
p^+	GaAs	$5\times10^{18}cm^{-3}$	8nm
Undopd	GaAs		5nm
n^-	AlGaAs	$5\times10^{16}cm^{-3}$	300nm
n^+	GaAs	$2\times10^{18}cm^{-3}$	500nm
(100) SI GaAs substrate			

Fig. 1 Material structure of ultra-thin base HBT

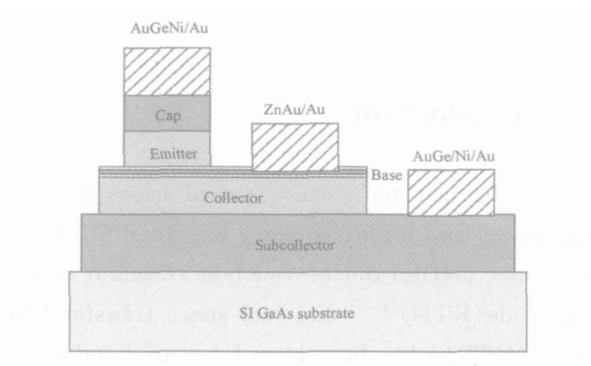

Fig. 2 Cross-section view of ultra-thin base HBT

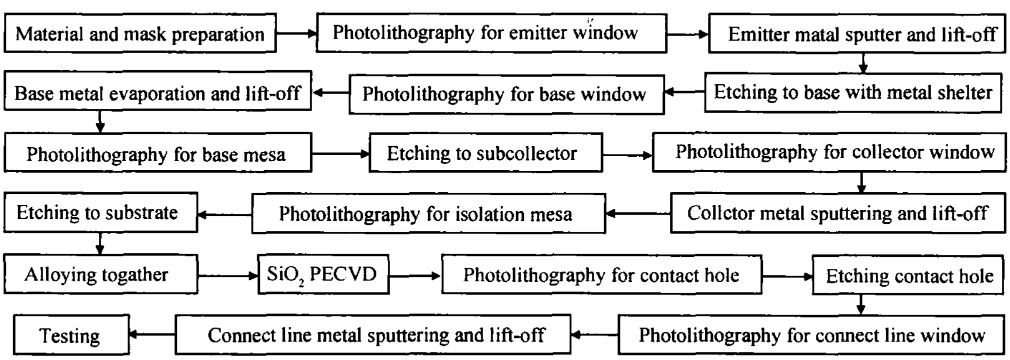

Fig. 3 Fabrication process of ultra-thin base HBT

3 NDR characteristics of device

Several batches of devices based on the same process have been fabricated successively and similar results are received. The novel ultra-thin base device exhibits special and obvious voltage-controlled NDR characteristic.

Figure 4 shows the device 's common-emitter I_c-V_c characteristic curves corresponding to different base voltages V_b, which are tested with an XJ2810 semiconductor curve tracer at 300 K. Figure 4 (a) shows the status of higher constant V_b and Figure 4 (b) shows the status of lower constant V_b. Every curve can be divided into four regions: negative current region, positive resistance region, negative resistance region, and second positive resistance region (shown in Fig. 4(a)). The peak collector current I_p rises markedly and moves to right slowly with base voltage V_b increasing. When V_b is smaller, the valley collector current I_v is almost down to 0 and the peak-to-valley current rate (PVCR) is very high. When V_b is bigger, I_v increases and PVCR decreases gradually. As an example, $I_p = 120\mu A$, $I_v < 1\mu A$ and PVCR > 120 when V_b = 5V. So a high PVCR is very suitable for application.

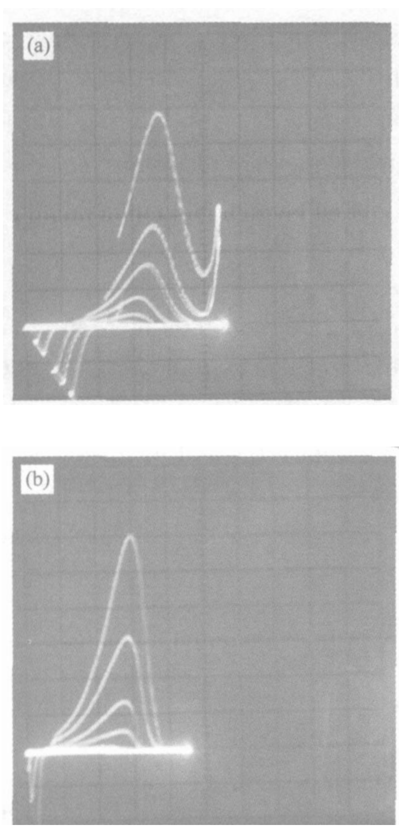

Fig. 4 Common-emitter DC characteristic of ultra-thin base HBT (a) X: 2V/ div; Y: 0. 5mA/ div; V_b step: 1V; (b) X: 2V/ div; Y: 20μA/ div; V_b step: 0. 5V

4 Device simulation and mechanism discussion

In order to explain the NDR mechanism, we simulate the constant voltage common-emitter DC characteristics of ultra-thin base HBT using an ATLAS structure simulator produced by the Silvaco Company on the SUN workstation of Tsinghua University. During the simulation, material structure is designed according to actual condition. Avalanche breakdown, interface and surface recombination are ignored, in order to search the main reason for causing NDR and reduce the consumed time. Isothermal simulation is adopted to exclude any self-heating effect. Hydrodynamic transport model, thermionic emission model, and high field mobility degradation are used for abrupt hetero-interfaces existing. The simulation results are shown in Fig. 5, which approximates the testing result. Figure 6 shows the change of space charge in the base along with the collector voltage (V_c) when V_b = 2V. The valley voltage (V_c = 6V) corresponds to the transformation point from partial depletion base to full depletion base. Through synthetical analysis of ev-

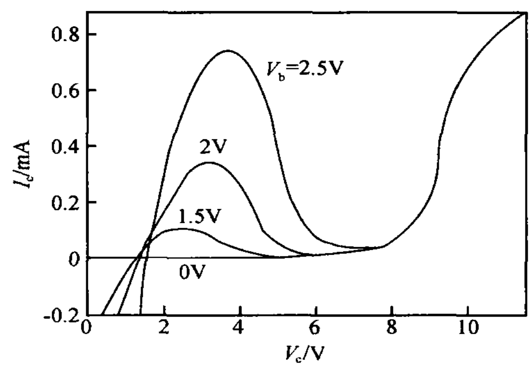

Fig. 5 Simulated common-emitter DC characteristics of ultra-thin base HBT at 300 K

ery electrode 's electron and hole current, space charge distributions, carrier distributions, electric field and potential distribution, we explain the cause of NDR of ultra-thin base HBT. It is well known that the depletion region of the collector

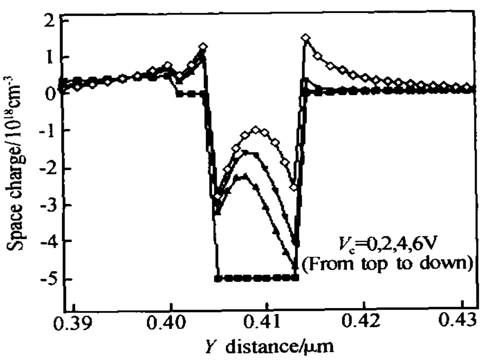

Fig. 6 Changes of space charge in base with V_c (V_b = 2V)

junction will extend towards the base region and collector region and the effective base thickness will be thinned when the collector biased voltage of HBT increases, namely early effect. For the base thickness of conventional HBT is above 40nm and base is heavy doped, the influence of early effect on characteristics is correspondingly trivial. When base thickness is designed under 10nm, the depletion region of the collector junction may joint the depletion region of emitter junction, and the base region may reach through. The device will transform from a bipolar transistor to a bulk barrier transistor[9]. The latter's electric characteristics have relation to material selection and doping concentration design. When base doping concentration is heavier ($\geq 5 \times 10^{18} cm^{-3}$), the turn-on voltage of a bulk barrier transistor may be higher (> 5V) and the current before turn-on is very low (≈0A). The transformation from bipolar state to bulk barrier state along with the collector voltage increasing is the reason for the NDR phenomenon of ultra-thin base AlGaAs/GaAs HBT. Base voltage causes the neutral base region to extend towards both sides and plays a reverse role with collector voltage. The higher the base voltage is, the bigger the negative collector current and the collector peak current becomes. The site where the positive collector current occurs moves right along with the base voltage increasing. Finally, all curves connect with the curve whose base voltage is 0V and which remains in a bulk barrier state all the time. Through analysis, we also know that this kind of device can show two types of NDR curve shapes. When the transform point appears in the saturation region of the bipolar state, the NDR curve will be a peak shape; when the transform point appears in the linear magnification region of the bipolar state, the NDR curve will be a desk shape.

Frequency characteristic is one of the key factors that restricts application of novel devices. Simulation shows that the cutoff frequency of the above device is about 60～80GHz in the usual current range ($I_c = 10^{-5} \sim 10^{-3}$ A/μm), which is near the value of common HBTs.

5 Summary

In this paper, a novel mesa ultra-thin base AlGaAs/GaAs HBT has been designed and fabricated. It has particular and obvious voltage-controlled NDR and the PVCR is larger than 120. Both device fabrication and device characteristics are reported for the first time. By way of device simulation, the cause of NDR is considered to be that increasing collector voltage makes the ultra-thin base reach through and the device transforms from a bipolar state to a bulk barrier state. In addition, the simulated cutoff frequency is about 60～80GHz. For having high speed and high frequency characteristics derived from HBT and intrinsic bistability and self-latching characters from NDR, the ultra-thin base NDR HBT is believed to have broad application in fields of high performance multiple value logic circuit and other function devices.

References

[1] Sun J P, Haddad G I, Mazumder P. Resonant tunneling diodes: models and properties. Proceedings of IEEE, 1998, 86(4): 641

[2] Zhang Shilin, Guo Weilian, Liang Huilai, et al. Switching characteristics of resonant tunneling diodes. Chinese Journal of Semiconductors, 2003, 24(suppl): 136 (in Chinese) [张世林, 郭维廉, 梁惠来, 等. 共振隧穿二极管的开关时间特性. 半导

体学报,2003,24(增刊):136]

[3] Qi Haitao, Zhang Zhisheng, Guo Weilian, et al. Simulating experiment and circuit simulation of RTD/HPT photo-controlled MOBILE. Transactions of Tianjin University, 2004, 10(3):217

[4] Qi Haitao, Zhang Zhisheng, Guo Weilian, et al. The development of real-space transfer transistors. Research & Progress of Solid State Electronics, 2004, 24(4):411 (in chinese) [齐海涛,张之圣,郭维廉. 实空间转移晶体管研究进展. 固体电子学研究与进展,2004,24(4):411]

[5] Tian H, Kim K W, Michael A, et al. Novel heterojunction real-space transfer logic transistor structure: a model-based investigation. IEEE Trans Electron Devices, 1992, 39(10):2189

[6] Liu W C, Wang W C, Pan H J, et al. Multiple-route and multiple-state current-voltage characteristics of an InP/AlInGaAs switch for multiple-valued logic applications. IEEE Trans Electron Devices, 2000, 47(8):1553

[7] Chang C Y, Wang Y H, Liu W C, et al. MBE grown n^+-i-(p^+)-i-n^+ GaAs V-groove barrier transistor. IEEE Electron Device Lett, 1985, 6(3):123

[8] Ikossi-Anastasiou K, Ezis A, Evans K R, et al. Low-temprature characterization of high-current-gain graded-emitter AlGaAs/GaAs narrow base heterojunction bipolar transistor. IEEE Electron Device Lett, 1992, 13(8):414

[9] Yarn K F, Wang Y H, Chang C Y. Characterization of a GaAs current-controlled bipolar-unipolar transition negative differential resistance transistor. Appl Phys Lett, 1990, 57:777

AlGaAs/GaAs 超薄基区负阻 HBT 的研制与模拟*

齐海涛　张世林　郭维廉　梁惠来　毛陆虹

(天津大学电子信息工程学院, 天津 300072)

摘要: 利用化学湿法选择技术和监控电极技术设计并研制了一种新型台面结构超薄基区 AlGaAs/GaAs 负阻异质结双极晶体管,该器件具有独特且显著的电压控制型负阻特性,其峰谷比可高于 120. 通过器件模拟分析,解释了该器件产生负阻的原因,即不断增加的集电极电压致使超薄基区穿通,器件由双极管工作状态向体势垒管工作状态转化造成的. 另外,模拟结果表明器件可能具有较高频率特性(f_T 约为 60～80 GHz).

关键词: 异质结双极晶体管; 超薄基区; 器件模拟; 电压控制型负阻; 峰谷比

EEACC: 2550F; 2560E

中图分类号: TN325$^+$.3　　**文献标识码**: A　　**文章编号**: 0253-4177(2005)08-1495-05

* 国家重点基础研究发展计划资助项目(批准号:2002CB311905)

齐海涛　男,1975 年出生,博士,主要研究方向为新型半导体器件与集成技术.

2005-02-15 收到,2005-04-10 定稿