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Hybrid Systems-in-Foil

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Abstract: Hybrid Systems-in-Foil (HySiF) is a concept that extends the potential of conventional More-than-More Systems-in/on-Package (SiPs and SoPs) to the flexible electronics world. In HySiF, an economical implementation of flexible electronic systems is possible by integrating a minimum number of embedded silicon chips and a maximum number of on-foil components. Here, the complementary characteristics of CMOS SoCs and larger-area organic and printed electronics are combined in a HySiF-compatible polymeric substrate. Within the HySiF scope, the fabrication process steps and the integration design rules together with all the accompanying boundary conditions concerning material compatibility, surface properties, and thermal budget are defined. This Element serves as an introduction to the HySiF concept. A summary of recent ultrathin chip fabrication and flexible packaging techniques is presented. Several bendable electronic components are discussed, demonstrating the benefits of HySiF. Finally, prototypes of flexible wireless sensor systems that adopt the HySiF concept are demonstrated.

Keywords: Hybrid System-in-Foil, flexible electronics, ultrathin chip, ChipFilm Patch, electronic skin

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1.1 Motivation

Silicon device miniaturization and very-large-scale integration (VLSI) have followed the well-known Moore's law for the last 50 years.[1] Integrated digital functions and information processing have downscaled steadily in what is known as the "More Moore" (MM) trend. Alternatively, real-world sensory interactions and analog functional diversification have indirectly benefited from Moore's law, but they do not necessarily scale in size or cost, which gave rise to a new growth trend known as "More than Moore" (MtM). Figure 1.1a illustrates the timeline of CMOS technology scaling and highlights topics that drive the digital and non-digital integrated functionality.

Complex digital integrated circuits (ICs) were developed on a silicon die in a so-called system-on-chip (SoC) approach. For implementing more system functionality and due to limited access to custom IC foundries, multiple chips were jointly assembled for achieving a higher abstraction level, arranged in a so-called multi-chip module (MCM). The steady scaling of devices in digital ICs is accompanied by continuous improvement of miniaturized passive and active components such as capacitors, inductors, micro-electromechanical systems (MEMS), and analog circuitry, which, when combined with SoCs, give rise to a new level of integration known as system-in-package (SiP) and later system-on-package (SoP).

Reports cite the world's largest IC foundry Taiwan Semiconductor Manufacturing Company (TSMC) as having said, "Moore's Law is not dead, it's not slowing down, it's not even sick."[2] However, several physical, material, power-thermal, technological, and economical challenges are facing the continuation of device miniaturization, and reports are already speculating on the imminent end or slowing down of Moore's law.[3], [4]

Other materials such as gallium arsenide (GaAs), gallium nitride (GaN), and small-molecule organic semiconductors have found their application fields away from scaled silicon technology. Nonetheless, non-silicon semiconductor manufacturing benefits from the success story of silicon integration and miniaturization. Figure 1.1b shows different semiconductor materials and their operating frequency versus power-handling ranges. Note the optimal place occupied by the irreplaceable high-performance silicon semiconductor industry, which has led to the modern digital age of the Internet, computing, and portable electronics.

1.2 Flexible Electronics

Flexible electronics is considered one of the main enablers of the Internet of Things (IoT), as it introduces smartness to every *Thing* in our daily life

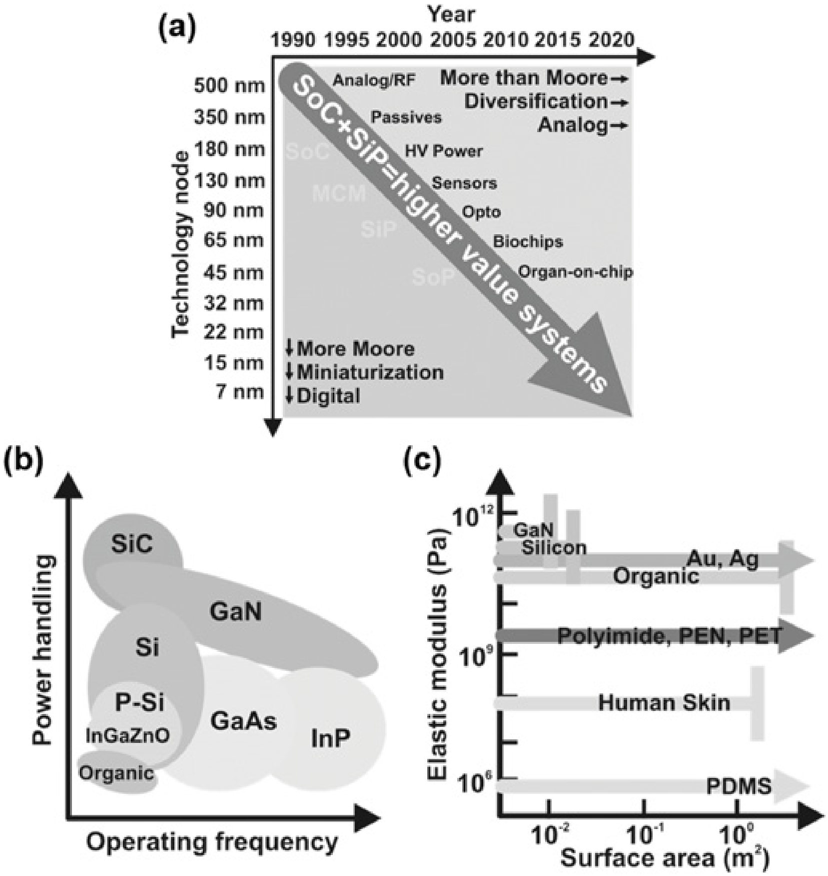

Figure 1.1 (a) The combined need for digital and non-digital functionalities in an integrated system is translated as a dual trend in miniaturization of the digital functions ("More Moore") and functional diversification ("More than Moore"). [5] (b) Power-handling capability of different semiconductor materials illustrated against the operating frequency range. (c) Elasticity of frequently used materials in flexible and printed electronics and its potential surface area coverage.

regardless of its form factor and surface properties. Flexible, printable, and organic electronics, when combined with new materials and advanced fabrication processes, offer unique characteristics such as mechanical flexibility, thin-form factor, large area scaling feasibility, and adaptability to irregular surfaces. However, most flexible electronic components are currently either fabricated as stand-alone components or combined with bulky sensor readout and/or wireless communication modules assembled to the surface of a flexible substrate.[6], [7], [8] Other flexible electronic systems benefit from only one technology (e.g., integrated temperature sensor and analog-to-digital converter [ADC] using amorphous Indium-Gallium-Zinc-Oxide [InGaZnO] thin-film transistors [TFTs]).[9]

Figure 1.1c shows the elasticity of frequently used materials in flexible and printed electronics and its potential surface area coverage. Thin-film organic, small-molecule, and inorganic poly-Si semiconductor materials are inherently flexible and applied to low-speed and large-area electronic applications. Due to the strengthened requirement on material purity and uniformity, single-crystalline silicon has a limited surface area coverage governed by the maximum available wafer size. Ultrathin chips (UTCs) are a promising candidate for high-performance bendable electronic applications with embedded intelligence. UTCs can be considered the extension of mature silicon technology to flexible electronics. However, a cost-effective and reliable UTC flexible packaging solution is still in development. Note that GaN and GaAs on thin silicon have extended the operating frequency of flexible and stretchable microwave devices and circuits reaching 10 GHz and beyond.[10], [11] Substrates based on polyimides, polyethylene naphthalate (PEN), and polydimethylsiloxane (PDMS) are potential platforms for flexible systems integration complementing the conventional rigid printed circuit boards (PCBs).

1.2.1 Hybrid Systems-in-Foil Definition

Hybrid Systems-in-Foil (HySiF) is a concept that extends the potential of conventional MtM SiPs and SoPs to the flexible electronics world. HySiF targets an economical implementation of flexible electronic systems by integrating a minimum number of embedded silicon chips and a maximum number of on-foil components.[12], [13] The complementary characteristics of CMOS SoCs and larger-area organic and printed electronics are combined in a HySiF-compatible polymeric substrate. Within the HySiF scope, the fabrication process steps and design rules for integrating such flexible electronic components with all the accompanying boundary conditions concerning material compatibility, surface properties, and thermal budget are defined.

In many electronic systems (e.g., data converters and microprocessors), standard criteria for performance evaluation are designed to reflect the trade-offs between operational parameters such as power consumption, speed, and accuracy. Walden and Schreier figures of merit (FoM) are known values to evaluate data converters' performance. In this context, a new figure of merit (FoM_{Flex}) for flexible smart electronic systems (i.e., bendable and/or stretchable electronic systems with digital outputs) includes key features such as mechanical flexibility, low-power operation, accuracy, and processing speed. This newly introduced FoM is defined as follows (Eq. 1.1):

$$FoM_{Flex}(Pa.J) = \frac{E\ (Pa) \times P\ (W)}{F_{sync}\ (s^{-1}) \times SNR}, \tag{1.1}$$

where E is Young's (or the Elastic) modulus of the complete flexible system or substrate, P is the power consumption, F_{sync} is the maximum data rate supported by the flexible system, and SNR is the signal-to-noise ratio of the integrated front end. More elasticity, higher speed, and SNR at lower power results in better FoM. As shown in Figure 1.3, silicon-based UTCs outperform organic and inorganic TFT technologies. However, large area coverage, low-temperature processing, and shorter manufacturing time are the main advantages for organic and inorganic TFT technologies and are challenging parameters to be evaluated using a standardized FoM.

For purely digital IP blocks, such as microprocessors (μP), microcontrollers (μC), and near-field communication (NFC), the maximum data rate supported by the flexible system in samples/second and SNR of 2 are used. Figure 1.2 depicts the proposed FoM_{Flex} against system energy consumption of selected flexible silicon, inorganic, and organic TFT smart systems. Table 1.1 provides a detailed comparison of the specifications of the blocks represented in Figure 1.2.

1.2.2 Device Integration and Interconnect Technologies

For flexible systems exploiting metallic foil substrates, wire interconnects are already available, and their properties are coupled to the substrate properties. In other systems that have insulating substrates, metallic films are deposited to electrically connect different electronic components. Conventional CMOS-compatible lithography could be used to trade off smaller area coverage and lower throughput with fine-pitch interconnects. Fortunately, the thinner the material, the more flexible it becomes. This is true in the case of thin-film metals, such as gold (Au), silver (Ag), and aluminum (Al), which normally are used to manufacture flexible electronic components. However, the thinner the metal, the higher the sheet resistance. As an example of this trade-off, multiple overpasses are performed during metal inkjet printing to tailor the sheet resistance to that of a printed single metal layer. Long wire interconnects that are often used in large-area flexible electronics affect signal integrity, as they limit the precision and speed of the embedded systems by adding line delays (higher parasitic RLC).

Coplanar circuit interconnects are usually used in flexible sensor systems. Since metals have higher Young's moduli compared to polymers, the density