Millimeter-Wave Integrated Circuits

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Dedication

To our wives, Aileen and Phil.

Contents

Preface

The design and implementation of millimetre-wave (mm-wave) integrated circuits using MMIC technology are explored in this work. To make possible the widespread use of MMIC technology for mm-wave applications, high performance MMIC mm-wave transceivers must be shown to be viable for high-volume production. Low noise amplifiers (LNAs), mixers and frequency multipliers, circuit functions critical to the development of a mm-wave transceiver, are studied in this work. The circuit design material presented is augmented by theoretical analyses where possible.

All the designs were fabricated on a commercial 0.25 μm GaAs pHEMT foundry process. The performance realised is compared with simulations for all the fabricated circuits, and where necessary, the causes of significant discrepancies are discussed. All the designs presented are novel to a certain extent. The 40 GHz LNA design approach is particularly novel and outstanding circuit performance has been realised with this design. The conceptual analysis approach presented for HEMT mixer circuits simplifies the understanding of how these circuits work and also aids their design for best performance. A simple but very effective fundamental analysis has been developed for FET frequency multipliers. This approach is successfully applied to balanced multipliers as well. Novel frequency multiplier architectures are proposed that are suitable for the generation of high power levels at very high frequencies. The material presented in this work advances the knowledge base associated with mm-wave integrated circuits. In particular, it demonstrates that high quality circuits can be realised on conventional fabrication processes, thereby suggesting that high-volume mm-wave circuit developments can indeed become a commercial reality.

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Chapter 1

AN INTRODUCTION TO mm-WAVE INTEGRATED CIRCUITS

1. INTRODUCTION

The primary topic of this work is mm-wave integrated circuits. The main focal points are, firstly, fundamental circuit analyses of some of the building blocks necessary for the widespread employment of MMIC technology for mm-wavelength applications, and, secondly, circuit design methodologies pertinent to these building blocks. The analytical/theoretical treatment is supplemented by specific mm-wave MMIC designs of varied complexity.

2. MOTIVATION FOR mm-WAVES

The term mm-waves is generally used to describe the range of frequencies between about 30 and 300 GHz where the wavelength is of the order of a millimeter. With the ever-increasing demand on wireless spectrum, as evidenced by emerging applications such as third-generation (3G) mobile phones at RF frequencies, and both Multipoint Video Distribution System (MVDS) and Local Multipoint Distribution System (LMDS) in the mm-wave frequency range[1, 2], there is a growing need to exploit higher and higher frequencies. The mm-wave frequency range is very attractive for various applications for a number of reasons. In the first instance, there is inherent in the high frequencies involved, a proportionately large amount of spectrum available. This naturally lends itself to systems demanding wide bandwidths that are simply unavailable at lower frequencies. Secondly, some parts of the mm-wave range have interesting propagation characteristics. For example, the inherent atmospheric attenuation near 60 GHz, due to oxygen absorption, makes this region of the spectrum very useful for short-hop communications links, which are naturally secure and suitable for extensive use with a low likelihood of interference with frequency re-use. Other frequencies have low propagation losses and are suited to longer hop-length links. Additionally, smaller antennas are required at higher frequencies, and this factor, coupled with the good distance resolution capability, has been a key driver in the development of automotive radar sensors at 77 GHz.

3. MOTIVATION FOR MONOLITHIC GaAs INTEGRATED CIRCUITS

The conventional implementation for such mm-wave systems involves extensive use of waveguide technology. Such waveguide components are heavy, bulky and expensive and are not well suited to high volume manufacturing. Therefore, with these emerging volume applications, there is a growing need for monolithic front-end components for the required transceivers. Such monolithic solutions would almost certainly be more easily manufactured in volume, should be physically smaller and lighter and hence more attractive for many size-sensitive applications, and most importantly of all, should reduce the overall cost. Due to the high frequencies involved, much effort has been expended worldwide in developing high frequency semiconductor fabrication capability. Gallium Arsenide (GaAs) has long been recognised for its advantages at high frequencies. GaAs technology is not nearly as mature as that of Silicon (Si), but it does offer benefits in terms of electron velocity that make it extremely attractive for use in mm-wave applications. Initial GaAs circuit developments were based on the Metal Semiconductor Field Effect Transistor (MESFET) transistor. Over time, a number of more sophisticated GaAs based field effect transistor devices, such as the High Electron Mobility Transistor (HEMT) and pseudomorphic-HEMT (pHEMT), have evolved. These have more complex material layering structures than the conventional MESFET, which improve further their high frequency characteristics. GaAs based bipolar transistors, Heterojunction Bipolar Transistors (HBTs), have also been developed which are suitable for high power applications at high frequencies and these make possible levels of performance simply not achievable with conventional silicon bipolar transistors. The availability of such high frequency devices from high frequency fabrication processes facilitates the development of monolithic mm-wave circuit designs for new high volume applications.

4. MOTIVATION FOR IMPROVED FUNDAMENTAL CIRCUIT UNDERSTANDING

GaAs IC fabrication facilities are more expensive to construct than Si facilities, and GaAs material itself is more expensive and more difficult to handle. Moreover, GaAs based ICs are typically developed for specific requirements that cannot be met with a Si solution. The vast majority of worldwide demand for semiconductor products can be more than adequately addressed using Si. As a consequence, GaAs IC fabrication facilities are not as widespread as those based on Si. There are a relatively small number of companies worldwide with their own internal GaAs IC fabrication capability. Some of these companies make their fabrication processes available commercially as a foundry. Due to the high material and wafer fabrication costs, foundry runs can be expensive, in particular for high frequency processes. Moreover, due to the relatively immature science of mm-wave monolithic circuit design, the risk associated with a design can be relatively high, and this level of risk combined with the high cost can result in many mm-wave MMIC developments never getting past the conceptual stage.

In this work, efforts have been made to put mm-wave MMIC design strategies on a more solid foundation. This has been carried out by means of a combination of extensive high frequency design and evaluation, and also a detailed theoretical study of key components of vital interest to the eventual exploitation of MMIC technology for high volume mm-wave applications. In this context, design methodologies for some of the building blocks are proposed.

5. KEY COMPONENTS

Key components of mm-waves transceiver circuits have been studied and evaluated during the course of this work. These circuits include low noise amplifiers (LNAs), a balanced diode mixer suitable for both up and down-conversion, and frequency multipliers. Practical circuit realisations have targeted transceiver applications operating near 40 GHz and 57 GHz.

Specifically, the MMIC circuits, which have been fabricated and tested, are:

- 57 GHz LNA
- 40 GHz LNA
- Balanced Diode Mixer (as both an up and a down-converter)
- Balanced HEMT Mixer as down-converter
- HEMT Frequency Tripler

- HEMT Frequency Doubler
- 57 GHz Transceiver using integrated building blocks

These circuits are represented graphically in Fig. 1-1.

All the above circuits have been designed using the foundry models for the GEC-Marconi Materials Technology (GMMT) H40 GaAs process, and have been fabricated at GMMT's Caswell wafer fabrication facility in the UK using two distinct mask sets. Both wafer runs were implemented as multi-project masks with multiple designs being fabricated on a single wafer. Bookham Technology purchased the Caswell facility from GMMT in February 2002. Refer to[3] for details on the foundry service offered at Caswell.

All the fabricated MMICs were evaluated. Both on-wafer and packaged tests were carried out. The on-wafer evaluations were carried out at the University of Glasgow; the packaged tests were conducted at Farran Technology using specially designed housings. The performance achieved with the various building blocks is very promising. All circuits worked, at least to an extent, at the intended frequencies, and particularly in the cases of the 40 GHz designs, functioned with promising levels of performance. The 57 GHz circuits did not all work as well as predicted, but taking account of the constraints imposed by the GaAs process used and the models available, we consider the achieved performance significant.

6. STRUCTURE OF THIS WORK

This work is structured as follows. In Chapter 2, the characteristics of semiconductor materials suitable for high frequency circuits are described and materials with such properties are outlined. The fabrication technology pertinent to such high frequency material processing is discussed. Diode and transistor devices, based on the material systems discussed in Chapter 2, which are appropriate for high frequency circuit development, are presented in Chapter 3. In particular, the Schottky diode and variants of the MESFET transistor device are detailed.

A primary goal of this work is to improve the fundamental understanding of mm-wave MMIC operation with a view to facilitating the exploitation of MMIC technology for high volume mm-wave applications. In particular, this is driving the demand for fully integrated MMIC transceivers operating in the mm-wave frequency range, and these issues are discussed in more detail in Chapter 4. In particular, the transceiver topology most suitable for implementation in a monolithic design is considered. The concept of yield is introduced and the relationship between circuit yield and circuit complexity is explored.

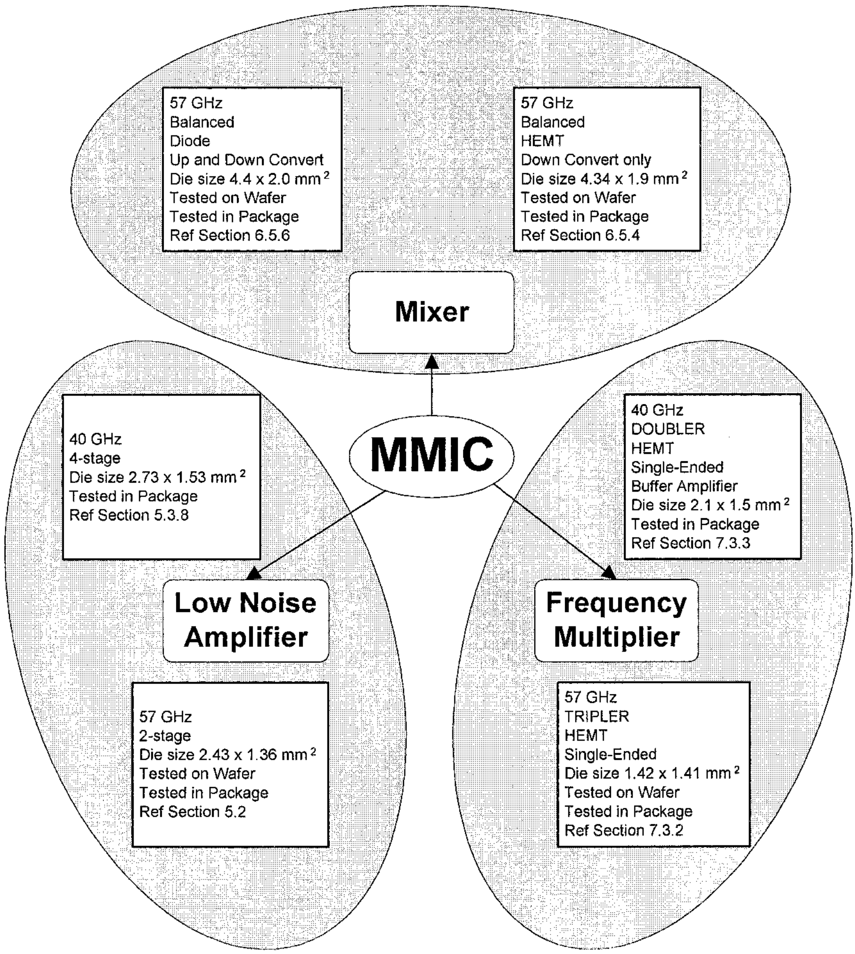

Figure 1-1. Graphical summary of the MMIC designs developed and characterised in this work.

The next three chapters consist of detailed studies of three key building blocks required for mm-wave transceiver developments. In Chapter 5, the Low Noise Amplifier (LNA) is considered. A novel design approach, which is suited to mm-wave circuits, is presented; this is validated by the measured performance associated with a 40 GHz LNA design. This circuit performs very well over a broad band and a good fit is achieved between measurement and simulation. Details of a 57 GHz LNA circuit design are also presented. Monolithic mixers are considered in Chapter 6 and a fundamental understanding of the operation of FET-based mixers presented. Measured results for practical diode and HEMT mixers are also detailed in this chapter. A number of aspects associated with mm-wave frequency multipliers are discussed in Chapter 7; the measured performance achieved with a mm-wave doubler and a frequency tripler are also presented. A novel theoretical treatment of the performance of a generic FET frequency multiplier is outlined, and the measured performance of the practical circuits are compared with that expected in light of the theory presented. The possibilities introduced by balancing are also discussed. A novel balanced multiplier topology, which is suited to a flexible harmonic multiplication factor, is also proposed. The viability of state of the art mm-wave processes for the generation of high power levels at 100 GHz is analysed in the context of a feasibility study and a design topology suitable for a practical realisation is proposed.

In Chapter 8, details are presented of a novel 57 GHz transceiver chip. This is a fully integrated up- and down-converter, and has been implemented by integrating into a single layout a number of building blocks described in Chapters 5 – 7. The performance achieved with this MMIC does not match that expected, and the discrepancy is analysed and discussed. However, the transceiver is functional and this is a highly significant result given the constraints imposed by the capability of the H40 process at 57 GHz.

An in-depth discussion of this work and the contribution it makes to the field of mm-wave MMIC development is presented in Chapter 9. The novel aspects are pointed out, and the key practical and technical achievements listed. The work closes with a discussion of likely future trends in high frequency MMICs, both in terms of circuit design and also in terms of process and device developments.

Chapter 2

HIGH FREQUENCY MATERIALS AND TECHNOLOGY

1. INTRODUCTION

Silicon (Si) is undoubtedly the workhorse semiconductor material of the electronic age. It has many characteristics, both chemical and electrical, which have contributed to its unrivalled status – see for example Sze[4]. Both bipolar and metal oxide semiconductor (MOS) type devices, fabricated on Si substrates, are widely used for a large number of applications[4]. As we will see in Section 3.2 of this chapter however, Si based devices are constrained in terms of their performance capability at high frequencies, in particular in the microwave range and above. In this chapter, the characteristics of semiconductor materials more suited to high frequency devices are discussed. These characteristics are firstly presented in a generic sense, essentially defining the 'ideal' high frequency semiconductor material. Subsequently, the characteristics of some of the high frequency materials in use today are outlined. These materials tend to be III-V compound semiconductors, and the reasons for this will be discussed. Some of the key wafer fabrication techniques involved in the processing of high frequency materials, and particularly pertinent to their high frequency characteristics, are described. Finally, some of the main aspects associated with the realisation of effective mm-wave MMIC layouts are discussed. These are generic considerations which need to be taken into account throughout the circuit design effort in order to ensure that the resulting layouts are not needlessly constrained from a high frequency performance perspective. These considerations include a description of circuit layout techniques to facilitate circuit testing and subsequent wafer sawing or dicing.

2. ELECTRICAL CHARACTERISTICS OF IDEAL HIGH-FREQUENCY SEMICONDUCTOR MATERIAL

There are a number of electrical characteristics that render a semiconductor material suitable for high frequency applications development. A device with high carrier mobility, μ, is desirable. Such a material will be responsive to rapid changes in an applied electric field. A quantum mechanical analysis of semiconductor material band structures shows that the mobility of a material is dependent on the curvature of the band valleys and peaks[5]. As a consequence, in order for high mobility to be achieved, a semiconductor should have sharply curved bands. It is the case with semiconductor materials that the electron mobility exceeds that of the holes and this is particularly true of high frequency semiconductor materials. It is therefore not surprising that most high frequency devices use electrons – see Chapter 3.

It is known that there is a definite correlation between the mobility of carriers in a semiconductor and the material's energy band-gap. In fact, it is found that higher mobilities are generally associated with smaller band-gaps. As a consequence, one could reasonably expect that a small band-gap would be an essential feature of a high-speed semiconductor. However, a small band-gap would also lead to a relatively high leakage current due to a large number of carriers having sufficient thermal energy to traverse the energy gap. Accordingly, an ideal semiconductor has as small a band-gap as is practical such that leakage current does not become a concern.

It is intuitively clear that in order that a material be suitable for high frequency circuit developments, high carrier velocities must be possible. Such high velocities result in short transit times for carriers to traverse the device geometry, thereby making the device responsive to high frequency excitations. There is a limitation to the carrier velocity which can be realised in a given semiconductor material. From a purely relativistic standpoint, the carrier velocity cannot exceed the speed of light, c. In real materials, scattering events ensure that carrier saturation velocities are in fact much less than c. These scattering events can be associated with collisions with the lattice, including dopant sites. Scattering events lead to sudden changes in the carrier velocity and energy, and the scattering path describes how the carrier shifts from one high-energy band to another (low-energy) band. When an increasing field is applied to a material, the field accelerates the carriers. As the field increases, different scattering mechanisms become important. The result is that the rate of carrier acceleration falls as additional scattering effects come into play. At medium fields, the carriers may have sufficient energy to excite acoustic phonon vibrations in the material lattice.

This effect is especially important in indirect band-gap materials where the large number of conduction band minima increases the likelihood of such an event occurring. Higher fields can lead to the excitation of optical phonons. Further field increases lead to energy being transferred directly to the lattice (heating) and the carrier velocity saturates. In order that the onset of saturation occurs at high fields, and hence high carrier velocities can be achieved, a direct band-gap material is necessary.

An important property of high quality semiconductor devices is carrier confinement or localisation. This requires that the physical space in which carriers traverse the device is well controlled and understood. In early devices, this confinement was achieved by the use of p-n junctions. These devices are constrained in their high frequency capability due to hole mobility limitations. For many of the widely used high frequency devices, a Schottky junction provides the confinement. Band structure plays a major role, particularly in the case of high frequency materials. This is brought about by the use of hetero-structures. A hetero-structure is a combination of at least two semiconductor materials with different band-gaps. The differing band-gaps introduce some interesting possibilities, as will be explained in Section 2.4 of Chapter 3 for the high electron mobility transistor (HEMT) device. In the HEMT, the localisation is realised as a two-dimensional electron gas in an undoped GaAs layer. This makes possible the major advantage of having the channel in undoped GaAs, which has a much higher mobility than doped GaAs. In order that hetero-structures can be fabricated between two semiconductor materials, they must have similar lattice constants (i.e. they are approximately lattice-matched). This is required such that atomic bonding can be continued, without interruption, across the interface. Thus, an ideal semiconductor should be lattice matched to at least one other material.

In conclusion, a high-speed semiconductor should consist of a direct, narrow band-gap material (but not too narrow) lattice-matched to at least one other such material. Compound semiconductors, such as GaAs, come closest to matching these ideal requirements.

3. ELECTRICAL CHARACTERISTICS OF REAL HIGH FREQUENCY MATERIALS

In this section, a brief outline of the major compound semiconductors is presented. Firstly, the electrical properties of GaAs are discussed, in particular in the context of a comparison with silicon. Subsequently, properties of some of the other compound semiconductors used at high frequencies are considered, and the current trends in high frequency device developments are discussed.

3.1 Gallium Arsenide (GaAs)

Gallium Arsenide (GaAs) has gained wide acceptance as the semiconductor material of choice for high frequency applications, in particular in the microwave and mm-wave ranges. Since the early GaAs development activities, a number of device structures have evolved which exploit its excellent high frequency characteristics. The GaAs Schottky diode remains a very commonly used device, particularly at high mm-wave and even sub mm-wave frequencies, where active devices with gain cannot yet be realised. The non-linear diode characteristic makes this device a very useful candidate for high frequency mixers, detectors and frequency multipliers, and thus the Schottky diode plays a key role in very high frequency receivers[6]. At somewhat lower frequencies (RF and microwave), the GaAs MESFET is the conventional active transistor device. Due to certain limitations associated with the MESFET, other GaAs based FET-type transistors have evolved, including the HEMT, the p-HEMT, the lattice-matched HEMT (on InP substrate), and the metamorphic HEMT. The bipolar-type HBT transistor has also emerged as a device with great high frequency potential. These various high frequency GaAs-based circuit devices will be discussed in detail in Chapter 3.

3.2 GaAs / Si Comparison

The dominance of GaAs as the primary semiconductor material for high frequency applications is due to its excellent physical parameters, some of which are compared with those of Si in Tables 2-1 and 2-2[7]. It should be noted that these comparisons are valid for specific doping densities in the two materials – 10^{16} cm^{-3} and 10^{17}cm^{-3} in Tables 2-1 and 2-2 respectively.

Table 2-1. GaAs/Si parameter comparison ($N_d = 10^{16}$ cm^{-3} , 300K)

PARAMETER	GaAs	Si
Saturated Drift Velocity (cm/s)	1 –2 x 10^7	0.7 x 10^7
Electron Mobility (cm^2/V/s)	5000	1300
Hole Mobility (cm^2/V/s)	330	430
Band-gap (eV)	1.42	1.12

The tabulated mobilities correspond to *low-field* operation. It can be seen that both the mobilities and the saturated drift velocity parameters are functions of the doping level. The greater the doping concentration, the lower the mobility, due to an increased likelihood of collisions with the dopants. The velocity versus field curves associated with Table 2-2 are shown in Fig. 2-1. This Figure also includes the corresponding curve for InP.

Table 2-2. GaAs/Si parameter comparison ($N_d = 10^{17}$ cm^{-3}, 300K)

PARAMETER	GaAs	Si
Saturated Drift Velocity (cm/s)	8×10^6	6.5×10^6
Electron Mobility ($cm^2/V/s$)	3500	800
Hole Mobility ($cm^2/V/s$)	250	300

In fact, the mobilities of *undoped* GaAs are 8500 $cm^2V^{-1}s^{-1}$ (electrons) and 400 $cm^2V^{-1}s^{-1}$ (holes)[8]. This is of great significance in some hetero-junction based devices to be discussed later in Chapter 3. Additional mobility values as a function of doping density are shown in Table 2-3.

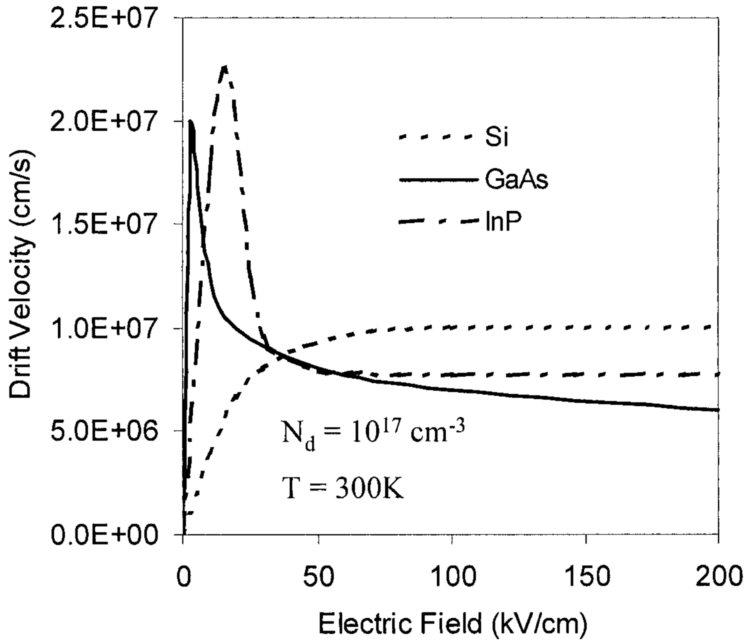

Figure 2-1. Electron drift velocity versus electric field ε.

It should be borne in mind that for many applications, the saturation velocity is of primary interest. However, for very high frequency applications, the much higher carrier velocities in compound semiconductors at lower fields are of interest due to the overshoot effects observed in devices of very small size.

GaAs has a higher intrinsic power delivery capability than Si. This can be seen directly from the following expression for the power-frequency-squared limit[9],

$$Pf^2 \approx \left(\frac{E_c v_s}{2\pi}\right)\frac{1}{X_c}$$

where E_c is the effective electric field before avalanche breakdown, v_s is the electron drift velocity, and X_c is known as the *device impedance level.* Since E_c and v_s are higher for GaAs than for Si, it follows that the power-frequency-squared limit is also higher for GaAs.

Table 2-3. GaAs electron mobility as a function of doping density

Doping Density cm^{-3}	Electron Mobility ($cm^2/V/s$)	Hole Mobility ($cm^2/V/s$)
Undoped	8500	400
10^{16}	5000	330
10^{17}	3500	250
10^{18}	2000	-
10^{19}	300	80
3×10^{19}	-	40

Applying the above relationship for GaAs and Si material, and using typical values for X_c (based on the material and the device structure), the following estimated theoretical limits have been reported[9]

$$\text{GaAs} \rightarrow Pf^2 \approx 5 \times 10^{21}\,\text{Ws}^{-2}$$

$$\text{Si} \rightarrow Pf^2 \approx 5 \times 10^{20}\,\text{Ws}^{-2}$$

This suggests that at a given frequency, for similar device geometrical structures and sizes, a GaAs based active device is capable of delivering about 10 times as much power as its Si equivalent. Alternatively, the GaAs device is capable of driving a given power level at a maximum frequency which is more than 3 times the maximum frequency for the equivalent Si device. This explains why GaAs is the preferred material at mm-wave frequencies.

GaAs is also capable of providing more gain than Si. This is mainly due to its higher electron mobility, which implies that, for a given electric field, a greater electron velocity will be achieved in GaAs, in particular due to overshoot effects in small devices at high frequencies. This can be interpreted in terms of a greater output load current flowing for a given applied input voltage, which is associated with a higher gain.

An additional characteristic of GaAs is that the GaAs substrate material is a very good electrical insulator. This can be a very important factor in the development of high frequency monolithic circuits, which are typically microstrip-based. Si substrates are much poorer insulators and as a consequence, passive structures on Si tend to be much lossier than their GaAs equivalents.

GaAs based amplifiers are capable of providing a lower noise figure than Si. This is due to a number of factors. Primarily, the greater mobility means that the random noise events (e.g. collisions) are less significant relative to the drift currents. Moreover, a FET type device (most GaAs high frequency circuits utilise FET type devices) contains fewer sources of noise (e.g. no shot noise). As outlined by Pavlidis[10], the presence of capacitive coupling between the gate and the channel in a MESFET type structure results in the overall noise being determined by subtracting part of the gate noise from the drain noise. This is a unique property of FETs and can lead to very low noise performance.

Another important distinction between GaAs and Si is that GaAs is a *direct band-gap* material[4]. This means that the minimum energy separation between the conduction and valence bands occurs at the same momentum. Si, on the other hand, is an *indirect band-gap* semiconductor, which implies that its conduction band minimum is separated in momentum from the valence band maximum[7]. This direct band-gap property is typical of many compound semiconductors and their alloys, and is critical to the opto-electronic operation of these materials. Electron - photon interactions are much more efficient in the direct band-gap materials as they do not require an associated phonon scattering event. The direct band-gap also leads to some desirable consequences for electron transport, and in particular is consistent with the high electron velocities achievable in GaAs. A visual representation of the direct/indirect band-gap properties of GaAs and Si is presented in Fig. 2-2.

For completeness, it is appropriate to mention that the cause of the unusual shape to the velocity – electric field curve for GaAs is that a secondary conduction band minimum (or valley) exists which is offset in momentum from the valence band peak. This secondary minimum is at a higher energy than the direct primary valley. The mobility associated with electrons in this secondary valley (refer to Fig. 2-2) is lower than in the main valley because of the secondary valley's much lower curvature characteristic. Thus, as the electric field is increased, and some of the electrons achieve sufficient energy to make the transition to the secondary valley, their mobility (and hence velocity) falls. As the field increases further, more of the electrons can make the transition, and the average velocity continues to tail off towards a lower asymptotic limit. This falling velocity for increasing field (above the critical field) is a phenomenon peculiar to some compound semiconductors. It can be modelled as a negative differential resistance which makes bulk material suitable for the generation of high frequency oscillations under certain conditions (such an oscillator is known as a Transferred Electron Device; a well-known example is the Gunn oscillator).

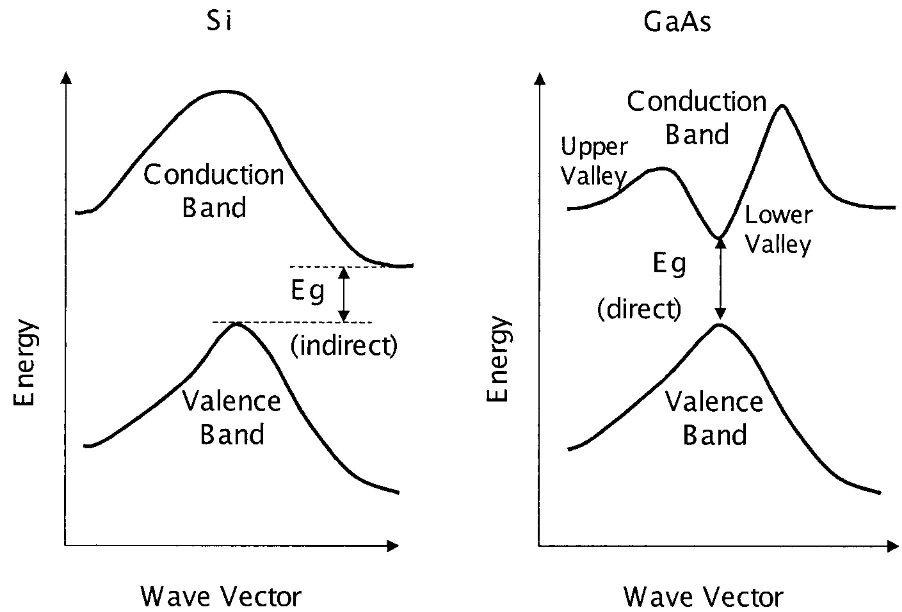

Figure 2-2. Direct and indirect band-gap characteristics of Si and GaAs.

Of course, GaAs does have disadvantages. Si based fabrication processes, being substantially more mature, are cheaper to develop, install and maintain, and are better characterised and understood. Reliability and yield optimisations have been performed much more extensively on Si processes. Silicon material is intrinsically more stable, and has the major advantage of having an excellent native oxide.

Silicon-Germanium (SiGe) hetero-structures with Si are a topic of significant research at present. They offer the potential for many of the benefits associated with hetero-structures in general while, at the same time, they are largely compatible with standard Si IC processing techniques. SiGe transistors with promising high frequency capability have been reported recently[11].

3.3 InP

It has been recognised for a long time that Indium Phosphide (InP) material is blessed with a number of excellent high frequency characteristics. In particular, the peak electron velocity associated with bulk InP is significantly higher than the corresponding values for either GaAs or Si, see Fig. 2-1. As a consequence, for a MESFET type device with a given gate length, the transit time for electrons under the gate is potentially lower in InP. It immediately follows that the transition frequency, f_t, which is defined and discussed in Chapter 3, Section 2.6, is higher (for a gate length of 1 μm, the f_t of InP is 48% higher than that of GaAs), and one might reasonably expect that the InP-based device should be capable of performing at higher frequencies. In much the same way that the transit time for InP is smaller than for GaAs, it is found that InP also has a higher value for transconductance, g_m, for the same bias current[12].

It is indeed true that the use of InP material is beneficial in some application areas. For example, InP bulk material is commonly used in transferred electron devices like Gunn oscillators. When used in this way, the domains generated can traverse the device more rapidly and hence more domains are generated per unit time than for a similar GaAs structure. It then follows that higher frequency oscillators can be developed.

However, in the case of integrated circuit technology, the expected performance advantages of InP over GaAs have not manifested themselves due to a number of factors, including non-optimum material characteristics, buffer layer and substrate quality problems, and technical issues associated with the low barrier characteristics of InP Schottky gates.

The InP gate electrode has a low barrier height. This low barrier leads to an increased leakage current due to thermally excited electrons. The reverse I_{gd} for an InP based MESFET type device is 1000 times larger than that for an equivalent GaAs device[12]. It should be noted that the breakdown voltage of InP is somewhat greater than that associated with GaAs[13].

Another consequence of the smaller energy band-gap is the fact that InP is a poorer insulator than GaAs. Typically, the resistivity of InP is 10,000 times less than that of GaAs[12]. This reduced resistivity has a very significant effect. The current through the substrate at large V_{ds} is greater, and the output conductance is increased. As discussed elsewhere, an ideal device has zero output conductance.

The gate-drain capacitance of an InP device is much larger than that of its GaAs equivalent. It has been explained[12] that this is due to the fact that InP requires a higher field for the onset of velocity peaking and the associated domain formation. As a result, for the bias levels generally used, the Gunn domain formation is weaker (in fact, if the drain bias were increased