

A Novel SOI CMOS Compatible Thermal Device Technology

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ABSTRACT: A radiation-hardened SOI CMOS compatible thermal transducer intended for on-chip data isolation for mixed-signal systems-on-a-chip (SoC) is presented. This device technology is much smaller in size than on-chip inductors and MEMS devices, and requires no post-processing. Further, the device is capable of faster switching speeds (up to two orders of magnitude) than equivalent thermal-based MEMS structures due in part to the smaller thermal mass present in the transducer structure. Structure performance was verified using two- and three-dimensional finite-element simulators. Results show that a thermal-based data isolator can propagate a data bit in under a microsecond, which meets the targeted I²C bus specifications thus proving viability in select SoC applications.

1 INTRODUCTION

Electrical isolation is utilized to improve the robustness, reliability, and noise immunity of electrical systems. An important requirement of systems-on-a-chip (SoC), with combinations of analog, digital and RF circuitry, is on-chip electrical isolation. Isolation improves the noise performance of the overall system by reducing the coupling between the various technologies. Further, it helps to reduce the chances of cascading failures in a system.

Currently available on-chip isolation approaches are either not CMOS compatible (MEMS, optical), not viable for radiation filled environments (optical) or have not yet performed as desired (on-chip transformers, MEMS) [Streetman 1980]. On-chip transformers require significant die area, on the order of 100,000 μm^2 , and the circuits used to drive them consume a considerable amount of power [Nguyen & Meyer 1990]. Even in specialized processes allowing MEMS, devices such as these are typically much larger and slower to respond than required [Parameswaran et al. 1991], [Wojciak et al. 1997].

One solution to a reliable source of data isolation is the use of an on-chip, CMOS compatible electrothermal device. The advantage of using thermal, as opposed to magnetics, as a means of isolation is the current availability of on-chip devices that are able to transmit and receive thermal signals. Also, the thermal based transducers described here can be made much smaller than their magnetic counterparts, typically around 1,600 μm^2 .

The results presented here are based on isolator designs fabricated in 0.8 μm and 0.35 μm silicon-on-insulator (SOI) CMOS processes. SOI technology performs much better in a radiation filled environment compared with bulk CMOS technology [Colinge 1997]. Bulk processes are prone to single-event latchup (SEL), single-event upset (SEU), and other effects caused by particle bombardment. SOI technology is immune to SEL and has proven to be ten times less sensitive to SEU than bulk technology. Furthermore, SOI technology offers superior temperature performance over bulk, including functionality up to 800K.

2 THERMAL TRANSDUCER DEVICE STRUCTURE

Figure 1 shows a cross sectional view followed by a top view of a thermal transducer structure. The transducer structures presented here are approximately 40 μm on a side. The transducer can be decomposed into two sides, the input, or primary side, consisting of a resistor (polysilicon in this illustration) and the output, or secondary side, consisting of a thermal detector (a diode in this illustration). The polysilicon resistor acts as a heater that converts the incident electrical signal to a thermal signal. The diode converts the thermal signal back to an electrical signal. This is accomplished by biasing the detection diode at a fixed forward voltage. When the temperature in the diode structure rises, the detected electrical result is an increase in the diode's forward current. The coupling between the primary and secondary side is enhanced through the use of a thermal lens (aluminum in Fig. 1).

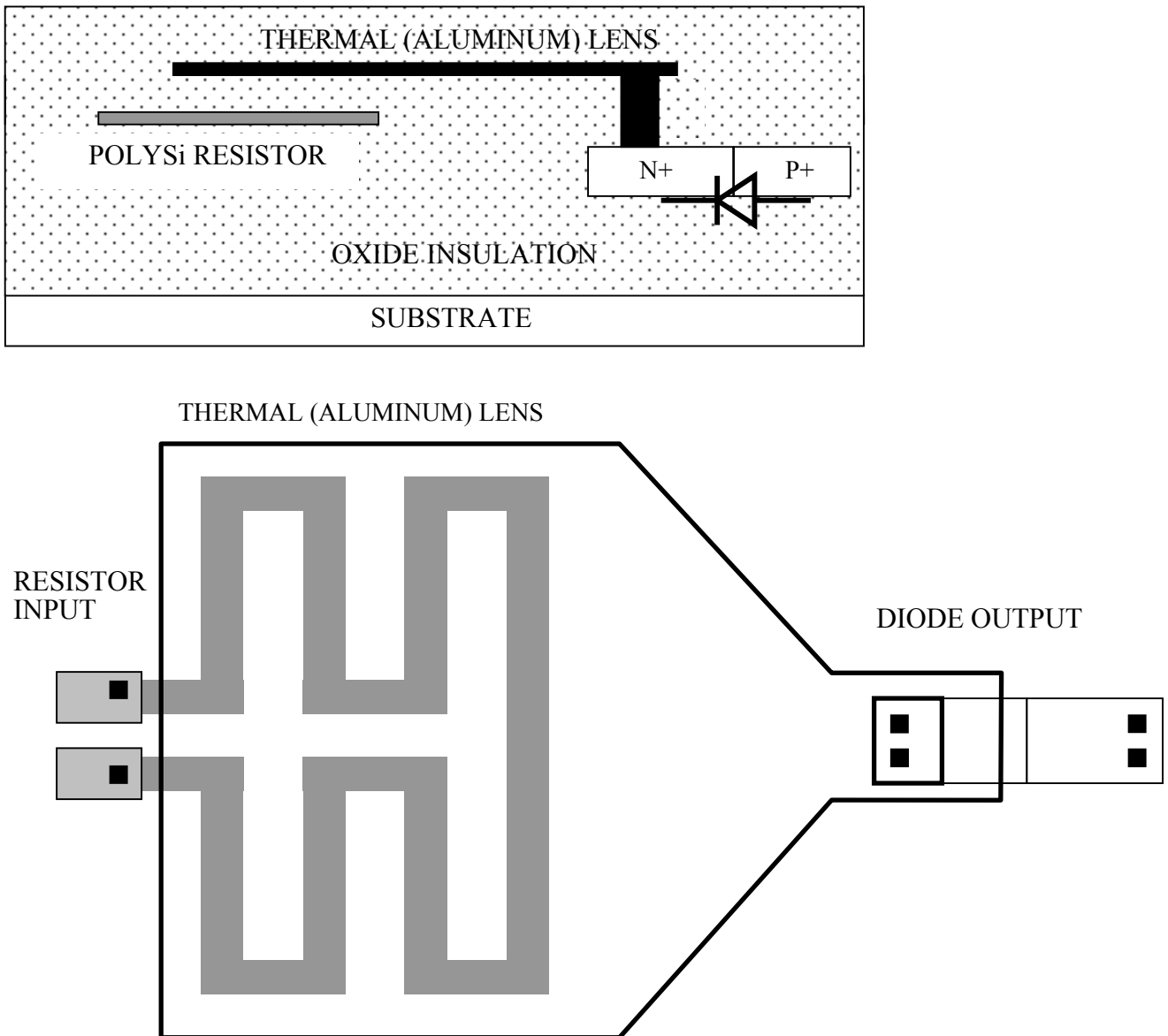


Figure 1. Cross sectional (above) and top view of SOI CMOS compatible data isolator.

The thermal signals generated by the heater propagate outward in all three dimensions. The thermal signal produced by the heater is gathered by the thermal lens and directed toward a set of vias that are connected directly to the cathode of the diode. The thermal signal also propagates directly toward the sensing diode providing two paths for the heat flux. The spacing between the polysilicon resistor and the aluminum thermal lens, as well as the spacing of the sensing diode from the resistor, determine the response time and the electrical isolation characteristics between the primary and secondary sides of the device.

Typically, the thermal transducer structure is chosen such that the realized isolation voltage will meet or exceed the specified isolation voltage. The fundamental criterion in choosing a transducer structure for a specific application is the above mentioned oxide thickness between the primary and the secondary sides. Due to process layout rules, generally the oxide thickness between the resistor and thermal lens is the determining factor in the achievable isolation of a structure.

In Fig. 1 the oxide layer thickness between the polysilicon and the first level of metal in the process is $\sim 0.5 \mu\text{m}$. The spacing of the diode from the poly resistor is governed by the process layout rules to be about $1 \mu\text{m}$. These distances provide enough information to compute the electrical isolation achievable ($\sim 330\text{V}$ maximum for these dimensions) as well as simulate the thermal response time of the device.

Other novel structures can also be built in a typical SOI process. A slightly thicker oxide is achievable using a diffused silicon resistor with an aluminum (Metal 1) lens. The SOI process used here allows a linear capacitor option that consists of a polysilicon top plate with an $n++$ doped diffused bottom plate. The resulting oxide thickness is about an order of magnitude thinner than the poly to metal 1 oxide, which reduces the amount of required input power and/or provides faster response times, but at the same time yields a lower electrical isolation rating ($\sim 60\text{V}$).

3 THERMAL TRANSDUCER OPERATION PRINCIPLES

3.1 THERMAL TRANSDUCER PRIMARY SIDE

Basically, the primary side of the transducer consists of a resistor. The resistor material (e.g., Si or polySi) can vary depending on the transducer structure selected. Once a transducer structure has been chosen according to isolation and speed specifications, a 3D finite element thermal simulator, such as Flotherm[®] [Flomerics, Ltd.], is employed to determine the power dissipated in the resistor that yields a target ΔT ($1\text{--}1.5 \text{ }^\circ\text{C}$ for Fig. 1) at the diode such that a detectable electrical signal ($\Delta I = 1 \mu\text{A}$) is created.

The power dissipated in the resistor must create enough thermal energy to cause the diode temperature to increase by ΔT in the specified amount of time, e.g., the transducer in Fig. 1 is able to pass a data bit in less than $1 \mu\text{s}$ to meet I²C bus specifications. The figure of dissipated power, P_{dis} , is found from the 3D thermal simulation, as shown in Figure 2. Fig. 2 demonstrates the transient thermal analysis of the transducer, where 25 mW of power (a figure that is found to produce the desired response) was dissipated in the resistor. The top graph is a 3D outline of the transducer with a cutaway of the temperature distribution after $1 \mu\text{s}$ superimposed to demonstrate the ΔT at the diode. The bottom graph is a plot of the resistor and diode layer temperatures as a function of time. The dissipated power is then used to find the input current, I , needed according to $P_{dis} = IV$, where V is the

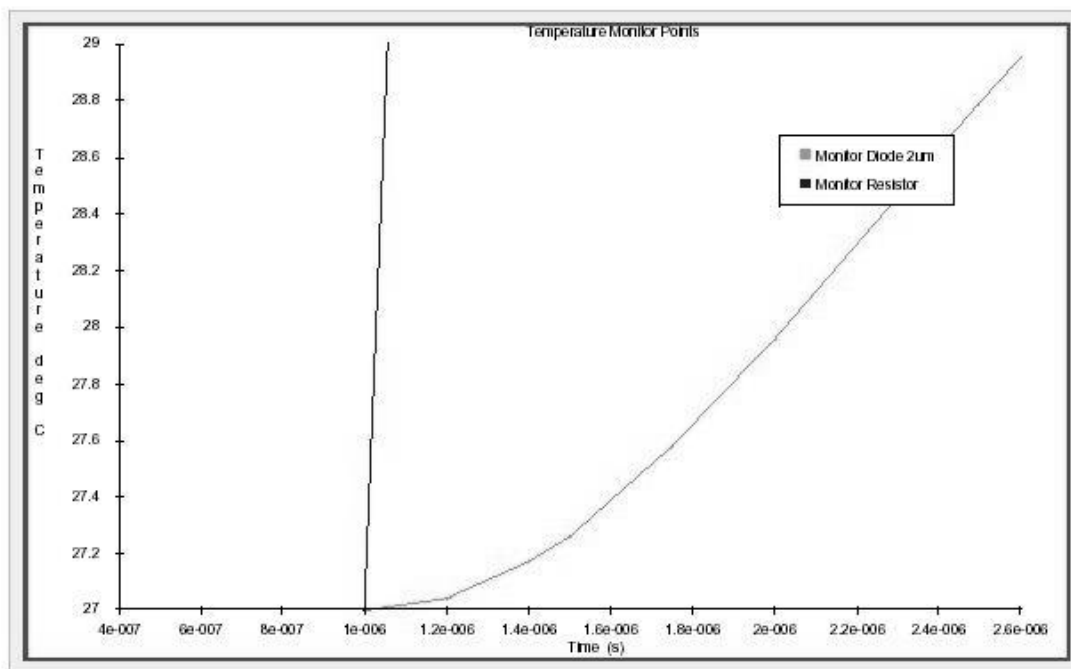
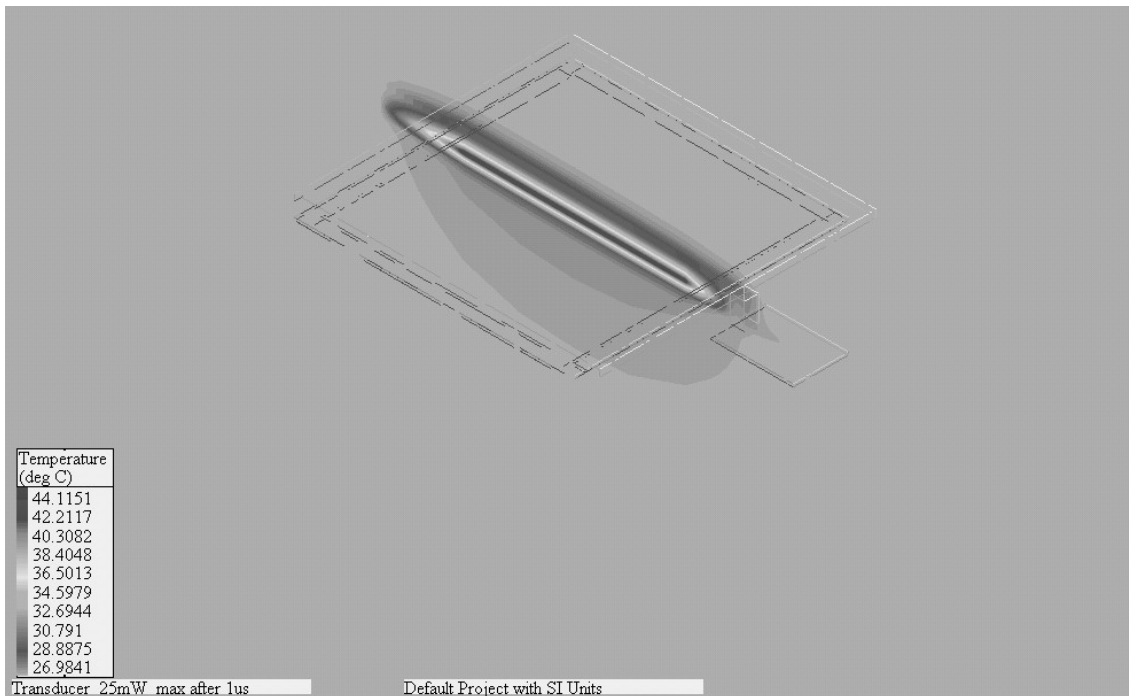


Figure 2. Three-dimensional transient thermal temperature distribution for transducer in Fig. 1 after 1 μ s (above) and plot of the resistor and diode temperature vs. time.

input voltage. The input current dictates the minimum resistor width that can be realized according to the process current ratings.

The value of the input resistance, R , is also calculated from the dissipated power according to $P_{dis} = V^2/R$. The final layout of the resistor cannot exceed the size constraints of

that simulated in 3D, otherwise the effective power density under the thermal lens and thus the change in the sensing diode temperature are reduced (i.e., the simulated structure is too small). If this violation occurs, the 3D simulation process must be repeated to achieve a new power figure, because the original power figure is insufficient for the resistor's resulting thermal mass.

On the other hand, if the original structure analyzed was found to be larger than necessary, then the power dissipation figure is also larger than necessary. Therefore, another iteration with a smaller thermal mass is required to optimize the power efficiency and switching speed of the device. The transducer shown in Fig. 1 was found to work acceptably well in the range of 20 μm to 40 μm per side.

3.2 THERMAL TRANSDUCER SECONDARY SIDE

The thermal signal produced at the primary side is sensed on the secondary side by a forward biased diode. This implementation detects a change in diode current as a function of changing temperature. The change in diode current, i.e., electrical analog signal, can be used to reconstruct the original digital data signal with additional circuitry.

The additional circuitry is designed such that a current reference value is established against which changing device temperatures are monitored. The resolution of this signal reconstruction circuitry determines the specifications of the diode sensor. The circuit utilized in testing the transducer in Fig. 1 was found to operate adequately with a diode biased at 0.7 V. The detectable change in current, ΔI , of the diode was 1 μA .

The diode used to detect the thermal signal is sized through device analysis using the Medici[®] finite element simulator package [Avanti Corp.]. Given the doping levels and layer thicknesses for the selected process, the diode is constructed in Medici and a sweep of the bias voltage is performed to obtain the current per micrometer. This figure is then used to calculate the diode area that yields the desired current for the bias voltage chosen previously (0.7 V), e.g. the diode used in Fig. 1 yields 129.3 μA at 0.7 V. Utilizing the same diode structure, an electrothermal simulation is then performed in Medici to obtain the minimum temperature change, ΔT , that the diode can sense and transition into a detectable ΔI (1 μA).

4 CONCLUSION

Two- and three-dimensional finite element analysis tools were used to analyze a thermal transducer design. The results have demonstrated acceptable performance. The transducer in Fig. 1 can achieve a propagation delay time on the order of 1 μs , which meets I²C bus specifications. Also, the transducer developed with the linear capacitor option, providing less electrical isolation, can meet these same specifications dissipating only 5 mW of power.

Logic dictates that a thermal-based transducer would suffer from environmental effects created by ambient temperature swings and on-chip localized heating due to circuitry and/or neighboring transducers. Also, of concern would be thermal saturation of the transducer rendering it insensitive to incoming signals. All of these issues are valid concerns. However, each one can be addressed through appropriate external circuitry. Using transducers in dual configurations, where the second transducer is used as a means of isolation between a sensor and control circuitry for shutting down the initial transducer, can address thermal saturation effects. Further, appropriate digital logic on the primary side of the initial transducer propagates signals through the device based on edge detection rather than data values. Likewise, other environmental concerns can be dealt with through additional

diode sensors and circuitry and layout rules. Future work will involve testing fabricated transducers along with circuitry to address these environmental concerns.

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