

ELECTRONIC PACKAGING SCIENCE AND TECHNOLOGY

KING-NING TU | CHIH CHEN | HUNG-MING CHEN



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**Electronic Packaging
Science and Technology**

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Preface

As we enter the big data era, mobile devices are ubiquitous. Internet of things (IoT) is everywhere, and we have man-to-man, man-to-machine, and machine-to-machine communications. Furthermore, in the Covid-19 virus pandemic period, the trend of distance teaching, distance medicine, home office, and on-line meeting has increased greatly the need of advanced consumer electronic products, demanding smaller form factor, larger memory, more functions, faster and larger data collection and transmission, cheaper cost, and superb reliability. At the same time, 5G advanced communication technology and 3D IC devices have begun their impact to our society, and many new artificial intelligence (AI) applications have been invented.

With the perceived slowing down of Moore's law of miniaturization of Si chip technology, microelectronic industry is searching for alternative ways to sustain Moore's law. 3D IC is most promising in achieving more-than-Moore, wherein the up-scale of packaging technology is critical. Indeed, new advanced packaging factories are being built worldwide. We ask what will be the technical innovations in electronic packaging for 3D IC devices in order to enhance performance and reliability? Or, what are the challenging issues in electronic packaging technology that are essential in the near future development of semiconductor technology?

The goal of this book to present the science and engineering of advanced electronic packaging technology for a deeper understanding of the essence in development and manufacturing of the more-than-Moore technology. Especially, what is new in this book are the subjects of Cu-to-Cu direct bonding by using the (111) uni-directionally oriented nanotwin Cu, innovative 3D IC systems in packaging integration for high performance of wide bandwidth and low power devices, and the analysis of mean-time-to-failure equations based on entropy production.

After the introduction chapter, the following chapters will be divided into three parts. In Part I, the history of bonding technology will be covered in

Chapter 2, starting from wire-bonding, tab-automated bonding, flip chip C-4 solder joint bonding, micro-bump bonding, Cu-to-Cu direct bonding, and hybrid bonding. The microstructure, properties, and applications of randomly oriented and (111) uni-directionally oriented nano-twin Cu will be covered in Chapter 3. Then, Chapter 4 and Chapter 5 will be dedicated to chemical reactions and kinetic processes in Cu-Sn reactions for solder joint formation. Chapter 4 will review solid-liquid interfacial diffusion (SLID) reactions between liquid solder and Cu. Chapter 5 will review solid-solid reactions between solid solder and Cu. The kinetics of growth of intermetallic compound (IMC), which is a stoichiometric compound and has no composition gradient, has been an outstanding problem in solid-solid reactions. We introduce Wagner's diffusivity to overcome it.

Part II consists of chapters on electric circuit integration in packaging technology. The emphasis is on the design of low power devices and intelligent integration. The technical issues related to the need for faster rates and increased amounts of data transport in 2.5D/3D IC are discussed. It is explained how to increase the I/O density and the bandwidth in packaging technology.

Part III is a collection of chapters on reliability science. It begins with a chapter on irreversible processes of atomic flow, heat flow, and charge flow in open systems. The most important issue of Joule heating will be analyzed. The topics of electromigration, thermomigration, stress migration, and failure analysis will be covered. Equations of mean-time-to-failure (MTTF) will be reanalyzed on the basis of entropy production.

Finally, in Chapter 14, a brief discussion on how to use artificial intelligence to accelerate reliability testing will be presented. We propose an x-ray based graphic processing unit (X-GPU) to analyze early reliability failure before it occurs in any newly developed 3D IC device for mass production. The goal of AI here is to change the time-dependent and time-consuming reliability tests to time-independent tests. The basic idea of mean microstructure-change to failure (MMTF) will be introduced, so that we can link MTTF to MMTF.

We appreciate the capable help of Mrs. Jody Lee and Mr. John Wu at NCTU in preparing the book.

Hsinchu, December 2020

King-Ning Tu
Chih Chen
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1

Introduction

1.1 Introduction

As we enter the big data era, mobile devices are ubiquitous. On hardware, nearly everyone has a cell phone. On software, internet of things (IOT) reaches everywhere. We have man-to-man, man-to-machine, and machine-to-machine communications. Furthermore, during the Covid-19 virus pandemic, the trend of distance teaching, distance medicine, home office, and online meeting has increased greatly the need of advanced consumer electronic products, demanding smaller form factor, larger memory, more function, cheaper cost, faster and greater rate of data transmission, and superb reliability. Actually, the advanced 5G communication technology and 3-dimensional integration of circuits (3D IC) have already begun their impact to our society. No doubt the world around us is changing rapidly. In human history, this is the second time of a fundamental revolution.

In eighteenth century, we had industrial revolution when steam engine was invented. It developed machine power to replace human power and animal power. The activities in civilization were changing from agriculture to industry. We had railroad trains, ocean liners, automobiles, airplanes, and electricity. While industrial production has transformed human society from feudal to democratic, it was accompanied by capitalism, then communism, and then socialism. Indeed, the impact to human society was huge in the last two to three hundred years.

In twentieth century, after the invention of transistor, very-large-scale integration of transistor circuits, and mobile technology, we have data power to enhance machine power. What is coming is to have artificial intelligence (AI) revolution. We have robots, and human-less vehicles and

aircrafts to serve us. Mobile technology supported by mobile internet will have a long way to go in the near future. Accompanying the rapid progress, however, Moore's law of miniaturization in Si chip technology is near ending, so people wonder whether the rapid progress can be sustained.

If we look back to the last 10–20 years, semiconductor industry has had some interesting events. Namely, Japan has lost the leadership in semiconductor technology. The large European countries such as England, France, and Russia have no presence in microelectronics. On the other hand, Taiwan and Korea have gained the leadership due to the success of Taiwan Semiconductor Manufacturing Corporation (TSMC) and Samsung. Today, China has identified semiconductor device development and manufacturing to be a national goal and will spend a large sum of money to achieve it. One of the key reasons behind the trade war between United States and China is due to the competition in advanced semiconductor technology and in manufacturing of consumer electronic products. At the same time, 5G communication technology and AI applications are with us and they exert an unlimited impact and change to our society.

There were many reasons of Japan's failure, such as the critical change in currency exchange rate between yuan and dollar, and also the heavy punishments of Fujitsu by United States. However, Japan has recently joined TSMC to form an advanced electronic packaging factory in Japan to maintain its impact. The weaker and weaker presence of England and France is because of the insufficient financial support on semiconductor technology due to socialism. They tended to support rather uniformly the popular needs of society, but did not concentrate on supporting semiconductor technology. Today, to build a Si-based transistor factory will take 3–5 billion US dollars, so fewer and fewer countries can afford it. Russia is simply poor. Samsung in Korea has had the government's focused support to do so. TSMC in Taiwan is unique that it takes orders from all over the world to make VLSI devices, so it knows the major trend of the technology. Thus, it can spend the money it earned to keep improving the technology with innovation. For example, the technique of immersion lithography has enabled TSMC to lead the manufacturing of nanoscale semiconductor devices for the past five generations. Now, we are having the 5 nm node of nanotechnology, and 3 nm and 2 nm nodes are coming.

Some experts in China commented that China might take 10 years to catch up. No reason was given why it will take so long! On the other hand, China has been very successful in high-speed train and satellite technology. When China can make transistors as cheap as those made in United States, it is a sign that China has caught up. A plausible reason is given below.

A Chinese classic philosopher, Wang Yang-Ming, said “Knowing is hard, but practice is easy.” Semiconductor technology is completely opposite that “Knowing is easy, but practice is hard.” Take an example of teaching a child to play violin or piano; we can find the best teacher to teach the child all the technique and tricks of how to play well. Even a very talented child, he/she still has to take 10–20 years of practice to be good. It is the “experience” that is needed to do well. Indeed, “experience” cannot be taught quickly and cannot be copied or cannot be steal. Furthermore, in semiconductor manufacturing, the experience is not just of one person, it is of an entire industry.

1.2 Impact of Moore's Law on Si Technology

Moore's law states that the transistor density per chip area is doubling every 18–24 months without the increase of production cost. Figure 1.1 depicts the achievements of 2D IC of Si technology according to Moore's law. From 1970 to 1985, the density has increased from 1K to 1M per chip, which is an increase of 1000 times. From 1985 to 2005, the increase was from 1M to 1G, which is another increase of 1000 times. It is the most successful event of sustainability for about 40 years of any human activity.

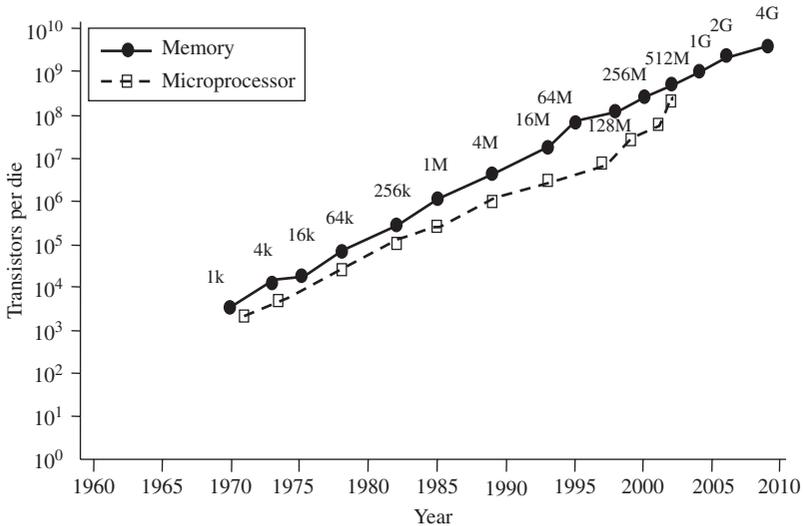
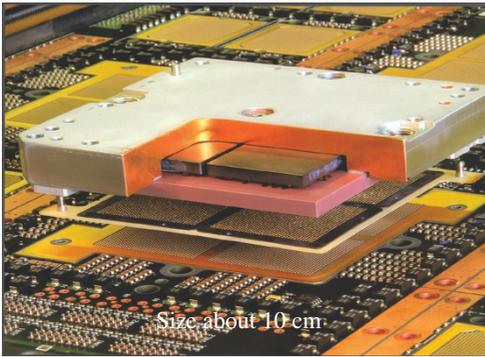


Figure 1.1 A sketch of the achievements of 2D IC of Si technology according to Moore's law.



Physical size reduction

There are 110 Si chips in the module of a mainframe Computer in 2002.

IBM J. of R&D.,
November, 2002.

If we replace the 110 chips by 1 chip, we can make the mobile phone now!

Also replace key-board by finger-touch.

Figure 1.2 An image of part of the device structure of the mainframe computer in 2002. The size of the module is about 10×10 cm.

The law has had two significant impacts. First, the price of one transistor is now cheaper than the printing of one alphabet on a newspaper, which is a significant consequence of the Moore's law that circuit density can be doubled without the increase of production cost. Hence, we can have very low cost use of transistors. Second, it enables the reduction of physical size of a computer so that handheld and mobile devices can be made. Figure 1.2 shows part of a mainframe computer in 2002. The module size is about 10×10 cm, and between two of the ceramic plates in the module, there are $10 \times 11 = 110$ pieces of Si chips. According to Moore's law shown in Figure 1.1, the circuit density per chip in 2002 is about 256 M. If we can integrate the central processing unit (CPU) and the memory on the 110 chips into a single chip, we can build a mobile device or a mobile computer by using a single chip! No doubt, we also need to reduce the packaging structure, as well as to replace a keyboard by the finger-touching technique. It is worth mentioning that in Figure 1.2, while we do not see the chips but we see the electronic packaging structure, wherein the bright solder joints are everywhere. It shows how important is solder joint technology in electronic device manufacturing. This is because solder joint is still the best way to join two Cu wires, even two nanowires of Cu.

1.3 5G Technology and AI Applications

Those advances mentioned in the above have changed internet to mobile internet. Internet means computer-to-computer communication. Mobile internet means mobile computer (cell phone)-to-mobile computer communication. At this moment, the rapid advances in 5G and AI require Moore's

law to keep going ahead for at the least another 10–20 years, but Moore’s law is ending.

In human civilization, the technique of communication has advanced step-by-step slowly from language, written words, printing, telephone and telegraph, television, internet, and now to mobile internet. Today, the advanced communication technology behind mobile internet is defined as 5G, with a standard of certain required performance. Figure 1.3 shows the drawing of a flower, which has six petals. There are two sets of petals: the inner brighter ones and the outer darker ones. The latter represents 5G technology and the former represents 4G technology. Each petal defines a specific technical requirement, as shown in Table 1.1. For example, on

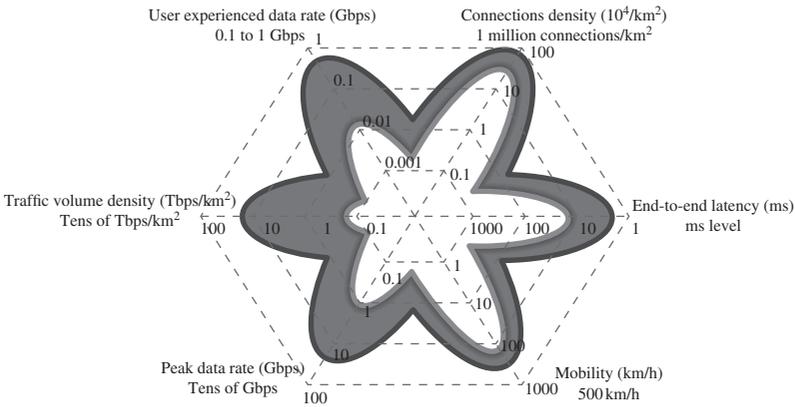


Figure 1.3 The petals of flower, which shows the required functions in 4G and 5G communication technology.

Table 1.1 5G technical requirements.

-
- Primary requirements:
 - End-to-end latency (mille sec)
 - Peak data rate (mobility, km/h)
 - Traffic volume density (tens of Tbps/km²)
 - Density of base stations (10⁴/km²)
 - Internet of everything
 - Energy efficiency
 - Secondary requirements:
 - Security and reliability
 - Low cost
-

point-to-point latency of signals, it was 10 ms in 4G and about 1 ms in 5G. If we can advance the required performance beyond the petals of 5G, it will be 6G.

In 2014, it was already predicted that around 2020, the 5G technology will be widely available. However, the company, Huawei in China, announced that its 5G technology is ready in 2019, ahead of everyone. It became a critical issue in the trade war between China and United States. The latter has put Huawei on its entity list or ban list. The hardware in 5G consists of satellites, servers, optical fiber lines, base stations, cell phones, and terminal sensors, and the software consists of various mobile internets, such as Android of Google. Huawei is especially good at making base stations.

Data and signals can be transmitted via satellites in sky, but satellites can be shot down easily in the beginning of a war. It can be transmitted via optical fibers underground and across oceans. The making of optical fiber requires the doping of rare-earth elements, so the strategic importance of rare-earth elements can be appreciated. Also it can be transmitted via base stations on land surface, so the construction of a large number of base stations is of national security concern. It is worth mentioning that Taiwan has successfully used its network of base stations to detect and control the motion and contact of people with Covid virus.

In the late nineties, dot-com was developed but soon burst because cell phones were not available. After cell phone becomes popular, Apple, Microsoft, Amazon, etc. are now the biggest companies in the world, no more GE, IBM, and Exxon, because of the wide applications of mobile technology.

About the global standard of requirements in 5G technology, see Table 1.1, the first is point-to-point latency of signals, which is only a few milli second. Latency means the total time spent to send out a signal and to receive it back. In a chain of moving cars, if the first car stops suddenly, the second car must stop within the time of latency, otherwise an accident would occur. If we consider a human-less vehicle, the LiDAR (not radar) on top of the car should be able to detect a sudden appearance of a pedestrian or a car, so that it can stop to avoid an accident.

Moreover, LiDAR and radar are line-of-sight techniques. Yet, we need to have a network of vehicle-to-everything in order to have non-line-of-sight awareness to know what is behind a stationary or a moving object. Also it should have an ultrafast rate of transport of data in order to show clearly the change of images of the surrounding of a car moving at high speed. Besides, it can download or upload instantly news or weather reports. To download a movie will now take only three seconds in 5G technology. For the success of 5G, it must have a very large number of base stations, so that information can be received and transmitted

continuously from place to place. It is no need to explain other standard requirements in Table 1.1, they should be clear. For example, any device being used under the hood of a car should have a high reliability because of heat. Then, low cost is important for the use of internet of everything in our home and office.

No doubt, 5G technology will enhance AI applications. At the end of this book, in Chapter 14, we shall discuss the need of using AI to accelerate the study of reliability, so that we may change it from a time-dependent event to a time-independent event. Another area for the use of AI will be the biomedical and health applications. For example, Chinese medicine has been based on big data for many years, and the technique of acupuncture could be improved with modern microelectronic devices. The link between microelectronics and biomedical applications will be the most important advanced technology in the future.

1.4 3D IC Packaging Technology

As the trend of miniaturization in Si technology slows down, microelectronics industry has been looking for ways to keep the downsizing momentum going, meaning to go to more-than-Moore! [1–3] The critical feature size in Si devices has already reached nanoscale, below 10 nm. Hence, it is harder and harder to make transistor circuits on a Si chip smaller and smaller without a large cost increase. At present, the most promising way to extend Moore's law is to go from 2D IC to 3D IC. Actually, the paradigm change has occurred more than 10 years ago, but 3D IC is not in mass production, because of cost and reliability.

In semiconductor manufacturing, because the product quantity is extremely large, so high yield and high reliability are critically important. Low yield will increase cost, and poor reliability will lead to recall; one example is the battery failure of cell phones. For any consumer electronic product in mass production, the concern of reliability is critical, especially the electronic packaging in 3D IC for advanced consumer electronic products, which are widely used now for distance teaching and home office.

In this introductory chapter, we explain what is electronic packaging? Also, what are the science and engineering in it, especially those relate to reliability? If we want to add more functions to hand-held devices, the operations of memory, logic, and special functions must be increased. At the same time, power as well as battery capacity must be increased too. A larger size battery will squeeze the volume of the rest of the device, which makes the heating problem worse. To remove heat, we must have a

temperature gradient. If we consider a temperature difference of 1°C across a microstructure of $10\mu\text{m}$ in diameter, the temperature gradient is $1000^{\circ}\text{C}/\text{cm}$, which will induce thermomigration. In turn, Joule heating will enhance electromigration, and thermo-stress will induce stress-migration. While these are time-dependent events, they are of major reliability concern.

Figure 1.4 is a scanning electron microscopy (SEM) image of the cross-section of a 2.5D IC test device. It has only two pieces of Si chips stacking on a polymer board. Electrically, they are interconnected by three sets of solder joints. At the bottom or on the outside of the polymer board is the set of the largest solder balls of diameter up to $760\mu\text{m}$, which is called the ball-grid-array (BGA). These balls allow the test device to be connected to the circuits on a printed circuit board. Within the polymer board, there are Cu wirings, as well as Cu plated-through-holes, which are not shown in the image. On top of the polymer board, there is the second set of flip chip solder balls of diameter about $100\mu\text{m}$, the so-called C-4 (controlled collapse chip connection) solder balls, connecting the board to the first Si chip, which is the “interposer.” In this test device, there is no transistor on the interposer, which is passive and serves only as a substrate without introducing thermal stress to the active Si chip on the top. Often this test device is called 2.5D IC due to the fact that the interposer has no transistors. If the interposer has transistors, it becomes 3D IC.

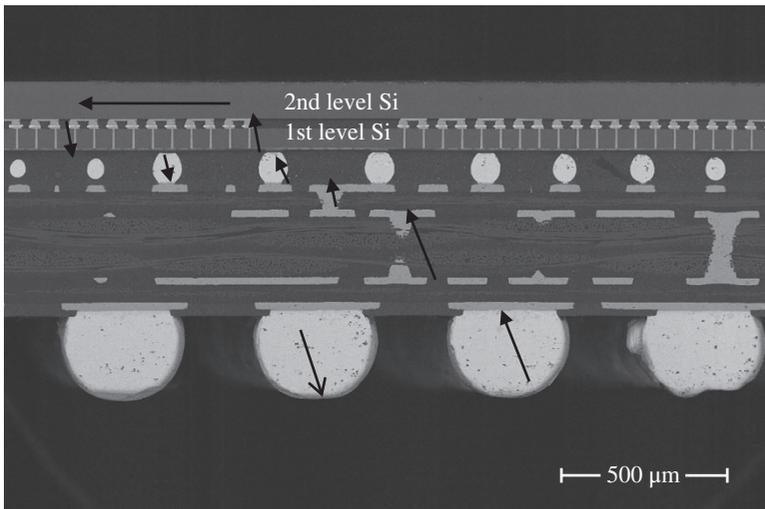


Figure 1.4 Scanning electron microscopy (SEM) image of the cross-section of a 2.5D IC test device. It has only two pieces of Si chips stacking on a polymer board.

In the interposer, there are arrays of vertical through-Si-vias (TSV) plated with Cu, making connections to the third arrays of solder joints of diameter about 10–20 μm , the so-called micro-bumps or μ -bumps, which join the interposer to the top Si chip. The top Si chip is an active device chip, so it has transistors. The thickness of the device in Figure 1.4 is about that of a US penny. The thinness of the device is a critical requirement due to the limit of form factor of mobile consumer electronic products. Consequently, the thickness of Si chips is thin too. The thickness of the Si interposer is about 50 μm , which is much thinner than that of a convention Si chip of 200 μm in thickness. The thin interposer has caused the warpage problem, as well as the heat conduction issue, to be discussed in the later chapters. The diameter of the TSV in the interposer is about 5 μm , so the aspect ratio of the TSV is 10.

In the above example, besides the active Si chip, the rest, which includes the interposer, can be regarded as electronic packaging. The packaging enables the Si chip to function, as well as to allow us, to interact with the outside world. In the packaging, it is worth mentioning that between two sets of solder joints of different sizes, there should be a redistribution layer (RDL) structure for circuit fan-out. It increases the number of input–output (I/O) contacts of a circuit in going from a low density of solder joints to a high density of solder joints. The higher the density of I/O, the better the resolution of frequency of a digital electromagnetic wave, because each I/O is designed to transmit a small width of the wave.

At the moment, there are two critically important challenges in electronic packaging technology. The first is the need of denser and denser I/O, which means the diameter of micro-bump and the pitch between them has to be reduced. As to be shown in Chapter 3, hybrid-bonds consist of Cu-to-Cu bonds together with dielectric-to-dielectric bonds are being developed. The second is Joule heating and heat dissipation, which will be discussed in Chapter 9.

About the increase of I/O, from BGA to C-4 joints, there is a RDL of Cu wires in the upper part of the polymer board. From C-4 joints to μ -bumps, there is an RDL of Cu wires at the lower part of the interposer chip. This second RDL is invisible in the figure, but it is new in 3D IC because it does not exist in 2D IC devices, where typically there are only two levels of solder joints. The failure of the new RDL is of concern.

Figure 1.5a and b show synchrotron radiation tomographic images of a 3D IC and part of a 2.5D IC device, respectively. The latter has a length about 4 mm, and a thickness and a height of about 0.5 mm. Due to the weak absorption of X-ray, the two Si chips and the polymer substrate become invisible. We can see the vertical TSV pillars. Also, the solder balls and the

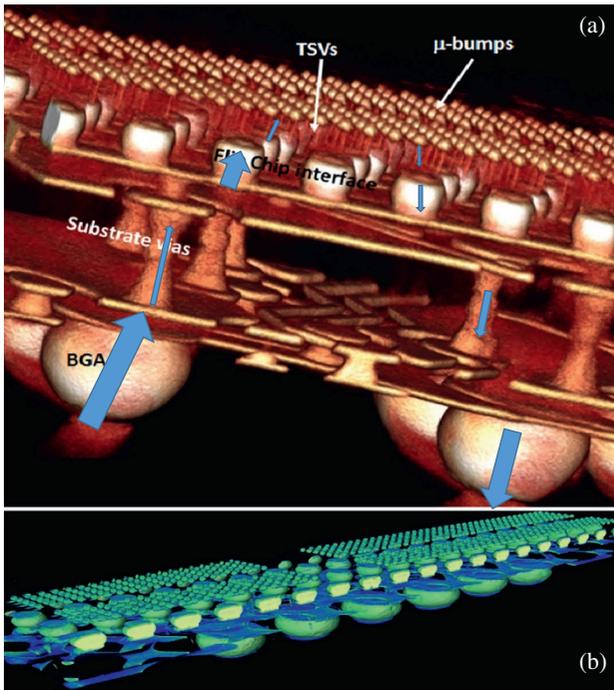


Figure 1.5 (a) Synchrotron radiation tomographic images of a similar device as shown in Figure 1.1. Due to the weak absorption of X-ray, the two Si chips and the polymer substrate become invisible. But the solder balls and the Cu wires are shown clearly. (b) Synchrotron radiation tomographic image of a 2.5D IC device, having a length about 4 mm, and a thickness and a height of about 0.5 mm. The vertical TSV pillars can be seen.

Cu wires are shown clearly. In Figure 1.5a, by using a pair of the BGA balls as the cathode and the anode and by passing 50 mA at 100 °C, following the arrows which indicate the conduction path, we can study time-dependent failures caused by electromigration and Joule heating, to be discussed in Chapter 10.

Why do we emphasize electromigration and Joule heating? This is because electronic devices are current-voltage (I-V) devices, so the applied electric current goes in and out of the devices in an open system. It causes Joule heating and electromigration, which are of key reliability concern. Figure 1.6 is a schematic diagram of the cross-section of a typical 3D IC device. The structure, in essence, is the same as that shown in Figure 1.4, except that on the right-hand side, there is a stack of memory chips on a logic chip as the CPU. If we replace the stack by an optical or

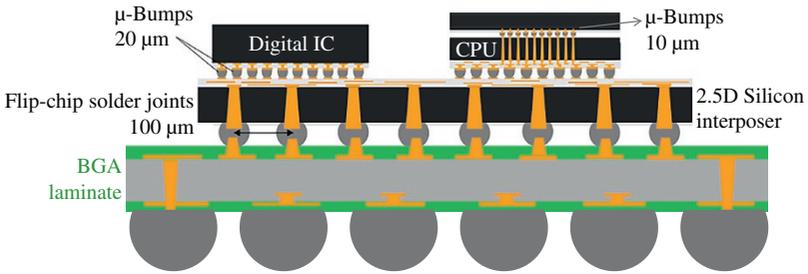


Figure 1.6 Schematic diagram of the cross-section of a typical 3D IC device.

compound semiconductor or MEMS chip, it becomes heterogeneous integration.

In comparing the structure of 3D IC to that of 2D IC, the difference is the stacking of multilayer of chips and the interconnects using TSV and μ -bumps. On processing TSV, the thinner the chip, the easier the drilling of vias. On making μ -bumps, its melting point should be lower than that of C-4 joints, so that the latter will not melt upon the melting of the former. Thus, the basic challenges are that the wafer is thinner and the processing temperature is lower.

From the viewpoint of packaging technology, we may say that the essence or the major challenge in 3D IC is to scale down the dimension of packaging structures so that it can match those in the chip technology. There is no Moore's law in packaging technology, so it has room to shrink.

What are the key functions of electronic packaging? The cell phone held in our hands is a movable electronic packaging product or a mobile computer, which enables us to compute and to communicate with the world around us. The set of chips in the cell phone can be arranged horizontally, side by side, but it takes space. Or they can be arranged vertically, one on top of the other, this is called 3D IC, and it reduces the form factor and takes less space. However, heat dissipation in 3D IC is harder because the packing is denser. When over-heat occurs, it induces reliability problems. Over all, the product should be electrically, mechanically, chemically, and thermally stable.

1.5 Reliability Science and Engineering

An electronic device in operation is an open system because electrical charges flow in and out of the device. While the number of charges in transport is conserved, entropy production is not. The waste heat in entropy

production is Joule heating on the basis of irreversible processes. [4, 5] For electrical conduction, Onsager's Eq. (1.1) below shows that entropy production is the product of the conjugated flux of j (current density = coulomb/cm²-sec) and the conjugated driving force of E (electric field $E = j\rho$, where ρ is resistivity). Derivation of the Onsager equation will be given in Chapter 9.

$$\frac{TdS}{Vdt} = jE = j^2\rho \quad (1.1)$$

where T is the temperature, V is the volume of sample, dS/dt is the entropy production rate, and $j^2\rho$ is the Joule heating per unit volume per unit time. Typically, the power from Joule heating is written as $P = I^2R = j^2\rho V$, where I is the applied current and R is the resistance of the sample. Thus, $j^2\rho$ is power density or Joule heating per unit volume per unit time of the sample, in units of Watt/cm³, and I^2R is Joule heating per unit time for the entire sample, in units of Watt. Clearly, this is the reason why we need low-power devices or low entropy production devices.

While the cost of production of 3D IC can be reduced when it is in mass production, the problem of reliability due to over-heating has to be solved fundamentally by a smart system design or by design-for-reliability (DfR) and by a critical selection in materials integration. To put it simply, we need to design low-power devices, and also we need to understand heat production (Joule heating) in irreversible processes and heat dissipation in the device structure. [6] Hence, the science and engineering of electronic packaging come into focus.

Entropy production is the most relevant understanding of failure induced by electromigration, thermomigration, and stress-migration in irreversible processes. [7] Statistical analysis of failure requires the knowing of mean-time-to-failure (MTTF). An example is Black's equation of MTTF for electromigration. In Chapter 13, we shall present a unified model of MTTF for electromigration, thermomigration, and stress-migration on the basis of entropy production.

Figure 1.7 shows an example of electromigration-induced damage in Cu interconnects. The high current density in the interconnect has induced a flow of atoms along the electron flow direction, going from the cathode to the anode, leading to vacancy accumulation and void formation in the cathode region. Resistance of the interconnect increases gradually until an opening in the circuit occurs, where the resistance increases dramatically.

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