Studies on gallium arsenide heterojunction bipolar transistors (HBTs) for microwave power applications

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**Studies on Gallium Arsenide Heterojunction
Bipolar Transistors (HBTs) for Microwave Power
Applications**

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A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

2006

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To My
Father and Mother

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Summary

In this work, high performance GaAs-based power HBT technology is developed. The devices fabricated on un-thinned GaAs substrate demonstrate a power density of 5 W/mm at 10 GHz. This is comparable to the state of the art of GaAs power HBTs using complicated substrate thinning and via whole processes.

GaAs-based double HBTs using InGaP for emitter and collector are also fabricated. A detailed investigation of carrier multiplication behaviour in InGaP collector is performed, and electron impact ionization coefficient of InGaP is extracted. Compared to the previously reported data based on photocurrent (PCM) measurements, our results extend the electron impact ionization coefficient of InGaP by two orders of magnitude down to 1 cm^{-1} with the electric field as low as 330 kV/cm.

The temperature dependence of InGaP electron impact ionization coefficients is studied in the temperature range 300-450 K. As compared to binary compounds such as InP and GaP, the ternary InGaP shows a lower electron ionization coefficient and much weaker temperature dependence. The widely used Okuto-Crowell relation, which only considers phonon scattering, is found not applicable for the prediction of ionization coefficient and its temperature dependence of InGaP. It has been found that additional scattering mechanism such as alloy scattering has to be considered.

CHAPTER 1 INTRODUCTION

Chapter 1

Introduction

1.1 Motivations

The advantages of the heterojunction bipolar transistor (HBT) were first recognized by Shockley in a patent filed in 1948 [1]. The concept was later developed by Kroemer in 1957 [2]. The realization of working devices was not possible until the early 1970s when significant progress was made on high-precision epitaxial growth systems for III-V compounds such as molecular beam epitaxy and metal-organic chemical vapour deposition. Main advantages of HBT over homojunction bipolar transistor are:

- (i) High emitter efficiency. The current ratio of electron injection and hole injection can be extremely large due to the band gap difference.
- (ii) Low junction capacitance due to low emitter doping and low base layer sheet resistance due to high base doping.

The first commercialized HBT was made using GaAs/AlGaAs material system and demonstrated the significant advantages for high speed and high frequency applications. Despite their maturity, optimization of layer structure and device design, and improving the device fabrication yield remain an important topic in recent years. This is particular true for the high frequency power devices which are operated at high voltage and high current density and require proper device design.

Using InGaP to replace AlGaAs in GaAs-based HBT has been one of the most important research and development efforts in the last decade. The advantages of the ternary compound $\text{In}_{0.52}\text{Ga}_{0.48}\text{P}$ over AlGaAs such as having a larger bandgap (1.85 eV

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[3]) with most of the bandgap discontinuity is in the valence band as opposed to the conduction band, low carrier impact ionization coefficients, absence of DX centers as compared to Al-based material and a high etching selectivity against GaAs have made it an excellent alternative for a variety of GaAs-based device applications. One of the main limiting factors for power devices is the onset of avalanche multiplication governed by impact ionization. Accurate characterization of carrier impact ionization coefficients in InGaP are important for the prediction of the avalanche breakdown characteristics of GaAs-based HBTs and HEMTs, which is the key design parameter for device structure using InGaP layers.

The work shown in this thesis was motivated by the desire to develop high performance power HBT technology, and study the impact of device structure and process on DC and high frequency performance. In view of this, we seek to develop a baseline GaAs-based power HBT fabrication process. In particular, HBT technology using InGaP/GaAs material system is focused. To study the potential of use InGaP double HBT structure to improve the device breakdown voltage and achieve better power performance, a fundamental study of electron ionization coefficient in InGaP will be carried out.

1.2 Objectives

There are two main objectives in this work. The first objective is to develop high performance and high yield fabrication process for GaAs HBTs. The devices are designed to sustain high frequency performance while maintaining required breakdown voltages. Trade-offs between device performance and process limitation have to be taken

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into account in the mask design. Based on the established device fabrication process, AlGaAs/GaAs SHBTs and InGaP/GaAs/InGaP DHBTs were studied. The second objective of this work is to carry out a fundamental study of InGaP electron ionization coefficient using the fabricated devices. The understanding on impact ionization and its the temperature dependence is important for designing high power devices because junction temperature can be much higher than room temperature during high power operation.

1.3 Major contribution of the Thesis

A GaAs-based power HBT process using conventional optical lithography and wet etching has been developed in this work. High performance GaAs HBTs are demonstrated. One of the important material parameters which shows great impact in the design of power devices: electron ionization coefficient, is studied for InGaP material using the fabricated InGaP DHBT. A DHBT is chosen over diode because the accuracy of electron ionization coefficient for diode at low electric field is limited by the uncertainty in the primary photocurrent. The most important contributions of this thesis are summarized as follows:

- (1) Ability to design and fabricate high performance power AlGaAs/GaAs HBT is demonstrated. The 4, 8, 12, 16 finger AlGaAs/GaAs HBTs, with each finger dimension $2 \times 10 \text{ } \mu\text{m}^2$, shows a power result of approximate 5 W/mm at 10 GHz in common emitter configuration. This is considered high for an unlapped wafer and compared favorably with the typically value of 5 W/mm reported in literature for thinned wafer, e.g. [4].

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- (2) Development of InGaP/GaAs/InGaP HBT fabrication technology is also demonstrated and a detailed investigation is done on the InGaP electron ionization coefficient extracted from the fabricated DHBT.
- (3) Detailed investigation on the extraction of electron impact ionization for InGaP using InGaP/GaAs/InGaP DHBT has been carried out. The results extend the previously reported data in low electric field by two orders of magnitude down to 1 cm^{-1} and two times of magnitude in high field, up to 10^5 cm^{-1} .
- (4) The electron impact ionization coefficients for InGaP in the temperature range of 300-450 K under an electrical field of 380 to 650 kV/cm were characterized. As expected the results show that electron impact ionization is suppressed at elevated temperatures.
- (5) The electron impact ionization is found not to fit well with Okuto-Crowell relation and additional scattering mechanism, alloy scattering, is suggested to give a better interpretation on the low electron impact ionization and its weak temperature dependence observed in InGaP.

1.4 Organization of the Thesis

The motivation and objectives of this project are explained in Chapter 1. The theoretical background related to the bipolar junction and heterojunction bipolar transistor mechanism, impact ionization, alloy scattering, device DC and RF figures of merit and power parameter are reviewed in Chapter 2. Chapter 3 describes the AlGaAs/GaAs HBT layer structures, layout design and fabrication technology developed

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in this work. In Chapter 4, the DC, microwave and power performance of the fabricated devices are presented. Chapter 5 describes the accurate extraction of electron impact ionization coefficient for InGaP using InGaP/GaAs/InGaP DHBT. Studies on the temperature dependence of electron impact ionization coefficient in InGaP are presented in Chapter 6. A model for the explanation of suppressed electron ionization coefficient and its weak temperature dependence in InGaP is developed in Chapter 7. Finally, Chapter 8 presents the conclusions of the present work and further recommendations for future work.

CHAPTER 2 DEVICE PHYSICS

Chapter 2

Device Physics

2.1 Overview of Bipolar Junction and Heterojunction Bipolar Transistor

A bipolar junction transistor (BJT) is a semiconductor crystal divided into three regions with the center region doped differently from the other two regions. The three regions are known as emitter, base and collector of the transistor, each of these regions has a contact, making the bipolar transistor a three-terminal device. The base terminal serves as a control electrode; it allows the so-called transfer current to be controlled. In npn transistors, this transfer current by electrons that flow from the emitter to the collector. Forward biasing the emitter-base (EB) junction reduces the height of potential barrier and enables electrons to be injected into the base layer. These can either recombine in the base layer or diffuse to the base-collector (BC) junction. A representative band diagram for an npn BJT is shown in Fig 2.1 (a).

Choosing the thickness of the base layer to be small in comparison with the diffusion length of the electrons will allows most electrons to reach BC space-charge layer. There, the electric field will transport them to the collector region. With a change of forward bias of base-emitter junction voltage V_{BE} , the current of electrons injected into the base layers changes, and therefore the current of electrons that arrives at the BC space-charge layer. By this mechanism, the collector current I_C is controlled by V_{BE} .

Forward biasing the EB junction causes injection of holes into the emitter, where they recombine. These holes form part of the base current which decreases forward current gain. In order to suppress the injection of holes from the base to the emitter, the

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doping concentration in the emitter is chosen to be much larger than the doping concentration in the base layer.

Heterojunction bipolar transistors (HBTs) employ one or two heterojunctions, in order to improve device performance in comparison with homojunction BJTs. Single heterojunction benefit from a base layer with a reduced bandgap, which however equals to the bandgap within the collector region. Double heterojunction bipolar transistors have an additional heterojunction between the base and the wider-gap collector region. This offers the advantage of an increased breakdown voltage and reduces the offset voltage in switching applications.

Heterojunctions are formed at the interfaces between different semiconductor materials. The different band structures of the adjacent semiconductor materials result in a potential gradient that affects the motion of carriers across the heterojunction.

Heterojunction transistors usually have a bandgap in the emitter region exceeds the bandgap in the base region ($E_{gE} > E_{gB}$). The change in energy gap ΔE_g between the emitter and base is made up of a conduction band energy step ΔE_c and a valence energy step ΔE_v ($\Delta E_g = \Delta E_c + \Delta E_v$). A representative band diagram for an npn HBT with a wide bandgap emitter and an abrupt emitter base junction is shown in Fig 2.1 (b). The energy barrier in the conduction band at the emitter-base junction tends to retard the flow of electrons from emitter to base. This decrease the emitter efficiency, but it provides benefits for high-speed operation because the electrons that surmount the barrier are injected into the base with high forward velocities, reducing base transit time. To improve current gain of the HBTs, the compositions of material may be graded to establish a gradual change in bandgap from emitter to base. With wider emitter bandgap,

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fewer carriers will be injected into the emitter at a given transfer current density in comparison with a conventional transistor [2], [5]. The current gain increases according to $\exp\left(\frac{\Delta E_g}{kT}\right)$ for a smooth graded emitter-base junction and according to $\exp\left(\frac{\Delta E_v}{kT}\right)$ for a spiked emitter-base junction [28], as long as recombination in the base layer is negligible. In both cases, the current gain generally decreases with increasing temperature, in contrast to homojunction BJTs, which current gain increases with increasing temperature, mainly due to bandgap narrowing in the heavily doped emitter.

Wide-gap emitters allow one to dope the base region more heavily than the emitter region, without losing too much current gain. This is of great importance for the realization of high-frequency bipolar transistors as the highly doped base leads to a reduction of base resistance, which in turn improves the maximum oscillation frequency (f_{max}). The higher doped base also allows narrower base thickness to be used without sacrificing the base resistance. This in turn gives rise to lower base transit time thus higher cut-off frequency (f_T).

An additional crucial effect for high-speed operation is the elimination of minority-carrier charge storage in the emitter, thus increasing f_T . Both higher f_T and f_{max} values are desirable for high frequency applications. In addition to the improved current gain, f_T and f_{max} , introduction of a heterojunction to the bipolar transistor design also results in major differences in device characteristics. For example, the base punchthrough voltage in HBT can be extremely high which leads to lower base width modulation thus higher Early voltage. This gives rise to improved device linearity which is attractive for certain applications such as in power amplifiers for communications applications. Furthermore, emitter doping levels can be reduced, allowing the emitter-base space-

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charge region to broaden on the emitter side of junction and leading to a reduction in emitter junction capacitance. Important device parameters are reviewed later.

Fig 2.1 Band diagram for an (a) npn BJT (b) abrupt emitter-base npn HBT.

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2.2 Impact Ionization in Semiconductor

Considering that the major part of research in this thesis is the study of power device and electron impact ionization in InGaP, the fundamental of carrier transport and impact ionization in semiconductors will be reviewed in this section.

Carrier multiplication by impact ionization determines the breakdown behavior of heterojunction bipolar transistors and heterojunction field effect transistors [6,7]. Thus, impact ionization imposed a fundamental limit on the applied field for semiconductor junction and hence limits the power output of transistors.

Impact ionization results from a three-particle process corresponding to the exact inverse of the Auger process: a highly energetic conduction-band electron collides with a valence-band electron which is ionized over the band gap, leaving two conduction electrons and a hole. This is illustrated in Fig 2.2.

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Fig 2.2 A schematic one-dimension representation of a direct, two-band impact ionization process: (a) by an energetic electron (b) by an energetic hole.

Theories of electrical breakdown in solids via electronic impact ionization date from von Hippel [8] and Frohlich [9]. The first attempt to calculate Townsend's ionization coefficient in semiconductors was made by Wolff [10]. Wolff regarded the electrons energetic enough to create an electron-hole pair to be those in the tail of the equilibrium distribution. Assuming the latter to be nearly isotropic, he solved the Boltzmann equation and obtained a Maxwellian distribution for a simple band structure. From this he deduced that the ionization coefficient, α , varied with electric field, E , according to the form:

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$$\alpha \sim \exp(-a/E^2) \quad (2.1)$$

This treatment is questionable because the band structure at energies remote from the band edge is not simple and that it is possible that impact ionization may be more associated with non-equilibrium electrons than with those in a nearly isotropic equilibrated distribution.

The complexity of band structure in semiconductors made the first objection difficult to overcome. The second objection formed the basis of a rather different approach by Shockley [11], which has become known as the lucky-electron model. Shockley saw impact ionization as produced by electrons which happened to avoid collision. If λ was the mean free path between collisions, considered a constant, and E_I was the threshold energy for ionization, the probability of an electron avoiding a collision was simply $\exp(-E_I/eE\lambda)$ and so the ionization coefficient, in the simplest formulation, took the form

$$\alpha = (eE/E_I) \exp(-E_I/eE\lambda) \quad (2.2)$$

which has a distinctly different dependence on field from Wolff's result. In practice, the range of fields over which α is measured is often too small to decide definitively between the two predicted field dependence, and both types of field dependence may be found in the literature. The major objection to the lucky-electron model is quantitative, in that the expected values of the collision path are so small ($\sim 50 \text{ \AA}$) that lucky electrons cannot occur with sufficient probability.

The first attempt to compute the hot-electron distribution numerically from the Boltzmann equation, and hence obtain the ionization coefficient, was made by Baraff [12], whose results have been very widely applied to experiment. Baraff's result, in the

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form of curves, involve as adjustable parameters the threshold energy for ionization, the optical phonon scattering, the ionization mean free path, and the mean free path for optical phonon scattering, the optical phonon scattering mean free path being considered energy-independent. Only non-polar optical phonon scattering was considered, along with a simple band structure. If the phonon energy is considered to be known and the ionization occur instantly once threshold is reached, the number of adjustable parameters reduces to two, namely the threshold energy and the optical phonon mean free path. The assumptions of a simple band structure and an energy-independent mean free path are, however, unsatisfactory features and it means that the quantitative results of the theory are of uncertain status. Nor, being numerical, does the theory illuminate the physical processes and provide insight into the ionization mechanism. Yet Baraff's theory at the time was important for two reasons: regarding the physics of the process, it succeeded in showing that the parameters emphasized by either Wolff's or Shockley's components were not the most important, but rather some essentially diffusive peak in the distribution; regarding the experiment, it provided a framework for comparing different sets of measurements.

In a strict sense Baraff's treatment applies only to non-polar materials, but this turns out to be not very restrictive in practice simply because in polar materials polar scattering is weak at high carrier energies and non-polar scattering dominates. The success of Baraff's theory in fitting experimental results has been remarkable in view of the simple assumptions about band structure and scattering which underpin it.

A semiclassical theory developed by Ridley [13] extended Shockley's lucky electron model by differentiating the rate between momentum relaxation and energy

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relaxation. The lucky drift motion, instead of the lucky ballistic motion of Shockley, was assumed by Ridley and hence the theory is known as the “lucky drift” model. This state of drift motion of electrons is intermediate between Shockley’s ballistic state and Wolff’s equilibrium state. Under the assumption of a simple band structure and an energy-independent mean free path as that of Baraff, the impact ionization coefficients predicted by Ridley’s simple analytic formula agree well with Baraff’s numerical results over four orders of magnitude. The lucky drift model has been further improved by adopting the concept of “soft threshold energy” [14,15]. However, these models still assume a constant mean free path and the exact form of energy distribution is not given.

Current approaches include full scale Monte Carlo simulation (e.g. Brennan et al [16], Hess [17], Fischetti [18], Bude and Hess [19]) but tend to assume that the ionization cross sections can be modeled by simple algebraic expressions, and the well known Keldysh result [20], where scattering rates vary as the square of the kinetic energy, measured from threshold, is often used. However, Keldysh’s expression is derived under the assumption that the valence and conduction bands are spherical and parabolic, the band gap is direct and ignores the anisotropy of ionization threshold. A Monte Carlo simulation including full band structure and an anisotropic impact ionization model was carried out by Kunikiyo et al [21] to estimate the impact ionization in Si. The impact ionization rate was calculated by using Fermi’s golden rule directly from the full band structure as well as the dielectric function depending on both wave vector and transition energy. The impact ionization rate obtained shows strong anisotropy, which is ignored by the Keldysh formula.

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However, the input parameters to the large-scale Monte Carlo simulations are subject to considerable uncertainty and the method requires very long computation times.

2.3 Alloy Scattering

Alloy scattering refers to the scattering present in alloys due to the random distribution of component atoms among the available lattice sites. This scattering can be considered as an additional scattering mechanisms presented in alloy materials. In the later part of the thesis, the effect of alloy scattering on high field carrier transport and impact ionization in InGaP will be addressed.

The effect of alloy scattering is described by the virtual-crystal model by Harrison and Hausser [22]. In their model a ternary crystal $A_xB_{1-x}C$ is considered to be divided into a perfectly periodic array of potentials, the virtual crystal, composed of weighted potentials of the different kinds of atoms, and a random part due to the difference between the potentials of the actual crystal and the virtual crystal.

The model is restricted to the case of ternary III-V compounds where one of the elements, denoted by C , is common to both of the constituent compounds. The crystal structure of the pure compounds is the tetrahedral zinc-blende structure and the alloys also exhibit the tetrahedral zinc-blende structure. The zinc-blende lattice can be subdivided onto two interpenetrating face-centered-cubic (fcc) lattices. The dimension of the cubes is the lattice constant a and the nearest-neighbor distance is $\frac{1}{4}\sqrt{3}a$. In this arrangement each atom in the lattice, except at the crystal surfaces, has four nearest neighbors with the angle between the bonds at about 107.5° .

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The model used two interpenetrating fcc lattices. Denoting the general lattice vector by $\vec{r}$, one fcc lattice consists of the set of lattice points $\{\vec{r} = \vec{\gamma}\}$, and the other fcc lattice consists of the lattice points $\{\vec{r} = \vec{\zeta}\}$. Suppose that all of the points of the $\vec{\gamma}$ lattice are occupied by the atoms of type C, but that the points of the $\vec{\zeta}$ lattice are shared between atoms of type A and type B. If the total number of lattice points on $\vec{\zeta}$ lattice is N_{ζ} , and N_A, N_B denote, respectively, the number of A atoms and the number of B atoms, then we have:

$$N_A + N_B = N_{\zeta} \quad (2.3)$$

$$x = N_A / N_{\zeta} = C_A \quad (2.4)$$

$$1 - x = N_B / N_{\zeta} = C_B \quad (2.5)$$

In this arrangement a type-C atom may have all type-A nearest neighbors, or all type-B nearest neighbors, or a mixture of type-A and type-B nearest neighbors. The type-A or type-B atoms, however, will always have all type-C neighbors. In effect the model is an fcc lattice of A-C and B-C molecules, with intermolecular bonding as well as intramolecular bonding. The structure described above constitutes what is referred to as a “pseudobinary alloy” with the properties determined by the relative concentrations of A and B.

Nordheim [23] was the first to consider the problem of calculating the resistivity of alloys using quantum mechanical concepts. Nordheim dealt with the perfectly random crystal by introducing the concept of the virtual crystal. The actual crystal was considered to be divided into a perfectly periodic array of potentials, the virtual crystal, composed of the composition weighted potentials due to the different kinds of atoms making up the

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crystal, and a random part due to the difference between the actual crystal potential and the virtual crystal potential at a given lattice point. This random part was used as a perturbation potential, leading to a matrix element for transition between electron states. Hall [24] reformulated Nordheim's approach to calculating residual resistivity for a binary alloy and used the Warren-Cowley order parameters [25]. The one-electron Schrödinger wave function for an electron in a binary alloy was written with the potential $U(\vec{r})$ divided into a virtual crystal part:

$$U_1(\vec{r}) = \sum_{\vec{r}} [C_A U_A(\vec{r} - \vec{r}) + C_B U_B(\vec{r} - \vec{r})] \quad (2.6)$$

and a random part:

$$U_2(\vec{r}) = \Delta U(\vec{r} - \vec{r}) = \sum_{\vec{r}} C_{\vec{r}} [U_A(\vec{r} - \vec{r}) - U_B(\vec{r} - \vec{r})] \quad (2.7)$$

where $C_{\vec{r}}$ is a random function which is defined only at lattice sites $\vec{r}$. The function has the value at these points:

$$C_{\vec{r}} = \begin{cases} (1 - C_A) & \text{for an A atom at } \vec{r} \\ -C_A & \text{for a B atom at } \vec{r}, \end{cases} \quad (2.8)$$

and have the following properties [25]:

$$\sum_{\vec{r}} C_{\vec{r}} = 0 \quad (2.9)$$

$$\sum_{\vec{r}} C_{\vec{r}} C_{\vec{r} + \vec{r}} = N C_A (1 - C_A) \alpha_{\vec{r}} \quad (2.10)$$

where $\alpha_{\vec{r}}$ is the Warren-Cowley order parameter. The approach of Hall was further developed by Asch and Hall [26]. This development included the change in lattice parameter with alloying and the change in effective number of conduction electrons per

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atom with composition. Asch and Hall shown that the square of the transition matrix between initial and final states is given by:

$$|M(\bar{\mathbf{K}}, \bar{\mathbf{K}}')|^2 = \sum_{\bar{\tau}}^N \alpha_{\bar{\tau}} J(\bar{\mathbf{K}}, \bar{\mathbf{K}}', \bar{\tau}) \quad (2.11)$$

where

$$\alpha_{\bar{\tau}} = \sum_{\bar{\tau}'}^N \frac{C_{\bar{\tau}'} C_{\bar{\tau}'+\bar{\tau}}}{NC_A C_B} \quad (2.12)$$

$$J(\bar{\mathbf{K}}, \bar{\mathbf{K}}', \bar{\tau}) = NC_A C_B \left| \frac{1}{N\Omega} \int_{vol} \psi_{\mathbf{K}}^* \Delta U(\bar{\mathbf{r}} - \bar{\tau}) \psi_{\mathbf{K}} d\bar{\mathbf{r}} \right|^2 \quad (2.13)$$

and $\Delta U(\bar{\mathbf{r}} - \bar{\tau})$ is the random potential due to the alloying effect. In terms of the Bloch functions, the integral expression Eq. (2.13) becomes:

$$J(\bar{\mathbf{K}}, \bar{\mathbf{K}}', \bar{\tau}) = NC_A C_B \exp[i(\bar{\mathbf{K}} - \bar{\mathbf{K}}') \cdot \bar{\tau}] \left| \frac{1}{N\Omega} \int_{vol} u_{\mathbf{K}}^* u_{\mathbf{K}} \Delta U(\bar{\mathbf{r}} - \bar{\tau}) \exp[i(\bar{\mathbf{K}} - \bar{\mathbf{K}}') \cdot \bar{\mathbf{r}}] d\bar{\mathbf{r}} \right|^2 \quad (2.14)$$

Applying the virtual crystal concept of Nordheim, and treating the deviations from the perfect periodicity of the virtual crystal model as a perturbation potential, the matrix elements for a transition from state K to K' can be worked out. The matrix element squared is presented in Eq. (2.11) for all degrees of order which can be specified by the Warren-Cowley order-parameter set $\{\alpha_{\bar{\tau}}\}$. In the completely random alloy, this expression reduces to:

$$|M(\bar{\mathbf{K}}, \bar{\mathbf{K}}')|^2 = \frac{C_A(1-C_B)}{N\Omega^2} \left| \int_{vol} \psi_{\mathbf{K}}^* \Delta U(\bar{\mathbf{r}} - \bar{\tau}) \psi_{\mathbf{K}} d\bar{\mathbf{r}} \right|^2 \quad (2.15)$$

Mott [27] considered the effects of substitution in dilute alloys. He considered a solvent lattice in which the electron wave functions, $\psi_{\mathbf{K}} = u_{\mathbf{K}}(\bar{\mathbf{r}}) \exp(i\bar{\mathbf{K}} \cdot \bar{\mathbf{r}})$ are solutions to the Schrödinger equation, and conduction-band electrons have energies given by:

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$$W(K) = \frac{\hbar^2 K^2}{2m} + W_0 \quad (2.16)$$

where W_0 is the energy of the band edge. When an atom of a different potential is substituted for a “native” atom, the wave function in the Wigner-Seitz cell about the substitute will become $\psi_{\mathbf{K}'} = u_{\mathbf{K}'}(\vec{\mathbf{r}}) \exp(i\vec{\mathbf{K}}' \cdot \mathbf{r})$ and have energy:

$$W(K') = \frac{\hbar^2 K'^2}{2m} + W'_0 \quad (2.17)$$

corresponding to the altered wavelength, K' , in the altered potential region. An electron traveling from a “normal” region into the altered region will experience a change in potential. As pointed out by Mott, the problem is the same as the scattering of a beam of electrons by a potential, which he termed the “inner potential”:

$$\Delta U = \begin{cases} W_0 - W'_0 & r \leq r_0 \\ 0 & r > r_0 \end{cases} \quad (2.18)$$

where r_0 is the radius of the Wigner-Seitz cell (assumed spherical). This “square well” potential is used to derive, by means of the first Born approximation, an expression for the relaxation time due to scattering in a random alloy.

The matrix element, using Born approximation, for a transition due to a “square well” potential of strength ΔE and extent $r \leq r_0$ is:

$$m(K, K') = \int_{vol} e^{i\Delta\vec{\mathbf{K}} \cdot \vec{\mathbf{r}}} \Delta U d\vec{\mathbf{r}} \quad (2.19)$$

where

$$\Delta\vec{\mathbf{K}} = \vec{\mathbf{K}} - \vec{\mathbf{K}}'$$

$$d\vec{\mathbf{r}} = r^2 dr \sin \theta d\theta d\phi$$

Due to azimuthal symmetry, integration on ϕ gives a factor 2π and this gives:

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$$m(K, K') = 4\pi \frac{\Delta W}{\Delta K} \int_0^\infty \sin(\Delta K r) r dr \quad (2.20)$$

Evaluating the integral gives:

$$m(K, K') = 4\pi \frac{\Delta W}{(\Delta K)^3} [\sin(\Delta K r_0) - \Delta K r_0 \cos(\Delta K r_0)] \quad (2.21)$$

Using series expansion of *sin* and *cos* terms yield:

$$m(K, K') = 4\pi (\Delta W) r_0^3 \left(\frac{1}{3} - \frac{1}{30} \Delta K^2 r_0^2 + \dots \right) \quad (2.22)$$

The square of the matrix element is:

$$|m(K, K')|^2 = 16\pi^2 (\Delta W)^2 r_0^6 \left(\frac{1}{9} - \frac{1}{45} \Delta K^2 r_0^2 + \dots \right) \quad (2.23)$$

The neglect of the higher-order terms can be justified on the basis that $r_0 \approx 2.5 \times 10^{-10}$ m

and $\Delta K_{\max} \approx \left(3kT \frac{2m^*}{\hbar^2} \right)^{1/2}$. Therefore $(\Delta K r_0)_{\max} \approx 8.5 \times 10^{-2}$ and to a good approximation:

$$|m(K, K')|^2 = \frac{16}{9} \pi^2 (\Delta W)^2 r_0^6 \quad (2.24)$$

The choice of the value for r_0 is somewhat arbitrary. Substitution of a “foreign” atom of the same valence as a “native” atom in the center of a tetrahedral unit would be expected to change the energy levels at least out to the nearest neighbors, or $r_0 = \frac{1}{4} \sqrt{3} a$. Using this

value, we get

$$|m(K, K')|^2 = \frac{3}{9} \pi^2 \Omega^2 (\Delta W)^2 \quad (2.25)$$

The random case gives:

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$$|m(K, K')|^2 = 3\pi^2 C_A (1 - C_A) (\Delta W)^2 / 16N \quad (2.26)$$

Evaluating the collision integral term for the Boltzmann transport equation gives the relaxation time expression due to scattering in a random alloy:

$$\tau_{AR} = \frac{8N_A \hbar^4 \varepsilon^{-1/2}}{3\sqrt{2}\pi C_A (1 - C_A) (\Delta W)^2 m^{*3/2} (kT)^{1/2}} \quad (2.27)$$

where $\varepsilon = W / kT$.

2.4 DC Characteristics and Microwave Figures of Merit of an HBT

In this section, the important DC and high frequency characteristics which will be used for the characterization of the fabricated HBTs are summarized. The influence of the device layer structure, layout, and fabrication process on DC and high frequency characteristics are also addressed.

2.4.1 DC Parameters

1) Common-Emitter Current Gain

The static common-emitter current gain β is defined by:

$$\beta = \frac{I_c}{I_b} \quad (2.28)$$

The HBT common-emitter current gain is often quoted as a figure of merit for an HBT. However, it should be noted that being the ratio of two currents, the gain changes as either current changes. Therefore, to understand the device design and device characteristics, both the collector current and the base current, not just the current gain should be considered. For a given HBT material and fabrication process, the current gain can be increased or decreased by the base doping level and thickness. Generally

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speaking, higher base doping and thicker base layer result in lower β . However, for microwave circuit applications, extremely high current gain may not be desirable. Compromising current gain with the base resistance is necessary.

2) Gummel Plot and Ideality Factors

A *Gummel Plots* plot both the collector current I_C and the base current I_B on a logarithmic scale as a function of the forward-bias voltage V_{BE} applied between the base and the emitter terminals, and can be represented as:

$$I \sim \exp[qV_{BE}/(nkT)] \quad (2.29)$$

where n is the ideality factor. For a device with good material quality, both the base and the collector currents are approximately ideal (n close to 1) in the medium current level.

At low current levels, the base current could be larger than its ideal value. This is due to the bulk defects or surface states giving rise to significant generation-recombination current. The generation-recombination current usually can be recognized by its $\sim 2kT$ ($n \sim 2$) dependence on V_{BE} . In HBTs, the generation-recombination current adds to the base current and hence degrades the dc current gain. By optimizing material growth and device fabrication processes to reduce the defect density, generation-recombination can be reduced.

At high currents, the reduction of the base and collector currents from its ideal behavior is mainly due the effect of emitter and base parasitic series resistances. As the currents flow through these parasitic resistors, voltage drops on these resistors tend to offset the externally applied voltages and thus degrade the base and collector currents.

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Proper design of emitter and base doping level and optimization of the fabrication process are necessary.

3) Output Conductance

High voltage gain and device linearity result from low output conductance g_o given by:

$$g_o = \frac{dI_c}{dV_{ce}} \quad (2.30)$$

Both base-width modulation by the base-collector voltage (Early effect) and impact ionization in the collector can increase output conductance.

4) Breakdown Voltage

The HBT breakdown voltages involving the collector-base junction, emitter-base junction, and collector-emitter structure limit the HBT performance such as linearity and output power. The breakdown voltages are defined as follows:

Collector-Base Junction Breakdown (Emitter Open), BV_{cbo} : High BV_{cbo} is desired for high linearity and high-power application. The BV_{cbo} is mainly decided by the collector doping and thickness. Thicker and lower doped collector increases the breakdown voltage (avalanche process) at the cost of increased effective transit times.

Emitter-Base Junction Breakdown (Collector Open) BV_{ebo} : This junction, which controls the current gain, is the most sensitive to reverse-bias currents that can damage the device.

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The breakdown mechanism is a combination of avalanche and Zener tunnelling processes. High BV_{ebo} is required for only a few applications.

Collector-Emitter Breakdown, BV_{ceo} : This voltage is governed by collector-base breakdown coupled with a feedback multiplication factor of the current gain when measured as the base is driven by a current source. The relationship of BV_{ceo} and BV_{cbo} can be written as

$$BV_{ceo} = BV_{cbo}(1-\alpha)^{1/\eta} \approx BV_{cbo}(\beta)^{-1/\eta} \quad (2.31)$$

where α is common-base current gain. Notice that higher β results in lower BV_{ceo} .

2.4.2 Microwave Figures of Merit

The microwave characteristics of HBT can be divided into two categories: small-signal and large-signal characteristics.

(A) Small Signal Analysis

Some of the commonly used small-signal figures of merit for HBT are listed here:

1) Unit current gain cut-off frequency, f_T

For small-signal applications, the cut-off frequency, f_T is defined as the transition frequency at which the common-emitter, short-circuit load, small-signal current gain drops to unity. The unit current gain cut-off frequency (f_T) of an HBT is given by

$$f_T = \frac{1}{2\pi\tau_{ec}} \quad (2.32)$$

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where $\tau_{ec} = \tau_{ee} + \tau_b + \tau_c + \tau_{cc}$ is the total HBT emitter-to-collector transit time, where $\tau_{ee} = (kT/qI_c)C_{be}$ is the emitter-base charging time, τ_b is the base transit time including diffusion and drift terms, τ_c is the collector depletion-layer transit time, and $\tau_{cc} = (kT/qI_c + R_e + R_c)C_{bc}$ is the collector charging time. Thus, f_T can be written as:

$$f_T = \frac{1}{2\pi \left[\frac{kT}{qI_c} C_{be} + \tau_b + \tau_c + \left(\frac{kT}{qI_c} + R_e + R_c \right) C_{bc} \right]} \quad (2.33)$$

At low current densities, the cut-off frequency is determined by the emitter-base and collector-base charging time. At high current densities, f_T is mainly decided by the base and collector depletion layer transit time. To maximize f_T , the capacitance C_{be} and C_{bc} and forward transit time τ_b and τ_c should all be minimized. The simplest way to minimize these capacitances is to use advanced device structures that have small parasitic capacitance. The base transit time can be reduced effectively by reducing the intrinsic base thickness. However, reducing base thickness alone will lead to a large intrinsic base resistance.

It should be pointed out that, at sufficiently large collector current density, base widening becomes important causing the rapid increase of τ_b , and hence f_T decreases rapidly with further increase in current density. A simple way to increase the peak f_T of an HBT is to increase its collector doping concentration to shift the f_T roll-off to high current, provided that the device breakdown voltages remain acceptable.

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2) Maximum frequency of Oscillation, f_{max} (unity power gain)

f_{max} is defined as the frequency at unity gain intercept point of unilateral power gain U where U is the maximum available power gain when a lossless external feedback is used to adjust the reverse power gain to zero. For a two-port network, U can be obtained to be:

$$U = \frac{1/2|S_{21}/S_{12} - 1|^2}{k|S_{21}/S_{12}| - \text{Re}(S_{21}/S_{12})} \quad (2.34)$$

where S with subscripts are referred to as S parameter and k is the stability factor [28]. f_{max} defines the boundary between active and passive operations of the device. In lumped parameter, f_{max} is presented as follows:

$$f_{max} = \sqrt{\frac{f_t}{8\pi R_b C_{bc} + 4\pi[C'_{bc}(R_e + R_c) + C_{bc}R_e]\cos\phi_m}} \quad (2.35)$$

where R_e , R_b and R_c are the emitter, base and collector series resistances, respectively. C_{bc} is the BC junction capacitance, and C'_{bc} is the parasitic capacitance between BC junction. The contribution of $\cos\phi_m$ can be viewed as the effect of the transadmittance phase delay. By ignoring this effect, the classical expression of f_{max} for bipolar transistor can be obtained as:

$$f_{max} = \sqrt{\frac{f_T}{8\pi R_b C_{bc}}} \quad (2.36)$$

The optimization of the $R_b C_{bc}$ charging time constant is critical in designing and fabricating high performance HBTs for microwave applications. However, maximizing f_{max} by reducing R_b and C_{bc} is a complex tradeoff process. Designs that increase f_T at the expense of increasing R_b can result in the decrease of f_{max} . If C_{bc} is reduced by reducing the collector doping concentration, base widening will occur at a lower collector current

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density, which in turn can reduce the f_T of the HBT. Recent experimental results indicate that, reducing C_{bc} by undercutting extrinsic collector could be an effective approach for the increase of f_T and f_{max} in HBTs.

3) Maximum Available Gain and Maximum Stable Gain, MAG/MSG

Maximum available gain (MAG) is the maximum power gain (done by conjugate match the input and output port) that can be realized by a two port network without external feedback when the two-port network is unconditionally stable, i.e. $k > 1$.

Maximum stable gain (MSG) is the maximum power gain when the two-port network is conditionally stable, i.e. $k < 1$. This maximum gain can be achieved by resistively loading the two-port such that $k = 1$ and then simultaneously conjugately matching the input and output ports.

In two-port network, they are given by:

$$MAG = \frac{|S_{21}|}{|S_{12}|} \left(k - \sqrt{k^2 - 1} \right) \quad k > 1 \quad (2.37)$$

$$MSG = \frac{|S_{21}|}{|S_{12}|} \quad k < 1 \quad (2.38)$$

(B) Large-Signal Analysis

For large signal analysis, the two main figure of merits are the output power P_{out} and the power-added efficiency PAE . For power transistors, the amount of microwave power that can be delivered to the load is of primary importance, whereas the noise figure is of no concern. In power amplifiers where heat dissipation or battery power is of concern, the power-added efficiency is an important figure of merit. It is defined as the

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difference of microwave output power (P_{out}) and input power (P_{in}) divided by the DC power ($P_{in}(dc)$) supplied to the device:

$$PAE = \frac{P_{out} - P_{in}}{P_{in}(dc)} \quad (2.39)$$

For transistor operating in common emitter, class A amplifier configuration, the value of load (R_L) under a matched load condition is given by:

$$R_L = \frac{BV_{ceo} - V_K}{I_{C\max}} \quad (2.40)$$

where $I_{C\max}$ is the maximum collector current when collector-emitter voltage is biased at knee voltage, i.e. $V_{CE} = V_K$. The maximum output power obtained under this matched load condition is:

$$P_{out,\max} = \frac{I_{C\max}(BV_{ceo} - V_k)}{8} = \frac{(BV_{ceo} - V_k)^2}{8R_L} \quad (2.41)$$

High output power is obtained when a transistor possesses a high operating current, a large breakdown voltage and a small knee voltage.

The power-added efficiency under the above maximum output power condition is:

$$PAE = \frac{1}{2} \frac{BV_{ceo} - V_K}{BV_{ceo} + V_k} \left(1 - \frac{1}{G}\right) \quad (2.42)$$

where G is the large signal gain, i.e. $G = \frac{P_{out}}{P_{in}}$. A low knee voltage and high gain is required for high PAE . In the limit of infinite gain and zero knee voltage, the theoretical upper limit of PAE under class A operation is 50%.

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Chapter 3

HB T Fabrication Process Development

3.1 Introduction

Developing a high yield fabrication process was one of important task in this work. Based on the existing device fabrication equipment in our cleanroom, a process with ion-implanted isolation and air-bridged interconnects has been developed for HBT fabrication. The main steps for the fabrication of HBT are: 1) ion-implantation 2) emitter metal and mesa formation, 3) base metal and base mesa formation, 4) collector metal formation 5) interconnect and airbridge formation. In this chapter, the HBT epitaxial layer structure, layout design is given first followed by a detailed process flow.

3.2 HBT Epitaxial Layer Structure

The vertical layer structures and layout design play an important role in the determination of the performance of AlGaAs/GaAs HBTs. In this work, our devices are required to sustain high frequency while maintaining required breakdown voltages. An optimum layer structure is chosen in order to meet the specification requirements. The layer structure for AlGaAs/GaAs HBTs grown by MOCVD is shown in Fig. 3.1. The dopants used are silicon for n-type and carbon for p-type. Compared with the previous NTU base line GaAs HBTs, some modifications were made on the layer structure to ensure the device can meet the requirements for power applications:

- (i) A thicker InGaAs emitter cap with higher indium composition is chosen to minimize the emitter contact resistance.

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- (ii) Thinner base layer (80 nm) is used to improve base transit time.
- (iii) The 1000 nm GaAs collector layer with $5 \times 10^{16} \text{ cm}^{-3}$ doping is chosen by considering the collector transit time delay and breakdown requirements.

Layer	Material	Doping (cm^{-3})	Thickness ($\text{\AA}$)
Emitter contact	$\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$	$\text{N} - 1.0 \times 10^{19}$	500
	$\text{In}_{0.5}\text{Ga}_{0.5}\text{As} \rightarrow \text{GaAs}$	$\text{N} - 1.0 \times 10^{19}$	500
Emitter cap	GaAs	$\text{N} - 4.5 \times 10^{18}$	1200
Emitter	$\text{GaAs} \rightarrow \text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	$\text{N} - 5 \times 10^{17}$	300
	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	$\text{N} - 5 \times 10^{17}$	500
	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \rightarrow \text{GaAs}$	$\text{N} - 5 \times 10^{17}$	300
Base	GaAs	$\text{P} - 4.0 \times 10^{19}$	800
Collector	GaAs	$\text{N} - 5.0 \times 10^{16}$	10000
Sub-collector	GaAs	$\text{N} - 4.5 \times 10^{18}$	8000
SI GaAs Substrate			500 μm

Fig. 3.1 Layer structure grown by MOCVD for AlGaAs/GaAs HBTs device fabrication.

3.3 Layout Design

A ten-level mask set is designed for device fabrication. Trade-offs between device performance and process limitation have to be taken into account in the mask design. Too complicated design will result in reduced yield and reliability. Key geometries such as emitter width, emitter length and number of emitter fingers must be optimized. In general, the frequency performance, operating voltage, power gain are given in advance. Of course, trade-offs between layout and process limitation must be made to achieve reasonable device performance and yield.

More than 100 different HBTs were laid out in an $8 \times 10 \text{ mm}^2$ die. Most of the HBTs in this die utilize self-aligned base contacts process. The open and short test

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structures used for equivalent circuit extraction are also laid out with the devices. In addition, some structures for process control are also included in this die.

3.4 Process Flow

The HBT fabrication process used in this work is illustrated in Fig. 3.2. The mesa approach combined with H⁺ implantation isolation avoids complex dopant implantations or diffusions required in planar-layer process. Process enhancements including self-aligned technology were used. The processing methods commonly applied to our GaAs-based HEMTs were used for the HBT fabrication. But the special layer structure compared with HEMT's added more complexity on the fabrication. The fabrication sequence basically consisted of device isolation by H⁺ implantation, etching to reveal layers in the structure and fabricating electrical contacts to each layer. The main process steps used for HBT's fabrication are given below and the process run sheet is given in Appendix A.

(1) Device isolation by H⁺ implantation:

The major parameters deciding the final ion-implantation profile are the ion energy and the dose. The ion energy is specified by the accelerating potential. Ion dose N_s pertains to the total number of ions implanted per unit area and is given by the product of the number of ions reaching the GaAs per second and the exposure time.

The implantation distribution profile can be represented by Gaussian distribution with a peak depth R_p , which is the mean range, and a half-width ΔR_p , which is the straggle range:

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$$N(x) = \frac{N_s}{\sqrt{(2\pi)\Delta R_p}} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^2}\right] \quad (3.1)$$

The GaAs active area is defined by the photoresist mask which protects it from ion bombardment. Using buffer HF solution, a thin layer of Si₃N₄ helps lift-off the photoresist after implantation. Figure 3.2 (a) - (c) correspond to this step.

(2) Deposit and lift-off emitter ohmic contacts:

The metallization is patterned by transferring the designed mask pattern to photoresist and then to metal. Conventional lift-off technique is used in this work. This technique involves deposition of the ohmic contact metal layer on top of the patterned photoresist, followed by lifting off unwanted metal by dissolving the underlying photoresist with acetone. For effective lift-off, an overhang of the photoresist is used to separate the metal on the semiconductor and that on the photoresist. This not only allows solvent to penetrate and dissolve the photoresist, but also prevents ragged metal edges due to peeling of the metal. An image reversal lithography process using AZ 5214 photoresist is developed to form the overhang of the resist. Ti/Au is used as the non-alloyed contact metal to the emitter layer. Figure 3.2 (d) corresponds to this step.

(3) Pattern and etch emitter layer to access base layer:

Using emitter metal formed in the previous step as a mask, the emitter layer is etched away, leaving the base layer exposed. The mesa depth is confirmed by using a DEKTEK profiler. Figure 3.2 (e) corresponds to this step.

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(4) Deposit TiAu and lift-off for base ohmic contact:

Similarly to step 2, Ti/Au is deposited on base layer. Care is chosen on the thickness of metal deposited such that it does not exceed the emitter layer thickness, so that it will not be shorted to the emitter metal layer.

(5) Pattern and etch base and n- collector layer to expose n+ sub-collector layer:

Positive photoresist AZ 1518 is spun on the wafer. Photoresist on designated area of the wafer are developed away by conventional lithography method and these areas are etched to the subcollector layer. Step 4 and 5 correspond to Figure 3.2 (f).

(6) Deposit and lift-off Ni/Ge/Au/Ni/Au for collector ohmic contacts followed by rapid thermal annealing:

Following step 2, Ni/Ge/Au/Ni/Au are deposited on the subcollector layer. It then undergoes Rapid Thermal Annealing at 410°C for 10 sec in order to form ohmic contact to the n+ GaAs layer. . Figure 3.2 (g) corresponds to this step.

(7) Plate airbridge and interconnect metal layer:

To connect the emitter, base and collector metal layer to their respective thick metal pads used for probing or bonding areas, an air-bridge interconnect process is developed. Air- bridge interconnection technology is one of the most critical process steps in the power HBT process. The requirement for an air-bridge interconnection is high strength and low parasitic. Gold thickness above 2 μm is essential for a long span and high strength air-bridge interconnection. Since the air-bridge and the bottom metal form a parasitic capacitance, therefore, air-bridge height plays an important role for the low

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parasitic. It is clear that the higher the height the lower the parasitic. In this work, the height is 2 μm that is defined by a thick photoresist. In addition to the air-bridge height, the bridge span is another consideration. The bridge span cannot be too long otherwise it will give rise to a bowl like profile. The empirical bridge span limit is 60 μm . Fig. 3.2(h) - (n) shows the fabrication process flow of air-bridge technology.

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Remove Thick Resist & SiN Cap
(c)

Emitter metal formation
(d)

Emitter mesa formation
(e)

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Base metal formation and collector mesa etch
(f)

Collector metal formation
(g)

Pillar Photoresist Formation
(h)

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Seed Metal Deposition
(i)

Air-bridge Photoresist Formation
(j)

Gold Electroplating
(k)

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Air-bridge Photoresist Remove
(l)

Seed Metal Etch
(m)

Air-bridge Photoresist Remove
(n)

Fig. 3.2 Process Flow Steps (a) – (n).

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Figure 3.3 show the cross-sectional view of the completed HBT layout. The implanted mesa provides a smoother coverage for the metal finger thus less stress and better adhesion which in turn results in better yield. Figure 3.4 is the top of a fabricated power device with 16 emitter fingers. Each emitter finger size is $2 \times 10 \mu\text{m}^2$.

Fig 3.3 Cross-section view of HBT.

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Fig 3.4 Top view of a fabricated power device with 16 emitter fingers. Each emitter finger size is $2 \times 10 \mu\text{m}^2$.

CHAPTER 4 DEVICE CHARACTERISTICS

Chapter 4

Device Characteristics

4.1 Introduction

Two most important figure of merits used to characterize a transistor are its DC and microwave performance. DC characteristics show the gain and breakdown voltage while the microwave characteristics shows the frequency dependence of the gain of transistor. The DC and microwave characteristics of AlGaAs/GaAs HBTs fabricated in this work are presented here. DC measurement is performed on a 8-finger HBT, each finger being $2 \times 10 \text{ } \mu\text{m}^2$. Small-signal microwave measurement is performed on 2 to 16 finger HBTs. Power measurements are carried out on 4 to 16 finger HBTs without substrate thinning.

4.2 DC Characteristics

An 8-finger HBT with $2 \times 10 \text{ } \mu\text{m}^2$ emitters was measured using an HP4155 semiconductor parameter analyzer. The I_c - V_{ce} characteristics of the device are shown in Figure 4.1. The I - V characteristics indicate that the device has low output conductance and small offset voltage. DC current gain is shown in Figure 4.2 and Gummel plot is shown in Figure 4.3. The collector-base junction breakdown BV_{cbo} and emitter-base junction breakdown BV_{ebo} are approximately 18 V and 7.8 V respectively, and are shown in Figure 4.4 and 4.5. The DC current gain is only about 1 at low current and approximately 10 at high current. This is probably due to high surfaces states at the base-emitter periphery, giving rise to high generation-recombination current which have an

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ideality factor of 2. The slope of I_B in Fig. 4.3 indeed corresponds closely to 2. The two main factors for the defects are material growth and process fabrication.

Fig 4.1 I_C - V_{CE} performance of 8 fingers ($2 \times 10 \mu\text{m}^2$ per finger) HBT.

Fig 4.2 DC current gain of 8-fingers ($2 \times 10 \mu\text{m}^2$ per finger) HBT.

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Fig. 4.3 Gummel plot of 8-fingers ($2 \times 10 \mu\text{m}^2$ per finger) HBT.

Fig 4.4 I_C versus V_{BC} of 8-fingers ($2 \times 10 \mu\text{m}^2$ per finger) HBT.

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Fig 4.5 I_B versus V_{BE} of 8-fingers ($2 \times 10 \mu\text{m}^2$ per finger) HBT.

4.3 Microwave Characteristics

Microwave small-signal measurements were carried on an HP8510 network analyzer with an on-wafer Cascade probe station. S-parameters were measured in the frequency range 1 to 40 GHz. From the S-parameters, the conversion to h-parameters yields the common emitter current gain (h_{21}), MAG/MSG and U . The unity current gain cut-off frequency (f_T) and maximum frequency of oscillation (f_{max}) were obtained by extrapolating h_{21} and U , respectively. The h_{21} and MAG/MSG for self-aligned HBT for 2 and 16 fingers $2 \times 10 \mu\text{m}^2$ HBTs are shown at Figure 4.6 and 4.7 respectively, and the 2, 4, 8, 12, 16 fingers HBT f_T and f_{max} are summarized in Fig. 4.8. The f_T and f_{max} of 2 and 4 fingers HBT are almost the same but drop from 8 fingers HBT onward.

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Fig 4.6 $|h_{21}|^2$, MAG/MSG, and U as a function of frequency of 2 fingers $2 \times 10 \mu\text{m}^2$ HBT.

Fig 4.7 $|h_{21}|^2$, MAG/MSG, and U as a function of frequency of 16 fingers $2 \times 10 \mu\text{m}^2$ HBT.

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Fig 4.8 Summary of f_T and f_{max} for 2 to 16 fingers HBT.

To examine the roll off of frequency with increasing HBT fingers, phase of S-parameter S21 at 10 GHz are plotted in Fig. 4.9 where phase differences are referenced from the 2-fingers HBT. The phase difference between the 4 and 2 fingers HBTs is bigger than that of 16- and 8- fingers HBTs. Therefore phase difference between the fingers could not be the single reason for the trend observed. However, temperature for the center finger of multi-finger HBTs can be higher than its edge fingers [29, 30]. The temperature difference of the center finger to edge finger also increases with number of fingers. This temperature differences result in non-uniform current in each finger, with the center fingers conducting the lowest current. With f_T and f_{max} highly dependence on the current density [31], it is possible the overall they will drops with more non-uniformity in current between the center and edge finger as number of fingers increased. Hence, heating effect could be the reason for the observed trend. However, phase

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difference is coupled to the self-heating effect and cannot be ignored also. Hence we can only conclude the roll-off is due to non-uniform distribution of current and/or phase between the fingers.

Fig 4.9 Phase of S21 and their phase difference for 2 to 16 fingers HBT.

Microwave power measurement was carried out at 10 GHz for the devices with from 4 to 16 fingers, in common emitter configuration using on wafer ATN load-pull system (LP1). The power measurement shows approximate 5 W/mm for the devices, which is considered high for an un-thinned wafer, as 5 W/mm is the typical value reported in thinned wafer [4]. Figure 4.10 and 4.11 show the output power, gain and PAE for 4 and 16 fingers HBT, respectively. Figure 4.12 summaries the result for 4, 8, 12 and 16 finger HBTs. The maximum output power is 0.88 W with an PAE of 47% and a gain of 6.5 dB for a 16 finger HBT.

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Fig 4.10 Microwave power performance of 4 fingers $2 \times 10 \mu\text{m}^2$ HBT.

Fig 4.11 Microwave power performance of 16 fingers $2 \times 10 \mu\text{m}^2$ HBT.

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Fig 4.12 Summary of Pout, Gain and PAE at 10 GHz for 4 to 16 fingers HBTs.

A peak PAE ~65% is obtained for the 4 fingers HBTs. At low input power P_{in} , the transistor is operating in Class A operation. However, the theoretical limit of Class A amplifier efficiency is 50%. The point of peak efficiency is very likely to be operating in Class C operation [4]. This implies the transistor operation has moved from Class A to Class B and then to Class C as the input power increases. In this whole input power range, the power gain is fairly constant indicating good linearity. Multiple reasons could give rise to the peak and decrease in the power gain curve as power: (i) transistor matched at high power condition (ii) changes in mode of the transistor operation Class (iii) the rise of transistor temperature with increases of input power. The peak PAE is not obtained for the 16 fingers HBT as limited by the power that can be delivered by the instruments. However, comparing the P_{out} curve with the 4 fingers HBTs, we would expect that its peak PAE would be smaller than that of 4 fingers HBTs. This could be

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attributed to the lower large-signal ac gain with the increase of number of fingers in HBTs increased as suggested from small-signal ac gain f_T , f_{max} in Fig 4.8. Nevertheless, the power gain curve of 16 fingers HBTs go to a small peak before decreasing as input power increases, similar to that of 4 fingers HBTs. Moreover, the power gain shows better linearity than the 4 fingers HBTs. The output power P_{out} drops from 6.6 W/mm for 4 fingers HBTs to 5.6 W/mm for 16 fingers HBTs. The summary of PAE, power gain and P_{out} for 4, 8, 12 and 16 finger HBTs is shown in Fig. 4.12. We can see that PAE and power gain curves indeed decrease with the number of fingers in HBTs.

4.4 Summary

DC measurement performed on 8 finger $2 \times 10 \mu\text{m}^2$ HBT shows a low current gain which is attributed to the high surfaces states at the base-emitter periphery. However, a current gain of more than 10 is sufficient for microwave power applications. f_T , f_{max} are presented with increasing number of HBT fingers. Their roll-off with increasing number of fingers number is attributed to non-uniform distribution of current or phase between the fingers. Microwave power measurement demonstrates good linearity and power performance of $\sim 5\text{W/mm}$ our HBTs without substrate thinning.

CHAPTER 5 MEASUREMENT OF INGaP ELECTRON IONIZATION COEFFICIENT

Chapter 5**Measurements of InGaP Electron Ionization Coefficient using InGaP/GaAs/InGaP Double Heterojunction Bipolar Transistors****5.1 Introduction**

The advantages of the ternary compound $\text{In}_{0.52}\text{Ga}_{0.48}\text{P}$ over AlGaAs such as having a larger bandgap (1.9 eV [32]) with low carrier impact ionization coefficients, the absence of DX centers as compared to Al-based material and a high etching selectivity against GaAs have made it an excellent alternative for a variety of GaAs-based device applications. There include the use of heterojunction bipolar transistors (HBTs) and pseudomorphic high electron mobility transistors (pHEMTs) for power applications [33], [34]. Despite these advantages, the replacement to InGaP for AlGaAs/GaAs HEMT is undesirable because high ΔE_C is needed for high 2-DEG electron concentration to be formed; ΔE_C for InGaP/GaAs is 0.034eV while 0.22eV for AlGaAs/GaAs layer. However, if a thin layer of pseudomorphic InGaAs layer is used as the channel layer, a high ΔE_C of 0.4eV can be formed [34]. The onset of avalanche multiplication, and ultimately breakdown, is one of the main limiting factors for power devices. An accurate characterization of carrier impact ionization coefficients in InGaP is important for the prediction of carrier multiplication and avalanche breakdown characteristics.

Photocurrent multiplication (PCM) measurements on p-i-n photodiodes have been widely used for quantitatively determining the electron and hole impact ionization coefficients, α and β , respectively under high field. However, in this experimental

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technique, the accuracy of α and β in low electric field is limited by the uncertainty in the primary photocurrent (baseline for the avalanche gain). On InGaP lattice-matched to GaAs, the electron and hole impact ionization coefficients measured using the PCM method have been reported over the electric field range of 430 kV to 910 kV/cm by Ghin et al [35], [36] and 370 kV to 670 kV by Fu et al [37]. Their results are comparable at high fields, but are rather different at low fields.

To explore electron impact ionization in a wider electric field range, a different experimental technique based on the measurements of the impact ionization multiplication coefficient ($M-1$) in heterojunction bipolar transistors (HBTs) has been proposed and demonstrated for different material systems [38], [6], [39]. By using this fully electrical measurement method, electron and hole impact ionization coefficients in a wider electric field range have been characterized in various materials such GaAs [38] and InGaAs [6], [39]. However, no data were reported for InGaP. In this work, we report on the electric field dependence of electron ionization coefficient for InGaP estimated from the electric measurement of $M-1$ in InGaP collector of the InGaP/GaAs/InGaP HBTs. By identifying the Early and thermal effect in the experimental results, the α of InGaP has been extended more than two orders of magnitude in the low electric field region down to a value of $\alpha = 1 \text{ cm}^{-1}$. The measured electron impact ionization coefficient are in agreement with that reported by Ghin et al [35], [36] at medium and low field, but are rather different from that reported by Fu et al [37] at low field.

5.2 Experiments

A. Sample Description

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The epitaxial layers were grown by metal organic chemical vapour deposition (MOCVD). Carbon and Silicon are used as p- and n-type dopants, respectively. The detailed layer structure of the DHBT is shown in Fig. 5.1. The layer thickness and doping concentration are well calibrated. A 10 nm highly n-type doped InGaP tunnel layer at the collector is used to reduce the current-blocking effect. The mesa-isolated devices with emitter dimension of $30\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$ were used for tests. The transistor is characterized by dc gain ≈ 40 at $I_C \approx 1\text{ mA}$ with low base-collector junction leakage current (I_{CBO}) of $\sim 12\text{ nA}$ at $V_{CB} = 15\text{ V}$.

Fig. 5.1 Cross section of InGaP/GaAs/InGaP HBT. A 10 nm highly n-type doped InGaP tunnel layer at the collector is used to reduce the current-blocking effect. Area of emitter is $30\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$.

B. Electrical Multiplication Measurements

The basic definition of multiplication factor $M-1$ in the common base configuration is [40], [6]:

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$$M - 1 = \frac{I_C - I_{CBO}}{I_{CI}} - 1 \quad (5.1)$$

where I_{CI} is the current of carriers injected from base to the collector.

It should be pointed out that, when the V_{CB} is increased, beside impact ionization, several mechanisms can induce a change in collector current: i) Early effect increases current and thereby I_C ; ii) I_{CBO} increases; iii) the increase in power dissipation and junction temperature (thermal effect) results in the decrease in current gain and thus I_C ; iv) the possible carrier blocking at abrupt base-collector may cause the variation of collector current. For an accurate calculation of impact ionization coefficients, all above-mentioned secondary effects have to be considered carefully. Different from conventional single HBTs, the electron blocking at the abrupt GaAs/InGaP base-collector (B-C) junction interface may directly influences the extraction of impact ionization coefficients. To reduce the current blocking, a 10 nm heavily doped InGaP layer is inserted at B-C junction interface as shown in Fig. 5.1. The conduction band potential spike at B-C junction interface can be effectively narrowed to enhance the probability for electron tunneling through the potential spike and reduce the current blocking. This is confirmed by the calculation of energy band diagram by solving the Poisson's equation as shown in the inset (b) of Fig. 5.2. For V_{BC} less than -10 V, which is the voltage range for the measurement of $M-1$ in this work, the potential spike is found to be below the conduction band of the GaAs base. This can be further supported by the common-base (Fig. 5.2) and common-emitter [inset (a) of Fig. 5.2] $I-V$ characteristics measured from a small high frequency device (emitter size: $1.5 \times 10 \mu\text{m}^2$). The device shows a low knee voltage and sharp turn-on indicating the negligible current blocking [41], [42].

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Fig. 5.2 Common-base I - V characteristics measured from a small high frequency device (emitter size: $1.5 \times 10 \mu\text{m}^2$). Inset: (a) common emitter I - V characteristics, (b) comparison of conduction band diagrams at base-collector interface between the structures with and without the tunnel layer.

To evaluate the thermal effect, measurements of M -1 were carried out at different current densities. By reducing the emitter current density from 42 A/cm^2 to 8 A/cm^2 , only $\sim 1\%$ difference on the M -1 was observed at high field. Therefore, in order to exclude the influence of collector junction leakage current, the current density of 42 A/cm^2 is chosen so that the ratio between I_{CI} and I_{CBO} could be maintained at the values higher than 200 in the full measurement range. Fig. 6.3 shows a typical I_C - V_{CB} characteristics measured under common-base configuration. A slightly decrease in collector current in the voltage range of 7 to 10 V before the onset of multiplication. The decrease in collector current is due to the thermal effect. If we assume a linear decrease of I_C due to thermal effect and extrapolate the collector current from the thermal effect dominate region to obtain the

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I_{CI} , the multiplication factor $M-1$ can thus be evaluated based on (5.1), which is shown in the inset of Fig. 5.3. The error induced by Early effect is corrected by using the analytical method provided by Shamir et al [43].

Fig. 5.3 Early and thermal effect in the measured collector current of InGaP/GaAs DHBT under common base configuration. The inset is the $M-1$ as a function V_{CB} measured on the DHBT by taking the thermal effect into account.

5.3 Results and Discussions

Based on the constant electrical field approximation [6], the electron ionization coefficient can be evaluated from:

$$\alpha = \frac{E}{V_{bi} + V_{CB}} \frac{M-1}{M}, \quad E = \frac{(V_{bi} + V_{CB})}{W} \quad (5.2)$$

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where W is the depleted width calculated with the depletion approximation which includes the both thickness of collector layer and thin tunnel layer. The built-in voltage for the InGaP/GaAs junction is 1.4 V. The calculated electron ionization coefficient based on eqn. (5.2) and measured $M-1$ in InGaP collector is plotted in Fig. 5.4. Plotted alongside Fig. 5.4 are also the data obtained by photomultiplication methods from [36] and [37]. Present data measured for our InGaP/GaAs DHBT's agree very well with those from [36]. Compared with the data reported in [36], the α of InGaP obtained here has been extended more than one order of magnitude in the low electric field region down to a value of $\alpha \approx 1 \text{ cm}^{-1}$ at the electric field of 330 kV/cm. A large discrepancy ($\times 10$) between our measurement and the data reported by Fu et al can be seen at low electric fields. The parameterized form of α fitted to this measured α is:

$$\alpha = 5.15 \times 10^5 \exp \left[- \left(\frac{1.39 \times 10^6 \text{ V/cm}}{E} \right)^{1.76} \right] \text{ cm}^{-1}. \quad (5.3)$$

A slight deviation between the parameterized fitting defined by above expression and measurement data is presented at extreme low electrical field region. Proper correction needs to be made before eqn. (5.3) can be used for the prediction of device multiplication and breakdown behavior in this extremely low field region.

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Fig. 5.4 Electron ionization coefficient in InGaP measured from the HBT collector layer using electrical method. The experimental data reported in [36] and [37] using optical method are also plotted for comparison. The overall experimental errors of extracted α due to the variations of both collector layer thickness and doping concentration are represented by the dashed area. Inset: Relative errors on the impact ionization coefficients due to the variation of collector layer thickness and doping concentration.

The possible inaccuracy in the calculation of α arises from the approximation of constant electric field in the collector region, which has been widely used for the extraction of α for different material based on the measurement of $M-1$ in HBT's. Fig. 6.5 shows the electric field profile in the collector region at $V_{CB} = 15$ V. The origin starts from the tunnel layer. A sharp increase of electric field at base-collector interface due to the highly doped tunnel layer can be observed. The value of average electric field used in the electron ionization calculation is plotted as the dashed line. To confirm the validity of the extracted α given by eqn. (5.3), we calculate $M-1$ using both uncorrected local model

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and dead space corrected model shown as an inset of Fig. 5.5. The electrical field profiles for different V_{CB} were obtained by solving Poisson's equation. The contribution of dead space effect is taken into account by [44]:

$$1 - \frac{1}{M} = \left[1 + \int_0^{x_{th}} \beta dx \right] \int_{x_{th}}^W \alpha \exp\left[-\int_{x_{th}}^x (\alpha - \beta) dx' \right] dx, \quad (5.4)$$

where x_{th} is obtained by

$$\varepsilon_{th} = \int_0^{x_{th}} E(x) dx. \quad (5.5)$$

ε_{th} is the threshold energy of ionization taken to be 2.11 eV for InGaP [45]. It can be seen that using the extracted α corrected by dead space effect, the calculated $M-1$ fits well the experimental results. In other words, the experimentally determined electron ionization coefficients defined by eqn. (5.3) already excludes dead-space and could be considered as the “bulk” parameter. One of the reasons could be attributed to the use of constant field approximation in deriving the ionization coefficient.

The major errors on the extracted impact ionization coefficient could be associated with the possible variations in the layer thickness and doping concentrations, which will cause the variations on the corresponding electric fields. By carefully calibrating the layer thickness using different in-line and off-line measurement technique such as RHEED, C-V, and surface profiler, the experimental error on the InGaP in the devices has been estimated to be around 3%. The maximum experiment error on the doping concentration is 10%. The inset of Fig. 5.4 shows the impact of the variation of layer thickness and doping concentration on the relative errors of impact ionization coefficients. The impact ionization coefficient is more sensitive to the layer thickness. Larger experiment errors can be found in low electric field region. The overall

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experimental error of extracted α due to the variations of both layer thickness and doping concentration are represented by the dashed area shown in Fig. 5.4. The possible inaccuracy of α in the low electric field region which could be induced by inter-related carrier dynamics such as impact ionization under thermal effects due to self-heating is also investigated. By reducing emitter injection current from 400 μA (32 A/cm^2) to 100 μA (8 A/cm^2) to suppress the self-heating, only a slight decrease of α in extremely low field region can be observed. The difference is much smaller than the error of α induced by the variations of both layer thickness and doping concentration.

Fig. 5.5 Electric field profile in the collector region at $V_{CB}=15$ V. The dash line indicates the average electric field used. Inset: Calculated $M-1$ using eqn. (5.3) with and without the consideration of dead space effect.

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5.4 Summary

The electron impact ionization coefficients in InGaP have been measured in InGaP/GaAs DHBT's using the electrical method. The electron ionization coefficients of InGaP determined in this work are consistent with the results reported by Ghin et al. in high fields and extends the previously reported data by two orders of magnitude down to 1 cm^{-1} with the electric field as low as 330 kV/cm. The accurate determination of carrier impact ionization coefficients in InGaP is important for the prediction of avalanche breakdown characteristics of GaAs-based devices using InGaP.

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Chapter 6

Temperature Dependence of the Electron Impact Ionization in InGaP/GaAs/InGaP Double Heterojunction Bipolar Transistors (HBTs)

6.1 Introduction

For high power devices such as InGaP/GaAs DHBTs utilizing InGaP as the collector to extend the device power capability, an understanding on the temperature dependence of impact ionization at elevated temperatures becomes important as junction temperature can be much higher than room temperature during the device operation. However, the study of temperature dependence of electron multiplication and junction breakdown in InGaP device is rather limited. The currently available information was reported by Ghin *et al.* [46] based on the measurements performed on InGaP p-i-n diodes. A 16% increment of junction breakdown voltage with the increase of temperature from 20 to 600 K was observed.

In this chapter, we extend the work of Chapter 5 to determine the temperature dependence of avalanche multiplication characteristics in InGaP/GaAs/InGaP double HBTs. The electron impact ionization coefficients for InGaP in the temperature range 300-450 K under electrical field of 380 to 650 kV/cm were characterized. As compared to InP and GaP binaries, the ternary InGaP shows a lower electron ionization coefficient and much weak temperature dependence. This resulted in a relatively small negative temperature dependence of junction breakdown.

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Physical theory describing the impact ionization process in semiconductors was developed by Baraff [12] which is based on the assumption of that the optical phonon scattering is the dominant scattering process during impact ionization. Baraff solved the time-dependent Boltzmann transport equation and demonstrated that his model could cover both low and high electric field region, which was earlier described by Shockley's low-field model [11] and Wolff's high-field model [10]. The Baraff's theory was further improved by Okuto and Crowell in early 1970s which obtained a simple analytic formula for α and β with better fitting at high-field region [47]. Okuto-Crowell formulation has been widely used for the prediction of carrier impact ionization and its temperature dependence. By choosing suitable impact ionization threshold energy E_{th} , phonon energy E_r , and phonon scattering mean free length λ , the Okuto-Crowell formulation has been found to provide reasonable prediction for many semiconductors such as Si, GaAs, InP etc. However, it has not been evaluated whether the Okuto-Crowell formulation can be applied to InGaP. We will show that, the Okuto-Crowell expression along with Crowell-Sze temperature dependence of E_r and λ [48] based on contribution from optical phonon scattering may not be sufficient to fit the measured impact ionization and its temperature dependence. In order to explain our experimental data, additional scattering mechanism has to be introduced. Introducing additional scattering mechanism such as alloy scattering [49], which may have relatively larger contribution in ternary compounds, would provide a better interpretation for the experimental data.

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6.2 Sample description and measurement techniques

The detailed layer structure of the InGaP DHBT follows Fig. 5.1. Measurements on temperature dependence were carried out on a thermal chuck where sample temperatures were controlled within $\pm 1.5^\circ\text{C}$. Six set of data are collected from $T = 300$ to 450 K in step of 30 K . The calculation of $M-1$ and electron ionization coefficient α follows as Chapter 5.

6.3 Results and discussions

A. Temperature Dependence of Device Breakdown Behavior

Fig. 6.1 shows the B-C junction leakage current measured from two HBTs using GaAs or InGaP as the collectors at temperature of 300 and 450 K . Although an increase in junction leakage can be observed when the temperature is increased, the I_{cbo} remains less than $\sim 1\text{ }\mu\text{A}$ until breakdown even if the temperature is as high as 450 K . The small junction leakage insures negligible effect of B-C junction leakage on the extraction accuracy of junction multiplication factors shown in the later part of the work. Both devices show the hard junction breakdown behaviour which could be attributed to carrier impact ionization. The temperature dependence of B-C junction breakdown voltage (BV_{cbo}) for the double HBT and its referenced single HBT is shown in Fig. 6.2. The breakdown voltage is defined as the voltage corresponding the reverse junction current of $100\text{ }\mu\text{A}$. As the temperature increased from 300 to 450 K , the device with InGaP collector shows a slight increase of BV_{cbo} from 24.7 to 25.5 V . However, the variation of BV_{cbo} in the GaAs collector is more pronounced from 18 to 20.4 V .

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Fig. 6.1 B-C junction reverse current-voltage (*I*-*V*) characteristics measured at 300 and 450 K.

Fig. 6.2 B-C junction breakdown voltages versus temperature for InGaP and GaAs collectors. Inset: B-C junction reverse *I*-*V* characteristics in the voltage region closed to breakdown as a function of ambient temperature measured from InGaP and GaAs collectors.

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Similar measurements are performed under common-emitter configuration. For the devices biased under common-emitter configuration, the breakdown voltage is determined by avalanche multiplication in the B-C junction as well as the dc gain. Fig. 6.3(a) shows the common-emitter breakdown voltages versus temperature as a function of injection current measured from the InGaP-GaAs double HBT at two different ambient temperatures (300 K and 450 K). For reference, same measurements performed on an AlGaAs-GaAs single HBT with a 600 nm GaAs collector are also plotted for comparison. Again, compared to the single HBT, the DHBT using InGaP as collector shows only a 0.4 V increment of off-state breakdown voltage (BV_{ceo}) when the temperature is increased from 300 to 450 K. The single HBT with the GaAs collector exhibits a larger temperature dependence with a ~ 3 V increase in BV_{ceo} . The observed increase of breakdown with increasing temperature is similar to the previous report on AlGaAs-GaAs HBTs [50]. It has been reported that the positive temperature dependence of junction breakdown in GaAs collector can be attributed to the negative dependence of the electron impact ionization coefficient. In other words, the weak temperature dependence of breakdown observed in double HBT could be due to a weak temperature dependence of electron impact ionization coefficients in InGaP. Note that, the common-emitter breakdown voltage could be affected by dc gain. The difference of the dc gains of AlGaAs-GaAs and InGaP-GaAs as temperature changes could also contribute to the overall variation of the BV_{ceo} . To have a more accurate assessment of electron impact ionization behavior, electron multiplication factors as well as impact ionization coefficients at different temperatures have to be extracted. The results are outlined in next section.

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Fig. 6.3 Typical common emitter I - V characteristics of (a) AlGaAs/GaAs single and (b) InGaP/GaAs double HBTs measured up to collector breakdown measured at two different ambient temperatures (300 K and 450 K).

B. M -1 and Electron Impact Ionization Coefficients at Different Temperatures

To extract the temperature dependence of M -1, common-base I - V curves obtained at an emitter current of 500 μ A (i.e., emitter current density of ~ 40 A/cm²) is measured at different temperatures. The ~ 40 A/cm² current density is selected for maintaining high dc gain, low self-heating and high injection current with respect to junction leakage. The M -1 values extracted from the common-base I - V curves is plotted in Fig. 6.4. If we look into

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the high reverse bias voltage region as shown in the inset of Fig. 6.4, a negative temperature dependence of $M-1$ is obtained.

Fig. 6.4 $M-1$ as a function V_{CB} measured on the InGaP-GaAs-InGaP DHBT at $I_E = 500 \mu A$ under common-base configuration in the temperature range of 300 to 450 K. Inset: Exploded view of $M-1$ versus V_{CB} in high V_{CB} region.

The electron impact ionization coefficients α are calculated and plotted in Fig. 6.5. Only 3 sets of temperature data are plotted for clarity. They clearly show a negative temperature dependence.

Based on our present data, following the Chynoweth's law, we can empirically determine a formula for the temperature dependence of electron ionization coefficient of InGaP as:

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$$\alpha = A(T) \exp \left\{ - \left(\frac{B(T)}{E} \right)^{m(T)} \right\} \quad (6.1)$$

where

$$m(T) = 2.25 - 1.64 \times 10^{-3} T;$$

$$A(T) = 1.66 \times 10^6 - 9.58 \times 10^3 T + 19.33 T^2 \text{ cm}^{-1};$$

$$B(T) = 1.24 \times 10^6 - 1.25 \times 10^3 T + 5.86 T^2 \text{ V/cm};$$

and T is temperature in K . This empirical equation can be easily used for the prediction of α for InGaP in the temperature range of 300 to 450 K for device simulators. Note that the equation is valid for the electric field between 380 to 650 kV/cm. The calculated data plotted as the solid lines using eqn. (6.1) fit well with the experimental results as shown in Fig. 6.5. The previous reported room temperature experimental data for InP[51] and GaP[47] are also plotted in Fig. 6.5 for comparison. It is interesting to see that the values of α for InGaP do not fall in between the values for the InP and GaP. In fact, the values obtained from InGaP are smaller than the ones for GaP even though GaP has a larger bandgap (and thus E_{th}). This is similar to the reported $\text{Al}_x\text{Ga}_{1-x}\text{As}$ [52], [54] and InGaAsP [53] data where impact ionization coefficients measured from the ternaries or quaternaries fall below the values of the binaries. Also, the α of InGaP shows a much weaker temperature dependence as compared to InP. To have a better understanding of the measured data, more theoretical analysis is needed.

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Fig. 6.5 Experimental data of electron impact ionization coefficients of InGaP at different temperature. The calculated data based on the empirical (6.1) is plotted as the solid lines. Previous reported room temperature experimental data for InP and GaP are also plotted for comparison.

C. Comparison with Physics Model

The simple analytic formula obtained by Okuto and Crowell for electron ionization coefficient [47] is:

$$\alpha = \frac{qE}{E_{th}} \exp \left\{ 0.217 \left(\frac{E_{th}}{E_r} \right)^{1.14} - \left[\left(0.217 \left(\frac{E_{th}}{E_r} \right)^{1.14} \right)^2 + \left(\frac{E_{th}}{qE\lambda} \right)^2 \right]^{0.5} \right\} \quad (6.2)$$

where E_{th} is the impact ionization threshold energy assuming to scale with the bandgap, E_r and λ_r are phonon energy and phonon scattering mean free length, respectively. The temperature dependences of E_r and λ_r were proposed by Crowell and Sze [48] as:

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$$E_r = E_{r0} \tanh\left(\frac{E_{r0}}{2kT}\right), \quad \lambda_r = \lambda_{r0} \tanh\left(\frac{E_{r0}}{2kT}\right) \quad (6.3)$$

where E_{r0} and λ_{r0} are phonon energy and phonon scattering mean free length at 0 K. Okuto-Crowell formulation has been widely used for the prediction of carrier impact ionization and its temperature dependence. Although it has been reported, the above-mentioned analytic models which does not include a completed bandstructure, may be oversimplification the problem, and full-band Monte Carlo simulation would provide more rigorous prediction on the carrier impact ionization. However, by choosing suitable impact ionization threshold energy E_{th} , phonon energy E_r , and phonon scattering mean free time λ_r , the Okuto-Crowell formulation has been found to provide reasonable prediction for many semiconductors in particular to those with “hard” threshold energy such as Si, GaAs, InP etc. Considering the bandstructure of InGaP which has large bandgap of $E_g \approx 1.85$ eV (at 300 K) with small $E_{\Gamma-L} \approx 0.15$ eV and $E_{\Gamma-X} \approx 0.40$ eV (Table 6.1), the threshold will be “hard” [19] in the sense that hot electron that have sufficient energy to create an electron-hole pair would easily find some $\vec{k}$ for momentum conservation, keeping the impact ionization energy of electron to a small range. Therefore, we shall assume InGaP has a well-defined threshold energy E_{th} and its temperature dependence scales with the one for bandgap and apply the Okuto-Crowell relation for our discussion.

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Table 6.1

Material parameters at 300 K.

Material	E_X (eV)	E_I (eV)	E_L (eV)	E_{th} (eV)	E_r (meV)	λ_r (Å)	E_r/λ_r (eV/cm)
	[3]	[3]	[3]	[54]	[54]	[54]	($\times 10^5$)
InP	2.19	1.34	1.93	1.84	32.9	29.8	1.1040
GaP	2.26	2.78	2.6	2.6	38	31	1.2258
InGaP	2.25	1.85	2.0	2.22	35 ^a	30.4 ^a	1.16

^a This work

Note that a fundamental assumption - the optical phonon scattering is the dominant scattering process during impact ionization, was used in above-mentioned models. Compared to GaP, the bandgap of InGaP is smaller and thereby E_{th} . Furthermore, the smaller carrier effective mass in InGaP would result in less frequent scattering events. If we assume that the electron impact ionization in InGaP is determined just by the ionization threshold and optical phonon scattering, then the smaller E_{th} in conjunction with less optical phonon scattering would result in a larger α in InGaP as compared to the one in GaP. This is different from our experimental observations. For the temperature dependence of α , the effects from the optical phonon scattering and threshold energy E_{th} are opposite. Phonon scattering increases with temperature, thus reduces the population of the high-energy tail of the electron distribution and lower the ionization rate. On the other hand, the decrease of bandgap energy would lower the threshold energy an electron needs to achieve, thus enhance impact ionization. Usually, the dominant effect is the

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phonon scattering. The temperature dependence of α is mainly determined by the temperature dependence of phonon scattering, which is the case for InP, GaAs and many other semiconductors. Judging from Fig. 6.5 and 6.6, we could conclude that the widely used Okuto-Crowell relation may not be simply applied to fit our experimental data. At least, using the optical phonon energy approximately to the data obtained by Raman spectroscopy or the optical branch of phonon spectral curve fails to do so. We also observed that reasonable fitting parameters could not be found to satisfy simultaneously the temperature dependence and the field dependence of α even if arbitrary values were chosen for E_{r0} and λ_{r0} .

One of the possible reasons for the discrepancies between the experimental data and Okuto-Crowell relation could be due to the involvement of additional scattering mechanism. Considering the study of electron impact ionization, which is the case under high electric field, only those scattering mechanisms with high scattering rate at high electric field could play important roles in determining the abnormal temperature dependence of α in InGaP. Studies in ternary compound such as AlGaAs [55], InGaAs [56], and InAsP [22] have shown that, at high electric field, alloy scattering through random angles has much higher scattering rate over the other scattering mechanisms. The involvement of alloy scattering would randomize the carriers traveling in a given electric field and consequently affect the carrier impact ionization behavior, and the weaker temperature dependence of alloy scattering as compared to phonon scattering [49] is consistent with weak temperature dependence of α observed here. It should emphasize that the above analysis based on the analytic Okuto-Crowell relation could only provide a

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qualitative image. To have a rigorous and accurate understanding, a full-band Monte Carlo simulation is necessary.

Fig. 6.6 Comparison of the theoretical calculation of α using Okuto-Crowell relation with the experimental result.

D. Implication on Weak Temperature Dependence of Electron Impact Ionization Coefficients

The implication of the weak temperature dependence of electron impact ionization is twofold. For power HBTs operated close to breakdown, the thermal and electrical stabilities are determined by the temperature dependence of the current gain and collector impact ionization rate. In conventional AlGaAs-GaAs NPN single HBTs, the fast decrease in impact ionization with the increase of device power (i.e. junction temperature), in conjunction with the large reduction of emitter injection efficiency due to small valance band discontinuity, may restrain the collector current when the device

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approaches avalanche breakdown. This makes the device more robust and less likely to burn out. For InGaP-GaAs double HBTs, the weak temperature dependence of electron impact ionization and dc gain could weaken the self-limiting effect and result in a higher possibility for B-C junction catastrophic breakdown. In fact, experimental evidence has been observed in our InGaP-GaAs double HBTs. Compared to the referenced AlGaAs-GaAs single HBTs, the double HBTs exhibit much higher tendency to burn out during dc and microwave measurements. The electro-thermal management in the design of InGaP-GaAs DHBT is more important.

On the other hand, the weak temperature dependence of electron impact ionization coefficients in InGaP make this material promising for device applications such as avalanche photodiodes (APDs). In general, the performance characteristics in APDs are highly temperature sensitive, such temperature dependence is undesirable from the standpoints of device application. In GaAs-based APDs, a suppression of temperature sensitivity could be expected if InGaP can be used as the material for the avalanche region.

6.4 Summary

The temperature dependence of electron impact ionization at elevated temperatures for InGaP material has been studied based on the electron multiplications measurements using an InGaP-GaAs double HBT. An empirical expression is obtained to predict the electron ionization coefficients at elevated temperature up to 450 K in the electric field range of 380 to 650 kV/cm. As compared to binaries compounds such as InP and GaP, the ternary InGaP shows a lower electron ionization coefficient and much

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weaker temperature dependence. The widely used Okuto-Crowell relation, which only considers phonon scattering, is found not applicable for the prediction of ionization coefficient and its temperature dependence of InGaP. Introducing additional scattering mechanism such as alloy scattering may provide a better interpretation on the low electron impact ionization and its weak temperature dependence observed in InGaP.

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Chapter 7

Effects of Alloy Scattering on InGaP Electron Ionization Coefficient

7.1 Introduction

The direct band-gap InGaP lattice-matched to GaAs is an important material for both microelectronic and optoelectronic devices. Understanding carrier impact ionization coefficients in InGaP is of great importance for the prediction of its behaviour under high electrical field. An interesting feature of InGaP is that it contains regions that exhibit CuPt-type ordering cluster on the group-III sublattice, which leads to a variation in energy band. The formation of CuPt-type ordering cluster is determined by growth conditions; theoretically the variation of bandgap due to the clustering effect can be as large as 260 meV [57]. It has been confirmed both theoretically and experimentally that the low field transport properties of InGaP such as electron mobility could be largely affected by clustering. By treating spherically ordered domains as clusters, Friedman *et al* [58] calculated that scattering at clusters so-called alloy scattering in InGaP strongly affects Hall mobility. Their calculation predicated an increase in Hall mobility at high temperature for samples with larger cluster radius. This phenomenon was lately confirmed by Bauhuis *et al.* [59]. An *increase* in Hall mobility at elevated temperature was even experimentally observed. However, compared to the significant efforts made on low electric field transport properties, the role of alloy scattering on high field transport properties such impact ionization has not been fully explored. The impact ionization coefficients (α_n) of InGaP at room temperature were recently characterized by using both photo [37, 36] and electrical injection of carriers as described in Chapter 5. The

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measurement results reveal a lower α_n for InGaP as compared to those reported for binary InP and GaP. The temperature dependence of electron impact ionization coefficient (α_n) of InGaP in the range of 300 to 450 K using an InGaP/GaAs double heterojunction bipolar transistor is extracted in Chapter 6 [60]. A very weak temperature dependence of α_n in InGaP was obtained, which correlated well with some published temperature-dependent junction breakdown data [46]. However, we found that the widely used Okuto-Crowell relation [47] simplified from Baraff formalism [12], which assumes the optical phonon scattering to be dominant, fails to predict the measured temperature dependent α_n . A fundamental understanding on the discrepancy between our experimental data and Okuto-Crowell model is necessary. In this chapter, we will show that deviation of experimental α_n from the Okuto-Crowell relation can be consistently ascribed to alloy scattering. A physical model taking alloy scattering into account is required for accurately predicting impact ionization in InGaP.

7.2 Results and discussions

The detailed layer structure of the InGaP DHBT follows Fig. 5.1 and temperature dependence measurements can be found from Chapter 6. Figure 7.1(a) shows the α_n measured at different temperatures and only three sets of temperature data are plotted for clarity. The temperature dependence is plotted in Fig. 7.1(b) along with InP and GaP.

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Fig. 7.1 (a) Electron ionization coefficient, α_n of InGaP measured from InGaP/GaAs/InGaP DHBT at different junction temperatures. Dashed lines show the electron ionization of InP and GaP at room temperature and the solid lines are the electron ionization of InGaP calculated by using Okuto-Crowell expression. (b) Comparison of temperature dependence of α_n for InP, GaP and InGaP at electric field of 430 kV/cm. T^{-1} (solid line) and T^{-3} (dashed lines) relations are plotted in the figure for reference.

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Comprehensive physics theory to describe the impact ionization process in semiconductors was first developed by Baraff [12] which based on the assumption of that the optical phonon scattering is the dominant scattering process during impact ionization. In his model, the time-dependent Boltzmann transport equation was solved and demonstrated that carrier impact ionization in both low and high electric field regions which was earlier described by Shockley's low-field model [11] and Wolff's high-field model [10] could be covered. The Baraff's theory was lately simplified by Okuto and Crowell in early 1970s to obtain analytic formula for both electron and hole impact ionization coefficients with improved fitting in high-field region [47]. By choosing suitable impact ionization threshold energy E_{th} , phonon energy E_r , and phonon scattering mean free length λ_r , the Okuto-Crowell formulation has been found to provide reasonable prediction for many semiconductors such as Si, GaAs, InP and is widely used for device simulation. However, it has not been evaluated whether the Okuto-Crowell formulation can be applied to InGaP. In fact, as we can see in Fig. 7.1(a), the calculated α_n based on the Okuto-Crowell expression, eqn (6.2), along with Crowell-Sze temperature dependence of E_r and λ_r [48] for optical phonon scattering, eqn (6.3), is not sufficient to provide a reasonable fitting to the experimental data. The $E_{th} = 2.22$ eV, $E_r = 35.3$ meV, and $\lambda = 30.4$ Å at room temperature used for calculation are interpolated from the data reported for InP and GaP [54]. The calculation using Okuto-Crowell expression shows a higher α_n with larger temperature dependence. Notice that a fundamental assumption - the optical phonon scattering is the only dominant scattering process during impact ionization, was used in above-mentioned models. However, judging from Fig. 7.1,

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the large discrepancy between the experimental result and theoretical suggests that it is necessary to reassess this fundamental assumption by considering the other scattering mechanisms. It has long been realized, besides the optical-phonon scattering, the other scattering mechanisms such as piezoelectric (acoustic-phonon) scattering, ionized impurity scattering as well as alloy scattering could also involve in III-V compound semiconductors [49]. However, the mean free times of piezoelectric and ionized impurity scattering were found to increase with energy of carriers [49], in other words, the reduction of scattering rates for piezoelectric and ionized impurity scattering would be expected at high electric field. Therefore, the influence of piezoelectric and ionized impurity scattering on the electron impact ionization should be insignificant, because the study of electron impact ionization is limited in high electrical field region. On the other hand, the mean free path of alloy scattering is believed to be insensitive to carrier kinetic energy and temperature, eqn (2.27) or [49], and hence its scattering will increase with energy of carrier. Therefore, at high electric field for which the impact ionization could occur, alloy scattering may play a substantially important role, and is strongly suggested as an additional scattering mechanism affecting the carrier impact ionization behavior in InGaP. The interpolation of E_{th} , E_r and λ put into Okuto-Crowell expression above may be a questionable approach to compare it with the experimental data. However, we have attempted arbitrary values but that do not come out well, reasonable fitting parameters cannot be found to satisfy simultaneously the temperature dependence and the high and low field dependence behavior. In the following part, we will show that by introducing the alloy scattering as the additional scattering mechanism during carrier impact

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ionization, the suppression of α_n and its temperature dependence can be quantitatively explained.

7.3 Role of Alloy Scattering on Electron Ionization

Considering the involvement of alloy scattering, the electron scattering mean free path (MFP) in InGaP, λ , can be expressed as:

$$\frac{1}{\lambda} = \frac{1}{\lambda_r} + \frac{1}{\lambda_a}, \quad (7.1)$$

where λ_a is alloy scattering mean free path. Introduce the energy-balance equation for an electron:

$$qE \frac{v_d}{v_\theta} = \frac{E_r}{\lambda_r} + \alpha E_{th} \quad (7.2)$$

where v_d is the drift velocity and v_θ is the random thermal velocity. Also, the drift velocity can be given by [61]:

$$v_d = \frac{q}{m^*} \langle\langle \tau \rangle\rangle E \quad (7.3)$$

where m^* is electron effective mass, $\langle\langle \tau \rangle\rangle$ is the mean free time, which can be approximated by:

$$\langle\langle \tau \rangle\rangle \approx \lambda / v_\theta. \quad (7.4)$$

However, eqn. (7.3) is valid only for low electric field, but we could modify it to accommodate to high electric field by:

$$v_d = \eta \frac{q}{m^*} \langle\langle \tau \rangle\rangle E \quad (7.5)$$

where $\eta = \eta(T, E)$ depend on temperature and electric field.

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Combining equations (6.2), (6.3), and (7.1) to (7.5), we thus can obtain an expression for the average kinetic energy of an electron with respect to electric field:

$$K.E. = \frac{1}{2}m^*v_{\theta}^2 + \frac{1}{2}m^*v_d^2 = \eta \frac{q^2 E^2 \lambda}{E_r / \lambda_r + \alpha E_{th}} \left[1 + \left(\frac{E_r / \lambda_r + \alpha E_{th}}{qE} \right)^2 \right]. \quad (7.6)$$

It can be seen that the average kinetic energy is proportional to λ . Although the alloy scattering is generally considered as an elastic event without energy loss, the kinetic energy could still be affected by the presence of alloy scattering through the variation of λ .

A more quantitative analysis of the data requires the determination of alloy scattering mean free path λ_a . Using a first order approximation, the λ_a of InGaP in our device can be estimated based on the extracted electron saturation velocity in the InGaP collector. The electron saturation velocity v_s is given by [62]:

$$v_s = \sqrt{\frac{E_m}{m^*}} \quad (7.7)$$

where E_m is the mean energy lost per mean free path. The energy lost per unit length in this saturation regime would be the sum of energy lost per unit length through the optical phonon and alloy scattering if only these two scattering mechanisms are considered. Since alloy scattering is elastic and therefore we have:

$$\frac{E_m}{\lambda} = \frac{E_r}{\lambda_r} \quad (7.8)$$

At T=300K, if the alloy scattering is not presented, $E_m = E_r = 35.3$ meV, $\lambda = \lambda_r = 30.4$ Å and the saturation velocity $v_s \sim 6.5 \times 10^6$ cm/s is calculated by Monte Carlo simulation without the consideration of alloy scattering [63]. However, a lower value of v_s , which is around 5.1×10^6 cm/s, is extracted from our device following the method

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proposed by Yee *et al* [64]. Assuming that the lower v_s obtained by experimental measurements is solely due to alloy scattering, using $v_s=5.1 \times 10^6$ and 6.5×10^6 cm/s in equations (7.1), (7.7) and (7.8) for the cases with and without alloy scattering, λ_a of 3.44 nm can be determined. Using the temperature dependence of v_s [64], the temperature dependence of λ and v_0 can be determined by eqn (7.1) and (7.2) respectively. Setting $m^*=m_e$, the temperature dependence of η can be determined by using eqn (7.4) and (7.5). As this value of η is determined at electric field where saturation velocity value is determined, we shall assume η value to remain the same at higher electric field in our data, i.e. $\eta = \eta(T, E) \approx \eta(T)$. With this and using equations (7.1) and (7.6), the electric field dependence of average electron kinetic energy at different temperatures with or without alloy scattering is calculated and plotted in Fig. 7.2. It is seen that, by introducing the alloy scattering with $\lambda_a=3.44$ nm, the kinetic energy of electron is drastically reduced. Also, the temperature dependence of kinetic energy becomes smaller. The reduction of kinetic energy with relative weak temperature dependence suppresses α_n and its temperature sensitivity observed in InGaP.

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Fig. 7.2 Comparison of average kinetic energy of electron with and without the consideration of alloy scattering in InGaP in the temperature range of 300 to 450 K.

To illustrate the strong effect of alloy scattering on impact ionization, we plot the scattering rates of optical phonon, alloy, and impact ionization against the average kinetic energy of electron in Fig. 7.3. The scattering rates of optical phonon, alloy, and impact ionization can be approximately defined as v_0/λ_r , $v_0/\lambda_{\text{alloy}}$, and $\alpha_n v_0$, respectively. It is interesting to see that, with alloy scattering, although a smaller α_n is found for a given electric field as shown in Fig. 7.1, a significant enhancement of electron impact ionization rate can be obtained if the electrons can reach the same average kinetic energy as in the case where alloy scattering is absent. This could be due to the enhanced randomizing caused by additional alloy scattering, which allows the carriers to have a bigger cross-section for impact ionization.

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Fig. 7.3 Scattering rates of optical phonons, alloy and impact ionization in InGaP at different temperatures.

In conclusion, ternaries such as $\text{Ga}_x\text{In}_{1-x}\text{P}$, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{Ga}_x\text{In}_{1-x}\text{As}$ bandgap energy increases with x and it would be expected that impact ionization coefficient reduces gradually with x as higher energy is needed to create electron-hole pair. However, alloy scattering peaks at $x=0.5$ and this changes impact ionization coefficient profile with x to be valley-like.

In the above analytic models, we ignored about intervalley scattering, which is important at high field and had oversimplified the problem. Only a full band Monte Carlo simulations could give a reasonable solution. However, under many simplifying

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assumptions, we would like to discuss the physics responsible for the weak temperature of InGaP ionization coefficient:

- (i) Baraff's model considered only the acoustic and nonpolar optical scattering, and used a spherical symmetrical and parabolic energy band. These assumptions restrict the full validity of the results to almost no semiconductor in principle, yet the results have proven to be almost applicable to most semiconductors where there is substantial amount of polar optical phonon scattering and intervalley scattering [54].
- (ii) Baraff's result do not yield a closed-form solution, but Okuto and Crowell [47] has obtained a fairly simple analytic expression that relates exceptionally well to the numerical results.
- (iii) Monte Carlo simulation for GaAs [65] confirmed the validity of most of Baraff's findings. However, intervalley scattering is not considered in their discussion. Instead, phonon scattering rate for the satellite valley is taken to be the same as for the central valley. This overestimates the scattering rate when the electrons are in the satellite valleys. They argues that this simplification is partly justified by the fact that scattering rates of different valley approach each other at high energies and are partly compensated by intervalley scattering. The general features shown in this GaAs simulation are also shown for Monte Carlo simulation of Si where intervalley scattering is included [66].

Noting these few points, the model of energy loss by nonpolar optical phonon used in Baraff's model could be the sum contributed by all types of optical scattering at high energies, including intervalley scattering. After all, intervalley scattering is also due to phonon scattering and has the same form as nonpolar optical scattering, except the optical phonon energy is replaced by the intervalley phonon energy. Notice that the

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intervalley phonon energy has a value between the optical and acoustic phonon energies near the edge of the Brillion zone [67].

7.4 Summary

In conclusion, the electron impact ionization coefficients of InGaP at elevated temperature are analyzed. The widely used Okuto-Crowell relation based on the assumption that the optical phonon scattering is the only dominant scattering process during impact ionization fails to predict the measured α_n and its temperature dependence. We show that the experimental observation can be consistently explained by considering the involvement of alloy scattering in InGaP. The presence of alloy scattering reduces the electron kinetic energy and its temperature dependence and consequently affects the carrier impact ionization behavior. However, we have neglect the consideration of intervalley scattering and used only Baraff’s nonpolar optical phonons energy and mean free path in our work. Much is discussed the implications of this and perhaps only a full band Monte Carlo simulations could justify the correctness of our conclusions.

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

Chapter 8

Conclusion and Recommendations

8.1 Conclusions

The results reported in this work demonstrated our ability to design and fabricate high performance power AlGaAs/GaAs HBT. The 4, 8, 12, 16 finger AlGaAs/GaAs HBTs, with each finger dimension $2 \times 10 \text{ } \mu\text{m}^2$, shows a power result of approximate 5 W/mm at 10 GHz in common emitter configuration. This is considered high for an unlappped wafer.

Development of InGaP/GaAs/InGaP HBT fabrication technology is also demonstrated and a detailed investigation is done on the InGaP electron ionization coefficient extracted from the fabricated DHBT. We managed to extend the previously reported data in low electric field by two orders of magnitude down to 1 cm^{-1} and two times of magnitude in high field, up to 10^5 cm^{-1} . The temperature dependence of InGaP electron impact ionization coefficients is further studied further for the temperature range of 300-450 K under electrical field of 380 to 650 kV/cm. The study suggest that additional scattering mechanism such as alloy scattering may provide a better interpretation on the low electron impact ionization and its weak temperature dependence observed in InGaP.

8.2 Recommendations for future research

The following suggestions represent a collection of topics related to this work which for either lack of time or equipment readiness has not been accomplished. The

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device performance is expected to improve with the implementation of these recommendations:

(1) Optimization of Device Layer Structure to Improve Device Performance

Device epitaxial layer structures have great impacts on device performance. Although we have achieved good performance for AlGaAs/GaAs HBT, further improvement can still be achieved if the effect of device layer on the performance is studied comprehensively. For the InGaP/GaAs/InGaP, the tunnel layer doping and thickness is especially important. It is believed that a high doping and reduced thickness will increase the current density where the device can operate without suffering much current-blocking effect. However, the collector breakdown will be reduced due to the high field developed at the tunnel layer. Therefore, a detailed study needs to be done to achieve a trade-offs.

(2) Device Fabrication Process

Current fabrication process could be further study to produce a better yield and reliable device performance. Process such as collector undercut, surface passivation using SiN, SiO₂ and BCB, thermal shunt process, planarization process for high level integration, backside process such as lapping and via hole needed to be developed and studied to achieve a higher performance device and learnt the trade-off involved.

(3) Different HBTs Comparison

The merits of (i) AlGaAs/GaAs and InGaP/GaAs single HBTs and/or

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(ii) AlGaAs/GaAs/AlGaAs and InGaP/GaAs/InGaP double HBTs, could be compared and a better understanding on which device applications suit each best.

AUTHOR'S PUBLICATIONS

Author's Publications

1. Wah-Peng Neo, Hong Wang, "A Unified Explanation for Suppressed Electron Ionization Coefficient and its Weak Temperature Dependence in InGaP," *Appl. Phys. Lett.*, vol. 85, no. 15, pp. 3119-3121, 2004.
2. Wah-Peng Neo, Hong Wang, "Temperature dependence of the electron impact ionization in InGaP-GaAs-InGaP DHBTs," *IEEE Trans. Electron Device*, vol. 51, no. 3, pp. 304-311, 2004.
3. Wah-Peng Neo, Hong Wang, K. Radhakrishnan, "Temperature dependence of electron ionization coefficients of InGaP measured in InGaP/GaAs/InGaP DHBTs," *Journal of Crystal Growth*, vol. 268, pp. 406-409, 2004.
4. Hong Wang, Hong Yang, Wah-Peng Neo, Radhakrishnan, K., Chee Leong Tan, "Temperature dependence of avalanche multiplication in InP-based HBTs with InGaAs/InP composite collector: device characterization and physics model," *IEEE Trans. Electron Device*, vol. 50, no. 12, pp. 2335-2343, 2003.
5. Wah-Peng Neo, Hong Wang, and Radhakrishnan, K., "Measurements of InGaP electron ionization coefficient using InGaP-GaAs-InGaP double HBTs," *IEEE Trans. Electron Device*, vol. 50, no. 7, pp. 1711-1714, 2003.

BIBLIOGRAPHY

Bibliography

- [1] W. Shockley, U.S. Patent 2,569,347, June 1948.
- [2] H. Kroemer, "Theory of a wide-gap emitter for transistors", *Proc. IRE*, vol. 45, no. 11, pp. 1535-1537, 1957.
- [3] M. Levinshtein, S. Rumyantsev, and M. Shur, *Handbook Series on Semiconductor Parameters*, World Scientific, vol. 2, pp. 38, 1999.
- [4] T. Shimura, M. Sakai, S. Izumi, H. Nakano, H. Matsuoka, A. Inoue, J. Udomoto, K. Kosaki, T. Kuragaki, H. Takano, T. Sonoda, and S. Takamiya, "1 W Ku-Band AlGaAs/GaAs Power HBT's with 72% Peak Power-Added Efficiency," *IEEE Trans. Electron Devices*, vol. 42, pp 1890-1896, 1995.
- [5] H. Krömer, "Heterostructure bipolar transistors and integrated circuits," *Proc. IEEE*, 70 (1), pp. 13-25, 1982.
- [6] D. Ritter, R. A. Hamm, A. Feygenson, and M. B. Panish, "Anomalous electric field and temperature dependence of collector multiplication in InP/Ga_{0.47}In_{0.53}As heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 60, no. 25, pp. 3150-3152, 1995.
- [7] G. G. Zhou, A. Fischer-Colbrie, and J. S. Harris Jr., "V Kink in InAlAs/InGaAs MODFET's due to weak impact ionization process in the InGaAs channel," in *Proc. 6th Int. Conf. Indium Phosphide and Related Materials*, pp. 435-438, 1994.
- [8] A. Von Hippel, *Z. Phys.*, vol. 75, pp. 145, 1932.

BIBLIOGRAPHY

- [9] H. Frohlich, "Theory of Electric Breakdown in Ionic Crystals, *Proc. R. Soc. A*, vol. 160, pp. 230–241, 1937.
- [10] P. A. Wolff, "Theory of Electron Multiplication in Silicon and Germanium," *Phys. Rev.*, vol. 95, no. 6, pp. 1415-1420, 1954.
- [11] W. Shockley, "Problems related to p-n junctions," *Solid-State Electron.*, vol. 2, pp. 35-60, 1961.
- [12] G. A. Baraff, "Distribution Functions and Ionization Rates for Hot Electrons in Semiconductors," *Phys. Rev.*, vol. 128, no. 6, pp. 2507-2517, 1962.
- [13] B. K. Ridley, "Lucky-drift mechanism for impact ionisation in semiconductors," *J. Phys. C*, vol. 16, pp. 3373-3388, 1983.
- [14] R. C. Woods, "'Soft' energy thresholds in impact ionization: A classical model," *IEEE Trans. Electron Devices*, vol. 34, no. 5, pp. 1116-1120, 1987.
- [15] J. S. Marsland, "A lucky drift model, including a soft threshold energy, fitted to experimental measurements of ionization coefficients," *Solid-State Electron.*, vol. 30, pp. 125-132, 1987.
- [16] K. F. Brennan, D. H. Park and Y. Wang, "Design and comparison of advanced semiconductor devices using computer experiments: application to APDs and HEMTs," *IEEE Trans. Electron Devices*, vol. 37, pp. 536-547, 1990.
- [17] K. Hess (ed), *Monte-Carlo Device Simulations: Full Band and Beyond*, Dordrecht: Kluwer, 1991.
- [18] M. V. Fischetti, "Monte Carlo simulation of transport in technologically significant semiconductors of the diamond and zinc-blende structures. I.

BIBLIOGRAPHY

- Homogeneous transport,” *IEEE Trans. Electron Devices*, vol. 38, pp 634-649, 1991.
- [19] J. Bude and K. Hess, “Thresholds of impact ionization in semiconductors,” *J. Appl. Phys.*, vol. 72, pp. 3554-3561, 1992.
- [20] L. V. Keldysh, *Sov. Phys. JETP*, vol. 21, pp. 1135, 1965.
- [21] T. Kunikiyo, M. Takenaka, Y. Kamakura, M. Yamaji, H. Mizuno, M. Morifuji, K. Taniguchi, and C. Hamaguchi, “A Monte carlo simulation of anistropic electron transport in silicon including full band structure and ionisotropic impact-ionization mode,” *J. Appl. Phys.*, vol. 75, no. 1, pp. 297-312, 1994.
- [22] J. W. Harrison, and J. R. Hauser, “Alloy scattering in ternary III-V compounds,” *Phys. Rev. B*, vol. 13, pp. 5347-5350, 1976.
- [23] L. Nordheim, *Ann. Phys. (Leipz.)*, vol. 9, pp. 607, 1931.
- [24] G. L. Hall, “Nordheim’s Theory of the Resistivity of Alloys,” *Phys. Rev.*, vol. 116, pp. 604-605, 1959.
- [25] P. A. Flinn, “Electronic Theory of Local Order,” *Phys. Rev.*, vol. 104, pp. 350-356, 1956.
- [26] E. Asch and G. L. Hall, “Quantum Theory of the Residual Electrical Resistivity of Disordered Alloys,” *Phys. Rev.*, vol. 132, pp. 1047-1057, 1963.
- [27] N. F. Mott, *Proc. Cambridge Philos. Soc.*, vol. 32, pp. 281, 1936.
- [28] F. Schwier, J. J. Liou, “Modern Microwave Transistors”, J. Wiley & Sons, 2003.
- [29] L. L. Liou, B. Bayraktaroglu, and C. I. Huang, “Thermal Stability Analysis of Multiple Emitter Finger Microwave AlGaAs/GaAs Heterojunction Bipolar

BIBLIOGRAPHY

- Transistors”, Microwave Symposium Digest, IEEE MTT_S International, pp. 281-284, 1993.
- [30] W. Zhou, S. Sheu, J. J. Liou, and C.I. Huang, “A Multi-Emitter Finger AlGaAs/GaAs HBT Model including the effects of two-dimensional temperature distribution on emitter fingers”, Solid-State Electronics vol. 42, no.5, pp. 693-698, 1998.
- [31] J. J. Liou, L. L. Liou, C. I. Huang, and B. Bayraktaroglu, “ A Physics-Based, Analytical Heterojunction Bipolar Transistor Model Including Thermal and High-Current Effects”, IEEE Transactions on Electron Device, vol. 40, No. 9, pp. 1570-1577, 1993.
- [32] P. M. Enquist, L.P. Ramberg, and L.F. Eastman, “Comparison of compositionally graded to abrupt emitter-base junctions used in heterojunction bipolar transistor,” *J. Appl. Phys.*, vol. 61, pp. 2663-2669, 1987.
- [33] P.-F. Chen, U.-M. T. Hsin, R. J. Welty, P. M. Asbeck, R. L. Pierson, P. J. Zampardi, W.-J. Ho, M. C. Vincent Ho, and M. F. Chang, “Application of GaInP/GaAs DHBT’s to power amplifiers for wireless communications,” *IEEE Trans. Microwave Theory and Techniques*, vol. 47, no. 8, pp. 1433-1438, 1999.
- [34] M. Zaknoune, O. Schuler, S. Piotrowicz, F. Mollot, D. Theron, and Y. Crosnier, “High power V-band $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ pseudomorphic HEMT grown by gas source molecular beam epitaxy,” *IEEE Microwave and Guided Wave Lett.*, vol. 9, no. 1, pp. 28-30, 1999.

BIBLIOGRAPHY

- [35] R. Ghin, J. P. R. David, S. A. Plimmer, M. Hopkinson, G. J. Rees, D. C. Herbert, and D. R. Wight, "Avalanche Multiplication and Breakdown in $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$ Diodes," *IEEE Trans. Electron Devices*, vol. 45, pp. 2096-2101, 1998.
- [36] R. Ghin, J. P. R. David, M. Hopkinson, M. A. Pate, G. J. Rees, and P. N. Robson, "Impact ionization coefficients in GaInP p-i-n diodes," *Appl. Phys. Lett.*, vol. 70, pp. 3567-3569, 1997.
- [37] S. -L. Fu, T. P. Chin, M. C. Ho, C. W. Tu, and P. M. Asbeck, "Impact ionization coefficients in (100) GaInP," *Appl. Phys. Lett.*, vol. 66, pp. 3507-3509, 1995.
- [38] C. Canali, F. Capasso, R. Malik, A. Neviani, P. Pavan, C. Tedesco, and E. Zanoni, "Measurement of the electron ionization coefficient at low electric fields in GaAs-based heterojunction Bipolar Transistors," *IEEE Trans. Electron Devices*, vol. 15, pp. 354-356, 1994.
- [39] D. Buttari, A. Chinni, G. Meneghesso, E. Zanoni, D. Sawdai, D. Pavlidis, and S. S. H. Hsu, "Measurements of the InGaAs hole impact ionization coefficient in InAlAs/InGaAs pnp HBTs," *IEEE Electron Device Lett.*, vol. 22, no. 5, pp. 197-199, 2001.
- [40] S.M. Sze, *Physics of Semiconductor Devices*, New York: J. Wiley & Sons, 1981.
- [41] W.-C. Liu, S.-Y. Cheng, W.-L. Chang, H.-J. Pan, and Y.-H. Shie, "Application of δ -doped wide-gap collector structure for high-breakdown and low-offset voltage transistors," *Appl. Phys. Lett.*, vol. 73, no. 10, pp. 1397-1399, 1998.

BIBLIOGRAPHY

- [42] S. P. McAlister, W. R. McKinnon, D. Driad, and A. P. Renaud, "Use of dipole doping to suppress switching in indium phosphide double heterojunction bipolar transistors," *J. Appl. Phys.*, vol. 82, no. 10, pp. 5231-5234, 1997.
- [43] N. Shamir and D. Ritter, "Lower limit of method for the extraction of ionization coefficients for the electrical characteristics of heterojunction bipolar Transistors," *IEEE Trans. Electron Devices*, vol. 47, no. 2, pp. 488-490, 2000.
- [44] M. H. Woods, W. C. Johnson, and M. A. Lampert, "Use of a Schottky barrier to measure impact ionization coefficients in semiconductors," *Solid State Electron.*, vol. 16, pp. 381-394, 1973.
- [45] J. Allam, " 'Universal' dependence of avalanche breakdown on bandstructure: choosing materials for high-power devices," *Jpn. J. Appl. Phys.*, vol. 36, pp. 1529-1542, 1997.
- [46] R. Ghin, J. P. R. David, M. Hopkinson, M. A. Pate, J. G. Rees, P. N. Robson, D. C. Herbert, A. W. Higgs, and D. R. Wight, "Impact ionization and temperature dependence of breakdown in $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$," in *Proc. Inst. Phys. Conf. Series*, vol. 155, pp. 585-588, 1997.
- [47] Y. Okuto and C. R. Crowell, "Energy-Conservation considerations in characterization of impact ionization in semiconductors," *Phys. Rev. B*, vol. 6, pp. 3076-3081, 1972.
- [48] C. R. Crowell and S. M. Sze, "Temperature Dependence of Avalanche Multiplication in Semiconductors," *Appl. Phys. Lett.*, vol. 9, pp. 242-244, 1966.

BIBLIOGRAPHY

- [49] J. W. Harrison and J. R. Hauser, "Theoretical calculations of electron mobility in ternary III-V compounds," *J. Appl. Phys.*, vol. 47, pp. 292-300, 1976.
- [50] M. J. Malik, N. Chand, J. Nagle, R. W. Ryan, K. Alavi, and A. Y. Cho, "Temperature dependence of common-emitter I-V and collector breakdown voltage characteristics in AlGaAs/GaAs and AlInAs/GaInAs HBT's grown by MBE," *IEEE Electron Device Lett.*, vol. 13, no. 11, pp. 557-559, 1992.
- [51] K. Taguchi, T. Torikai, Y. Sugimoto, K. Makita, and H. Ishihara, "Temperature dependence of impact ionization coefficients in InP," *J. Appl. Phys.*, vol. 59, pp. 476-481, 1986.
- [52] V. M. Robbins, S. C. Smith, and G. E. Stillman, "Impact Ionization in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ for $x=0.1-0.4$," *Appl. Phys. Lett.*, vol. 52, pp. 296-298, 1988.
- [53] F. Osaka, T. Mikawa, and T. Kaneda, "Impact ionization coefficients of electrons and holes in (100)-Oriented $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{P}_{1-y}$," *IEEE J. Quantum Electron.*, vol. QE-21, no. 9, pp. 1326-1338, 1985.
- [54] H-F Chau and D. Pavlidis, "A physics-based fitting and extrapolation method for measured impact ionization coefficients in III-V semiconductors," *J. Appl. Phys.*, vol. 72, pp. 531-538, 1992.
- [55] S. Krishnamurthy, M. A. Berding, and A. Sher, "Ballistic transport in semiconductor alloys," *J. Appl. Phys.*, vol. 63, pp. 4540-4547, 1988.
- [56] J. H. Marsh, "Effect of compositional clustering on electron transport in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$," *Appl. Phys. Lett.*, vol. 41, pp. 732-734, 1982.

BIBLIOGRAPHY

- [57] S. H. Wei and A. Zunger, "Band-gap narrowing in ordered and disordered semiconductor alloys," *Appl. Phys. Lett.*, vol. 56, pp. 662-664, 1990.
- [58] D. J. Friedman, A. E. Kibbler, and J. M. Olson, "Cation Site ordering and conduction electron scattering in GaInP₂," *Appl. Phys. Lett.*, vol. 59, pp. 2998-3000, 1991.
- [59] G. I. Bauhuis, F. A. J. M. Driessen, and L. J. Giling, "Conduction mechanisms in ordered GaInP₂ epilayers," *Phys. Rev. B*, vol. 48, pp. 17239-17242, 1993.
- [60] W. P. Neo and H. Wang, "Temperature dependence of the electron impact ionization in InGaP-GaAs-InGaP DHBTs," *IEEE Trans. Electron Device*, vol. 51, no. 3, pp. 304-311, 2004.
- [61] M. Lundstrom, *Fundamentals of Carrier Transport*, vol. X, Addison-Wesley, 1990.
- [62] C. M. Wolf, N. Holonyak, Jr., and G. E. Stillman, *Physical properties of semiconductors*, Prentice Hall, 1989.
- [63] K. F. Brennan, "Calculated electron and hole steady-state drift velocities in lattice matched GaInP and AlGaInP," *J. Appl. Phys.*, vol. 71, pp. 1055-1057, 1992.
- [64] M. Yee, P. A. Houston, and J. P. R. David, "Measurement of electron saturation velocity in GaInP in a double heterojunction bipolar transistor," *J. Appl. Phys.*, vol. 91, pp. 1601-1605, 2002.
- [65] H. Shichijo and K. Hess, "Band-structure-dependent transport and impact ionization in GaAs," *Phys. Rev. B*, vol. 23, no. 8, pp. 4197-4207, 1981.

BIBLIOGRAPHY

- [66] J.Y. Tang and K. Hess, "Impact ionization of electrons in silicon (steady state)," *J. Appl. Phys.*, vol. 54, pp. 5139-5144, 1983.
- [67] David K. Ferry, *Semiconductors*, Macmillan Publishing Company, pp. 218, 1991.

APPENDIX A

Appendix A Process Run Sheet for AlGaAs/GaAs HBT

Phase 1. Si₃N₄ Deposition

STEP No.	STEP	INSTRUCTION
Step 1	Mark wafer	Orientation
Step 2	Clean chamber	PECVD chamber
Step 3	Clean wafers	
Step 4	Si ₃ N ₄ deposition	Si ₃ N ₄ 500 Å

Phase 2. Ion imp isolation masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	mask code : ISOL
Step 2	Clean wafers	
Step 3	Coat HDMS	Spin speed 3000 rpm, 30 sec, Soft bake at 105 °C hotplate for 1 min 45 sec
Step 3	Coat resist AZ 4620	Spin speed 3000 rpm, 30 sec, acetone EBR Soft bake at 105 °C hotplate for 5 min
Step 4	Align & expose	Orient wafer, 14.0 mw, 1 min
Step 5	Develop	AZ developer : DI water = 1:1 (200 ml : 200 ml), 150 sec
Step 6	Descum resist	
Step 7	Hard bake	110 °C, 15-30 min

Phase 3. Ion implant

STEP No.	STEP	INSTRUCTION
Step 1	ion bombardment	H ⁺

Phase 4. Etch Si₃N₄ & Shallow mesa

STEP No.	STEP	INSTRUCTION
Step 1	Etch Si ₃ N ₄	Dry etch PECVD
Step 2	Meas. Water °C	20 °C
Step 3	Prepare solution	H3PO4 : H2O2 : H2O = 10 : 10 : 380 ml
Step 4	Etch InGaAs cap and GaAs cap	etch time: 15 sec, E/R = 20 Å/S (InGaAs), E/R = 15 Å/S (GaAs) BV: InGaAs cap 1 ~ 2 V → GaAs cap 2~3 V

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Step 5	Remove Si ₃ N ₄	HF : DI water = 1:10 (10 : 100 ml), 20-30 min, use teflon
Step 6	If not fully remove	scratch the wafer with cotton bud and acetone
Step 7		Try HCL : DI water = 1:10 (10 : 100 ml)

Phase 5: Emitter Metal Masking

STEP No.	STEP	INSTRUCTION
Step 1	Etch InGaAs cap ~500 Å	etch time: 22 sec, H ₃ PO ₄ : H ₂ O ₂ : H ₂ O = 10 : 10 : 380 ml
Step 2	Clean maskplate	mask code : EMET
Step 3	Clean wafers	
Step 4	Coat resist AZ 5214	Spin speed 2000 rpm, 30 sec, acetone EBR Soft bake 105 °C, hotplate 1 min 45 sec
Step 5	Align & expose	14.0 mw, 3.0 sec.
Step 6	PEB	110 °C oven, 7.5 min
Step 7	Flood expose	No maskplate, 20-23 sec.
Step 8	Develop	AZ developer : DI water = 1:2 (100 ml : 200 ml), 70"
Step 9	Descum resist	RIE process

Phase 6. Emitter Metal Evaporation

STEP No.	STEP	INSTRUCTION
Step 1	Remove oxide	HCL : DI water = 1:10 (10 : 100 ml), 30 sec
Step 2	Evaporate	Ti\Au : 100\1000 nm
Step 3	Lift-off	

Phase 7. Emitter Island Etching

STEP No.	STEP	INSTRUCTION
Step 1	Meas. thk.	Measure metal thk. at test pattern*
Step 2	Meas. water °C	= 20 °C
Step 3	Prepare solution	H ₃ PO ₄ : H ₂ O ₂ : H ₂ O = 10 : 10 : 380 ml
Step 4	Etch InGaAs cap 1000 Å	etch time: 15 sec, E/R = 20 Å/S (InGaAs), E/R = 15 Å/S (GaAs) breakdown voltage: InGaAs cap 1 ~ 2 V → GaAs cap 4 V
Step 5	meas. depth	
Step 6	Prepare solution	NH ₄ OH : H ₂ O ₂ : H ₂ O = 10 : 4 : 500 ml

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Step 7	E/R calibration	Etch rate
Step 8	Etch	breakdown voltage: cap GaAs 4 V → AlGaAs 8-10 V → base 1-2 V Total etch time ≈ 45'' ~ 50''

Phase 8. Base Metal Masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	mask code : BMET
Step 2	Clean wafers	
Step 3	Coat resist AZ 5214	Spin speed 2000 rpm, 30 sec, acetone EBR Soft bake 105 °C, hotplate 1 min 45 sec
Step 4	Align & expose	14.0 mw, 3.5 sec.
Step 5	PEB	110 °C oven, 7.5 min
Step 6	Flood expose	No maskplate, 20-23 sec.
Step 7	Develop	AZ developer : DI water = 1:2 (100 : 200 ml), 70''
Step 8	Descum resist	RIE process

Phase 9. Base Metal Evaporation

STEP No.	STEP	INSTRUCTION
Step 1	Remove oxide	HCL : DI water = 1:10 (10 : 100 ml), dip 30 sec
Step 2	Evaporate	Ti\Au=30\120 nm
Step 3	Lift-off	

Phase 10. Base Island Masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	mask code : BISL
Step 2	Clean wafers	
Step 3	Coat resist AZ 1518	Spin speed 4000 rpm, 30 sec, acetone EBR Soft bake at 105 °C hotplate for 1 min 45 sec
Step 4	Align & expose	14.0 mw, 20sec
Step 5	Develop	AZ developer : DI water = 1:2 (100 ml : 200 ml), 70sec
Step 6	Hard bake	110°C oven, 15-30 min
Step 7	Descum resist	RIE process

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Phase 11. Base Island Etching

STEP No.	STEP	INSTRUCTION
Step 1	Meas. thk.	Measure metal thk. at test pattern*
Step 2	Meas. water °C	= 20 °C
Step 3	Prepare solution	NH4OH : H2O2 : H2O = 10 : 4 : 500 ml
Step 4	E/R calibration	
Step 5	Etch	Etched depth = 10800 + 1000 = 11800 Å, breakdown voltage: base 1-2 V → collector 10-14 V → sub-col 4 V
Step 6	Remove resist	Squeeze bottle acetone, IPA, DI water rinse , N2

Phase 12. Collector Metal Masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	mask code : CTRENCH
Step 2	Clean wafers	
Step 3	Coat resist AZ 5214	Spin speed 2000 rpm, 30 sec, acetone EBR Soft bake 105 °C, hotplate 1 min 45 sec
Step 4	Align & expose	14.0 mw, 3.0 sec.
Step 5	PEB	110 °C oven, 7.5 min
Step 6	Flood expose	No maskplate, 20-23 sec.
Step 7	Develop	AZ developer : DI water = 1:2 (100 : 200 ml), 70"
Step 8	Descum resist	RIE process

Phase 13. Collector Metal Evaporation

STEP No.	STEP	INSTRUCTION
Step 1	Remove oxide	HCL : DI water = 1:10 (10 : 100 ml), dip 30 sec
Step 2	Evaporate	Ni\Ge\Au\Ni\Au=5\25\100\20\200 nm
Step 3	Lift-off	

Phase 14. Annealing

STEP No.	STEP	INSTRUCTION
Step 1	Prepare	AST RTP
Step 2	Anneal	RTP 400 °C, 10 sec

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Phase 15. Pillar Masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	mask code : AB Pillar
Step 2	Clean wafers	Boiling acetone 1 min, IPA 1 min, DI water rinse 1 min, N2 blow dry. Wafer dehydration in 110 °C oven, 10 min.
Step 3	Coat resist AZ 1518	3000 rpm, 30 sec, acetone EBR Soft bake 105 °C, hotplate 1 min 45 sec
Step 4	Align & expose	14.0 mw, 25 sec
Step 5	Develop	AZ developer : DI water = 1:2 (100 : 200 ml) 75 sec
Step 6	Descum resist	RIE process peo2.prc
Step 7	Reflow hard bk.	110 °C, 15-30 min

Phase 16. Seed Metal Evaporation

STEP No.	STEP	INSTRUCTION
Step 1	Surface clean	HCL : DI water = 1:10 (10 : 100 ml), dip 30"sec
Step 2	Evaporate	CHA Ti\Au= 20:60 nm or sputter Au 40 nm (~40s for 0.3 A, 26 sccm)

Phase 17. Air-bridge Masking

STEP No.	STEP	INSTRUCTION
Step 1	Clean maskplate	Mask code : Interconnect
Step 2	Coat resist AZ 1518	Spin speed 2000 rpm, 30 sec, acetone EBR Soft bake 105 °C, hotplate 1 min 45 sec
Step 3	Align & expose	14.0 mw, 30-35 sec.
Step 4	Develop	AZ developer : DI water = 1:2 (100 : 200 ml) , 70"
Step 5	Descum resist	RIE process

Phase 18. Electroplating

STEP No.	STEP	INSTRUCTION
Step 1	System stable	Turn on bath, waiting for 55 °C stable

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Step 2	Remove corner resist	Remove corner resist with for contact
Step 3	Electroplate	3 μ m, 10 min, 0.01A , 5ms on - 15 ms off

Phase 19. Seed Metal Etching

STEP No.	STEP	INSTRUCTION
Step 1	Flood expose	25sec
Step 2	Remove bridge resist	AZ developer no dilute, 15 sec
Step 3	Descum resist	RIE process peo2.prc
Step 4	Au etching	K/IK, ultrasonic if necessary , 40sec, inspect
Step 5	Ti etching	HF : H2O = 10 ml: 100 ml, dip to etch Ti, 8~10 sec, bubbles Ti form complex with photoresist
Step 6	Remove Pillar resist	Aceton