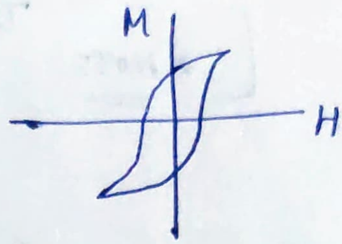
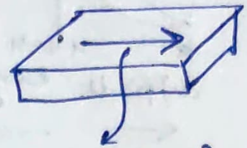
Case 3 : This also is going to show a ferromagnetic behaviour



* Case 2 (AFM + FM coupling)

↓

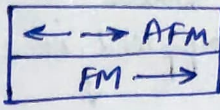
here is the most important case to consider



FM layer

direction in which spins are aligned

Here both layers must be very thin



AFM layer contains spins aligned in opposite directions

(Since the interaction entirely happens at the interface

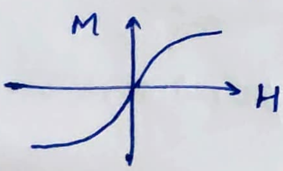
↓

and does not depend on the volume of the two layers)

* { NOTE: For AFM itself

↓

M-H loop looks like:

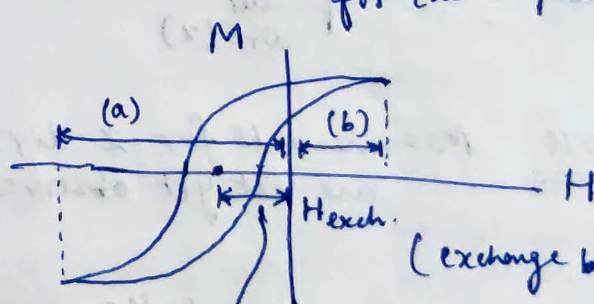


}

We perform pinning here

↓

so the new M-H curve for the couple looks as :



(exchange bias)

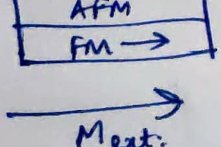
* NOTE: this is observed for the case when field is externally applied in parallel dir^n ⟸

Clearly we see that here (a) ≠ (b)

↓

so there is anisotropy

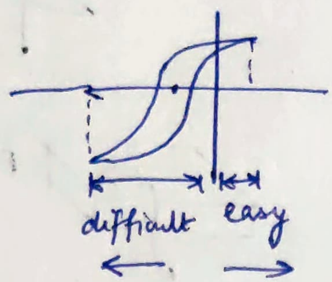
a characteristic feature is this shift of the hysteresis loop from the origin



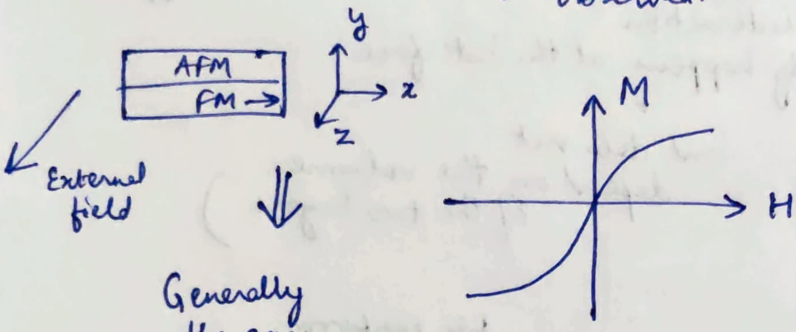
{ NOTE: This curve is always shifted towards this side only

}

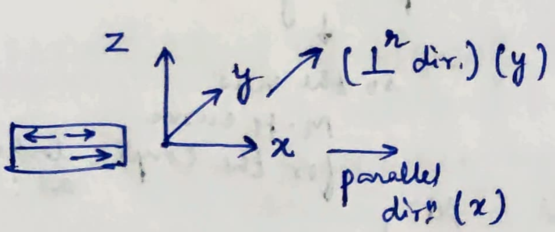
[*NOTE: The reason for anisometry is that one direction is "easy", as the spins are originally aligned in that direction
↓
so that is shorter than the other]



Now, for the case when external field is applied in $\perp^r$ direction
↓
No hysteresis is observed.

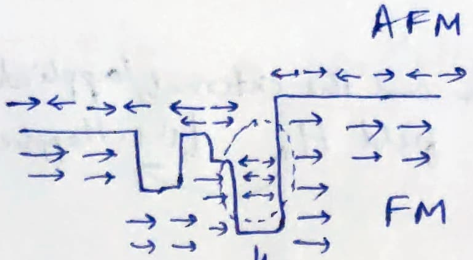


Generally the axes are labelled as:



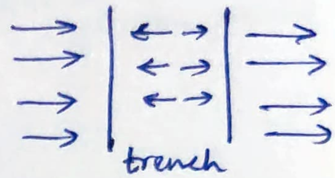
*NOTE: Measurements for z-dir^n are not yet observed.

86] The explanation behind the anisotropy observed (which we call exchange bias)
↓
is based on a
* "bad interface"



in such "trenches"
+
the AFM region
would normally have
spins of the form $\leftrightarrow$

+
But due to very strong
effects of FM surrounding it
+
a certain "pinning" phenomena
occurs



⇓
thus this causes
the AFM local
spins
to get a certain amount
of ferromagnetic
character

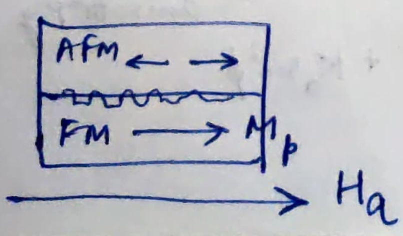
this
is the
reasoning
given behind
the exchange bias

* NOTE: Since it
is the FM layer
which determines the
preferential
direction
and affects the
other layer
↓
thus this FM layer
is called the
"pinning" layer
(and AFM layer is the pinned layer)

[** NOTE: This
is currently
a theoretical conjecture
without any experiment
to support/disprove
it ↓
No experiment has
been performed to
verify it]

LECTURE 26 (15/04/2024)

87] We have already looked
at a qualitative understanding
of exchange bias
in the AFM + FM couple



We have
some external field H_a

M_p : Pinning magnetization (of FM layer)

Now, consider ϕ to be the angle b/w magnetization and the external/applied field H_a (i.e. $H_{applied}$)

Then we can write:

$$E_{tot.} = -\mu_0 M_p H_a \cos\phi$$

But now, we know there is also some exchange field $H_{ex.}$

due to which we should write:

$$E_{tot.} = -\mu_0 M_p H_a \cos\phi - \underbrace{\mu_0 M' H_{ex.}}_{K_{ex.}} \cos\phi$$

(NOTE! This angle ϕ is the same as the ϕ b/w M_p and H_a)

i.e. we can write!

$$H_{ex.} = \frac{K_{ex.}}{\mu_0 M'}$$

However, to take into account anisotropy out of the plane, we cannot just rely on a $\cos\phi$ term

$\Downarrow$

thus, we include an additional term:

$$\therefore E_{tot.} = -\mu_0 M_p H_a \cos\phi - \mu_0 M' H_{ex.} \cos\phi + K_a \sin^2\phi$$

$$= -\mu_0 M_p H_a \cos\phi - K_{ex.} \cos\phi + K_a \sin^2\phi$$

* Both $K_{ex.}$ and K_a are material constants related to anisotropy

Thus:

$$E_{tot.} = -(\mu_0 M_p H_a + K_{ex.}) \cos\phi + K_a \sin^2\phi$$

$$\frac{dE_{tot.}}{d\phi} = (\mu_0 M_p H_a + K_{ex.}) \sin\phi + 2K_a \sin\phi \cos\phi = 0$$

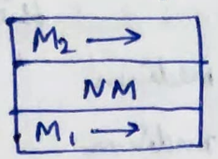
$$\Rightarrow \sin\phi = 0$$

Thus, we get that :

$\phi = 0 \longrightarrow$ Stable state

Also, for $\phi = \frac{\pi}{2} \longrightarrow$ "unstable" (technically, a switching state) {like an inflection point}

88] Another kind of stacking :



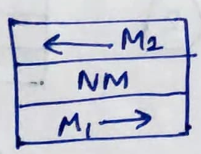
Two Ferromagnetic layers (with Non-magnetic sandwiched b/w them)

$\Rightarrow$ this shows a special property called

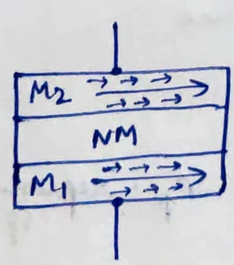
* GMR (Giant Magneto-Resistance)

NOTE: { A Nobel prize was awarded for a discovery based on this }

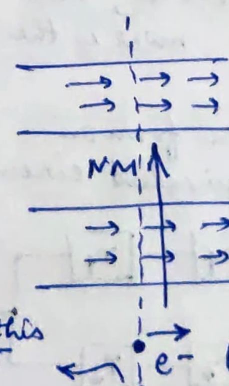
Another possibility :



89] In these setups, resistance is measured along the top and bottom :



$R_{\uparrow\uparrow}$ is the total resistance of this stack $\Leftarrow$ $\Rightarrow$



$\therefore$ (i) $R_\uparrow \Rightarrow$ Low

(ii) $R_\downarrow \Rightarrow$ High

* { $R_\uparrow$: resistance for up spin e⁻'s going through $\uparrow\uparrow$

$R_\downarrow$: resistance for down spin e⁻'s going through $\uparrow\uparrow$ }

(if e⁻ has spin along some parallel dir.ⁿ)

$\Downarrow$

Passing through both layers (that are ferromagnetic) will be easy

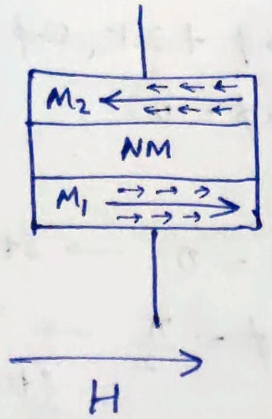
This is Low Resistance case (i)

for this e⁻ spin is in opposite dir.ⁿ

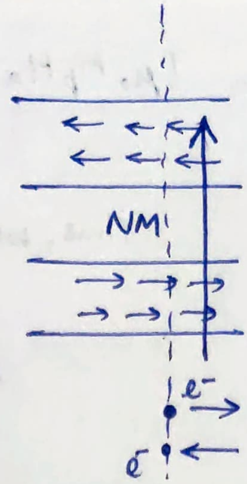
$\therefore$ $\Downarrow$ will experience high resistance (ii)

90]

$R_{\uparrow\downarrow}$ $\Leftarrow$ is the total resistance of this stack



$\Rightarrow$



Here both up and down spin e's will experience medium resistance when going through the layers.

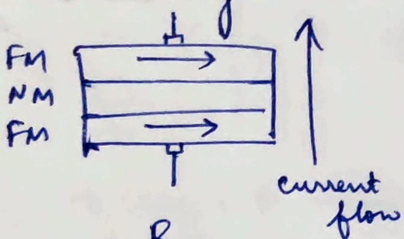
$\therefore$ $R_\uparrow \Rightarrow$ medium

$R_\downarrow \Rightarrow$ medium

LECTURE 27 (18/04/2024) :

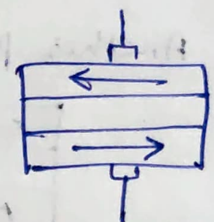
91] As we have already seen:

1



$R_{\uparrow\uparrow}$

2

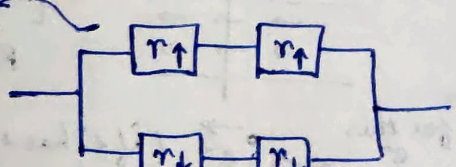


$R_{\uparrow\downarrow}$

The more the no. of scattering events, the more is the resistance

For 1, we can form an equivalent circuit:

up spin going through

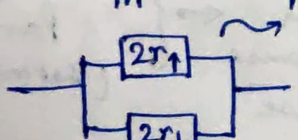


down spin going through

$r_\uparrow$: represents a spin parallel to dir.ⁿ of layer

$r_\downarrow$: represents spin antiparallel to dir.ⁿ of layer

$\equiv$



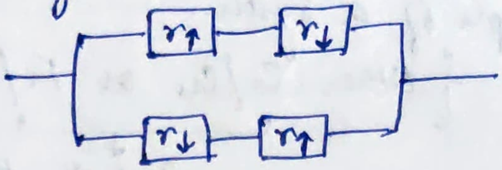
Here $r_\uparrow \to 0$

thus

$\Downarrow$

$\boxed{R_{\uparrow\uparrow} \text{ is Low}}$ (i.e. $R_{\uparrow\uparrow} \approx 0$)

For ② we get :

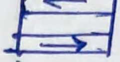


{ **NOTE:** Since the 2 e^-s are in independent channels, thus we draw them in parallel in the circuit }

$$\equiv$$

$$\boxed{R_{\uparrow\downarrow} = \frac{r_\downarrow}{2}}$$

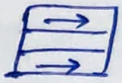
(which is HIGH)

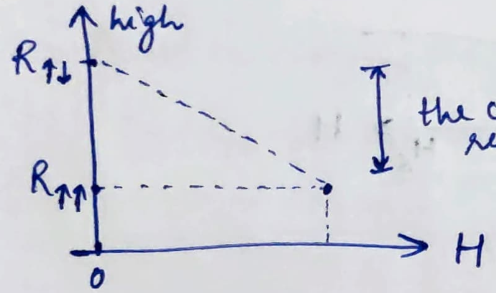
92] It actually turns out that  is the "ground state"

↓

and when we apply some magnetic field $H > 0$

↓

then it flips it to 



the change in resistance in GMR is very large (~50%)

Conceptually this can be explained as

↓

The application of H field causes a motion in linear dir^n to change to helical

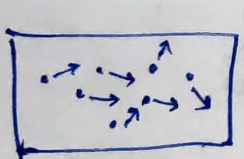
↓

so mean free path (l) $\uparrow \Rightarrow \therefore \tau \uparrow$ (relaxation time)

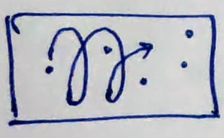
$\Downarrow$

Thus, due to increase in τ, Resistance ↓

$\{ l = v_F \tau \}$

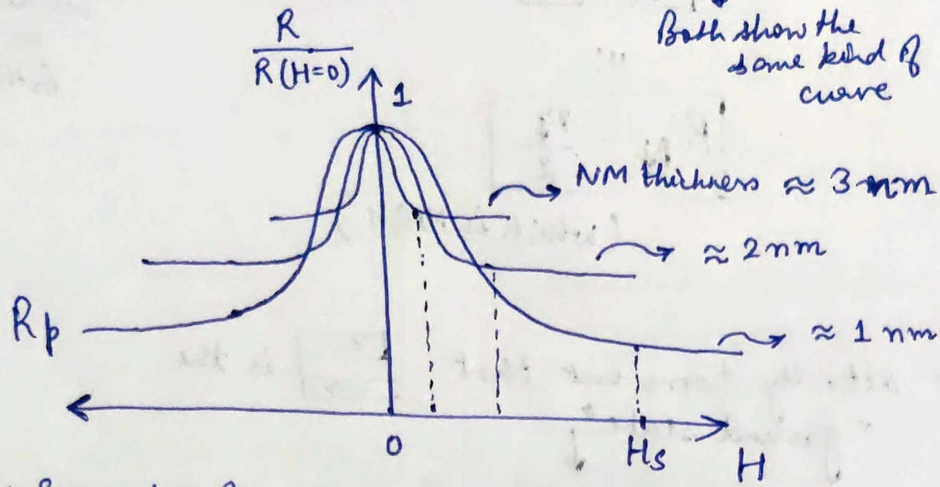


⇓



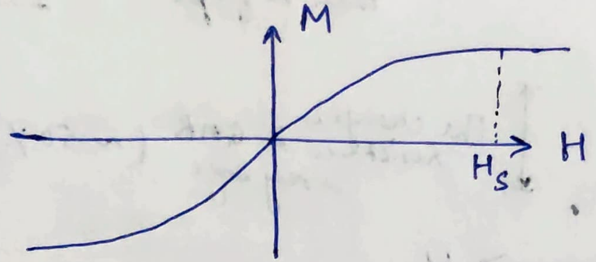
93] Taking the example of a system
{ Either Co/Cu or Fe/Cr }

Both show the same kind of curve



{NOTE: Symmetry of curve is expected since there is no difference b/w +ve and −ve dirn H}

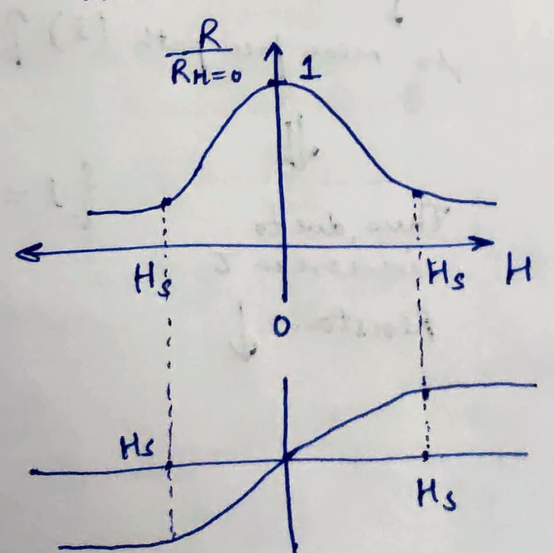
(H_s : saturation field)



LECTURE 28 (22/04/2024)

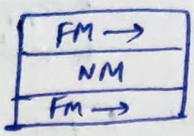
94] Spin valve → we can use the 3-layer stack we discussed to make spin valves

We have seen:

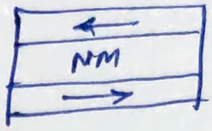


We can use this concept of GMR
↓
to manipulate spins and create <u>spin valves</u>

(STATE 2)

95] 

J → if thickness of NM is lower
↓
interaction b/w the two FM layers increases



Low R
(STATE 1)

High R

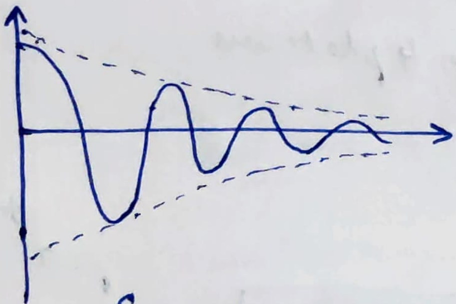
* Currently we have assumed that NM is a <u>metallic</u> layer (it contains free $\bar{e}$s)

We can write the interaction term as :

$$\underbrace{\mathcal{H}}_{\text{Hamiltonian}} = -J \underbrace{\vec{S_i} \cdot \vec{S_j}}$$

here $\vec{S_i}$ and $\vec{S_j}$ are the magnetization vectors of the top and bottom layers

Based on changing the thickness
↓
we oscillate b/w FM and AFM type layers
(and consequently, J changes its sign)



i.e. ⇐
<u>+ve means</u>
⇓
in absence of external field
↓
FM is the stable layer (ground state) → (STATE 1)

{* <u>NOTE</u>: This

whereas, <u>-ve means</u>
⇓
in ground state (with zero external field)
AFM configuration exists → (STATE 2)

NOTE: We want STATE 1 kind of a system to make a spin valve

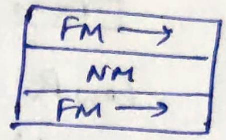
↓

since it has low R

→ This STATE 1 itself can be considered a spin valve

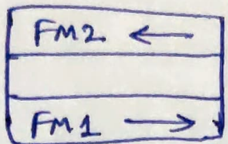
(though this approach is not optimal)

APPROACH ①



96] There are several other approaches

APPROACH ②:



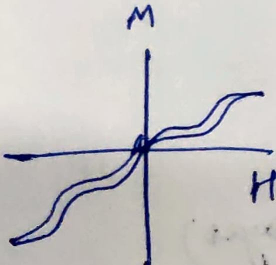
with Low H_c

with High H_c

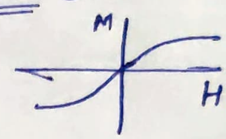
external field

⇓

Here, we will observe a hysteresis loop in M-H curve & containing 4 plateaus



* {**NOTE:** Earlier we saw



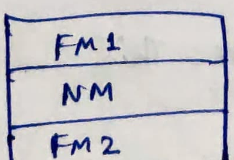
M-H curve

⇓

Thus it had zero coercive field}

* {**NOTE:** * [May be asked in Exam] Explaining granular spin valves using M-H curve}

97] APPROACH ③



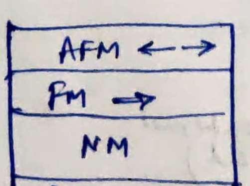
large nonmagnetic layer

the advantage of this is that it allows us to weaken the interaction b/w FM 1 & FM 2

↓

and we can ourselves control the flipping of FM layer spins

APPROACH ④



} exchange bias exists for this

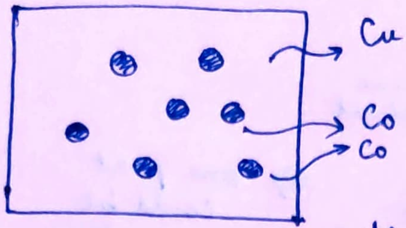
large thickness

⇓

Here pinning is used to help control the spin direction

98] There is another unique kind of spin valve
↓
called <u>Granular spin valve</u>

APPROACH 5



} Cobalt granules are present within

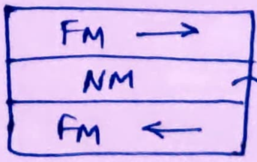
this is created (and can be tuned and modified) through alloying

Here
Cu (acts as NM "layer")
Co (acts as the FM magnetic "layer")

{ *NOTE: This geometry is the most uncontrolled one }

99] Till now, we have always assumed NM layer to be thin (or sometimes thicker) but <u>metallic</u>
↓
another approach is to use a
* <u>thin and insulating NM layer</u>

APPROACH 6 : TMR (Tunneling Magneto-Resistance)



→ insulating (has to be extremely thin)

Through the NM layer
↓
tunneling takes place

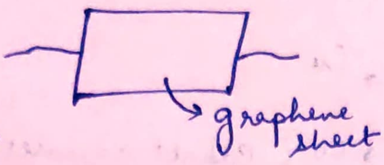
* **NOTE:** [In the Exam]

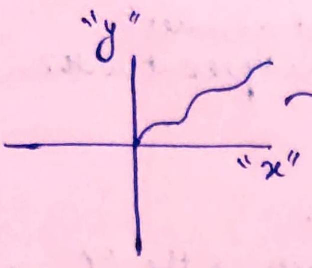
Questions can be there of the form:

Containing plots → and then asking for some explanation about them

(some experimental plots)

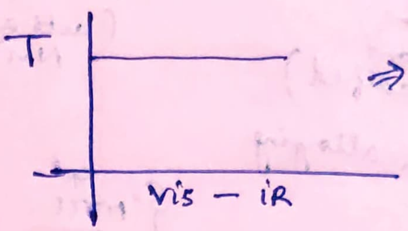
eg:





→ some plot related to this ⇒ one part could be on this (requiring explanation)

[probably R_x and R_y] ?



⇒ one part could be on transmittance curve

* **NOTE:** Have the formulas in your cheatsheet if possible (particularly for mechanical oscillators)

(check the formulae and constants from reference textbook)