Abstract—Temperature management of the food supply-chain is important for ensuring compliance and the quality of perishable products like vaccines and fish. While conventional strategies have relied on using monitors attached to packaging containers, self-powered time-temperature monitoring is attractive because the technology can be embedded with passive RFID tags and can be integrated with every food or medical package. In this paper we propose a self-powered sensor that can monitor the time-temperature information without the need for any external powering. The sensor exploits the physics of Fowler-Nordheim (FN) tunneling where electrons are thermally excited and are continuously integrated on a floating-gate. The steady-state FN integrator’s response depends on the temperature and corresponds to a temporal curve that is unique to a specific ambient temperature. Deviation from the set ambient temperature results in the deviation from its reference response curve hence can be captured by the sensor. Measured results from sensors prototyped in a 0.5 \( \mu \)m CMOS process show a temperature sensitivity of 1.5mV/°C over a monitoring duration of 100 hours.

I. INTRODUCTION

Continuous monitoring of time-temperature history is one of the keys towards ensuring product quality in cold supply-chain management. For perishable products like vaccines and antibiotics, exposure to out-of-range temperatures could lead to a significant reduction in drug efficacy and also increase in the likelihood of spoilage [1], [2], an example being the 2015 incident [3] involving improperly stored medicines. Traditional cold supply-chain regulatory systems can monitor these assets in large batches (using electronic temperature sensors inside containers) or using passive labels or tags that indicate the shelf-life of each product. This procedure could potentially lead to unnecessary wastage of food because the actual quality of the product could be still good beyond the indicated expiry date. Also, the use of static expiry date labels could lead to the insertion of spoiled or bad quality products in the supply-chain due to varying storage conditions. This is especially true for perishable products like antibiotics and perishable foods which are sensitive to temperature and their respective quality show a time-temperature dependent deterioration [4] as shown in Fig. 1(a).

While time-temperature indicators (TTI) are popular in literature such as [5], [6], they are based on chemical or diffusion processes that require careful calibration and compensation. Also, other passive solutions can potentially monitor instantaneous changes in storage temperature, these devices cannot detect and store historical data of temperature. This is because the passive devices do not have access to continuous source of power required for historical monitoring of temperature over time.

In this paper, we propose a new type self-powered time-temperature indicator based on our previous work of the self-powered time-keeping device [7]. The sensor shows temperature-dependent integration behavior, hence can continuously monitor the ambient temperature over the lifetime of the product supply-chain. An example use case is illustrated in Fig. 1(b) where a passive RFID tag integrated with the proposed sensor is attached to every product such as vaccine in the supply-chain. During different stages of the supply-chain including packaging, transportation, storage and the consumer shelves (as illustrated in Fig. 1(c)), the sensor would continuously monitor the ambient temperature with respect to time, and functions as a time-temperature indicator. The operational principle of the proposed sensor is based on the physics of FN tunneling as illustrated in Fig. 2(a) which is a two step process. The electrons are first thermally activated to a high energy level where it encounters a triangular tunneling barrier through which the electrons leak into a floating-gate. The probability distribution of the electrons activated to different energy levels is a function of the ambient temperature which determines the rate of electrons tunneling into the floating-gate. The floating-gate also serves as a non-volatile memory.
whose value can be retrieved by an end user using a RFID reader or a RFID enabled smartphone (shown in Fig. 1(b)). The difference between the retrieved value and a control value is used to then determine the compliance and efficacy of the drug. The system view of the proposed temperature sensor is shown in Fig. 2(b), the programming, calibration and readout of the sensor can be achieved using a RFID interface. While wireless retrieval of sensor data using RFID constitutes an important aspect in the proposed cold supply-chain monitoring, this paper will only focus on the design of the proposed self-powered time-temperature indicator. The paper is organized as follows: in section II we will discuss the operational principle of the proposed time-temperature indicator in details, followed by the measurement results from prototyped structures on a standard 0.5-μm CMOS process in Section III. We conclude the paper in Section IV.

II. MODELING OF SELF-POWERED TEMPERATURE SENSOR

The temperature sensor is designed based on the self-powered integrator whose architecture is described in detail in our previous work [7]. It is composed of a stripe of polycrystalline silicon (polysilicon) which is completely insulated by high-quality, thermally grown silicon dioxide. The piece of polysilicon, also referred as floating-gate, acts as a reservoir of charge. As described in [7], the floating-gate charge can be altered by FN tunneling, the physics of which is a two-step process. The electrons are first thermally activated, which depends on the ambient temperature, and then tunnel through the energy barrier formed by the silicon dioxide. Mathematically the combination of thermal activation and electron tunneling can be expressed by the FN tunneling current density $J$ as [8]:

$$J = \frac{q}{h} \gamma \int_{-\infty}^{\infty} P_T(\zeta) T_P(\zeta) d\zeta$$

where $P_T(\zeta)$ is the probability density function corresponding to an electron occupying an energy level $\zeta$ and $T_P(\zeta)$ represents the tunneling probability of the electron and is a function of the barrier thickness. The parameters $h$ and $q$ correspond to the Plank’s constant and charge of free electrons respectively. $\gamma$ represents a transmission parameter that is a function of the interface properties.

A more complete expression for the FN tunneling current density $J$ that captures these effects is given by [9]

$$J = \alpha \frac{1}{w^2(y)} \gamma(T) E^2 \exp(-\frac{\beta v(y)}{E})$$

which includes an explicit dependence on temperature through $\gamma(T)$ and two correction terms $w(y)$ and $v(y)$ which captures the lowering of the triangular tunneling barrier through an image force effect [10]. Here $T$ represents the ambient temperature. These correction terms are tabulated elliptic integrals, and $y$ is a function of the barrier height and electric field as

$$y = \frac{1}{\phi} \left( \frac{\sqrt{E}}{A\phi} \right)^2$$

$\alpha$ and $\beta$ are functions of physics parameters. Although the tunneling process itself is temperature independent, the number of electrons of a given incident energy on the barrier is a function of temperature and the barrier height $\phi$ also depends on temperature. The dependence of electron momentum distribution on temperature as shown in Fig. 2(a) can be corrected using $\gamma(T)$ which is given by

$$\gamma(T) = \frac{\pi c k T}{\sin(\pi c k T)}$$

where

$$c = \frac{4\pi (2m^*\phi)^{1/2}}{hE}$$

It is impossible to derive a closed dependence of floating-gate voltage $V_{fg}$ on time $t$ using the general form 2 for arbitrary temperature $T$, however, if the temperature is fixed, using a similar derivation method in [11], $V_{fg}$ depends on time $t$ in the form of

$$V_{fg}(t, T) = \frac{k_2}{\ln(k_1 t + k_0)} + V_{sub}$$

where

$$k_0 = \exp(-\frac{\beta T}{E_0}), \quad k_1 = \frac{A\alpha' \beta'}{C r t o_x}, \quad k_2 = \beta' t_{ox}$$

Here $\alpha' = \alpha \frac{1}{T^2(T)} \gamma(y)$ and $\beta' = \beta v(y)$. Therefore, $V_{fg}$ is not only a function of $t$, but also a function of the ambient temperature $T$. As $k_1$ shows positive dependence on temperature $T$ as equation 7 implies, $V_{fg}$ shows a faster response with the same initial $V_{fg0}$ when temperature is higher. This time-temperature

![Fig. 2. (a) Principle of operation of the proposed temperature sensor based on FN tunneling of electrons; and (b) system architecture showing the integration of the self-powered temperature sensor with an RFID powered programming and read-out interface.](image-url)
The proposed self-powered time-temperature indicator was prototyped in a standard 0.5-µm CMOS process and the microphotograph of the die is shown in Fig. 3, where four sensors marked as "TTI1" to "TTI4" with identical tunneling junction area but with different gate capacitances were fabricated. The gate capacitances of TTI1 to TTI4 are 2pF, 4pF, 8pF and 16pF respectively. The circuit is also plotted in Fig. 3 where the floating-gate is formed by the gate of a pMOS transistor which is also used for programming the initial charge onto the floating-gate [12]. FN tunneling removes the electrons from the floating-gate node by applying a high-voltage (15 V in a 0.5µm CMOS process) across a parasitic nMOS capacitor $C_{\text{tun}}$ (as shown in Fig. 3). Hot-electron injection, however, requires lower voltage (4.2 V in 0.5µm CMOS process) than tunneling and hence is the primary mechanism for precise programming of floating-gates. The hot-electron programming procedure involves applying greater than 4.2 V across the source and drain terminals of the transistor M. The large electric field near the drain of the pMOS transistor creates impact-ionized hot-electrons whose energy when exceeds the gate-oxide potential barrier (3.2 eV) can get injected onto the floating-gate. Because the hot-electron injection in a pMOS transistor is a positive feedback process and can only be used to add electrons to the floating gate, the process needs to be carefully controlled and periodically monitored to ensure the floating-gate voltage is programmed to a desired precision. The methods proposed in literature achieve the desired precision either by adjusting the duration for which the FG transistor is injected or by adjusting the magnitude of the injection pulses [12]. The gate oxide of transistor M in Fig. 3 functions as the tunneling junction for integration. A unity gain buffer with larger than 70 dB open-loop gain is employed to read the floating-gate voltage as shown in Fig. 3.

The first group of experiments were conducted to characterize the time-temperature dependence of the sensor. The sensor with 54 µm$^2$ tunneling junction area and 2pF gate capacitance was set in an environmental chamber whose temperature can be accurately controlled. The initial floating-gate voltage of the sensor was programmed accurately to 7.9V for each measurement, and the dynamic responses were tested and measured for 10°C, 20°C, 30°C and 40°C respectively. Fig. 4 shows the reduction of the floating-gate voltage of the sensor with respect to time at different temperatures. As can be seen, the sensors exhibit time-temperature dependent behavior where at a higher temperature, the floating-gate voltage reduces faster. This monotonic dependence on time and temperature verifies the model represented by Equation 6 and therefore can be used for designing time-temperature indicators.

The second group of experiment were designed to verify the indicator’s sensitivity of temperature. Equation 8 implies that after a long time of running, the floating-gate voltage reduction is independent of temperature at a constant-

![Microphotograph of the fabricated timer.](image)

![Time-temperature dependence of the timer’s response.](image)
Fig. 5. Measured temperature sensitivity of the sensor.

Fig. 6. The evolution of voltage difference between measured results at T=10°C and T=40°C for sensors with different gate capacitances.

temperature environment, which was verified in [7]. By programming the sensor’s initial value at 8.5V and running for 1×10^6 s, we recorded the voltage difference of sensors at different temperatures with respect to that at 10°C, and the result is plotted in Fig. 5. The voltage difference shows a linear dependence on temperature and the sensitivity is around 1.5 mV/°C. This sensitivity relationship can be used to derive the ambient temperature according to the sensor’s output.

The last group of experiments were conducted to verify the impact of gate capacitances on the sensor’s behavior. Four sensors with gate capacitance of 2pF, 4pF, 8pF and 16pF were programmed to the same initial voltage of 8.3V and put in the environmental chamber. All the sensors’ responses were measured and recorded at temperature 10°C and 40°C respectively. Fig. 6 plots the measured voltage difference between 10°C and 40°C with respect to time for different gate capacitances. The results show that the voltage difference get saturated after a long time of running, which validates the conclusion of equation 8 where the voltage change will become independent of temperature eventually. The results also validate that the sensor’s response is a function of the capacitance. With a larger gate capacitance, the time required for reaching a certain voltage reduction (we can view it as the quality degradation of the monitoring product) is larger than that with smaller gate capacitance. This attribute can be used for designing time-temperature indicators with different monitoring periods, and fit the quality degradation attributes of different products.

IV. CONCLUSIONS

In this paper we proposed and demonstrated a self-powered sensor whose dynamic response shows dependence on both time and temperature. As a result the sensor could be used as time-temperature indicators in cold supply-chain management. The sensor is self-powered by thermal activation of electrons through an FN tunneling barrier and a floating-gate is used for continuous integration and storage of the electrons. Measurement results from prototypes of the sensor fabricated on a standard 0.5 μm CMOS process validate the operation of the sensor over monitoring periods in excess of 100 hours. The measurement results also verify that the response of the temperature sensor can be modulated by choosing a different floating-gate capacitance which can be used for adjusting the indication period. Future work will focus on combining the response of different sensor devices to enhance the temperature sensitivity and calibrating the time-temperature relationship with respect to the degradation characteristics of the monitoring products.

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REFERENCES