IEICE TRANS. ELECTRON., VOL.E94–C, NO.4 APRIL 2011

INVITED PAPER *Special Section on Circuits and Design Techniques for Advanced Large Scale Integration*

Prospective Silicon Applications and Technologies in 2025

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SUMMARY Today, practical semiconductor products are an integral part of our lives and the infrastructure of society, and this trend will continue in the future. New areas of application will expand into medical, environmental, and agriculture (food)-related fields in addition to the conventional information and communication technology (ICT)-related field. Low-cost semiconductor devices with advanced functions have thus far been realized by miniaturization. However, we are now approaching the physical limit of miniaturization, and also, the investment required for new semiconductor manufacturing facilities has become huge. Under such circumstances, we propose an approach based on semiconductor devices called microcube chips and ideas of semiconductor development, i.e., agile integration and "inch-fab." Our approach is expected to contribute to expanding the range of companies that can fabricate semiconductor devices to include small-size companies, exploring new applications of semiconductor devices, and providing a wide variety of semiconductor devices at a low cost from the semiconductor industry.
key words: *microcube chip, agile integration, inch-fab*

1. Introduction

Semiconductor devices are now used for various applications at home and in society's infrastructure; modern society cannot function without semiconductor devices. It goes without saying that semiconductor devices are indispensable to human society and in conserving the global environment.

According to Moore's law, used in roadmaps of semiconductor, transistors per unit area that can be placed on an IC increases exponentially with time. By extrapolating the prediction in the International Technology Roadmap for Semiconductors (ITRS) up to 2025 on the basis of Moore's law, it is expected that the metal 1 (M1) half-pitch of semiconductor devices will be reduced to 8 nm by miniaturization. Conventionally, the increased integration of transistors and improvements in their performance and functions have been the driving forces of miniaturization. As of 2010, a performance equivalent to 100 giga operations per second (GOPS), which exceeds that of a large-scale computer a decade ago, has been realized by a system on a chip (SoC). If the trend of miniaturization of semiconductor devices continues in the future, the computing power of a moderately priced computer will become comparable to the human computing power of the total population on earth by 2050 (Fig. 1) [1]. In the future, anti-aging measures and food factories enabling the mass production of cheap food may be realized by biotechnology. Also, nanoscale robots consisting of molecules artificially synthesized by nanotechnology may support human society.

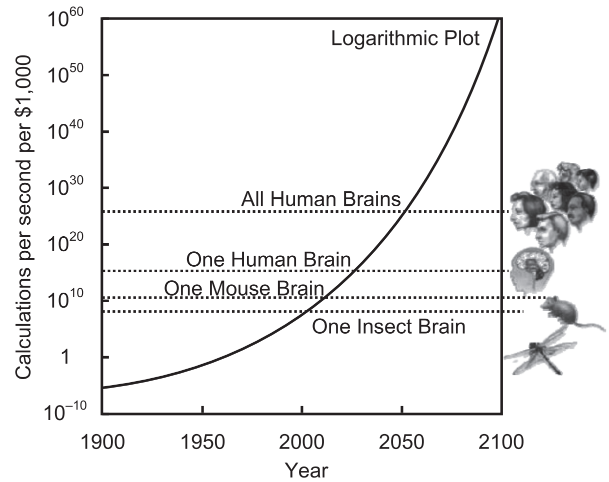

Fig. 1 Exponential growth of computing in 20th and 21st century [1].

Continuous technological development related to the miniaturization of semiconductor devices has been the driving force behind the creation of new applications of semiconductor products. However, improvements in the performance and functions achieved by miniaturization and the trend toward low-price devices may reach a plateau because of a significant increase in the amount of labor required for design as a result of the increased circuit scale and the rising price of equipment used in leading-edge microfabrication. Moreover, it is necessary to reduce the energy and resources consumed at every stage in the life of a semiconductor device from design and production to application so that human society and the global environment can continue to benefit from semiconductor devices in the future. Under such circumstances, a wide variety of semiconductor devices will be required to control the products related to their applications, such as robotics and artificial intelligence. As we face the limit of miniaturization from the viewpoint of semiconductor technology, it will be necessary to discuss what type of semiconductor devices we should fabricate and how they should be fabricated in the future.

In this paper, an approach based on microcube chips, agile integration, and "inch-fab" is proposed as a breakthrough for various fields such as environmental, medical,

Manuscript received November 2, 2010.
Manuscript revised December 20, 2010.
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DOI: 10.1587/transele.E94.C.386

and food-related fields, which are expected to become future markets of semiconductor devices.

2. Microcube Chips

In addition to improving the performance and functions of semiconductor devices by exponentially increasing the number of transistors per unit area on chips as an extension of the conventional method of miniaturization, the following new direction is also considered. Namely, LSIs are miniaturized while maintaining a sufficient number of transistors on a chip, since such semiconductor devices for general users will enter the market in massive numbers at an extremely low price. In an era of ubiquitous networks, the services realized by application software operating on large-scale network systems will provide value for users, and LSIs themselves will not be the main source of profits. The volume-based market of practical semiconductor products is predicted to continuously shift from developed countries to developing countries (Fig. 2) [2]. Therefore, further decreases in price are desired. In other words, a trend toward the reduction of chip size as a result of the miniaturization of transistors is expected to occur. Here, two cases are examined, assuming that the M1 half-pitch of semiconductor devices will decrease to 8 nm by 2025, focusing on the applications that will benefit from chips having a reduced size while retaining their performance and functions [6].

In the first case, the size of a semiconductor device is estimated when a number of transistors equivalent to that of a conventional chip are integrated on a chip assuming that current SoCs [3]–[5] have sufficient performance to be used in daily activities by people (Fig. 3). For example, one type of radio-frequency identification (RFID) tag has dimensions of $150 \times 150\,\mu\text{m}^2$. As shown in Fig. 4, when 128 1.2-μm-thick chips are integrated three-dimensionally, a total of two million transistor logic circuits and 2 GB of memory are expected to be integrated on the RFID tag. This value indicates that the tag has the capacity to include most of the functions of current SoCs.

In the second case, medical nanorobots and cell processors are expected to be realized as a result of the miniaturization of chips. The diameter of human cells ranges from 2 to 30 μm. Assuming eight layers of 1.2-μm-thick chips are laminated and embedded in the size of a cell, 100,000 transistors can be integrated in the cell (Fig. 5). The capacity of such a system is equivalent to that of a system consisting of an 8-bit microcomputer with peripheral circuits. Although unsolved issues such as biocompatibility still remain, such devices may be promising future examples of applications prepared by ultimate microfabrication techniques.

The above two cases indicate the potential resulting from the miniaturization of semiconductors not only for in-

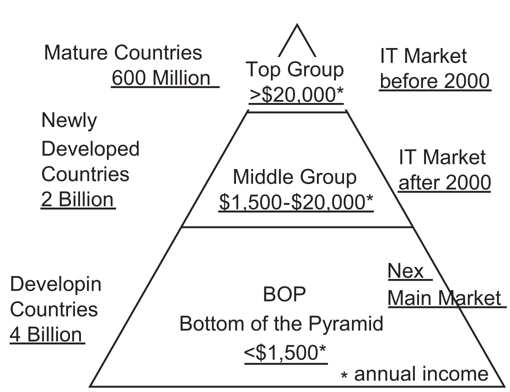

Fig. 2 Changes in information and communication technology (ICT) market [2].

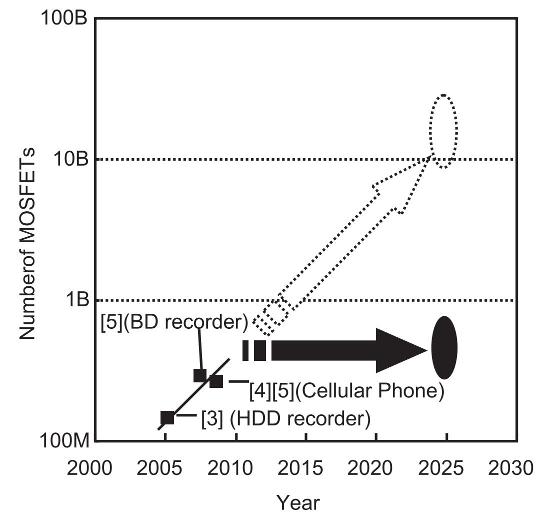

Fig. 3 Trends of the number of MOSFETs per LSI. The dotted arrow shows the case of constant chip size, and the solid arrow shows the case of reduced chip size.

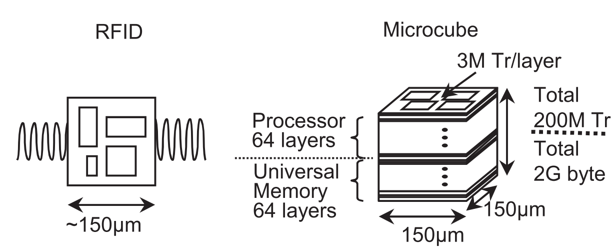

Fig. 4 Example of a microcube with the same size as an RFID [6].

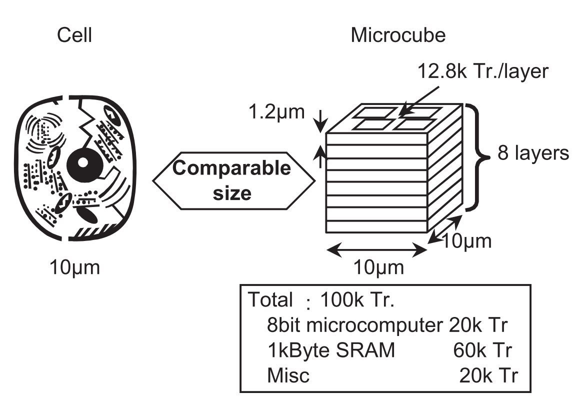

Fig. 5 Example of a microcube with the same size as a cell [6].

creasing the level of integration but also for miniaturizing chips. In the next section, miniaturized LSIs, called microcube chips, are further discussed.

3. Technical Problems of Microcube Chips

3.1 Three-Dimensional Lamination Technique Based on Epitaxial Growth

The three-dimensional integration of LSIs is required to realize microcube chips. Considering current mounting technology, the fabrication of a three-dimensional integration consisting of micrometer-size microchips by system in package (SIP) technology is not realistic. The research and development of three-dimensional integration technology by the through silicon via (TSV) technique have been actively carried out recently. Considering the small size of LSIs, three-dimensional integration by epitaxial growth is also an option.

3.2 Noncontact Interfaces

Mounting a conventional pad used for external connection on a microcube chip is difficult because of its large size. Therefore, noncontact input-outputs (IOs), including the power source, are considered as an alternative. To realize a noncontact interface, wireless power transmission as well as ultralow-power-consumption wireless communication technology should be established.

3.3 Ultralow Power Consumption

The heat radiation efficiency of three-dimensional microcube chips is low; thus, heat radiation due to power consumption should be suppressed. For a processor of $10\,\mu\text{m}^3$ size, the power consumption per unit area of the chip surface should be suppressed to the current level of two-dimensional chips when natural cooling is assumed, which means that the power consumption should be suppressed to $50\,\mu\text{W}$ or less for a microcube chip of $10\,\mu\text{m}^3$ size. This is as low as 1/1000 of the power consumption realized only by miniaturization with keeping current supply voltage. When chips are used in cells, it is reasonable to use the cell potential as a power source. To achieve this, a significant breakthrough, including the use of materials different from those conventionally used for chips, will be required. Furthermore, the technology for effectively utilizing a several tens mV potential difference or the technology for effectively utilizing a potential equivalent to that of thermal noise is also required.

3.4 Environmental Compatibility

Microcube chips should be used so that they have no adverse effects on the environment and living organisms. This may be difficult considering the expected size and number of microcube chips. Procedures for the collection and reuse of microcube chips should also be considered. It is desirable that microcube chips are made from materials that have no adverse effects on the environment after their disposal.

In the case of medical and food-related applications, the chip utilization time may be extremely short. From the viewpoint of environmental impact, it is unacceptable to invest huge amounts of energy and precious resources for the production of semiconductor devices with short lifetimes. Therefore, reducing the energy and resources required to fabricate microcube chips should also be considered.

3.5 Development of Electronic Design Automation (EDA) Technology

Because the trend toward large-diameter wafers along with the trend of miniaturization may lead to a price increase of process units, this trend may saturate in the future for economic reasons, except for memory devices that are mass-produced. The economic limit of miniaturization may be overcome and the trend of miniaturization may be continued by reducing the chip size and fabricating a wide variety of chips for each application. In an era requiring a wide variety of chips, LSIs with unique specifications may be required to differentiate one final product from others, even in companies that had not been directly related to the semiconductor industry. For the smooth entry of such fields into semiconductor-related businesses, it is necessary to achieve a marked improvement in the development efficiency of hardware and software using EDA technology that is considerably advanced compared with current technology, so that anyone can easily design semiconductor devices.

3.6 Miniaturization of Devices Other than Transistors

The miniaturization of all types of devices that are integrated on chips, including transistors, is necessary. Along with the trend of miniaturization of chips, a reduction in the sizes of peripheral components, such as passive devices and sensors, is also required.

4. Market of Microcube Chips

4.1 The Dawn of Ubiquitous Networks and the Semiconductor Industry

We are facing an era of ubiquitous networks, centered around business models based on services realized by the mutual connection of a large number of practical semiconductor products via networks. Making a profit only from semiconductor devices is becoming increasingly difficult because a low price is strongly demanded for each semiconductor device. Some innovations based on application services are required for practical semiconductor products in ubiquitous networks. In consideration of the history of technological development, technologies in their infancy and the mechanisms of technological development should be examined. For example, more than 20 years have passed since the concept of the Internet first entering public awareness in the late 1960s to its widespread use in the 1990s; now, it is used worldwide. Until it became widespread, steady technological development and trial-and-error examinations of business models were carried out. During the period of its rapid growth, only companies realizing groundbreaking innovations made huge profits from the spread of the Internet, regardless of the fact that many companies made steady progress in technological development. Currently, companies are preparing for new business models using ubiquitous networks. It is necessary to improve future industrial competitiveness by creating new services as well as developing technologies required in a society based on ubiquitous networks.

4.2 Expansion of Semiconductor Application to New Fields

The number of processors used per person is currently approximately 20–30; this will increase to 2000–3000 per person by around 2025 if the current rate of increase continues, although many people may not be conscious of the ubiquity of processors in their lives (Fig. 6) [7]. For example, for average-income households in Japan, only 3.29% of their total expenditure is on digital products (Fig. 7) [8]. However,

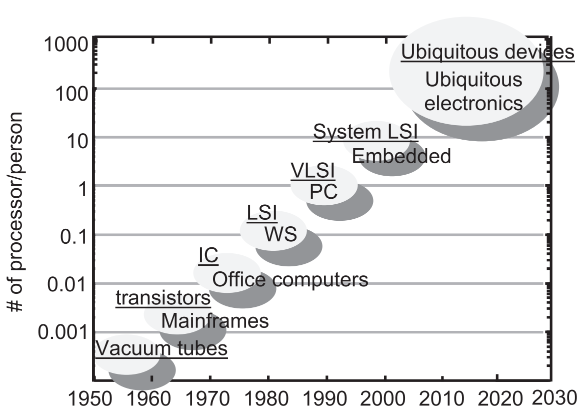

Fig. 6 Trend of the number of processors used per person [7].

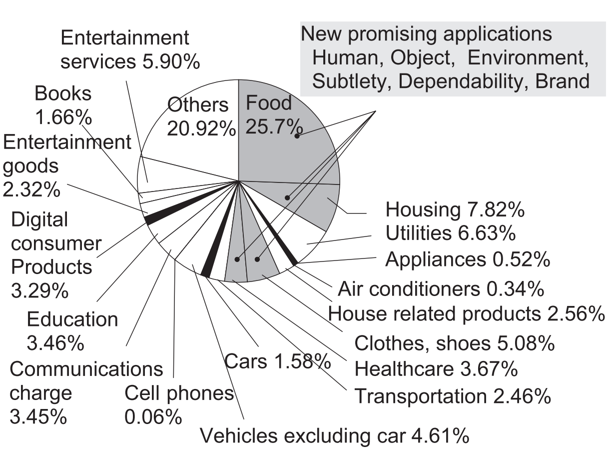

Fig. 7 Distribution of annual expenses of Japanese family unit [8].

in an era of widespread ubiquitous networks, semiconductor devices will be extensively used in food- and medical-related fields; processors will be unknowingly used by people through the purchase of foods or when receiving medical services. In other words, semiconductor devices will be applied in fields previously unrelated to the semiconductor industry.

4.3 Participation in Bottom-of-Pyramid (BOP) Market

Microcube chips are expected to have a competitive advantage in the sales of semiconductor devices to developing countries, which have more than 4 billion people, two-thirds of the world population, who have hardly benefitted from semiconductor devices. Before 2000, Japan had a high share of the market in developed countries and made profits by targeting the approximately 0.6 billion people in those countries. These days, the markets of Brazil, Russia, India, and China (BRICS) and Vietnam, Indonesia, South Africa, Turkey, and Argentina (VISTA), countries with lower incomes than the conventionally targeted developed countries, are also targeted, i.e., a total of 2 billion people are now potential users of semiconductor devices. In these markets, high-functionality and high-performance products, which sold well in developed countries, are not always successful. Also, people at the bottom of the pyramid (BOP) may be target users in the future.

It is expected that by 2025, the world population will reach 7.9 billion, owing to continuous population increases in countries mainly in Asia and Africa. Considering this figure, it is time for Japan to reconsider its strategies of manufacturing and sales. To compete successfully in various markets in the world, measures to cope with future markets (fields), including the BOP and emerging markets (areas), and the polarization of consumption patterns, i.e., high-end and low-end consumers, are required.

What are the future markets? How should we cope with emerging markets? People in the BOP are trying to start new businesses utilizing cell phones and the Internet. Although the initial investment is limited owing to their low economic power, they are operating new businesses effectively using these IT technologies with the help of microfinance from other people in the BOP. In the BOP market, products with the required functions may have to be sold at 1/100 of the price of that sold to people in developed countries. Therefore, high technological strength to generate significant innovations that can enable products to be sold at ultralow prices in the BOP market is essential.

4.4 Mass-Use Chips Applicable in Developed and BOP Countries — Lifetime-Aware Products

The lifetime of most conventional semiconductor products, such as computers, electrical products, and communication equipment, is several years or several tens of years. Semiconductor devices are consumed when new products are developed or replaced. Markets with sufficient growth potential and size to recover the costs of design and production and to make a profit are required.

In the future, the application of semiconductor devices in the environmental, medical, and food-related fields will become particularly important. Among them, semiconductor devices used in the environmental field, such as devices for disaster countermeasures, structural monitoring, and metrological sensors, must have long lifetimes comparable to those of conventional electrical products. In contrast, the semiconductor devices used in medical and food-related fields are likely to be adapted for various specific applications, such as daily activities related to the consumption and growth of plants and livestock as well as the detection and treatment of diseases. Furthermore, it is considered that they will fulfill their roles with shorter lifetimes than those of conventional electrical products. The ID tag is a typical example. The control of food using ID tags has already started to be used to trace the production and distribution processes. The lifetime of such ID tags is assumed to be from several months to several years to include the period of production and distribution. For ID tags that are swallowed or embedded in the human body for medical examination, the lifetime is assumed to be from several hours to several months. This means that a market requiring a large number of semiconductor devices will be generated because semiconductor devices will be applied in fields where the product objectives are accomplished within a short period of time, such as daily activities related to the consumption, growth of plants and livestock, and the detection and treatment of diseases. This relationship is expressed as

$$\Sigma_{chips} = \left(\frac{T_{fab}}{T_{product}}\right) \cdot N_{chips} \cdot N_{products} \quad (1)$$

where Σ_{chips} represents the total number of chips used per person, and T_{fab}, $T_{product}$, N_{chips} and $N_{products}$ represent the lifetime of a manufacturing facility for semiconductor devices, the lifetime of a semiconductor product, the number of chips used in the product, and the number of the products distributed at some point, respectively. Because many of the conventional semiconductor products have long lifetimes, returns on investment in manufacturing facility have been obtained by increasing the number of chips of one type by mass production (i.e., increasing the $N_{products}$) and thereby increasing the total number of chips produced during the lifetime of one manufacturing facility. In contrast, for semiconductor devices used in applications with short lifetimes, returns on investment in manufacturing facility can be obtained, even for low-price semiconductor devices, by increasing the number of chips used per person. Let's take an example in the case of the manufacturing facility with the lifetime of ten years. When a product is developed in which one user consumes one chip per a couple of days, no fewer than 1,000 chips are used during the lifetime of the manufacturing facility. It means that we open up a new product equivalent to 1,000 legacy products with the lifetime of ten years (Fig. 8).

Viewpoints on semiconductor design and returns on in-

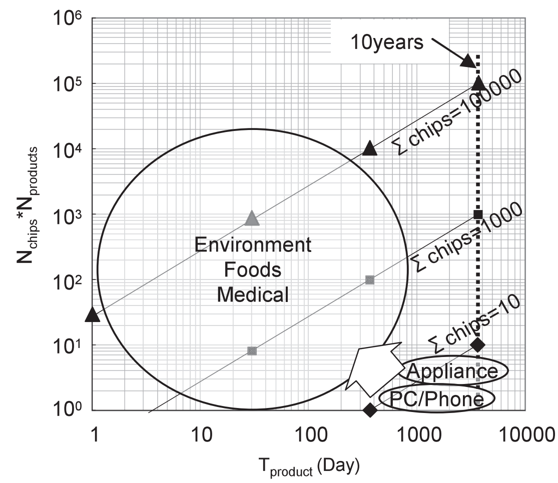

Fig. 8 Number of semiconductors used per person as a function of application lifetime. Current typical semiconductor application is shown in the graph.

vestment in manufacturing facilities with an awareness of the lifetime of devices will be important. It is necessary to optimize the design quality in accordance with the lifetime of each product. From the viewpoint of reusing resources, it will be imperative to establish a cycle, including the collection and reuse of mass-consumed semiconductor products with short lifetimes, without causing adverse effects on the global environment.

5. Agile Integration and Inch-Fab

In Sect. 4, we argued that environmental, medical, and food-related fields may be emerging markets for semiconductor devices. With increasing demand for the adaption of devices to specific applications, the number of types of semiconductor device will markedly increase, and methods of providing large numbers and a wide variety of semiconductor devices will be required. It is well known that the cost of investing in the equipment and facilities for leading-edge microfabrication has become huge. There are only a handful of companies worldwide that can invest several to several tens billion dollars in manufacturing facilities of semiconductor devices with high mass-production capability. In this section, we propose two concepts, agile integration and inch-fab.

5.1 Agile Integration [9]

In the business model based on current leading-edge microfabrication technology, applications in which huge numbers of products are supplied, for example, a million pieces per month, are assumed necessary to recover the large investment in their development and manufacturing facilities. However, in practice, fostering applications in which huge numbers of semiconductor devices are consumed without fail is a difficult task. Therefore, a methodology is required for actively promoting the use of semiconductor devices in applications where they were not used previously and for

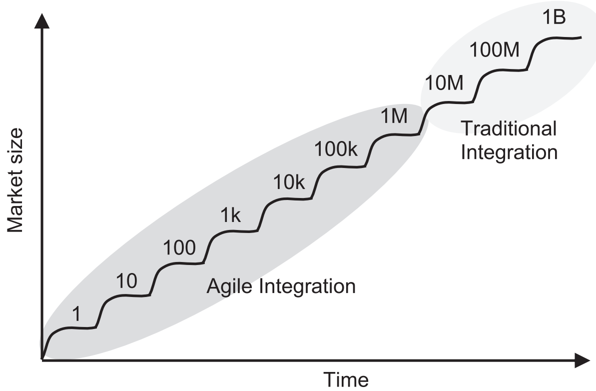

Fig. 9 Concept of market incubation utilizing agile integration [9].

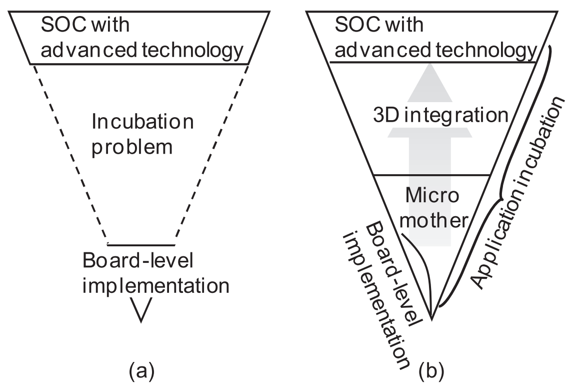

Fig. 10 Evolution of semiconductor development method by (a) traditional integration and (b) agile integration [9].

providing the appropriate type and number of semiconductor devices at a reasonable production cost to match the expansion of demand while fostering new applications. In this methodology, applications are gradually nurtured with only a small number of devices being initially required (Fig. 9). Here, the key will be the realization of an integration technology for semiconductor devices which has a low development cost and a short development period, can respond flexibly to changes in the number of devices required, and can accommodate various techniques. Ideally, it is desirable to make a profit even if the number of applications required is only one. Here, such an integration technology that can ensure a profit for the volume of production corresponding to the demand at the time is named agile integration technology. For agile integration, the method of supplying products is adjusted in a stepwise manner in accordance with the demand for the application and the possible development cost. In the prototype production stage when there is low demand, semiconductor devices are developed using printed circuit boards, as in the conventional method. In the next stage of commercialization of the devices, several steps are carried out instead of directly developing semiconductor devices by a leading-edge microfabrication method from the start.

Figure 10(a) shows the method of developing semiconductor devices by conventional integration technology.

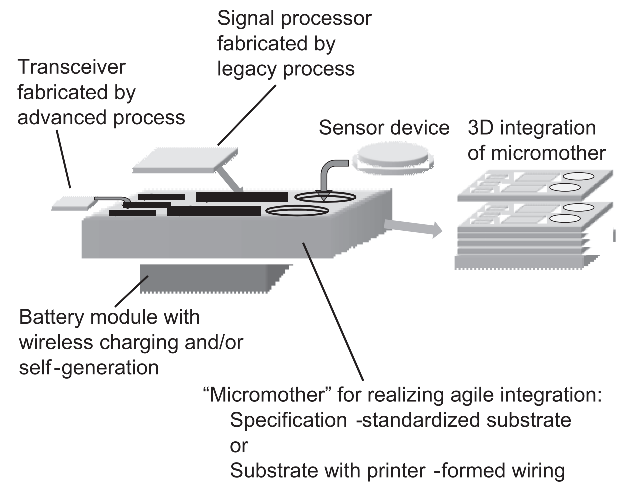

Fig. 11 Example of micromother board [9].

As shown in the figure, the microfabrication of SoCs using advanced technology directly follows the preparation of printed circuit boards. In contrast, in agile integration, several intermediate steps are included: the implementation of an ultrasmall general-purpose board (called a micro-motherboard (Fig. 11)), three-dimensional semiconductor integration, and system LSI by microfabrication using advanced technology, as shown in Fig. 10(b). A micromotherboard is a general-purpose ultrasmall motherboard, on which the components required for each user application are mounted. There are several types of micro-motherboard; users can select the appropriate type depending on the application and the components implemented.

By defining a new platform assuming the expansion of the range of applications rather than specialization in a specific application such as conventional motherboards in PCs, the range of choices for the user can be expanded. To achieve the widespread adoption of the micro-motherboard, low-cost fabrication and the standardization of interfaces will be required. A technique for wiring by printing is under development and further progress in its research and development is hoped for. The three-dimensional implementation of semiconductor devices is a potential key agile integration technology. We hope that the low-cost fabrication of system LSIs by integrating different types of devices as well as devices made by different-generation processes, in addition to increased integration by three-dimensional integration, will be achieved. Although conventional integration technologies such as SIP and package on package (PoP) are available, such technologies alone are insufficient to realize the concept of agile integration, because end users, who are most familiar with applications, cannot develop the devices freely. Field-programmable gate arrays (FPGAs) and reconfigurable processors are also device technologies; however, these devices alone cannot solve the above problems. For example, these devices are incompatible with the radio frequency (RF), analog signals, power sources, and interfaces required for the system because overheads, in terms of power consumption, operating speed, and area, are greater than those of standard cells. For agile integration, the key is to realize a technology that can integrate devices with different functions, such as electronic circuits, sensors, and actuators, without the need for redesigning. The interconnect technology between different devices is an example required for agile integration. Concretely, the development of new optical and wireless connection technologies and micro-electro-mechanical system (MEMS) technology to implement these technologies is expected to be targeted in future research. The significance of agile integration is that the end users or suppliers of end products can select a development method with an appropriate cost in accordance with the demand for the application as a result of the development of a series of integration technologies used in micro-motherboard, three-dimensional implementation, and microfabrication with advanced technologies. A technological system will be developed that can respond to various electronic applications using agile integration as the core, and the fostering of potential applications will be supported that will require such large quantities of semiconductor devices that the volume efficiency of mass production can be realized owing to the miniaturization of semiconductors.

5.2 Inch-Fab

The second concept in dealing with the wide variety of mass-produced semiconductor devices is to develop manufacturing facilities for leading-edge processes, at a cost that small-size companies can afford. Assuming that a 45-cm-diameter wafer is used in a future when the M1 half-pitch is 8 nm, seven million LSI cubes of side 150 μm can be supplied from one wafer. In the case of the microcube chips discussed in Sect. 2, six million LSI cubes of side 10 μm or thirty thousand LSI cubes of side 150 μm can be produced on a one-inch-square wafer. Large-diameter wafers will no longer be needed if the chip size is so small that a one-inch-square wafer can produce several tens of thousands to several million LSIs. It is desirable to realize manufacturing facilities of semiconductor devices using small-size wafers at an extremely low cost. Similar concept of miniaturization of manufacturing for reducing fabrication cost is also proposed by Hara et al., where it is called minimal fab [10]. For example, assuming that a manufacturing facility that costs approximately one billion yen for fabricating microcube chips from a one-inch-square wafer is realized and that ten thousand companies install such a facility, a total production capacity equivalent to that realized by several large manufacturers will be achieved. This means that a semiconductor production infrastructure for a wide variety of semiconductor devices can be realized worldwide.

In the business of producing a wide variety of semiconductor devices used in environmental, medical, and food-related fields, product differentiation in the market is achieved by precisely responding to market needs. It will become necessary that each company has a manufacturing facility for semiconductor devices as a measure for developing and improving their products at the final stage before they become end products. Having their own fabrication capability is beneficial in that it enables small-size companies to achieve their technological potential.

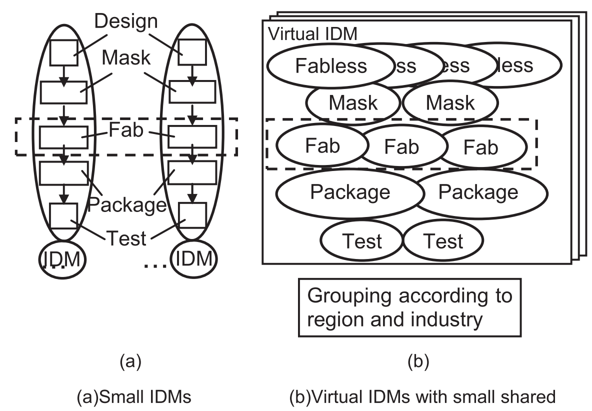

Fig. 12 Many-fabrication type of semiconductor manufacturing system using inch fab in the cases of (a) small IDMs and (b) virtual IDMs with shared small fabs.

In an era of a wide variety of semiconductor devices, a business style in which design and fabrication are conducted at each small-size company, each of which targets its own specialist market, is predicted to arise. Each small-size company should take a vertical integration approach that is suitable for product development and should have a small-size foundry (fab) appropriate for the characteristics of the market, thus forming a new production system called small integrated device manufacturers (IDMs) (Fig. 12(a)). It is predicted that a more advanced industrial structure will emerge as small IDMs increase, i.e., virtual IDMs with shared small fabs with the aim of achieving efficient operation (Fig. 12(b)).

Improvements in the performance and functions of semiconductor devices that are designed and fabricated by conventional production systems, such as those used in computer and communication devices, consumer electronics, automobiles, and industrial equipment, are expected to be promoted by increasing the density of integration, as in the conventional method, although this has not been discussed in this paper. The above-mentioned production systems, i.e., multi-fab vertical integration and multi-fab vertical disintegration, which target a wide variety of semiconductor devices used in various fields such as environmental, medical, and food-related fields, can coexist with conventional production systems that are suitable for large-scale mass production because the range of companies involved in designing and manufacturing and the range of applications are different.

6. Conclusions

Recently, the limit of the miniaturization of semiconductor devices has been extensively discussed and it is hoped that new applications of semiconductor devices will be developed in the environmental, medical, and food-related fields.

In this paper, we proposed an approach based on microcube chips, agile integration, and inch-fab to provide a wide variety of low-cost semiconductor devices in large quantities. These approaches are not only related to the development of new technology but are also expected to bring about a structural change in the entire semiconductor industry through the participation of many small-size companies in the design and manufacturing of semiconductor devices. Our mission is to guide the evolution of semiconductor technology in an appropriate direction by considering the trends and changes throughout society in addition to the extension of current technologies.

Acknowledgments

This paper is based on the discussion at two workshops held by the Electronics Society Technical Committee on Integrated Circuits and Devices of the Institute of Electronics, Information and Communication Engineers at Ishigaki Island in March 2008 [6] and at Chichijima, one of the Ogasawara Islands, in March 2009 [9]. We are deeply grateful to Professor Hiroto Yasuura of Kyushu University, Professor Takayasu Sakurai of The University of Tokyo, and other researchers who participated in the discussion for their helpful comments.

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