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Theory of Magnon Transport and Magnetic Sensing in Magnetic Insulator Heterostructures

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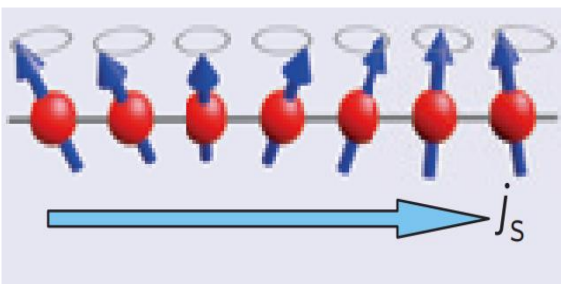
Motivation:

Propose a fully quantum mechanical theory for the transport of magnons in two-sublattice magnetic insulators

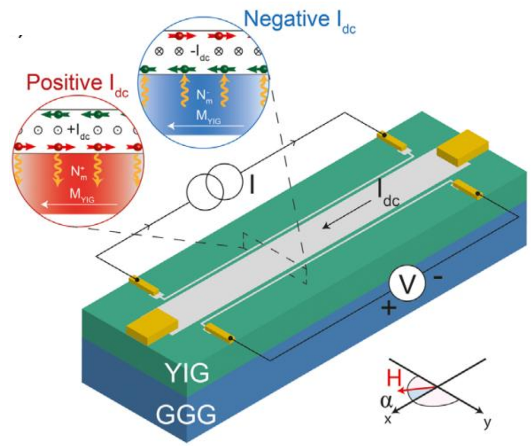
Magnon:

Elementary excitation in magnetic system



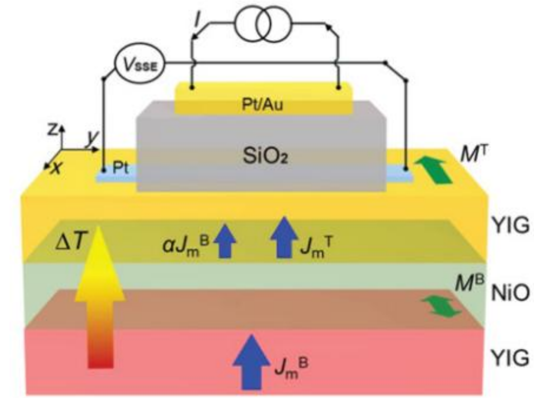
Chumak, et al, Nat. Phys. 11, 453 (2015)

Electronic



Cornelissen, et al, PRL, 120, 097702 (2018)

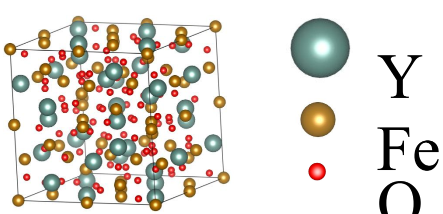
Thermal



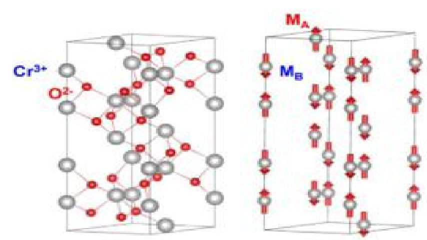
Guo, et al, PRB, 98, 134426 (2018)

Magnonic experiment system:

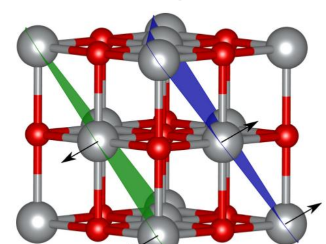
YIG (Yttrium Iron Garnet)



Cr_2O_3



NiO



Method

1. Second quantization

Hamiltonian of two-sublattice magnetic insulators:

$$\hat{H} = -J_{AB}\sum_{<i,m>}\hat{\boldsymbol{S}}_i\cdot\hat{\boldsymbol{S}}_m - J_A\sum_{\ll i,j\gg}\hat{\boldsymbol{S}}_i\cdot\hat{\boldsymbol{S}}_j - J_B\sum_{\ll m,n\gg}\hat{\boldsymbol{S}}_m\cdot\hat{\boldsymbol{S}}_n - h_{\text{ext}}\left(\sum_i \mu_A\hat{S}_i^z + \sum_m \mu_B\hat{S}_m^z\right)$$

Using Holstein - Primakoff (H-P), Bogoliubov and Fourier transformation

$$\Rightarrow \hat{H} = \sum_k [w_k^\alpha \hat{\alpha}_k^\dagger \hat{\alpha}_k + w_k^\beta \hat{\beta}_k^\dagger \hat{\beta}_k]$$

Two independent magnon mode!

2. Non-equilibrium Green's function

① Hamiltonian

$$\boxed{\hat{H}} = \sum_k [w_k^\alpha \hat{\alpha}_k^\dagger \hat{\alpha}_k + w_k^\beta \hat{\beta}_k^\dagger \hat{\beta}_k]$$

② Green's function

$$\boxed{\mathcal{G}^{R(A)}(\epsilon)} = [\epsilon - \boxed{h} - U(\epsilon) - \hbar\Sigma^{R(A)}(\epsilon)]^{-1}$$

③ Density matrix

$$\boxed{\rho_{j,j'}} = \int d\epsilon\, [\boxed{\mathcal{G}^R(\epsilon)}\, i\hbar\Sigma^<(\epsilon)\boxed{\mathcal{G}^A(\epsilon)}]_{j,j'}$$

④ Magnon current

$$< j_{m,jj'} > \; = -i(h_{j,j'}\boxed{\rho_{j',j}} - h_{j',j}\boxed{\rho_{j,j'}})$$

Results

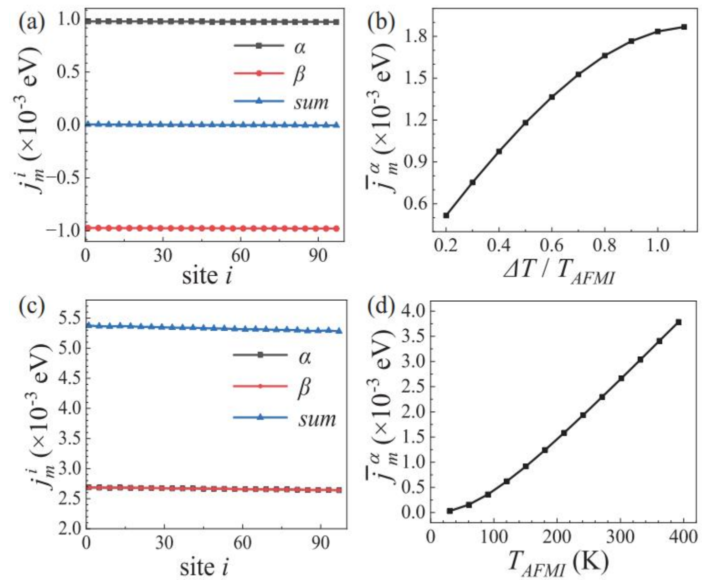
Model

- In this setup, the FIMI or AFMI is connected to two HMs with temperatures T_R, T_L and spin chemical potentials μ_L, μ_R.
- The magnon current is driven by the difference of temperature or spin chemical potential between two HMs .

$\mu_L = \mu_R = 0$
$k_B T_{AFMI} = 0.026$ eV
$T_L = 1.2\ T_{AFMI}$
$T_R = 0.8\ T_{AFMI}$

$\mu_L = 0.1$
$\mu_R = 0$
$k_B T_{AFMI} = 0.026$ eV
$T_L = T_{AFMI} = T_R$

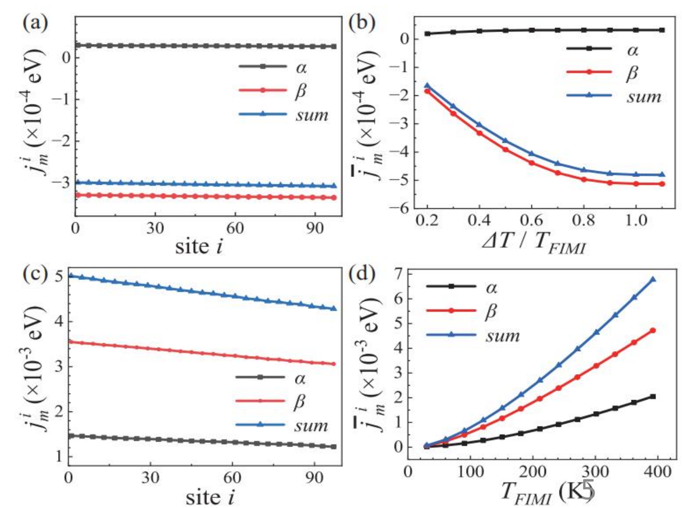
AFMI



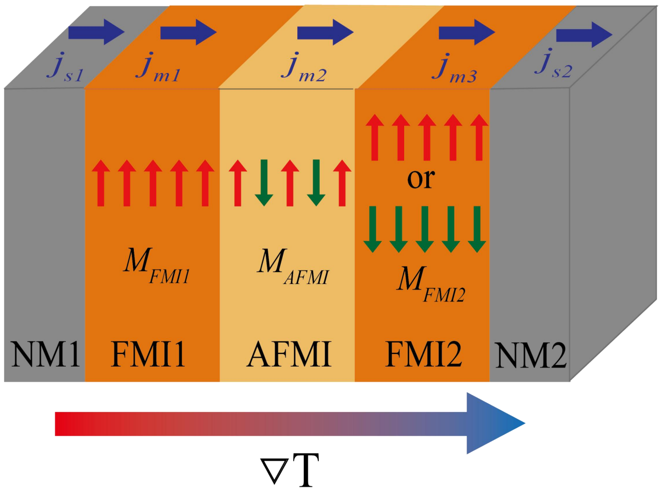
$\mu_L = \mu_R = 0$
$k_B T_{FIMI} = 0.026$ eV
$T_L = 1.2\ T_{FIMI}$
$T_R = 0.8\ T_{FIMI}$

$\mu_L = 0.1$
$\mu_R = 0$
$k_B T_{FIMI} = 0.026$ eV
$T_L = T_{FIMI} = T_R$

FIMI



Results and Conclusion



Parameters:

$k_B T_{NM1} = 0.026$ eV, $T_{FMI1} = 0.9\ T_{NM1}$,
$T_{AFMI} = 0.8\ T_{NM1}$, $T_{FMI2} = 0.7\ T_{NM1}$, $T_{NM2} = 0.6\ T_{NM1}$

Parallel state: $J_{m,\uparrow\uparrow} = 6.53 \times 10^{-4}$ eV

Antiparallel state: $J_{m,\uparrow\downarrow} = 4.79 \times 10^{-7}$ eV

Magnon junction ratio MJR $= \dfrac{J_{m,\uparrow\uparrow} - J_{m,\uparrow\downarrow}}{J_{m,\uparrow\uparrow} + J_{m,\uparrow\downarrow}} = 99.85\%$

Conclusion:

- Using H-P transformation, Fourier transformer and non-equilibrium Green's function, we proposed a full quantum theory for magnon transport in two-sublattice magnetic insulators and magnon junctions.
- Our results can be used to calculate the magnon current induced by electron current and temperature gradient.

Tianyi Zhang and Xiufeng Han, ***Phys. Rev. B*** **108**, 104421 (2023).

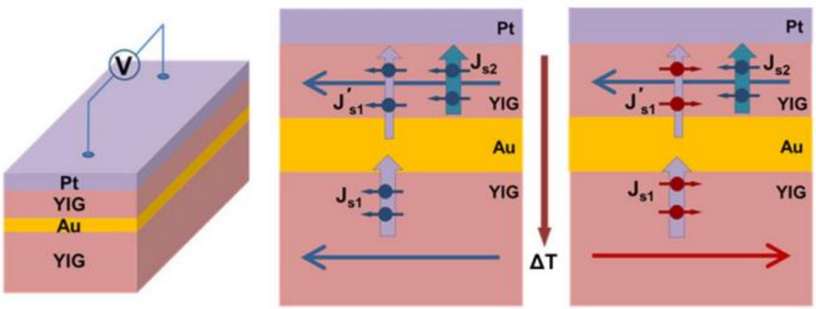
Contents

② In-Plane Magnon Valve Effect in Magnetic Insulator/Heavy Metal/ Magnetic Insulator Device - Background

Motivation:

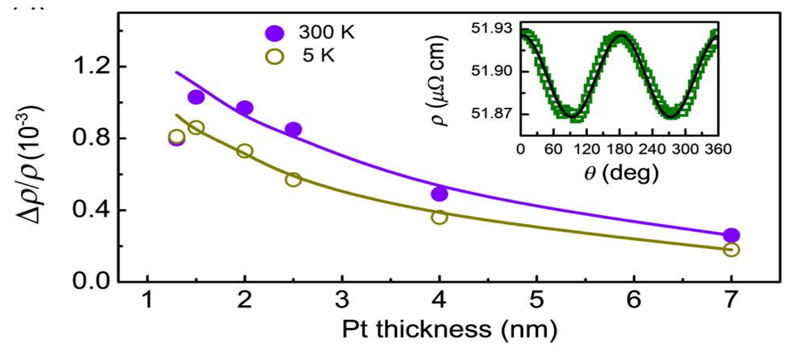
Use magnon valve as a magnetic sensor.

Magnon valve



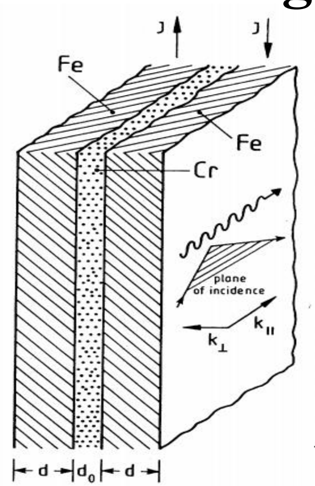
Wu, et al. PRL, 120, 097205 (2018)

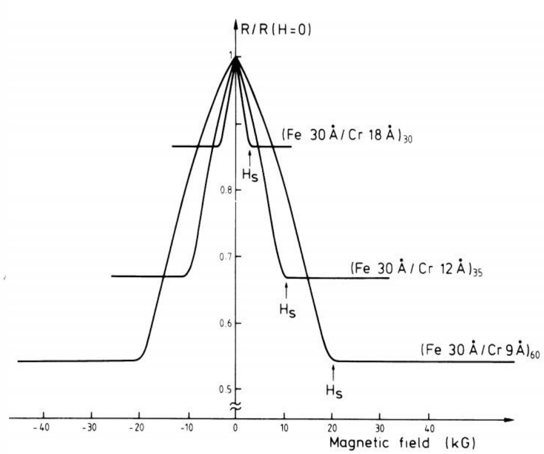
Magnetic proximity effect



Lu, et al. PRL 110, 147207 (2013)

Giant Magnetoresistance effect





Binasch, et al. PRB, 39, 4828 (1989)
Baibich, et al. PRL, 61, 2472 (1988)

Advantages:

1. Low coercive force (~ 1 Oe), high sensitivity.
2. Wide intrinsic frequency range (GHz to THz) of YIG, improved high requency response.

Method

Coherent potential approximation

Hamiltonian of the Pt layer electronic system:

$$\hat{H} = \sum_{s,i} \varepsilon_{is} \hat{a}_{is}^{\dagger} \hat{a}_{is} + \sum_{s,<i,j>} t_{ijs} \hat{a}_{is}^{\dagger} \hat{a}_{js}$$

The on-site energy at the n-th layer ε_{ns} takes values ε_{ns}^{m} and ε_{ns}^{unm} with probabilities x_n and $y_n = 1 - x_n$ respectively.

The conductance of Pt

$$\sigma_{xx}^{MPE} = \sum_{m,n,s} \gamma_{m,n,s} \frac{\tau_{m,n,s}}{\Delta_{n,s} + \Delta_{m,s}}$$

Two key parameters that influence the conductance

ΔU: Difference of Coulomb interaction between magnetized and non-magnetized Pt atom.

$\Delta\varepsilon$: Difference of nuclear potential energy between magnetized and non-magnetized Pt atom

Results and Conclusion

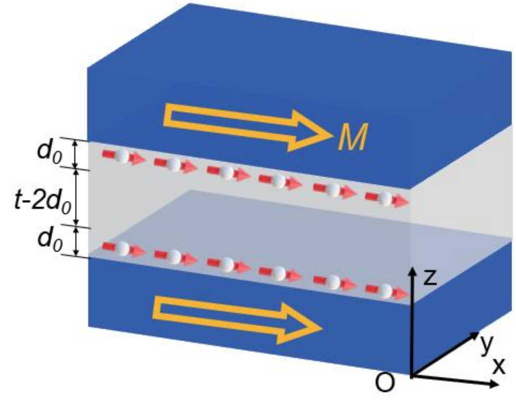
Parameter

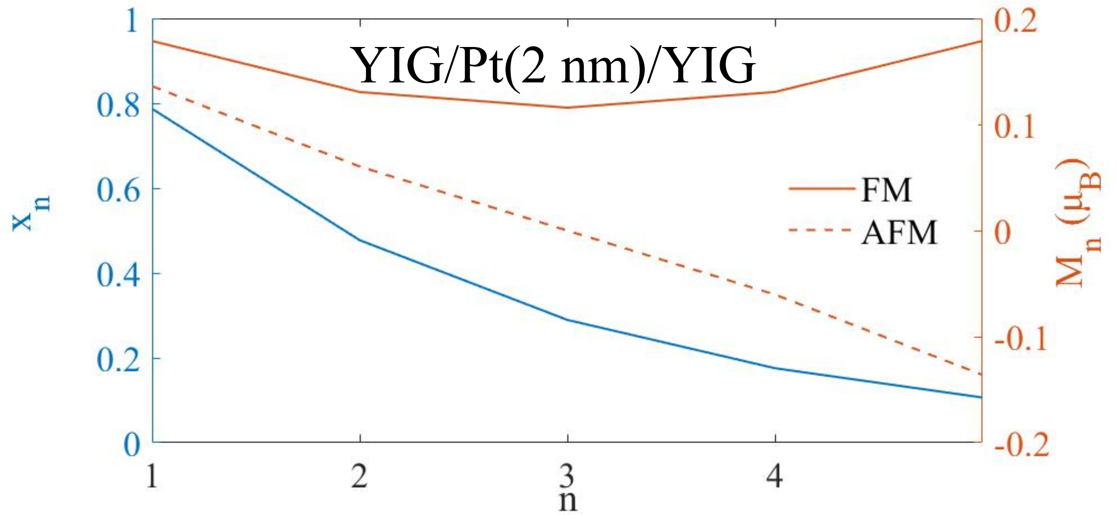
TABLE I. Parameters of YIG/Pt/YIG used in the simulation.

Parameters	Symbol	Value
Magnetized atoms' magnetic moment	μ_0	$0.2\mu_B$ [21, 22, 41]
Characteristic length of the MPE	d_0	0.4 nm [21]
Gilbert damping constant of YIG	α	0.001 [28]
Electrons and magnons coupling	η	8 [29]
On-site energy of YIG	ε_i	1 eV [9, 30, 31]
Nearest neighbor transition energy	t_{ij}	-0.4 eV [9, 30, 31]
Spin Hall angle of Pt	θ_{SH}	0.01 [32]
Conductivity of Pt	σ	$10^7\ \Omega^{-1}m^{-1}$ [33]
Spin diffusion length of Pt	λ_{sd}	1.5 nm [34]
Length of Pt	l	100 μ m
Width of Pt	w	10 μ m
Thickness of Pt	t	2 nm
Real part of spin mixing conductance	G_r	$10^{15}\ \Omega^{-1}m^{-2}$ [35]

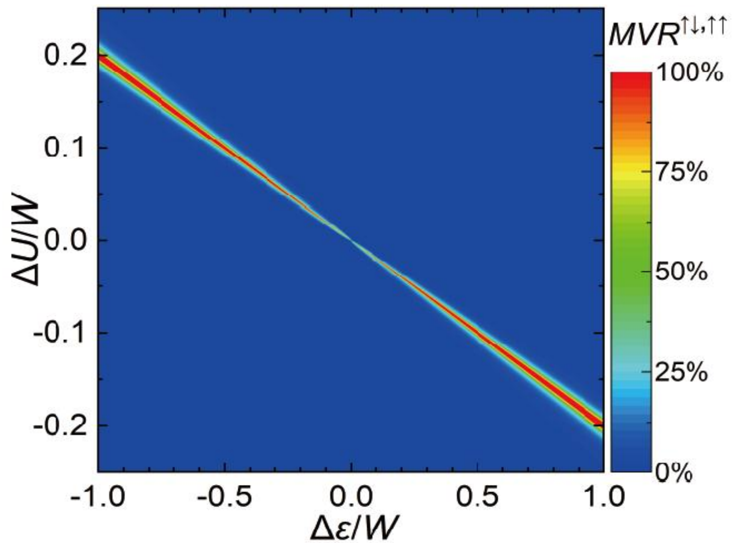
Results and Conclusion

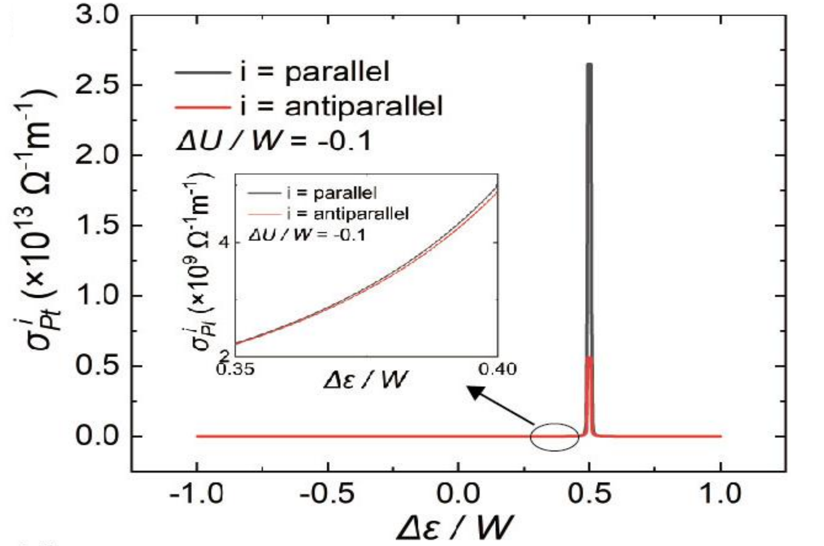
The distribution of magnetized atomic propotion and magnetic moments in each sublayer:





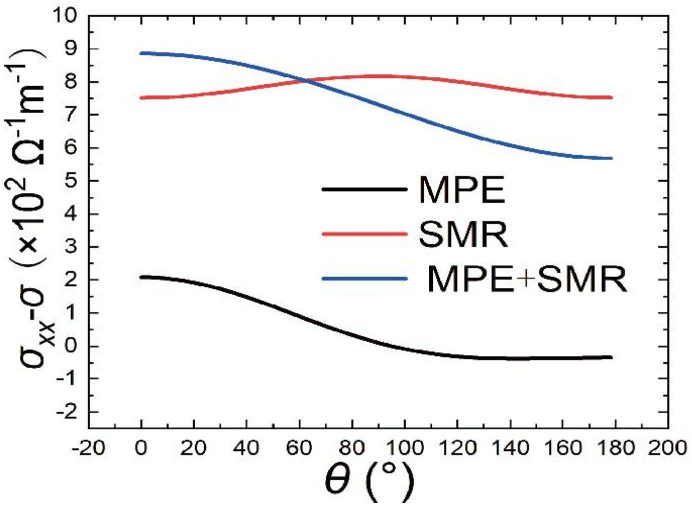
Magnon valve ratio $MVR^{\uparrow\uparrow,\uparrow\downarrow} \equiv \left(\sigma_{xx,\uparrow\uparrow} - \sigma_{xx,\uparrow\downarrow}\right) / \sigma_{xx,\uparrow\uparrow}$

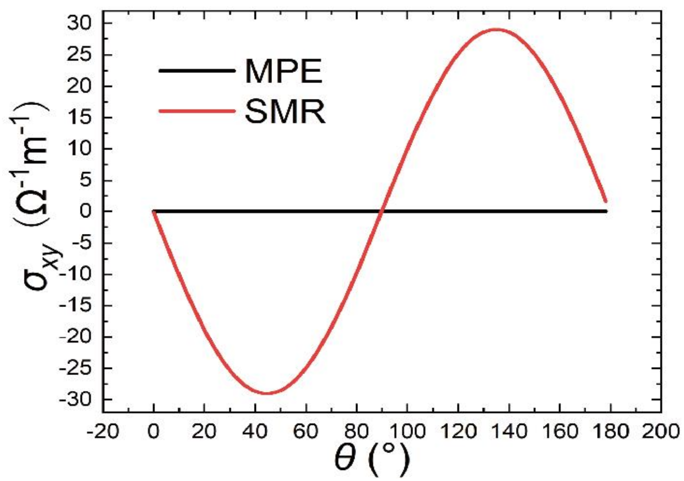




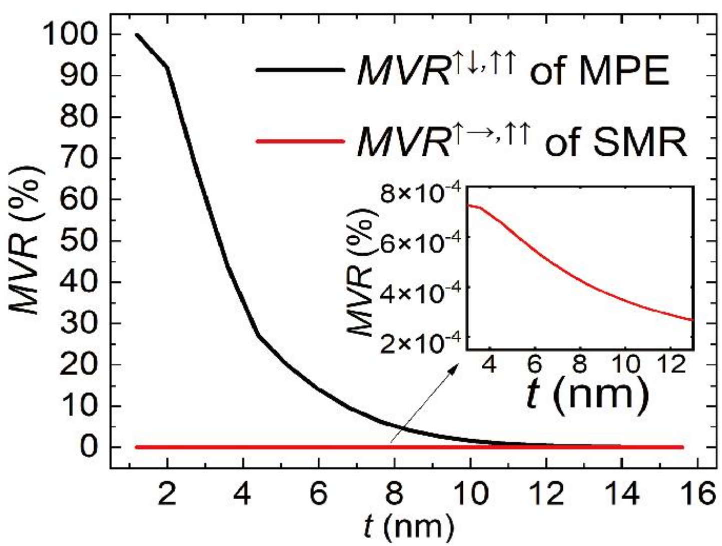
Results and Conclusion

The influence of spin Hall magnetoresistance(**SMR**)





The dependence of magnon valve ratio on the thickness of Pt layer



As t increases, the MVR exhibits an exponential decay.

Summary and perspective

- Based on the second quantization and non-equilibrium Green's function method, we propose a framework for calculating the transport of magnon currents in bipartite magnetic insulators and magnonic junctions [1].
- Based on the magnetic proximity effect (MPE), we propose a theory of magnetic sensing in magnetic insulator heterostructures [2].
- The external layer of magnon valve need to be magnetic insulator, such as **YIG**, **GdIG**, **TmIG**, middle layer needs to have the MPE, and the materials currently reported to both be conductive and have the MPE are such as **Pt**, **graphene**, **WSe_2.**

[1] **Tianyi Zhang** and Xiufeng Han, Phys. Rev. B **108**, 104421 (2023).
[2] **Tianyi Zhang** , Caihua Wan and Xiufeng Han, arXiv:2312.17413 (2024).

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