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Emerging Research Devices 2014
Collective Spin Devices

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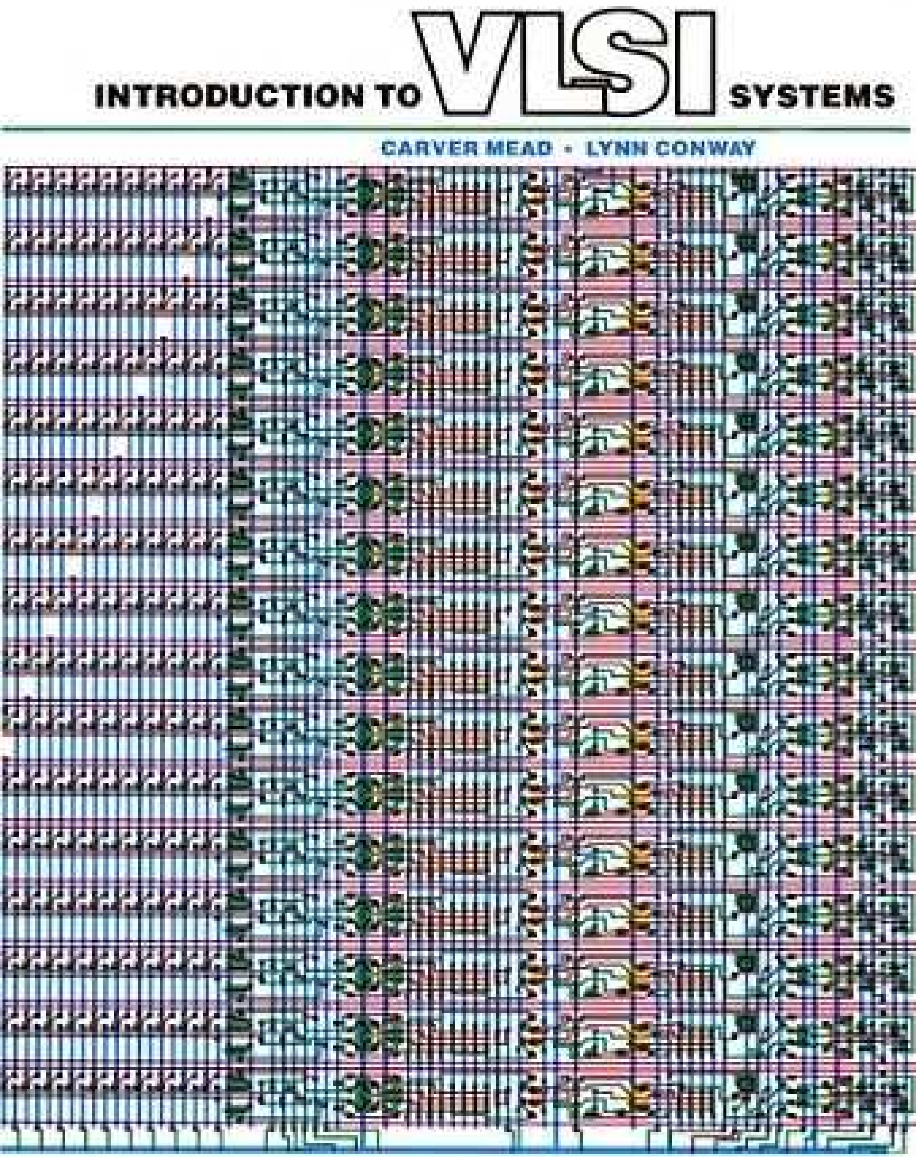
LDRD

LABORATORY DIRECTED RESEARCH & DEVELOPMENT



Collective-Spin Systems:

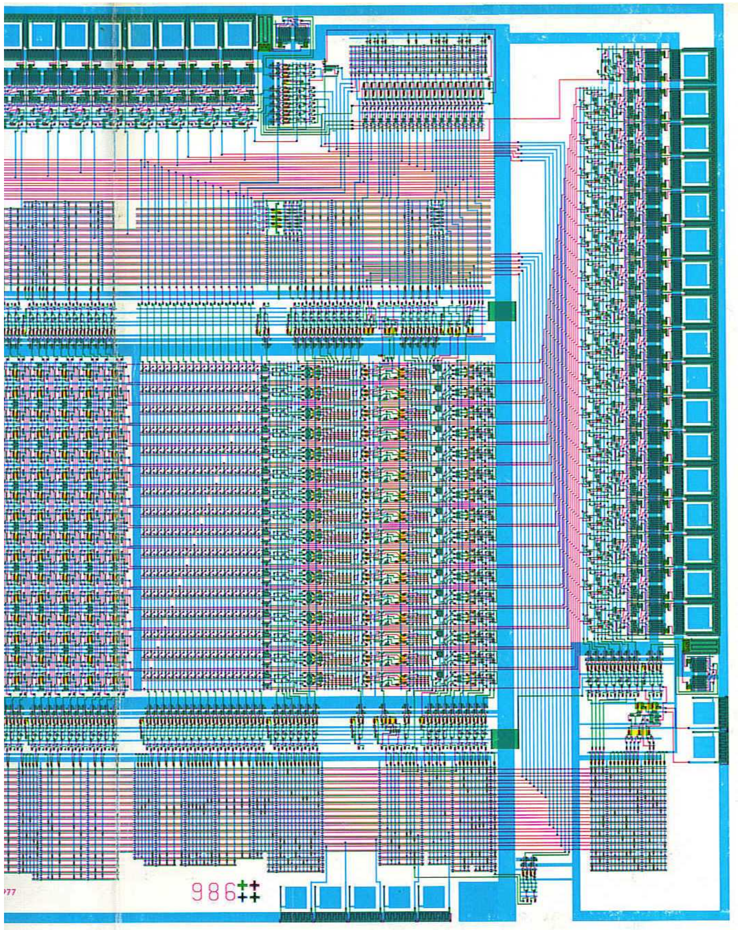
-Spin wave logic

-Nanomagnet logic

Can one construct something at this scale using spin wave or nanomagnet – based architectures?

What are the challenges in trying to do that?

- Digital logic requires (Cf. Keyes Rep. Prog. Phys. '05):
  - Gain
  - Signal Restoration
  - I/O isolation
  - Boolean completeness
  - Concatenability
- "Wires" are needed
- Scaling is another constraint
- Analog applications have no consistent benchmarks



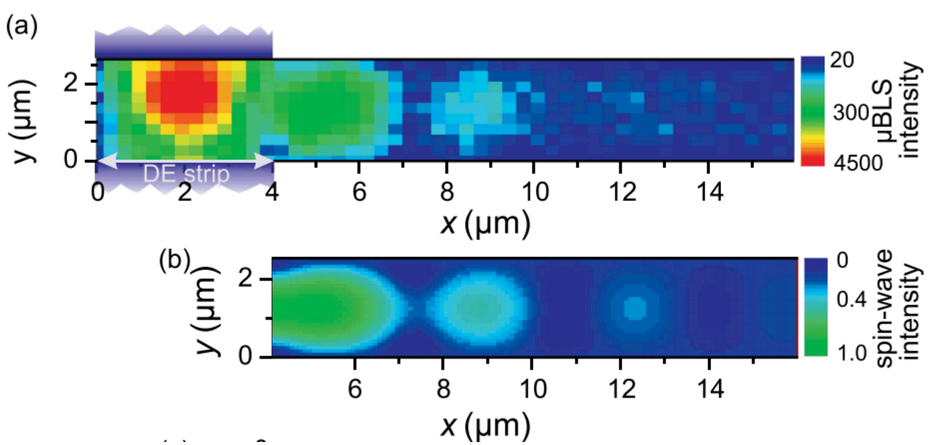
Spin waves obey magnetostatic Maxwell's equations

$$\nabla \cdot \mathbf{B} = \nabla \cdot (\mathbf{H} + 4\pi \mathbf{M}) = 0, \qquad \nabla \times \mathbf{H} = 0,$$

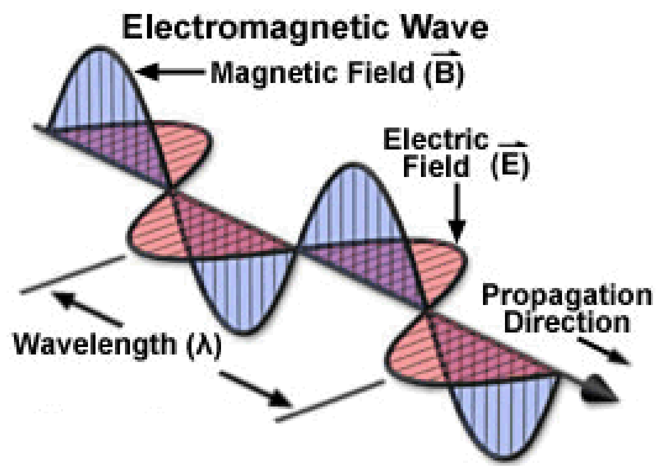
Walker, Phys. Rev. '57, Kittel, Phys. Rev. '48

Spin wave computing = Optical computing

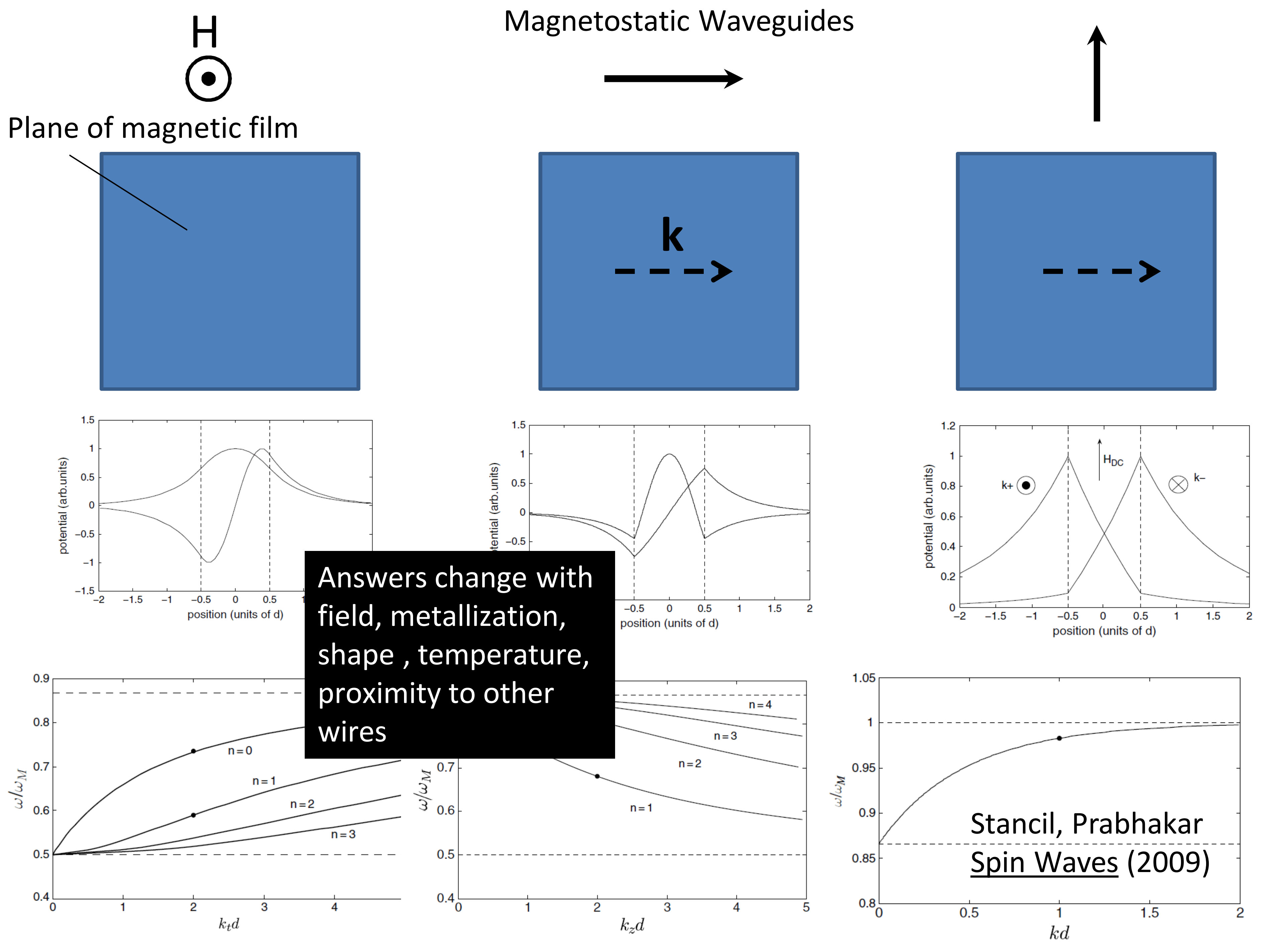
A "photon" with large B, small E. Wavelength ~μm at 10 GHz



Real-space image of MS wave and simulation
Bracher, APL (2013)

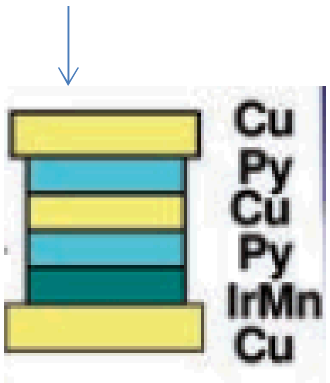


Speed of spin wave ~ c/10^4

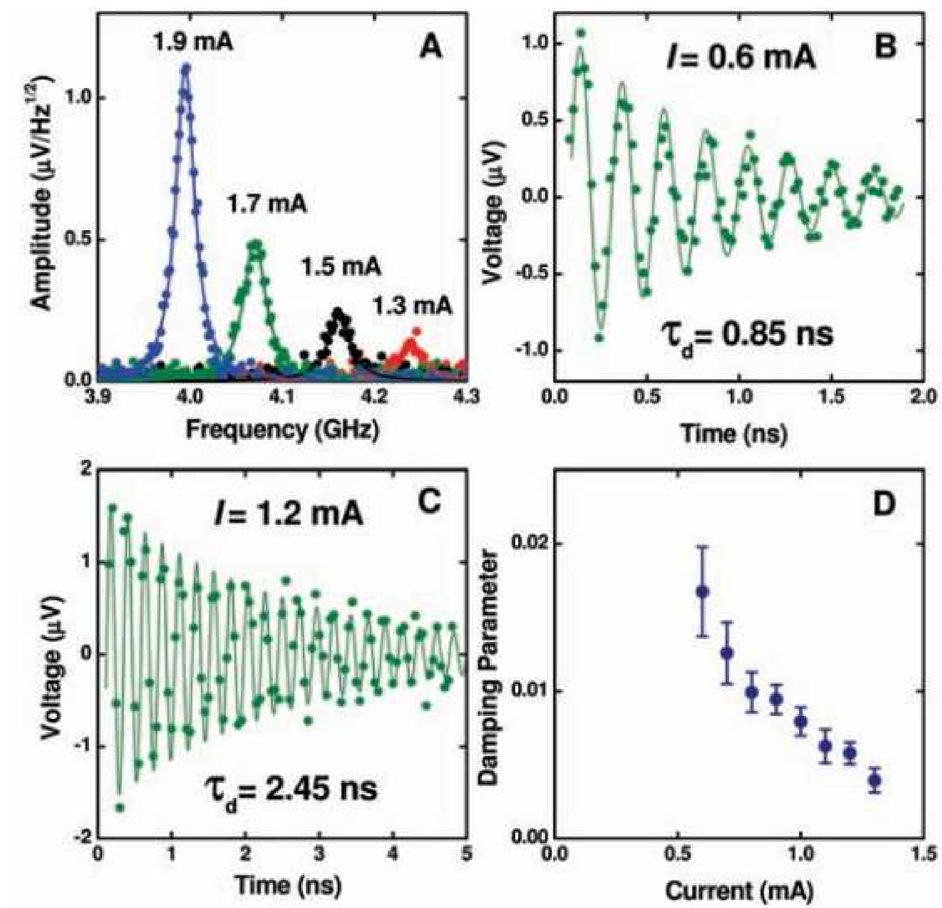


Magnetostatic Waveguides
H
Plane of magnetic film
k
potential (arb.units)
position (units of d)
H_DC
k+
k–
n=0
n=1
n=2
n=3
n=4
ω/ω_M
k_t d
k_z d
kd
Answers change with field, metallization, shape , temperature, proximity to other wires
Stancil, Prabhakar
Spin Waves (2009)

Generation of spin waves



-spin valves
-MTJ
-point contacts

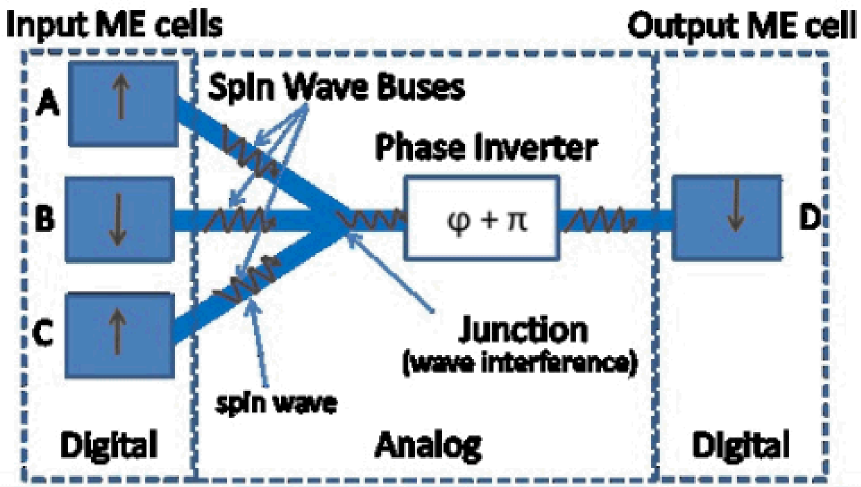


$J \sim 10^7$ A/cm^2

Krivorotov et al. Science 05

Logic unit for SW computing: an interferometer

- -Very sensitive to dimensions
- -No intrinsic gain
  - -signal restoration neede
  - -overhead has cost implications
- -Standing wave modes for spin waves at dimensions ~ wavelength
- -localization
- -Reflections at boundaries

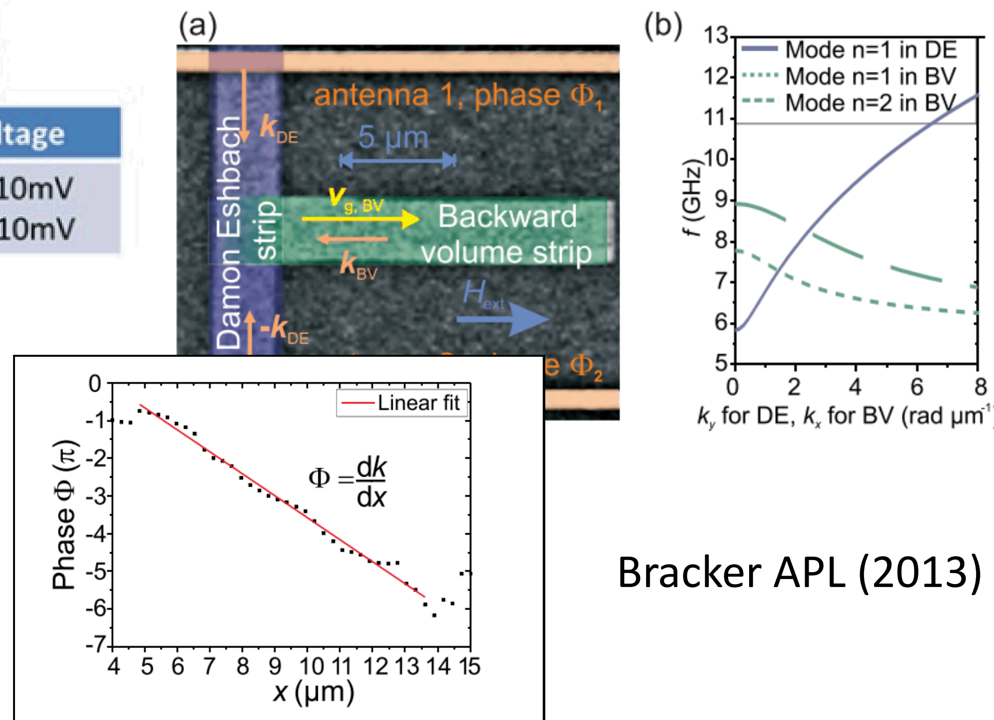


voltage	phase
+ 10mV	0
- 10mV	π

A	B	C	Junction	Inverter
0	0	0	0	π
0	0	π	0	π
0	π	0	0	π
0	π	π	π	0
π	0	0	0	π
π	0	π	π	0
π	π	0	π	0
π	π	π	π	0

phase	voltage
0	+ 10mV
π	- 10mV

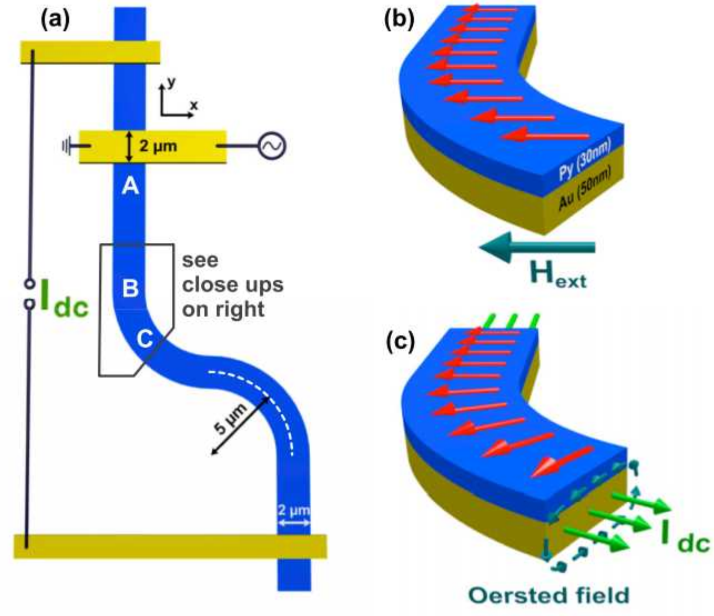
Khitun, Proc. SPIE (2013)



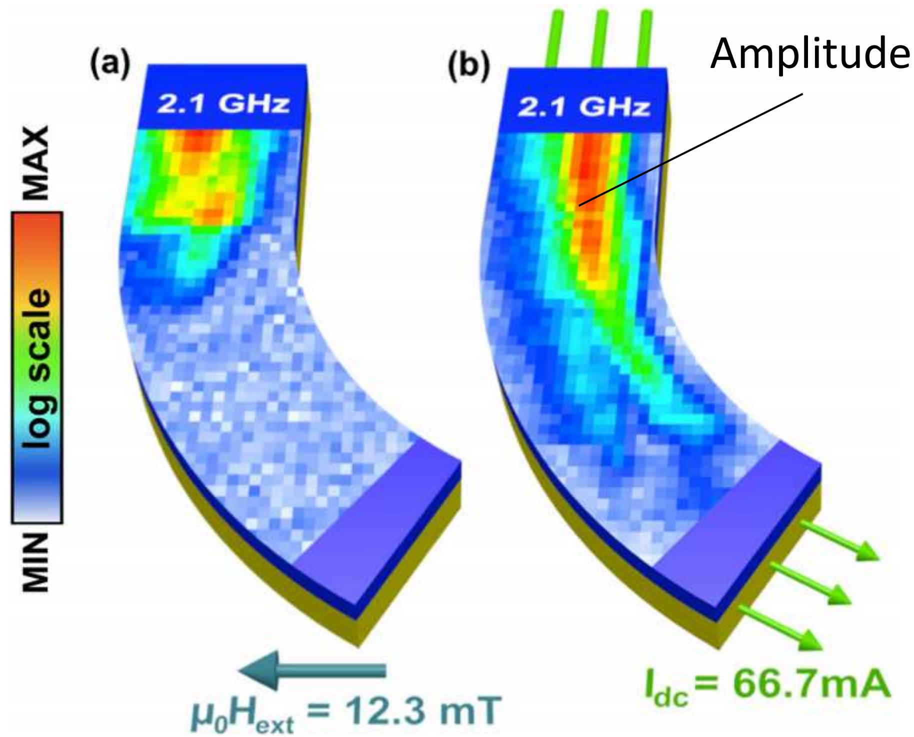
Bracker APL (2013)

Keyes theorem: interferometers do not make good logic devices

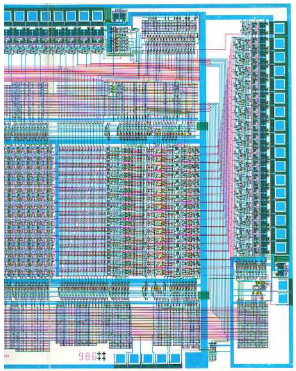
Wires are also a problem



Vogt APL (2012)



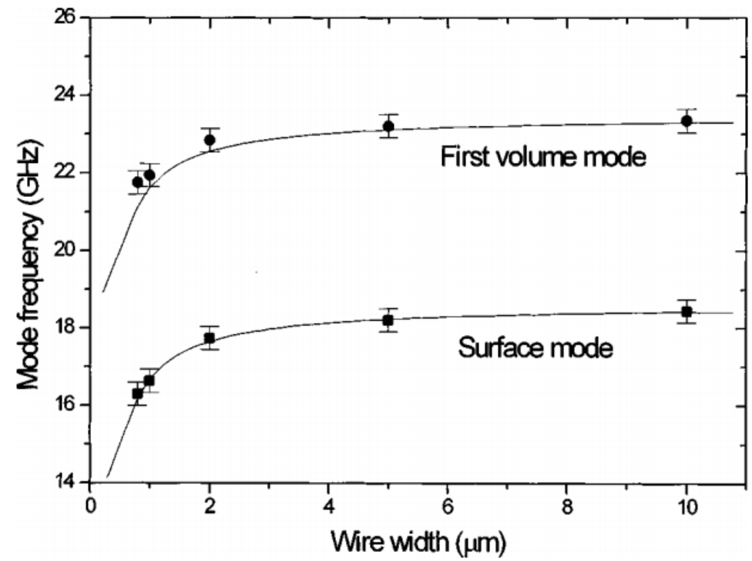
This will be very difficult to implement:



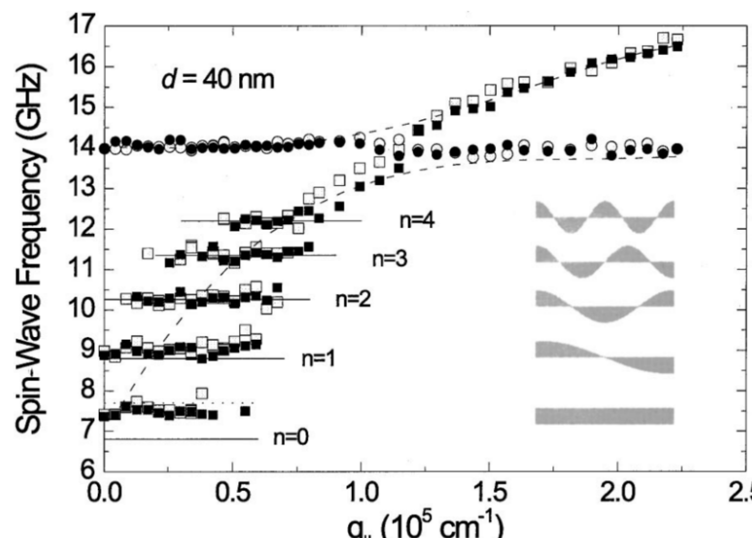
Scaling of MSW wires

Ercole PRB (‘98)

-Dispersion, group velocity change strongly with dimensions



Jorzick, PRB (99)



-1 μm wire width, 40 nm thickness,

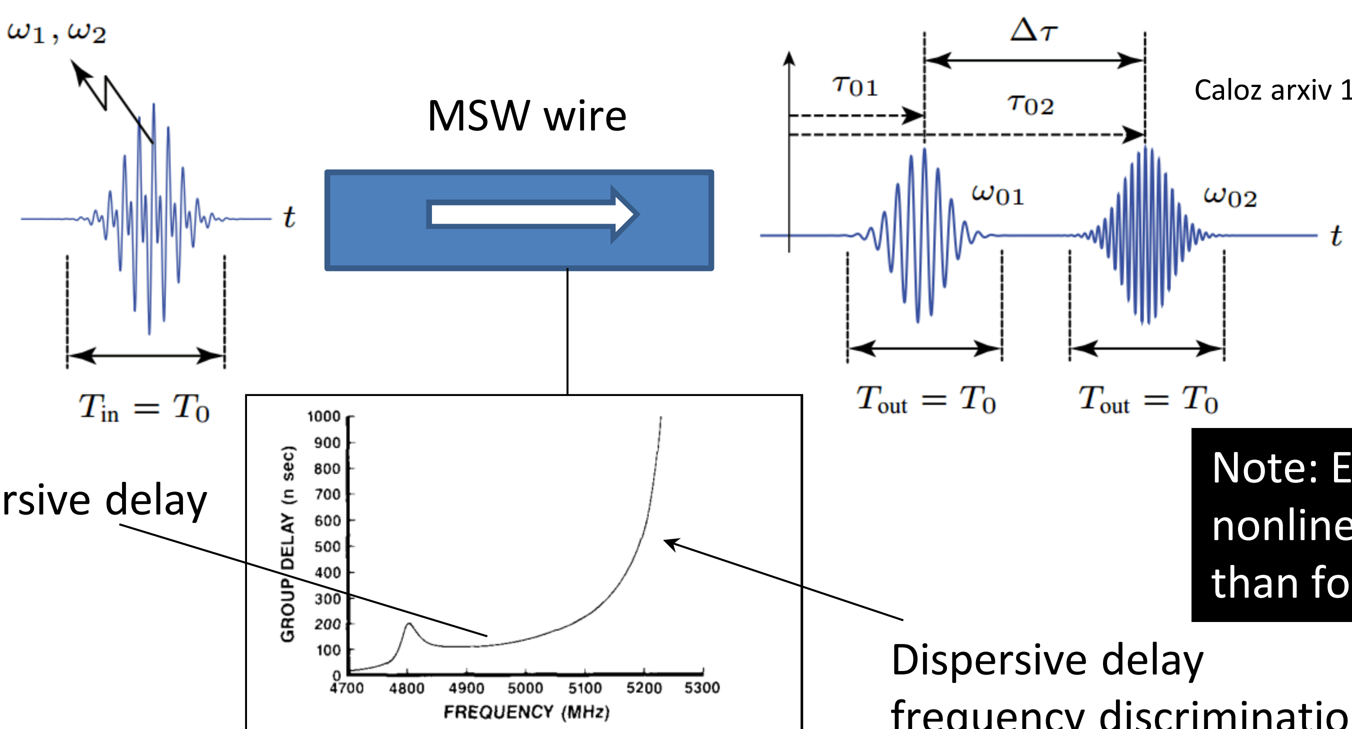
1 μm spacing

-Spin wave modes no longer propagate

-Nodes at ends of logic gate

Non-Boolean applications

Gain is less important
High throughput: send multiple frequencies along same wire
We consider frequency discrimination as an example
MSW devices have long been used for analog microwave electronics (peak in'80s)
Cf. Ishak <u>Magnetostatic Wave Technology: A Review</u> Proc. IEEE (88)



Caloz arxiv 1307.2618

Non-dispersive delay

Dispersive delay
frequency discrimination

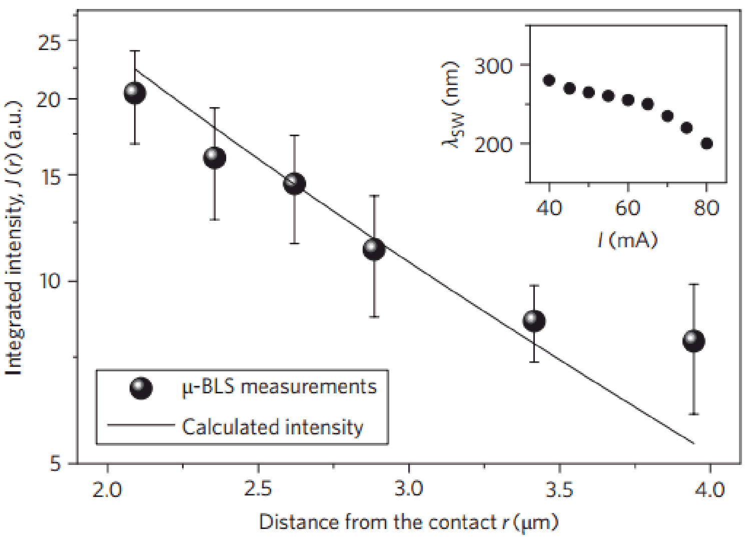
Note: Easier to get nonlinear interactions than for optics

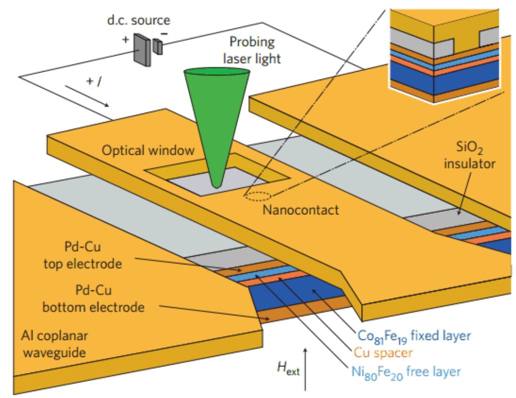
Typical numbers: Δf = 100 MHz leads to $\Delta\tau$=30 ns over 3 mm with microwave stripline excitation

-Microwaves striplines are power/cost prohibitive for computation

-How would frequency discrimination change using a scalable excitation method?

-Spin valves, for example, J~10^7-10^8 A/cm^2, with propagating MSW wavelengths of ~200 nm



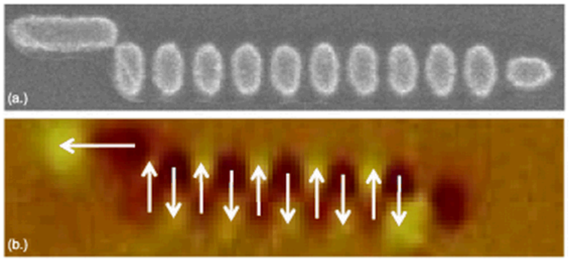


Madami, Nat. Nanotech. 11

Frequency discrimination:
group velocity ~ 10^4 m/s
Coherence length ~ 1 μm
$\Delta\tau$=100 ps
-comparable to ~10 GHz frequency

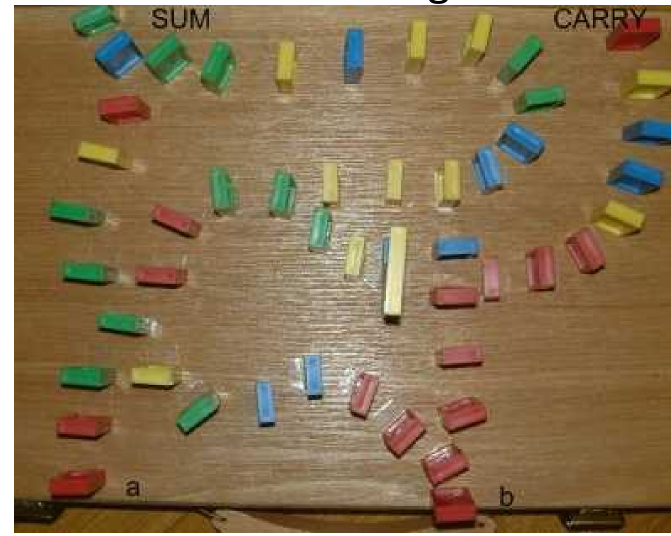
Logic with nanomagnets

-Magnetic Cellular Automata
-Nanomagnetic logic



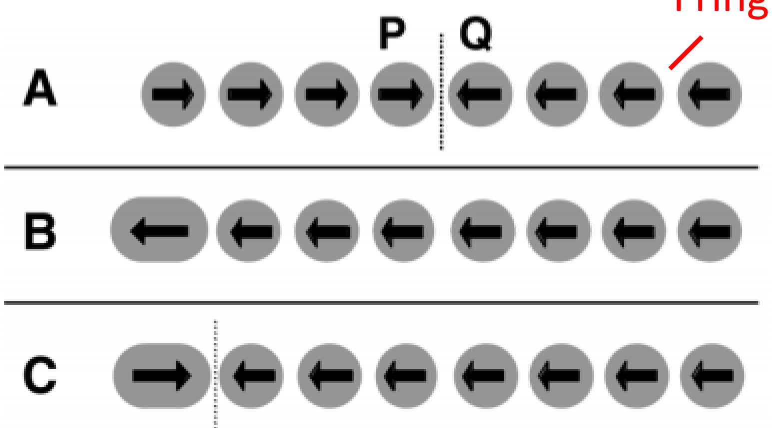
Niemier, J.Phys.Cond. Mat. (11)

Domino logic



(+ CMOS equivalent)

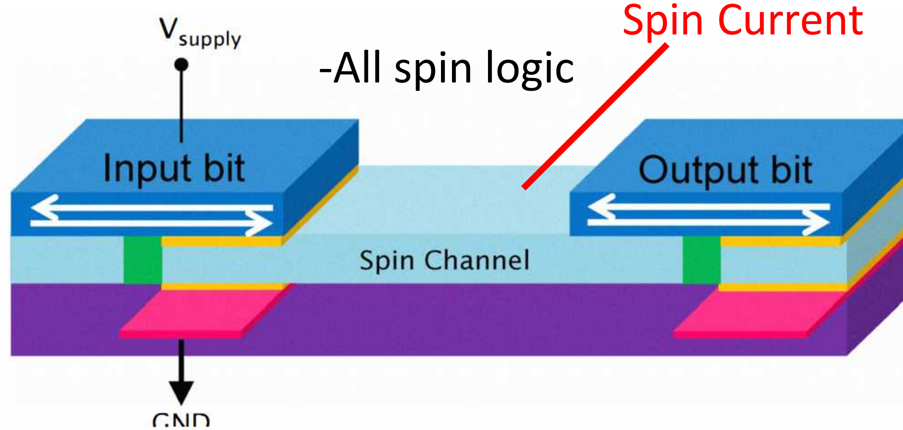
Fringing fields



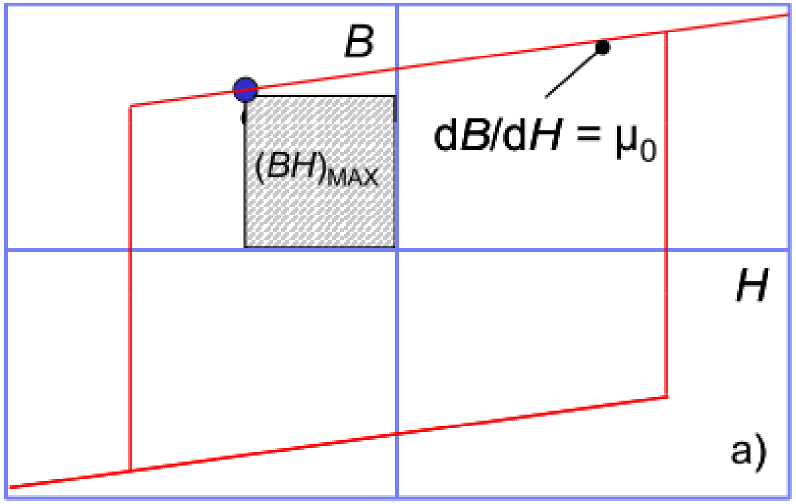
Cowburn, Welland Science (2000)

-All spin logic

Spin Current



Behin-Aein, Nature (2010)



Coey, J. Phys. Cond. Mat (2014)

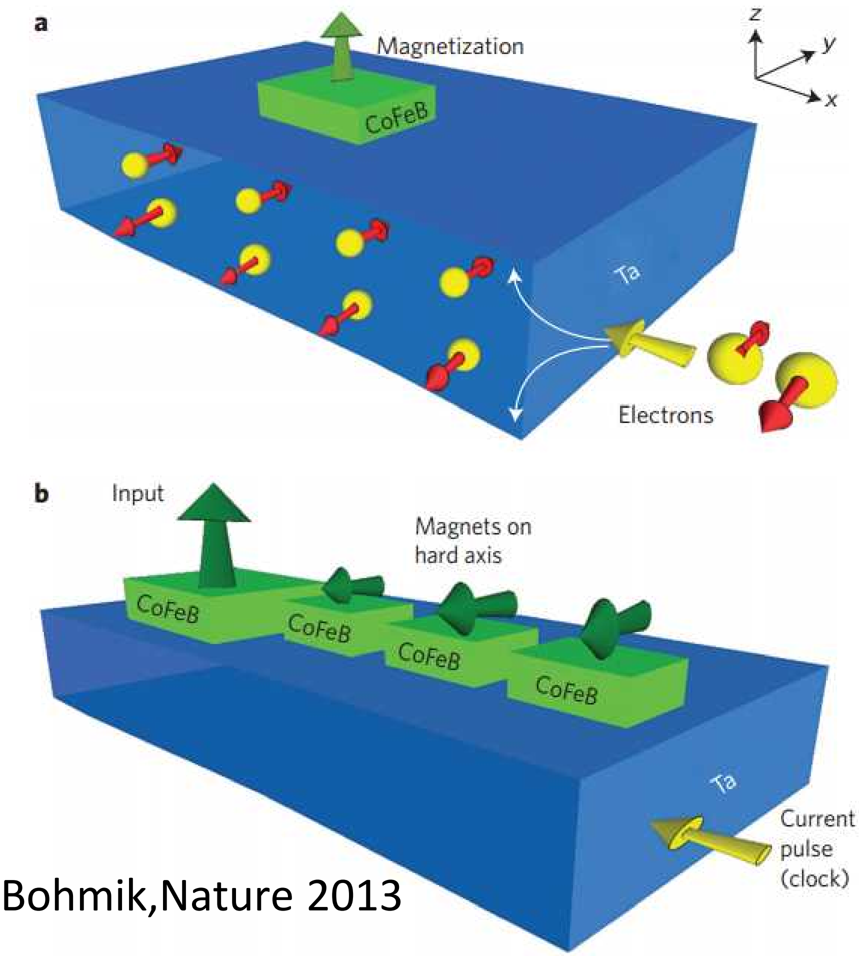
-Gain originates from bistability of magnets

-Logic requirements have been addressed using numerous proposals.

-More experiments needed to test proposals

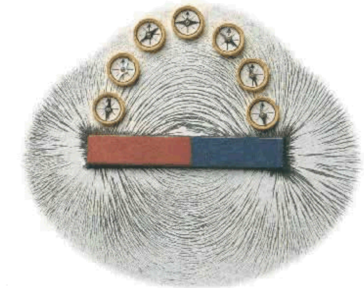
-Global magnetic field clocks (cost/size prohibitive) may not be needed, using (current-driven) spin Hall effect instead

-We look at scaling problems intrinsic to magnets

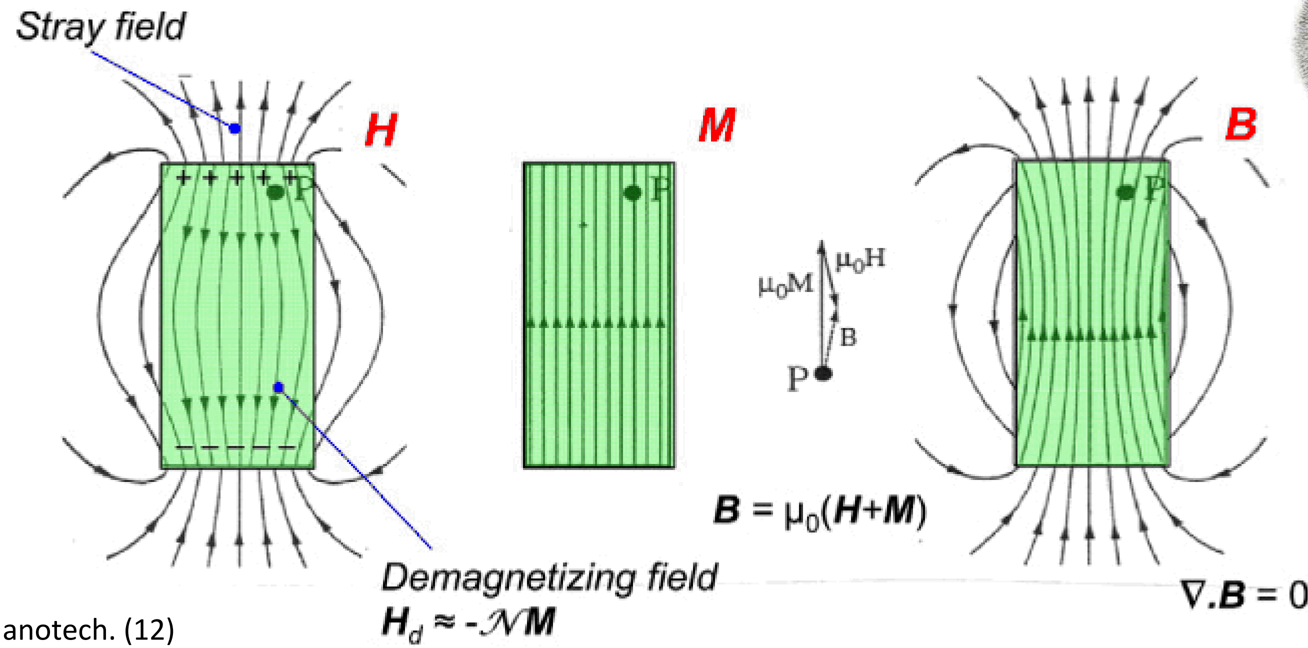


Bohmik,Nature 2013

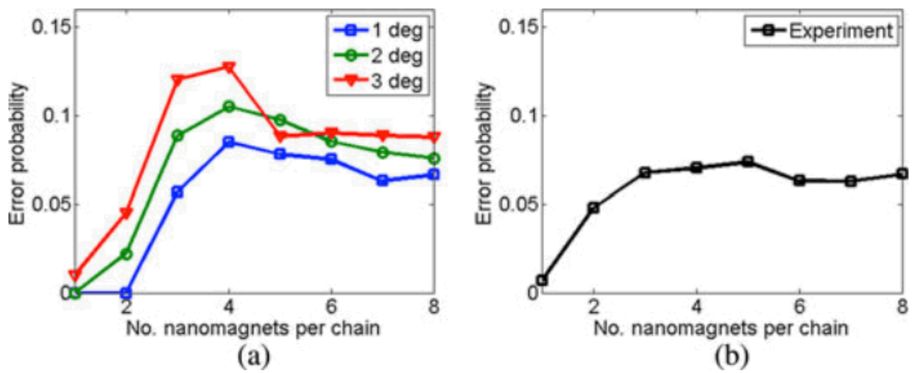
Scaling for magnetics

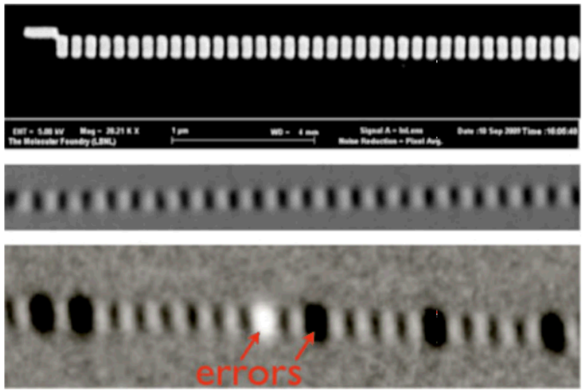


Coey (14)



Carlton, IEEE Nanotech. (12)





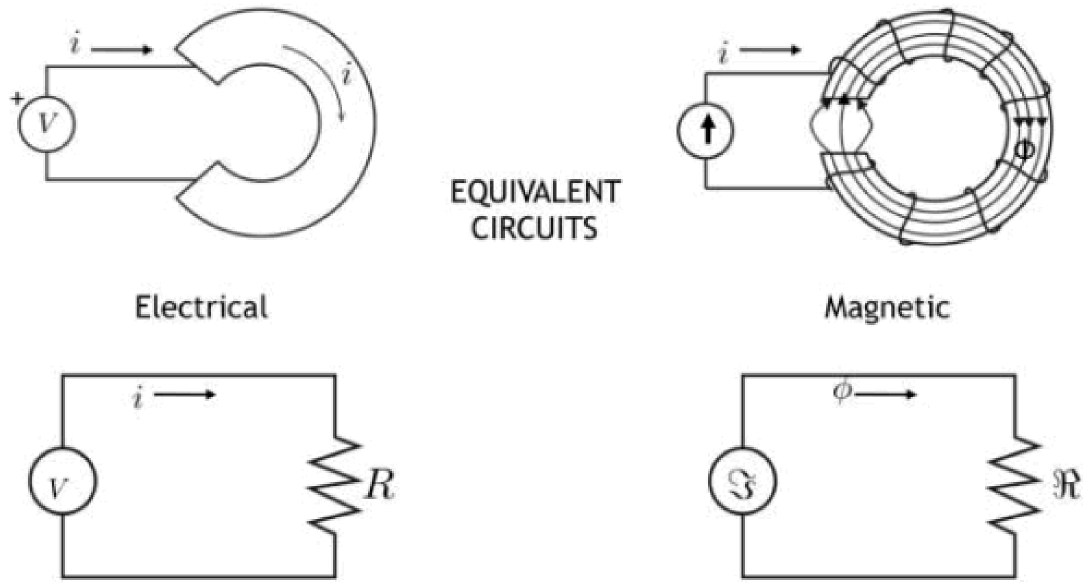
Litho-based errors in preferred axis alignment

Unwanted stray fields may have similar effect

-key problem: it is difficult to confine magnetic flux, what happens when magnets densely packed?

-Analogous to leakage current problems in CMOS

Electrical Circuit Analogy

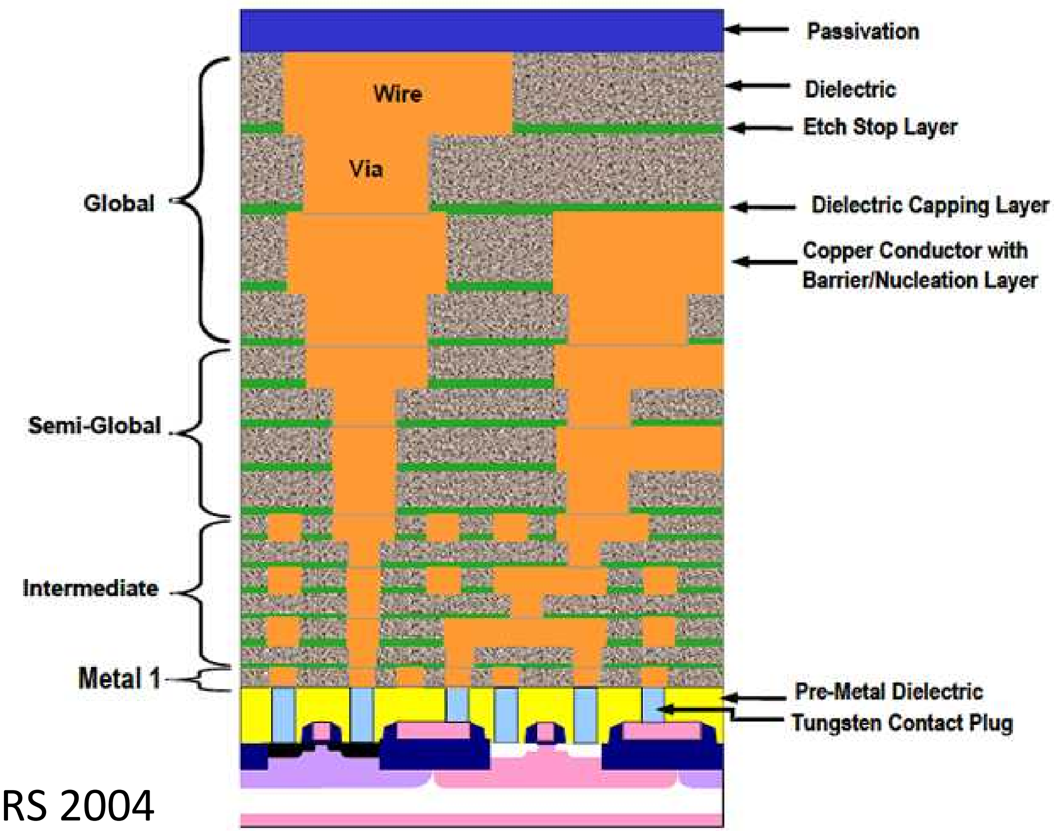


Electrical	Magnetic
Voltage v	Magnetomotive Force $\Im = Ni$
Current i	Magnetic Flux ϕ
Resistance R	Reluctance $\Re$
Conductivity $1/\rho$	Permeability μ
Current Density J	Magnetic Flux Density B
Electric Field E	Magnetic Field Intensity H

MIT open course, Electromagnetic Energy, From motors to lasers

	Conductivity (1/Ω m)
Air	10^{-15}
Thermal SiO_2 on Si	10^{-16}–10^{-9}
Sea water	4.8
Silicon	10^{-4}–10^{4}
Metals (Au, W, etc..)	10^{7}

23 orders of magnitude



ITRS 2004

Cramming more magnetic components onto integrated circuits

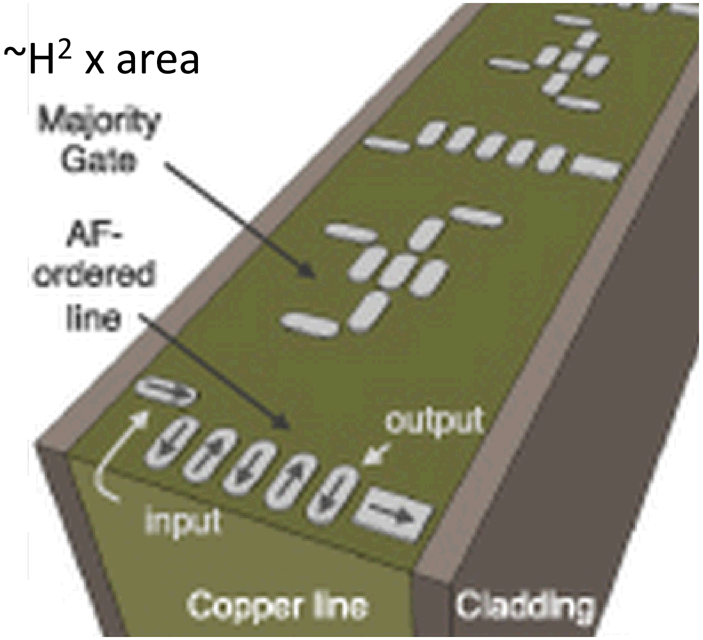
Force between two magnets ~H^2 x area

Permeability*

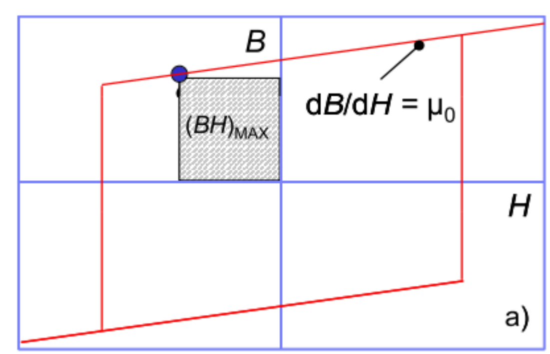
Type I superconductors	0
Air	~1
Metals (Au, W, ..)	~1
Sea Water	~1
Silicon	~1
<u>Magnets:</u>	
NdFeCo	~1
CoPt	~1
Ni	10^2
Py (FeNi)	10^3
mu metal (NiFeCoMo)	10^4
Fe (99.99%)	10^4
Metglass	10^6

*Depends on size, field, shape; largest number chosen

6 orders of magnitude

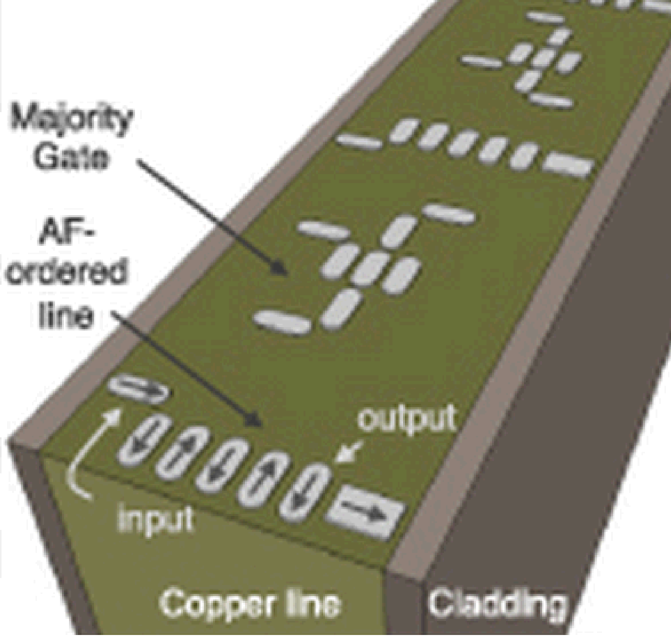


Niemier (2011)

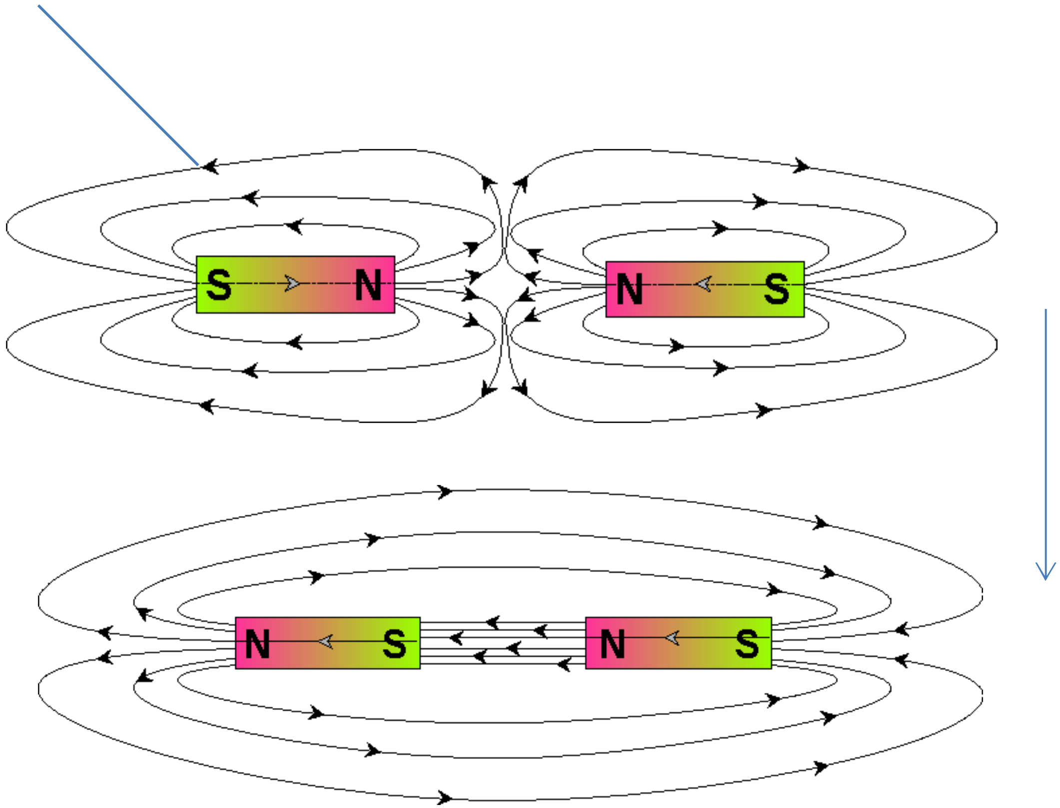


Force between two magnets ~H^2 x area

Scaling: reduce magnet size
-Switching barrier decreases
-Force decreases
-Flux leakage still present



Flux leakage, will reduce force between magnets



How many magnets can be concatenated together?

Permeability	
Air	1
Magnet	1–10^4

Conductivity	
Air	10^{-15}
Si (insulating)	10^{-4}
Water	1
Si (conducting)	10^4
Metal	10^7