Physically Flexible High Performance Single Crystal CMOS Integrated with Printed Electronics

Richard L. Chaney, Douglas R. Hackler, Dale G. Wilson, and Brian N. Meek
American Semiconductor, Inc.
Boise, Idaho 83705 USA

***Abstract*— Flexible electronic systems have been limited by the ability to integrate IC functionality. Traditional silicon-based ICs are not flexible, and flexible transistors are too large and too slow to approach silicon-based IC density and performance. Transferring standard silicon IC wafers to polymer substrates addresses these limitations by transforming traditional ICs into a physically flexible form factor. Integrating these flexible ICs with printed electronics creates Flexible Hybrid Systems and enables a new generation of electronics.**

Keywords—flexible; FleX; FHS

I. Introduction

Flexible and conformal electronic products have been discussed for years and are gaining interest in consumer, industrial, and defense markets. However, there are still barriers that must be overcome to drive widespread adoption. Flexible systems have been limited by the ability to incorporate integrated circuits (ICs) or IC-type functionality into a physically flexible form factor.

Traditionally packaged ICs are thick, rigid, and require attachment and connection methods that are not directly compatible with flexible circuit boards. Printed transistors have very large feature sizes are significantly larger than silicon based technologies. Printed transistor line widths are measured in tens of microns while silicon transistor lines are measured in tens of nanometers. Additionally, flexible printed transistors have very low electron mobilities and are orders of magnitude slower than silicon based ICs as illustrated in Fig. 1. Without the ICs, flexible systems lack the functionality that high performance ICs offer. This gap has limited the usefulness and market adoption of flexible electronics.

These limitations have been addressed by the FleX™ Silicon-on-Polymer™ process where standard full thickness Silicon On Insulator (SOI) wafers are transformed into flexible wafers and subsequently singulated die. The IC becomes ultra-thin and physically flexible, enabling new attachment and connection methods that are compatible with flexible circuit manufacturing.

The FleX process can be applied to any SOI wafer. However, the replacement of silicon substrate with polymer in the final wafer can change some parameters. For example, completely removing the handle silicon will typically improve the RF performance by eliminating the parasitics of the handle silicon. Reducing the parasitic capacitance can also increase the frequency of operation and lower the power consumption. The transistor performance improvements demand optimized electrical models which are provided in the FleX Process Design Kit (PDK).

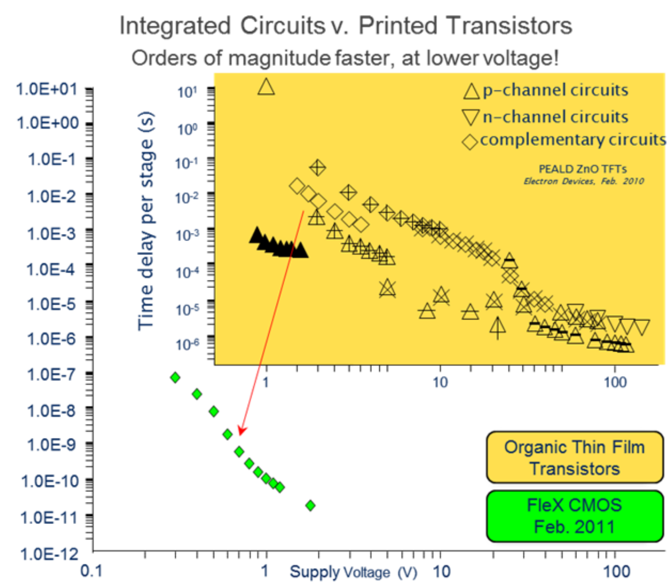

Fig. 1: Transistor Performance of Printed vs. FleX

II. Flexible Hybrid Systems

Flexible printed electronics and silicon IC technologies each have properties and characteristics that are desirable for conformal and physically flexible products. However, neither can meet the full set of requirements alone. Flexible hybrid technology combines flexible printed electronics and high performance flexible ICs into a Flexible Hybrid System (FHS) that delivers the best of both technologies as illustrated in Fig. 2 [1]. The flexible printed electronics deliver large form factor elements such as sensors, interconnects, and antenna elements. FleX Silicon-on-Polymer delivers integrated circuit (IC) functions in a flexible form factor that is compatible with the printed electronics.

The benefits of FHS are clear. Combining printed electronics with FleX ICs creates very thin, very flexible circuits and systems in a form factor that is compatible with conformal and bendable requirements. An example can be envisioned with sensor systems. Printed sensors are inherently flexible, low cost, and can have very large footprints, up to wing- or fuselage-size in structural health monitoring applications. FleX ICs provide the ability for localized signal processing and control. Local signal processing greatly improves the sensor performance reducing signal loss from long transmission lines. In addition, local processing allows the use of data communication protocols between sensors, controllers and central processing hubs.

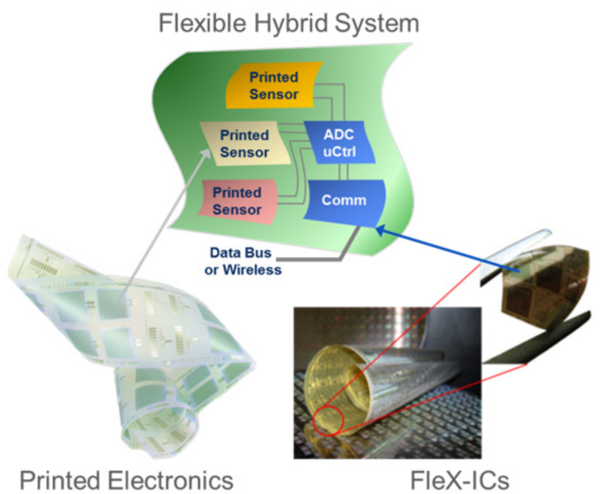

Fig. 2: Flexible Hybrid System

III. FLEX SILICON-ON-POLYMER

FleX is a proprietary process to transform standard silicon wafers into flexible wafers. American Semiconductor has demonstrated its revolutionary FleX process by creating flexible, ultra-thin, single-crystalline CMOS with multi-layer metal interconnect [2,3]. CMOS is first fabricated using a standard SOI process on 200mm wafers and then the silicon substrate is removed. The FleX process completely removes the handle silicon and adds a polymer mechanical substrate to create ultra-thin flexible wafers as shown in Fig 3 [4]. The resulting FleX wafers may be used at wafer-scale or singulated into individual FleX ICs.

FleX is a post-fab process that can be applied to any SOI CMOS wafer and has been demonstrated on three different processes from two different CMOS wafer foundries. FleX delivers fully functional, flexible wafers with a final silicon thickness of less than 200nm. Although the finished CMOS and polymer substrate can be less than 25um in total thickness, the wafer is very durable and can be easily handled for assembly. FleX has been demonstrated with functional CMOS ICs successful launched into space in June 2012 and August 2013 under the NASA RockSat program.

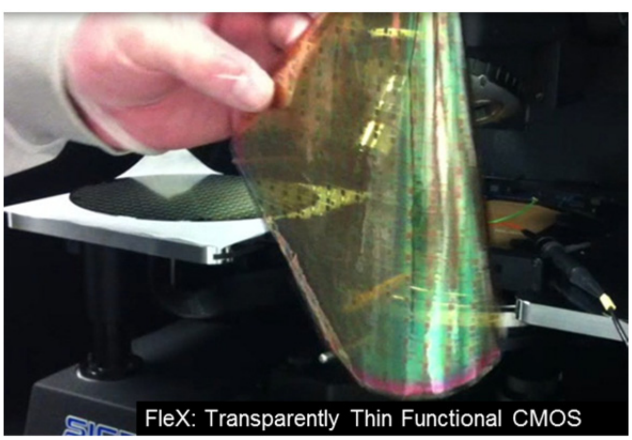

Fig 3: FleX Wafer – 130nm CMOS

American Semiconductor has demonstrated FleX ICs operating when deformed to a 5mm radius of curvature in both concave and convex directions and with die orientations of 0 and 90 degrees as shown in Fig. 4.

Fig. 4: FleX-ICs Deformed for Testing Concave (left) Convex (right)

IV. ICS IN JAZZ CS18-FLEX

The FleX process has been demonstrated with functional CMOS from multiple processes including TowerJazz Semiconductor's CS13 130nm and CS18 180nm partially depleted SOI CMOS processes. FleX-ICs fabricated in CS13/18 have created the industry's first commercially available flexible CMOS foundry processes. American Semiconductor and TowerJazz Semiconductor have partnered to demonstrate the TowerJazz CS13 process in FleX and subsequently deliver a FleX-PDK for designers to use when creating FleX-ICs.

The initial development of FleX-ICs in CS13/18 is being demonstrated with the FleX-MCU, FleX-ADC, and FleX-RFIC. The FleX-MCU is a full featured, peripheral rich, 8-bit RISC microcontroller with 8KB SRAM. The FleX-MCU contains over 2 million transistors. The FleX-MCU has demonstrated functionality as a physically flexible IC [5]. The FleX-ADC is an 8-bit successive approximation analog-to-digital converter with a 2-wire I^2C interface. The FleX-RFIC is a radio frequency communications IC using the IP-X™ TTO protocol at 860-960MHz (UHF) and programmable via a 2-wire I^2C interface. In addition to providing a demonstration vehicle for FleX-ICs, the FleX-MCU, FleX-ADC, and FleX-RFIC provide a prototype platform for Flexible Hybrid Systems as well as a set of silicon-proven IP blocks that can be used to create custom FleX Application Specific ICs (ASICs).

TowerJazz CS13/18-FleX are the industry's first commercially available flexible foundry processed. Testing to date has shown excellent results. The wafers show extraordinary physical results after the FleX process is complete, as shown in Fig. 5.

Figure 5: Jazz CMOS Wafer After FleX Processing

DC test data taken pre- and post-FleX shows no shift in transistor performance, which is the desired result [6]. Data is presented in Fig 6. from the same wafer in full thickness and FleX forms for both NMOS (top) and PMOS (bottom) transistors, where the full thickness wafer data is shown in red and the FleX wafer data is shown in blue.

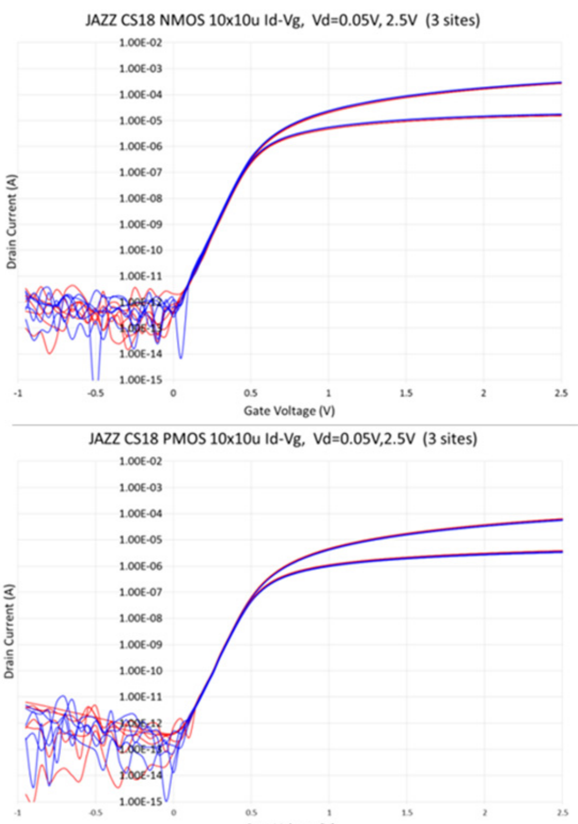

Fig. 6: Jazz CS18 NMOS (top) and PMOS (bottom) transistors pre-FleX (red) and post-FleX (blue)

V. FLEXIBLE HYBRID MANUFACTURING

Flexible Hybrid Systems have been created as prototypes and conceptualized for high volume manufacturing. Prototyping can be rapidly accomplished using a variety of low-cost printing techniques combined with FleX-ICs. Methods such as direct writing and screen printing using materials such as silver conductive epoxies and silver ink have been demonstrated. Fig. 7 shows a laboratory prototype where a FleX-MCU die has been attached to a flexible substrate and connected with direct write interconnects. This illustrates the ease in which rapid FHS prototypes may be created.

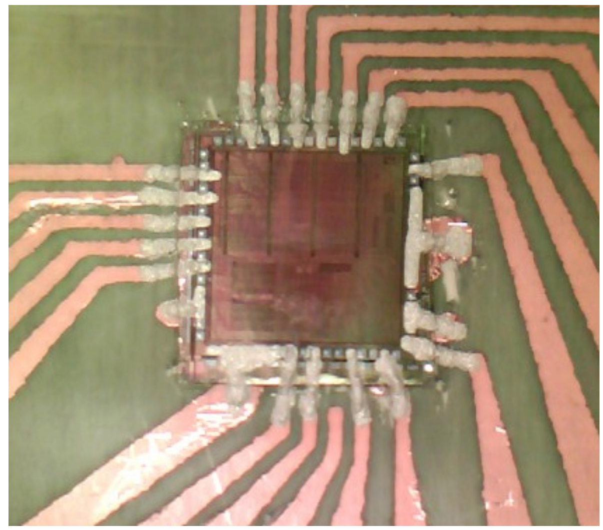

Fig. 7: Conformally Attached FleX IC Prototype with Direct Write Flexible Interconnects

High volume manufacturing for Flexible Hybrid Systems has been conceptualized where a FleX IC integration station is added in a roll-to-roll printed electronics line, as shown in Fig 8 [6]. The example shows the FleX die integration at the end of the process, although it could feasibly be added at any point in the line as the product requires. With this methodology, Flexible Hybrid Systems can be produced in high volume at low cost.

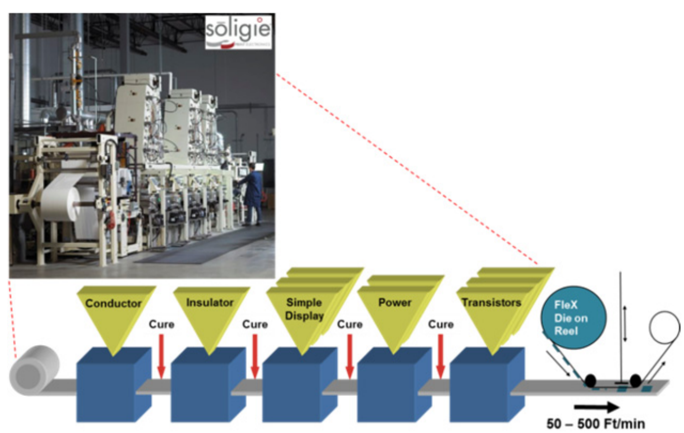

Fig 8: Flexible Hybrid Manufacturing Line

VI. FLEX IC AND FLEXIBLE HYBRID APPLICATIONS

Flexible ICs and Flexible Hybrid Systems open the door to innovation in a variety of different markets and applications. The Consumer Electronics Show (CES) held in January 2014 resulted in widespread media coverage of novel products such as wearable devices such as “smart watches” and curved smart phones. Aviation companies and their customers, including the U.S. Air Force, are interested in flexible products that can be bonded to surfaces for structural health monitoring (SHM) or embedded in composites to create multifunctional aircraft structures (MAS) for applications such as conformal load-bearing antenna structures (CLAS) [7]. FleX ICs and FHS hold the promise of revolutionary advances for medical technologies, including wearable, surgical, and implantable devices.

CLAS is one implementation of multifunctional aircraft structures where FleX-ICs and FHS are desirable and beneficial. American Semiconductor recently delivered proof-of-feasibility CLAS prototypes to the Air Force Research Laboratory demonstrating Flexible Hybrid System integration. These Phase I prototypes showed clear benefits of using FleX ICs and printed electronics in cutting edge UAV and aviation applications.

The technology developed by American Semiconductor to create its CLAS prototypes is directly compatible with manufacturing advanced MAS sensors and localized processing capability required for structural health monitoring and fly-by-feel applications.

Structural Health Monitoring (SHM) embeds strain gauges, temperature sensors, pressure sensors, and other sensors into the structural components of aircraft. SHM would enable aircraft maintenance based on need rather than by schedule, potentially saving millions of dollars each year across military or commercial aviation fleets. Additionally, SHM improves safety by monitoring the aircraft dynamically, in flight and on the ground, providing valuable lifetime information which can be critical as both military and civilian assets are often operated beyond their designed lifetimes.

Flexible Hybrid sensor systems can also be integrated into existing medical technology to improve performance. FHS has the potential to revolutionize medical technology by embedding sensors and control where it has not been possible before. Fig. 9 illustrates potential medical applications such as futuristic implantable and surgical devices. Wearable medical devices exist but have limitations due to their size, weight, and overall form factor. The improvements enabled by FHS extend the utility of wearable medical devices on the battlefield, in the hospital, and in the home.

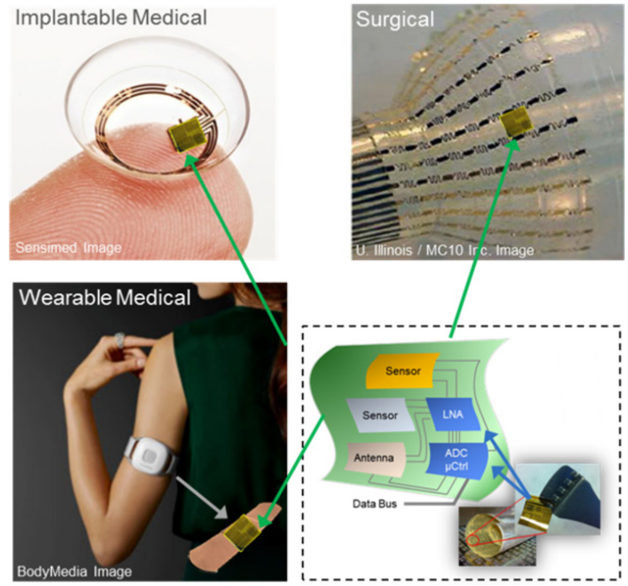

Fig. 9: Flexible Hybrid Systems in Medical Applications

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REFERENCES

[1] R. Chaney, D. Hackler, D. Wilson, “Pliable Smart Sensor System”. GOMAC, March 2012. url: www.americansemi.com/GOMAC2012_31.9.pdf

[2] D. Hackler, R. Chaney, “Semiconducor on Polymer Substrate”. US. Patent Application 13/242,376

[3] R. Chaney, D. Hackler, “Performance Electronics Integration in Flexible Technology”. GOMAC, March 2010. url: www.americansemi.com/GOMAC2010_28-18.pdf

[4] R. Chaney, D. Hackler, “High Performance Single Crystal CMOS on Flexible Polymer Substrate” GOMAC, March 2011. url: www.americansemi.com/GOMAC2011_30-16.pdf

[5] S. Wald, B. Meek, D. Wilson, “8MHz Physically Flexible Microcontroller”. Unpublished.

[6] R. Chaney, D. Hackler, D. Wilson, B. Meek, ”FleX Silicon-on-Polymer: Flexible (Pliable) ICs from Commercial Foundry Processes”. GOMAC, March 2013. url: www.americansemi.com/GOMAC2013_31.2.pdf

[7] R. Chaney, D. Hackler, D. Wilson, B. Meek, “Advanced Conformal Load-Bearing Antenna Structures”. GOMAC, March 2013. url: www.americansemi.com/GOMAC2013_36.2.pdf