SYSTEM-ON-A-CHIP (SOC) MODELING OF A BIO-MEMS SENSOR

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ABSTRACT

This paper brings System-on-a-Chip design principles to the field of biomedical engineering. Herein presented is a system-level approach to the development of SoC models of biosensor devices. A detailed analysis of biosensor device operation and a description of SoC modeling design principles of such sensors is provided.

1. INTRODUCTION

Recent IC designs have seen the integration of sets of complete yet complex devices in the development of systems-on-a-chip (SoCs). SoC designs are ameliorating the advancement of image processing, biomedical engineering, communications, and network systems. [1, 2] Such systems typically contain many processors, ASICs and thousands to millions of lines of embedded code. Essential to today's semiconductor industry is rapid delivery of these systems. As such, early and accurate modeling of an entire system is essential for lowering the time-to-market of complex embedded SOC systems. Modeling SoCs requires the development of system-level design specifications that define both the hardware and embedded software contained within SoCs. [3]

This paper will show a set of SoC models for biosensor devices. Typically, full system modeling of sensors and related SoC devices involves the analysis of circuit equations that describe the functionality of the system. Today's biosensor modeling is limited to computer-aided electrical circuit analysis software such as SPICE and AMS. The models presented here differ from previous work [4,5] in that they are developed to be system modules that can be applied to System-C library and Matlab/Simulink environments. In addition to this, the output characterization of these SoC modules will be compared against those of traditional SPICE models.

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This paper is divided as follows. Section II will discuss SoC Modeling techniques as they related to System-C and related HDLs. In Section III, we present an in depth overview of a bio-sensor which will be modeled according to system-level design principles. Section IV, provides a description of the SoC model of the biosensor. Section V, is a discussion of conclusions for this modeling design principle and its relevance to the development of a bio-sensor subblocks designed for system-on-a-chip integration.

2. SOC MODELING

SystemC and other HDLs make it easy to combine multiple IP blocks into a single simulation. As such, the proposed models are high-level descriptions of biosensor devices. Figure 1 presents a block diagram of the biosensor presented in this study. The approach to module development (system level design) of biosensors involves creating the full model of the sensor and capturing the inputs and outputs between each stage of the system. The output of the systems modules are then compared against simulated outputs of electrical equivalent circuits. The system module development scheme described herein will augment traditional methods of developing models of biosensor devices and facilitate the incorporation of these sensors in SoC designs.

3. BIO-MEMS SENSOR FOR REAL-TIME FLUIDIC PROPERTY ANALYSIS

Restoration of normal chemical balance in the body is an integral component of treatment of illness. In healthy people, this balance is maintained by a number of biological sensors and actuators, which enable the complex functions of major organs including the liver, kidney, and pancreas. Physicians and health care professionals use biological fluid samples taken from patients for analysis in order to assess the status of the

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component hemeostatic mechanisms of the body and then determine appropriate therapy. To that end scientists in many fields of worked together to develop electronic, biochemical, and chemical biosensors and BioMEMS Devices to aide in the monitoring of patient fluids and related statistics.

Biosensors have proven useful for many facets of the medical field including: modeling shear stress in arterial bifurcations, performing early warning analysis of elevated protein levels in biological fluid, and developing interfaces between biological systems and retinal prosthetics. [6, 7] This work focuses on the development of SoC models of biosensors for fluidic property analysis. Characterization of fluid properties is essential to the development of early warning devices for the rapid detection of biodegradable substances in water and for in-vitro monitoring of fluids in kidney dialysis patience and individuals with diabetes. [8, 9]

More specifically, bio-MEMS sensors have proven useful for many facets of the medical field. [6, 7] This work also considers the development of SoC models of bio-MEMS sensors for shear stress analysis. Characterization of shear stress in arterial trees is essential to understanding the effects of spatial versus temporal shear stress gradients on the biological activities of endothelial cells (EC). In [6], we find a micro electrical mechanical systems (MEMS) sensor has been developed, which mimics the spatial and temporal resolution of an EC. Shear stress is relevant as it regulates EC morphology and their related complex biological activities.

Essential to the construction of micro-fabricated arterial bifurcations is a flow system designed to deliver well defined flow profiles simulating pulsatile and oscillating flow conditions in arterial circulation. Pulsatile flow in a two-dimensional channel can be defined in terms of decomposed sine/cosine functions and angular frequency. The theoretical formulation of pulsatile flow as shown by the channel in figure 5 can be found on line at http://atvb.ahajournals.org. The system-level view of the flow channel can be found in figure 6.

4. SOC MODELING, DESIGN LANGUAGES, AND BIO-SENSOR SUBBLOCKS

The semiconductor industry will soon see software and hardware design streamlined into a single flow process. The increasing complexity of Systems on a Chip (SoCs) has introduced the need for abstract executable specifications that cover both hardware and embedded software. Hardware description languages (HDLs) like SystemC ameliorate the development of such specifications (models).

SystemC is a standard design and verification language that spans from concept to implementation in hardware and software. Prior to 1999 there were many proprietary C or C++ based SoC design environments that did not have an open standard. As such their usefulness was limited since model availability from IP vendors did not exist. SystemC was developed by the Open SystemC Initiative (OSCI) a consortium of major EDA and IP companies that contributes to and governs SystemC development and distribution. It has now become the de facto standard for system level design. As such, IP vendors are beginning to provide SystemC compatible models of their IP.

A SoC system may be modeled as a collection of modules that contain processes, ports, channels, and in some instances other modules. Processes define the behavior of a particular module and provide a method for expressing concurrency. A channel implements one or more interfaces. Such interfaces are collections of methods (function definitions). A process accesses a channel's interface via a port on the module. The success of a system-level design (SLD) process depends on the SLDs ability to provide system designers with a continuous flow of system information from specification through implementation.

The biosensor evaluated in this work and shown in figure 1 measures the balance in output voltage and current over each of the two stages of the device. The first stage is a cascade configuration comprised of two diode-connected transistors and a voltage controlled transistors. Varying the input voltage on the voltage controlled transistor allows for controllability in current flowing through both stages of the sensor network. The second stage is made up of 3 diode connected transistors connected in parallel. As water-based fluids possess dielectric constants equal to 4-times the K-value of the transistors, the center sensor in stage 2 is comprised of 4 parallel diode-connected transistors.

Contact between the fluid and the gate are made with the aide of a MEMS sacrificial etch step. When fluid comes in contact with the gate, the K value of the transistors becomes modified by the inherent dielectric properties of the fluid under test. This results in a shift in current flowing through the second stage of the biosensor system. Figure 2 (a)

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and (b) shows a SPICE simulated output of normal device operation (a) and normal device operation with an altered K-parameter. In both graphs the control voltage, Vset is varied from 0 – 5V in to isolate the input voltage that achieves the required circuit balance.

The process of transforming this device into an equivalent SoC sub-block model involves: translating the analog circuit design of figure 1 into an equivalent system-level model (as shown in figure 3) followed by generating the logic schematic of the complete digital system. This system-level equivalent device is modeled with VHDL and translated into its system-on-a-chip equivalent sub-block as defined by SystemC specifications. At this stage of modeling the SoC sub-block implementation of the fluid property test chip can now be downloaded and added to any library globally; thus, facilitating circuit design and time-to-market challenges.

5. CONCLUSIONS

The authors present a procedure for developing system-on-a-chip (SoC) models of biosensor and bioMEMS devices. The ideas behind this work involve translating the analog model of a biosensor into a system-level model and equivalent digital logic structure. The resulting combinational logic for the biosensor is then translated into VHDL. The VHDL model is automatically translated into a SoC model with the aide of vhdl-to-systemC. The SoC system-level modeling procedure biosensor and bio-MEMS devices are presented.

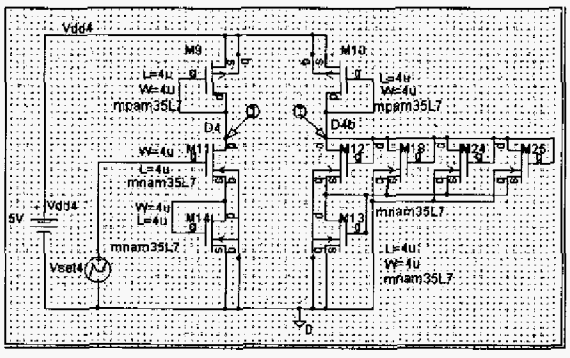

Figure 1: Analog Implementation of Voltage Controlled BioSensor

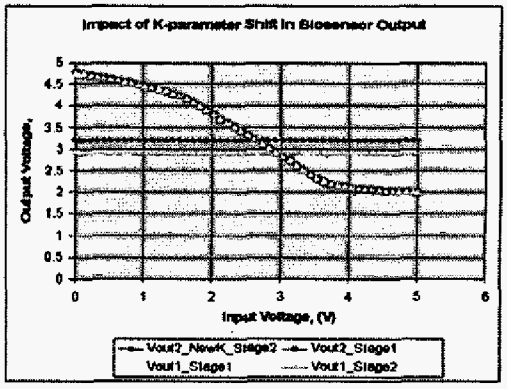

Figure 2. This figure shows the shift in the balanced output of the biosensor device for unique K-parameter values. It is a simulation of the output of a biosensor in- and out- of the presence of a fluid.

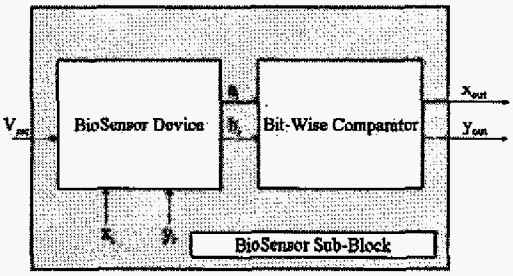

Figure 3: System-level implementation of SoC biosensor test device.

VHDL For The Biosensor Circuit

```
-- Interface
entity BIOS_CNTRL is
port
  (YI, XI, AI, BI : in BIT;
   XOUT, YOUT :  out BIT;
end BIOS_CNTRL;

-- Body
architecture STRUCTURE of BIOS_CNTRL is
--Declare logic operators
 component AND2_OP
    port(A, B : in BIT; z : out BIT;
  end component
component OR2_OP
    port(A, B : in BIT; z : out BIT);
end component
component NOT_OP
  port (A : in BIT; Z_BAR : out BIT);
end component
```


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```
-- Declare signals to interconnect logic operators
signal BIO1_BAR, BIO2_BAR, BIO3_BAR,
BIO4_BAR, INT2, INT1 : BIT;
begin
-- Logic for XOUT
I2: NOT_OP port map (BI, BIO2_BAR1);
I4 : NOT_OP port map (YI, BIO4_BAR);
A1 = AND2_OP port map (BIO2_BAR, AI,
BIO4_BAR, INT1);
O1 = OR2_OP port map (INT1, XI, XOUT)
-- Logic for YOUT
I1 : NOT_OP port map (AI, BIO1_BAR);
I3 :  NOT_OP port map (XI, BIO3_BAR);
A2 : AND2_OP port map (BIO3_BAR,
BIO4_BAR, BI, INT2);
O2 = OR2_OP port map (INT2, YI, YOUT);
end STRUCTURE:
```

Figure 4: VHDL Code of complete biosensor subblock.

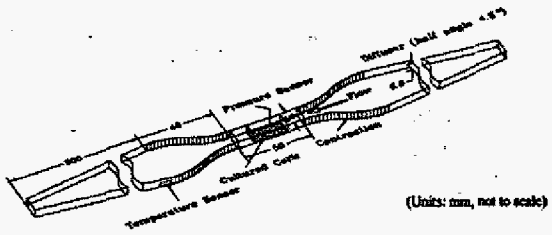

Figure 5. Parallel Plate Flow channel for Model of Pulsatile flow.

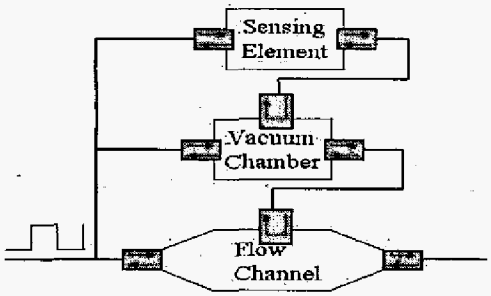

Figure 6. System-level design schematic of bio-MEMS sensor.

6. ACKNOWLEDGEMENTS

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