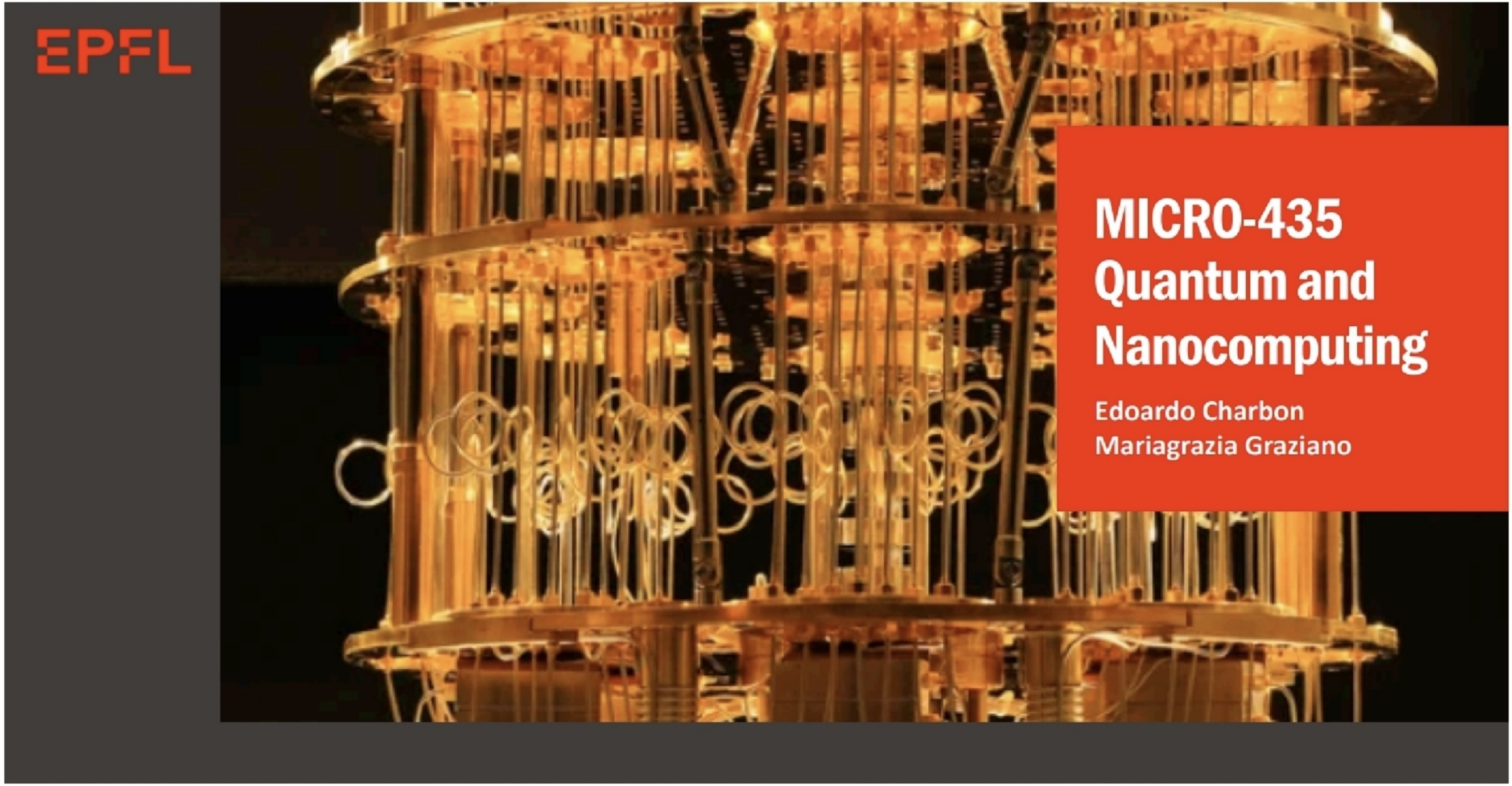


FROM INML TO MORE ADVANCED NANOMAGNETIC STRUCTURES - PNML

PERPENDICULAR

$N \perp L$

ANOTHER PROBLEM OF NML IS THE CLOCK ZONES ORGANIZATION WITH THE NECESSITY OF CREATING

→ ZONES

→ DIFFERENT CLOCKS SIGNALS

⇓

DOABLE BUT COMPLICATED

↓

ALTERNATIVE: PNML

PERPENDICULAR NANOMAGNETIC LOGIC

PNML

NML (N. DAME)

- MAGN. // TO PLANE
- PERMALLOY (MOSTLY) (NIKEL-IRON)
- SHAPE ANISOTROPY 
- RESET STATE FORCED BY CLOCK TO PROPAGATE INFO

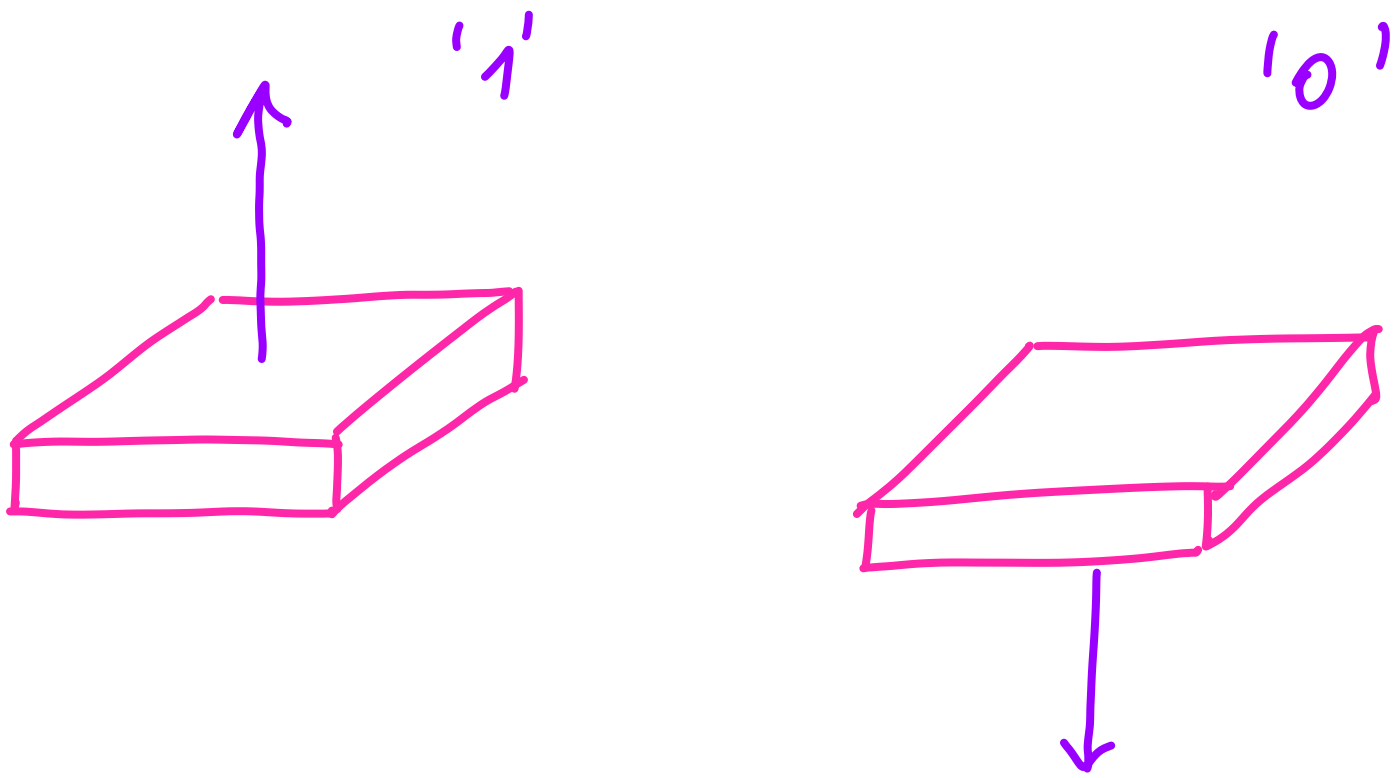
→ MORE COMPACT

→ SIMPLIER DESIGN

PNML (MUNICH ....)

- MAGN ⊥ TO PLANE
- MULTILAYERS OF Co/Pt*, Co/Ni, CoFeB*
- CRYSTALLINE. INTERFACE ANISOTROPY
- NO RESET, CK FIELD USED TO INDUCE PROPAGATION
- DW IS USED FOR INTERCONNECT & PROP. LOGIC

PERPENDICULAR MAGNETIC ANISOTROPY (PMA)

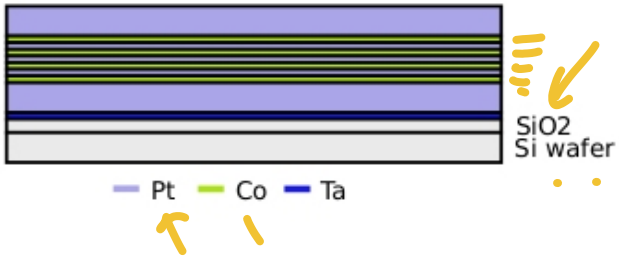


MAGNETIZATION PERPENDICULAR TO THE PLANE

FABRICATION (Co/Pt CASE)

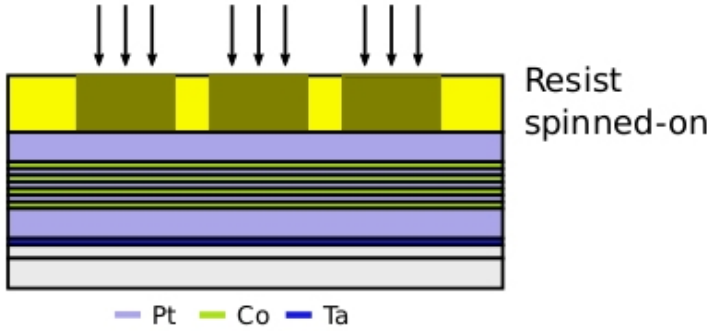
a)

Wafer cleaning and oxidation
+
Co/Pt multilayer deposition



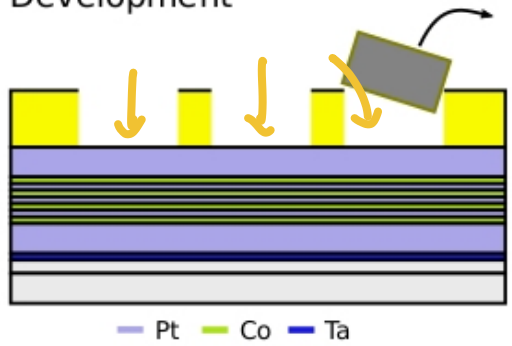
b)

FIB lithography



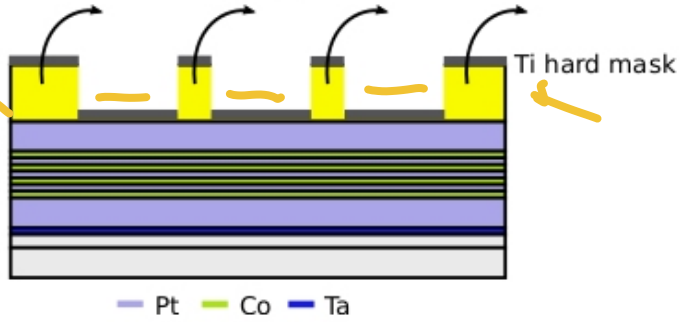
c)

Development



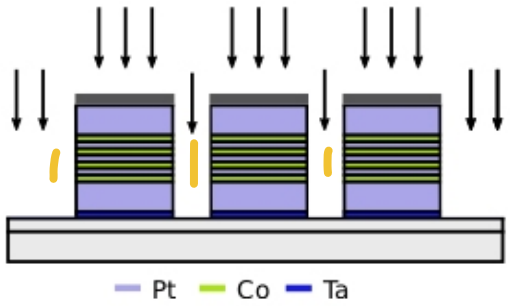
d)

Hard mask evaporation
+
lift-off



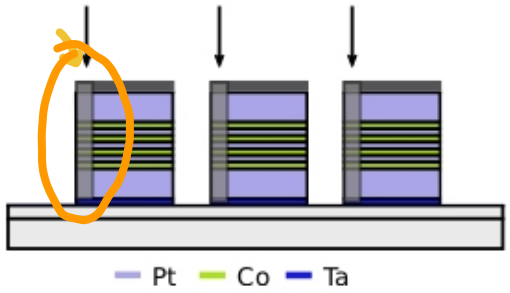
e)

Ion beam etching



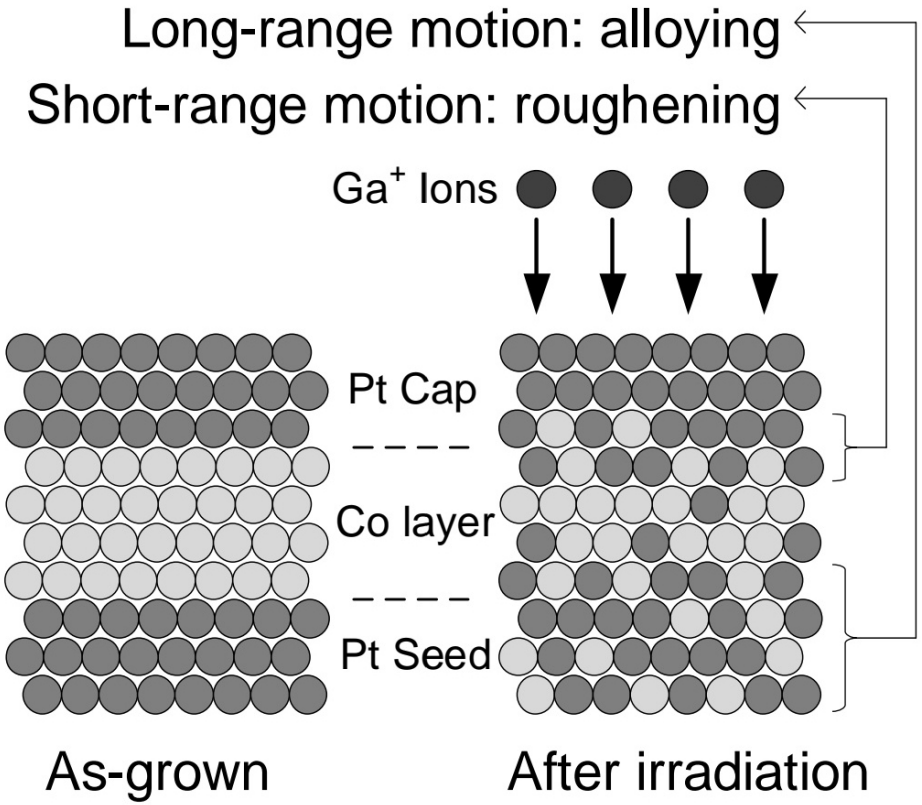
f)

Partial FIB irradiation

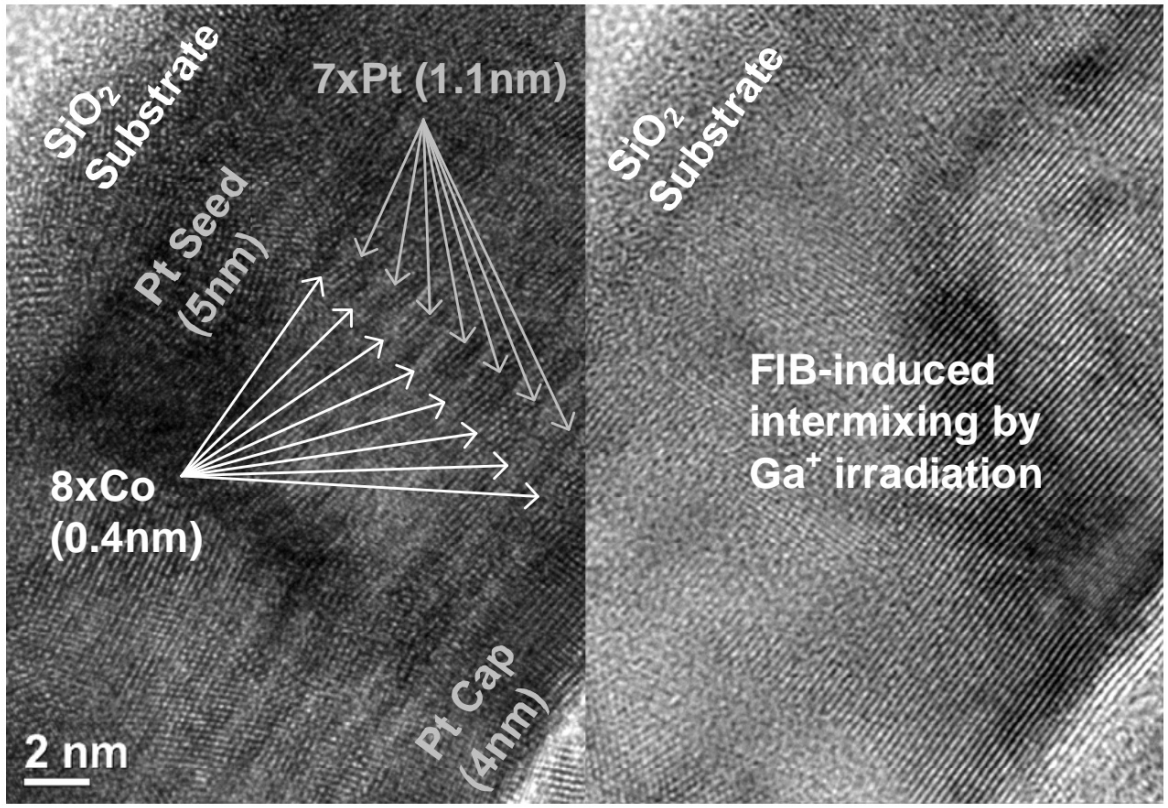


EFFECT OF F.I.B. IRRADIATION

a **Theory of Irradiation induced intermixing**



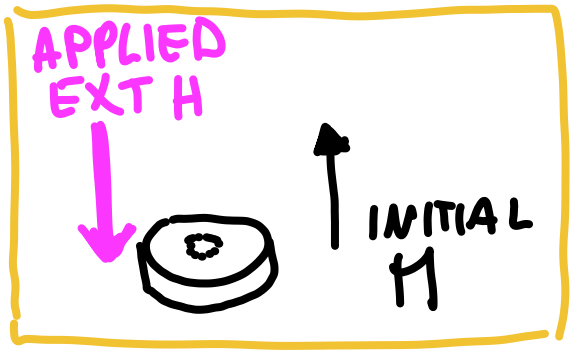
b **TEM images of a Co/Pt multilayer**

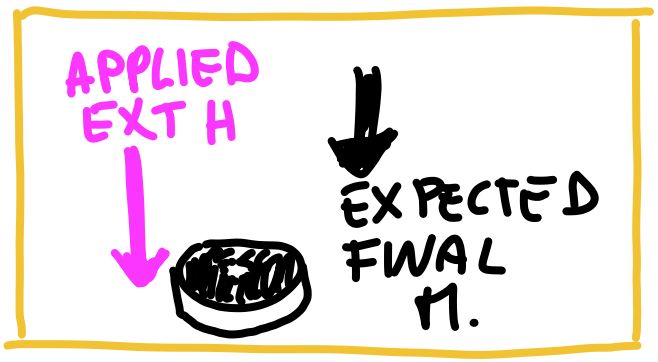


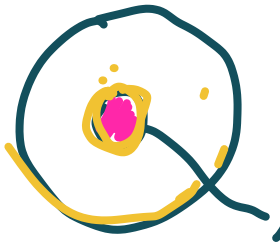
PhD DISSERTATION
TUM
S. BREIKREUT-VON GAHN.

ANISOTROPY IS REDUCED

VIDEOS
M.M. SIMULATIONS HUMAX







ANC

EXTERNAL FIELD INDUCES SWITCH

1) - DW NUCLEATES & PROP

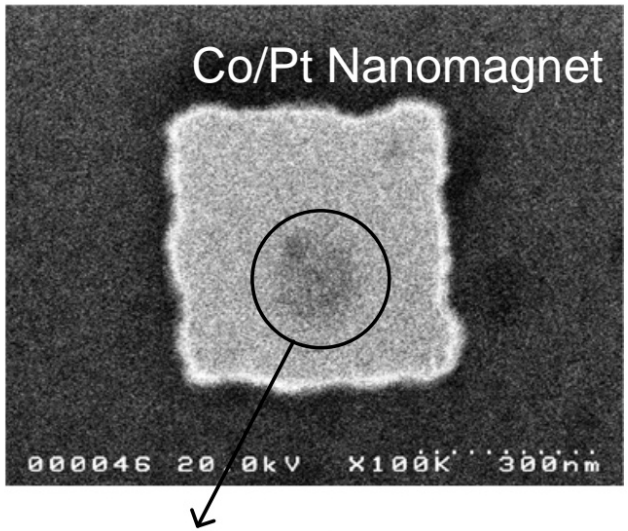
2) - DW NUCLEATES BUT DO NOT PROP

H_c SMALLER

SIMULATIONS CREDITS . F. RIENTÉ HUMAX

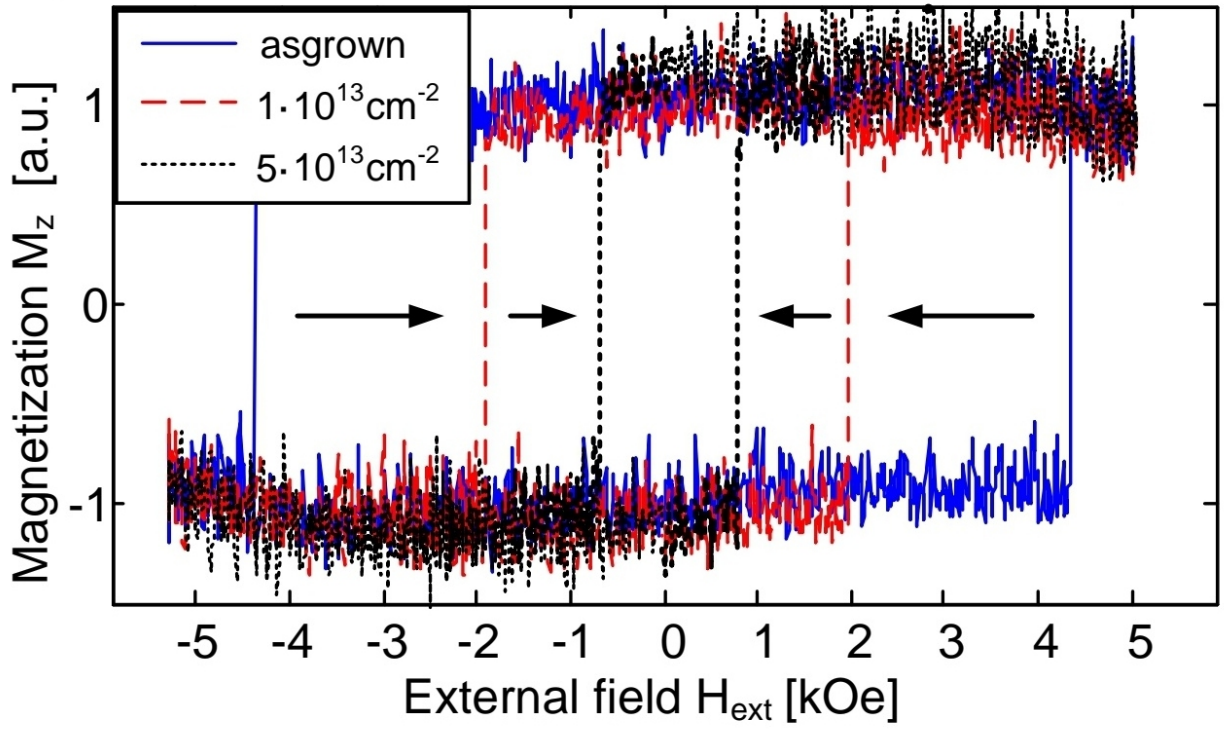
EXAMPLE MEASUREMENT: HYSTERESIS ASSOCIATED TO THE EXTERNAL H USED TO SWITCH

a **Nanomagnet with ANC by partial irradiation**



ANC by Ga^+ FIB irradiation
(100nm·100nm)

b **Hysteresis measurements**

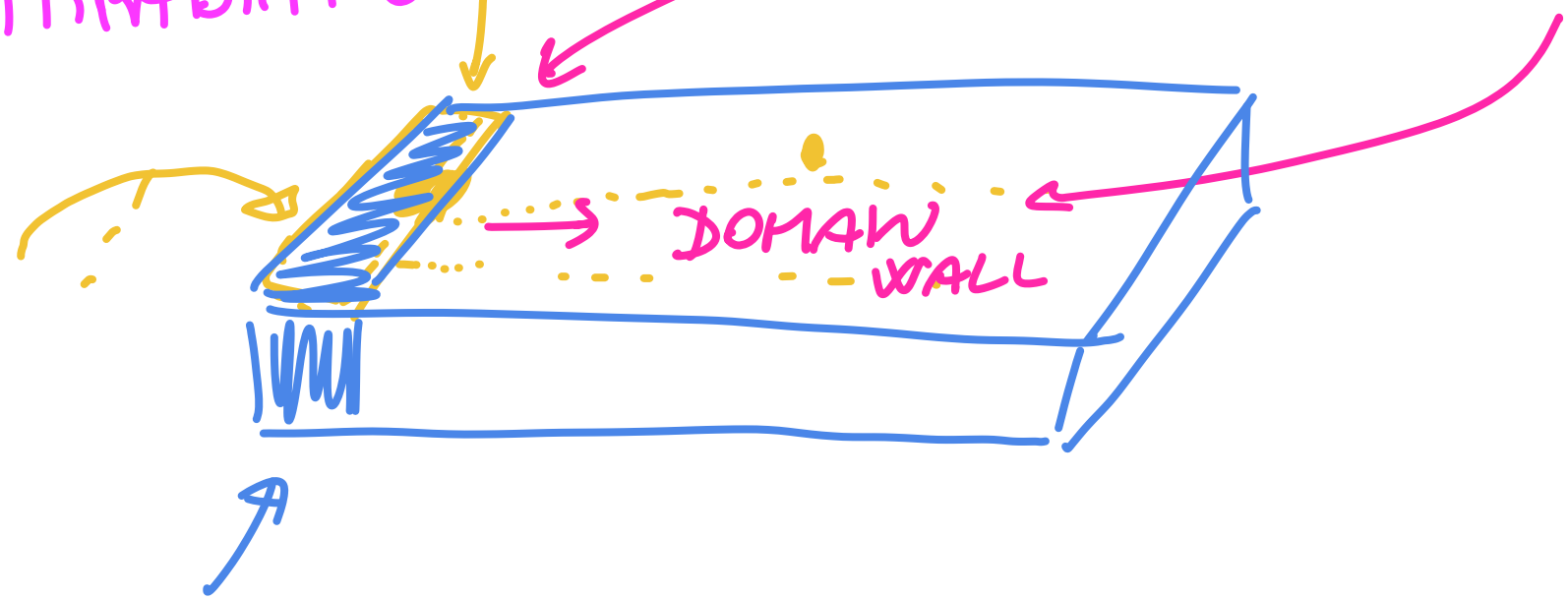


HYSTERESIS FOR DIFFERENT IRRADIATION DOSES SUPERPOSED

PhD DISSERTATION
TUM
S. BREIKREUT-VON GAMM.

FIB IRRADIATION

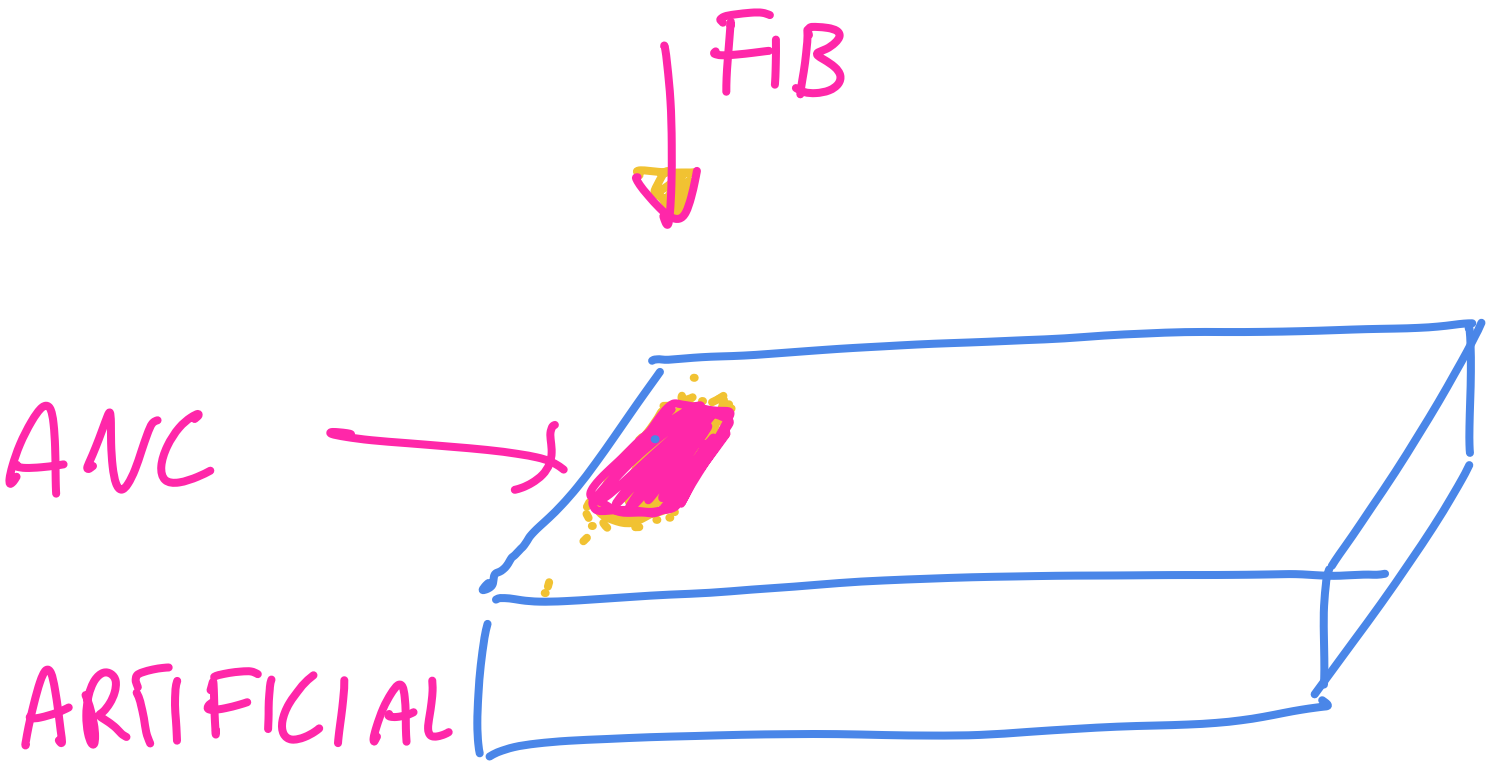
CREATES A DW NUCLEATION



MIXES THE LAYERS OF Co/Pt MULTILAYER STACK

↳ IT REDUCES → MAGNETOCRISTALLINE ANISOTROPY AT INTERFACE BETWEEN 2 MAGNETS

REDUCES THE FIELD NECESSARY TO SWITCH!

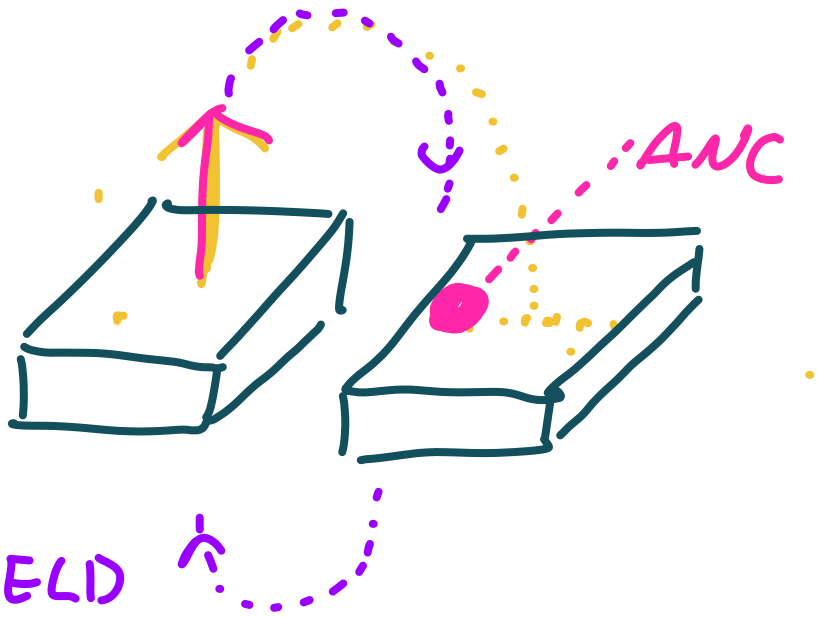


- GIVEN A MATERIAL -
- " A GEOMETRY
- " A ANC TYPE

COERCIVITY H_c → THE SWITCHING FIELD NECESSARY TO NUCLEATE THE DW CHANGES

INFLUENCE BETWEEN 2 MAGNETS

INVERTER



THE FIELD GENERATED BY THE NEAR MAGNET INDUCES A CHANGE THROUGH THE ANC

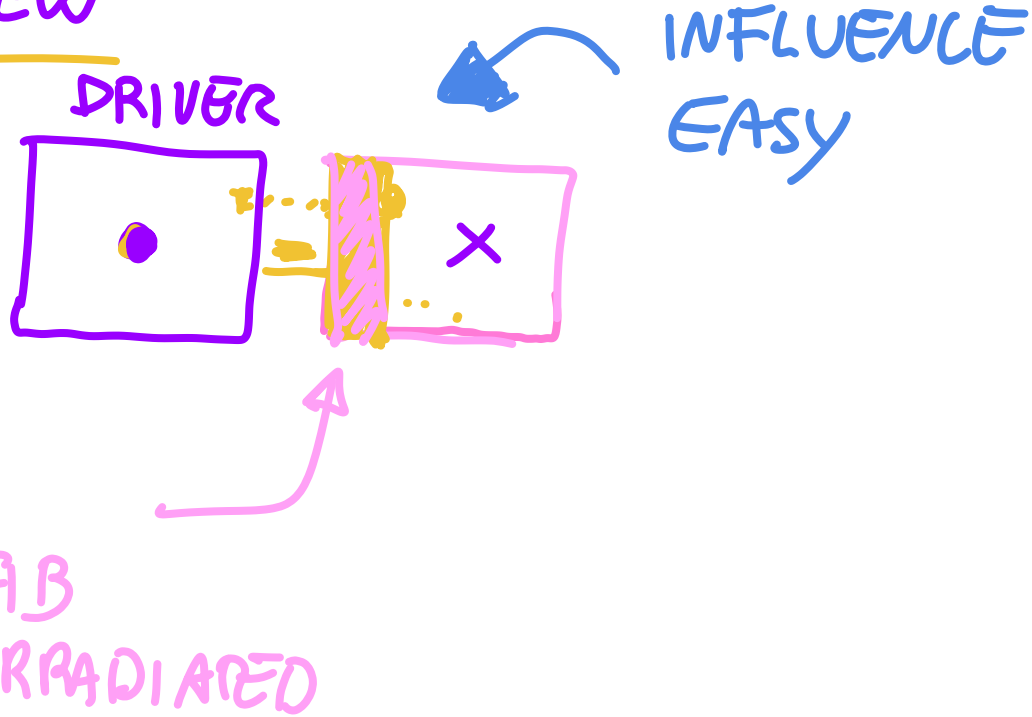
VIDEO – MICROMAGNETIC SIMULATION

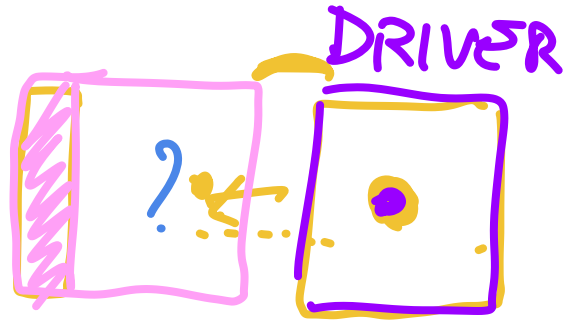
CREDITS F. RIENTÉ

THE FIB IRRADIATION GUARANTEES THE FLOW DIRECTIONALITY:

ONE PART OF THE MAGNET IS "SENSITIZED"

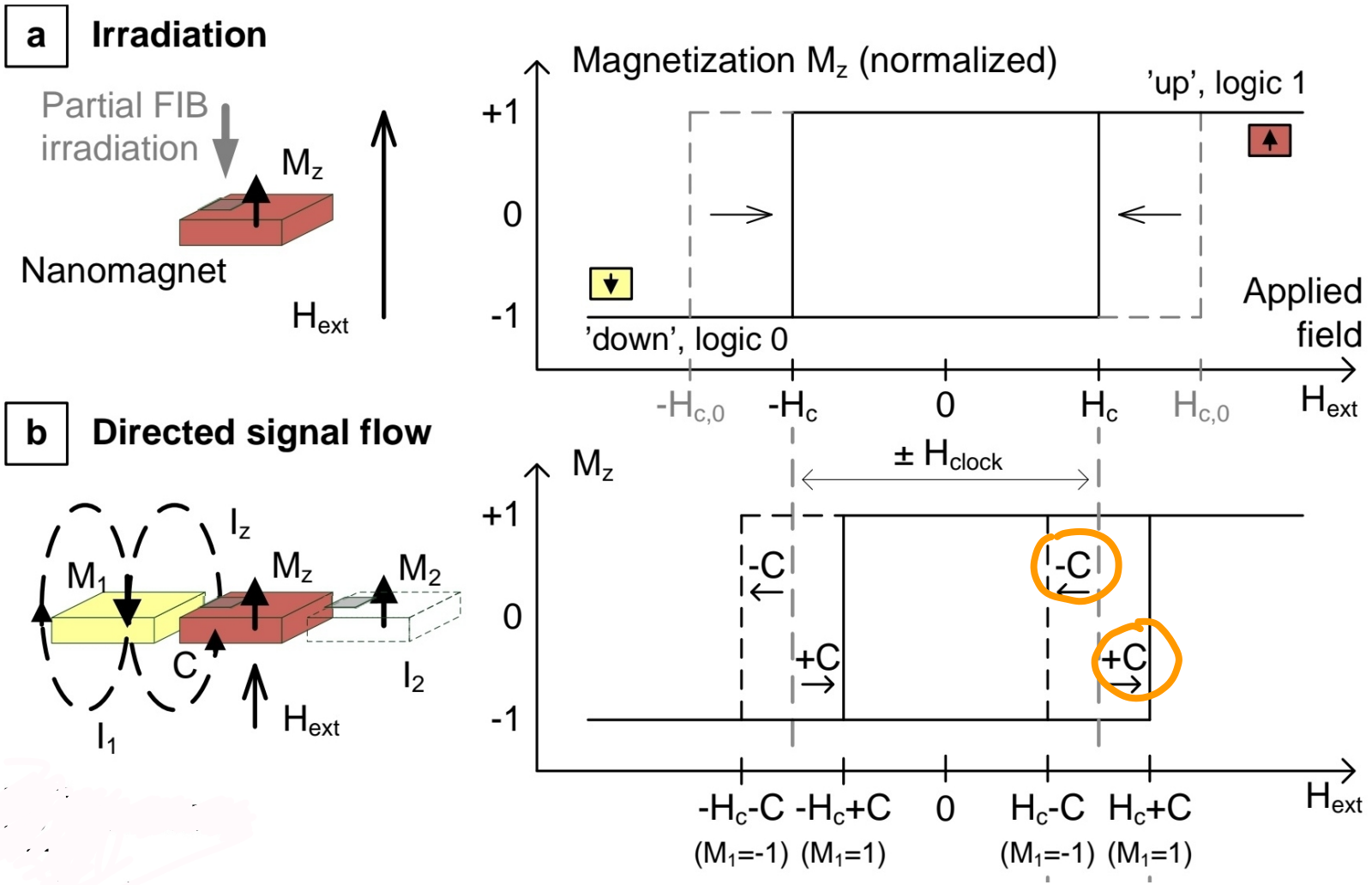
TOP VIEW





INFLUENCE MORE DIFFICULT

ANC, HEXT, INPUT



SINGLE MAGNET, ANC + HEXT ⇓ ANC REDUCES HYSTERESIS

MAGNET WITH ANC + HEXT + INPUT MAGNET

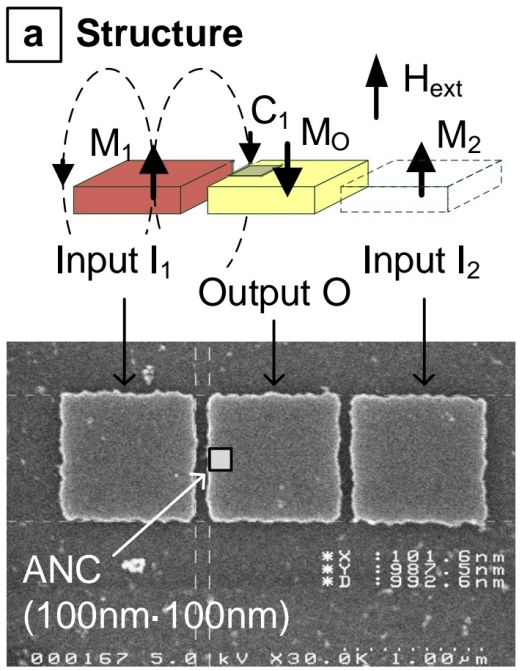
THE FIELD INDUCED BY INPUT ; COUPLING C, SHIFTS THE HYSTERESIS

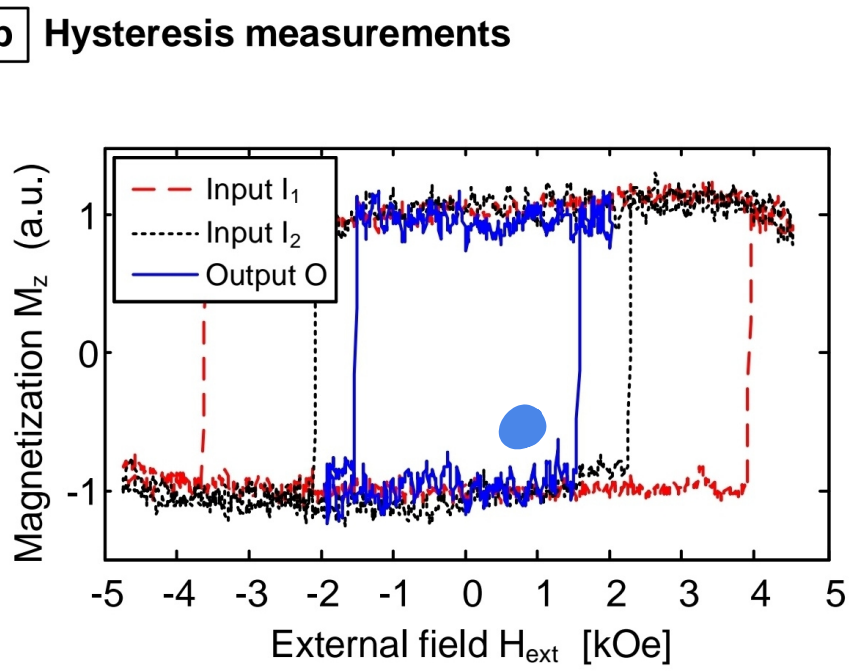
⇒ IN SUPERPOSITION OR IN OPPOSITION WITH HEXT

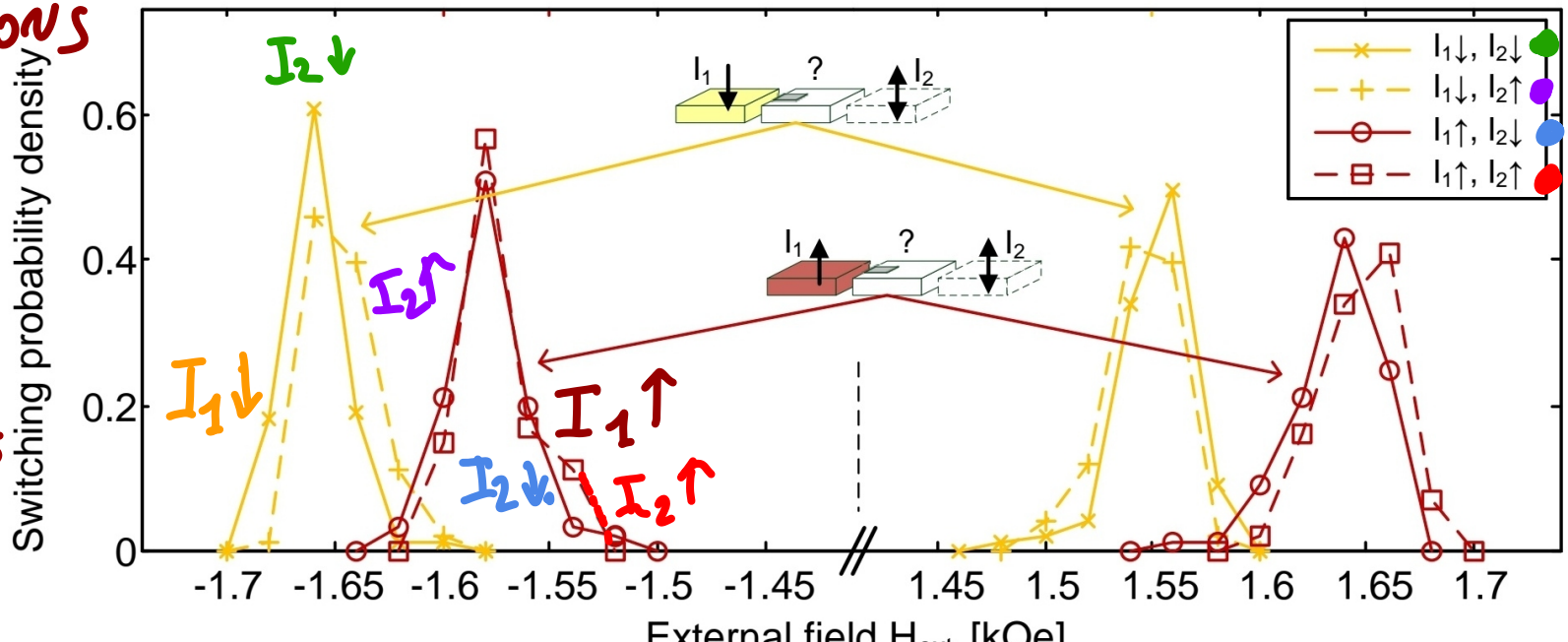
PROOF OF DIRECTIONALITY

- CENTRAL MAGNET IRRADIATED, ANC
- INPUTS I_1 LEFT I_2 RIGHT CONFIGURED IN 4 POSSIBLE COMBINATIONS
- CENTRAL MAGNET O MEASURED: HYSTERESIS

SWITCHIN PROBABILITY







MAGN. 2 IS TOO FAR

⇒ ONLY I_1 INFLUENCES THE O SWITCHING !

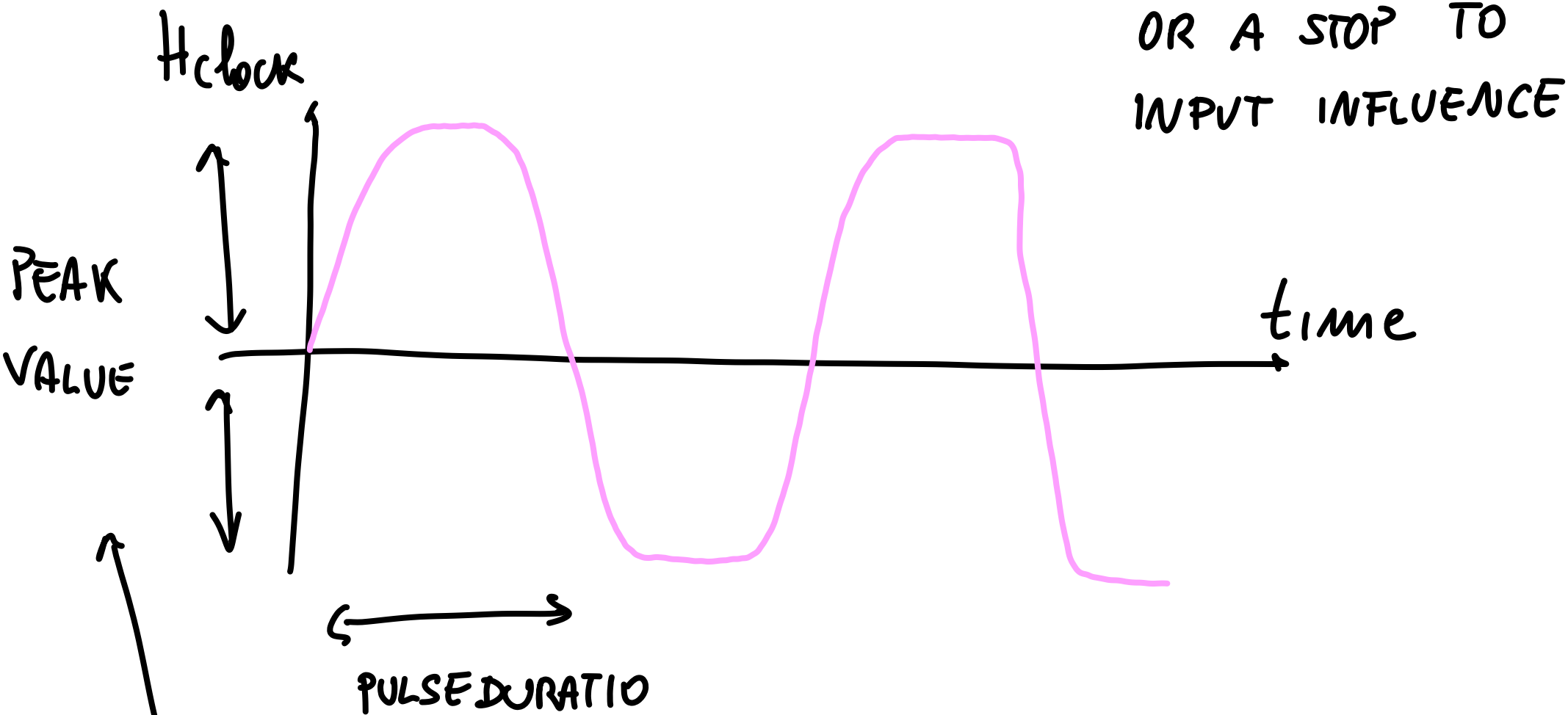
OVERALL, HOW IS THE INFO FLOW ORGANIZED?

→ SUPPORT OF AN EXTERAL CK FIELD H_{CK}

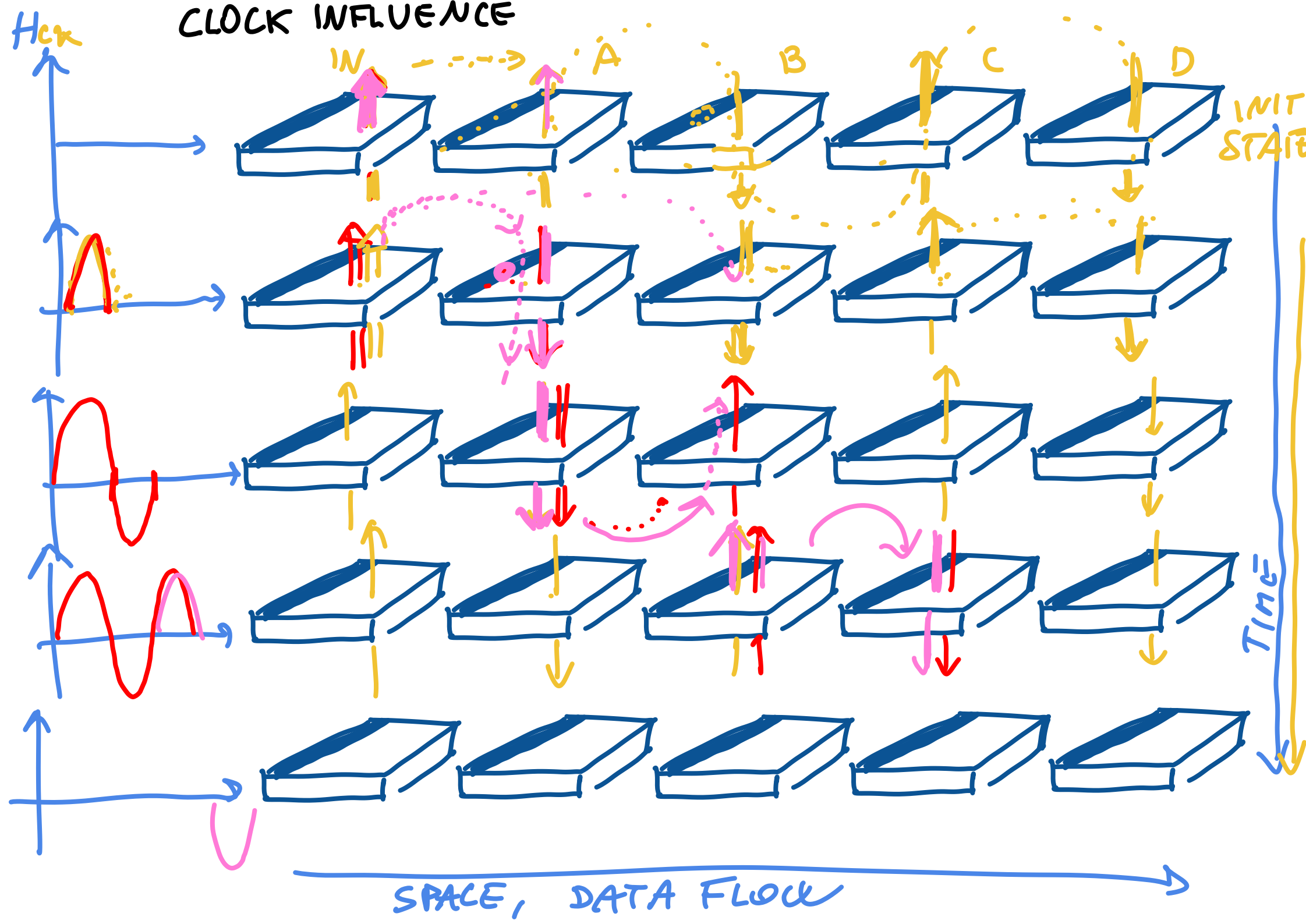
NO PHASES!

→ A UNIQUE H_{CK} FOR ALL THE CIRCUIT, SINE WAVE, DIRECTION ⊥ TO PLANE

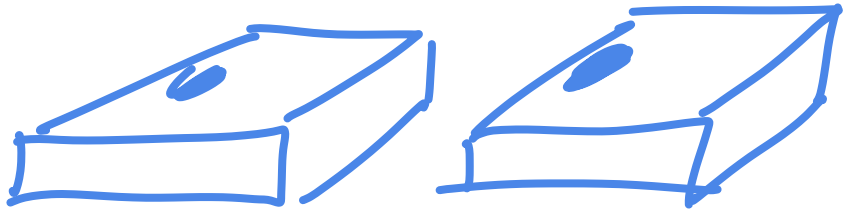
HCLOCK : GIVES A PUSH OR A STOP TO INPUT INFLUENCE



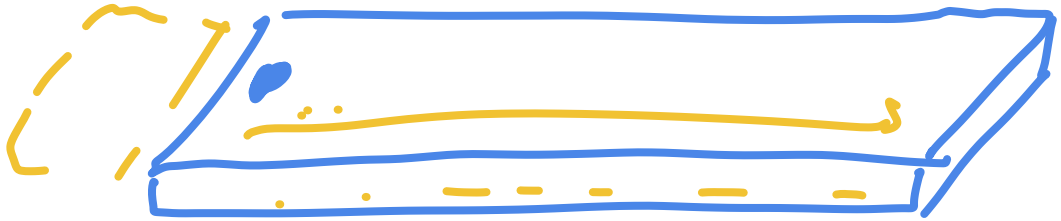
TO BE DEFINED PROPECLY (see after, consideration on speed)


CLOCK INFLUENCE
HCLK
IN
A
B
C
D
INIT STATE
TIME
SPACE, DATA FLOW

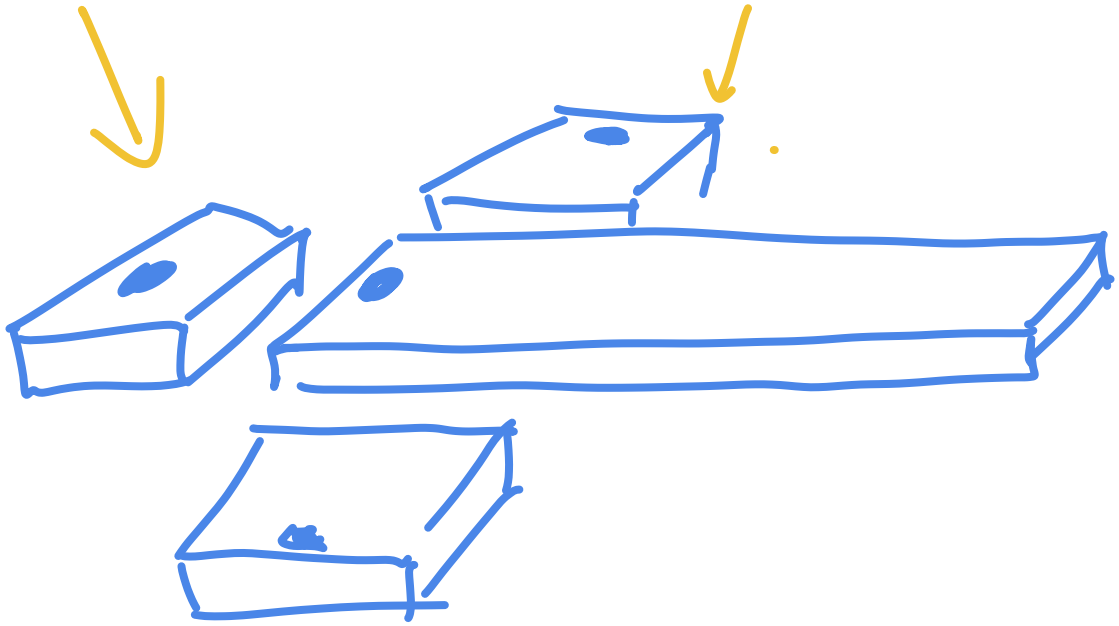
INFORMATION ELABORATION - BASIC BLOCKS



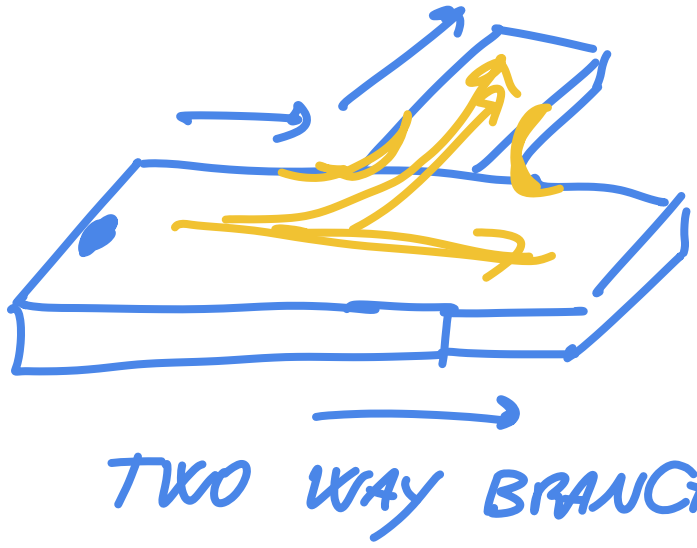
INVERTER



WIRE

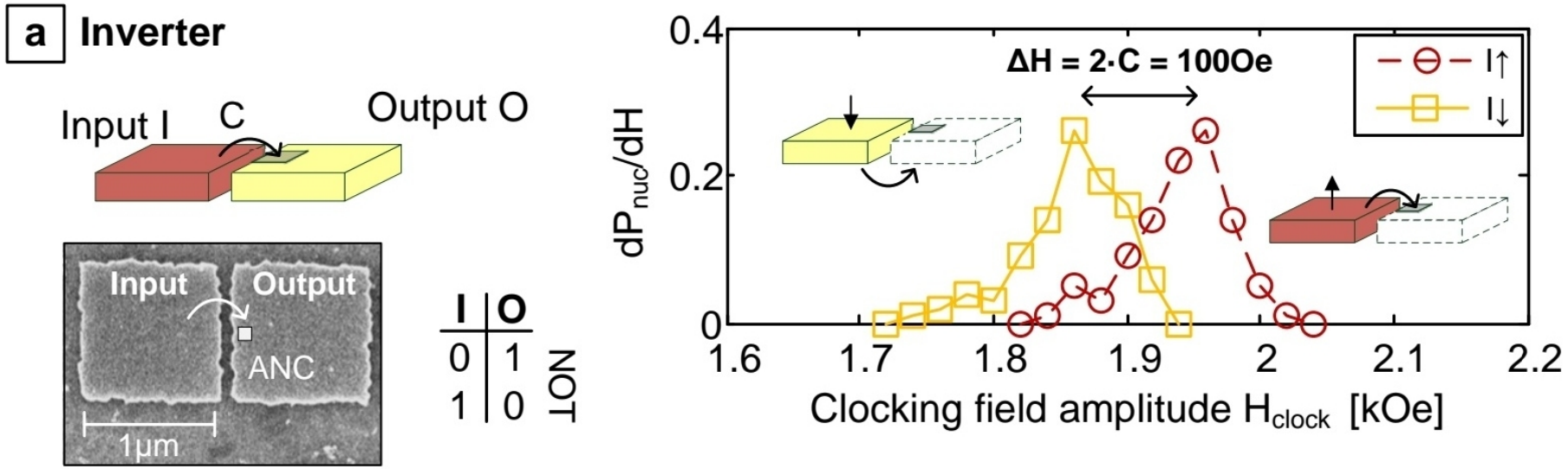


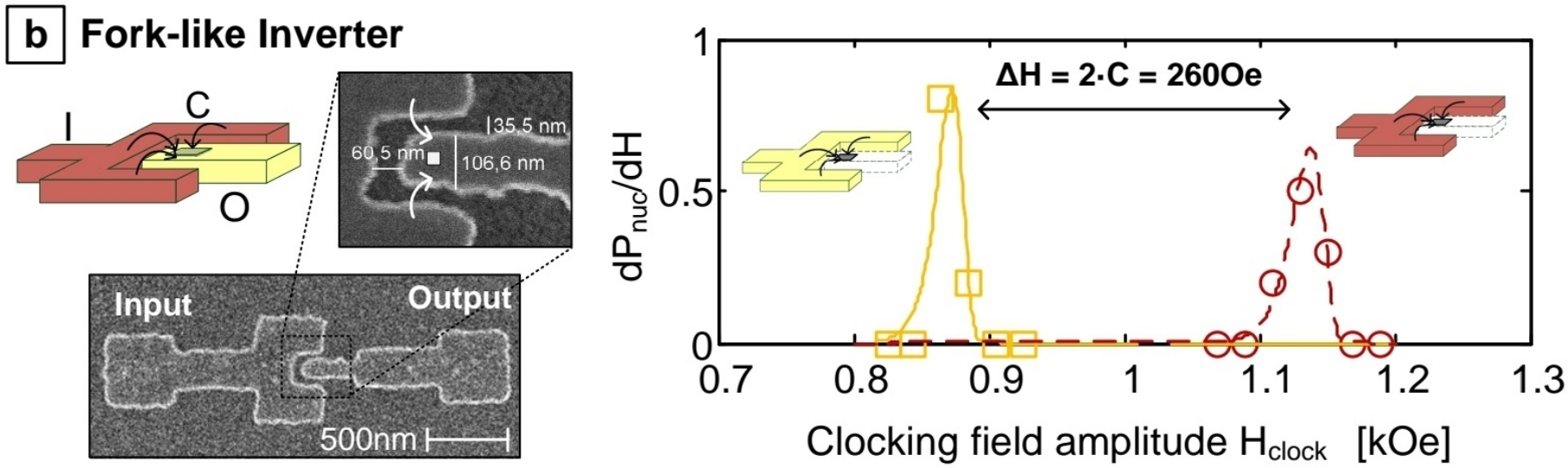
MAJORITY VOTER



TWO WAY BRANCH

INVERTER : BASIC AND IMPROVED

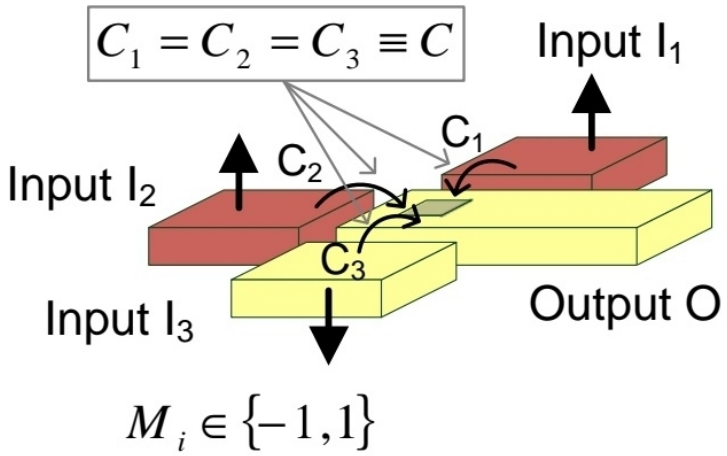




MORE EFFICIENT, BETTER COUPLING, REDUCED POWER

MAJORITY VOTER (MINORITY?)

a **Concept**



b **Majority operation**

$$C_{eff} = C \cdot (M_1 + M_2 + M_3)$$

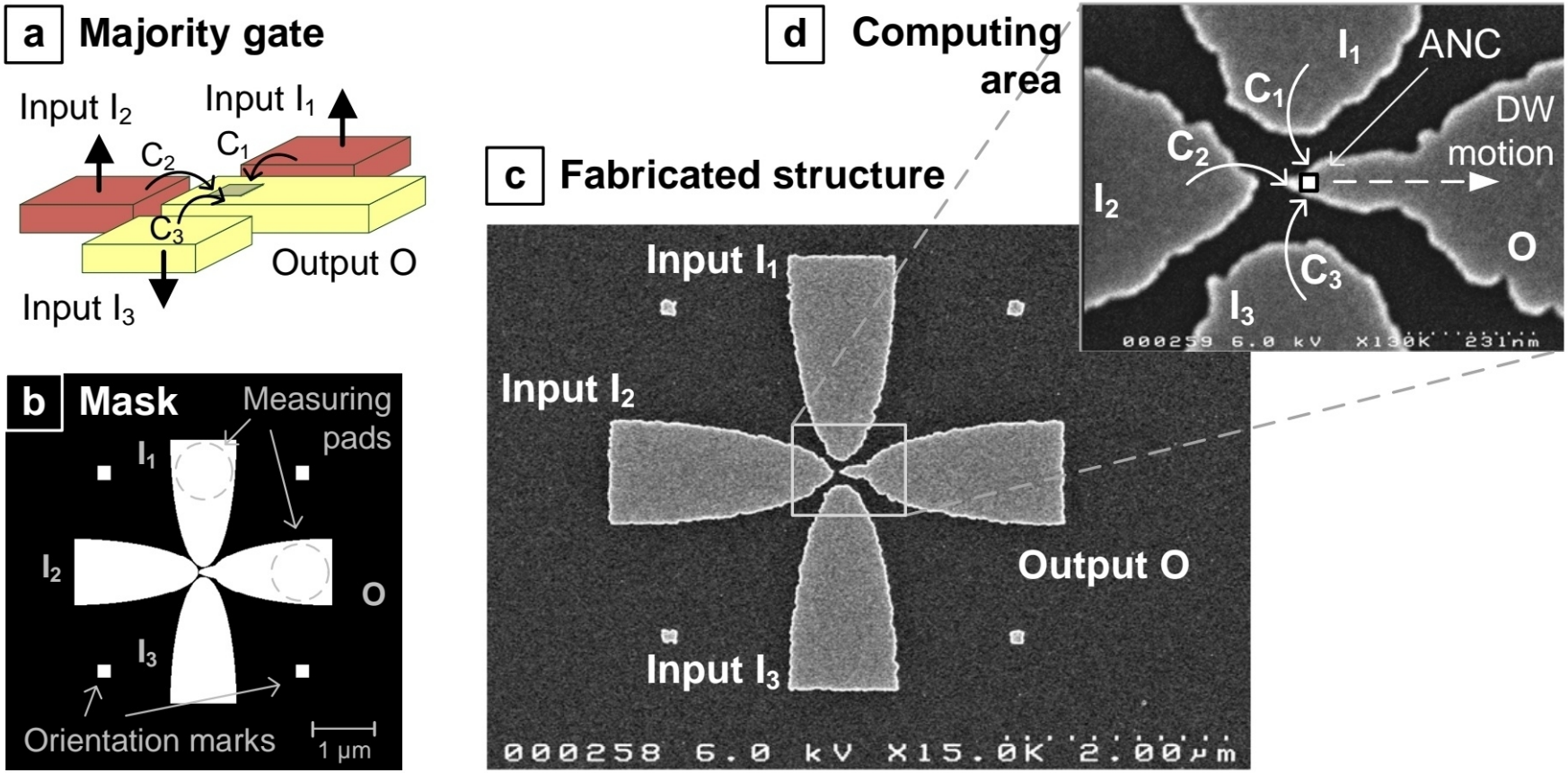
$$\Rightarrow M_O = -sign(M_1 + M_2 + M_3)$$

$$\Rightarrow O = \overline{\mathrm{M}(I_1, I_2, I_3)}$$

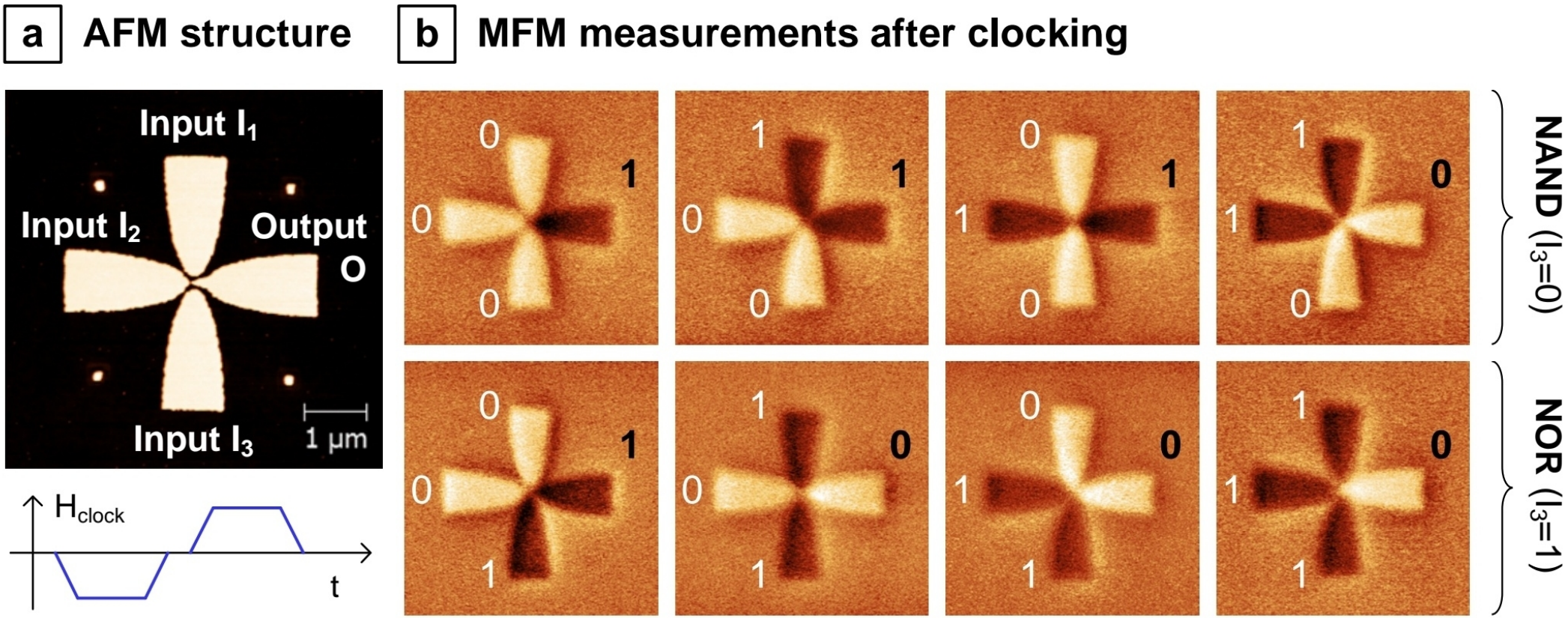
c **Truth table**

I1	I2	I3	O	
0	0	0	1	NAND
0	1	0	1	
1	0	0	1	
1	1	0	0	
0	0	1	1	NOR
0	1	1	0	
1	0	1	0	
1	1	1	0	

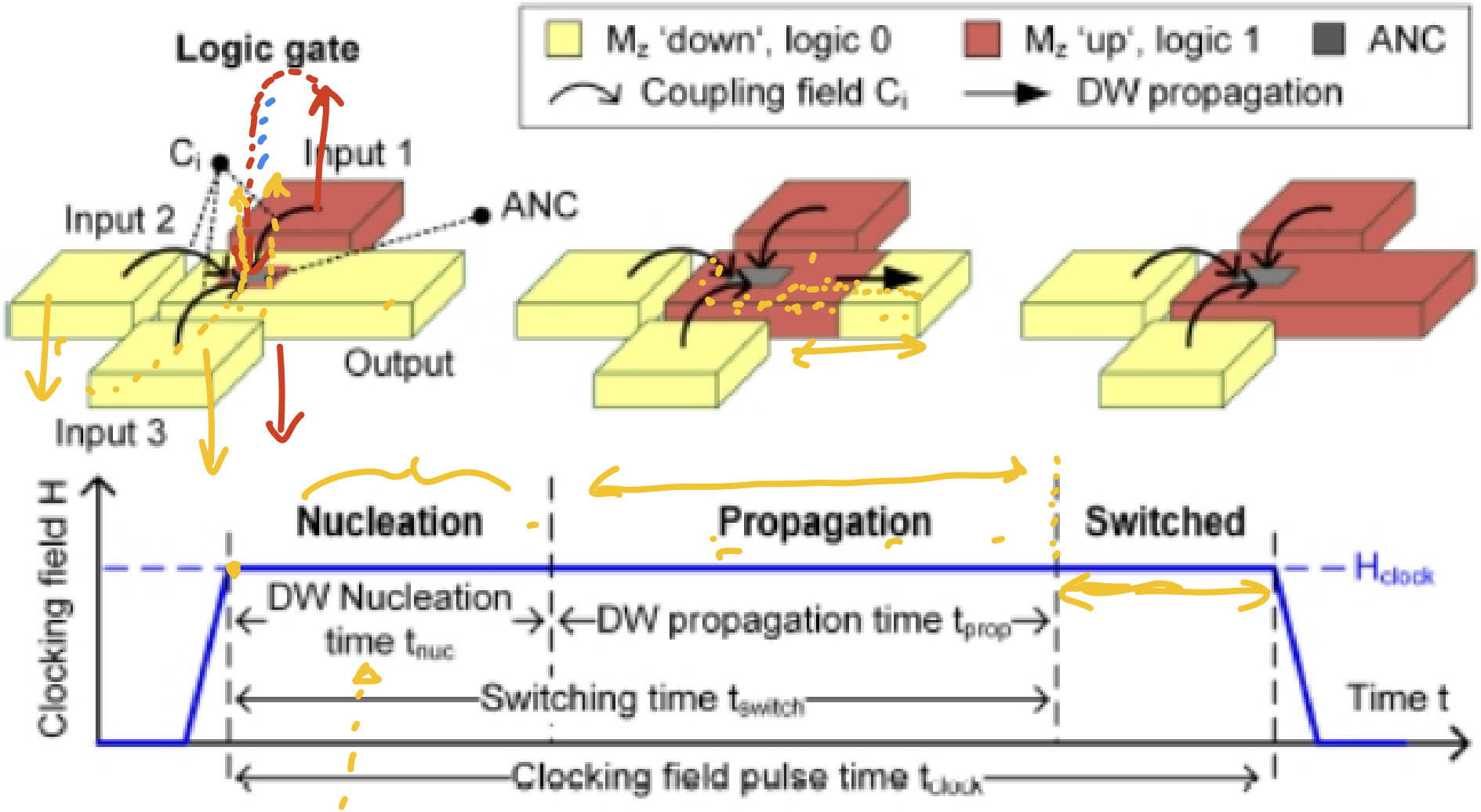
DEMONSTRATION



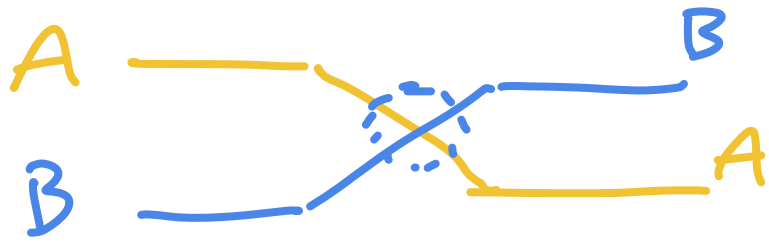
M.V. / AND/OR DEMONSTRATION

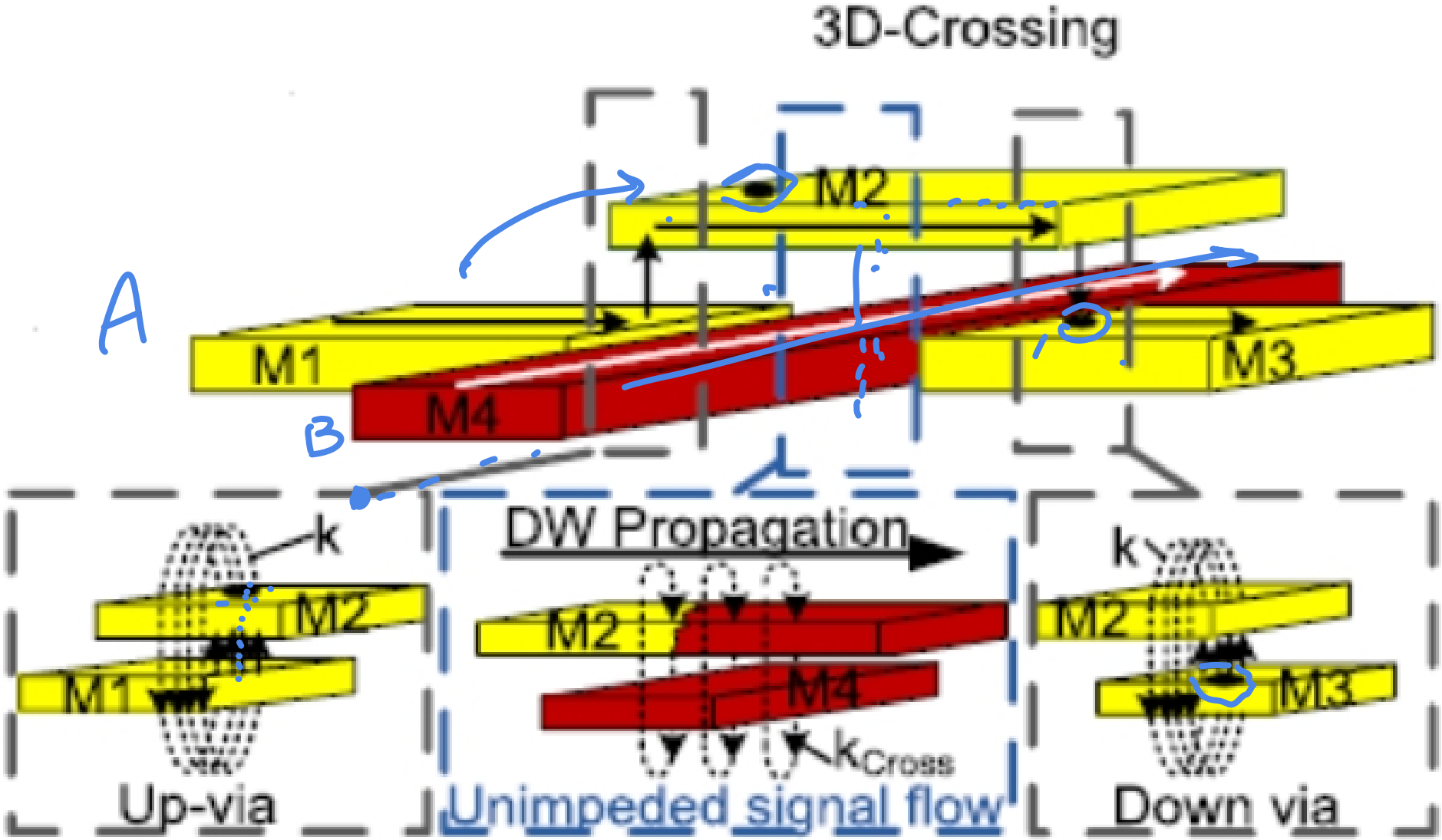


CLOCK PULSE DEFINITION

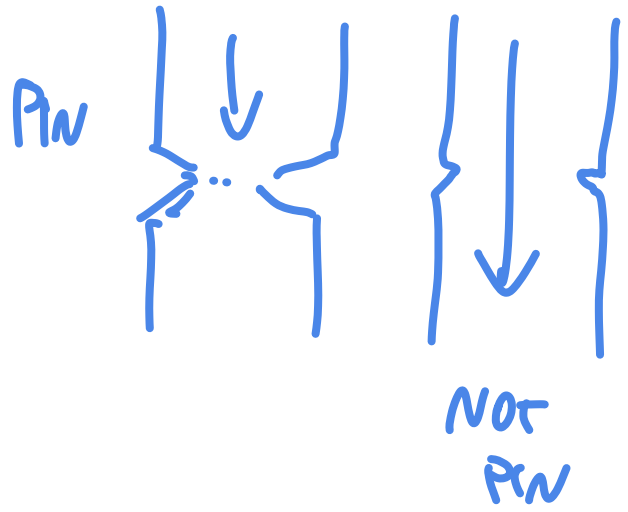


CROSSING


A
B
B
A


3D-Crossing
A
B
M1
M2
M3
M4
DW Propagation
k
k
M2
M1
M2
M4
M2
M3
k_{Cross}
Up-via
Unimpeded signal flow
Down via

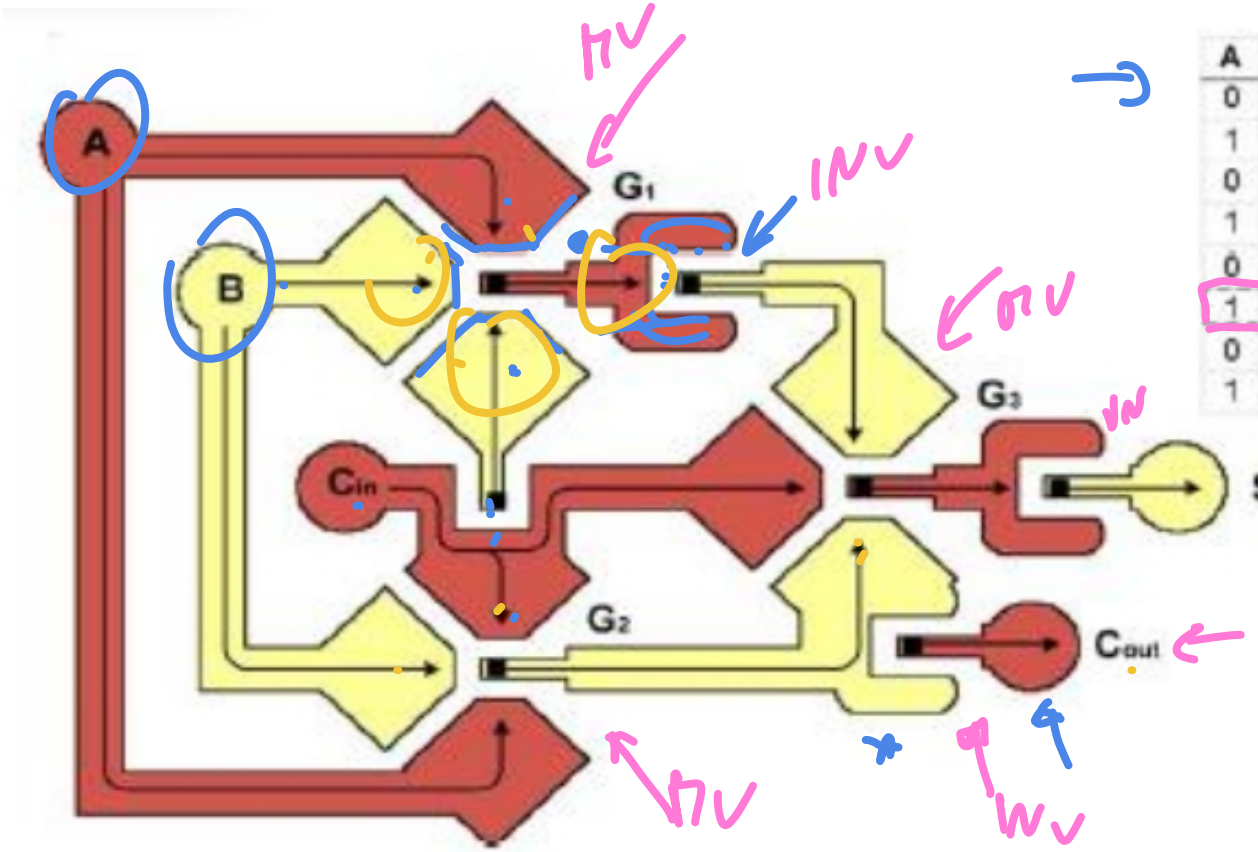
NOTCH



PINS THE PROPAGATION

TO DEPIN → EXTERNAL FIELD HAS TO BE APPLIED

TRY TO DECRIPT !



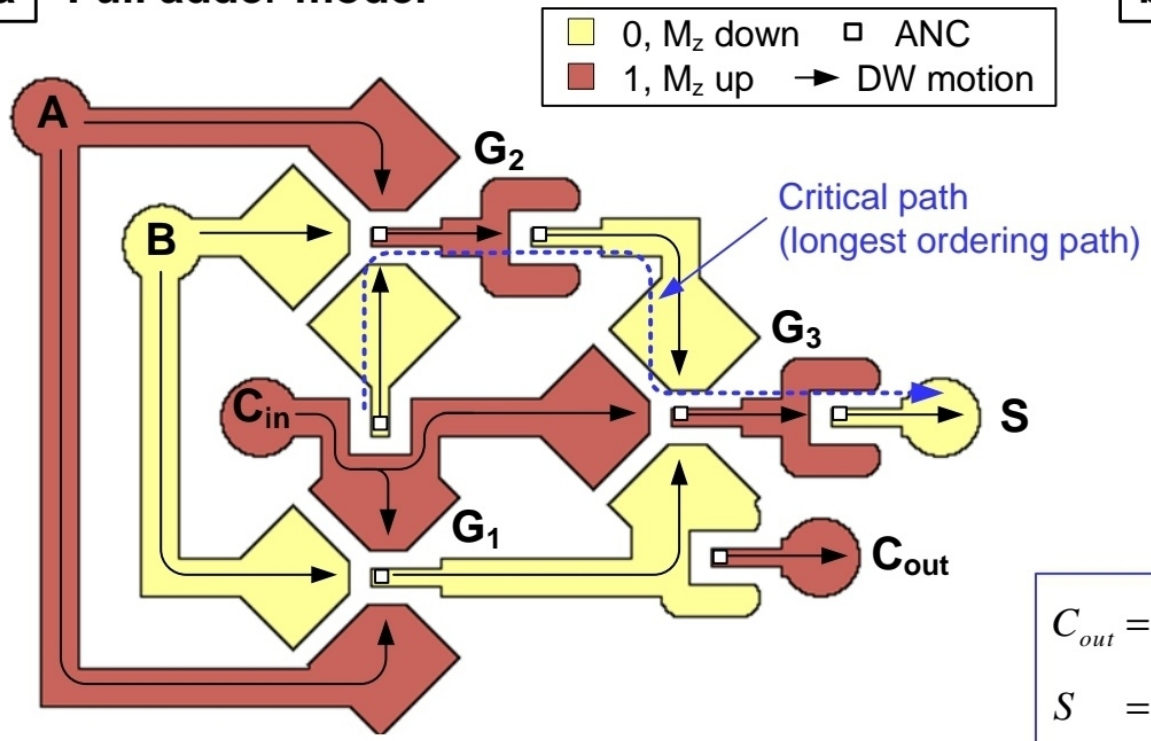
A	B	Cin	G1	G2	G3	S	Cout
0	0	0	1	1	1	0	0
1	0	0	0	1	0	1	0
0	1	0	0	1	0	1	0
1	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
1	0	1	1	0	1	0	1
0	1	1	1	0	1	0	1
1	1	1	0	0	0	1	1

FABRICATED – DEMOSTRATED

equivalent circuit ??

F.A. DYNAMICS

a Full adder model



b Truth table

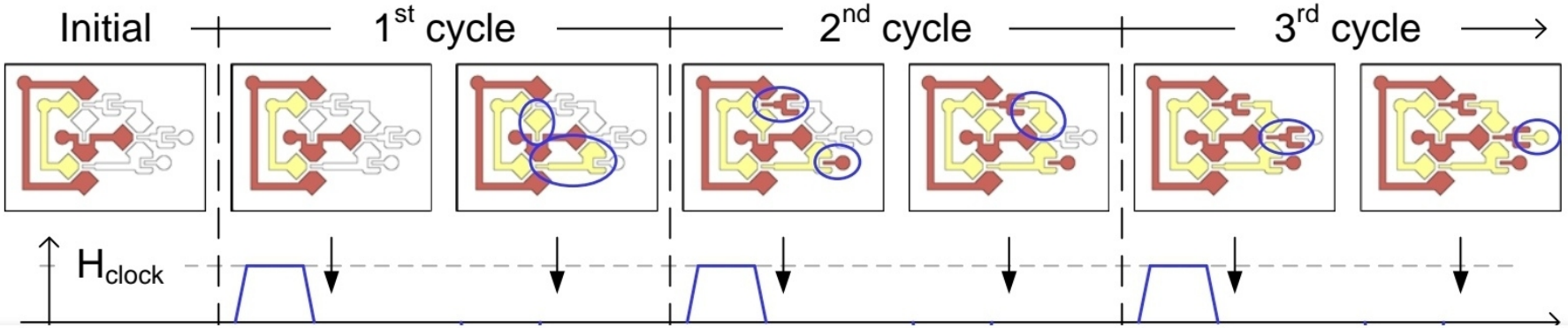
A	B	C_{in}	G_1	G_2	G_3	S	C_{out}
0	0	0	1	1	1	0	0
1	0	0	1	0	0	1	0
0	1	0	1	0	0	1	0
1	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
1	0	1	0	1	1	0	1
0	1	1	0	1	1	0	1
1	1	1	0	0	0	1	1

XOR
AND
OR
XNOR

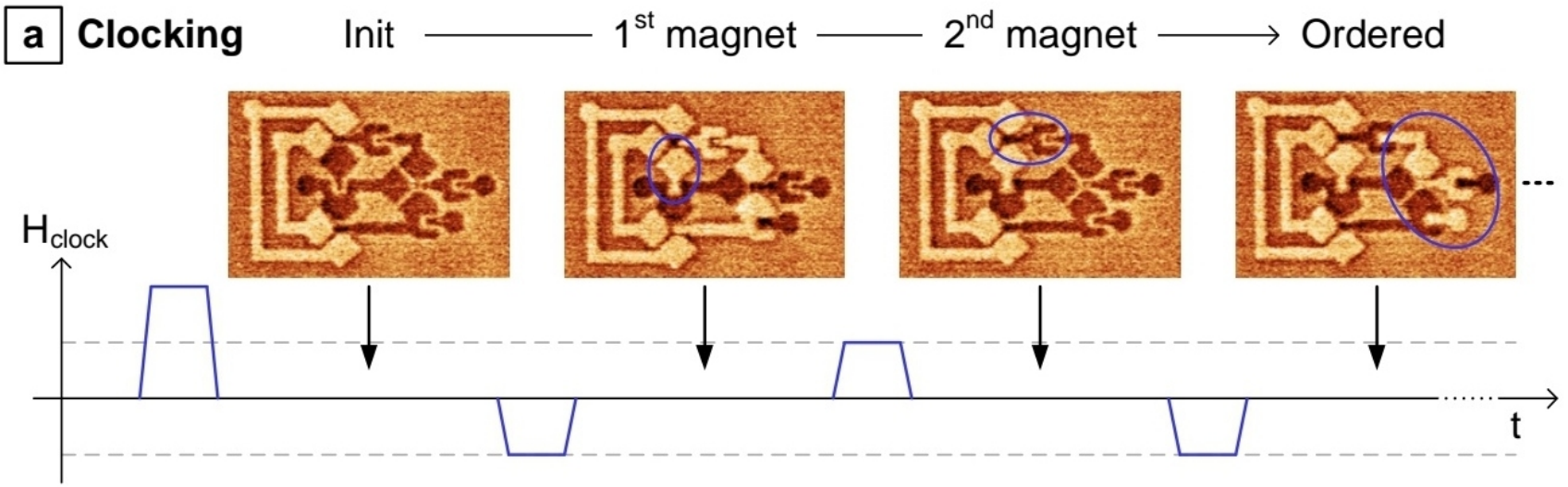
$$C_{out} = \overline{\overline{M}(A, B, C_{in})}$$

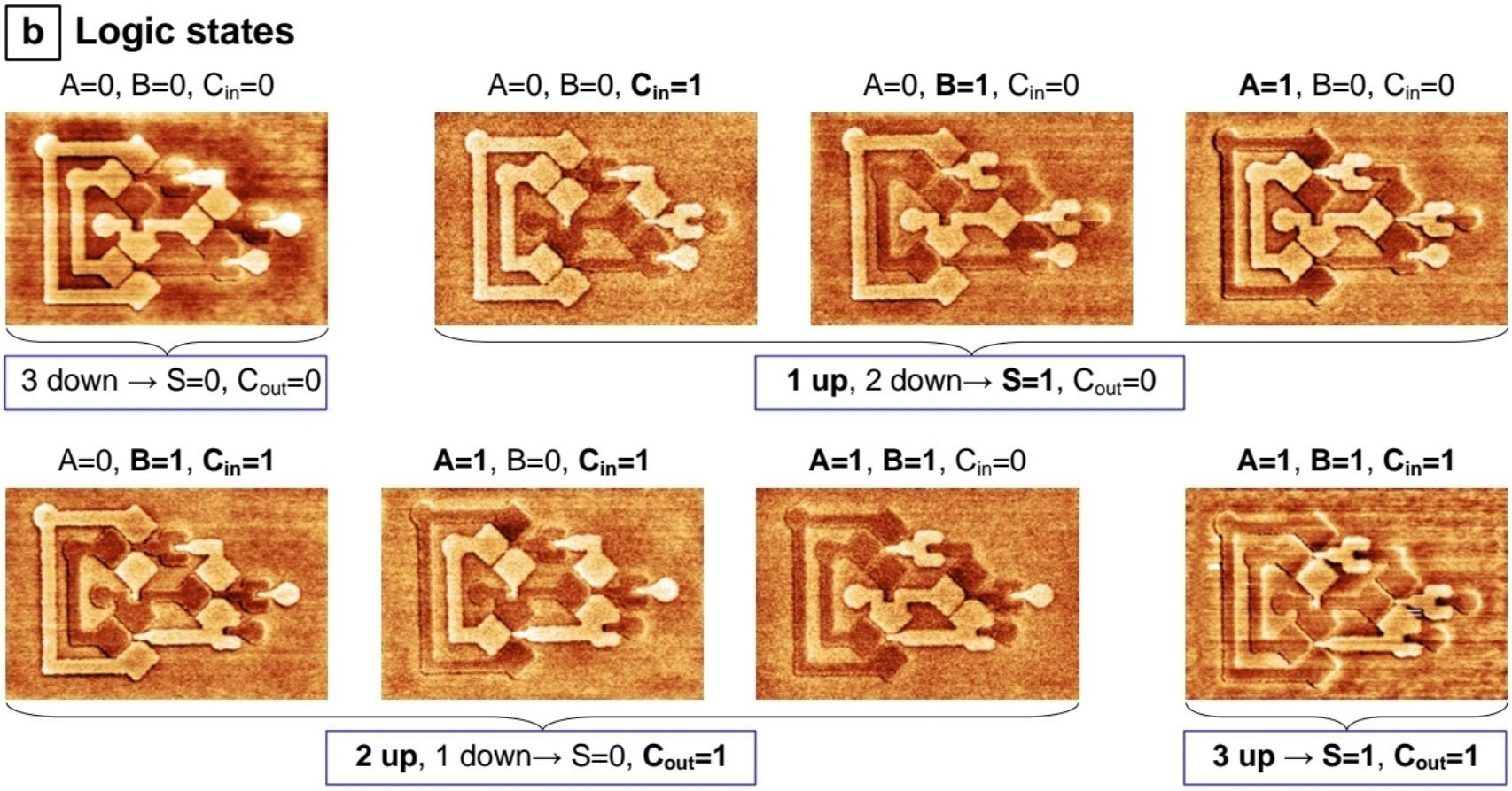
$$S = \overline{\overline{M}[\underbrace{\overline{M}(A, B, C_{in})}_{G_1=\overline{C_{out}}}, C_{in}, \underbrace{\overline{\overline{M}(A, B, \overline{C_{in}})}}_{G_2}]}$$

c Clocking



F.A. FULL DEMONSTRATION





EXERCISES

- create AND / OR
- XOR / XNOR
- RIPPLE CARRY ADDER 4 bits

FURTHER CONSIDERATIONS ON PNTL

(1) A couple of consideration on PNTL
(see L. Notes for further optional discussions
on PNTL model)

to guarantee a correct signal propagation,
and so the correct behavior of the PNTL circuit
the switching process should be completed
during the CLOCK FIXED PULSE TIME

$$t_{clock} > t_{nucl} + t_{prop}$$

nucl = NUCLEATION
prop = PROPAGATION

NUCLEATION

→ it means to REVERS the CURRENT MAGNETIZATION STAT IN THE ANC

→ it REQUIRES A FIELD H_{NUC} that REDUCES THE ENERGY BARRIER

$H_{NUC} \geq H_{ANI}$ ← MODELED BY STONER-WOHLFARTH MODEL

$$H_{ANI} = \frac{2\, K_{eff,ANC}}{\mu_0 M_S}$$

M_S = saturation magnetization of magnet

$K_{eff,ANC}$ = EFFECTIVE ANISOTROPY in ANC

each magnet is caracterized by a unique anisotropy term, which depends on crystal structure, the geometry, the material

The EFFECTIVE FIELD H_{eff}, that should be the H_{NUC} is INFLUENCED BY THE SUPERPOSITION OF

→ EXTERNAL FIELD H_{CLOCK}

→ COUPLING FIELD OF THE SURROUNDING MAGNETS $C_{eff} = \sum_{i=1}^{N} C_i M_i$, where

M_i is the NORMALIZED MAGNETIZATION OF A NEARBY MAGNET $\{1, -1\}$

C_i is the coupling field of an input

influence the energy barrier which increases or decreases according to the parallel or antiparallel state of input magnetization w.r.t. current state

$$H_{eff} = H_{CLOCK} - C_{eff}$$

PROPAGATION

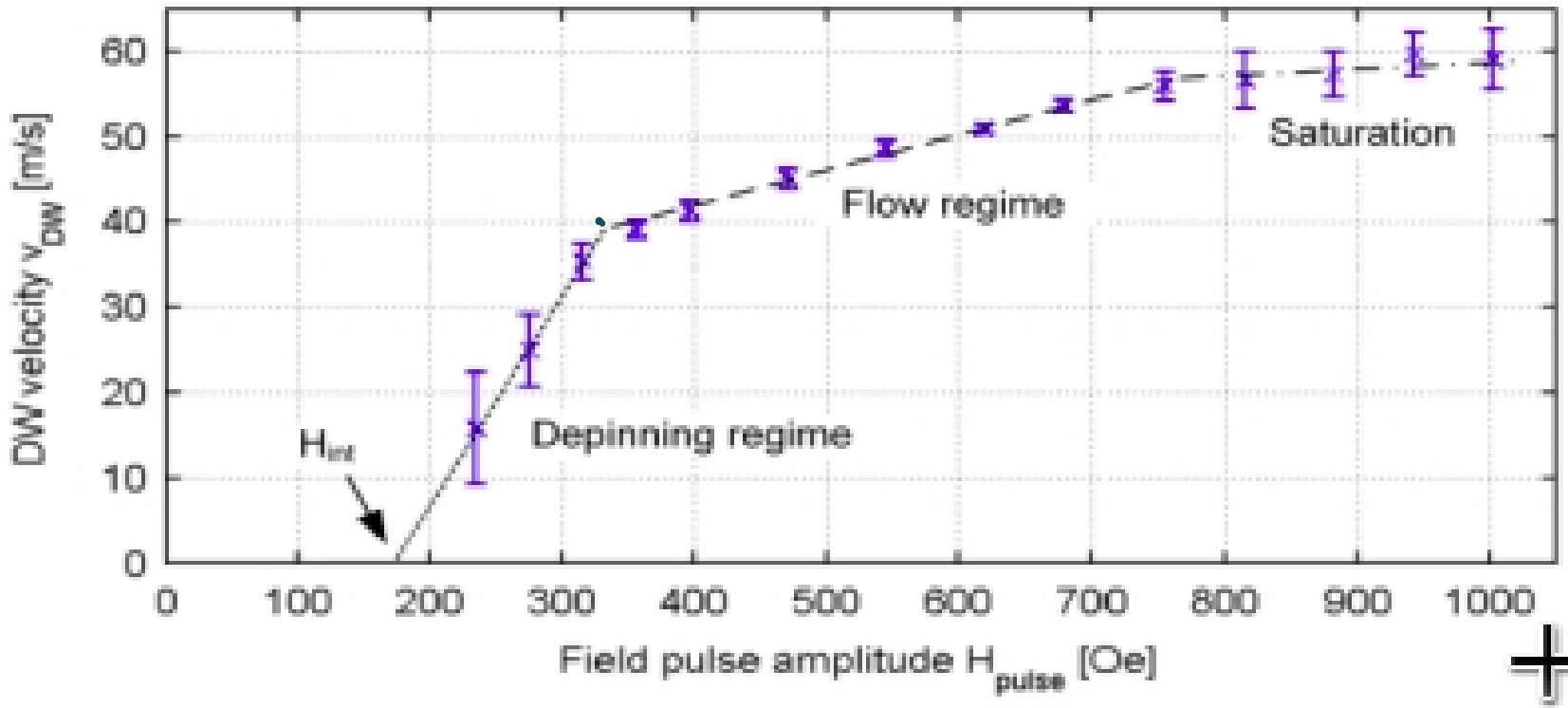
ONCE THE NANOMAGNET IS NUCLEATED BY THE EFFECTIVE FIELD H_{eff}, THE MAGNETIC STATE HAS TO PROPAGATE ALONG THE STRUCTURE, VIA THE CLOCKING FIELD

3 REGIMES IN THE PROPAGATION VELOCITIES

DEPINNING REGIME → applied field is smaller than the DEPINNING FIELD

FLOW REGIME → applied field is greater than the DEPINNING FIELD

SATURATION REGIME → Velocity saturates to a constant value



in FLOW REGIME $v_{DW}(H_z \gg H_{int}) = v_0 + \mu_w (H_z - H_{int})$

the velocity depends linearly on the applied field H_z

$\rightarrow t_{prop} = l_{MAG} / v_{DW}(H_z - H_{int})$ l_{MAG} LENGHT OF MAGNET

CRISTALLIZATION

- PNML : MIXES NML PRINCIPLE AND DW PROPAGATION

- A MIX AMONG: MAGNET INTERACTION AND H_EXT. FIELD SOLVES NML PROBLEMS

- H_CLOCK IS GENERAL, NO PHASES
- ALLOWS MULTILAYER ORGANIZATION
- SPEED CAN IMPROVE, WITH SHRINKING