Micro Power Precision Floating Gate Voltage Reference

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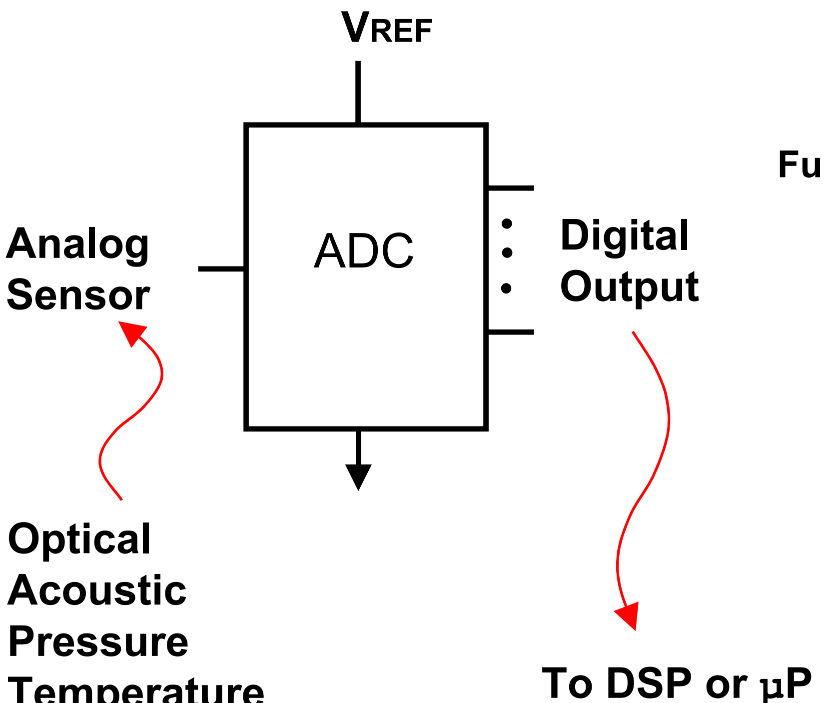
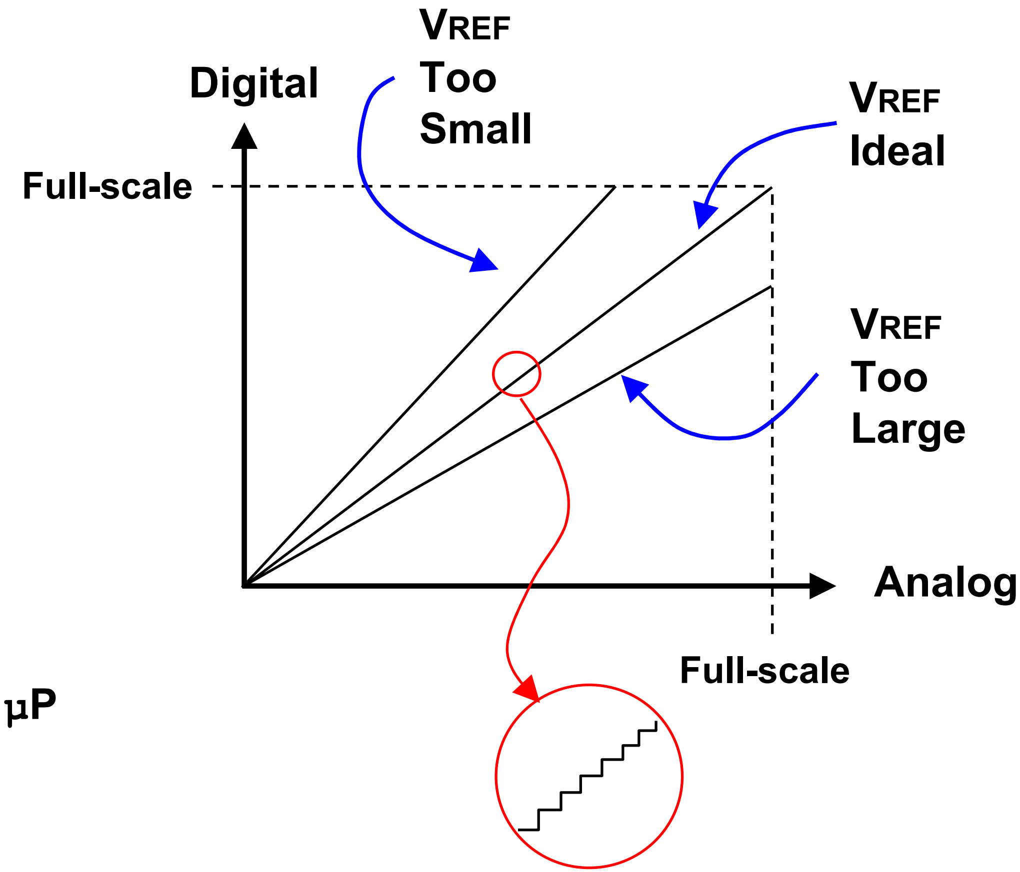
Precision Voltage Reference Using EEPROM Technology

- Overview
- Tunnel Diode as a Switch
- Circuit Techniques / Process Details
- Measured Performance
- Applications
- Summary

Voltage Reference: Analog-to-Digital Converter



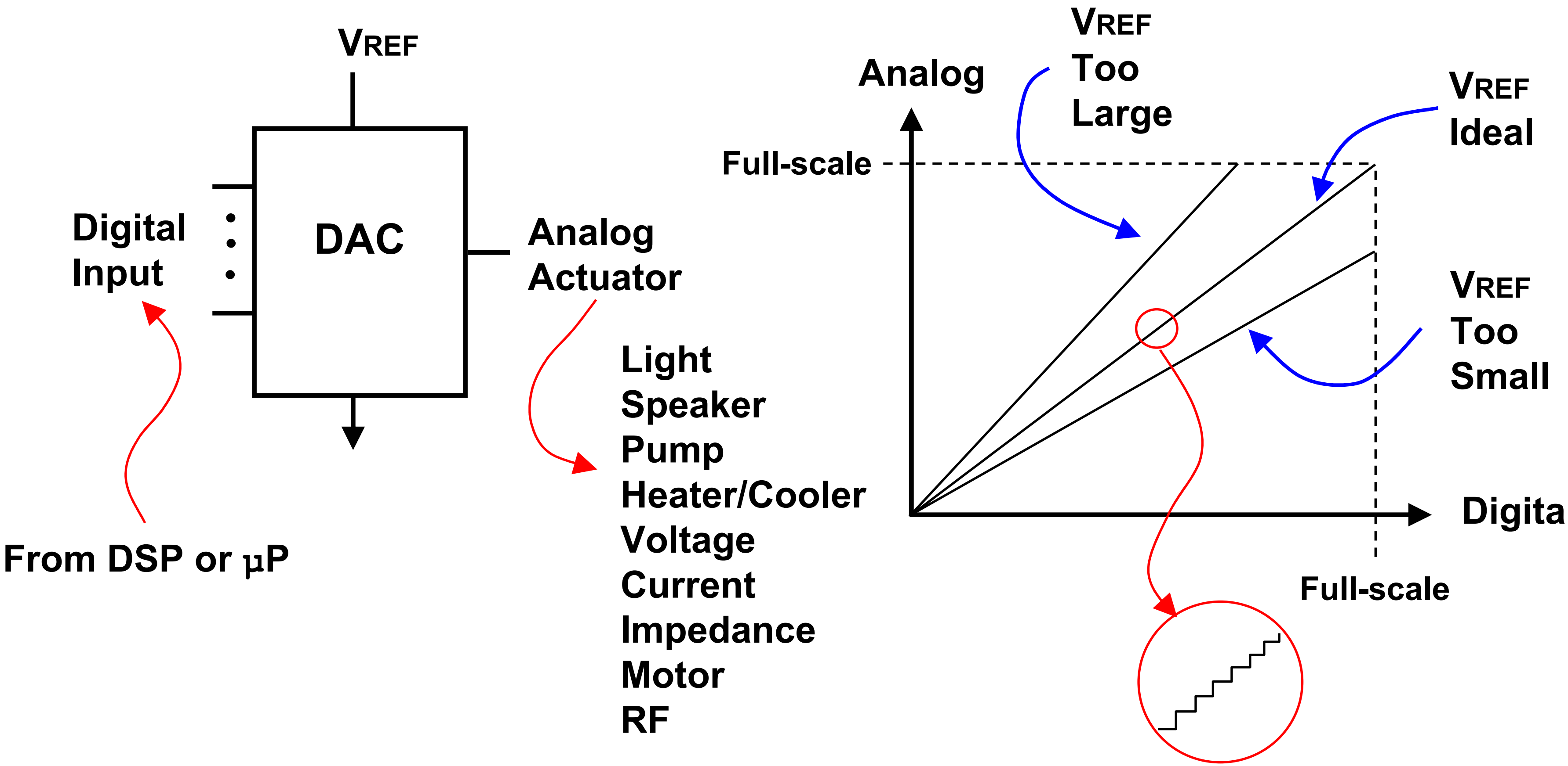
Optical
Acoustic
Pressure
Temperature
Humidity
Chemical
Voltage
Current
Impedance
RF



ADC Accuracy Requires an Accurate Voltage Reference

Quantizer Accuracy specified by Differential and Integral Linearity

Voltage Reference: Digital-to-Analog Converter



DAC Accuracy Requires an Accurate Voltage Reference

Quantizer Accuracy specified by Differential and Integral Linearity

Voltage Reference Performance Parameters

- Initial Accuracy
  - The absolute error from ideal value (volts)
- Temperature Coefficient
  - The fractional change in Vref over Temp (ppm/ºC)
- Supply Current
  - The total supply current excluding the load current
- Warm-up Time
  - The additional time after power-on settling required for the reference to reach final voltage within Initial Accuracy (+/- 0.5mV)
- Output Current
  - The maximum load current for which the reference still meets specifications
- Long Term Drift
  - The change in reference value at equilibrium over a long period of time (ppm/1000hrs)

IMPORTANT FOR HANDHELD BATTERY POWERED EQUIPMENT

What Reference Accuracy is Needed?

12 bit Accurate Converter

- 12 bit 5V has become standard
- Requires < 0.5 LSB quantization & Voltage reference error
- Requires voltage reference error < 0.5 LSB

Total Reference error = (initial accuracy) + (TempCo * 125ºC)

$$0.25 \text{ LSB Initial accuracy} = \frac{0.25 \text{ LSB} * 5\text{V}}{2^{12}} = 0.3\text{mV} \;\; !!$$

$$0.25 \text{ LSB Temperature coefficient} = \frac{0.25 \text{ LSB}}{2^{12} * 125^{\circ}\text{C}} = 0.5\text{ppm}/^{\circ}\text{C}$$

12bit Accurate Reference is difficult to achieve !!

Typical Performance of Available Accurate References

• Initial Accuracy	± 2mV
• Temperature Coefficient	< 3ppm/ºC
• Supply Current	1-5mA
• Warm-up Time	seconds to hours
• Output Current	10mA
• Long Term Drift	10ppm/1000hr
• Noise	< 10uV peak-peak

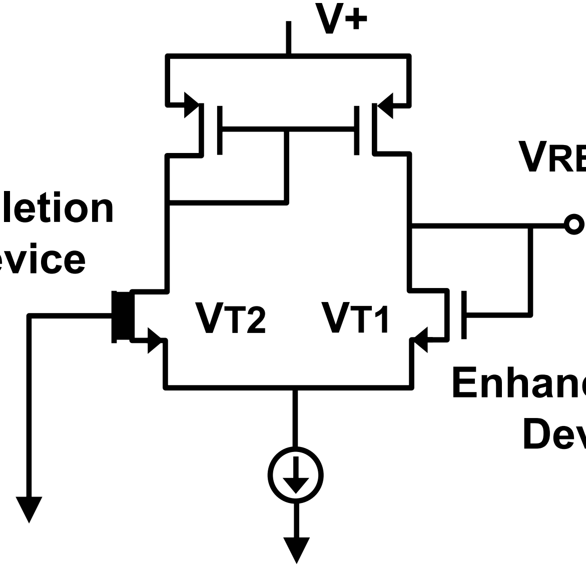
Most Voltage References Provide Only 10bit Accuracy !!

Conventional High Accuracy Reference Technologies

Type	Process	Vcc	Icc	Trim Technique
Buried-Zener	Bipolar	10V	5mA	Laser-Trim Thin-film Resistor or Fuses
Bandgap	CMOS/ Bipolar	2.4V	0.5mA	Laser-Trim Thin-film Resistor or Fuses
ΔV_T Reference	CMOS	(not considered high accuracy reference)		

New EEPROM CMOS Floating-gate reference competes with Bandgap and Buried-Zener references !!

Early CMOS ΔVT Reference



$V_{REF} = V_{T1} - V_{T2}$

$$V_{T1} = \frac{Q_E}{C_{gate}} + V_{T0}$$

and

$$V_{T2} = \frac{Q_D}{C_{gate}} + V_{T0}$$

Ideally: $V_{REF} = V_{T1} - V_{T2} = \dfrac{Q_E - Q_D}{C_{gate}}$

Independent of temperature !!

Problems: The implants affect device parameters (mobility and VT0).
This introduces temperature drifts that are difficult to cancel.
Also, Implant variations create large variations in Vref.

Result: Initial accuracy of ±15% =>requires high resolution trim network
Difficult to reduce Temperature coefficient <10ppm/ºC

Solution: The floating-gate reference solves these problems.

Characteristics of Ideal Reference

- Zero TC
- Zero LT Drift
- Zero DC POWER
- Zero Noise
- Arbitrary value—No Trim requirement

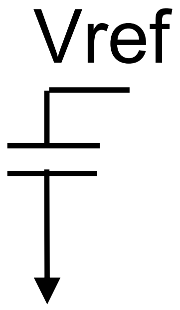
QUIZ

What Electrical Components can give us these Ideal characteristics in a Voltage Reference:

- ❑ Resistor
- ❑ Capacitor
- ❑ Inductor
- ❑ MOS Transistor
- ❑ Bipolar Transistor

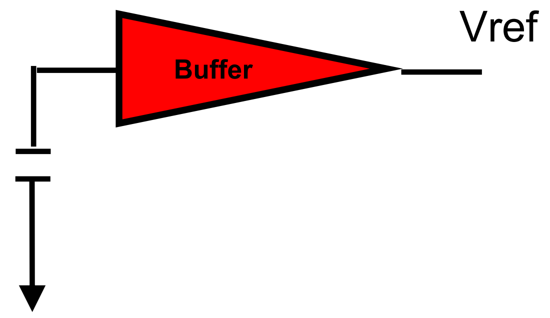
IDEAL REFERENCE

- Just a Capacitor



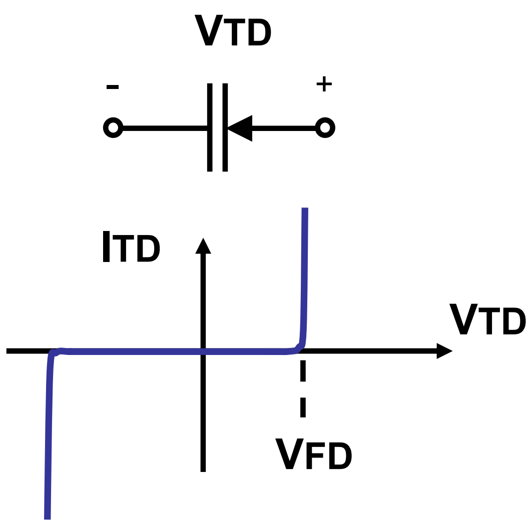
IDEAL REFERENCE

- OK, How about: Capacitor + Buffer



How do we place charge on this capacitor without causing leakage paths?

Tunnel-diode I-V Characteristic



The relationship between Tunnel diode current and voltage is defined by the Fowler-Nordheim equation:

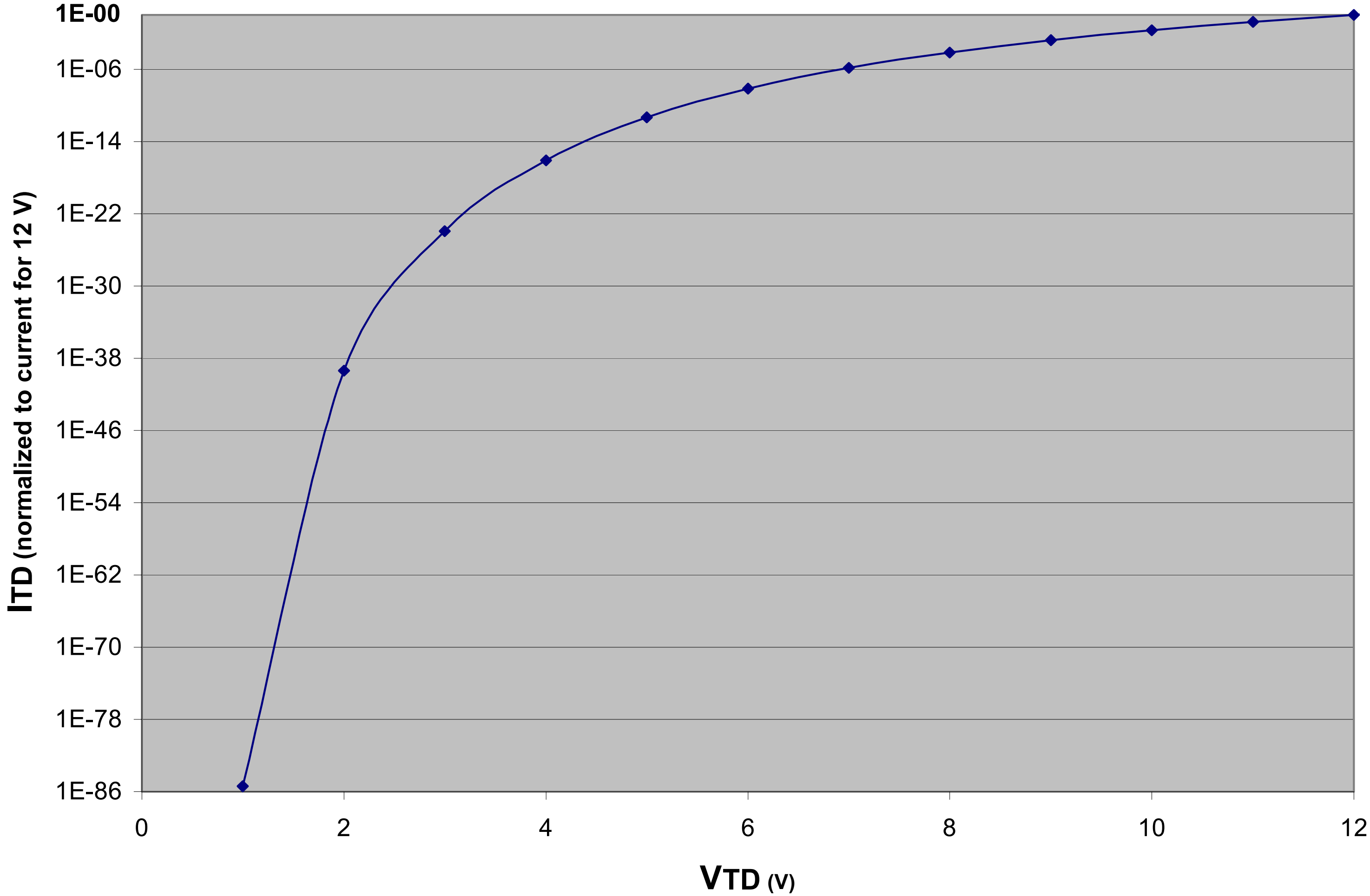
$$I_{TD} = C * V_{TD}^{\;2} * \exp(-\frac{a}{V_{TD}})$$

In which C and a are constants

As V_{TD} ↑, I_{TD} becomes large (follows quadratic)

As $V_{TD} \longrightarrow 0$, I_{TD} vanishes exponentially and current flow is negligible

Tunneling Current Versus Voltage

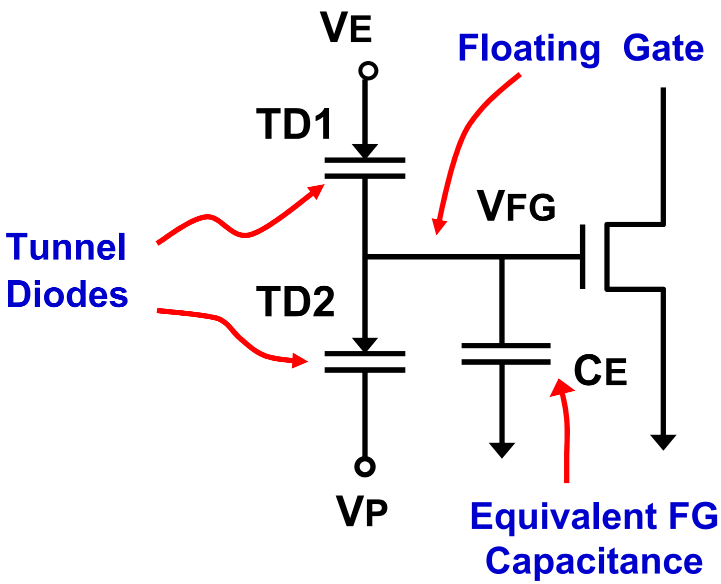


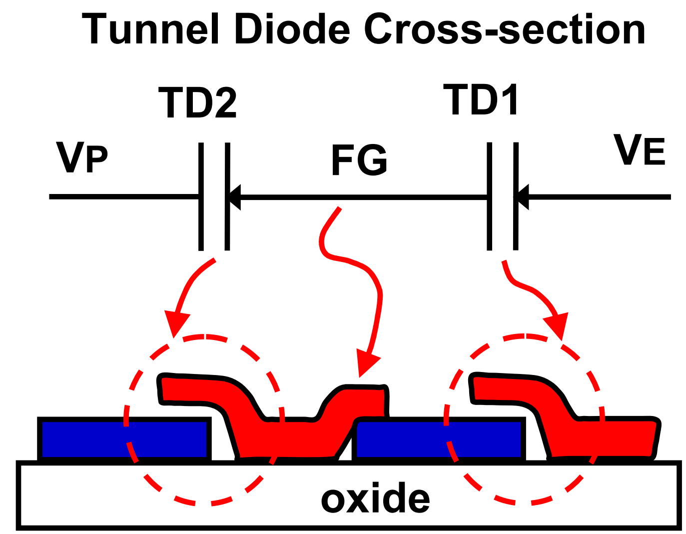
The TD current drops 38 orders of magnitude from 12V to 2V

➔Loss of 1 electron in several Trillion years @2V

➔16nV drift for a 10pf Storage capacitor

Simplified Schematic of Floating-gate Device





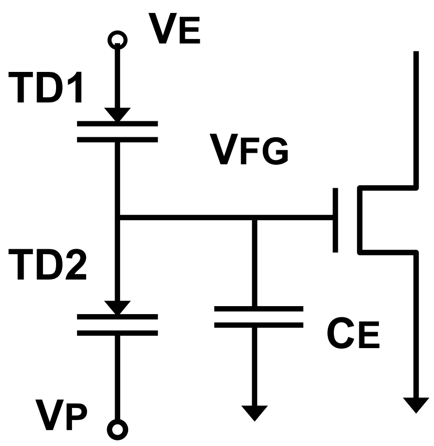
FG is isolated by oxide and cannot gain or lose charge under normal conditions

If V_E is raised to large positive voltage TD1 can conduct charge to FG

If V_P is lowered to large negative voltage TD2 can conduct charge from FG

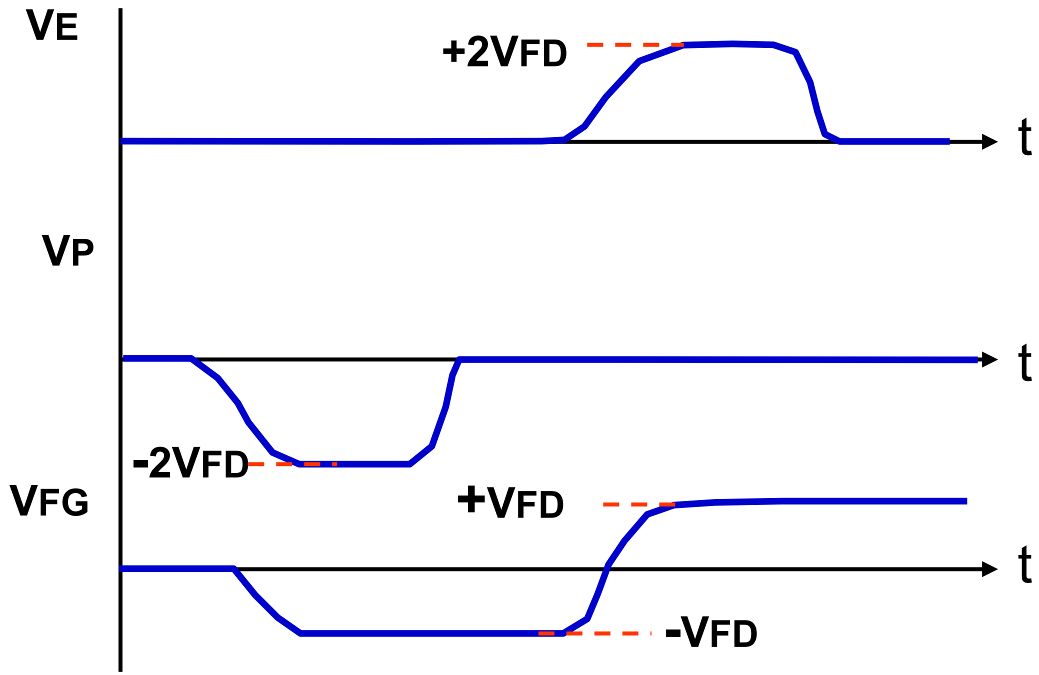
When V_E and V_P are at ground, there can be no charge transfer to or from FG

Tunnel Diodes to Change Floating-gate Voltage



Conceptual Analysis

Assuming all terminals initially at ground.



Voltage swing on FG conceptually 2VFD (= 24V for 12V VFD)
Large VFD voltage improves dynamic range and signal-to-noise ratio

Problem with this approach: does not provide analog control of VFG

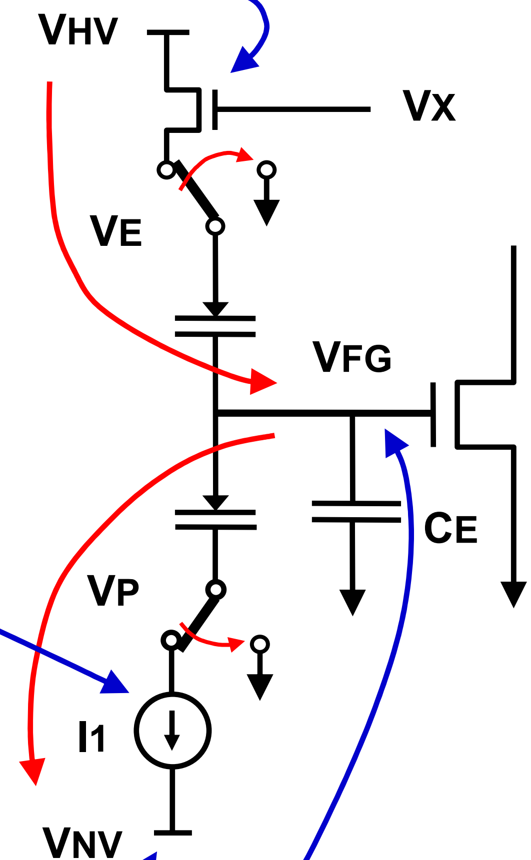
Analog Control of Floating-gate Voltage

Source-follower with Vx to control VE to a high voltage

Switches connect source-follower and current source and this enables conduction current

Current source I1 limits average current to safe value

I1 can pull VP to large negative voltage if necessary



Charge flows from or to the floating gate until equilibrium is reached and VFG is a stable D.C. voltage

Setting the Floating-gate Voltage

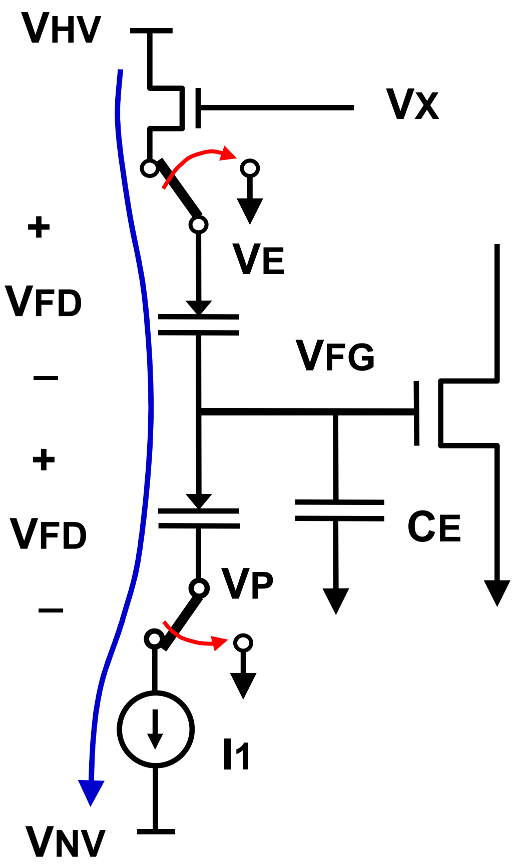
At equilibrium, all current flows through the tunnel diodes

Tunnel diode voltage drops = V_{FD}

Accounting for the source-follower threshold voltage V_T, the floating gate voltage is given by:

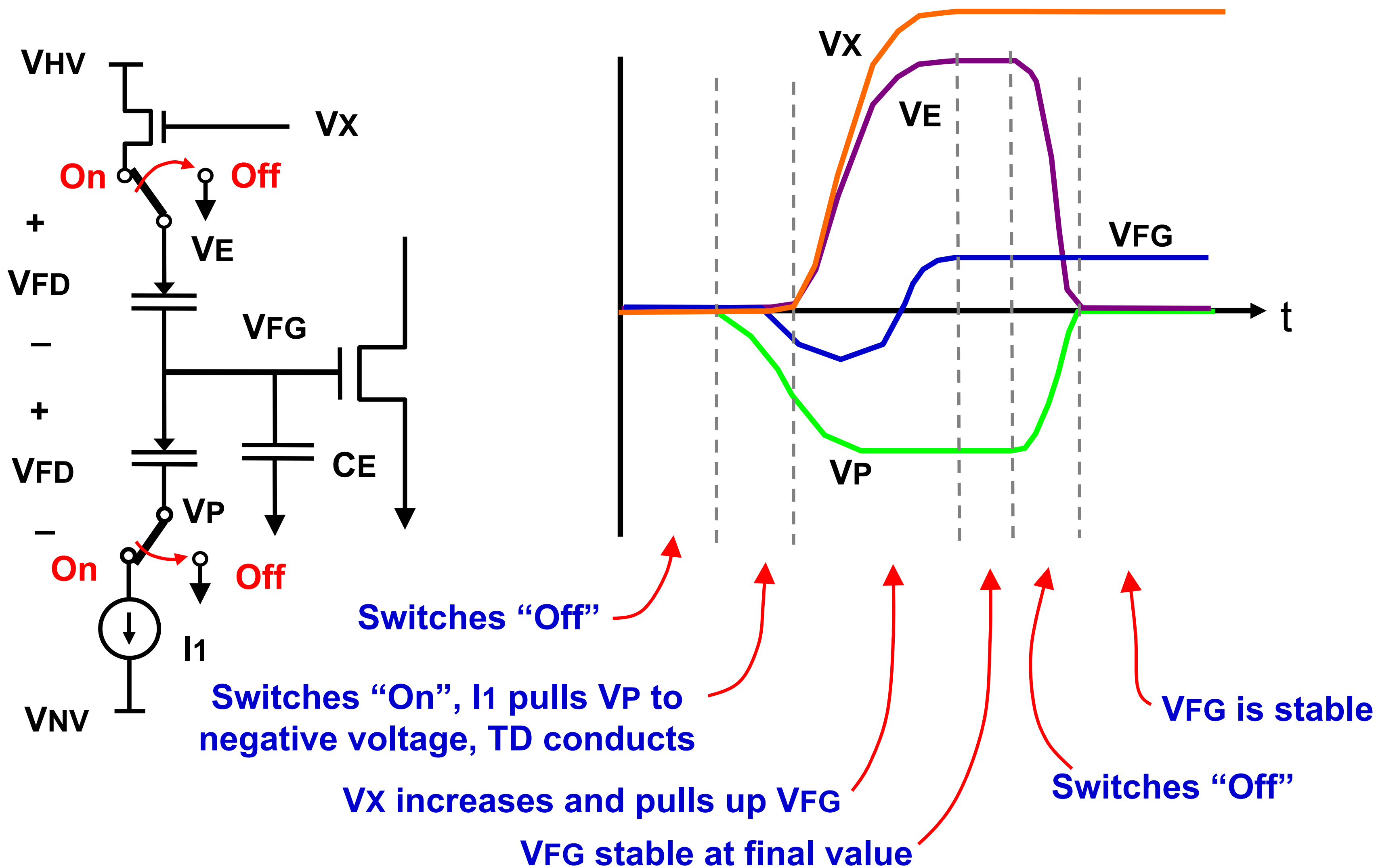
$$V_{FG} = V_X - V_T - V_{FD}$$

V_{FG} is an analog voltage that follows V_X

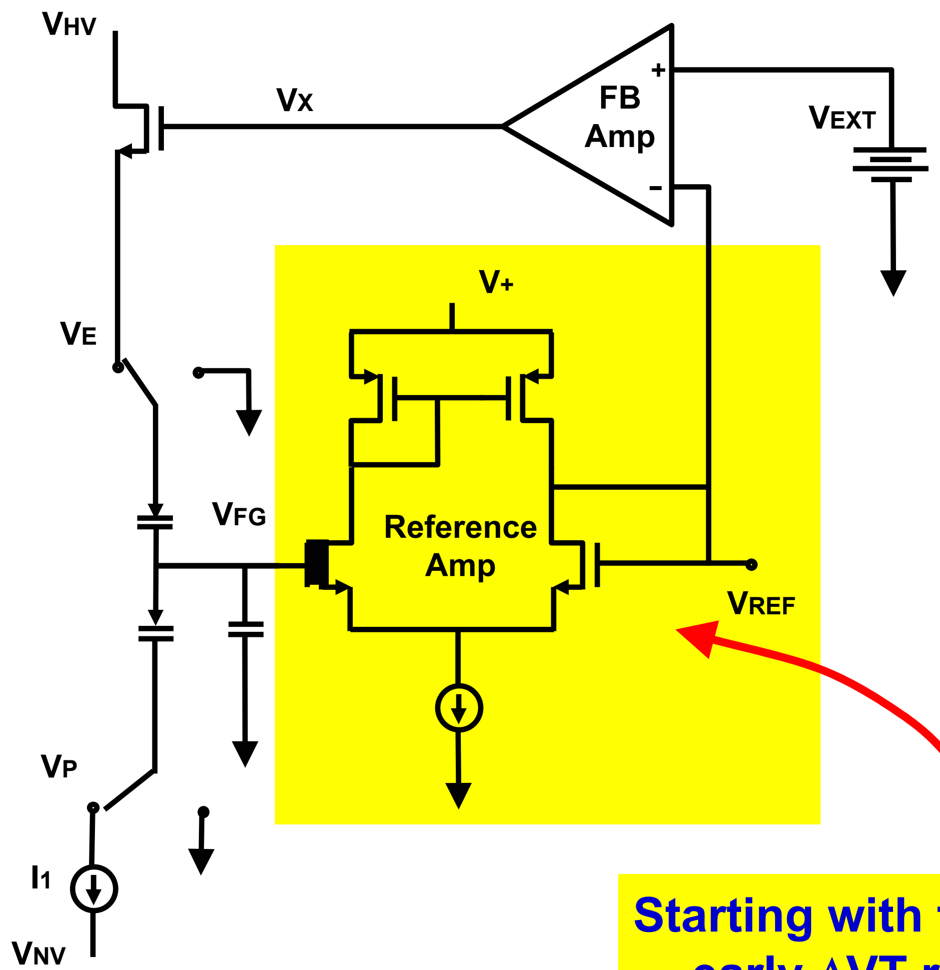


When both switches are connected to ground, charge is trapped on the floating gate and now V_{FG} is a stable D.C. voltage

Typical Floating-gate Voltage Waveforms

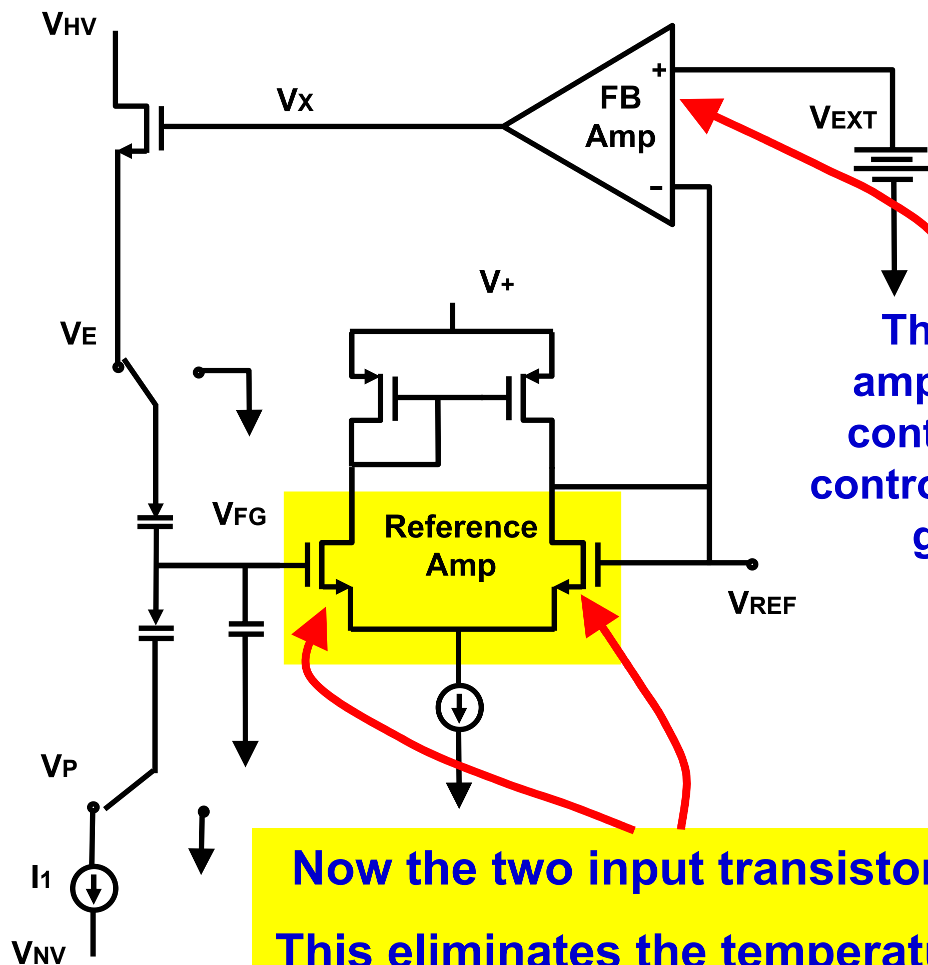


Simplified Schematic of Entire Reference



Starting with the original early ΔVT reference

Simplified Schematic of Entire Reference



The on-chip FB amplifier provides continuous analog control of the floating-gate voltage

Now the two input transistors are matched.

This eliminates the temperature dependence caused by transistor mismatch

Circuit Operation

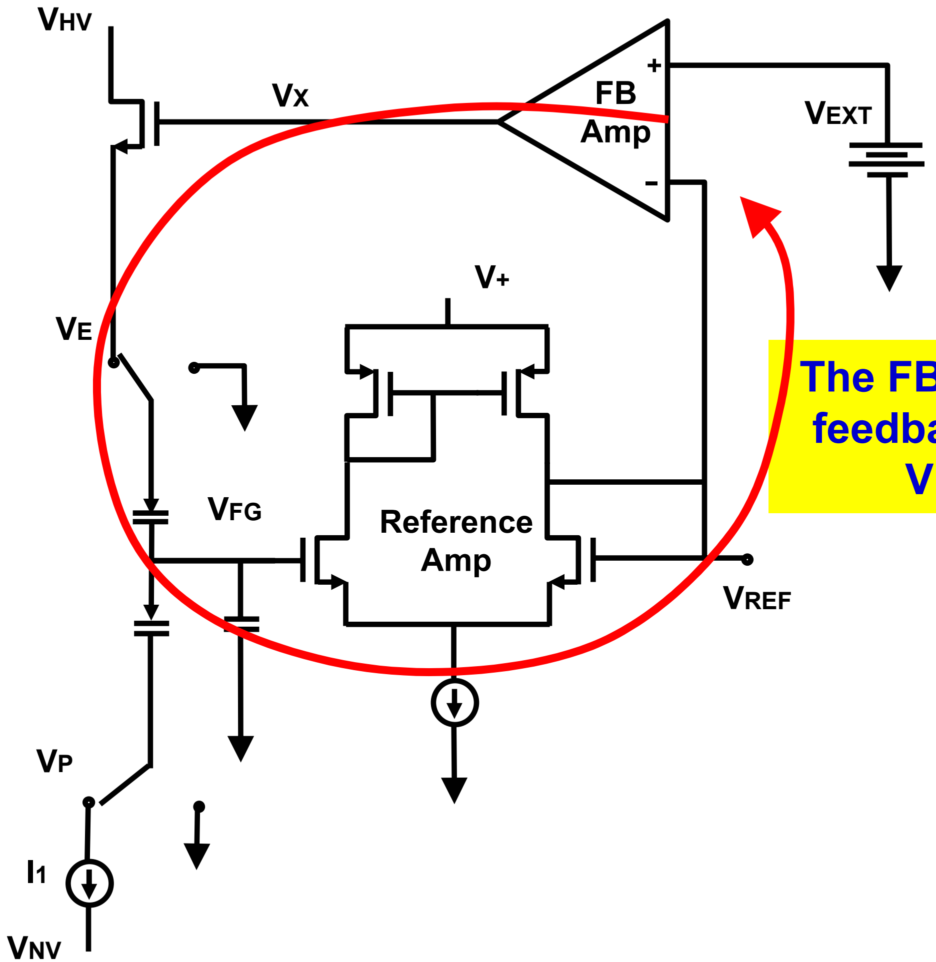
An external voltage source is connected to the FB Amp during reference calibration

On-chip HV charge pumps generate VNV and VHV

The FB AMP drives the internal feedback loop

This drives VX and sets VFG

The Reference Amp drives VREF = VFG



The FB Amp drives the feedback loop so that VREF = VEXT

Circuit Operation

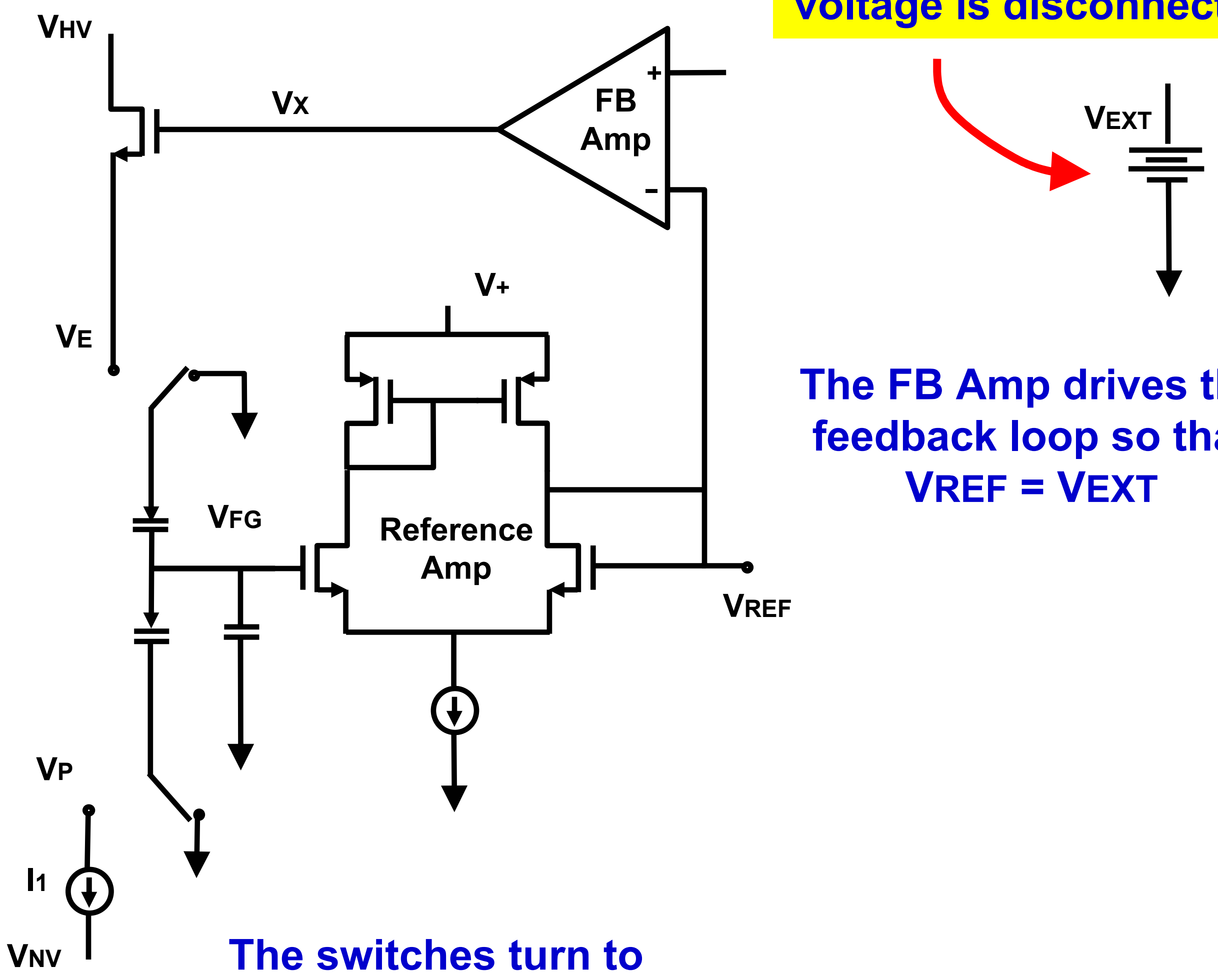
An external voltage source is connected to the FB Amp during reference calibration

On-chip HV charge pumps generate V_{NV} and V_{HV}

The FB AMP drives the internal feedback loop

This drives V_X and sets V_{FG}

The Reference Amp drives $V_{REF} = V_{FG}$

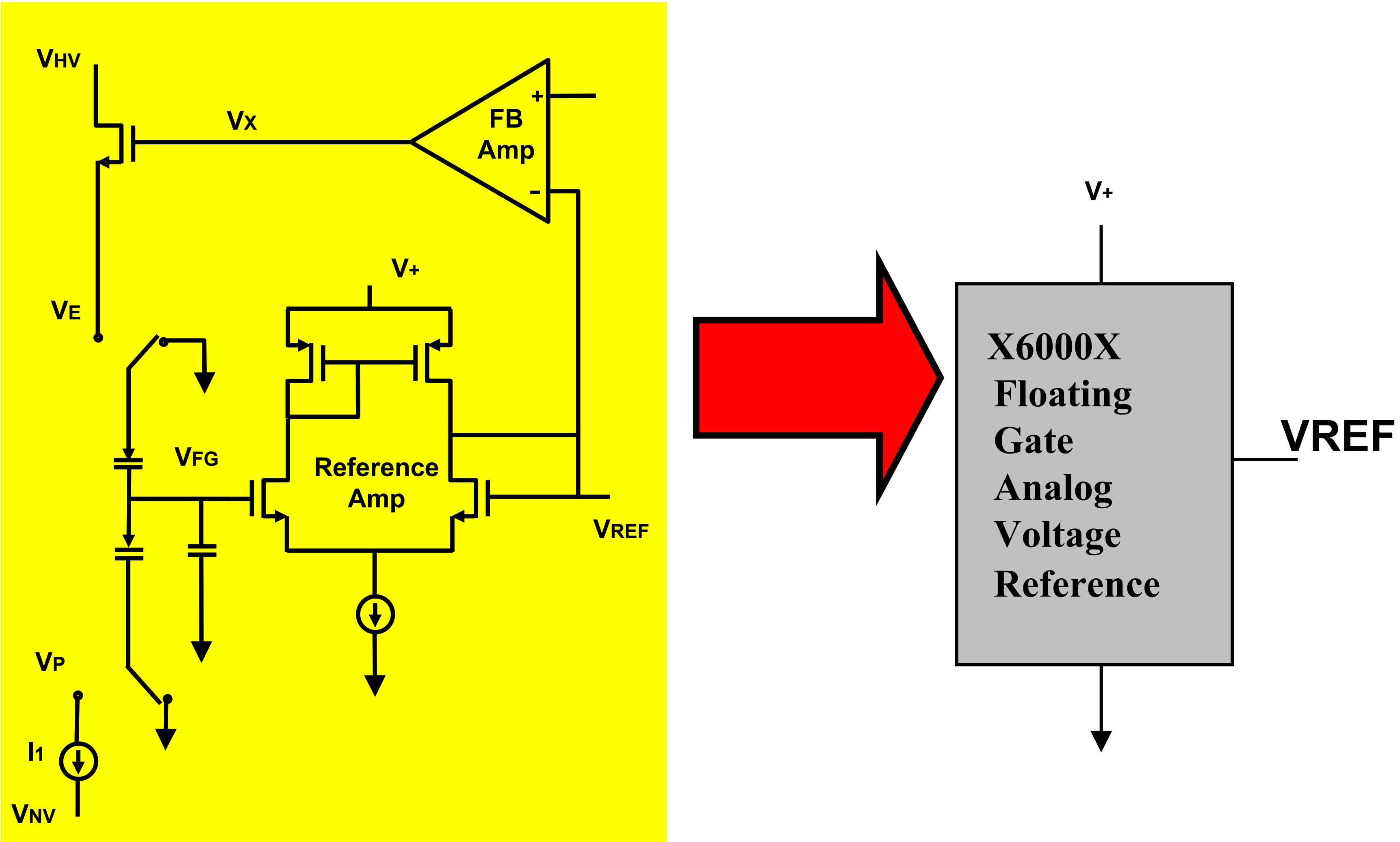


The external reference voltage is disconnected

The FB Amp drives the feedback loop so that $V_{REF} = V_{EXT}$

The switches turn to the off position

A Precision 3-terminal Voltage Reference



Process Technology

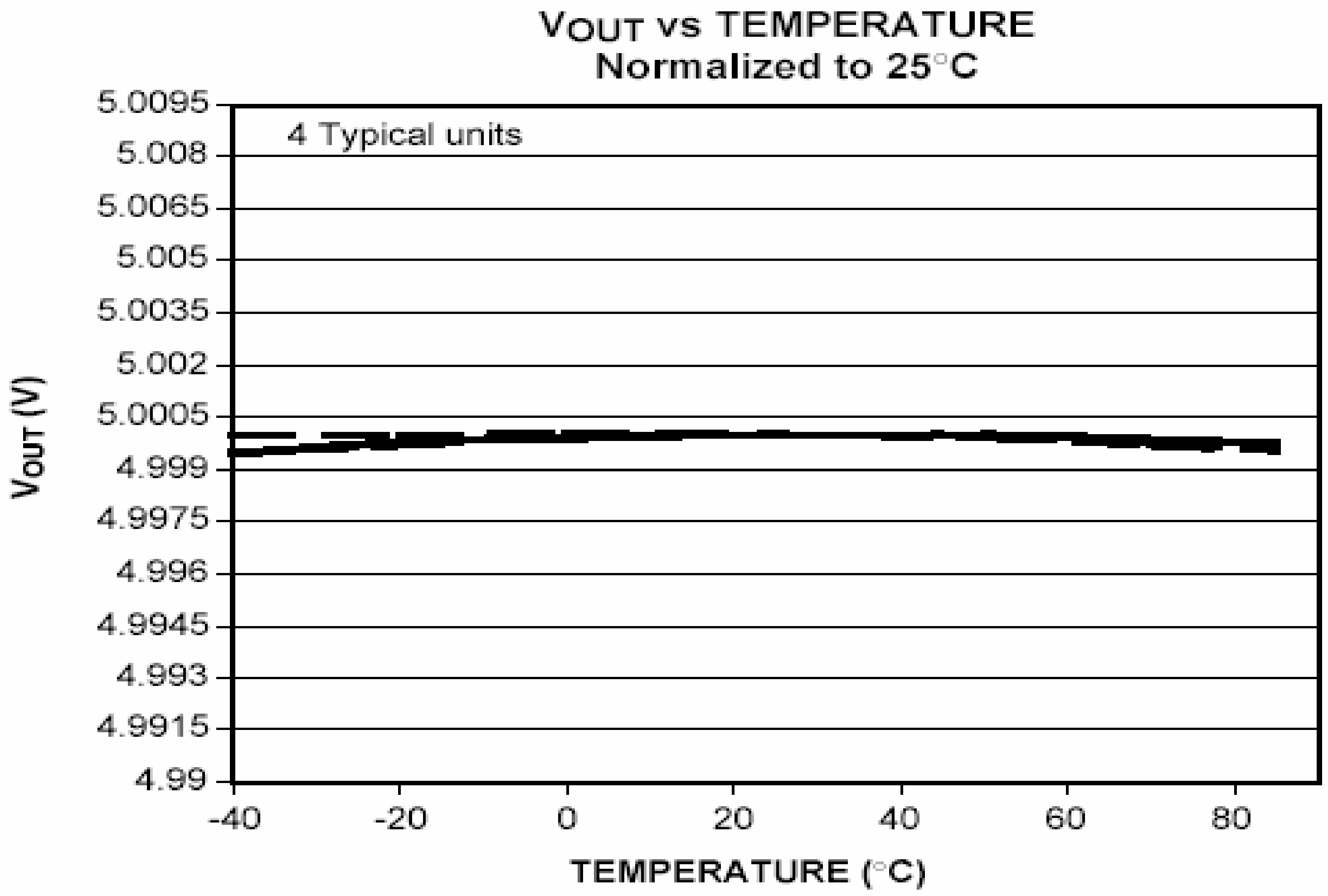
- CMOS E^2 25V Process
- Double Poly, 2 Metals, 1.5u technology
- Packages: SOIC8 and SOT23
- > 5KV (HBM) and 2KV (CDM) ESD

Measured Performance Data

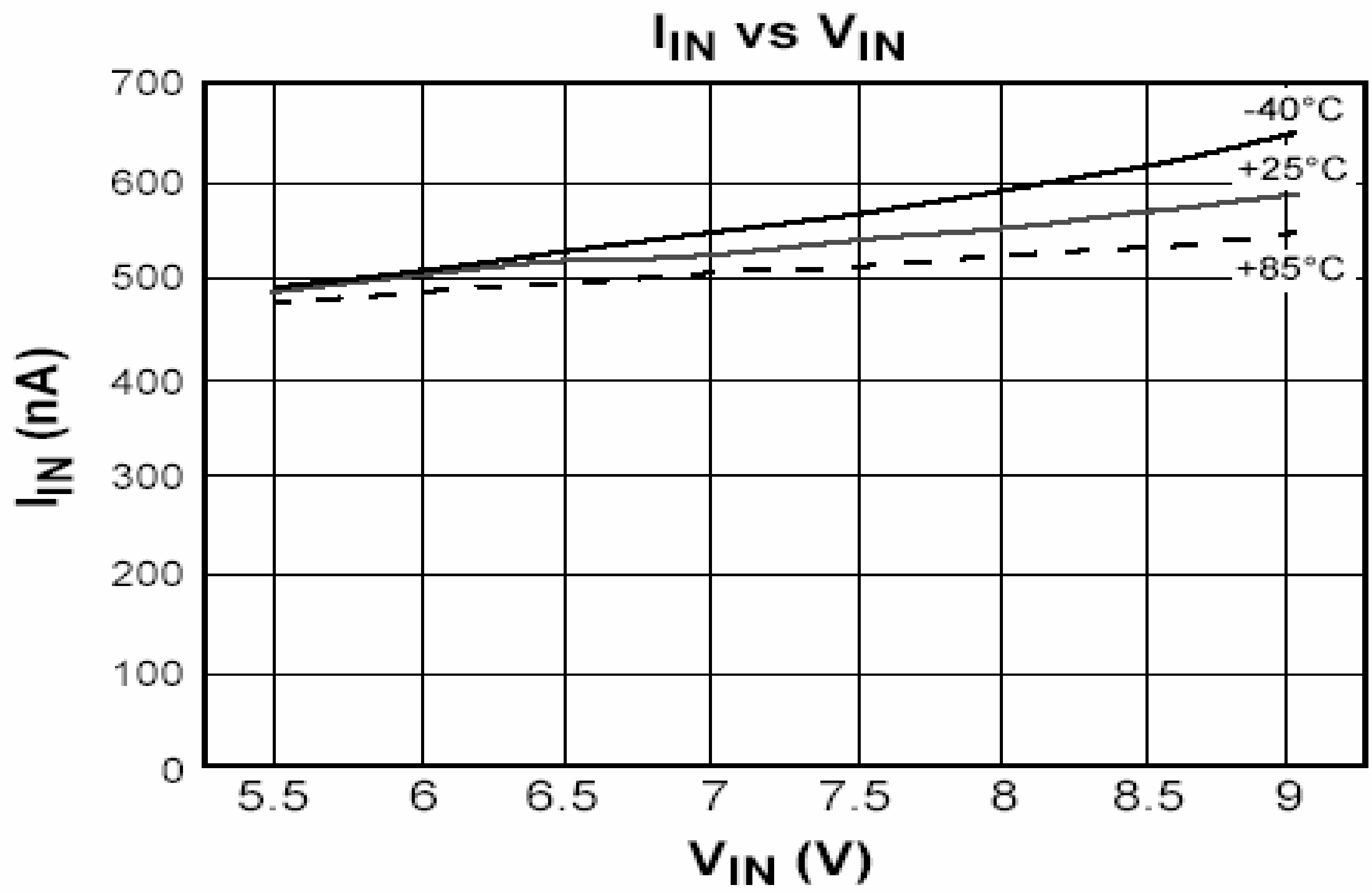
– Voltage Reference 5.000V, 4.096V, 2.500V, 1.250V	
– Initial Accuracy	< 0.5mV
– Temperature coefficient	< 1 ppm /°C over -40 to 85°C
– Low power	< 500nA at 5V
– Input Voltage VIN	9V down to 2.7V
– Long-term Drift	< 10ppm/1000hr ***
– Low Drop Out	~ 200mV
– Line Regulation	< 20ppm/V
– Output Load Current	±10mA
– Noise(0.1-10Hz)	< 30µV peak-peak
– Warm-up time after power-up	zero (for <0.5mV error)

The floating-gate analog reference has set the new performance standards for precision low-power voltage reference!

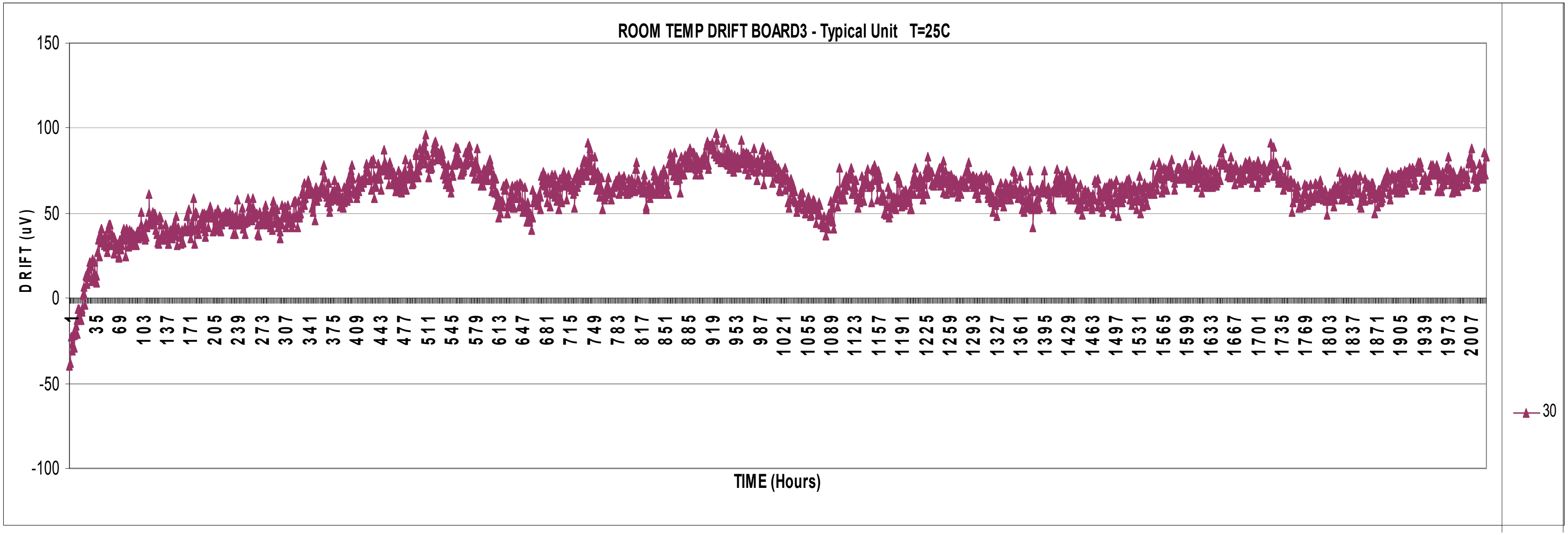
X60008 Grade A (TC < 1ppm/^{0}C)



Supply Current vs Voltage

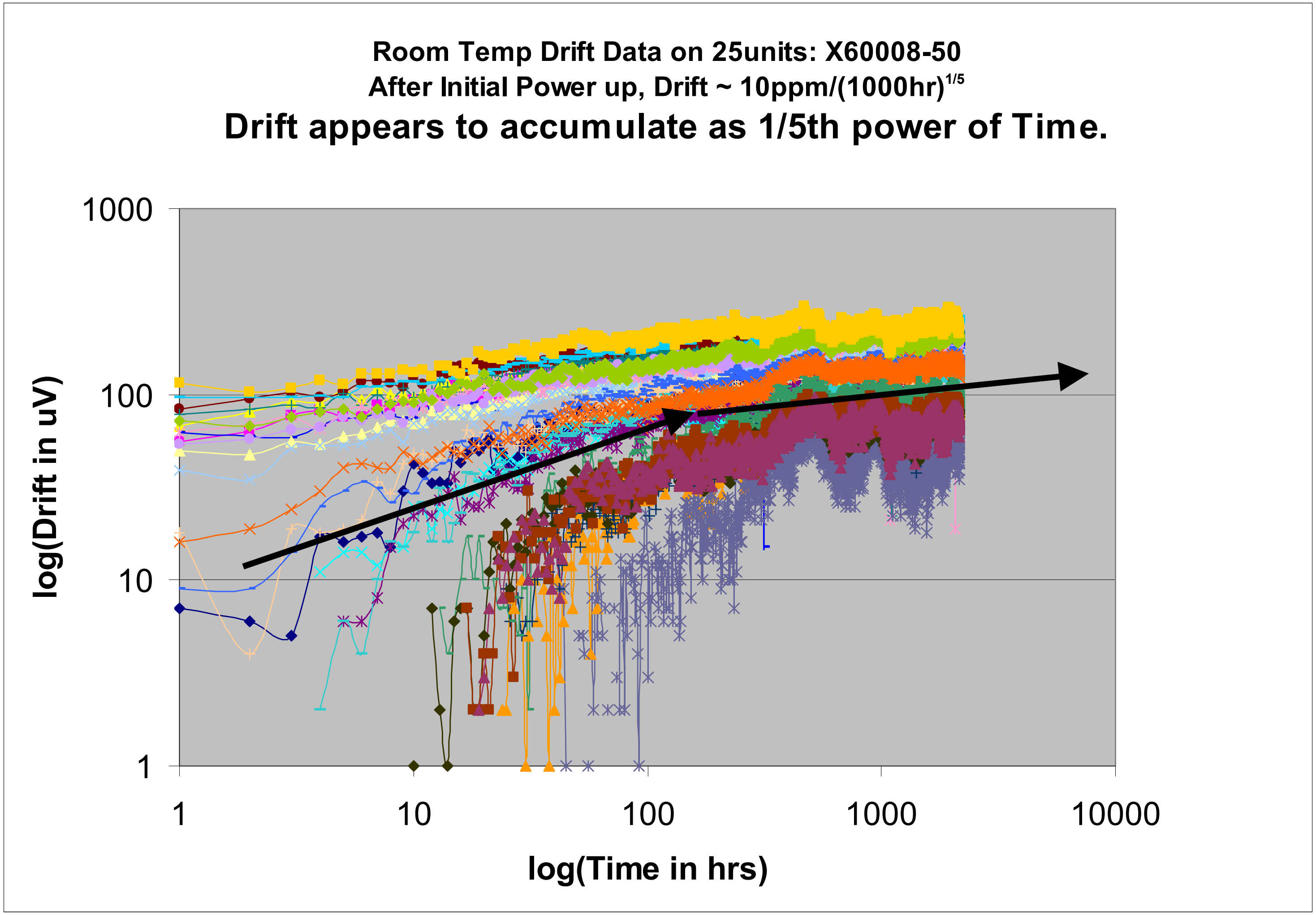


Long Term Drift Data (Unit #30) at 25^{0}C



Long Term Drift:

Mostly specified as linear accumulation with time such as 10ppm/1Khr
Some specify it as accumulation with sqrt(time) such as 10ppm/sqrt(1KHr)



Precision Reference Applications

- Precision test and measurement equipment
- Industrial process control
- Medical instruments
- Handheld battery-powered instruments

Floating-gate Reference Benefits

- **Highest Performance**
  - <0.5mV initial accuracy (set after assembly)
  - <1ppm/ºC temperature coefficient
  - <10ppm/1000hr*** long-term drift
- **Low Cost**
  - CMOS EEPROM Technology
  - NO Laser-trim or Fuses
  - Eliminates Thin-film technology
  - Eliminates Special package
- **Lowest Power < 500nA**
  - 10^{-4} times current of references of similar performance
- **No warm-up time to reach within Initial Accuracy.**
- **Any Value of VREF with 1X Buffer => Noise independent of Value.**

Ideal solution for Handheld Battery-powered instruments

SUMMARY

- Floating Gate Technology for Reference Voltage
- Precision Reference with No Trims in Standard CMOS
- Lowest Power/ TempCo/ LT Drift/ Initial Accuracy and Cost
- Ideal for Handheld Applications

ACKNOWLEDGEMENTS

- Design, Product and Test teams

Reference:

- J. McCreary "Conference Proceedings", IIC China 2004 Conference, Shanghai.