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GMR at THz frequencies in coplanar waveguides

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***Abstract*—Tapered THz coplanar waveguides (CPWs) formed from Co/Cu multilayers with embedded low-temperature-grown gallium arsenide photoconductive switches were designed in order to observe giant magnetoresistance (GMR). Pulsed THz radiation was excited using the switches, and was transmitted through both straight and tapered CPWs. GMR-induced changes in the transmitted THz pulse amplitude were demonstrated.**

I. Introduction and Background

THE discovery of giant magnetoresistance (GMR) revolutionised the computer industry, allowing the extreme scaling of magnetic bit size with the introduction of GMR based nanoscale sensors. Today, as the industry is continuously looking for faster and more efficient solutions, it becomes increasingly relevant to consider how these spin based processes function at higher frequencies which approach or overlap with timescales of fundamental magnetic effects such as the exchange and spin orbit interactions. It is therefore of importance to know how spin based systems behave at THz frequencies.

Anisotropic magnetoresistance (AMR) was measured at THz frequencies by Chau et al. [1] by performing free space THz spectroscopy measurements on dense Co particle ensembles. This type of sample is largely THz transparent due to coherent near field coupling of the surface plasmons. As the THz pulse passes through the medium, it excites localised electron oscillations within the skin depth of the metallic particles. When a magnetic field is applied across such samples parallel to the polarisation of the THz electric field, both an attenuation and time delay in the transmitted pulse was found. However, when the magnetic field is applied perpendicular to the THz electric field polarisation, no significant change was seen. This matches what would be expected from the AMR effect and demonstrates the interplay between surface plasmons and magnetoresistive effects.

GMR multilayers have also been investigated using a free-space THz spectroscopy method [2]. In that experiement, a THz pulse was passed through a thin (5 layers) GMR stack, and the change in pulse amplitude observed as the magnetic field across the multilayer is changed. By looking at the frequency spectra of the transmitted THz pulses, the spin dependent conductivity and electron momentum scattering times are calculated. The majority spin carriers were found to be roughly three times more conductive than the minority carriers.

Coherent magnetisation control has been demonstrated on 10nm films of Co [5]. Intense THz pulses are directed through the sample, and the out of plane magnetisation response is measured using the magneto optical Kerr effect (MOKE) with a femtosecond laser pulse. The magnetisation was found to follow the magnetic field of the THz pulse with a time difference of approximately 50 fs. This response could be understood using the Landau-Liftschitz-Gilbert equation. The magnetic response was found to be dominated by the Larmor frequency and the THz magnetic field, while damping effects had little influence in the time interval measured. In a similar experiment, intense THz pulses were directed through thin nickel [4] sheets. In this case, however, little coherent control was observed, and instead a rapid demagnetisation was recorded. It was proposed that the THz pulse transfers energy via the ponderomotive force, and this heats the nickel film above its Curie temperature (627K). Co has a much higher Curie temperature (1388K) than Ni which may explain why it permits coherent magnetisation control.

In our work, THz pulses are excited on-chip, and coupled directly into CPWs formed from GMR multilayers, which allows subwavelength concentration of the pulse energy. A change in pulse amplitude was measured as a function of magnetic field, which was found to decrease as the resistance of the GMR stack increases. Moreover, a magnetic field dependence of the THz pulse tail was measured and found to vary with time during the duration of the transmitted pulse.

II. Fabrication

Low temperature grown gallium arsenide (LT-GaAs) was epitaxially transferred onto quartz wafers, before being etched into 70 μm squares to be used as photoconductive switch regions. The CPW was then defined using standard lithographic methods. Co/Cu multilayers were grown in an ultra high vacuum sputterer with a base pressure of around 5E-8 Torr at growth rates of approximately 2 Å/s. The Cu thickness used was 10.5 Å to align with the first antiferromagnetic peak [3], and Co thickness of 35 Å to allow for low field saturation. The width of the centre conductor was 30 μm and the gap size was 10 μm. The ratio of centre conductor width to gap size was maintained at 3:1 throughout the tapered region, which was introduced gradually to avoid impedance discontinuities.

III. Results

The DC GMR of the waveguide was measured using IV measurements through the centre conductor of the CPW. The GMR was found to be around 12%. THz pulses were generated and detected using standard pump probe methods, using pairs of switches to determine the mode excited [6] and measuring the current induced by the THz pulse at the detection switch.

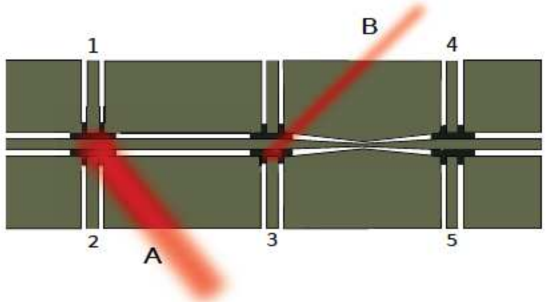

Fig. 1. Schematic of the CPW. Switch pairs (1 and 2 or 4 and 5) were used to determine the mode excited in the CPW. The pump beam (A) was defocused to allow this, while the probe beam (B) was focused on the single detection switch (3).

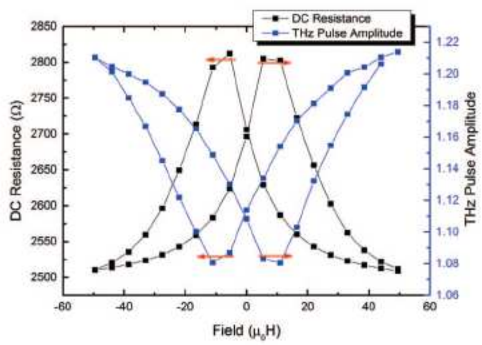

Fig. 2. The DC GMR of the CPW (black points) compared with the THz pulse amplitude change (blue). The THz pulse amplitude shows a minimum that corresponds with the resistance maximum. Red arrows indicate magnetic field sweep direction.

A schematic of the device can is shown in Fig. 1. It was found that the pulse amplitude of a transmitted THz pulse through a tapered CPW (4 and 5 to 3 in Fig. 1) varied by 12% with field as seen in Fig. 2, while the variation in an untapered region was only 6% (1 and 2 to 3 in Fig. 1). This is likely to be due to increased confinement in the tapered region, as verified by HFSS simulations (not shown). In contrast, the (less confined) slotline mode showed no field dependence in both the tapered and untapered regions. This suggests strongly that the pulse attenuation arises as a result of magnetoresistive effects induced in the waveguide.

Field sweeps were also performed at different points after the THz peak position, and the field dependence of the current measured was found to change with time delay after the peak. For a THz pulse transmitted through the entire waveguide (4 and 5 to 2 in Fig. 1) the current induced at the peak position is at a minimum when the magnetic layers are anti-aligned (zone 1 in Fig. 3). This is the high resistance state of the GMR multilayer. However this field dependence rapidly decreases, and several picoseconds after the peak position, the opposite field dependence (term "inverse field dependence" later) is observed (zone 2 in Fig. 3). The reason for the inverse field

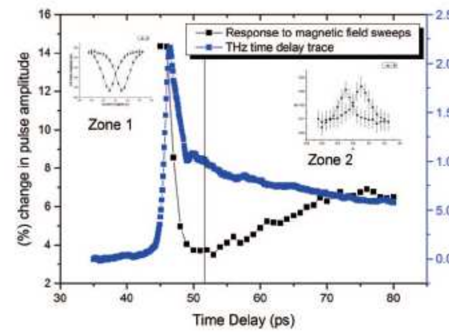

Fig. 3. The THz pulse measured (right axis) and the field dependent change in current (left axis). In zone 1, the measured current is smallest for the high resistance magnetic orientation, and in zone 2 the current is larger for the high resistance orientation. (See insets for functional form of field response)

dependence is not currently understood, though we speculate that it may be caused by interfacial scattering.

Measurements made on the "input" pulse (5 to 4 in Fig. 1) showed negligible field dependence in the rising edge of the THz pulse, however, weak inverse field dependence was noted at the input pulse peak, and this increases in strength picoseconds after the THz peak position. It is likely that the inverse field dependence in the input pulse has the same origin as that observed in the transmitted pulses.

IV. Conclusion

CPWs have been fabricated from GMR multilayers, and tested to show field effects on THz pulse amplitudes. Tapered waveguides showed a stronger field dependence than untapered waveguides, likely owing to increased interaction with the GMR multilayers as the electric field is concentrated in the tapered region. Additionally, field sweeps after the THz pulse peak revealed an inverse magnetic field dependence. This feature is not yet understood.

V. Acknowledgements

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