Energy Harvesting and Power-Management for Sensing Skins in SHM Applications

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ABSTRACT

Self-powered operation can substantially ease the deployment and adoption of SHM systems. In this work, thin-film power-management systems are presented, which achieve energy harvesting and wireless power delivery to sensing subsystems all using the same thin-film amorphous-silicon (a-Si) technology. This enables a future path to systems with low assembly complexity. Two thin-film inverter topologies for wireless power delivery are discussed: (1) a class-D switching power inverter; and (2) an LC-oscillator-based power inverter. Among these, the class-D power inverter achieves wireless power delivery of 120 μW at an efficiency of 22%, while LC-oscillator-based power inverter achieves wireless power delivery of 22 mW at an efficiency of 31%. Though the power levels are adequate for some SHM systems being envisioned, the superior power level of the LC oscillator makes it relevant for a wide range of systems.

INTRODUCTION

To avoid catastrophic failure and optimize maintenance investment, structural-health monitoring (SHM) of critical structures has gained interest. The corresponding systems, however, raise substantial technological challenges. Early-stage damage detection requires sensing over potentially large regions of a structure, yet with resolution as low as the centimeter scale. Unfortunately, the state-of-art technologies in SHM, such as fiber-optic sensors, face substantial challenges for providing robust sensing on this scale. Studies have shown that early-stage damage even 50 cm away from a sensor cannot be reliably detected [1]. This motivates a technology that can provide dense sensing. A possible technology that can address this need is large-area electronics (LAE).

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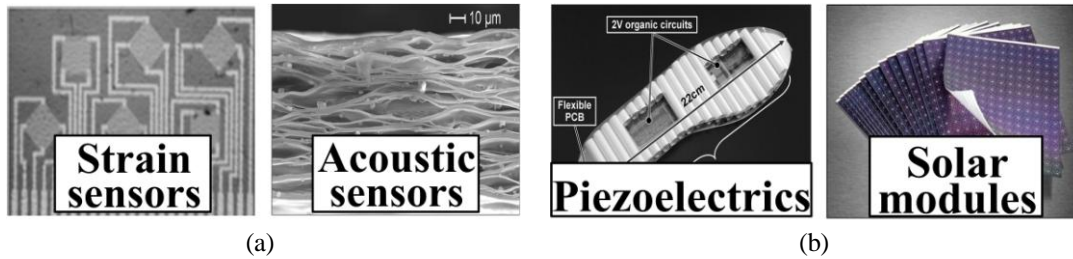Engineering Quadrangle Olden Street, Princeton, NJ 08540, U.S.A.

Figure 1. (a) examples of transducers for sensing in LAE: strain sensors [2] and acoustic sensors [3]; (b) examples of transducers for energy harvesting in LAE: piezoelectrics [4] and solar modules [5].

Large-area Electronics for SHM

LAE is a technology based on processing electrically functional thin-films at low temperatures. This has three critical benefits:

1. LAE can be fabricated on plastic substrates, enabling form factors that are large and conformal. Today, the basic processing involved can be achieved on substrates that are as large as $9m^2$ at an approximate cost of $200/m^2$. These attributes make LAE potentially compelling for SHM by raising the possibility of unprecedented scalability in sensing at low cost.
2. The low temperature processing of LAE allows diverse materials to be used, enabling the formation of a wide range of transducers for sensing. As shown in Figure 1(a), examples include strain sensors [2], acoustic sensors for microphones [3], etc.
3. In addition to transducers for sensing, LAE enables the formation of energy harvesting devices, and due to the attribute of large physical dimensions, these can harvest substantial power. As shown in Figure 1(b), examples include piezoelectrics [4] and flexible solar cells based on amorphous silicon (a-Si) [5];

These aspects imply that LAE makes it possible to integrate energy-harvesting devices with large-scale sensor arrays for fully-self-powered SHM systems. Thus a technological possibility exists for sensing skins that can achieve direct-damage detection spanning large surface of a structure with high spatial resolution without powering constraints.

ARCHITECTURES AND ENERGY REQUIREMENTS FOR SHM SYSTEM

In order to create a complete system for SHM, functions such as instrumentation, power-management, communication and embedded computation are required, in addition to sensing. While LAE offers benefits of sensing, energy-harvesting, and possibly low-loss wireline communication among the distributed sensors, the low-temperature processing limits the ability to form high-quality transistors. As a result, the transistors, which are required for realizing the mentioned system functions, have orders of magnitude lower performance and energy efficiency than those available in state-of-the-art CMOS silicon integrated circuits (ICs). Accordingly, to exploit the benefits of LAE in practical large-scale systems, a viable approach of combining the two technologies is needed.
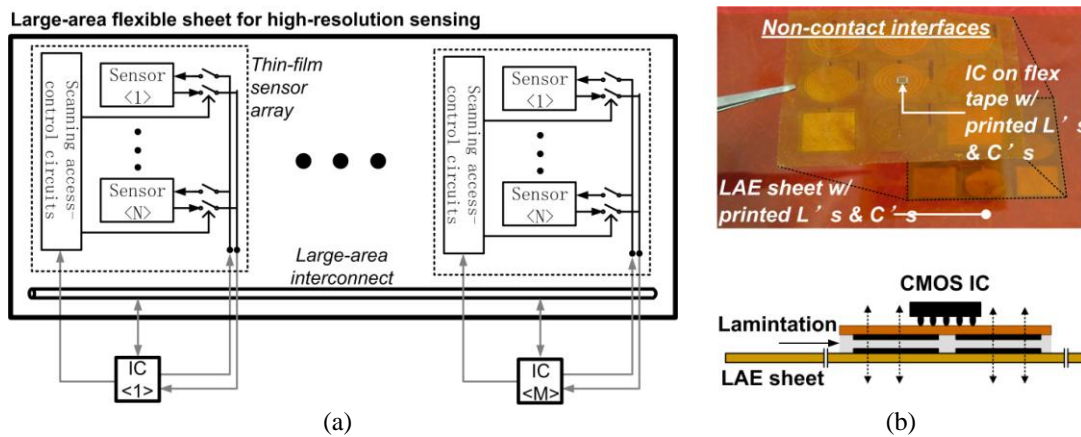
Figure 2. (a) Scalable hybrid SHM system concept with multiple ICs coupled to large-area sheet;
(b) non-contact interfaces for scalable system assembly, and side view of lamination approach

Scalable SHM Systems based on LAE and CMOS ICs

Recent work has resulted in hybrid systems that combine LAE with CMOS ICs for SHM application [6]. In that work, a-Si thin-film transistors (TFTs) are employed for the LAE processing on a flexible substrate. A-Si is currently the dominate technology, used commercially in flat-panel display applications.

The hybrid system architecture is shown in figure 2(a). It achieves two main functions: large-scale strain sensing and communication between distributed ICs. For sensing, thin-film strain sensor arrays are patterned on the flexible sheet, along with TFT sensor-accessing circuits. The CMOS ICs provide robust, energy-efficient instrumentation as well as sensor-access control. For communication, long-range interconnects are patterned in the LAE technology, while the CMOS IC provides energy-efficient transceivers.

Currently, there is no high-volume solution for electrically bonding CMOS ICs onto large-area, flexible substrates. Therefore, the key limitation to creating LAE-CMOS hybrid systems is the interfaces required between these two technologies. In order to address this, non-contact interfaces are developed in the system. Inductive and capacitive antennas are patterned both on LAE sheet and on flexible chip carrier that is several square centimeters in area and can thus by readily bonded to ICs, similar to RFID tags [7]. Complete system assembly is then achieved via sheet laminating of multiple IC carriers onto the large-area sensing substrate, as shown in figure 2(b).

The sensing system consumes 2.6 μJ and 270 nJ for sensor-access control and instrumentation respectively. With 10,000 sensors, covering 10 m^2, the system consumes 28.7 mJ to perform strain measurements over the sensing area. Assuming embedded processing of the acquired data with energy of 27 pJ per operation [8], the total energy for processing all sensor measurements is estimated at ~300 μJ. This implies roughly 30 mJ of energy required to acquire and process sensor measurements from the 10 m^2 area. For the sake of system analysis, we will assume a duty cycle of ten measurements from all sensors per hour, giving an average power consumption of roughly 100 μW.
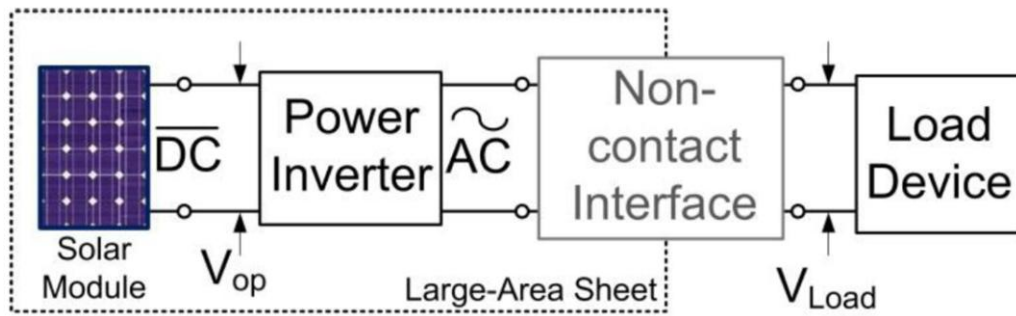
Figure 3. Generalized power inverter system, modulating DC solar cell output to AC for transmission over non-contact interfaces

Solar Energy Harvesting and Wireless Power Delivery

Taking full advantage of the capabilities offered by LAE towards a SHM system, self-powered operation can be realized. The self-powered operation requires energy-harvesting and power-management circuits in the SHM system. For energy harvesting, LAE offers the benefit of enabling physically-large harvesting devices, thus leading to substantial power. LAE enables a wide range of energy-harvesting devices ranging from solar cells, to piezoelectrics, to thermoelectric, etc. This work presented here focuses on a-Si solar cells given the availability of solar power in bridge-monitoring applications. Conservatively assuming indoor lighting conditions, a-Si solar cells can provide $10\mu W/cm^2$ (outdoor conditions, even overcast, lead to higher power).

While a-Si solar cells can provide power to the LAE domain, power must also be delivered to the CMOS ICs through the non-contact interfaces. Wireless power delivery from LAE to CMOS ICs requires power inverters in the LAE domain to convert the DC output from the solar cells into AC power. The IC can then realize high-efficiency power-management subsystems, including blocks for rectification, voltage regulation, and DC-DC conversion [9]. As derived, the required power inverters need to be able to deliver at least $100\mu W$ to the ICs for the SHM sensing system.

POWER INVERTER SYSTEMS

The required power inversion system is shown in figure 3. On the large-area sensing sheet, an a-Si solar module is patterned, providing a DC voltage V_{op} to a thin-film power inverter. The power inverter converts the DC power to AC for wireless power delivery via the non-contact interfaces to the CMOS IC load. The challenge in creating thin-film power inverters is to overcome the poor performance of the active devices, i.e., LAE TFTs.

a-Si Thin-film Transistors (a-Si TFTs)

The active devices adopted for the power inverter system are a-Si TFTs, which are currently the dominant transistor technology in LAE. A benefit of a-Si TFTs is that they can be fabricated in the same technology as the a-Si solar cells, thus enabling the
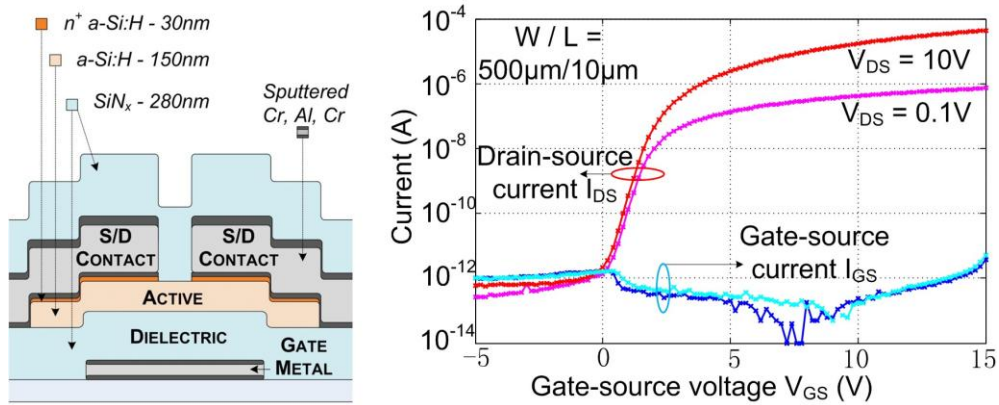
Figure 4. Processes and electrical characteristics of a-Si TFTs

possibility of integrating the power inverters with the energy harvesters. Figure 4 shows the processing and electrical characteristics of the fabricated a-Si TFTs. Although these represent the best established TFT technology [10], the following device limitations and corresponding power inverter discussions also transfer to other TFT technologies (e.g. organic TFTs, metal-oxide TFTs, and etc.).

Two main limitations in the TFTs affect their performance within power inverters: (1) instead of providing complementary devices, as in CMOS IC technology, only NMOS TFTs are available in a-Si technology; and (2) the performance and energy efficiency of TFTs is low, due to the low temperature processing of thin-films, which leads to degraded electrical characteristics. The result is a cut-off frequency for the TFTs that is orders of magnitude lower than that of CMOS IC transistors (e.g. a-Si TFT $f_T \sim$ 1MHz; CMOS IC transistors $f_T \sim$ 300GHz). To overcome these problems, we describe two topologies for the LAE power inverters: (1) a class-D switching converter; and (2) LC-oscillator-based converter.

Class-D Power Inverter

The class-D power inverter is based on a switching topology. In this case, ideally, all the current drawn from the power source is delivered to load devices. Figure 5 shows the topology adopted to create the class-D stage [11]. Since only NMOS TFTs
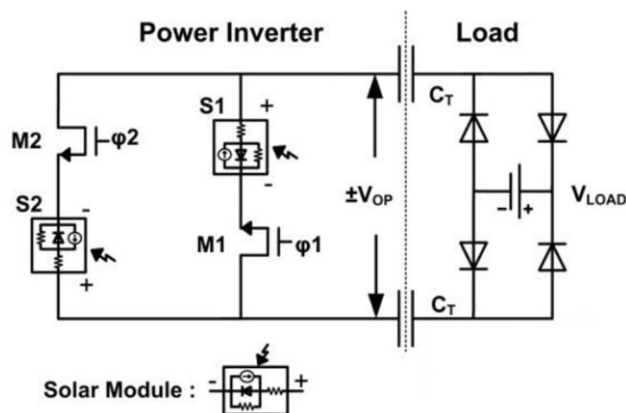

Figure 5. Class-D power inverter topology wirelessly delivery power to load using capacitors
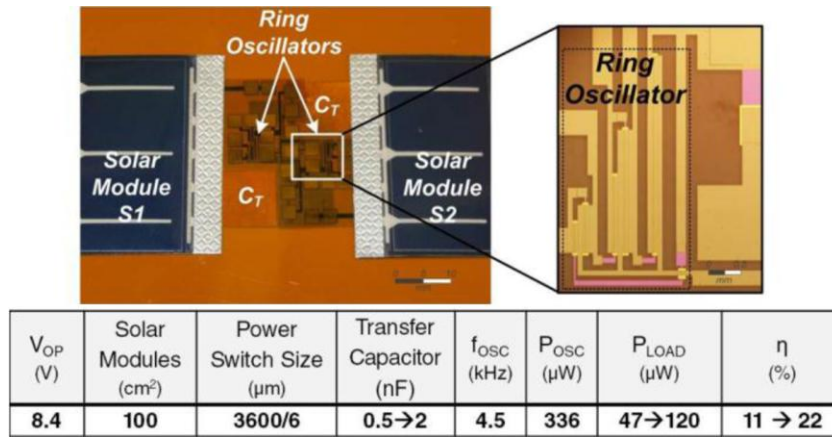
V_{OP} (V)	Solar Modules (cm²)	Power Switch Size (µm)	Transfer Capacitor (nF)	f_{OSC} (kHz)	P_{OSC} (µW)	P_{LOAD} (µW)	η (%)
8.4	100	3600/6	0.5→2	4.5	336	47→120	11 → 22

Figure 6. Class-D power inverter system prototype and performance table

are available in a-Si technology, two solar modules, which are alternatingly switched, are adopted to create the AC output current. Utilizing the two solar modules in this way overcomes the limitations associated with uni-polar (i.e., NMOS-only) devices. However, it requires complicated control circuits, due to oscillating voltage levels for the NMOS switches, which now oscillate with respect to each other. In order to fully turn on and off the power switches M1 and M2, the control circuitry must create a voltage signal that effectively switches by a voltage of $2V_{op}$. To achieve this, coupled ring oscillators that exploit capacitive bootstrapping are adopted within the control circuits [11].

Figure 6 shows the prototype class-D power inverter with solar modules. a-Si TFTs are fabricated on 50µm polyimide, at 180 °C at Princeton. Capacitive interfaces are adopted for the non-contact interfaces, with a typical transfer-capacitor size of 4×4cm².

The performance summary is given in Figure 6. The maximum efficiency achieved is 22%. While very high efficiencies can theoretically be achieved, in practice the efficiency is limited by the low performance of the power switches which impose large conduction and switching loss. Further, the complex control circuitry required due to the lack of complimentary transistors further degrades the efficiency. The maximum output power achieved is 120µW, which just meets the requirements of the SHM system described in the previous section. The achievable output power is limited by the frequency at which the power switches can be operated, which is fundamentally limited by the poor cut-off frequency of the TFTs.

LC-oscillator-based Power Inverter

The output power of the class-D power inverter is limited by the cut-off frequency of the TFTs, which makes it less desirable for broader SHM applications. To address this limitation, an LC-oscillator-based power inverter is developed to overcome the output power limitations. Figure 7 shows the topology of the LC-oscillator-based power inverter [12]. The cross-coupled TFTs form a positive-feedback loop in order to create resonance. The resonant current of the inductors couples to the load device through the inductive interfaces thus realizing wirelessly power delivery.
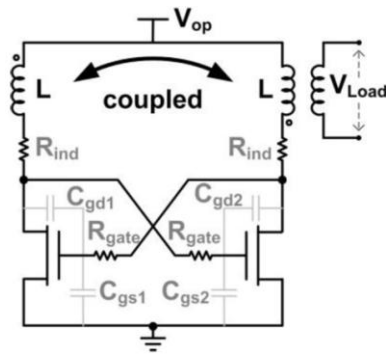
Figure 7. LC oscillator based power inverter wirelessly delivery power to load using inductors

Compared with the class-D power inverter, the LC-oscillator topology better exploits the attributes of LAE. In particular, the ability to pattern physically-large inductors enables the creation high-quality passives, which shift away the emphasis from the low quality active TFTs. Typical patterned inductors with a radius of 2 cm achieve a quality factor of 50 at 2 MHz. This allows the inductors to resonant with the parasitic capacitances of TFTs, enabling an operating frequency beyond the cut-off frequency of the TFTs. Therefore the output power can be significantly increased. In addition, high frequency also increases the quality factor of the resonant tank which helps to increase power transfer efficiency.

Figure 8 shows the prototype of the class-D power inverter with solar module. A-Si power inverter circuits are fabricated on 50µm polyimide, at 180 $^{\circ}$C at Princeton. Inductive interfaces are adopted for the non-contact interfaces, with a typical transfer inductor size of 4×4 cm^2. The inductive interfaces allow high power delivery and robust coupling.

The performance summary is given in figure 8. The maximum efficiency achieved is 31%. The efficiency is greater than that of the class-D topology primarily due to the lack of control circuits required, which can impose substantial overheads. Thanks to high-quality inductors, the maximal operating frequency measured is 3.64 MHz, which exceeds the cut-off frequency of TFTs. With the high-frequency operation, the maximum output power achievable is 22 mW, far exceeding the power levels achievable with the class-D topology. The achieved power level and efficiency are well beyond those needed for the envisioned SHM systems.

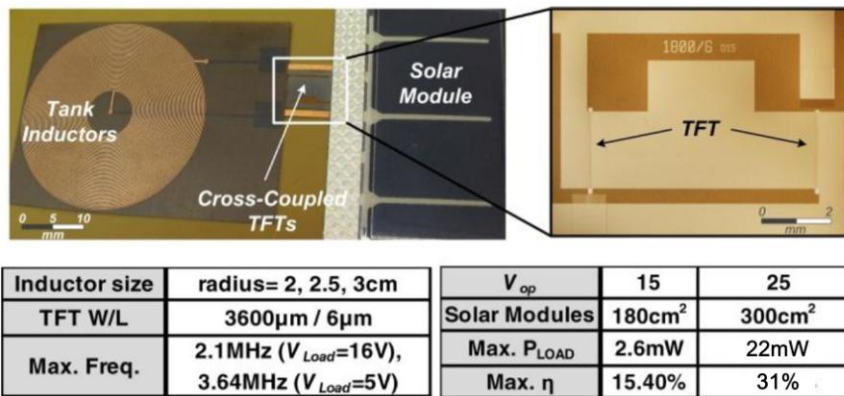| Inductor size	radius= 2, 2.5, 3cm		V_{op}	15	25
TFT W/L	3600µm / 6µm		Solar Modules	180cm^2	300cm^2
Max. Freq.	2.1MHz (V_{Load}=16V), 3.64MHz (V_{Load}=5V)		Max. P$_{LOAD}$	2.6mW	22mW
			Max. η	15.40%	31%

Figure 8. LC oscillator based power inverter system prototype and performance table

CONCLUSIONS

To enable self-powered operation of SHM systems, two thin-film power inverter systems are described. These achieve energy harvesting with a-Si solar modules. Power inversion from DC to AC is achieved by thin-film power inverters realized in the same technology as the a-Si solar modules, providing the possibility for full system integration. The AC power is wirelessly delivered to CMOS ICs through non-contact interfaces.

The LC-oscillator-based power inverter offers better performance than a class-D power inverter. It achieves 31% power delivery efficiency, due to elimination of control overheads. The output power achieved with the LC-oscillator-based power inverter is more than 100 times higher than that of the class-D power inverter, due to its ability to overcome the limitations of the active TFTs. The resulting power, delivered wirelessly, is well beyond the requirements for envisioned SHM systems, which could make such systems more viable and/or compelling for deployment.

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