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Published in:
Applied Physics Letters

DOI:
10.1063/1.3673908

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2012

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Local electrical characterization of resonant magnetization motion in a single ferromagnetic sub-micrometer particle in lateral geometry

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(Received 10 October 2011; accepted 9 December 2011; published online 5 January 2012)

In this article, a detailed characterization of a magnetization motion in a single sub-micrometer and multi-terminal ferromagnetic structure in lateral geometry is performed in a GHz regime using direct DC characterization technique. We have shown applicability of the Stoner-Wohlfarth model \cite{10.1063/1.1850233} to the long (large length to width ratio) magnetic nano-structure. Applying the model to experimental data, we are able to extract relevant magnetization motion parameters and show a correlation between high frequency inductive currents and local magnetization. DC voltage generated over the structure at the resonance, with external magnetic field under an angle to the shape anisotropy axis, is explained. \textcopyright 2012 American Institute of Physics. [doi:10.1063/1.3673908]

Multi-terminal ferromagnetic nanostructures are widely used in spintronics.\textsuperscript{1-3} Recent developments in the field\textsuperscript{4-6} brought enhanced interest to the topic, specially in combination with ultrafast magnetization dynamics.\textsuperscript{7} Proper inside into magnetization dynamics of an individual nanostructure is a challenging task.\textsuperscript{8} Most of the work in this direction is being done on relatively large structures,\textsuperscript{9} arrays of structures,\textsuperscript{10} by interpreting magnetization switching events,\textsuperscript{6} or by dynamic response to the magnetization motion.\textsuperscript{11} This methods are mostly limited to two terminal measurements.

The sample is prepared by means of electron beam lithography and lift-off. Scanning electron microscopy (SEM) image of the sample is shown in a Fig. 1(a). The sample consists of a ferromagnetic 3 \mu m long and 20 nm thick permalloy (Ni_{80}Fe_{20}) strip, contacted by eight 50 nm thick copper contacts. Width of the strip and the contacts is 100 nm. The strip is placed on 1 \mu m distance from a 150 nm thick and 1 \mu m wide golden coplanar waveguide. In order to ensure good electrical contacts and uniform magnetization, the permalloy strip and the copper contacts are fabricated by two steps of electron beam evaporation under 70° angle to the sample plane and along corresponding lines, without breaking vacuum.

The measurement technique is depicted in a Fig. 1(b). Coplanar waveguide is used to apply normal to the substrate radio frequency (RF) magnetic field to the permalloy strip. At the resonance, when the RF frequency matches Larmor precession frequency, the field induces Larmor precession of the strip magnetization around the static effective magnetic field ($\mathbf{B}_{\text{eff}}$). $\mathbf{B}_{\text{eff}}$ determining Larmor precession frequency is a vector sum of an applied external field ($\mathbf{B}_{\text{ext}}$) and a constant shape anisotropy field ($\mathbf{B}_{\text{an}}$) pointing along the strips longest (easy) axis. At the resonance, the angle of the magnetization precession is drastically increased and damped (no precession) otherwise.

In presented experiments, outer contacts to the strip are used as DC current probes and the inner contacts as voltage probes. Zero magnetic field resistance in this configuration found to be $R_0 = 121.5 \, \Omega$; this value is consistent with bulk material properties. By fitting anisotropic magnetoresistance\textsuperscript{13} (AMR) in the case of $\mathbf{B}_{\text{ext}}$ perpendicular to $\mathbf{B}_{\text{an}}$, values of $B_{\text{an}} = 0.137 \, \text{mT}$ and $\Delta R = 2.1 \, \Omega$ are extracted.

In Fig. 2(a), RF induced change of the resistance (red line) and change in DC voltage (black line) as a function of $\mathbf{B}_{\text{ext}}$, applied along the strip are shown. The measurements are done at fixed RF frequency while external magnetic field is scanned from negative to positive direction. Magnetization motion

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The training procedure is used to ensure monodomain state of the magnetization in the strip. Magnetization switching event is shown by a dashed (vertical) line. RF signal is (on, off) modulated at 17 Hz and DC current is alternated between $C_0$, 0 mA, and $\pm 0.1$ mA every 10 s. Offset in the resistance and voltage is subtracted, and the curves are shifted for clarity, by 20 m$\Omega$ and 6.7 $\mu$V, respectively.

The measurements at external magnetic field applied under $31^\circ$ to the strip easy axis are shown in Fig. 2(b). Most pronounced difference in this configuration from the previous plot is that the resonance can be observed as a deep in the voltage measurements indicated by black lines. Although, similar results have been observed previously, a systematic analysis over wide range of RF frequencies and a Stoner-Wohlfarth particle model to explain the observed dependences.

In Fig. 2(c), the $31^\circ$ angle data are zoomed in the frequency range from 8 GHz till 11.5 GHz and the field range from $-100$ mT till 100 mT. Resonance in magnetization motion is preserved over zero external magnetic field and defined by the shape anisotropy field. The voltage at the resonance is changing from a deep for negative external magnetic fields, to a peek for positive external magnetic fields, just before the magnetization switching.

To describe the observed results, when external magnetic field is applied under an angle $\beta$ to the easy axis of the ferromagnetic strip, we calculate expected angle between the axis and the magnetization $Q$ by solving the following equation: $(H_{\text{an}}/2)\sin(2Q) + H_{\text{ex}}\sin(Q - \beta) = 0$.

We extract center of each resonance and full width at half maximum (FWHM) by fitting observed resonances in the magnetoresistance curves with Lorentzian. RF frequency $F$ of the resonants is shown in Fig. 3(a). The data below 12 GHz are extracted from Fig. 2(c). Frequency dependence of the resonance position is well fitted with Kiel’s equation for small precession angles: $F = \gamma H_{\text{eff}}(H_{\text{eff}} + M_s)$, where $\mu_0$ is a permeability of a vacuum, $\gamma$ is the gyromagnetic ratio, and $M_s$ is a saturation magnetization.

Despite slight ellipticity expected in the magnetization motion, excellent agreement between fitting and the extracted data is achieved with $\gamma = 193.39$ GHz/T and $M_s = 969 000$ A/m, the fitting is shown in Fig. 3(a) by lines. During magnetization, switching 5 mT of the shape anisotropy field is pinned due to sample imperfection.

Average precession angle at the resonance $L$ extracted from the data using AMR resistance change and is shown in Fig. 3(b). Solving transverse RF field $H_{\text{y}}$ driven Landau-Lifschitz-Gilbert equation, we find that the precession angle $L$ at a resonance is inversely proportional to the RF frequency $\omega$: $L = \lambda/\omega$, where $\lambda = \mu_0 \gamma^2 M_s H_{\text{y}} = 6.95 \times 10^8$ Hz$^2$ and the dimensionless Gilbert damping parameter $\alpha = \lambda/(\mu_0 M_s \gamma) = 0.0104$ similar to the value observed previously. Calculated value of $L$ at $31^\circ$ is shown by continuous line and the value at $0^\circ$ by dashed line. Although, the

FIG. 2. (Color online) RF frequency dependence of resistance (lighter curve) and voltage (darker curve) versus external magnetic field. (a) Field is parallel to the ferromagnetic strip. (b) and (c) Field is under $31^\circ$ to the strip easy axis.

FIG. 3. (Color online) External magnetic field dependence of experimental (squares – $0^\circ$ and triangles – $31^\circ$) and calculated (lines) parameters. (a) Resonance RF frequency. (b) Average angle of the precession $L$ at the resonance. (c) DC voltage generated over the strip at the resonance.
measured values are scattered around the calculated lines, smearing separation between angular dependence, it is obvious that the general magnetic field dependence is well preserved.

At positive fields, just before the magnetization switching event, the average precession angle \( L \) is saturated, contrary to expected strong increase. The saturation could be explained by deviation of the magnetization motion from the Stoner-Wohlfarth particle model.

To determine Gilbert damping parameter, we use known\(^{19}\) frequency dependence of FWHM

\[
\Delta H_{\text{FWHM}}(\omega) = \Delta H_{\text{inhom}} + \frac{2}{\sqrt{3}v} M_s \coth(\omega
\]

where \( \Delta H_{\text{FWHM}}(\omega) \) is a frequency dependent value of FWHM extracted from Lorentzian fit, and \( \Delta H_{\text{inhom}} \) is a frequency independent inhomogeneous broadening due to local magnetization variations. Frequency independent (within experimental error) value of \( \Delta H_{\text{FWHM}}(\omega) \approx 16 \text{mT} \pm 2 \text{mT} \) at negative magnetic fields (before the switching) and \( \Delta H_{\text{FWHM}}(\omega) \approx 21 \text{mT} \pm 2 \text{mT} \) at positive fields (after the switching) is an indication of dominating contribution of \( \Delta H_{\text{inhom}} \). Moreover, higher value of the inhomogeneous broadening after the magnetization switching is consistent with an increase in magnetic inhomogeneity by the pinned magnetization.

To understand the generated voltages, we use already described model for the magnetization motion. An inductive current generated through the sample at the resonance is in phase with the magnetization motion; the difference in AMR current caused by magnetization switching. Calculated magnetic field dependence of DC voltage, using current of 140 \( \mu \text{A} \), is shown by lines in Fig. 3(c).

In summary, we investigated a resonant magnetization motion in multi-terminal ferromagnetic sub-micrometer structure using convenient DC measurements technique. DC resistance response of the structure at the resonance, also when the external magnetic field is applied under an angle to the strip easy axis, is explained. DC voltage generated at the resonance under an angle is also well understood. Local magnetization inhomogeneities and magnetization pinning are observed in the measured structure. Using these results, it is now possible to investigate local magnetization dynamics in different parts of a single ferromagnetic particle. Investigations in this direction will be summarized in following publication.

The authors would like to thank to Professor Caspar H. van der Wal for useful discussions as well as NanoNed for financial support.

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