games, however, Samsung is migrating towards a VI business structure. For MIA products, Samsung has the capability to produce all four-system segments, which is one of the reasons why Samsung has achieved business success in the last two years despite the economic depression and the IC industry downturn. Samsung is smartly mixing "closed and owned" technologies with technologies that are "the best imported from the outside." Therefore, the CVVI model is also applicable to Samsung.

Facing the growing SC era, ES manufacturers are actively working to secure sources for custom-designed, application-driven SCs. One model that can be used by ES manufacturers to achieve this target, is to form clustered programs with several IC design companies who can provide multiple functionality dies that will be merged in an MDSC. The system house acts as the leader and sometimes controls the software in using the SC. Another model is to directly engage a new breed of fabless companies called design-foundry companies, which provide both IP and design services and sometimes a turnkey supply of SCs. This type of design-foundry is valuable in the CVVI supply chain since it complements what the system house lacks in IC knowledge but wants to own the IP rights of the final products.

The success of SC will significantly increase the IC content in ES, and MDSC creates additional value over discrete chips, such as cost down of the motherboard and reduction of EMI noises. SC's merits should help to increase IC profit margins, thus pulling the industry out of the micro-profit age in which business was only driven by the manufacture of commodity ICs. Moreover, because MIAs are coming in to direct contact with end users, the SC industry will broaden the restrictive IC industry focus from one that has always prioritized B-to-B (business) over B-to-C (consumer), to a view that focuses on B-to-C first and B-to-B second. As a result, localization to meet local regional needs also stands out in its importance within today's globalization trend. Therefore, SC designers must understand the cultural differences between various end users in different regions to be successful. IC designers in the PC age were rarely faced with such challenges.

DESIGN AND TECHNOLOGY CHALLENGES FACING CVVI OF SYSTEM CHIPS

In parallel with business-structure reform to CVVI, both design and technology demand a CVVI also to achieve MDSC alone. The key to success is how to connect IC knowledge with ES knowledge and how to overcome several major challenges, such as: (1) reliable known-good-die (KGD) technologies with early design-for-reliability (DFR) and effective production-cost controls; (2) multilayer interconnected substrates, even including passive components sandwiched inside the layers; (3) micro-assembly technologies covering thinning wafers, stacking multiple dies, and encapsulating chips, or other exhaustive PoP or PiP technologies; (4) signal integrity on inter-die, intra-die, and from multiple dies on the substrate to the outside world, including interactions between MDSC and system field environments; (5) supply-voltage management on multiple-family dies, power and thermal control of the entire SC; (6) simulations on die-to-die, die-to-package and package-to-field to reduce the cost of MDSC experiments; (7) testing and verification of multiple circuit family behaviors; (8) reparability, error correction, programmability, etc.; and (9) all development challenges that must be overcome to migrate from GSI to terascale integration (TSI) in each specialty segment. The winning cluster in the SC era will be determined by how well and how thoroughly these companies can closely implement CVVI in their technologies.

The Taiwanese IC industry has grown in a horizontally segmented way and provides an illustration of the progress to CVVI among various companies with global participation, which allows the best glimpse into worldwide CVVI efforts [1]. As an example of the CVVI of design and fabrication segments, TSMC has been co-developing advanced-technology design-automation flow environments with electronic design automation (EDA) vendor partners. Targeted at 90-nanometer and beyond, TSMC's Reference Flow defines deep-submicron and design-for-manufacturability (DFM) issues and provides solutions before designers start to adopt advanced technology nodes. By demonstrating how to optimize power and speed tradeoffs with an ARM processor, Reference Flow 4.0 provides simulations on how leakage and power has been minimized while keeping the same clock speed by using various multi-threshold device solutions. An advantage of the aforementioned partnerships is to facilitate the accumulation of learning, and to secure a faster and smoother technology-scaling path to meet increasing design-complexity and decreasing time-to-volume demands.

As for manufacturing segments including wafer fabrication, packaging and testing, it is informative to examine the technical interactions between partners from various segments, aimed at achieving faster MDSC integration success. Advanced Semiconductor Engineering (ASE) and Amkor have co-developed various SiP technologies with its customers: stacked-die or stacked-package CSP, as well as modules supporting multiple dies.

Finally, several Taiwanese system companies have launched CVVI strategies; for example, Quanta Computer (a notebook ODM Company), BenQ (a LCD monitor company that has formed a closely integrated joint-venture called AU Optronics who supplies LCD panels) and Inventec (who was the first in Asia to combine a cellular phone and PDA as one handset, and differentiate the product by including a Chinese dictionary) have adopted various types of application-driven memory and system chips, as configured jointly with IC suppliers. These efforts have clearly shaped the CVVI trend of integration across clusters between the ES and IC industries.

CONCLUSION

Both ES and IC industries are undergoing major paradigm shifts. The emergence of HI is transforming both, especially the IC industry by four aspects: (1) synergistic growth of technologies; (2) different business structures; (3) growing emphasis on knowledge economy; and (4) mix-and-match in human culture and IC usages.

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About the Author

Well-known as chief executive, innovator, researcher and entrepreneur, Dr. Lu is a prominent figure in worldwide IC design and semiconductor industry. He is the chairman, CEO, and founder of Etron Technology, Inc., and the co-founder and executive of several other successful companies. He received his Ph.D. in electrical engineering from Stanford University. He was honored in 1999 with the membership of National Academy of Engineering of the United States. He was elected to be an IEEE fellow in 1991 and awarded the IEEE 1998 Solid State Circuits Field Award "for pioneering contributions to high speed dynamic memory design and cell technology."

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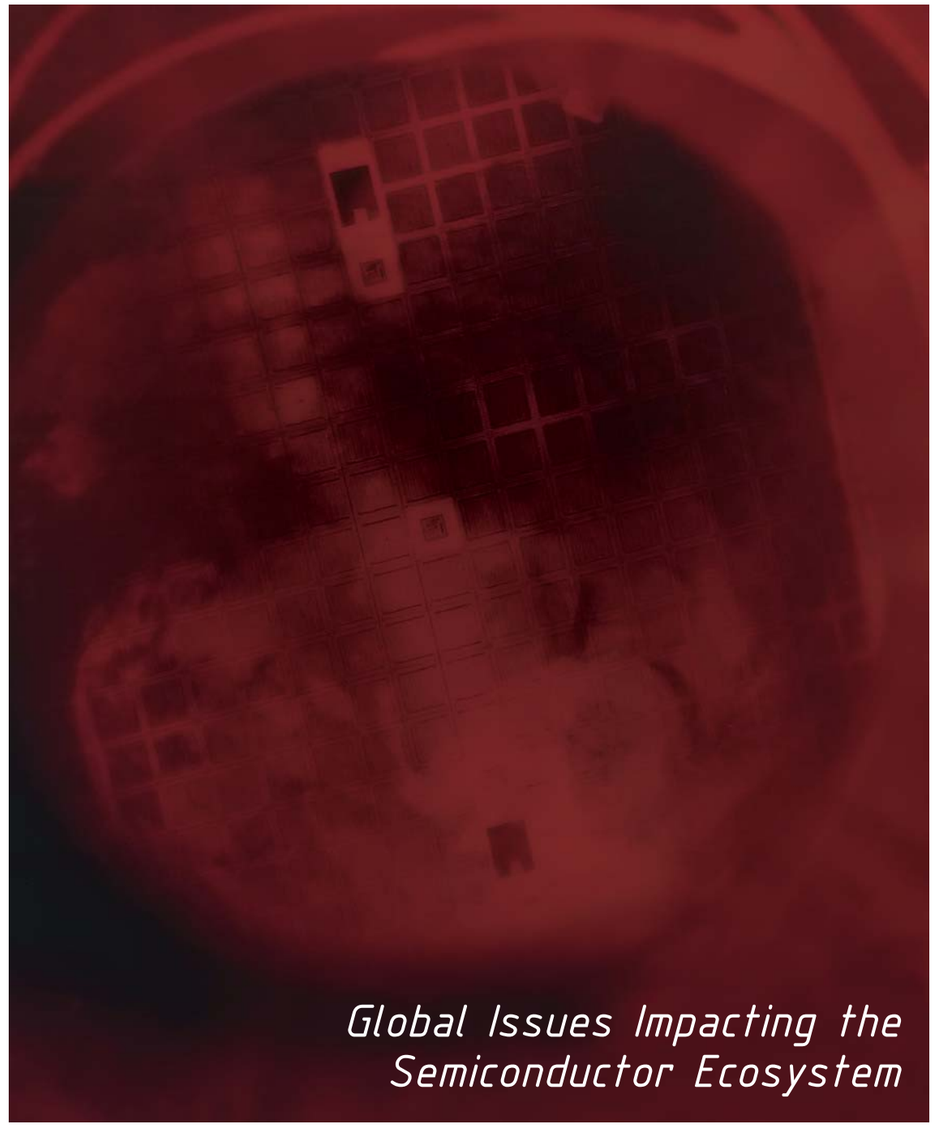


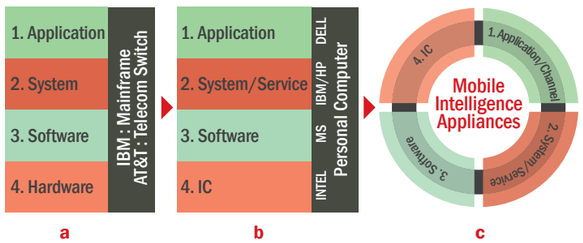
EMERGING ERA OF HETEROGENEOUS INTEGRATION FOR SYSTEM CHIPS: TECHNOLOGY AND BUSINESS SOLUTIONS

NICKY C.C. LU, CHAIRMAN, CEO, PRESIDENT AND FOUNDER, ETRON TECHNOLOGY, INC.

Over the last three decades, the IC industry has developed from small-scale integration (SSI) to today's gigascale integration (GSI, with $\geq 10^9$ transistors on a chip) [2]. In adjunction to Moore's Law [3], Meindl has derived a chip performance index (CPI) for digital switches to measure how technology scaling and integration can generate signal-transfer robustness per unit of energy from 10^{13} devices/J in SSI to 10^{24} devices/J in GSI. Therefore, electronic systems (ES) could be produced at a lower cost, in smaller form factors and with more complicated functionality by using more and more IC contents. This drove the migration of computer systems from bulky mainframes to compact PCs.

The business structure of the mainframe computer industry in the 1970s was based on the vertical integration (VI) of a closed system within one company; that is, most of the knowledge used to build an ES, covering specialized skills in the application, system architecture, software and hardware

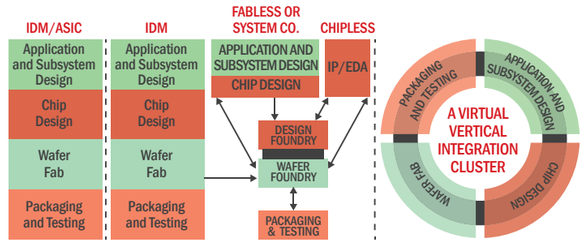
Figure 1. Business Structure Evolution in Electronic Systems



Business structure evolution in electronic systems: (a) vertical integration within one company, (b) horizontal segmentation for open system, and (c) virtual vertical integration of multiple companiesin clustered integrated circles.

segments (Figure 1a), was developed and owned by individual companies with internally defined standards; for example, IBM's mainframe computers. The corresponding VI business structure in the IC industry included an integration of application and subsystem design, chip design, wafer fabrication, and packaging and testing, within a single company (an integrated device manufacturer (IDM) model) (Figure 2a). The pervasive use of ICs has since facilitated the creation of open systems, such as PCs, which allow the insertion of IC components and software,

Figure 2. IC Business Structure Changes



IC business structure changes: (a) '80s: IDM/ASIC, (b) '90s: emerged fabless, system house, design foundry, waferfoundry, and backend service (F. Tseng VLSI '99; N. Lu), and (c) emerging clustered virtual vertical integration ofmultiple companies; the Chip-Design segment includes fabless, chipless, and design foundry (N. Lu).

even after the ES framework has been built. Open systems define clear interfaces across different knowledge segments, forming standards in the public domain and thus creating business opportunities for companies with unique core competencies, such as Microsoft in software, IBM and HP in systems and service, and Dell in channel segments, respectively (Figure 1b). The impact on the IC industry was to create more business opportunities to sell standard IC components in massive volume, allowing companies such as Intel to flourish. Therefore, in the mid-1980s through the 1990s, a new horizontal segmentation of the original IDM business structure in the IC industry created many new companies whose products focused on specialty knowledge segments, which include value-added distributors with special application skills, innovative-design fabless companies, independent photomask shops, pure-play wafer foundries, and packaging and testing vendors (Figure 2b).

SYSTEM CHIP TRENDS

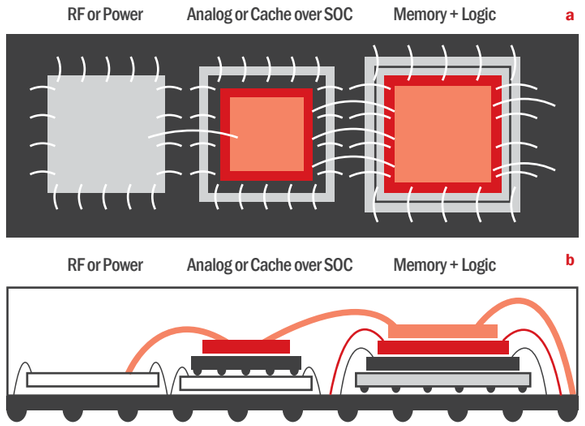
This work describes both significant changes and trends in the technology development and business models of the IC industry as it enters the 21st century. As both circuit techniques and process technologies, specialized for digital, analog, memory or radio frequency (RF) functions, advanced rapidly through the late 1990s, ICs with various functions were developed to further reduce the cost and size of ES, as well as to diversify their applications. The longstanding demand for a portable networking ES has driven the emergence of mobile-intelligence appliances (MIA), such as personal digital assistants (PDAs), portable audio/video devices, Bluetooth/GPS/other auto and home connectivity devices, digital cameras and cellular phones, etc. These MIAs were built as vertically integrated closed systems with an additional constraint that they be of a limited size (that is, with volume measured in cm3), but the system complexity is dramatically increasing along with the end user's desire for complete 4C (computer, communication, consumer and content) functionality through a single MIA. The pressure to drive down both cost and size while increasing the functionality embedded in MIAs, requires most subsystem functions to be implemented in ICs. These ICs need to merge digital, analog, memory, RF and power-related IC five families, as much as possible into a smaller packaging form factor. An era of system chips (SC) is thus emerging! It is believed that once the technology has matured, system chips will also be used for general applications. One trend being followed is to design a system-on-a-chip (SOC), which includes all or part of five families on a single die. Another alternative, known as system-in-package (SiP), is to assemble different IC family dies horizontally on the same substrate within a package. Meanwhile, a new technology permitting the stacking of multiple dies in a small chip-scale package (MCSP) is emerging, which allows the third-dimension to be used to achieve more function or density in a given footprint area. One example of a stacked CSP is a memory combo that can include six layers of memory dies in a ball grid-array (BGA) package. Besides conventional wire bonding, flip-chip techniques using solder bumps and interposers are being adopted increasingly.

A key challenge to the prosperity of the future IC industry is how to effectively assemble multiple functions into a limited form factor with justifiable cost controls while being able to optimize performance of individual IC families. However, a study of central processing units (CPUs) of digital, analog, memory and RF circuits [1] revealed that they exhibit quite different behaviors as technology is scaled. Combining different families on a die with a combined technology base may not permit an optimized solution. With the rapid development of SOC, SiP, product-in-package (PiP), package-on-package (PoP) and stacked CSP technologies, it is envisioned that the most powerful system chip in the coming years should incorporate an integrated structure using multiple dies with heterogeneous technologies and voltage operations, which fully utilize the multi-dimensional space within a CSP package. An example would include separately connected building blocks, including a stack of memory dies, an analog die overlaid on either a SOC or digital die, and an independent RF die located on top of a multi-layer interconnected substrate inside a package, each with different control and I/O paths (Figure 3). In addition, control software would be coded into the nonvolatile memory (NVM) in the memory stack. Making an appearance on the IC technology horizon is a new technology known as multidimensional die-integration system chips (MDSCs)! The architecture of MDSCs can be conceptualized as a metropolitan-city-like die society cluster, structured similarly to modern high-rise buildings such as New York or Taipei!

EMERGING BUSINESS STRUCTURES FOR SYSTEM-CHIP PRODUCERS

IC companies always face challenges from the risks induced by technology obsolescence and cyclic business shakeouts. A successful company must have a superior technology or a correct business model that fits with industry trends. The upcoming SC era will be characterized by more stringent competition based on advanced

Figure 3. A Schematic Illustration of an MDSC Structure



A schematic illustration of an MDSC (Multi-dimensional Die-integration System Chip) structure:(a) top view and (b) side view.

technologies with larger investments and shorter product cycles, and driven by application needs and multiple-heterogeneous-function integration, such as a SC Olympics.

Although implementing an MIA has brought back VI, the required business model is different from that of the mainframe period, due to more significant interactive modes among the four ES segments - channel/application, system architecture, software and hardware/ICs. The new VI system should not be viewed as a closed system, but should be developed as an integrated circle with direct interactions between any two segments, even between the application layer at the top and the IC layer at the bottom, thereby allowing faster SC product introduction (Figure 1c). Due to horizontal segmentation in the 1990s, however, not many companies today are capable of developing and owning technologies in all four segments. Instead, each segment has several successful specialty companies. A clustered integration structure allows various companies with complementary skills from different specialty segments to either form alliances or partnerships to realize effective vertical integration of knowledge. To shorten the IC design-win cycle, companies in a cluster need to engage each other early on to co-define specifications and to begin co-development sooner. Organizing a cluster of companies together to achieve effective vertical integration is termed clustered virtual-vertical integration (CVVI) (Figure 2c).

Several business models [1] have been developed by major companies in the IC industry, each of who possesses strong clustering forces. IBM branched out a business division that provides contractmanufacturing services using standard cells, licenses intellectual property (IP) and technologies to selected partner companies and co-develops advanced technologies in multiple alliances. In mid-2002, IBM further formed a technology and engineering service division to provide skills in various specialty segments to serve contract customers who have valuable application and business channels. This new business model allows outsiders to use IBM resources to co-develop products so that IBM and its partners can win markets together. IBM, known as a vertically integrated company since the early days of the IC industry, has thus made major strides to be virtually vertically integrated.

Samsung Electronics started as an electronic system house and developed its semiconductor division as an IDM. With recent successes in ICs, displays, cellular phones, home appliances and