Morphing Autonomous Gigascale Integrated Circuits: An Integrated Approach to Vanishing Programmable Resources

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Abstract—Significant progress has been made toward the demonstration of a millimeter-scale wireless sensor node that can be triggered to physically disappear. Xenon difluoride gas has been shown to turn silicon CMOS chips into silicon tetrafluoride gas and a crumbled pile of metalization and glass. Triggered gas release via membrane rupture has been demonstrated using both millimeter-scale nitrocellulose combustion and a MEMS micro-hammer. Wireless triggering of membrane rupture has been demonstrated. The key elements of a crystal-free, all-silicon CMOS radio have been demonstrated. A 4 mm² printed battery with sufficient voltage, current, and energy to run the wireless node for days has been demonstrated.

I. INTRODUCTION

A wireless sensor node, or mote, requires sensing, computation, communication, and power. Reliable low-power mesh networks of motes are deployed commercially all over the planet in industrial process automation and other applications [1]. To make such a mote transient, i.e. to be able to physically disappear on command, places constraints on the design of all of the components. If only a silicon etchant is used, as in this work, then circuit boards, connectors, and external passive components must be eliminated. A single-chip mote must be designed with all of the components of the system integrated into or onto the silicon chip, with zero external components.

The current system consists of a mote, a solid source of xenon difluoride (XeF₂) separated from the rest of the system by a membrane, and a mechanism to fracture the membrane. In the current system, the mote is a 2 cm square device on a PCB with a similarly sized lithium battery, and is assembled with the trigger and additional electronics to demonstrate system-level membrane fracture. All components of the system are being moved toward single-chip silicon implementation or integration.

II. XENON DIFLUORIDE RESULTS

To achieve transience of a silicon chip, XeF₂ is used to attack and etch the silicon based IC. A solid source of XeF₂ remains in an isolated chamber until it is time to etch the chip. At that point, the barrier between the two is removed allowing the gas to make contact with the silicon to begin the etch. The etch byproducts are never removed so the etch rate is both slower and less controllable than in commercial XeF₂ etching systems. To characterize this etch, experiments were run on 100 µm thick silicon chips in etch conditions similar to the in-package conditions. The experiments run at room temperature produced an etch rate of roughly 0.1 µm
per minute. Assuming that the target IC could be thinned to 50 $\mu$m, this would result in complete etching of the chip in just over 8 hours. Figure 2 shows how the etch rate changes as a function of temperature. In the best case a thinned silicon chip would etch in about 2 hours.

There is an XeF$_2$ etching modality that is much faster. If the silicon is brought into direct contact with solid XeF$_2$, a violent and rapid reaction occurs. This process is so exothermic that it has melted the silicon in some experiments. Contact etching could lead to the complete consumption of a thinned IC in less than 30 seconds.

**III. MEMBRANES, HEATERS, AND HAMMERS**

Two approaches are being developed to initiate the release of XeF$_2$ to the chip. The first method uses a metal foil to keep the XeF$_2$ and chip separated. This foil is ruptured by the pressure wave resulting from the ignition of nitrocellulose. The second method uses a microfabricated membrane to contain the XeF$_2$ until it is impacted with a MEMS actuator which releases the chemical.

The first approach utilizes heaters printed on glass using a silver nanoparticle ink. The heater ignites a millimeter-scale charge of nitrocellulose, which produces an overpressure that ruptures the membrane.

The microfabricated solution uses a MEMS actuator to store and rapidly release single-digit microjoules of mechanical energy to fracture the membrane between the chip and the XeF$_2$. The MEMS actuator developed for this task, called a MEMS Hammer for its ability to fracture other structures, is fabricated in a two-mask silicon-on-insulator (SOI) process and can be seen in Figure 4. This device is composed of three main components: a cylindrical impactor, energy storing beams and a latching mechanism. In standard operation, the lever arm is pushed towards the right using a probe tip. As the lever arm rotates about the pin, it catches the hammer and starts loading the energy storing beams. In the design shown, a mechanical latch is moved to the side to allow the lever arm to pass by. Finally, the mechanical latch is moved back into its resting position and the hammer is latched in a high-energy state. In different versions of the device, this latching is performed electrostatically by applying a potential across the electrostatic latch contacts. The impactor can then be released by either removing this potential or moving the mechanical latch [2].

The membrane that contains the XeF$_2$ is fabricated in the same two-mask SOI process as the MEMS Hammer. This process allows for the thin buried oxide to act as the barrier between the XeF$_2$ and the chip. Figure 5 shows a membrane with radius 600 $\mu$m from top down and in cross section. During use, the MEMS hammer is rotated such that its cylindrical impactor aligns with the center of the membrane, shown in Figure 6. Once the hammer is released, it makes contact with the membrane and fractures the buried oxide, releasing the XeF$_2$ into the area of the package containing the chip.

**IV. SINGLE CHIP MOTE**

The choice of XeF$_2$ as a destruction mechanism creates a unique set of circuit design criteria. Off-chip components are generally made out of ceramic, quartz, or other materials that are not affected by XeF$_2$ and therefore cannot be used. Thus the total system including a microprocessor, radio, power management, and sensor interfaces must be fully integrated in a silicon-based CMOS process. The system-level goal is to implement a destructible wireless sensor node, hereafter called Single Chip Mote (SCM), that can inter-operate with other existing hardware using the IEEE 802.15.4 standard. SCM is intended to leverage pre-existing work by implementing a Time Synchronized Channel Hopping (TSCH) network.
SCM is built around an ARM Cortex-M0 with custom digital hardware for operating the radio independent of the microprocessor as preferred in a low-power time synchronized network implementation. A block diagram of the current implementation of the transceiver is shown in Fig. 7. A suite of integrated timers provide the necessary hardware for operation with OpenWSN, which already supports running on a FPGA-based revision of the digital system. An on-chip ADC provides the capability to interface with a variety of silicon based MEMS sensors which could also be destroyed by XeF$_2$. The transceiver is designed with low power operation in mind and is intended to operate with a free running CMOS oscillator. Previous crystal-free transceivers have been built, but typically utilize non-standards based communication schemes [4], have large receiver bandwidths [5], or utilize other off-chip high-Q components [6].

An initial prototype was fabricated in TSMC 65nm which addressed the power consumption issue by implementing a design similar to [7] in which a passive RF front-end is used is place of a LNA and active down-conversion mixers. The on-chip RF local oscillator (LO) is the dominant power consumer in receive mode and is constructed from a free-running LC resonant tank which consumes 1 mA of bias current. The direct modulation transmitter consists of a Class D power amplifier outputting -5 dBm and is directly driven by the LO which is modulated by a digitally controlled capacitor bank. The transmitter uses this capacitor DAC to implement Minimum Shift Key which is equivalent to the OQSPK-HSS modulation required by IEEE 802.15.4 [8].

The lack of an accurate, off-chip timing reference affects RF performance, channel tuning, and network synchronization. Network synchronization typically utilizes a low frequency oscillator which is responsible for adhering to transmission and reception time slots dictated by the network schedule. It has been shown in [9] that network level feedback can be used to correct for the drift of a poor low frequency reference. The implicit exchange of timing information obtained through the use of a scheduled network can be used to keep nodes synchronized. The degradation in RF performance from the phase noise of a low power free running oscillator was investigated in [10] and found to be acceptable for an IEEE 802.15.4 receiver. The remaining challenge is then the accurate, repeatable tuning of the LO to a specific channel for transmission or reception. Phase noise and environmental factors like temperature will cause the frequency of the LO to vary and drift over time. Fig. 8 shows the average frequency of the LC oscillator averaged during every 100 ms interval over a span of 13 hours. The effect of temperature has been removed by placing the oscillator inside a temperature controlled chamber at 25 °C. It can be seen that from noise sources alone the free-running oscillator drifts less than the +/- 40 ppm specification dictated by IEEE 802.15.4.

The designed LC tank’s oscillation frequency does however have a significant dependency on temperature of 100 ppm/°C. Temperature is generally a slowly varying factor compared to the rate at which packets containing timing correction information can be exchanged within a network. In a low-Intermediate Frequency (IF) receiver it is possible to estimate the error in frequency between the transmitter and receiver by measuring the average IF during packet reception. This estimated frequency error can then be driven to zero using feedback. This will force the receiver to tune its LO in an attempt to hold the difference between transmit and receive frequencies at the desired IF. In order to validate this method a transmitter was subjected to a 2 °C/min temperature ramp while a receiver attempted to track it. Fig. 9 shows the result of measuring the average IF on a receiver with and without the feedback mechanism. The receiver is able to hold the IF constant to within the accuracy of its estimate, which is dependent on the accuracy of the network calibrated clock running the digital system.

The combination of techniques detailed here enable the deployment of wireless nodes with no external components that can be completely etched using XeF$_2$. Compensation using network level feedback in a TSCH network is key to implementing narrow-band transceivers using free-running CMOS oscillators.

V. BATTERIES

In order to support the power demands of each system component, an energy storage device needs to be incorporated in the final design. The storage device has several requirements,
including high energy density for inclusion in a chip-scale package, air stability to ease encapsulation specifications, and low series resistance to provide high (several milliWatts) instantaneous power delivery. While several commercially available devices were considered, a printed battery was chosen to provide seamless integration of device and energy storage and to allow greater design flexibility in its incorporation. Among several possible battery chemistries, silver-oxide batteries were most attractive for this application due to their high energy density of 130 Wh/kg, high discharge rate capability, good charge retention, and inherent air stability [11].

Development of a fully printed silver-oxide battery began with design of the separator and electrode materials. Each component ink was formulated within the rheological guidelines of stencil printing, which was the chosen fabrication method to print the thick active layers (50-500 µm) necessary to achieve high areal capacities. A novel poly(acrylic acid) (PAA) sol-gel electrolyte was first introduced as a free-standing separator layer with high ionic conductivity [12]. The PAA sol-gel was photopolymerized using the photoinitiator IGRA-cure 2959 and crosslinked with poly(ethylene glycol) divinyl ether. A 1 wt% crosslinker solution was used to maximize the Youngs modulus of the sol-gel while maintaining a suitable ink viscosity for stencil printing. Water soluble poly(ethylene oxide) binders were then prepared for the zinc and silver oxide electrode inks. Active species concentrations were maximized to improve areal and volumetric capacity while maintaining suitable ink viscosities. Additives were included in the zinc electrode ink to prevent zinc corrosion in the presence of potassium hydroxide.

Batteries were fabricated with a 4 mm² active area and displayed an open-circuit potential of 1.53-1.55 V. Discharge characteristics were observed for the fully printed cells at 2C, C, and C/2 rates with respect to silver oxide capacity (Figure 10). The highest observed areal capacity was 9.5 mAh cm⁻² at a C discharge rate of 4.8 mA cm⁻². Typical capacities ranged between 8-9 mAh cm⁻² with internal resistance values below 30 Ω. High silver oxide utilization was also achieved, ranging between 75-90% of the deposited silver oxide. In addition, battery scaling was demonstrated down to 0.5 mm² with similar areal capacities and internal resistance values below 100 Ω. Future work includes characterizing battery performance under trickle charging to simulate low duty-cycle discharging paired with the added capacity of an on-chip solar cell in tandem with the on-chip printed battery.

VI. CONCLUSION

Crystal-free mesh networks of millimeter-scale single-chip wireless sensor nodes appear to be possible. Triggered transience of such chips will leave behind only a plastic package, SiF₄ gas, and a small residue of crumpled CMOS metalization and thin-film battery.

REFERENCES