Reconfigurable Analog Electronics using the Memristor*

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- Practical reconfigurable analog design using the Memristor
  - Minimize the stress across the Memristor device
  - Programming/erasing the Memristor must be simple and reliable

- Biggest potential impact is found in circuits for
  - Analog trimming
  - Data conversion
  - Communications
  - Compensation for physical variations (temperature, sensor conditioning, etc.)

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Programming/Erasing the Memristor

- Drive PE (below) high
  - To erase, connect PE Voltage to a negative potential, for example, < -250 mV
  - To program connect PE to a positive potential > 250 mV

Package containing 12 Memristors fabricated at Boise State University.
Key Points

- Resistance of the Memristor can be scaled downwards by increasing cross-sectional device area.
- Larger area results in more consistent devices.
- Memory resistance retention improved by minimizing the voltage across the device.
  - Ideally voltage across the device is 0 when using the device!
Basic Beta-Multiplier Reference

M2 is made K-times wider than M1, in other words its Beta is multiplied up hence the name Beta-Multiplier Reference (BMR).

\[ I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{REF} \]

\[ V_{GS1} = \sqrt{\frac{I_{D1}}{2\beta}} + V_{THN} = V_{GS2} + I_{D2}R_{\text{memristor}} \]

\[ I_{REF} = \frac{2}{R_{\text{memristor}}^2 K P_n \cdot \frac{W_1}{L_1}} \left(1 - \frac{1}{\sqrt{K}}\right)^2 \]

Independent of VDD!  
Dependent on \( R_{\text{memristor}} \)
Nanometer CMOS BMR Reference using the Memristor

- Add amplifier to ensure better power supply insensitivity
- Add start-up circuit
- Program/Erase by driving PE signal high and applying a “PE Voltage”
- Do we minimize the voltage across the Memristor during non-PE operation?
- Does the resulting reference current vary with changes in \( VDD \)?
Variation of current with $R_{\text{memristor}}$ in 50 nm CMOS BMR

\begin{align*}
I_{\text{REF}} & = 10 \text{ k}\Omega \\
I_{\text{REF}} & = 50 \text{ k}\Omega \\
I_{\text{REF}} & = 100 \text{ k}\Omega \\
I_{\text{REF}} & = 500 \text{ k}\Omega \\
I_{\text{REF}} & = 1 \text{ M}\Omega
\end{align*}

VDD
What is the voltage across $R_{\text{memristor}}$?

$R_{\text{memristor}} = 10k, 50k, 100k, 500k, \text{ and } 1\text{MEG}$
50 mV across $R_{\text{memristor}}$ is good but can we reduce this stress further?

- Looking at the equation for the reference current (below) notice that if $K$ goes to 1 the current goes to zero and thus so does the voltage across $R_{\text{memristor}}$
- The result is reducing $K$ reduces the stress across the device!
- Dropping $K$ from 4 to 2 causes the voltage across $R_{\text{memristor}}$ to drop from 50 to 25 mV

$$I_{\text{REF}} = \frac{2}{R_{\text{memristor}}^2 K P_n \frac{W_1}{L_1}} \left(1 - \frac{1}{\sqrt{K}}\right)^2$$
Why is this approach to reconfigurable analog integrated circuits significant and how is it used?

- Programmability is non-volatile
- The circuit is small
- Currents can be used for power supply independent voltage generation
  - Dynamically scale data converter operating range
- Control oscillator frequency
  - Useful in PLLs, charge pumps, wake-up circuits, etc.
A Memristor-Controlled Oscillator using a Source-Coupled Topology

- Use the Memristor-programmed BMR to set, or control, the frequency of an oscillator
- Potential for very low power operation at high-frequencies
Simulation Results

- Oscillation frequency is near $I/C$
  - Here $I = 5 \, \mu A$ and $C = 100 \, fF$ so the oscillation frequency is close to 50 MHz
- Note that this oscillator is non-volatile, that is, on power-up the oscillation frequency remains on changed from power-down.
More Simulation Results

- Reducing, to 900 mV and increasing, to 1.1 V, shows that the oscillation frequency doesn’t change much (not an exponential relationship as in many integrated oscillators).

\[ VDD = 900 \text{ mV} \]

\[ VDD = 1.1 \text{ V} \]
Something simpler: A Voltage Divider

- Use the Memristor-controlled current to generate Memristor-controlled voltages
- Voltages tolerant to changes in the power supply voltage, $V_{DD}$
- Of course they are also non-volatile meaning power can be removed and then re-applied without losing the programmed voltage values
Simulation Results

- Below shows how various voltages can be generated by programming the Memristor.
- Note! These voltages are independent of VDD!
- Again, the programmed voltages are non-volatile.

\[ R_{\text{memristor}} = 10k \]

\[ R_{\text{memristor}} = 100k \]
How Can Use this Simple Voltage Divider in a Complex Circuit?

- Consider the Flash ADC seen at the left with simulation results shown below.
Reconfiguring the ADC’s input range

- What happens when the input signal amplitude shrinks?
- We get fewer output codes thus the noise added to the input signal increases
Quantization Noise

- The voltage dropped across each resistor in our simple 3-bit ADC is $\frac{V_{DD}}{8} = 125 \text{ mV} = V_{LSB}$
- This voltage, $V_{LSB}$, is also the resolution of the ADC
- The RMS value of the quantization noise is given by

$$V_{Qe,RMS} = \frac{V_{LSB}}{\sqrt{12}}$$

- The key point is that if we can reduce $V_{LSB}$ we can reduce the quantization noise added to the input signal
- Why not simply reduce the resistors or supply voltage driving the resistors to reduce the quantization noise?
  - Answer: then our input signal range is reduced!
  - We want to be able to reconfigure the design for low noise and wide input signal range
Using the Memristor to reconfigure the input signal range - 1

- Adding the Memristor-programmed BMR, $R_{\text{memristor}} = 10k$
- Output seen below for large input signal swings (same as before)

![Graph showing input and output signal swings with large swings and smooth transitions.](image)
Using the Memristor to reconfigure the input signal range - 2

- The left trace, again using $R_{\text{memristor}} = 10k$, shows how a reduction in the input signal results in no change in the ADC’s outputs!

- Reconfiguring the input range allows the ADC’s output to swing through all of its codes reducing the added $V_{QE,RMS}$.
Summary

- By incorporating the Memristor in the Beta-Multiplier Reference (BMR) we showed that we can
  - Minimize the stress (voltage) across the device
  - Use the Memristor to generate a non-volatile current that is independent of \( V_{DD} \)

- The Memristor-controlled BMR can then be used to
  - Implement re-configurable voltage references, ADCs, or any circuit that uses reference currents or voltages to control a characteristic of operation
  - Trimming currents or voltages for precision analog design, especially useful in nanometer CMOS where matching is poor (e.g., in a current steering DAC, removing the offset in an op-amp, etc.)