Sensing Circuits for Resistive Memory

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Abstract – A nascent class of memory cells based on magnetic- and glass-based materials display resistive characteristics. The variation of the resistance with some applied electrical stimulus must be sensed and interfaced with standard CMOS electronics. This talk will provide: (1) an overview of resistive memory cell operation (how the resistance of these cells can be used as a memory), (2) design concerns when sensing to keep from affecting the contents of the cell while maximizing the signal available for sensing, and (3) how precision components can be eliminated with the use of some simple signal processing techniques (making the sensing technique manufacturable). The talk will conclude with a practical design example showing how the techniques discussed can be applied to solve the sensing problem in real world memories.

Talk Outline

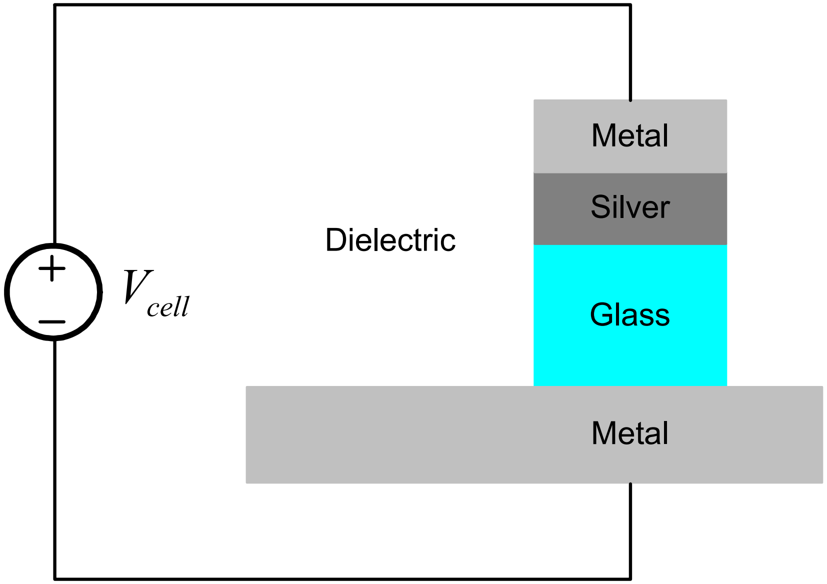
- ☐ Overview of resistive memory elements
  - ✓ Glass-based
  - ✓ Magnetic memory
- ☐ Resistive memory arrays
  - ✓ Cross point arrays (no access device)
  - ✓ 3D integration
- ☐ Sensing I – traditional circuit techniques
  - ✓ Qualitative explanation
  - ✓ The equipotential scheme
  - ✓ Problems: offset, integration time, noise

Talk Outline (cont'd)

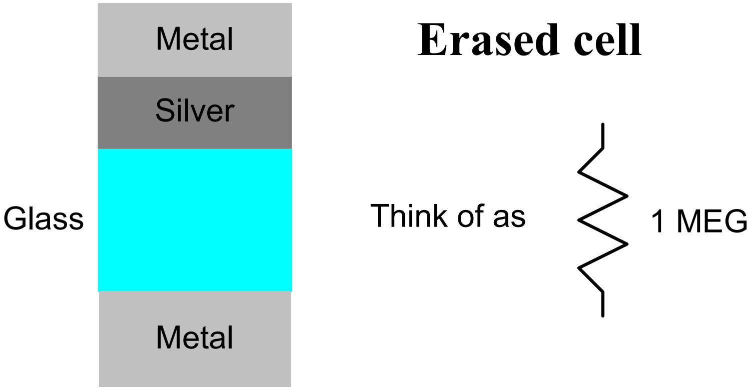
- ☐ Sensing II – using signal processing
  - ✓ Qualitative explanation
  - ✓ Noise-shaping techniques
  - ✓ Offset, integration time, noise
  - ✓ Process, voltage, temperature
  - ✓ Self-referencing (determining if the cell is a "1" or "0")
- ☐ Ongoing research

Glass-Based Memory Cells

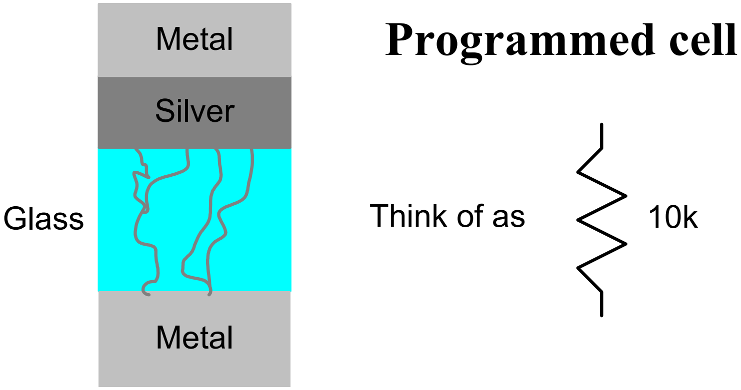
Programmable Resistance RAM (PRRAM)



Erased cell



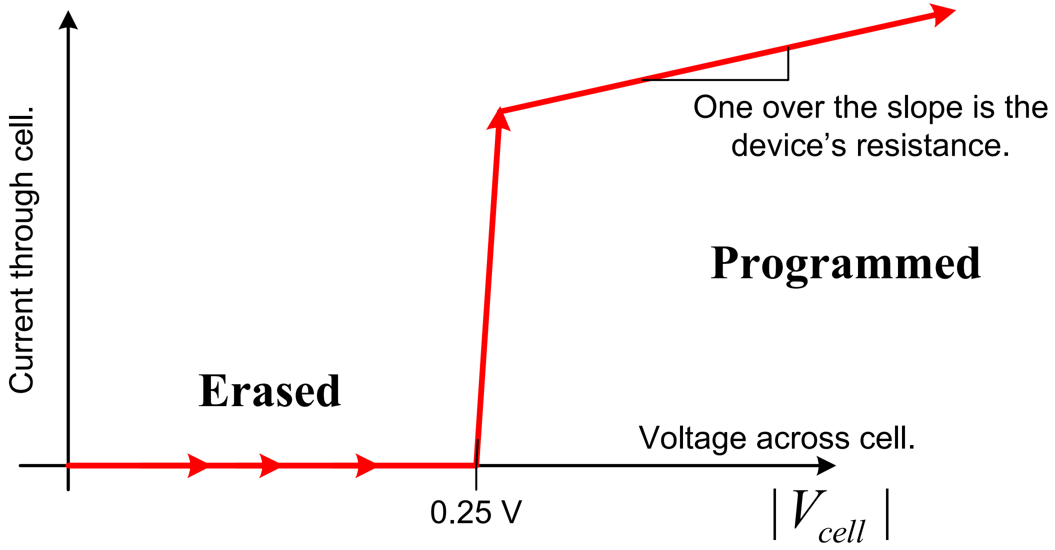
Programmed cell



For additional information see:
http://www.axontc.com/

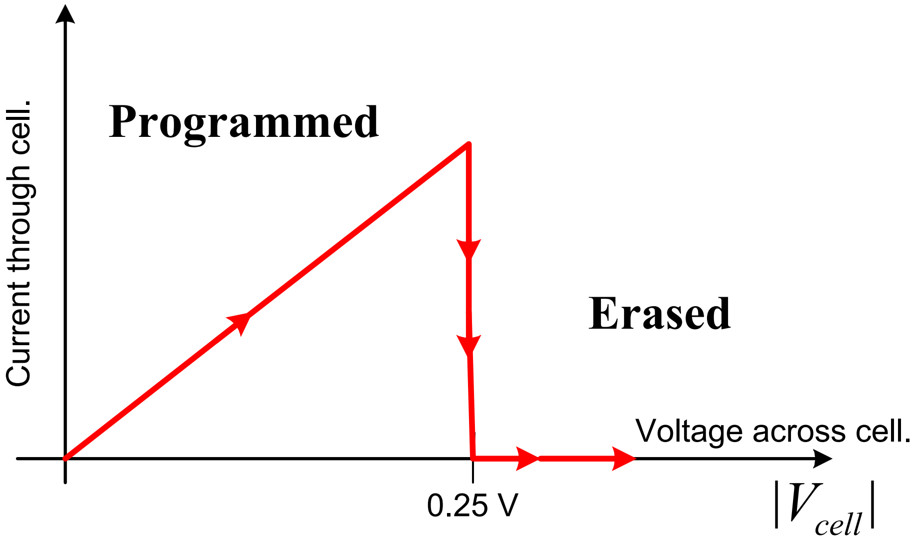
Programming the cell

Going from Erased to Programmed



Programming the cell (cont'd)

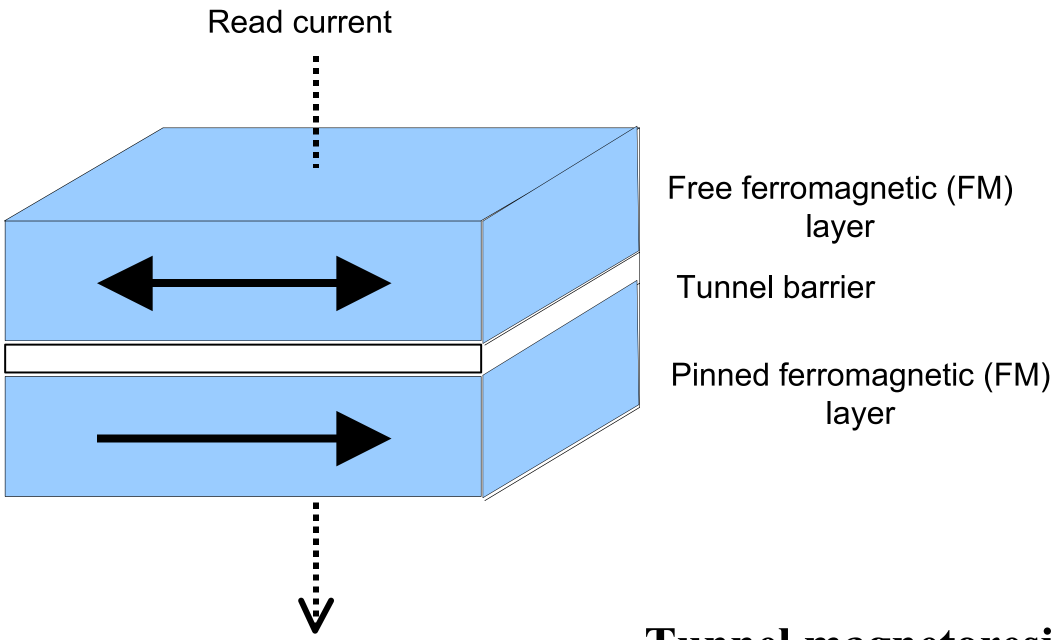
Going from Programmed to Erased



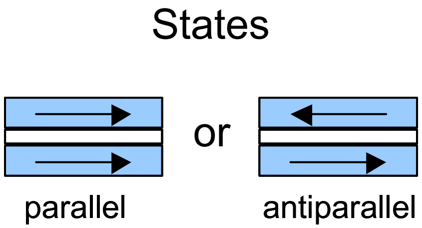
Key Points when Sensing (PRRAM)

- ☐ Must keep voltage across the cell to less than +/- 0.25 V
- ☐ More desirable - minimize the voltage across the cell
  - ✓ Increases retention time
  - ✓ Increases lifetime
  - ✓ Makes sensing more challenging
  - ✓ Makes process shifts in the actual switching voltage irrelevant
  - ✓ Minimizes power dissipation
- ☐ Must use an access device
  - ✓ Eliminates the possibility of 3D integration
  - ✓ Makes sensing much less challenging than sensing in MRAM

Magnetic Materials-Based Cells



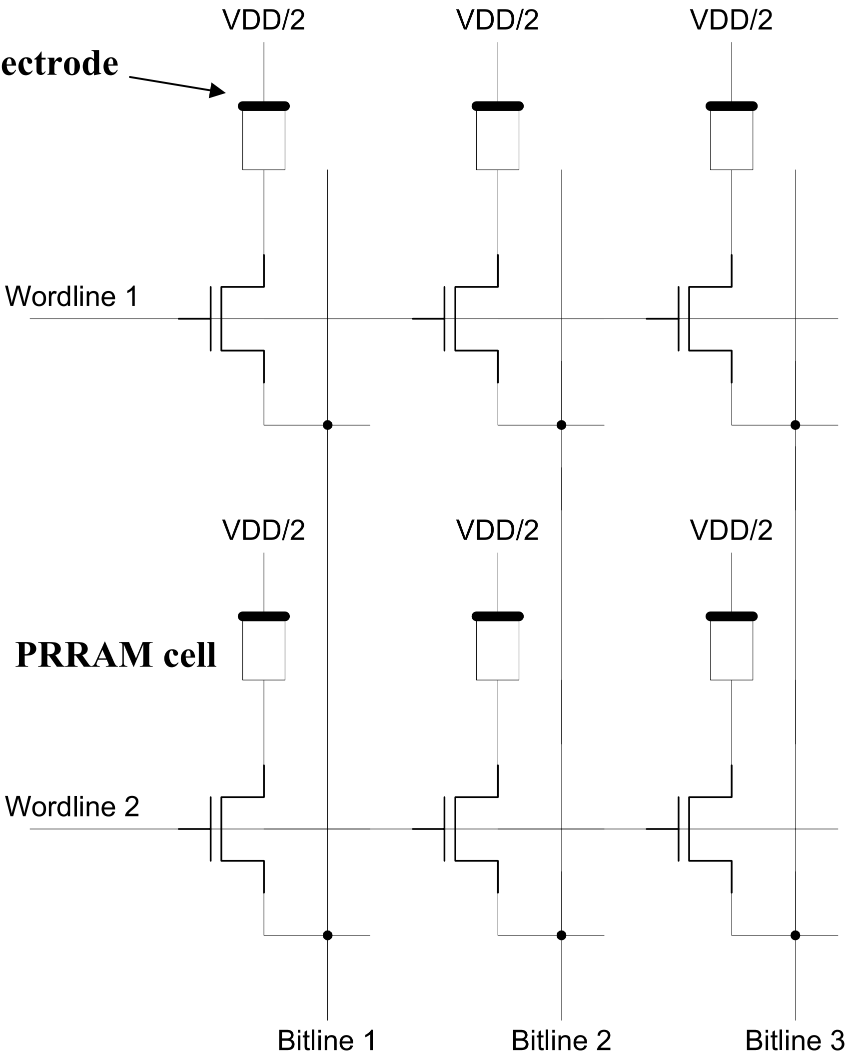
Tunnel magnetoresistive effects



MRAM Cell Operation

- ☐ MRAM utilizes magnetic storage elements (rather than capacitors as in DRAM) to form arrays of individually accessible bits.
- ☐ The main concept behind reading the data is based on the Magnetoresistive (MR) effect.
- ☐ MR occurs when the resistance of the memory cell depends upon the magnetic alignment of two separate magnetic layers. If the magnetic layers are aligned, the electrons are scattered less (lower R) than if the layers are not aligned.
- ☐ The method of writing the data is based on the generation of a magnetic field around a wire with the flow of current in the wire.
- ☐ A current run through orthogonal conductors over or under the magnetic element can change the orientation of the magnetic moment of the element by 180 degrees, thereby writing a “1”, or a “0” into the cell.
- ☐ The MR ratio is given as a percentage, and is the difference in resistance (between the two magnetic alignment states) divided by the original resistance.

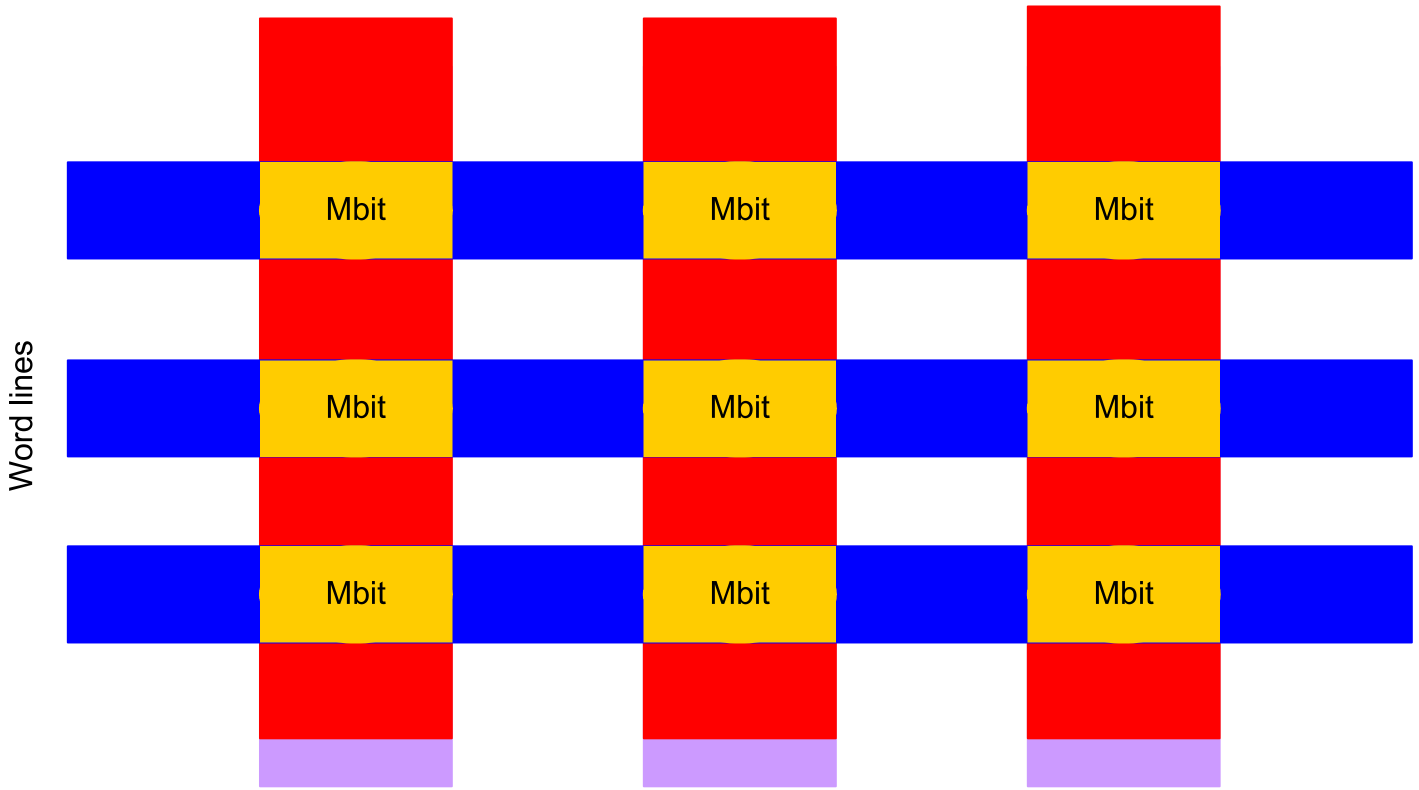
Resistive Memory Arrays



- ☐ PRRAM must use an access device because of the common VDD/2 node.
- ☐ Can’t be integrated in the third dimension (up).
- ☐ For sensing we think of the cell as a resistor connected to VDD/2.
- ☐ The main parasitic of importance is the bitline capacitance.

Cross Point Array Layout

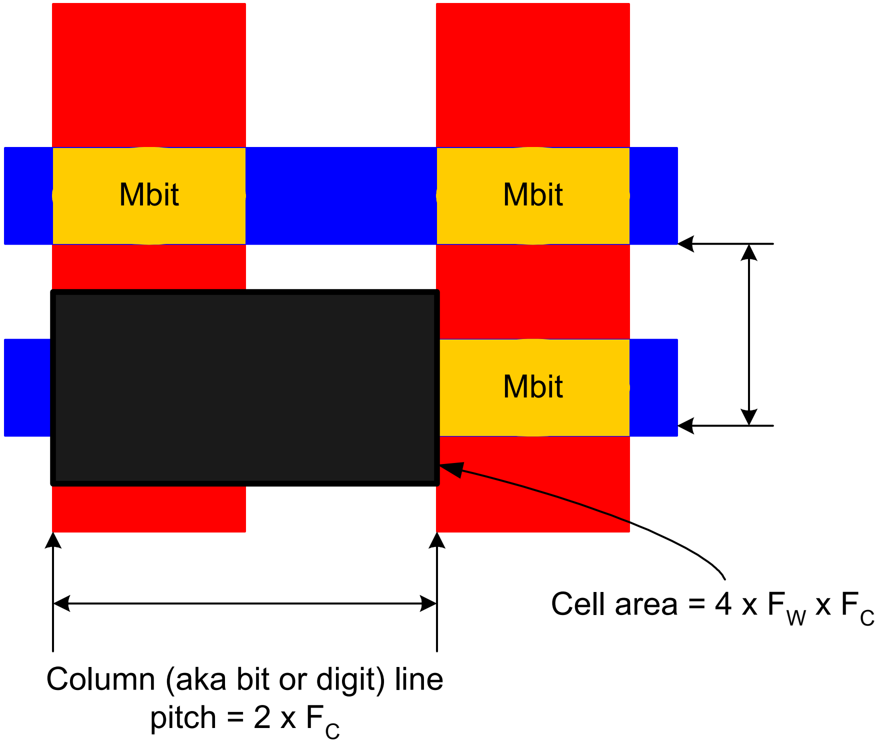
Layout of the MRAM cross point array



Digit, bit, or column lines

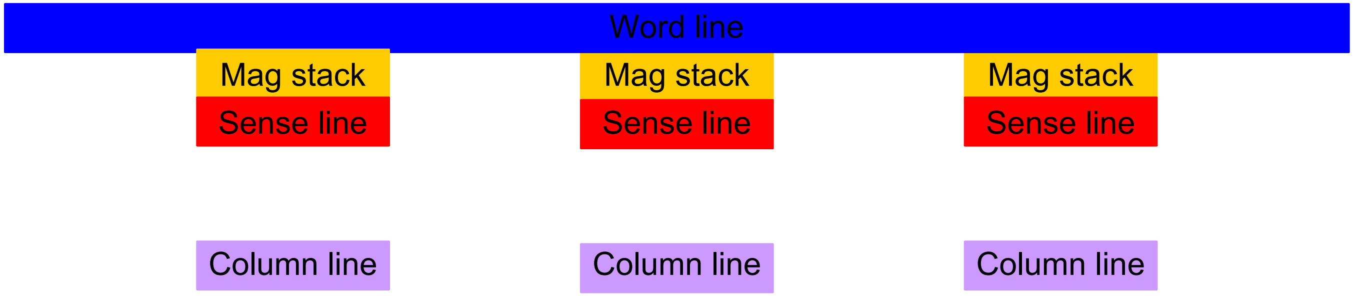
Cross Point Array (cont'd)

- ☐ MRAM, theoretically, doesn't require an access device.
- ☐ Cell size can approach a size of $4F^2$
- ☐ If the cells are integrated in the third dimension the cell size is further reduced.
- ☐ Integrating 4 planes of MRAM result in a cell size of F^2



3 Conductor MRAM Cell

Cross sectional view of the MRAM array.



Word line

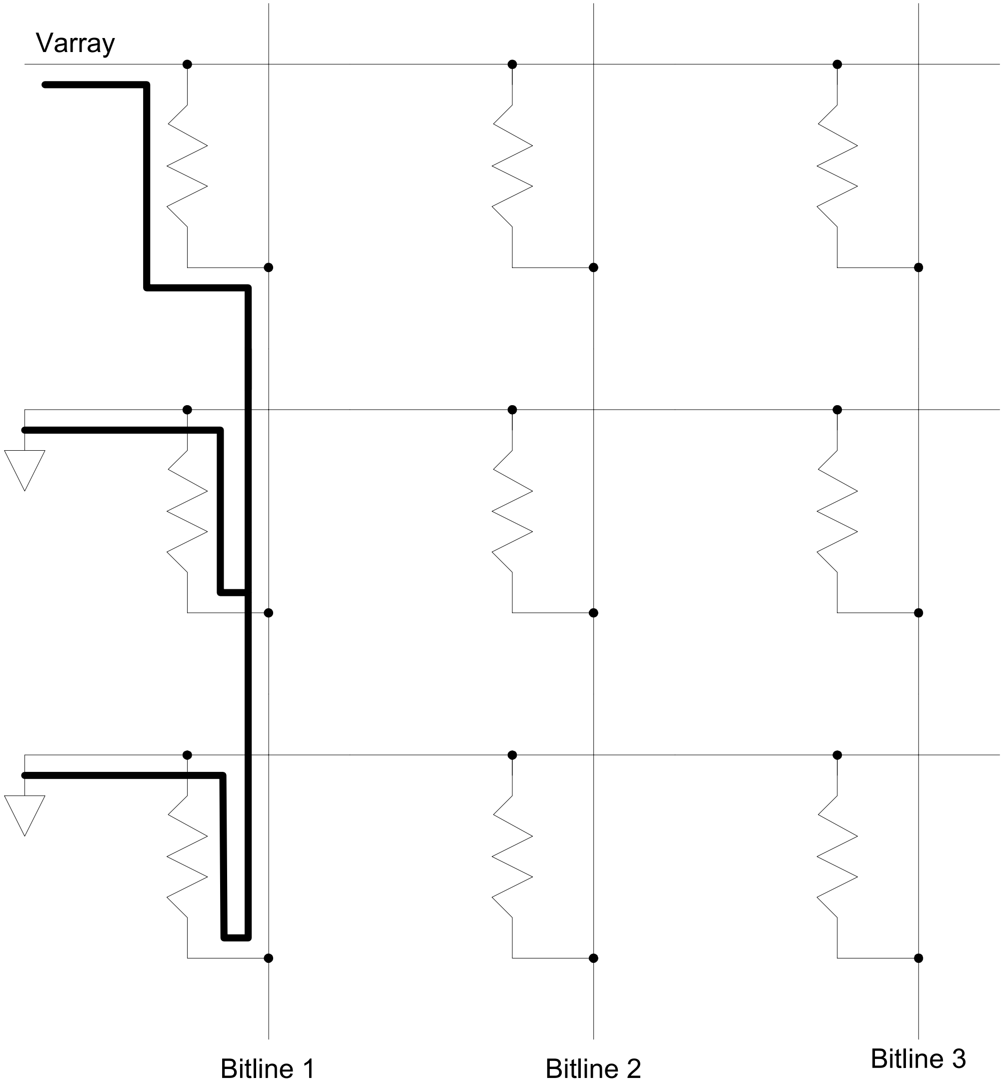
Mag stack
Sense line
Column line

Mag stack
Sense line
Column line

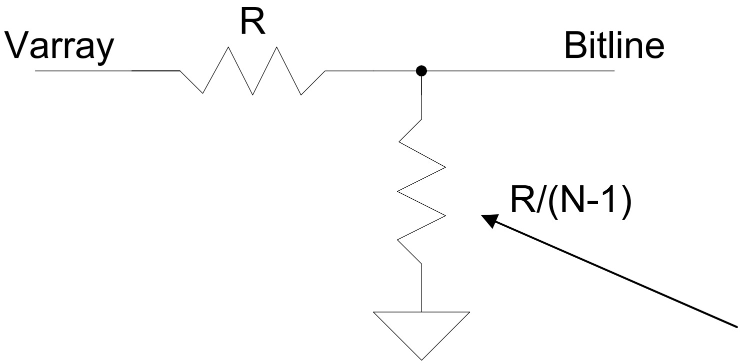
Mag stack
Sense line
Column line

- ❑ In a practical MRAM cell a second write conductor can be added to avoid breakdown.
- ❑ What we’re not discussing (and these are big): half-select problems (how to isolate the magnetic fields to a localized region), laying down consistently thin (say 10 Angstroms) of magnetic materials, and getting large, and repeatable, TMRs.

Circuit View of the Cross Point Array

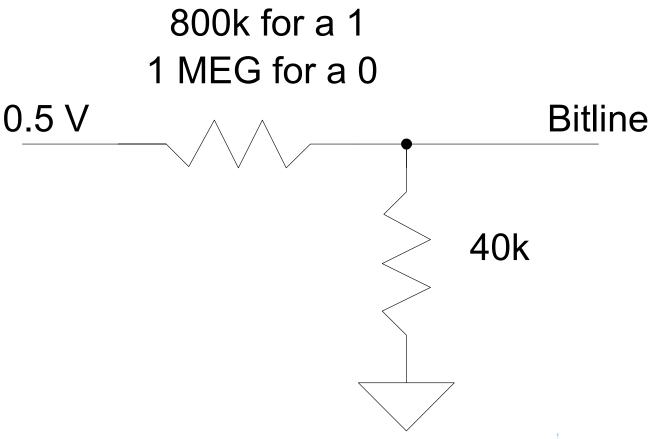


Simplified View



Sneak resistance

If R is nominally 1 MEG and N is 256 (= number of wordlines) then the sneak resistance is roughly 40k.

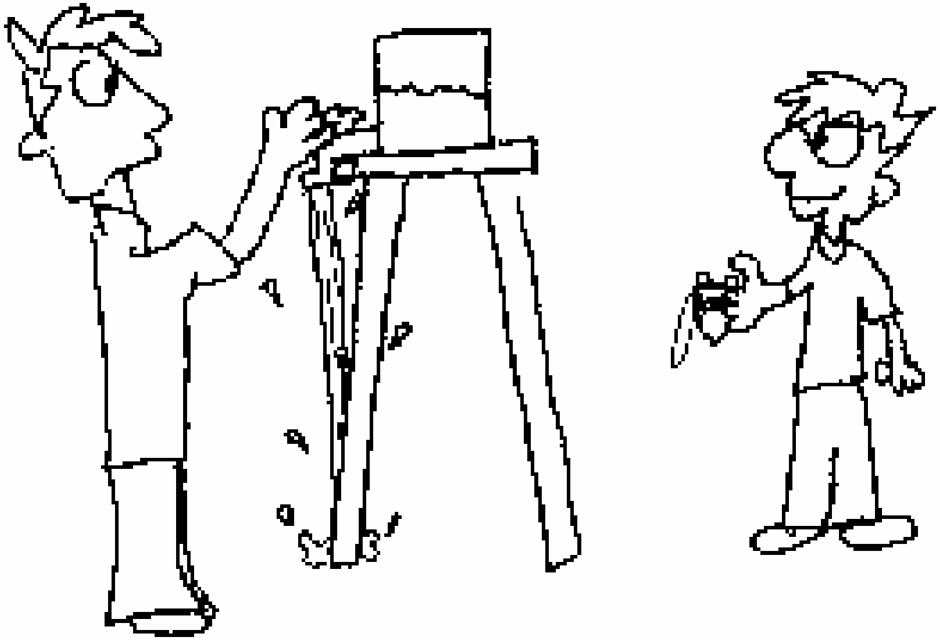


Bitline voltage for a 0 is 0.019 V
Bitline voltage for a 1 is 0.024 V

Difference is only 5 mV!!!

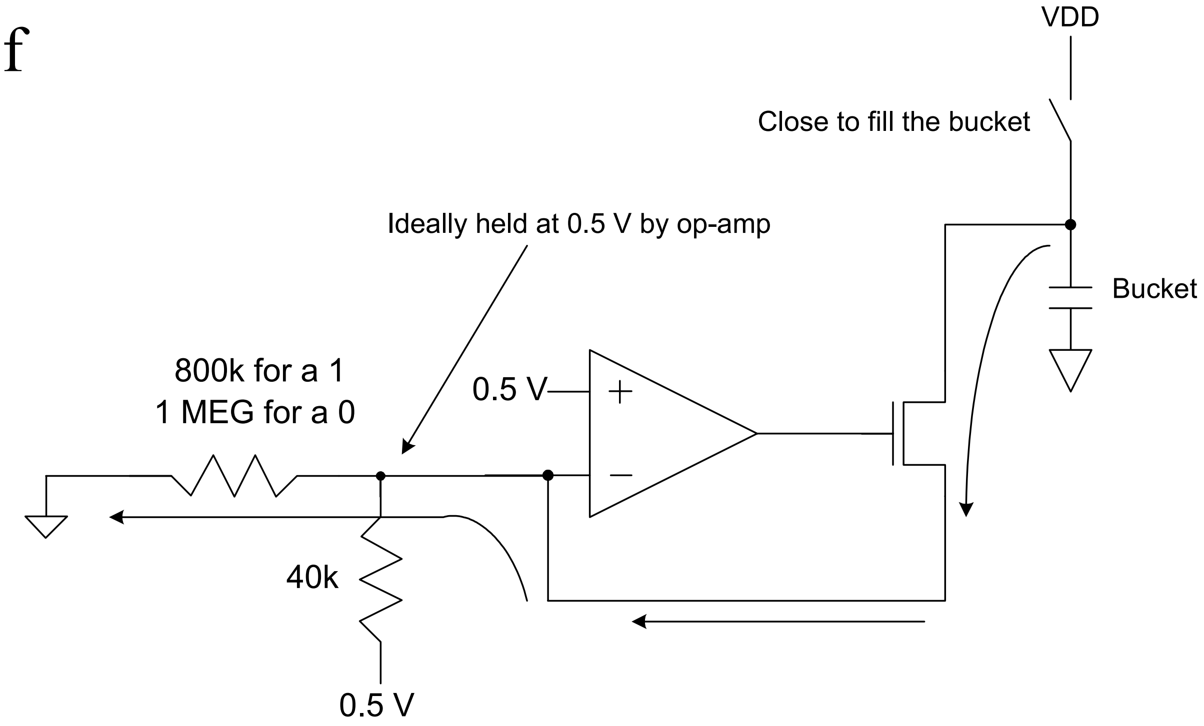
Sensing I – Traditional Circuit Techniques

- ☐ Traditional circuit techniques require precision components when sensing such small voltages.
- ☐ The cartoon illustrates the basic idea. One guy is trying to precisely set the rate of flow out of the bucket. The other guy is timing to see how long it will take for the bucket to empty.



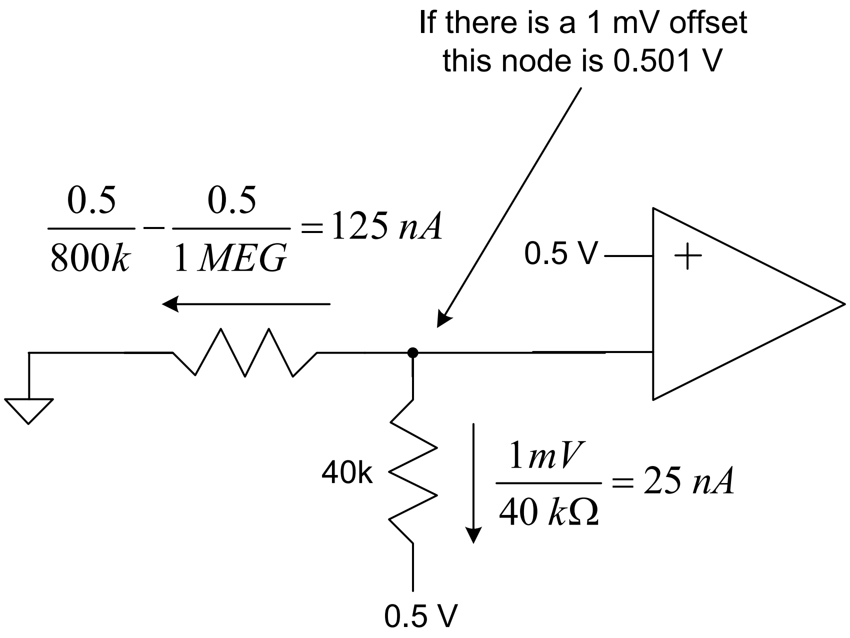
The Equipotential Scheme

- ☐ The op-amp is trying to precisely set the flow of current out of the capacitor.
- ☐ If everything is perfect there will be zero current through the 40k sneak resistance.
- ☐ A comparator and counter determine how long it takes to discharge the capacitor.



Equipotential Problems

- ❑ With only 1 mV of offset the sneak path current is 20% of the signal current.
- ❑ What happens if the offset varies, or more practically, the op-amp has finite gain?
- ❑ The desired signal will get lost as a result of the op-amp's imperfections.
- ❑ Remembering our cartoon, we can't precisely adjust the water flow out of the bucket.



If there is a 1 mV offset this node is 0.501 V

$$\frac{0.5}{800k} - \frac{0.5}{1\,MEG} = 125\ nA$$

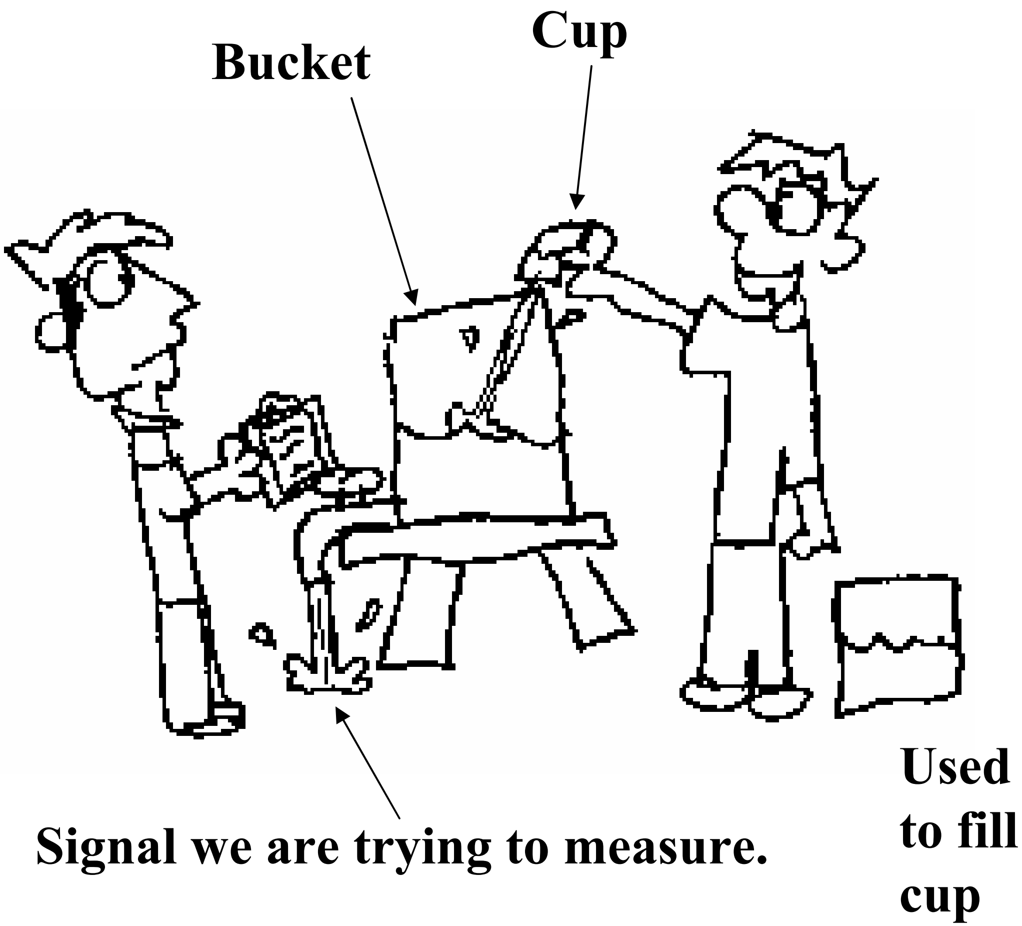
$$\frac{1\,mV}{40\ k\Omega} = 25\ nA$$

Some Other Practical Problems

- ☐ Integration time (the time it takes to empty the bucket)
  - ✓ Very dependent on the value of the resistor
  - ✓ Changes with imperfections in the op-amp (offset, noise, gain)
- ☐ A more subtle problem is circuit noise
  - ✓ The DC current is integrated (empties the bucket)
  - ✓ The thermal noise is integrated (resulting in a power spectral density of $1/f^2$)
  - ✓ The flicker noise is integrated resulting a PSD of $1/f^3$
- ☐ The problem is that increasing the size of the bucket so we can integrate longer (using a larger capacitor) will not result in a better estimate for the current. (The signal-to-noise ratio won't increase with longer integration times.)

Sensing II – Using Signal Processing

- Using some simple signal processing (here averaging) results in a robust sensing scheme.
- The cartoon illustrates the basic idea. One guy is adding water to the bucket in order to hold the water level at a constant value. The other guy is counting the number of added cups of water, over a given time.



Qualitative Explanation

- ☐ The bucket never empties in this scheme
  - ✓ The integration time is not important (we can sense indefinitely).
  - ✓ The size of the cup that adds water is important.
    - o Using too small of a cup results in the water draining out of the bucket. (We can't add the water fast enough).
    - o Using a small cup for adding water increases the resolution.
- ☐ What happens if the guy adding water to the bucket tries to hold the water level at a line other than the correct line (an offset)?
  - ✓ As long as he attempts to hold the water level at a constant value the actual level is unimportant (offset doesn't matter).
- ☐ What limits the resolution of this scheme? 1) A leaky bucket, and 2) imperfectly filling the cup (or slopping water out of the cup).

Qualitative Example

- ☐ Example: We add a cup of water, at most, every 10 seconds. Our cup size is 10 oz.
  - ✓ Say that the bucket is draining at a rate of 0.3 oz per second. We can write (assuming we want to keep, arbitrarily, 100 oz of water in the bucket):

Time (secs)	Add cup?	Bucket Vol. (oz)	Average # cups
0 (1)	Y	100	1 (1/1)
10 (2)	N	107	0.5 (1/2)
20 (3)	N	104	0.333 (1/3)
30 (4)	N	101	0.25 (1/4)
40 (5)	Y	98	0.4 (2/5)
50 (6)	N	105	0.333 (2/6)
60 (7)	N	102	0.286 (2/7)
70 (8)	Y	99	0.375 (3/8)
80 (9)	N	106	0.333 (3/9)

Qualitative Example (cont'd)

- ❑ Continuing we can write (noting it doesn't matter if our first decision was an add or not).

Time (secs)	Add cup?	Bucket Vol. (oz)	Average # cups
80 (9)	N	106	0.333 (3/9)
90 (10)	N	103	0.300 (3/10)
100 (11)	Y	100	0.364 (4/11)
110 (12)	N	107	0.333 (4/12)
120 (13)	N	104	0.308 (4/13)
130 (14)	N	101	0.285 (4/14)
140 (15)	Y	98	0.333 (5/15)
150 (16)	N	105	0.313 (5/16)
160 (17)	N	102	0.294 (5/17)
180 (18)	Y	99	0.333 (6/18)
190 (19)	N	106	0.316 (6/19)
200 (20)	N	103	0.300 (6/20)

Qualitative Example (cont'd)

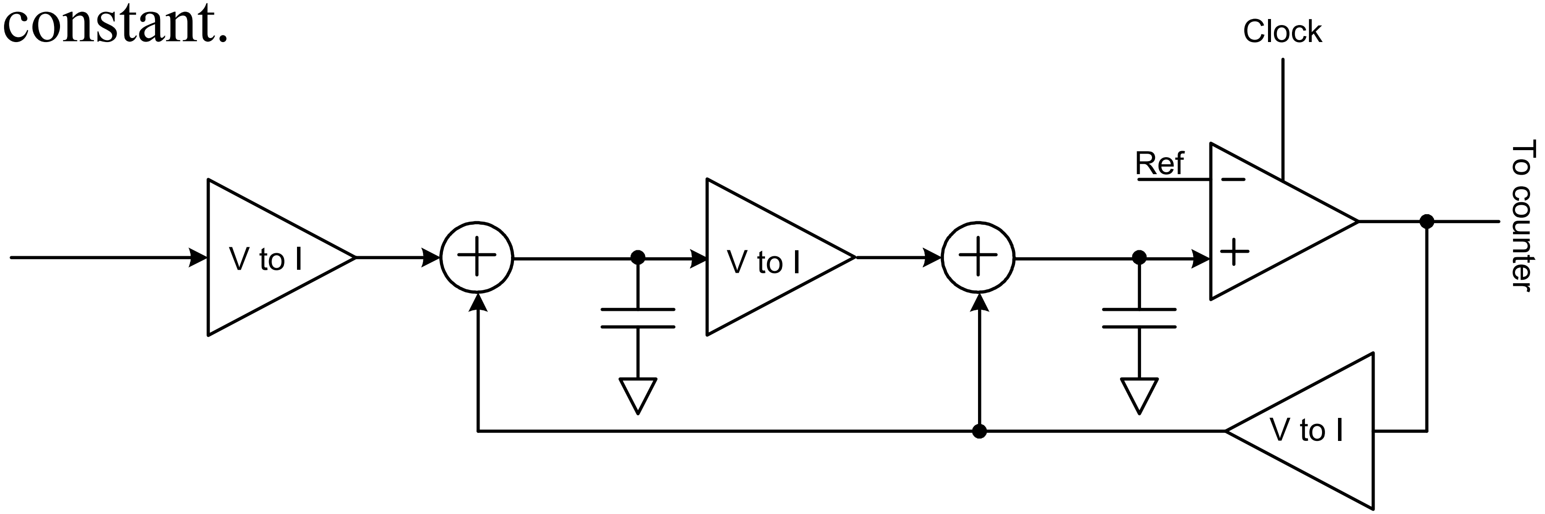
- ☐ Note how, as we increase the number of samples, the average bounces around 0.3.
  - ✓ The more samples we take the more the average converges on 0.3
- ☐ The signal is the product of the average and the cup size or 0.3*10 (which is 3 oz per 10 seconds).
- ☐ Note that if we make a wrong decision it doesn't really matter.
  - ✓ If we add a cup when we shouldn't have it really doesn't matter! (Comparator gain isn't important.)
  - ✓ A counter is used for averaging (count the number of times we add water to the bucket).

Resolution and Precision

- ☐ Again, the resolution is set by the size of the cup we use to add water to the bucket.
  - ✓ Smaller cup, faster, more accurate sense.
  - ✓ If the cup is too small we can’t add water fast enough.
- ☐ The precision is set by how accurately we add the water to the bucket.
  - ✓ Spilling water out of the cup reduces the sensing accuracy.
- ☐ The ultimate resolution is determined by how leaky the bucket is (keeping in mind that in a circuit an integrator is used for the bucket.)
- ☐ Note that the longer we sense the better the sense. (We don’t have to worry about the bucket emptying.)

Circuit Block Diagram

- ❑ Here, for an MRAM sensing circuit, we use two buckets (capacitors) in an effort to minimize the sensing time.
- ❑ The voltage on the digitline is converted to a current and integrated by the first capacitor. The pressure in this bucket (the voltage on the capacitor) is changed into a current and integrated by the second capacitor. The clocked comparator then provides a current back to each cap to hold their voltages essentially constant.



Self-Referencing

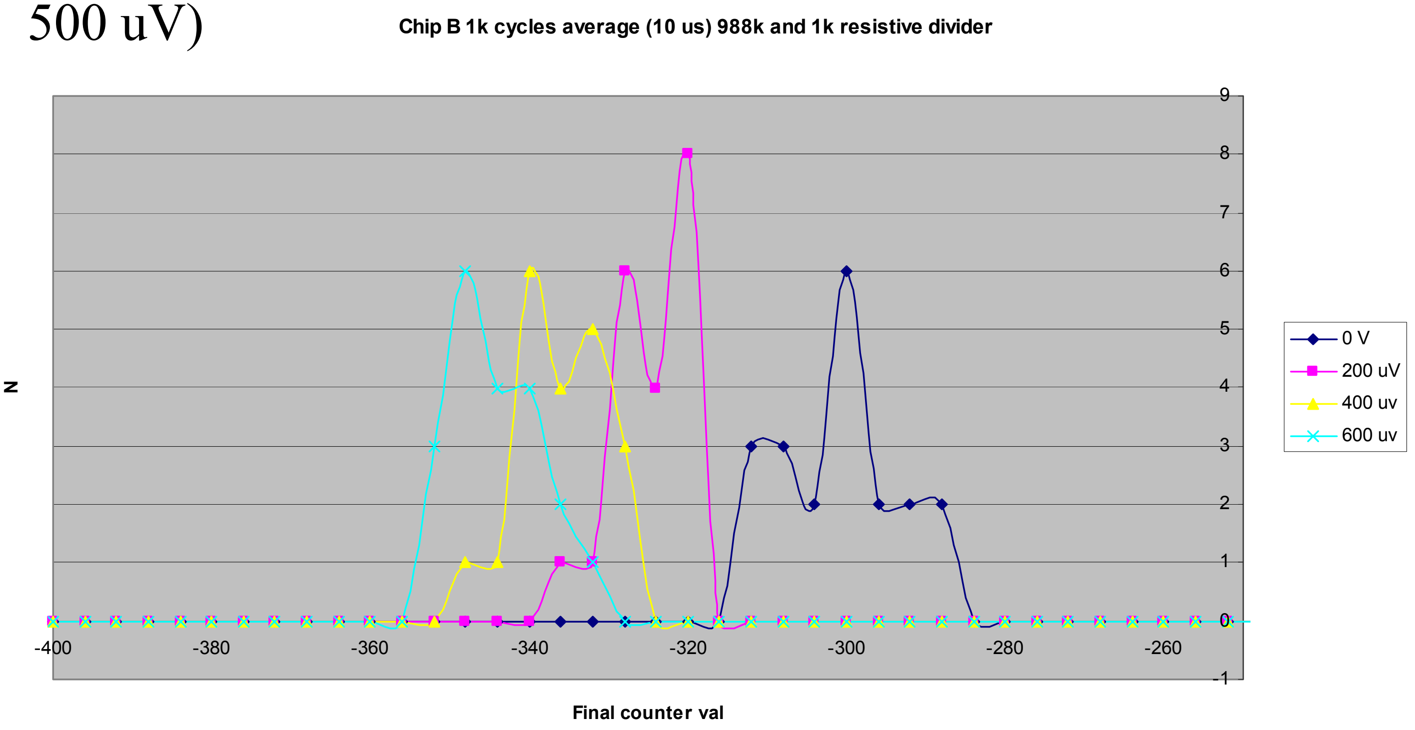
- ☐ So we have a counter code. How do we determine if we read a 1 or a 0?
- ☐ Consider the following: Say a 1 corresponds to a counter code of 222 and a 0 corresponds to 220.
- ☐ Reading a 1
  - ✓ Perform two reads on the cell. The counters contents are 444.
  - ✓ Write a known 1 into the cell. Make the counter count down instead of up during a sense. The counters contents are now 222.
  - ✓ Write a known 0 into the cell. Again, make the counter count down. The counters contents are 2. Since the number is positive the cell must be a 1. (Rewrite a 1 to the cell).

Self-Referencing (cont'd)

- ☐ Reading a 0 (again a 1 corresponds to 222 and a 0 to 220)
  - ✓ Perform two reads on the cell. The counters contents are 440.
  - ✓ Write a known 1 into the cell. Make the counter count down instead of up. The counters contents are now 218.
  - ✓ Write a known 0 into the cell. Again, make the counter count down. The counters contents are –2. Since the number is negative the cell must be a 0. (Rewrite a 0 to the cell).
- ☐ Note that we can reduce the sensing time by performing one read and then multiplying the result by 2.
- ☐ This self-referencing technique eliminates process, voltage, and temperature concerns. Even if the bit resistance has a long term variation as long as the short term variation is small the sensing works as expected.

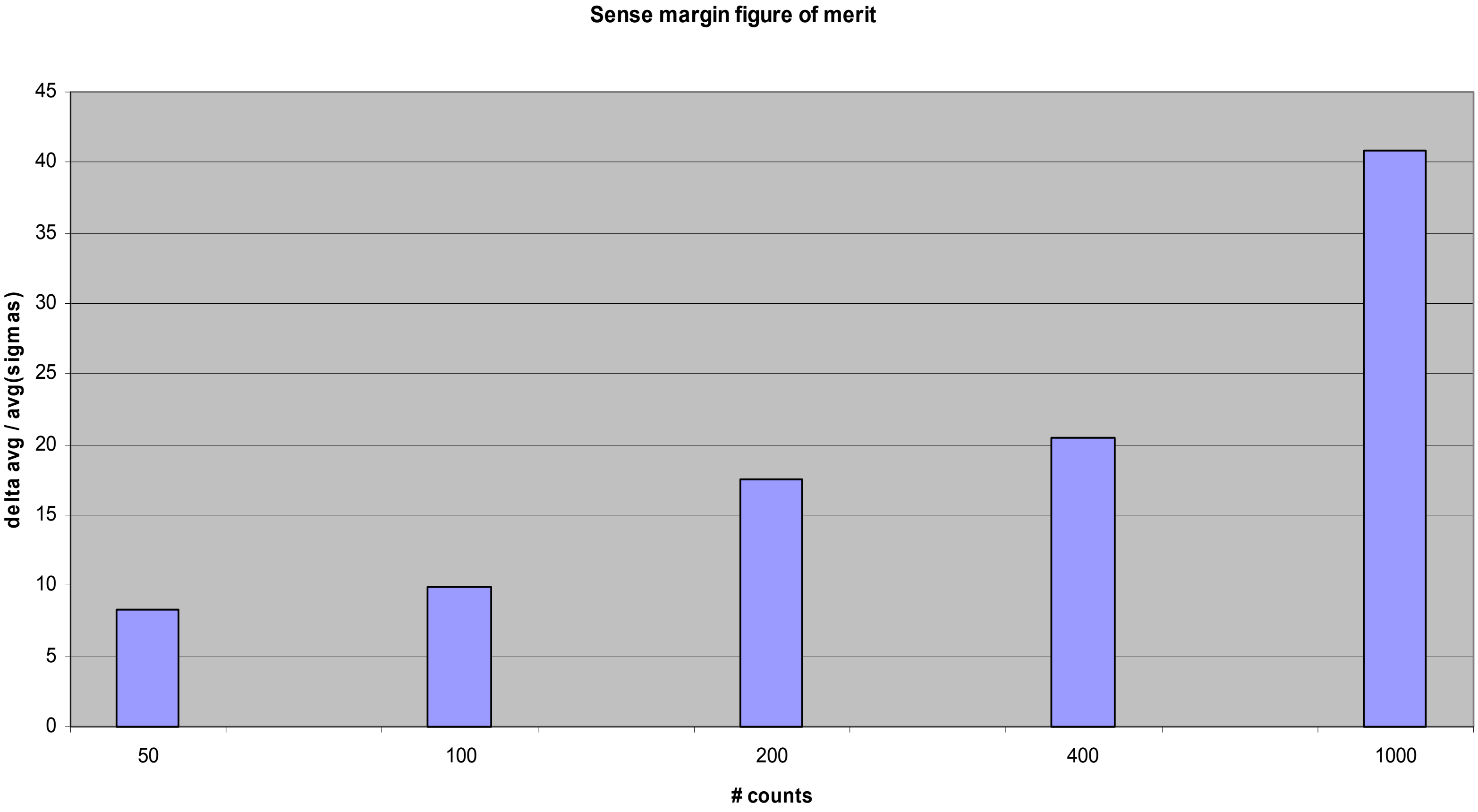
Sensing Experimental Results

- Sense-amp behaves like a voltage meter.
- Used probe station to gather results. (DC voltage ran through wires to a 1000:1 resistive divider on the wafer at the input of the sense amp!)
- With 1 MRAM plane sense signal is 2 mV (4 planes sense signal is 500 uV)



Sense time vs SNR

- ☐ How does the sensing time affect SNR?



On Going Research

- ☐ Circuit topologies that simplify the circuit design while at the same time provide sensitive sensing.
  - ✓ An example is the sensing circuit used with PRRAM. Using the parasitic digitline capacitance for the bucket (the integrator).
- ☐ Fabricating and testing the simulated designs.
- ☐ Looking at other digital filtering topologies (other than the basic counter) to enhance sensitivity for a given sensing time.