PREFACE

More-than-Moore Devices and Integration

Editors

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1.1. Introduction

The term “More than Moore” appeared and was readily adopted by the semiconductor community since the early 2000s, when, in addition to the decades-long focused effort to scale down the footprint of logic and memory devices according to the well-known Moore’s Law, an orthogonal trend in electronics miniaturisation had started to gain momentum.

In contrast to the aggressive pursuit of increasingly more powerful computing led by Moore’s Law (More Moore), the More than Moore trend focuses on the combination of an increasing number of functionalities within a miniaturised system [1]. One of the main application drives for More than Moore had clearly been the pursuit of smart portable systems, with smart phones being one of the consumer applications spearheading this new trend. While smart portable devices in the late ‘90’s and early 2000’s were still at a very early stage of development, mainly focused on mobile computing functionalities such as the palm-sized PCs and using rudimentary connectivity and awkward user interfaces, the launch of the first Apple iPhone model – among the first wave of truly multifunctional portable smart phones, precursor to today’s ubiquitous technologies – took place not too long afterwards, in 2007. The opportunity for such an extraordinary leap of smart systems with increasing complexity, number of functionalities and autonomy, all within an increasingly small form factor (More than Moore trend), has originated out of the simultaneous convergence of several key technologies, including the evolution of:

1) mobile communications, particularly digital cellular networks, also thanks to the development of ICs for wireless communications, including power MOSFET and RF ICs
2) integrated power sources and energy harvesting systems, key to ensuring autonomy
3) low-power ICs, specifically developed for mobile applications
4) user interfaces such as advanced touchscreen technologies
5) the availability of an increasing number of miniaturised functionalities, starting from the historically more advanced ones, such as digital CMOS cameras, MEMS technologies for sensors and actuators (loudspeakers, microphones, gyroscopes, etc) and optoelectronics (LEDs, etc)

More than Moore technologies have been taken into account in recent years in several International Roadmaps, in particular the NanoElectronics Roadmap for Europe (NEREID, [2]) and the IEEE International Roadmap for Devices and Systems (IRDS, [3]). While silicon technologies still play an absolutely central role, with many of the complementary functionalities to logic and memory still often using silicon as key material (MEMS, digital cameras, photonics, power, etc), the emphasis of More than Moore is not so much on the miniaturisation of the single components as in the More Moore digital technologies, but rather on the miniaturisation and the improvement of the multifunctional system performance as a whole.

In addition, where alternative semiconductors to silicon are undoubtedly performing better than silicon, such as in optoelectronics, power and flexible electronics, new semiconductor technologies – from III-V to organic - are also being introduced and brought up fast to fabrication capabilities at scale either in combination with, or complementary to silicon technologies [4-7]. This also means that we are seeing an increasingly more complex array of new semiconductors being brought onto a silicon fabrication platform, or different substrates to silicon being combined into the same system through advanced packaging.

An additional application drive for More than Moore technologies has undoubtedly been the rise of the Internet of Things, or Internet of Everything [8]. IoT usually refers to interconnected “smart” sensing nodes which could be serving any aspect from traffic to air and water quality, to healthcare, energy and manufacturing automation, as well as to a plethora of consumer applications.

Although the concept of IoT had already been discussed as early as the 90's [9], it is not until approximately a decade later that this concept developed practically over a large scale, supported by the progress in the 1-5 technologies above, but also importantly, supported by the advances in AI and Big Data analytics [10].

The schematic in Fig.1 depicts a typical IoT node and its functionalities. The note would be generally built around a generic sensing unit, which represents a very broad range of potential sensing technologies (MEMS, optical, etc) and specific applications. It would typically include an analog-to-digital converter (ADC) and potentially some embedded logic and memory, performing more or less extensive pre-processing operations on the acquired data. The processed data are then transmitted wirelessly to another node through the RF unit, which will include an appropriate antenna. Finally, another key component of an IoT node, is the power unit and integrated power sources.

Depending on the projected consumption of the IoT node and the desired level of autonomy, the hardware needs for power can vary extensively, particularly in terms of power sources. Power considerations are in fact a key aspect for More-than-Moore technologies, and an important theme of this book discussed in Chapters 1 and 2. Additional specific units may be required beyond what depicted in Fig.1, depending on the sensing purpose of the specific IoT node.

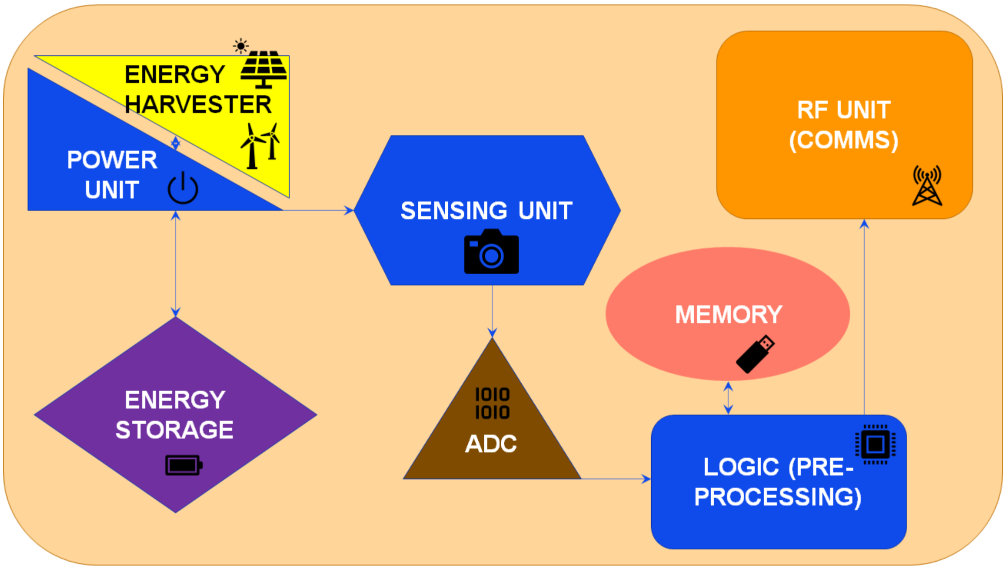

Fig.1 Simplified diagram representing the typical units and components required in a smart node of the Internet of Things.

IoT has generated a strong push for a further level of required miniaturisation and autonomy of multifunctional systems. Extreme miniaturisation allows for cutting-edge applications for example in healthcare - see, for example, ingestible sensors able to monitor the health of the gut with wireless transmission capabilities [11], only one of the endless possibilities offered by miniaturised, autonomous systems. Smart sensor nodes have also strongly driven the necessity for uninterrupted autonomous power, which in turn has also led to the development of efficient in-situ miniature storage such as microbatteries [12] and miniaturised supercapacitors [13], but also to ambient energy harvesting systems, as explained by Yeatman in Chapter 1. The importance of the further development and convergence of power harvesting, storage and management technologies for Moore-than-Moore systems cannot be overstated. The extraordinary recent advances made in power electronics using wide band-gap materials are therefore extremely welcome news, as explained by Zekentes et al. in Chapter 2.

Additional key enablers of the further progress of More than Moore are heterogeneous integration and advanced packaging. Over the last decades, as the complexity of integrating different semiconductors, functionalities and technology nodes within the same chip has reached higher complexity, the system-on-chip (SoC [14], Fig.2) trend has been slowing down as heterogeneous integration through advanced packaging has been expanding and greatly diversifying to cater for the numerous different technology combinations (see also the IEEE Heterogeneous Integration Roadmap, HIR [15]). While it would be difficult to provide an exhausting description of the plethora of relevant advanced packaging technologies available, it is useful to consider those enabled by the through-silicon-vias (TSV) technology, in particular the system-in-package (SiP) and system-on-package (SoP). They both aim at greatly reducing the footprint of a heterogeneous system by making use of silicon as either as a mostly passive interposer, connecting chips or “tiles” with different functionalities with much reduced pitch as compared to a PCB board (2.5D integration, [14]), or using active silicon chips to connect chips stacked in the vertical direction, also called 3D integration [14], respectively. These approaches are depicted in Fig.2. The main aim would be to contain the whole system in a single package hence dramatically reducing the system footprint, although this may not always be possible because of specific packaging requirements for example for sensing chips, which may need to have access to the ambient to perform their functions [16], or other restrictions.

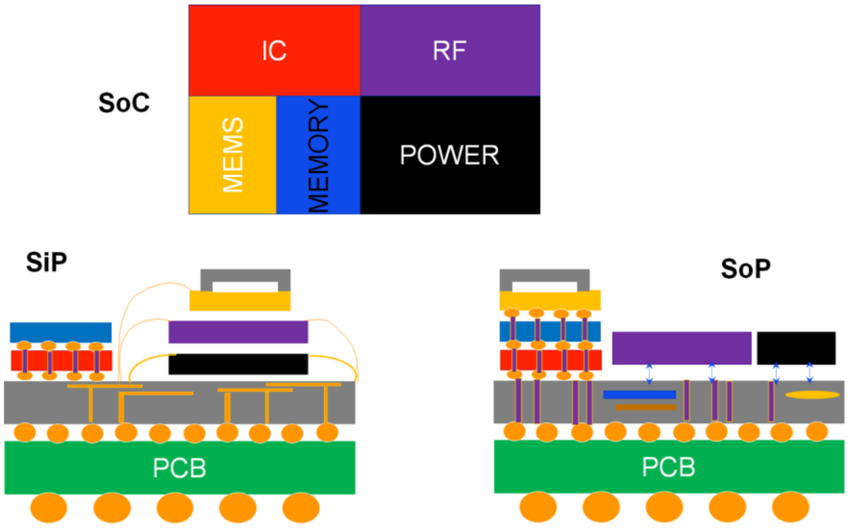

Fig.2 Schematic depicting different system integration strategies, such as system-on-chip (SoC), and advanced packaging approaches such as System-in-Package (SiP) and System-in-Package (SoP).

Further, there are several other trends in advanced packaging that are expected to deliver major contributions for More-than-Moore technologies. One is the “chiplets” or “dielets” route, which allows to combine two chips with an extreme pitch and is also currently providing a boost to logic chips [17]. Another important example, which represents a departure from a fully-rigid silicon-based package, is the flexible hybrid electronics [18]. This approach is going to be particularly favourable when considering system integration for wearables, allowing for the most advanced logic to be combined in the same system with flexible technologies based on organic and or printed electronics, including 3D-printed components such as antennas and filters [19]. The rise of flexible electronics and the advanced combination of rigid and flexible are key aspects of More-than-Moore for smart sensing, as explained by Iniguez in Chapter 3.

The rapid evolution and versatility of advanced packaging enables electronics, and particularly More-than-Moore integration, to keep bringing more and more complementary technologies and functionalities, as they become available, under a single package. In particular, the advancement of miniaturised photonics is primed to advance particular areas of computing, including quantum, as well as interconnects and sensing [20, 21]. The advent of metamaterials and metasurfaces [22] has also opened the door to a long awaited, dramatic miniaturisation of optical components by using semiconductor materials and processing, which could lead to unprecedented functionalities that include the vastly underexploited THz gap in electromagnetic radiation, as explained by Atakaramians et al. in Chapter 4.

Undoubtedly, heterogeneous integration has grown increasingly complex in recent times, opening new fabrication and reliability frontiers which still need to be completely settled and addressed.
In particular, the appearance of silicon effectively as a packaging material with the TSV technology, has created divergent views of ownership and handshake between silicon fabs and outsourced semiconductor assembly and test (OSAT) companies, which have been debated for almost a decade. This, together with the additional reliability challenges caused by the combination of the vastly different technologies - very different materials, with mismatched properties like CTE, elastic modulus, lattice constants and different thermal stabilities, and not as extensively known as silicon, different technology nodes, different packaging needs - serving the broad range of required functionalities, has made More-than-Moore integration an area potentially as challenging as that of Moore’s scaling.
Reliability is hence a key issue in More-than-Moore integration [23]. This book puts specific emphasis on mechanical reliability, more specifically fracture mechanisms, failure modes and their inspection and mitigation strategies (Chapter 5 by Zschech and Elizalde). Mechanical reliability is one very challenging aspect of such integrated systems, in addition to electrical reliability as well as thermal reliability, which still strongly limits the deployment of 3D integration to this date, due to the lack of an efficient heat removal technology [24, 25].

Finally, in this book we wanted to provide some tangible examples where More-than-Moore technologies are going to play an increasingly important role in enabling advanced integrated capabilities able to take full advantage of the sustained advances in artificial intelligence (AI). Chapter 6 by Delic and Afshar explains how advanced 3D packaging of advanced photonics, optoelectronics and CMOS-based neuromorphic computing can enable a portable navigation system based on event - driven imaging (LiDAR). The future development of truly neuromorphic hardware is expected to further enable autonomous miniaturised systems for low-latency, highly accurate event-driven AI operations, achieving powerful intelligent systems with minimal energy consumption.
Chapter 7 by Do, Duong and Lin, provides a snapshot into how our interaction with such a smart system could look like, thanks to brain-computer interfaces (BCIs) and AI. This aspect has a dual meaning, as it opens the door to a different way for humans to interact with electronic machines and smart systems, while also explaining how miniaturised technologies and the integration offered by More-than-Moore could advance non-invasive sensing for BCIs.

As neural interfaces, neuromorphic computing, wearable technologies, integrated power sources and integrated photonics advance further, it is clear to see what the next paradigm shift enabled by More-than-Moore integration is likely going to be. Human-computer integration [26] is going to change completely the way we interact with electronic systems and perhaps it is going to make the demarcation line between the biological parts and electronic extensions of a human being somewhat ambiguous. In other words, More-than-Moore integration is going to be at the core of the latest generation of the Internet of the Bodies [27], where human bodies and their technological extensions, both wearable or internal/implanted, will appear seamlessly integrated - be it different types of sensors, of communication interfaces, smart prosthetic devices [28], advanced pacemakers, artificial organs [29] and other forms of technological replacement or augmentation of the biological functions of the human body.

Book Title: More-than-Moore devices and integration

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References

[1] G. Q. Zhang, M. Graef, and F. v. Roosmalen, "The rationale and paradigm of "more than Moore"," in *56th Electronic Components and Technology Conference 2006*, 2006, pp. 151-157, doi: https://doi.org/10.1109/ECTC.2006.1645639.

[2] "NEREID | NanoElectronics Roadmap for Europe: Identification and Dissemination." https://www.nereid-h2020.eu/ (accessed 25/08/2022.

[3] "IEEE International Roadmap for Devices and Systems - IEEE IRDS." https://irds.ieee.org/ (accessed 25/08/2022.

[4] L. Basiricò, G. Mattana, and M. Mas-Torrent, "Editorial: organic electronics: future trends in materials, fabrication techniques and applications," *Front. Phys.,* vol. 10, p. 888155, 2022, doi: https://doi.org/10.3389/fphy.2022.888155.

[5] F. Iacopi, M. Van Hove, M. Charles, and K. Endo, "Power electronics with wide bandgap materials: toward greener, more efficient technologies," *MRS Bull.,* vol. 40, no. 5, pp. 390-395, 2015/05/01 2015, doi: https://doi.org/10.1557/mrs.2015.71.

[6] M. Tang *et al.*, "Integration of III-V lasers on Si for Si photonics," *Prog. Quantum Electron.,* vol. 66, pp. 1-18, 2019/08/01/ 2019, doi: https://doi.org/10.1016/j.pquantelec.2019.05.002.

[7] P. J. Wellmann, "Review of SiC crystal growth technology," *Semicond. Sci. Technol.,* vol. 33, no. 10, p. 103001, 2018/09/05 2018, doi: https://doi.org/10.1088/1361-6641/aad831.

[8] D. J. Langley, J. van Doorn, I. C. L. Ng, S. Stieglitz, A. Lazovik, and A. Boonstra, "The internet of everything: smart things and their impact on business models," *J. Bus. Res.,* vol. 122, pp. 853-863, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.jbusres.2019.12.035.

[9] M. Weiser, "The computer for the 21st century," *Sci. Am.,* vol. 265, pp. 94-104, 1991, doi: https://doi.org/10.1038/scientificamerican0991-94.

[10] E. Ahmed *et al.*, "The role of big data analytics in internet of things," *Comput. Netw.,* vol. 129, pp. 459-471, 2017/12/24/ 2017, doi: https://doi.org/10.1016/j.comnet.2017.06.013.

[11] K. Kalantar-zadeh, N. Ha, J. Z. Ou, and K. J. Berean, "Ingestible sensors," *ACS Sens.,* vol. 2, no. 4, pp. 468-483, 2017/04/28 2017, doi: https://doi.org/10.1021/acssensors.7b00045.

[12] Z. Zhu *et al.*, "Recent advances in high-performance microbatteries: construction, application, and perspective," *Small,* vol. 16, no. 39, p. 2003251, 2020, doi: https://doi.org/10.1002/smll.202003251.

[13] J. Liang, A. K. Mondal, D.-W. Wang, and F. Iacopi, "Graphene-based planar microsupercapacitors: recent advances and future challenges," *Adv. Mater. Technol.,* vol. 4, no. 1, p. 1800200, 2019, doi: https://doi.org/10.1002/admt.201800200.

[14] R. R. Tummala and M. Swaminathan, *Introduction to System-On-Package (SOP) : Miniaturization of the Entire System*. New York: McGraw-Hill, 2008.

[15] "Heterogeneous Integration Roadmap | SEMI." https://www.semi.org/en/communities/heterogeneous_integration_roadmap (accessed 25/08/2022.

[16] M. Chiao, Y.-T. Cheng, and L. Lin, "Introduction to MEMS Packaging," in *Microsystems and Nanotechnology*, Z. Zhou, Z. Wang, and L. Lin Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 415-446.

[17] P. Gupta and S. S. Iyer, "Goodbye, motherboard. Bare chiplets bonded to silicon will make computers smaller and more powerful: hello, silicon-interconnect fabric," *IEEE Spectr.,* vol. 56, no. 10, pp. 28-33, 2019, doi: https://doi.org/10.1109/MSPEC.2019.8847587.

[18] S. S. Iyer and A. Alam, "Flexible Hybrid Electronics using Fan-Out Wafer-Level Packaging," in *Embedded and Fan-Out Wafer and Panel Level Packaging Technologies for Advanced Application Spaces*: Wiley-IEEE Press, 2022, pp. 233-260.

[19] M. Li, Y. Yang, F. Iacopi, M. Yamada, and J. Nulman, "Compact multilayer bandpass filter using low-temperature additively manufacturing solution," *IEEE Trans. Electron Devices,* vol. 68, no. 7, pp. 3163-3169, 2021, doi: https://doi.org/10.1109/TED.2021.3072926.

[20] L. A. Coldren, P. A. Verrinder, and J. Klamkin, "A review of photonic systems-on-chip enabled by widely tunable lasers," *IEEE J. Quantum Electron.,* vol. 58, no. 4, pp. 1-10, 2022, doi: https://doi.org/10.1109/JQE.2022.3168041.

[21] Z. Zhou, B. Yin, and J. Michel, "On-chip light sources for silicon photonics," *Light Sci. Appl.,* vol. 4, no. 11, pp. e358-e358, 2015/11/01 2015, doi: https://doi.org/10.1038/lsa.2015.131.

[22] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nat. Mater.,* vol. 13, no. 2, pp. 139-150, 2014/02/01 2014, doi: https://doi.org/10.1038/nmat3839.

[23] R. Radojcic, *More-than-Moore 2.5D and 3D SiP Integration*, 1 ed. Cham: Springer, 2017.

[24] H. Liu *et al.*, "Thermal-mechanical reliability assessment of TSV structure for 3D IC integration," in *2016 IEEE 18th Electronics Packaging Technology Conference (EPTC)*, 2016, pp. 758-764, doi: https://doi.org/10.1109/EPTC.2016.7861584.

[25] C. Bäumler, J. Franke, and J. Lutz, "Reliability aspects of 3D integrated power devices," in *2021 Third International Symposium on 3D Power Electronics Integration and Manufacturing (3D-PEIM)*, 2021, pp. 1-6, doi: https://doi.org/10.1109/3D-PEIM49630.2021.9497262.

[26] M. Mehrali *et al.*, "Blending electronics with the human body: a pathway toward a cybernetic future," *Adv. Sci.,* vol. 5, no. 10, p. 1700931, 2018, doi: https://doi.org/10.1002/advs.201700931.

[27] G. Boddington, "The internet of bodies—alive, connected and collective: the virtual physical future of our bodies and our senses," *AI Soc.,* pp. 1-17, 2021/02/08 2021, doi: https://doi.org/10.1007/s00146-020-01137-1.

[28] L. J. Marks and J. W. Michael, "Artificial limbs," *BMJ,* vol. 323, no. 7315, pp. 732-735, 2001, doi: https://doi.org/10.1136/bmj.323.7315.732.

[29] X. Wang, "Bioartificial organ manufacturing technologies," *Cell Transplant.,* vol. 28, no. 1, pp. 5-17, 2019, doi: https://doi.org/10.1177/0963689718809918.