Citation for published version:
Nogaret, A, Stebliy, M, Portal, J-C, Samardak, A, Ognev, A, Beere, H & Ritchie, D 2014, 'Photovoltage spectroscopy of dipolar spin waves in Dy micromagnets', Solid State Phenomena, vol. 215, pp. 400-406. https://doi.org/10.4028/www.scientific.net/SSP.215.400

DOI:
10.4028/www.scientific.net/SSP.215.400

Publication date:
2014

Document Version
Early version, also known as pre-print

Link to publication

Photovoltage Spectroscopy of Dipolar Spin Waves in Dy Micromagnets

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Keywords: Spin wave resonance, Nanomagnetism, Electronic transport in mesoscopic systems

Abstract. We report on a sensitive spectroscopic technique for probing the spin excitations of individual submicron magnets. This technique uses a high mobility two dimensional electron gas (2DEG) confined in a GaAs/AlGaAs heterojunction to pick up the oscillating dipolar magnetic field emanating from the individual spin wave modes of micromagnets fabricated at its surface. We review a range of dynamic phenomena that demonstrate the formation of magnetostatic waves in finger gate arrays, dipolar edge spin waves in bar magnets, vortex hysteresis in magnetic dots and the photovoltage dependence on microwave polarization.

Introduction

On the submicron scale, magnetic ordering becomes increasingly dominated by surface effects and the geometry of the sample. Bar magnets generate inhomogeneous magnetic fields near magnetic poles which are responsible for closure domains and localized spin wave modes [1] while magnetic disks tend to minimize their energy by curling their magnetic moment into vortex structures [2]. At *microwave frequencies*, magnetostatic boundary conditions constrain spin wave modes to the surface of bar magnets. These include Damon-Eshbach modes [3,4,5] that propagate along the edges parallel to the d.c magnetic field whilst dipolar edge spin waves (DESW) propagate along the edges perpendicular to the applied magnetic field [6,7,8]. In magnetic dots, theory [9] and experiments [10] have demonstrated sub-GHz oscillations of vortex cores [11,12]. The coupling of two or more vortex core oscillations in overlapping dots was shown to give rise to waves of vortex core oscillations opening up the new field of vortex magnonics [13,14,15].

Understanding macrospin dynamics at GHz frequencies is primarily motivated by the need for ever denser magnetic memories and ever faster access to information. Secondly, spin waves physics is seen as increasingly relevant to low power electronics as spin waves carry pure spin currents freeing electronics from Joule heating. Dynamic exchange coupling mechanism was shown to pump spin polarized currents in normal metals [16,17] and induce spin accumulation via the spin Seebeck effect [18]. Thirdly, micromagnets may be arrayed to engineer magnonic crystals structures [19,20] and cavities for Bose-Einstein magnon condensates [21].

Traditionally, the dispersion curves of confined spin waves have been measured using Brillouin Light Scattering [1] and Magnetic Force Microscopy [22]. The finite wavelength of light however places a lower limit on the size of individual magnets. This is why sub-micron magnets need to be arrayed which has the drawback of introducing averaging and spurious dipolar coupling. In this paper we review a photovoltage technique that has the sensitivity required to probe spin excitations in individual nanomagnets [23]. This technique picks up the reversal of tiny magnetic moments through the long lived eddy currents they induce in high mobility 2D electron systems.

Organization of the paper

The paper is organized as follows. The first section describes sample preparation and the photovoltage spectroscopy technique. We then report on the magnetization waves of magnetostatically coupled array of ferromagnetic finger gates. We resolve the individual surface modes in magnetic quantum wells located near the polar surfaces. The resonances show pairs of peaks which indicate the lifting of the degeneracy in the frequency of spin wave modes trapped at opposite poles of the magnetic stripe. The frequency splitting gives a direct measurement of the dipolar interaction between confined modes. We discuss Damon-Eshbach modes. Thirdly, we evidence hysteretic phenomena associated with the nucleation of magnetic vortices inside manetic dots; and the dependence of magnetic excitations on the polarization of microwaves.

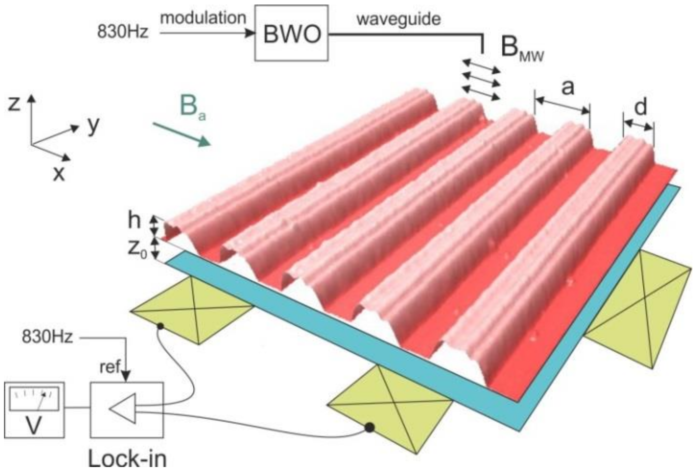

Fig. 1. Ferromagnetic finger gates fabricated on a GaAs/AlGaAs heterojunction. The fingers are magnetized by magnetic field B_a and irradiated by linearly polarized microwaves – magnetic field B_{MW} - supplied by a backward wave oscillator (BWO). Magnetic excitations are detected through the photovoltage they induce in the high mobility 2DEG.

Experimental

Dy micromagnets were fabricated at the surface of 2D electron systems using electron beam lithography [23]. The 2D electron systems were prior obtained by growing GaAs/AlGaAs heterojunctions using the modulation doping technique to achieve electron mobility in excess of $100 m^2.V^{-1}.s^{-1}$ at 4K. The stray magnetic field emanating from Dy threads the 2D electron gas located 30 nm below the GaAs surface with an inhomogeneous magnetic field of amplitude ~100mT [24]. A d.c. magnetic field, B_a, is applied parallel to the GaAs surface to magnetize Dy to saturation. This d.c. field has no effect on ballistic electrons in the 2DEG. The hybrid semiconductor-ferromagnetic structures were studied inside the variable temperature insert (1.3 K-300 K) of a superconducting magnet (15T). Microwaves (30GHz-110GHz) were supplied by a range of backward wave oscillators to the sample via an over-moded waveguide terminated by polarizer. At resonance spin excitations generate an a.c. magnetic field at the site of the 2DEG which is detected via the e.m.f induced between voltage probes (Fig.1). The long lived eddy currents make this detection method extremely sensitive to the reversal of tiny magnetic moments. The electromotive force is estimated as:

$$< e.m.f >_{rms} = -\frac{d\phi}{dt} = N(\omega)\, \omega M_s\, \eta\, (d, h, z_0, A) \qquad (1)$$

where $N(\omega)$ is the photon number density, ω is the microwave angular frequency, M_S is the saturation magnetization and η is the effective area which can be calculated from magnetostatic considerations [24] and which relates the amplitude of the magnetic modulation to M_s. Microwaves are modulated at 830Hz. This frequency is used as the reference of the lock-in amplifier which measures the photovoltage.

Magnetostatic waves

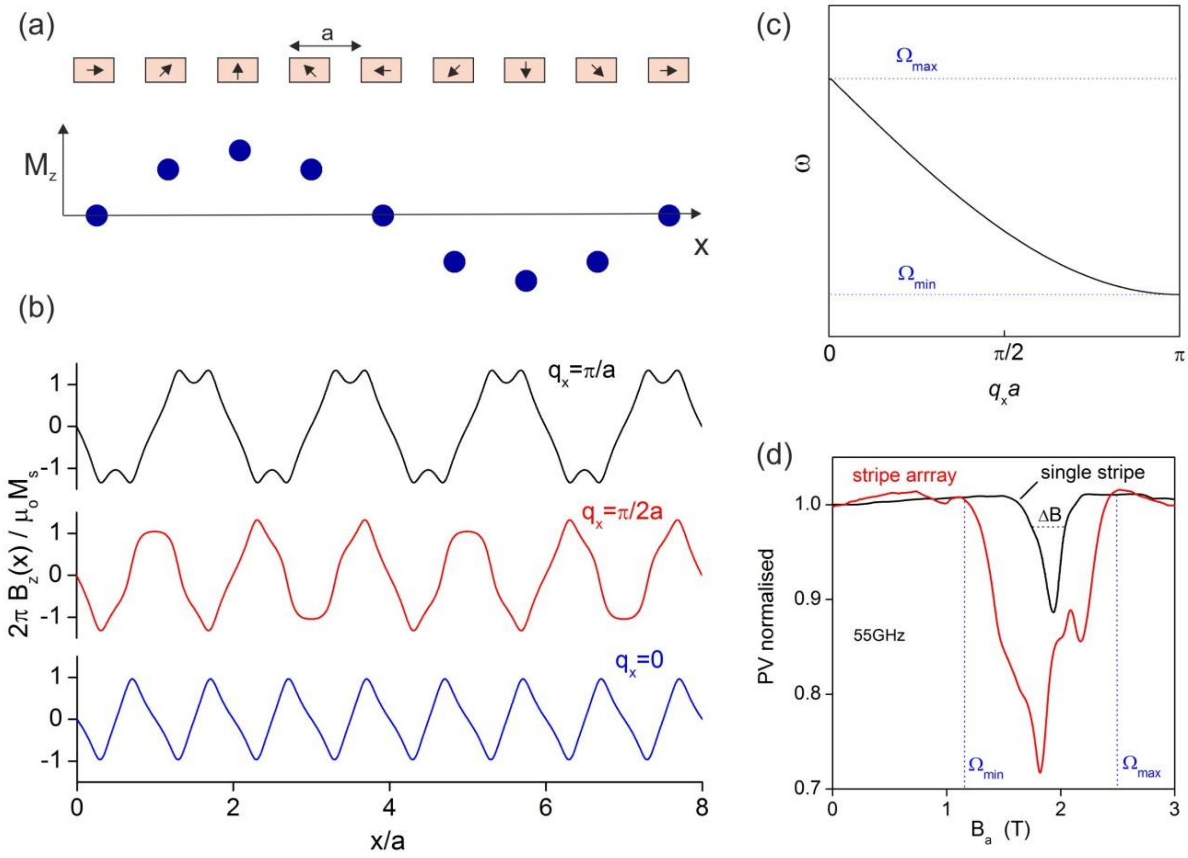

Fig. 2. (a) Magnetostatic waves in a ferromagnetic grating; (b) spatial variation of the amplitude of the ac magnetic field at the site of the 2DEG for 3 values of the wavevector $q_x = 0, \pi/2a, \pi/a$ where a is the grating period; (c) theoretical dispersion curve of magnetostatic waves in the grating; (d) experimental dependence of ferromagnetic resonance detected in the photovoltage of a single Dy finger gate (black) and an array of finger gates (red) with 300nm period.

Arrays of 180nm wide Dy finger gates separated by 120nm were studied. Dipolar interactions broaden spin resonances of individual elements into a band of magnetostatic waves such as the one depicted in Fig.2a. The magnetic modulation amplitudes corresponding to wavevectors $q_x = 0, \pi/2a, \pi/a$ were calculated [24] and plotted in Fig.2b. The dispersion curve of magnetostatic waves is obtained by generalizing Kittel's ferromagnetic resonance formula to finger gate arrays [23]. This is plotted in Fig.2c. The long wavelength excitations ($q_x = 0$) maximize the demagnetizing field inside individual stripes and therefore give the cut-off of ferromagnetic resonance (Ω_{max}). The broadening of ferromagnetic resonance by dipolar interactions is shown in Fig.2d ($\Omega_{max} - \Omega_{min}$). This may be compared with the broadening of ferromagnetic resonance in a single Dy stripes (dominated by anisotropy effects [25-28]). Saraiva et al. [23] have further studied gratings with different gate separations and found that the bandwidth $\Omega_{max} - \Omega_{min}$ increases proportionally to the magnetostatic coupling between stripes demonstrating the formation of a band of magnetostatic waves.

2D edge spin waves

These are 2D spin waves that propagate at the edges of bar magnets. Dipolar edge spin waves [6,7] are localized near the polar surfaces. Their stray field induces 2 pairs of spikes per stripe (Fig.3a). Damon Eshbach waves by contrast produce a modulation field delocalized over the width of the stripes. The Damon Eshbach modulation field (Fig.3b) is smaller than the DESW field.

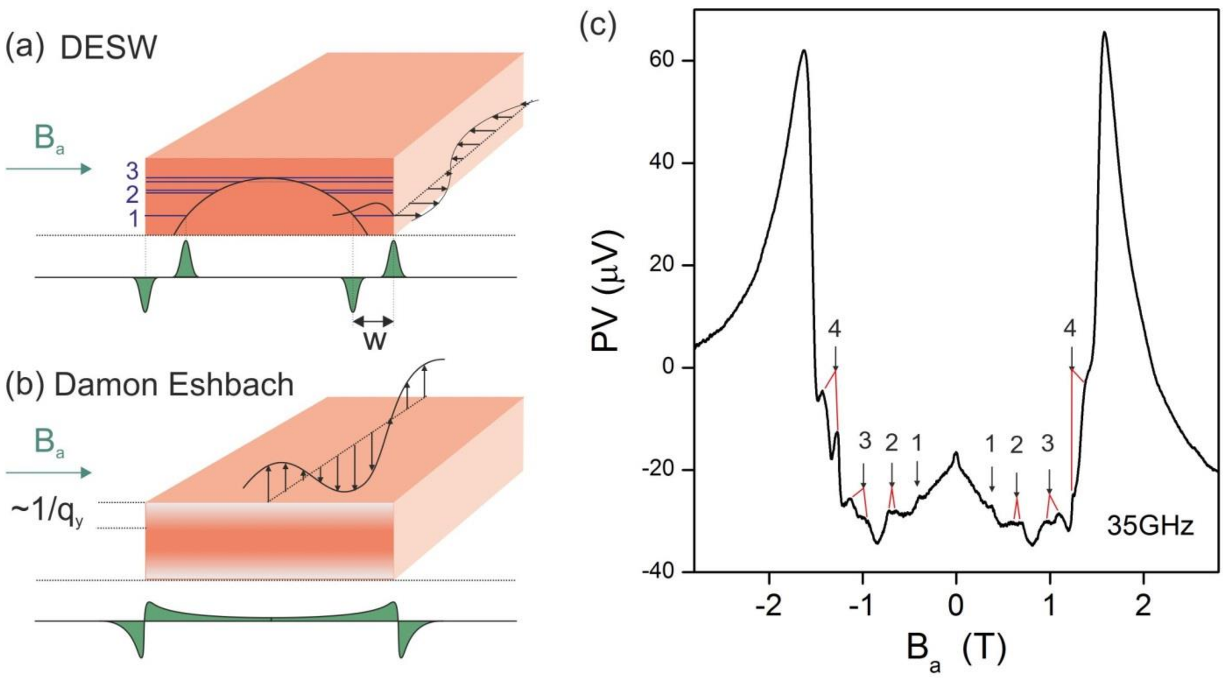

Fig. 3. (a) Dipolar edge spin waves confined in wells of magnetic field near magnetic poles. Spatial profile of the magnetic field induced by DESWs at the site of the 2DEG; (b) Damon-Eshbach spin wave mode and the corresponding magnetic field profile at the site of the 2DEG; (c) Photovoltage of a Dy grating (300nm period) showing discrete DESW modes. The lifting of peak degeneracy presumably corresponds to the increasing hybridization of equivalent modes across the magnetic potential barrier.

Photovoltage measurements on 180nm wide stripes (Fig.3c) show a series of small resonances associated with the quantized DESW modes 1, 2, 3 and 4 of Fig.3a. Resonances 2-4 support a fine structure exhibiting a pair of peaks. This pair splitting was predicted by theoretical calculations [1] but to our knowledge, has never been observed. Here, the magnetic field barrier that separates the two spin wave quantum wells at the poles (Fig.3a) is much thinner than in earlier experiments on wider stripes [1]. This facilitates the hybridization of the degenerate DESW modes into bonding and anti-bonding states separated by a few GHz (Fig.3c). Note that the splitting of the peak increases towards resonance 4 as the hybridization of higher lying states becomes more important.

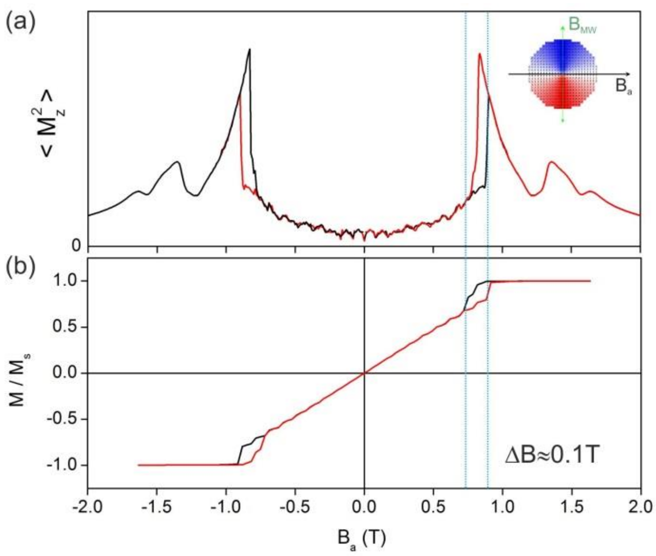

Fig. 4. Hysteretic effects associated with vortex core penetration in a Dy dot (a) ferromagnetic resonance calculated using OOMMF when the magnetic field is swept up/down; (b) simulated magnetization curve.

Damon-Eshbach modes should occur at magnetic fields between the resonance of DESW and volume waves. The data in Fig.3c do not show the signature peaks of Damon-Eshbach waves presumably because the stray magnetic field of Damon-Eshbach waves is much weaker than the DESW field.

Vortex hysteresis in Dy dots

We have also measured ferromagnetic resonance in Dy dots using the same technique. At certain frequencies we observe hysteretic behavior in the photovoltage as the magnetic field is first swept up and then swept down. This behavior has been investigated by simulating the photovoltage curves (Fig,4a) and the magnetization curves (Fig.4b) with OOMMF. The theoretical hysteresis does appear at 0.9T, close to the saturation of the magnetization. The experimental hysteresis is only observed in the photovoltage traces at microwave frequencies of 40-42GHz. This places the ferromagnetic resonance peak at B≈1.5T. Vortex nucleation and annihilation occurs at different magnetic fields [29] and is known to give hysteresis in the magnetization curves near the saturation field. We therefore ascribe the hysteresis in the photovoltage curves to the penetration and release of magnetic vortices. Photovoltage spectroscopy can thus sense vortex dynamics.

Dependence on microwave polarization

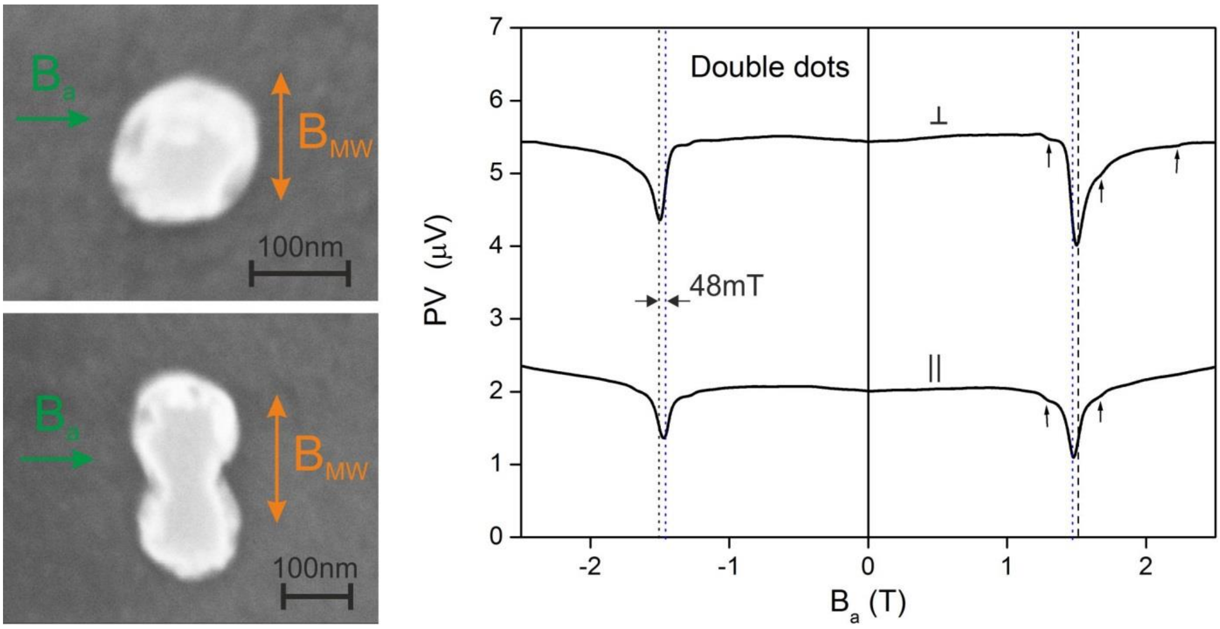

Fig. 5. (a) Dy dot and (b) overlapping dots. (c) Photovoltage spectroscopy of the overlapping dot when the microwave magnetic field is perpendicular to the plane of the 2DEG (⊥) or along the long axis of the double dot (||).

In the next step, we study single and overlapping dots (Figs.5a,b) which are of interest to vortex oscillations [12-15]. The detection of vortex magnetization suggests that photovoltage spectroscopy will be a useful tool for studying vortex magnonics [13]. Finally we are able to demonstrate small effects dependent of microwave polarization. Fig.5c shows the photovoltage traces of overlapping dots when the magnetic field of the microwaves is perpendicular to the GaAs surface (⊥) and in the plane, along the long axis (||). In both cases, B_{MW} is perpendicular to B_a. In the perpendicular configuration, the position of the resonance is 48mT higher and additional resonant structures are seen at higher magnetic field.

Summary

Through the examples presented here, we have shown photovoltage spectroscopy to be a useful technique for probing the magnetic excitations of individual magnets on scales down to 10 nm hence below the spatial resolution of Brillouin Light Scattering (~250 nm). The lower limit to this resolution is set by the minimum size of the Hall bar junction. This corresponds to the width of the depletion region in the case of GaAs/AlGaAs Hall bars (50nm) and the limit of resolution of electron beam lithography (10nm) for Bi Hall bars. The sensitivity of the photovoltage technique has revealed the theoretically predicted fine structure of confined spin waves and is expected to provide further insights into the magnetic properties of individual nanomagnets.

Acknowledgements

This work was supported in part by FP7 IRSES 2012 under grant number 318973.

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