A 200 µm by 100 µm Smart Dust System with an Average Current Consumption of 1.3 nA

Dominic A. Funke[†], Pierre Mayr[†], Lukas Straczek[*]
John S. McCaskill[‡], Jürgen Oehm[*], Nils Pohl[†]
Analogue Integrated Circuits Research Group, Ruhr-University Bochum[*]
Chair for Integrated Systems, Ruhr-University Bochum[†]
Microsystems Chemistry and BioIT (BioMIP), Ruhr-University Bochum[‡]

Abstract—**In this paper we present a microscale "Smart Dust" type system with a volume of 200 μm x 100 μm x 10 μm, called lablet. The lablet contains a 20 Hz low power clock generator, a sensor, electric actuators and a simple finite state machine to implement a predefined response to the sensor input. The system operates with supply voltages ranging from 0.3 V to 1.8 V and is thus suitable to be supplied from a capacitor with decreasing voltage. An input rectifier allows powering the lablet independent of polarity. The average current consumption of the system was measured to be 1.3 nA when supplied from a capacitor with an initial voltage of 1.8 V. The system is intended to be used within electrolyte solutions. The small system scale allows the investigation of "pourable electronics", a concept where large quantities of microsystems are deployed within a chemical solution to perform a predefined task. Several lablets have been designed and fabricated in a standard 180 nm CMOS process and the electrical functionality has been verified by contacting the lablet electrodes with multiple probe needles.**

I. INTRODUCTION

Several ultra miniaturized autonomous systems have been published and are often referred to as "Smart Dust" [1]. Smart Dust systems have a variety of functionality integrated into a volume of a few cubic millimeters or less [2]. System components include digital processing capabilities, different types of sensors (temperature, vibration, and others), analogue to digital converters [3], communication (optical [4], RF) and usually one type of energy harvesting and storage device. Smart Dust systems usually benefit from the combination of standard CMOS electronics and MEMS. CMOS circuits are capable of providing digital and analog signal processing, while the MEMS part provides sensing and energy harvesting functionality. Therefore, typical Smart Dust systems consist of several sub systems, each manufactured individually [5].

A significant further decrease in system volume is only possible if all necessary subsystems are implemented onto one monolith. The design of an autonomous system at microscopic scales (approaching that of living cells), namely 100 µm by 100 µm, called lablet, is proposed in [6]. This lablet is supposed to have all essential properties, except global wireless communication, of a Smart Dust mote like power supply, (digital) control circuitry as well as sensing and acting capabilities with a system volume which is a factor of 1000 smaller than other reported Smart Dust motes. Lablets avoid the large footprint of antennae using the novel concept of pairwise reversible self-assembly based communication. With these constrains given, every subsystem of the lablet must be optimized for minimum circuit area. Since the available energy in a lablet is also very small, ultra-low-power design is mandatory. In this paper we focus on the circuit design of the lablet. The presented system should be regarded as a demonstrator system, designed to investigate the possibilities of extreme system miniaturization. Even though the presented system area of 200 µm by 100 µm is larger than targeted in [6], all circuity is located within the 100 µm by 100 µm target area.

II. PROPOSED SYSTEM

The overall function of the proposed system is to respond to changes of the measured input potentials with different voltage patterns at the actuator electrodes. The schematic of the lablet circuitry is depicted in fig. 1. The system is clocked by the slow, low-power clock generator presented in [7] with a frequency of approx. 20 Hz and 4 flip-flops providing a /16 frequency division resulting in a clock frequency of approx. 1-2 Hz. Low clock frequencies are beneficial since dynamic power consumption is proportional to the system clock frequency. As the intended field of application is the interaction with chemical reactions, a response within the timescale of a second matches well the typical time constants of many chemical reactions which are usually in the second to minute timescale. The signal input to the circuit are sensor electrodes sens1 and sens2. A sensor circuit, which will be described in section III of this paper, compares the potential at both electrodes and outputs a binary signal to the subsequent finite state machine. Depending on the sensor output, the finite state machine generates control signals for the tri-state buffers. Power can be supplied to the circuit via the two supply electrodes sup1 and sup2. A rectifier makes the power supply independent of supply voltage polarity. For test purposes, the supply voltages nodes of the circuit can be directly accessed, bypassing the rectifier. As suggested in [6], future versions of the lablet are planned to be equipped with an on-chip supercapacitor providing a capacitance of a few μF. In [8] it has been demonstrated that it is possible to fabricate supercapacitors that are compatible with CMOS. The small amount of energy that can be provided by the storage capacitor necessitates ultra-low-power design. A second implication that arises from the use of a capacitor as energy storage is that the system should be able to operate with a large range of supply voltages, since the voltage of a capacitor decreases when current is consumed. If the system was not able to operate with lower supply voltages, the remaining charge in the capacitor would be waisted. To put things into context, it is assumed that the time of operation of the lablet must be at least 15 minutes in order to perform useful experiments and a supply voltage between 1.8 V and 0.3 V

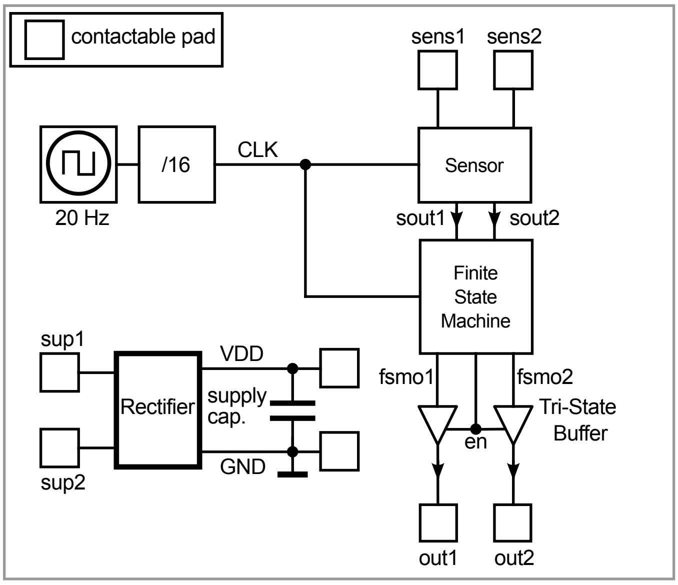

Fig. 1. System schematic of the proposed system consisting of clock generator, sensor circuitry, control logic and actuators. The supply capacitor is not yet implemented into the presented demonstrator.

is sufficient for the system to operate. The average current consumption must then be less than

$$I_{avg} = \frac{C \cdot \Delta U}{\Delta t} = 1.7\,nA. \tag{1}$$

Consequently the leakage current of the supply capacitor must be considerably smaller then I_{avg}.

The finite state machine is a 3 bit counter and a set of logic gates that translate the counter state to the signals fsmo1, fsmo2 and the enable signal for the output tri-state buffers. Possible output states for (out1/out2) are (1/0),(0/1) and (Z/Z), where Z means high impedance mode.

III. SENSOR CIRCUIT

The operating conditions of the lablet electronics are rather challenging for the design of a sensor integrated into the lablet: The power consumption must be below one nW to comply with the runtime and energy storage specification, the sensor must have a large power supply rejection ratio, since during operation the supply voltage of the lablet will drop from 1.8 V to approx. 0.3 V and the circuit area must be a fraction of the 200 μm by 100 μm chip area. Reference voltages that are often used in analogue to digital converters, require a minimum supply voltage and a constant current that represents a load to the energy supply of the circuit. For these reasons, a design without a reference voltage was pursued.

These requirements have been addressed by the circuit presented in fig. 3. Assuming a coating of the sensor electrodes is available that generates a differential voltage proportional to the (chemical) quantity to be measured at the sensor electrodes, the required information can be obtained by comparing the potential of the sensor electrodes [1]. For the intended application of the lablet, a high resolution of the sensor is not required. In fact it is sufficient if the sensor is able to detect a change of it's environment from one state to another. The lablet can then react to the detected change. The electrodes sens1 and sens2 are connected to the gates of M2 and M3, the currents I_{M2} and I_{M3} are therefore directly correlated to the potentials of sens1 and sens2. Since I_{M2} and I_{M3} must be provided by the energy source of the lablet, heavy duty-cycling has been used to comply with the low-power requirement. Instead of comparing I_{M2} and I_{M3} continuously, for instance by a source coupled pair, the two currents are used to charge capacitors C1 and C2, which are equal in capacitance. The transistor with the higher current is therefore faster in charging it's capacitor. The readout procedure starts with a rising edge of the clock signal. The pulse generator generates a short pulse (init) which activates transistors M4 and M5 which discharge capacitors C1 and C2. M1 is non-conducting during the discharge process to prevent short circuit currents. After the init signals returns back to 0, C1 and C2 are charged. When the voltage of capacitor C1 or C2 reaches the threshold voltage of it's corresponding CMOS inverter Inv1 or Inv2 in the evaluation circuit, the corresponding RS flip-flop is set to 1. If one of the flip-flops is set to 1, the activation of the other flip-flop is blocked by the feedback loop, which consists of the NOR and AND gates. The digital output can then be read at sout1 and sout2. sout1=1 and sout2=0 means the potential of sens1 is lower then sens2 and vice versa. The total readout time is within the ns scale. Short readout times are important for low power consumption, because Inv1 and Inv2 exhibit significant short circuit currents while their input voltage V_{in} is $V_{th,n} < V_{in} < VDD - V_{th,p}$. $V_{th,n,p}$ are the threshold voltages for n- and p-channel transistors.

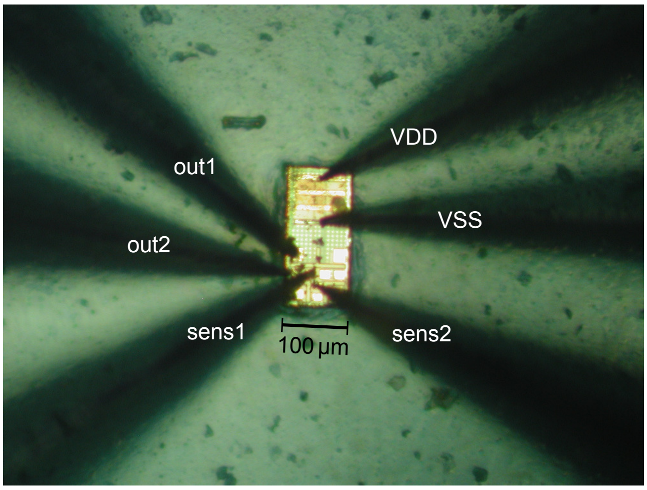

Fig. 2. Micro-photograph of the measured chip with probe needles attached to it.

IV. MEASUREMENT RESULTS

The system presented in the previous sections of this paper has been measured by making use of a wafer probing station. Up to six probe needles were connected to the lablet as depicted in fig. 2. The measurement setup used to verify the functionality of the sensor and state machine circuit is depicted in figure 4. In this setup the output signal of the lablet can be monitored in dependence of the sensor input signals sens1 and sens2 as well as the supply voltage VDD. Fig. 5 shows the distinguishable output signals for V(sens2) > V(sens1) and

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[1] Coating the gate electrode of a FET in a way that makes it respond to chemical properties (pH, concentration) is often referred to as ISFET (ion sensitive field effect transistor) or chemFET - a concept well investigated in literature [9], [10].

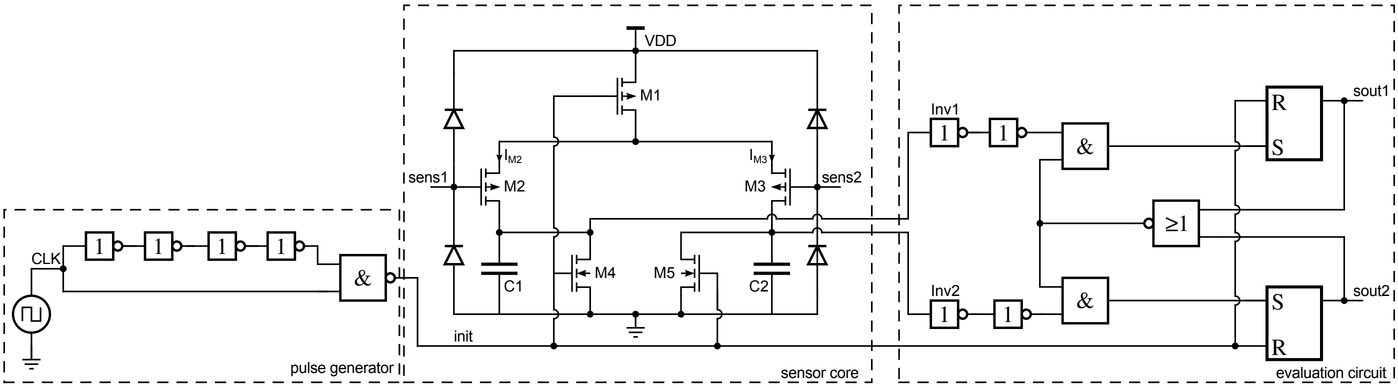

Fig. 3. Sensor circuit consisting of pulse generator, sensor core and evaluation circuit. sens1 and and sens2 are connected to the electrodes of the lablet. The diodes provide some basic protection against electro static discharge.

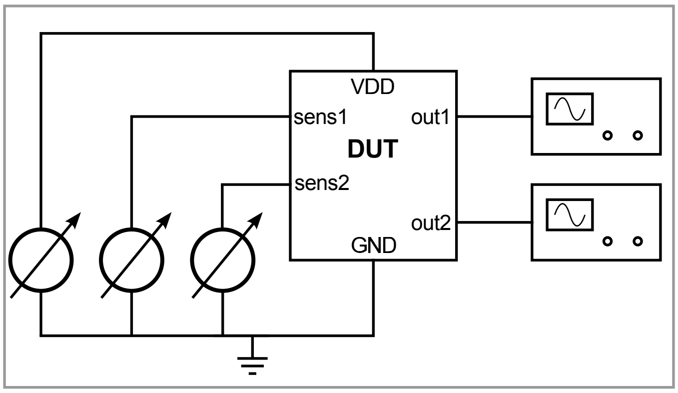

Fig. 4. Setup used to verify the functionality of the sensor circuit and the state machine.

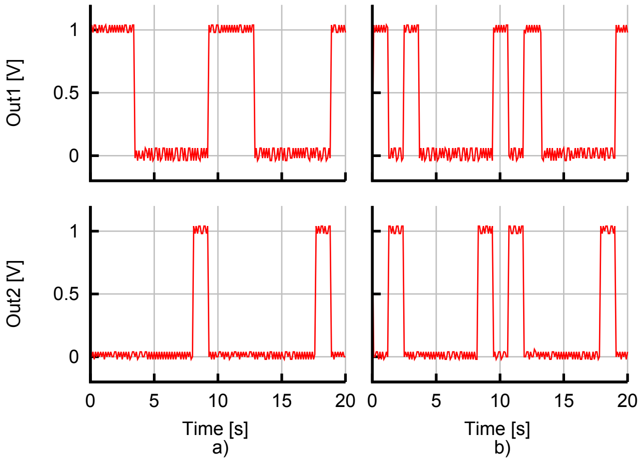

Fig. 5. Output signal of the lablet electrodes out1 and out2 for different sensor input signals. a): output pattern A and b): output pattern B. Pattern A occurs for sens2 > sens1 and pattern B occurs for sens1 > sens2.

V(sens2) < V(sens1). The sensor circuit has been tested for different supply voltages as well as different common mode voltages of sens1 and sens2. To determine the sensor threshold, the voltage of sens1 has been swept in steps of 1 mV while a constant potential was applied to sens2. When the potential difference between sens1 and sens2 was close to the sensor threshold, both patterns could be observed when observing the lablet over a longer period of time. This is most likely due to noise within the measurement setup. Therefore, the output pattern state was defined to be stable if 10 consecutive patterns where identical. Fig. 6 shows the results of the sweeps. As can be seen in the plots, the threshold voltage shifts in the measured set of parameters from approx. -10 mV to 10 mV. That means voltages differences of more than 20 mV can be clearly identified by the sensor circuit.

Since the system is intended to be supplied from a capacitor, the runtime of the lablet was estimated by connecting a 1 μF foil capacitor to the VDD and GND electrodes of the lablet as depicted in fig. 7. At the beginning of the experiment the capacitor was charged to 1.8 V. The oscilloscope used to observe the output of the lablet has an input resistance of only 1MΩ which is significantly lower then the equivalent resistance of the lablet. Therefore a buffer PCB was designed based on the Texas Instruments INA116 instrumentation amplifier. The INA116 has a FET input and according to it's data sheet a typical input bias current of 3 fA. Special attention was paid to minimize leakage currents through the PCB. With this setup it could be verified that the lablet is operating and since the voltage of the capacitor is the same as the high level of the output signal, the capacitor voltage can be monitored. A diagram of the capacitor voltage versus time is shown in fig. 8. The observed time of operation was approx. 19 minutes. This is equivalent to an average current consumption of

$$I_{avg} = \frac{C_{sup}[V_{start} - V_{end}]}{t_{op}} = 1.3\,nA \tag{2}$$

where C_{sup} is the supply capacitance, V_{start} and V_{end} are the capacitor voltages at the beginning and at the end of the experiment and t_{op} is the observed time of operation.

V. CONCLUSION

We have investigated the possibilities to design microscale electronic systems and found, that it is possible to design a system with dimensions of 200 μm by 100 μm. The presented demonstrator provides sensor and actor electrodes allowing the system to interact with it's environment. The interaction is defined by a finite state machine. As low power design is mandatory at the microscale, all system components were optimized for minimum power consumption. The average system current consumption was measured to be 1.3 nA when supplied from a 1 μF capacitor with an initial voltage of 1.8 V and a final

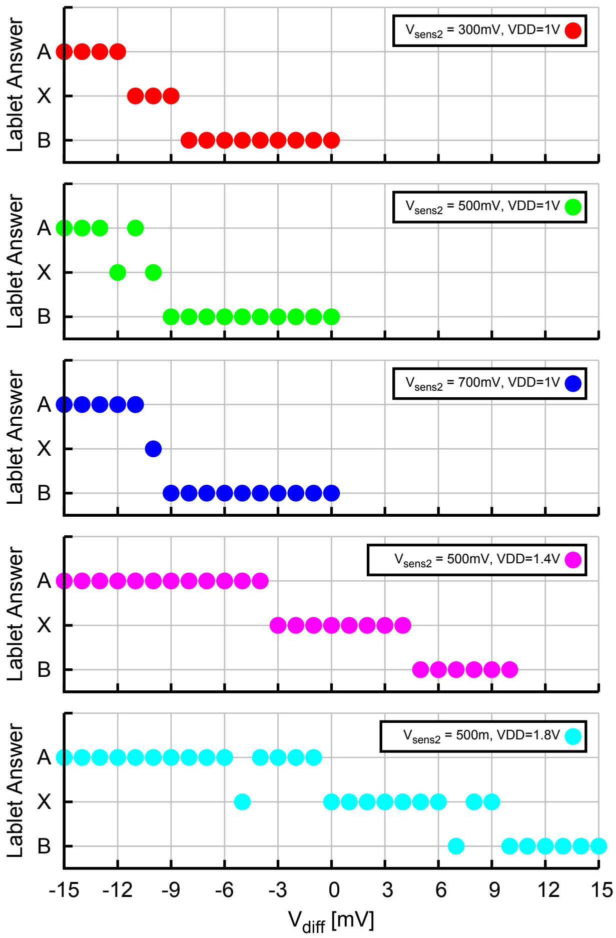

Fig. 6. Response of the Lablet in dependence of the differential sensor input voltage for different common mode voltages and different supply voltages. The y-axis indicates the observed pattern with reference to fig. 5.'X' means that both patterns could be observed during the period of 10 consecutive measurements. V_{diff} is the potential difference V(sens1) - V(sens2).

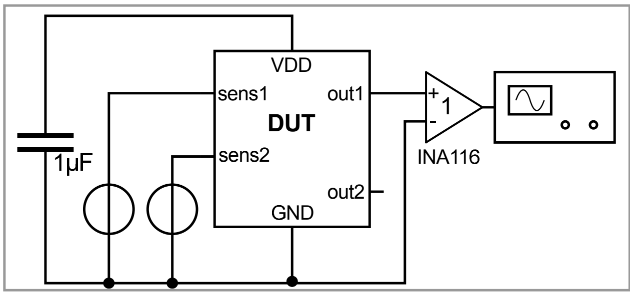

Fig. 7. Setup to determine the runtime of the lablet when supplied from a 1 μF capacitor. The instrumentation amplifier INA116 from Texas Instruments was inserted to protect the lablet from the low oscilloscope input resistance of only 1 MΩ. In this measurement sens1 was kept to 450 mV while sens2 was kept to 500 mV. Out2 was floating.

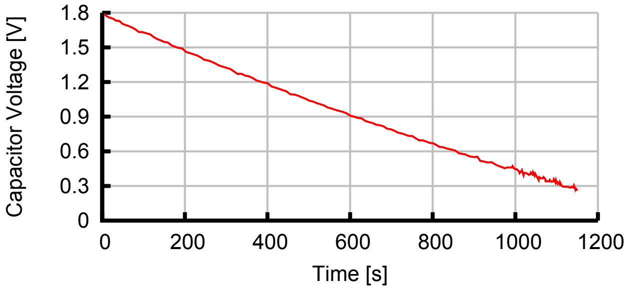

Fig. 8. Capacitor voltage estimated by the high level of the output signal of the lablet. Operation of the lablet could be observed for 1150 seconds.

voltage of 0.3 V. The runtime in this case was measured to be approx. 19 minutes. The presented work should be regarded as a demonstrator device for microscale electronic systems. Future versions of the lablet can include more complex digital circuitry that allows the lablet to execute a series of predefined tasks in dependence of it's chemical environment.

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