Scavenging Thermal-noise Energy for Implementing Long-term Self-powered CMOS Timers

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Outline

• Motivation

• Self-powered timers

• Measurement & Results

• Conclusions & Discussions
Motivation

Passive RFID sensors by VeryFields

915 MHz Self-powered RFID Sensor

13.56 MHz Self-powered RFID Sensor
Motivation

System analysis

- **Time-stamped**
  - Extra information for analysis
- **Self-powered**
  - Unavailability of extrinsic power sources
- **Long-term & Continuous**
  - More than 20 years
  - Lack of long-term batteries
  - Lack of system clock
- **Cost**
## Motivation

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W</td>
<td>Metabolic rate of Human Body</td>
</tr>
<tr>
<td>80W</td>
<td>Intel Pentium 4</td>
</tr>
<tr>
<td>30W</td>
<td>Power consumption of human brain</td>
</tr>
<tr>
<td>$10^{-2}$W</td>
<td>Laser in DVD ROM</td>
</tr>
<tr>
<td>$10^{-3}$W</td>
<td>Texas Instruments MSP430</td>
</tr>
<tr>
<td>$10^{-5}$W</td>
<td>Quartz wristwatch</td>
</tr>
<tr>
<td>$10^{-6}$W</td>
<td>Energy received at radio communication receivers</td>
</tr>
<tr>
<td>$10^{-9}$W</td>
<td>Air flow at 5m/s per sq mm</td>
</tr>
<tr>
<td>$10^{-12}$W</td>
<td>Average power consumption of a human cell</td>
</tr>
<tr>
<td>$10^{-18}$W</td>
<td>Thermal noise</td>
</tr>
<tr>
<td>$10^{-21}$W</td>
<td>Power received by deep space antenna from Galileo probe</td>
</tr>
</tbody>
</table>

Power scale showing the corresponding energy systems

This work.
Self-powered Timers

Random walk

- Thermal-diffusion based computers-Brownian computers
- DNA’s copy operation
- Electron’s move

Charles H. Bennett, 1982
Self-powered Timers

Basic physics processes

- **Trap-assisted Tunneling (TAT)**
  - Electrons directly tunnel to the unoccupied trap state in SiO2

- **Modified Poole-Frenkel (MPF)**
  - Emissions of trapped electrons into conduction band of SiO2

- **Thermal Field Emission (TFE)**
  - Emissions of Fermi-level electrons into conduction band of SiO2

- **Short term:** TAT
- **Long term:** MPF, TFE
Self-powered Timers

Leaking Characteristics

\[ \frac{\partial V}{\partial t} = \lambda V \exp(\kappa T) \]

\( \lambda, \kappa \) – relative coefficients

- Exponential to temperature
- Proportional to potential difference

RC discharging

\[ V = V_0 \exp\left(-\frac{t}{\tau}\right) \]
Self-powered Timers

Implementation

- **Floating-Gate Programming**
  - Fowler-Nordheim (FN) tunneling
  - Hot-electron injection

- **Measurement Consideration**
  - $V_{fg}$ drift due to charge leakage
  - 1V drift over 20 years$\sim$10µV/hour
  - Drain current depends exponentially on $V_{fg}$
  - Drain current depends exponentially on temperature

- **Differential Architecture**
  - Ideal FG without leakage
  - Extract current change caused by $T$
Self-powered Timers

Derivation

Sub-threshold currents satisfy

\[ I_D = I_0 \exp\left(-\frac{\kappa Q_{FG}}{U_T C_T}\right) \exp\left(\frac{V_s}{U_T}\right) \]

Using the ideal FG current results

\[ U_T = \frac{V_{s_1} - V_{s_2}}{\ln I_{\text{ref}, s_1} - \ln I_{\text{ref}, s_2}} \]

The charge change can be expressed as

\[ \Delta Q_{FG, i} = Q_{FG, i+1} - Q_{FG, i} = -\frac{C_T}{\kappa} \left[ U_{T, i} \ln \frac{I_{\text{out}, i}}{I_{\text{ref}, i}} - U_{T, i+1} \ln \frac{I_{\text{out}, i}}{I_{\text{ref}, i}} \right] \]

Since \[ I_{\text{kg}} = k \Delta V \]

\[ \frac{\kappa \Delta Q_{FG}}{C_T} = \frac{\kappa Q_{FG, 0}}{C_T} \left(1 - \exp\left(-\frac{k}{C_T} t\right)\right) \]
Measurement & Results

Test Results

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**Normalized Voltage Change**

- **Time (hours):** 10, 20, 30, 40
- **Normalized Voltage Change:** 0, 0.2, 0.4, 0.6, 0.8, 1

**Fitting for Timer1**

**Fitting for Timer2**

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**Current (A):**

- **Time (hours):** 0, 10, 20, 30, 40, 50, 60, 70
- **Current (A):** 2, 4, 6, 8, 10, 12

**x 10^-9**

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**Current (A):**

- **Time (hours):** 0, 10, 20, 30, 40, 50, 60, 70
- **Current (A):** 1.5, 1, 0.5, x 10^-8

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**REFERENCE**

**VIAs**
Measurement & Results

Test Results

![Graph showing relative and normalized voltage changes over time for different timers.](image)
Conclusions & Discussions

- Trap-state effect equals to a large resistor
- Leakage process is similar to RC discharging
- Time constant factors
  - Trap state
  - Capacitance
  \[
  \frac{\kappa \Delta Q_{FG}}{C_T} = \frac{\kappa Q_{FG,0}}{C_T} \left(1 - \exp\left(-\frac{k}{C_T} t\right)\right)
  \]
- Possible ways to adjust time constant
  - Defect distribution
  - Defect number
  - FG capacitance
- Temperature offset
Questions?

Thanks!