Laser-induced Femtosecond Spin Dynamics in Metallic Multilayers

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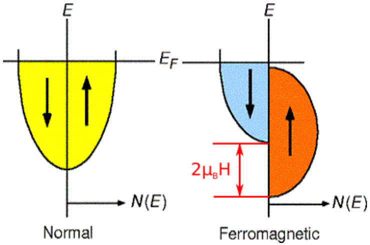
Spin-polarization in Fe

- energy spin splitting of valence band (different energies for *spin up* and *spin down*)
- therefore spin polarization ($N^{up} \neq N^{down}$)
- macroscopic magnetization due to spin polarization:

$$M = \mu_B \cdot (N^{up} - N^{down})$$

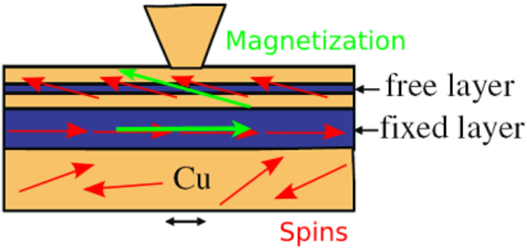
where $N^{up} - N^{down} \propto 2\mu_B H$



G.A. Prinz, Science 282 (1998) 1160

Spin-transfer by current

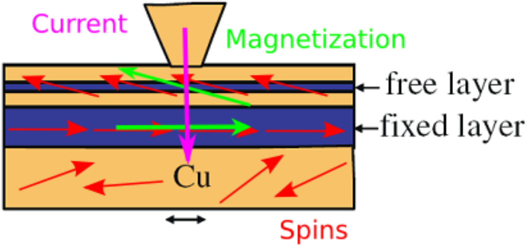
(Ralph, Stiles, JMMM 320 1190 (2008))



1. magnetization $\overrightarrow{M}$ in free and fixed layer is non-parallel

Spin-transfer by current

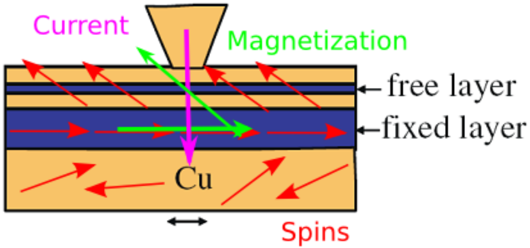
(Ralph, Stiles, JMMM 320 1190 (2008))



2. apply an external bias to induce a current from the bottom Cu-layer; the current is spin-polarized by the fixed layer

Spin-transfer by current

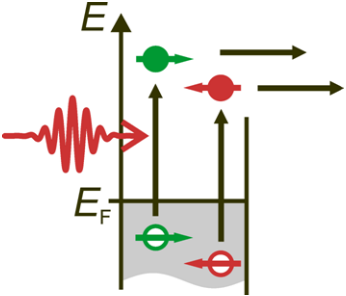
(Ralph, Stiles, JMMM 320 1190 (2008))



3. the spin-polarized current changes $\overrightarrow{M}$ in the free layer thus exerts a

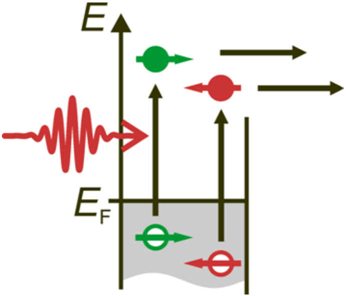
spin torque

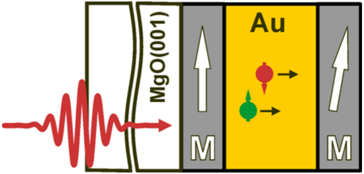
Spin-transfer by hot electrons



- a femtosecond laser can excite spin-polarized electrons as hot carriers

Spin-transfer by hot electrons

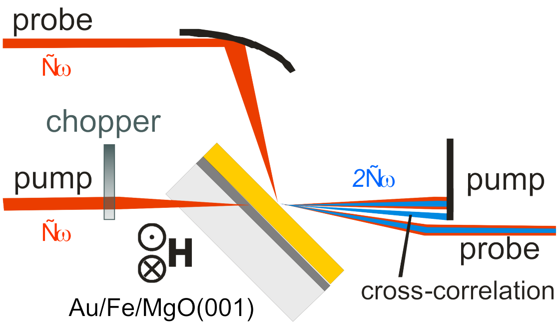




- a femtosecond laser can excite spin-polarized electrons as hot carriers

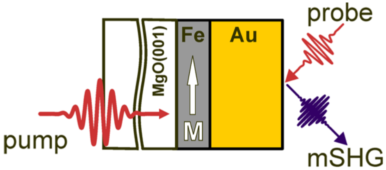
- so, can these spin-polarized hot electrons generate spin-transfer torque?

Optical pump-probe scheme

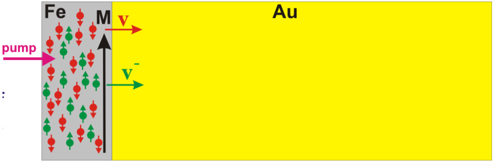


- cavity-dumped Ti:Sa oscillator, repitition rate: 76 MHz
- pulse-length: $\tau = 35$ fs
- energy: $E \approx 1.5$ eV $\rightarrow Flux \approx 1 \ \frac{\text{mJ}}{\text{cm}^2}$
- dumping rate: 1.5 MHz

Geometry of first samples
(MgO(100)/Fe/Au):



Time lapse of electron/spin-transport:
(ballistic vs. diffusive):



optical excitation of hot-carriers @ 0 fs

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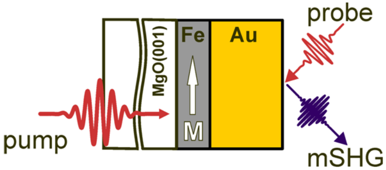

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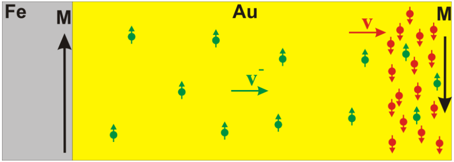

ballistic transport of minority carriers to surface @ 40 fs

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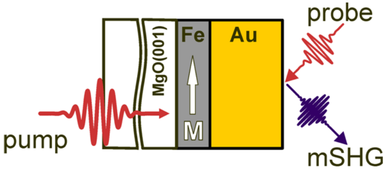

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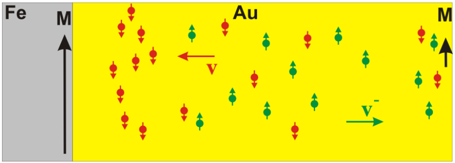

minority carriers are back-scattered at surface @ 150 fs

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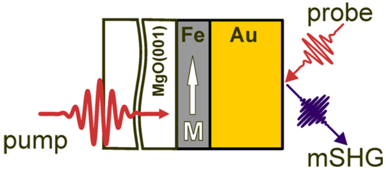

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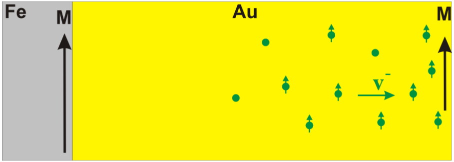

majority carriers reach surface diffusively @ 400 fs

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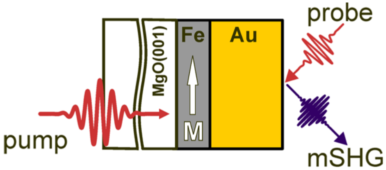

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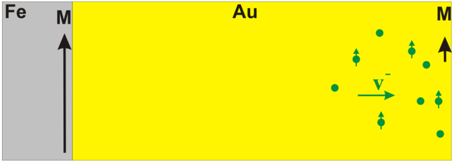

spin-disordering, thus magnetization relaxes @ 1000 fs

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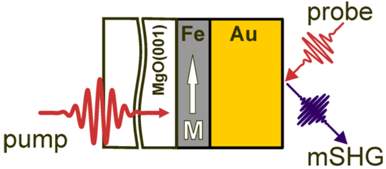

Electric field:

$$\overrightarrow{E}_{2\omega} = \overrightarrow{E}^{\,\text{even}}_{2\omega} + \overrightarrow{E}^{\,\text{odd}}_{2\omega} = \overrightarrow{\beta} + \overrightarrow{\alpha} M$$

Intensity (measured signal):

$$I^{\uparrow\downarrow}_{2\omega} \propto |\overrightarrow{E}^{\,\text{even}}_{2\omega} + \overrightarrow{E}^{\,\text{odd}}_{2\omega}|^2 = |\overrightarrow{E}^{\,\text{even}}_{2\omega}|^2 \pm 2|\overrightarrow{E}^{\,\text{even}}_{2\omega}\overrightarrow{E}^{\,\text{odd}}_{2\omega}|$$

* *the sign of the cross-term depends on direction of* $\overrightarrow{B}$

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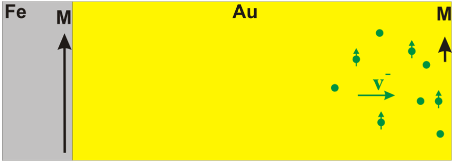

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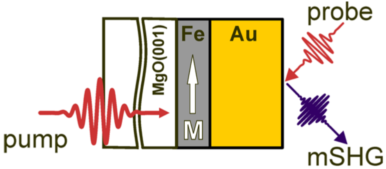

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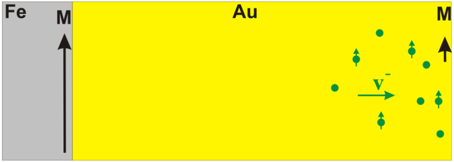

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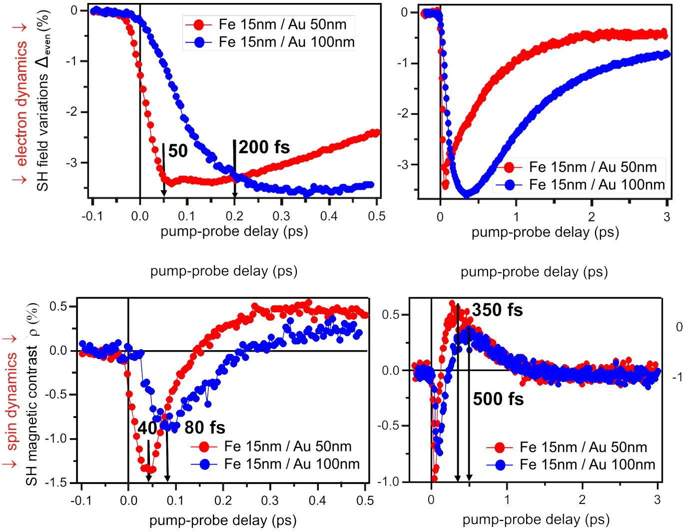
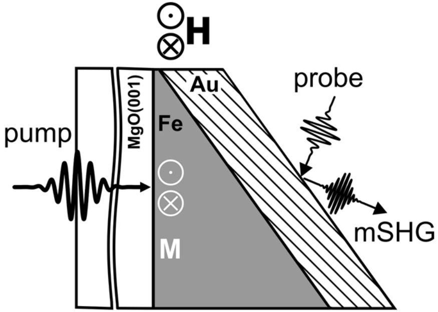
We are interested in relative quantities:

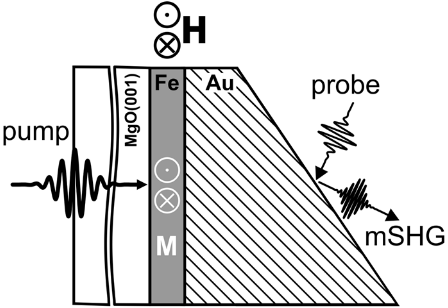
- $\Delta_{even} \approx \frac{E^{even}(t)}{E_0^{even}} - 1$
- $\Delta_{odd} \approx \frac{E^{odd}(t)}{E_0^{odd}} - 1 \approx \frac{\Delta M(t)}{M_0}$
- $\rho(t) \approx 2\frac{E_{odd}(t)}{E_{even}(t)} \propto M(t)$

Measured data

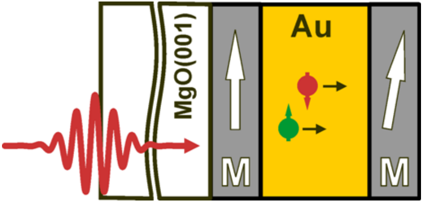




- to find the optimal thickness for the iron layer, we grow an iron wedge then scan along the wedge laterally
- optimal thickness lies between light penetration depth and ballistic length of the hot electrons



- grow a wedge analog to the iron wedge to find the proper thickness which suits both the ballistic mean free path of the electrons and the spin conservation length best



- Final Goal: After having determined optimal thicknesses for Fe and Au, grow a second Fe-layer onto Au with a free/different magnetization
- electrons from the first Fe-layer can now change magnetization in the second Fe-layer

Summary and Conclusion

- spin polarization occurs in ferromagnets due to band energy-splitting
- magnetization in thin films can be changed by direct spin-transfer with spin-polarized electrons
- spin-polarized carriers can be excited as hot carriers with a femtosecond laser
- minority carriers have higher velocities than majority carriers
- minority transport is mainly ballistically, majority mainly diffusively
- Final Goal: Spin transfer requires knowledge about optimal thicknesses for Fe/Au/Fe system

I would like to thank my working group and the DFG for funding our project.


Thank you for your attention !