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MACALO

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Deliverable D4.3) THERM-3: Report on design and validation of magnetoelectronic circuit architecture relying on spin waves and spin diffusion. [Month 36]

1. Introduction and previous work

Circuit theory is an efficient method to analyze, understand and compute the input-output characteristics of complex electronic circuits. The basic physics consists of linear response (Ohm's Law) and charge conservation (Kirchhoff Rules). More than a decade ago we developed a first-principles circuit theory for magnetoelectronic devices [a] that stood the test of time [b]. This circuit theory has been extended to include dynamic properties by taking into account spin pumping and spin transfer torques [b]. A magnetocaloritronic circuit theory designed for spin-dependent thermoelectric effects and thermal spin transfer torques has been developed for the EU project DYNAMAX [c]. Implicit in the older versions of circuit theory was the macrospin approximation, in which the magnetization was a sink for the transverse spin currents absorbed at the interface while the resulting torques were treated parametrically in the associated LLG equations for the macrospin. In the normal metal spacers the spin accumulation may be assumed constant in perpendicular spin valves in which the spacer is thinner than the spin-flip diffusion length.

In the present deliverable, we describe how the MACALO consortium extended the simple circuit theory during the project period in order to take into account spin waves, dynamic spin diffusion, and spin Seebeck effect. The theory is validated by computing the characteristics of a new device, a spin Seebeck power generator based on the spin valve effect.

2. Contributions of MACALO work package THERM to circuit theory

Dynamic spin diffusion: The dynamics of spin diffusion in a metal in contact with a ferromagnet under FMR conditions has been derived by the MACALO post doc H. Jiao, who showed that it gives rise to an ac inverse spin Hall effect that can be orders of magnitude larger than that the dc inverse spin Hall effect [c]. Our theoretical predictions have recently been experimentally confirmed [e].

Spin waves: The effects of spin pumping induced by spin waves, including the complications induced by the magnetic dipolar interaction has been discussed by Kapelrud and Brataas [f] finding that the surface waves are strongly affected, in agreement with experiments [g]. The spin Hall current-induced dynamics of a ferromagnet with finite spin wave stiffness and surface anisotropy has been calculated by Jiang and Bauer without [h] and by Zhou et al. including spin pumping [i]. Here we encounter difficulties to explain experiments by Kajiwara et al. [j]. The final word has not been spoken, since these experiments have not yet been reproduced either. We also used circuit theory to propose and analyze a spin torque transistor [k] that communicates by spin waves.

3. Validation of circuit theory with spin waves and spin diffusion

We validate the theory by using it for a newly proposed device, viz. a spin Seebeck power generator operating by spin valve spin-charge conversion as sketched in Fig. 1 [l]. We use our extended circuit theory to estimate an upper bound for the figure of merit ZT that deviates from that in conventional thermoelectrics because of the entirely different physical principles behind the Seebeck and spin Seebeck effect [n,m].

The efficiency of a thermodynamic power generator η is defined as the ratio between the maximal useful work output W and the heat current input Q. The former can be measured in terms of the energy dissipated in a load resistor R that is impedance-matched to the generator. The maximum efficiency of any thermodynamic machine is the Carnot efficiency:

$$\eta_c = \frac{T_H - T_L}{T_H}. \quad (1)$$

We can compute the efficiency of the machine in Fig. 1 by circuit theory analytically with some simplifying assumption. We assume that the heat current is limited by the FI|NM interface heat (Kapitza) conductance K, disregard any spin-flip in NM, while the spin Seebeck coefficient has been derived by Xiao *et al*. [l]. The transport through the NM|FM interface is parameterized by the interface conductance $G_F^{(I)}$ and its polarization P that includes the effect of the magnetically active part of the bulk material. Another parameter is the spin Seebeck conductance G_S that relates the spin current flowing back into the FI when a spin accumulation is present [o]. This allows formulating the spin current conservation or Kirchhoff rule in NM [a], the total charge current through the circuit, and the efficiency as defined above.

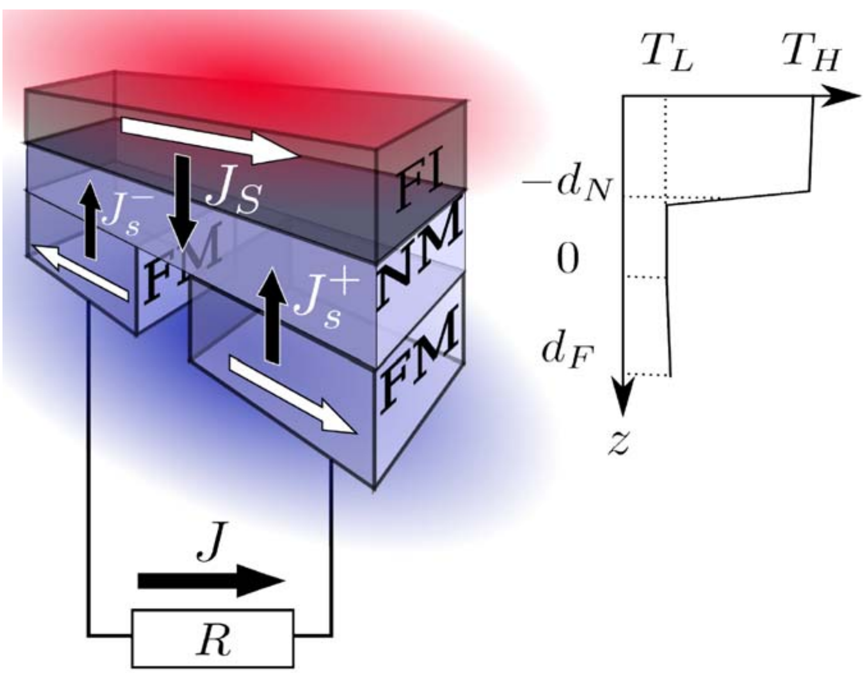

Figure 1: *Schematics of the spin Seebeck power generator[k]. A temperature difference over the device is assumed to fall at the interface between a ferromagnetic insulator(FI) and a normal metal film (NM) with spin flip dissipation length much larger than the film thickness d_N. On the cold side, two metallic ferromagnetic contacts transform the spin accumulation injected thermally into NM into an electric current J that flows through a load resistance R.*

The circuit theory thus allows us to compute the charge current through R and the efficiency can be expressed as

$$\eta = \eta_c \frac{\sqrt{1+Z\overline{\overline{T}}}-1}{\sqrt{1+Z\overline{\overline{T}}}+1}, \quad (2)$$

where the spin Seebeck figure of merit reads in the limit of $P \to 1$:

$$Z\overline{T} = \frac{S_S^2 \overline{T}}{K\left(G_S^{-1} + \left(G_F^{(I)}\right)^{-1} / 2\right)}. \tag{3}$$

In Fig. 2 we plot the figure of merit as a function of the key parameters of the device.

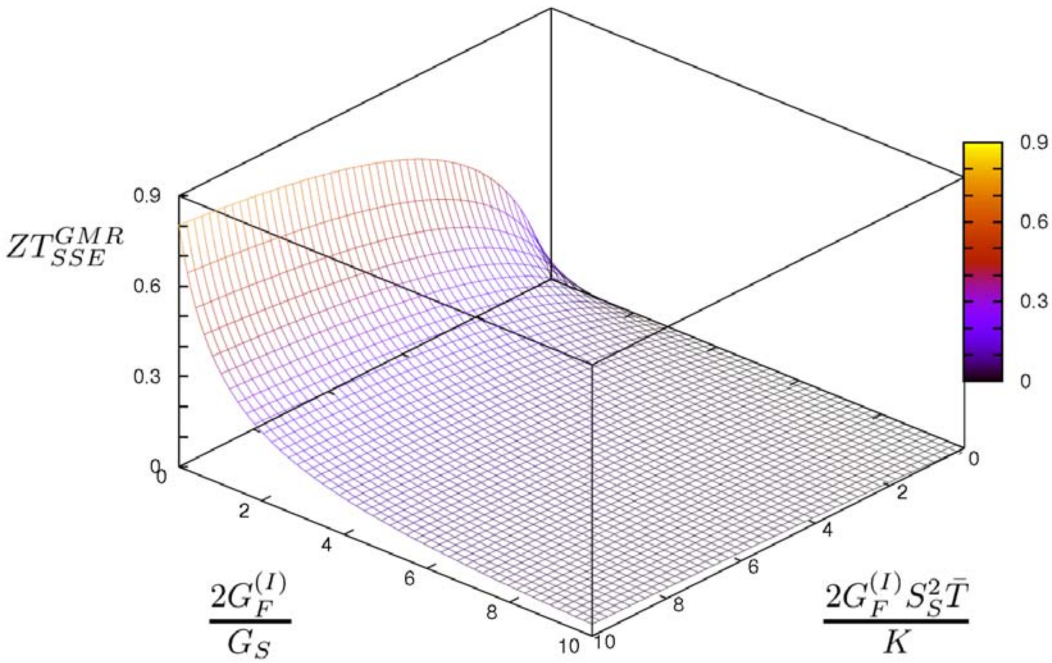

Figure 2: *Figure of merit of the spin Seebeck generator of Fig. 1 as a function of the key parameters.*

4. Summary

We have shown that circuit theory can be extended to include the effects of spin waves and spin currents in ferromagnetic insulators and dynamic spin diffusion in normal metals. It can thereby be employed to compute the characteristics of hybrid structures and devices that include magnetic insulators. This theory has been employed to obtain simple analytic results that can be used to predict parametric dependences and to prepare the ground for more accurate simulation packages for magnetocaloritronics that are being developed for MACALO, thereby meeting the deliverable objectives.

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