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Development of Sub-mm Wave Flip-Chip Interconnect



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Chapter 1

Introduction

1.1 Motivation

Recently, the demand for high frequency electronics has been increasing rapidly, particularly in the so far mostly unexploited terahertz (THz) region. THz commonly denominates the frequency range between 300 GHz and 3 THz, corresponding to a wavelength of 1 mm down to 0.1 mm. The THz range offers the possibility of a wide range of applications, such as in medical imaging or security scanning, radar systems, spectroscopy, as well as broadband wireless communications [1–7].

Regarding the development of THz electronics, besides optoelectronic devices, particularly THz transistors have been receiving a lot of attention. Several research groups are adding their efforts to increase the operation frequency of their monolithic microwave integrated circuits (MMICs) such as high-electron-mobility transistors (HEMT) or heterojunction bipolar transistors (HBT). These THz transistors are the main components supporting those ultimate-frequency applications. Without these transistors, frequency conversion systems using multiple circuits up to mm-wave range would be required, leading to drawbacks in bigger circuits, increasing losses, and yields.

But to develop high-speed chips is only one part of the story. These chips also need their connection to the outside world. Therefore, apart from the interconnects of these high-frequency transistors, the packaging, which is the outermost boundary to restrict operation

frequencies of a system also need to be developed in parallel. In practice, ideal zero-loss transitions cannot be fabricated, and special care has to be taken in the development to reduce parasitic losses to a minimum extent.

Principally, there are two important factors to be considered in order to create a proper sub-mm wave interconnect. These considerations are 1) selecting suitable chip connection methods and 2) choosing appropriate planar transmission lines. In general, there are two well-known interconnect technologies for chip connections. These are wire bond and flip-chip. With increasing frequencies, the wire bond technology suffers from intrinsic parasitic effects which are essentially self-made due to its wire length. For flip-chip technology, in contrast, the interconnect path through bumps is much shorter, yielding a significant reduction of parasitic inductances. This has turned flip-chip interconnects into a promising technology for sub-mm wave applications and justifies its use in the present thesis.

Apart from choosing the suitable chip-connection technology, to select an appropriate planar transmission line is also one of the key tasks in the design of devices with increased system bandwidth. The choice of a suitable transmission line should be based on the desired target frequency as well as the feasibility to be successfully integrated into the system. Among several line systems, microstrip (MS), coplanar waveguide (CPW) and stripline are potential candidates to fulfill these conditions.

Besides the criteria mentioned above, there are other substantial details which need to be considered during the development of high-frequency packaging at this level. These parameters are for example substrate materials, bump dimensions, bump pads, distance between chip and substrates and transmission line geometry. They need to be adjusted according to the application of the transition.

1.2 Scope and Outline

The goal of this research was to develop flip-chip interconnects for sub-millimeter wave frequencies and to implement them as a first-level packaging concept for InP heterojunction bipolar transistors (HBTs). Hence the operating frequency of interest is somewhere beyond 220 GHz. The major part of this work focuses on the fabrication of passive flip-chip interconnect modules using different planar transmission line concepts: coplanar waveguide (CPW)

and stripline designs in combination with eutectic AuSn bumps, leading to the development of three passive flip-chip modules suitable to the respective frequency bands up to 220, 325 and 500 GHz. In addition, a diamond layer is integrated to the construction. Due to its high thermal conductivity properties, the latter is considered as a heat sinking layer for the target InP HBTs.

A previous study [8] shows that keeping the transition areas as well as the bump dimension as small as possible helps to increase the frequency. Based on this knowledge, 10 μm AuSn microbumps have been developed for all of the experiments described in this thesis, including the AlN submounts for InP HBT chips [9].

Illustrated in Figure 1.1 is the project's development road map, providing different cross-sectional structures of four flip-chip experiments for the study timeline. Beginning in April 2012, the study started with the development of 220-GHz flip-chip module. Then the operating frequency has been increased to 325 GHz and further to 500-GHz. At the final stage of the study, which took place in December 2015, the flip-chip technology was implemented to the active HBTs. The details about each development phase will be provided in the following sections.

The thesis consists of seven chapters in total.

- The next chapter, chapter 2, reviews the background and state of the art of sub mm-wave packaging. Additionally, an overview of the planar transmission lines used in this work and details of flip-chip technology are given. The chapter closes with a small introduction to the FC150 bonder, as it was routinely used for this thesis.
- Chapter 3 presents the first flip-chip iteration up to 220 GHz utilizing CPW-to-CPW lines, including the fabrication details of the miniaturized AuSn bumps.
- Chapter 4 reports the second flip-chip development using a stripline-to-CPW structure, aiming at the frequencies beyond 250 GHz. The measurement results of the fabricated samples are discussed and compared to the values predicted by the simulations.
- Chapter 5 presents the third experiment using the stripline-to-stripline interconnect, extending the frequency up to 500 GHz. This exceeds the frequency values reported in the literature until now. Furthermore, the influence of process tolerances such as misalignment of bump positions, variation in line geometries, and dielectric thicknesses will be analyzed using 3D EM simulations.

- In chapter 6, the results of InP HBT flip-chip are discussed.
- Finally, chapter 7 gives an overall summary and provides an outlook for possible future work.

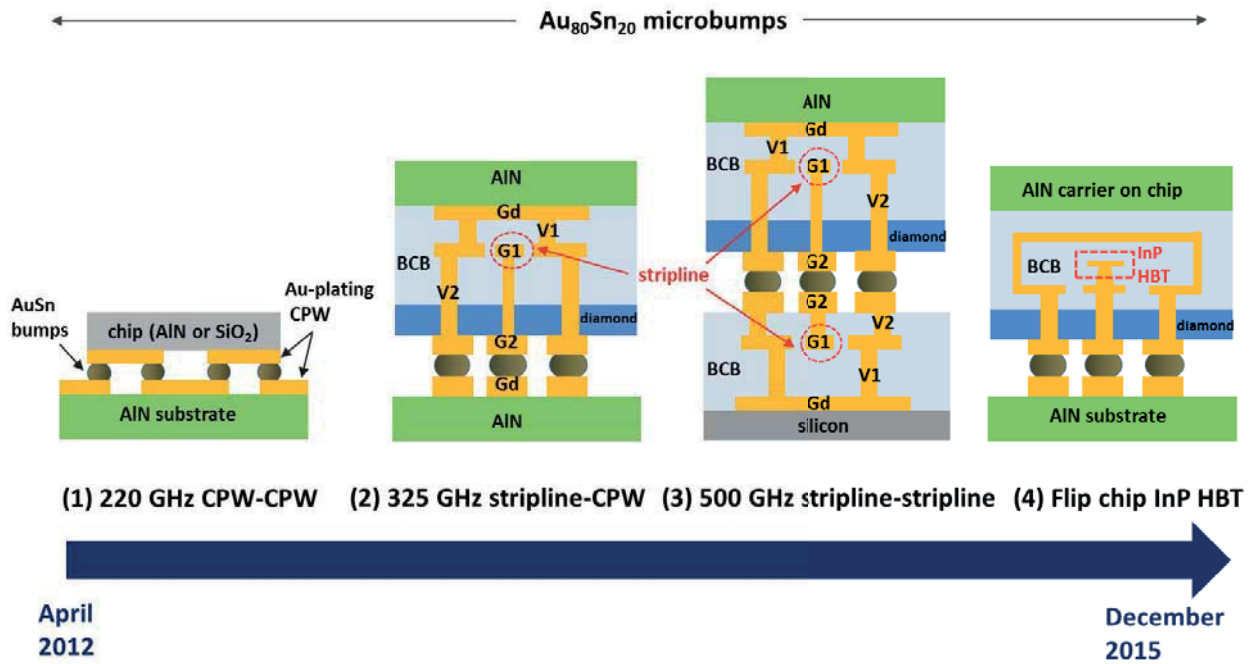


Figure 1.1: Development roadmap of flip-chip for sub-mm wave applications, showing four different cross-sectional structures of chips and substrates connected through AuSn bumps flip-chip. Three passive flip-chip interconnects were developed, using different combinations of planar transmission lines, gaining frequencies of 220 GHz, 325 GHz and 500 GHz (1)-(3). In the last development phase, the flip-chip technology was implemented to InP HBT (4).



Chapter 2

Sub-mm Wave Flip-Chip Interconnect

2.1 Microwave and mm-Wave Packaging

In general, the packaging system can be classified at least into three levels [10]. The first-level packaging (chip-to-package) relates to the connection of bare dies directly onto their carrier substrates to generate the first possible electrical contact of chips to the outside system. This can be done by several assembly techniques, mostly by wire bonding and flip-chip mounting. The second-level packaging (package-to-board) is the attachment of the first-level packaged chip onto a motherboard or printed circuit board (PCB). The third-level packaging refers to the assembly of several circuit boards into a system.

In a similar way as for low-frequency packaging, in microwave and millimeter-wave areas device packages also have their functions to deliver signal and power of IC circuits to outer systems, to support mechanical stability of chips and to protect the devices from the environment, as well as to dissipate heat from the system [10]. Note, however, that for high-frequency applications, as operating frequencies increase, parts of the packaging themselves can turn to be a source of parasitics, deteriorating signal propagation or provoking resonance in the system [11]. This adds more complications to the design of mm-wave packages as compared to conventional ones. A short review of some concerned topics which need extra considerations for high-frequency packaging is given as follows [12]:

Distributed effects

The point that makes mm-wave packaging totally different from the low-frequency one is that at high frequencies all of the packaging components such as wire bonds and dielectric mold compounds do not just act as a connection or a chassis of the system. At such frequencies, their hidden lumped elements, for example an inductance from wire bond and a capacitance from the dielectric material, behave differently. Depending on the operating frequencies the dielectric capacitance acts no longer as a pure capacitance but also emerges the inductive effect into combination. A wire bond is not solely a metal connection between two points. Instead, the signal starts radiating from the wire and converting the metal wire to an antenna of the system or distinctly presents the inductive effect. This phenomenon is called ‘distributed effect’, which means that the electrical behaviors change when the operating frequency is increased [12]. This occurs because at mm-wave frequencies, the physical dimensions of the devices become a fraction of a wavelength. As a result, the packaging strongly affects the electrical characteristics of the whole electronic system. Therefore, mm-wave packages have to be carefully designed based on their operating frequencies, taking the distributed effect into account.

Resonances from signal coupling and radiation

At mm-wave frequencies, undesired coupling and radiation can occur wherever in the circuit where metal lines are placed close to each other. Cross talk and radiation are the cause of resonances which degrade signal performances. The resonances not only occur from the coupling between circuits but they also happen from a cavity inside a metal package. It is difficult, however, to detect this problem during the design phase, because the coupling and radiation only appear while the electrical measurement is performed. Nevertheless, with modern EM simulation software these effects can be predicted, and rough distances that metal traces need to be separate from each other should be able to be defined.

Choice of materials

Choosing suitable materials is one of the critical subjects for mm-wave packaging, having in mind that the material properties affect the characteristic impedances, which directly

influence insertion losses. For instance different types of dielectric contribute in dielectric losses by their loss tangents, and metal types impact conductor losses.

Thermal management Another point which needs to be taken care of not only for low-frequency packaging but also for mm-wave packaging is the thermal management [11]. This is because devices generally rise up the heat during operation. Therefore it is important that the packages offer a good thermal management. This can be done by several techniques including the attachment of a heat-sinking material such as CuW, AlSiC and AlN [13–15], drilling thermal vias to connect to the high-thermal conductivity substrate and using flip-chip bumps for thermal dissipation.

The next section starts with the packaging construction concepts. This is to give an overview of mm-wave packaging/housing before further examining the interconnect concept of the first-level packaging, which is the focus of this dissertation.

2.1.1 Types of mm-Wave Packages

In principle, good mm-wave packagings need to fulfill two system requirements which are 1) providing excellent electrical performances and 2) having the potential for low cost production. In reality, to develop a choice of packages, which can combine these two aspects, is a big challenge. Obviously, these two requirements are a trade-off to each other. In the sub-section below, the overview of different mm-wave packagings is presented according to the purpose of their developments.

2.1.1.1 mm-Wave Packages with High Electrical Performance

Metal-housing packages [16]

For an excellent performance, metal housings are one of the best packaging solutions because they offer excellent shielding to the system. But using a metal chassis increases the packaging cost. Depending on the applications, metal packages are made for two types of devices, which are discrete devices and complex modules, as illustrated in Figure 2.1 (right).

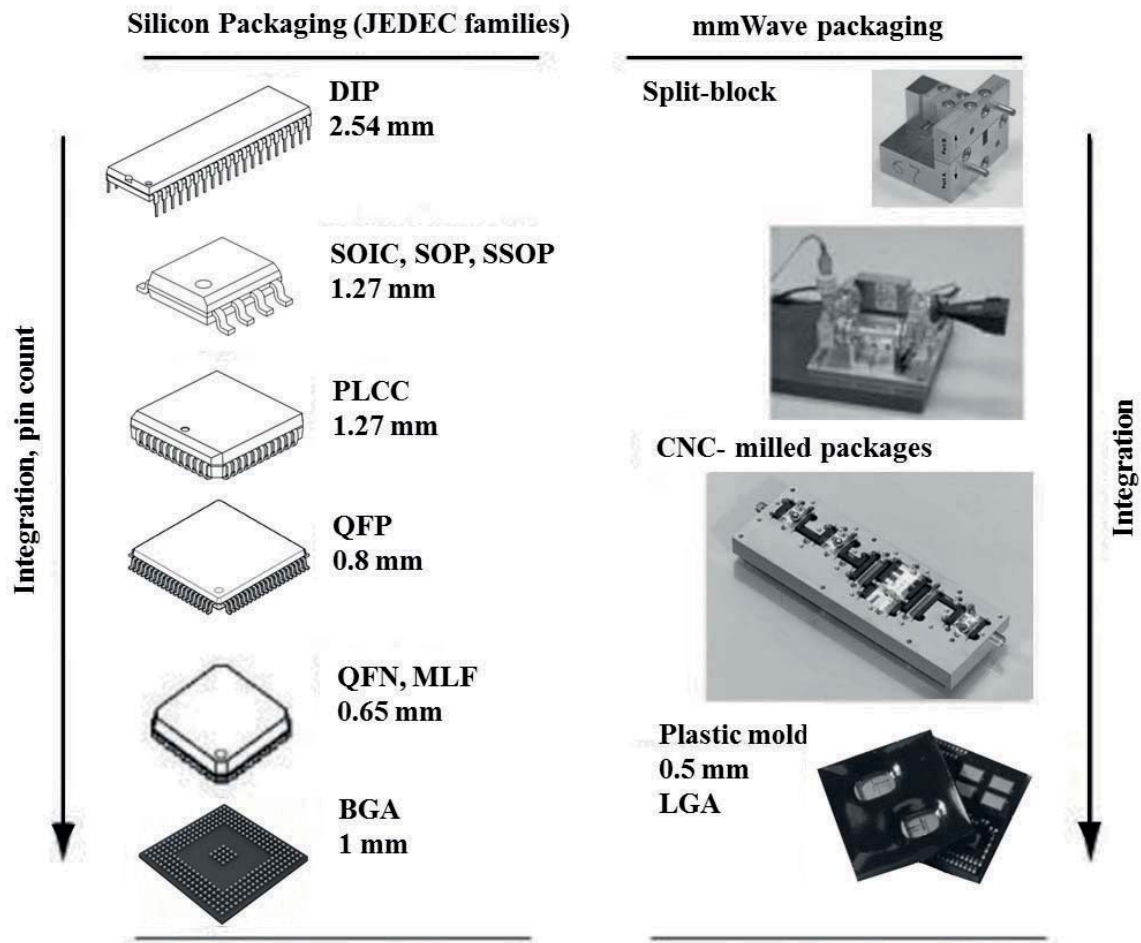


Figure 2.1: Development of mm wave packaging as compared to conventional packaging, adapted from [16].

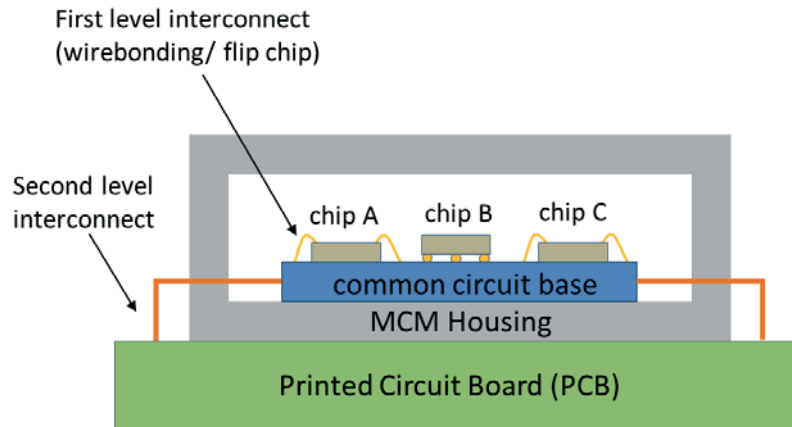


Figure 2.2: Illustration of MCM concept, adapted from [17].

For the discrete device package, it is named split-block package because the package is composed of two metal parts, combined together as an mm-wave housing. The split-block package is normally used for single devices such as MMIC, transistors and waveguide transitions. Unlike the split-block, the complex packaging module combines different device functions together in one metal block. Both of these metal packages are mostly made of aluminum, coated with gold to avoid corrosion. The construction of the packaging is done using a milling technique, most likely with the aid of computer numerical control (CNC). Therefore, these packages can be called ‘CNC Milled Metal Housing’.

For both packaging styles, several methods such as wire bonding or flip-chip technology are applied to connect a chip inside the metal body. To provide good RF isolation between the individual units the wave propagation inside the package is suppressed by limiting the width and height of the package less than half of the wavelength at the target operating frequency or by attaching absorbing materials to the packages.

Multichip-module packages (MCM) [16, 17]

Another attempt to increase packaging performances is by using multichip-module packages (MCM). The concept of this packaging is to connect several different chips through the first-level interconnect, and to reduce the second-level packaging or the outer connection as much as possible, as parasitic effects of this packaging level can easily degrade the total system

performance [17]. Additionally, using MCM also leads to the reduction of module size while increasing the degree of integration [18, 19].

Typically, the MCM packages can be classified into three types, depending on their substrate materials. These are MCM-L for laminated substrates, or PCB (printed circuit board), MCM-C for ceramic substrates and MCM-D for deposition of dielectric substrates. Amongst these three types of MCM, the ceramic MCM offers the best thermal conductivity and also the lowest loss.

2.1.1.2 Low-Cost Packages

Plastic-molding packaging

Plastic-molding packages are widely used as standard packaging technologies at low frequencies. These types of packages are for example DIP (dual in-line package), SOIC (small outline integrated circuit), PLCC (Plastic leaded chip carrier), QFP (Quad Flat Package), QFN (quad-flat no-leads) and BGA (ball grid array), as shown in Figure 2.1. In general, there are two different techniques of mounting the packages on a board. These are 1) through-hole (PTH) technology and 2) surface-mount (SMT or SMD) technology. For the PTH method, the package pins will be inserted into the exact footprint holes on the board. In contrast to the PTH, mounting the SMT can be done by placing and soldering the device on one side of a printed circuit board (PCB) without the package pins penetrating to another side of the PCB. In the group of the packages shown above only DIP represents the through-hole mounting type.

As plastic materials are much cheaper compared to metal packages, they are very attractive for high-frequency packaging in term of cost reduction. However, plastic materials are lossy. This can degrade the overall system performance.

Amongst all the conventional plastic packages used in low-frequency applications the QFN package is the one which is often adapted to mm-wave packaging [20]. In principle, the QFN package is done by attaching the MMIC dies on a lead frame using epoxy. These MMIC dies are connected to the electrical pads through wire-bonding technology before the whole construction is molded using a plastic compound, in the case of fully molded-package. Bessemoulin et al. [21] present the use of plastic QFN to power amplifier MMICs up to 20