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Coherent microwave emission from a nanomagnet using magnetic feedback

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Abstract
The magnetization of a nano-magnet can be controlled by spin transfer torque (STT)[1,2]. In particular, a combination of STT and magnetic field can drive a nano-magnet into oscillatory mode. We experimentally demonstrate a magnetic nano-oscillator based on a new mechanism which does not require STT [3]. We used a nano-pillar of magnetic tunnel junction (MTJ) powered by a dc current and connected to a coplanar waveguide (CPW) lying above the free layer of the MTJ. Any fluctuation of the free layer magnetization is converted into oscillating voltage via the tunneling magneto-resistance effect and is fed back into the MTJ by the CPW through inductive coupling. As a result of this feedback, the magnetization of the free layer can be driven into a continual precession. We could obtain high quality factor exceeding 10000 using this mechanism.

1. Introduction

Spin torque nano oscillators (STNOs) have attracted a considerable attention due to potential applications in various radio frequency (RF) devices and ultra-sensitive magnetic field sensors. A lot of research has been carried out to improve the output power and the quality factor of oscillations ($Q = f/\Delta f$) [4,5]. In the case of a oscillator based on magnetic vortex, linewidth (Δf) of 280 kHz resulting in a Q factor of 4000 has been reported [6]. In the case of a MgO-based MTJ oscillator with in-plane magnetization, the maximum Q value reported is 1000 with f = 10 GHz and Δf = 10 MHz [7]. S. Tamaru et al. have demonstrated extremely narrow line widths by developing a phase-lock loop (PLL) circuit designed for an STNO [8]. In this work [9] we demonstrate oscillations, with a large quality factor, using an entirely different scheme. Our scheme uses a co-planar waveguide (CPW) above the free layer of the MTJ. Magnetization fluctuations in the free layer are converted into electrical signal by the TMR effect and dc current passing through MTJ. The amplified signal is fed to the CPW. CPW creates oscillating magnetic field which couples back to the free layer and enhance the oscillations in the free layer.

2. Experiments

We fabricated an MTJ stack on thermally grown SiO_2 (500 nm) with the following structure: bottom contact (50) / Ta(3) / Ru(5) / IrMn(7) / CoFe(3) / Ru(0.8) / CoFeB(3) / CoFe(0.4) / MgO(0.9) / CoFeB(3) /Ta(5) / Ru(5)/ top contact (45) (numbers in bracket denotes the thickness in nm). The multilayer stack was patterned into elliptical nanopillars of size, 300 × 500 nm^2 using electron beam lithography and argon-ion milling methods. All the layers are magnetized in-plane. A CPW was fabricated on top of the MTJ nano-pillar as shown in Fig. 1, and is electrically insulated from the MTJ by a 100 nm thick SiO_2 layer.
The external magnetic field is applied along the y-axis. This creates a non-collinear alignment magnetic moments in the free and the fixed layers. A DC bias current was passed through the MTJ using a bias-T network. The RF port of the bias-T (feedback voltage) is connected to the CPW through a power splitter, phase shifter and an amplifier to amplify the feedback signal as shown in fig 1. The RF voltage, generated across the MTJ due to fluctuations of the magnetization in the free layer is divided into two parts: one part is measured by a spectrum analyzer, and the other part of it is fed into the CPW after passing it through an amplifier and phase shifter. The oscillating current passing through the CPW, creates an oscillating magnetic field. This oscillating magnetic field acts as the feedback signal. The feedback can amplify or suppress the fluctuations of the free layer magnetization depending on the phase difference between the feedback signal and the magnetization oscillations of the free layer.

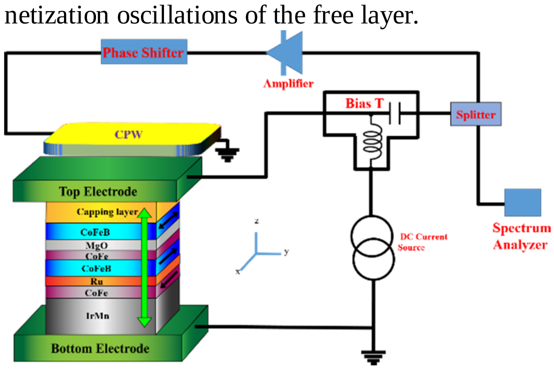

Fig1. Schematic diagram of the feedback oscillator circuit

3. Results and discussion

Figure 2 show the power spectra obtained on sample A with H = 92 Oe and I_{dc} = 1 mA. The red curve shows the spectrum obtained without feedback. The green and blue curve were obtained with the feedback path connected and amplifier gain set to 10 dB and 33 dB respectively.

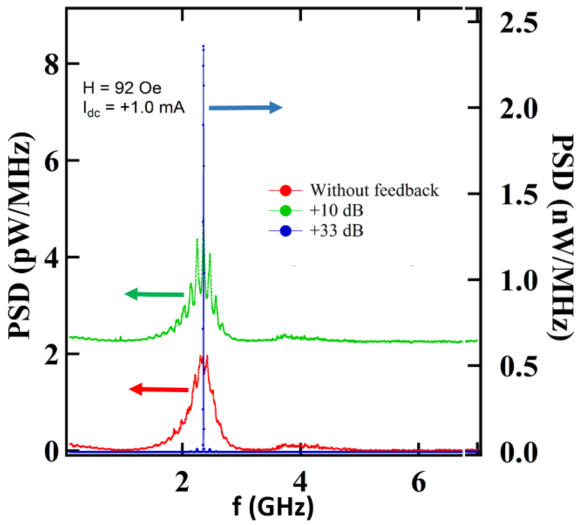

Fig 2. Red curve shows power spectral density when the feedback path is disconnected, green and blue curves show psd with feedback path connected as shown in fig 1. The amplifier gain was 10 dB and 33 dB for green and blue curves respectively.

Fig 2 shows that as we increase the amplifier gain, the amplitude of magnetic oscillations increases. We also observe a reduction in the resonance linewidth with an increase in the amplifier gain. With amplifier gain of 33 dB, the amplitude of PSD increased by about 1000 and line width decreased by a factor of 40 compared to the case where feedback was disconnected. These results show that STT effect is negligible in our experiment and the feedback effect is the dominant factor which gives rise to the oscillations. The amplified signal is not fed back into the MTJ directly, but rather coupled to the MTJ though the inductive coupling of feedback line. Thus even if there is any STT effect in MTJ, it is not amplified. Thus STT can not give rise to the results shown in fig 2.

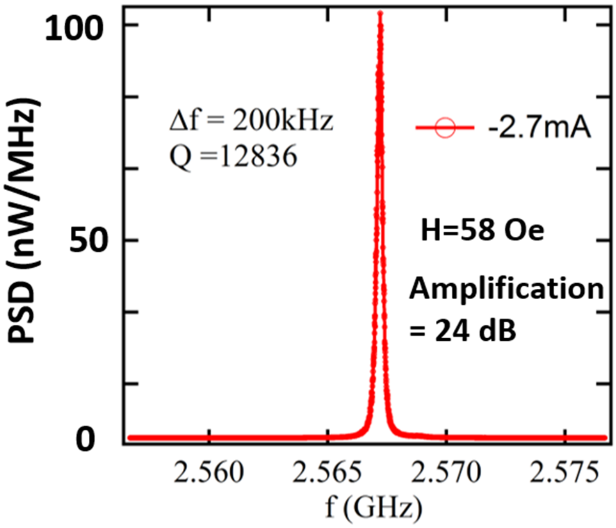

Fig 3 Power spectral density for H=58 oe and dc current=-2.7 mA. Amplifier gain was set to 24 dB.

Another point is that if we use an amplifier to simply amplify the noise signal (i.e. signal without feedback), we will get a larger power but the line width will remain the same. In this experiment, we see a substantial reduction in the line width as we increase the amplifier gain. This happens due to the feedback effect. Further, the green curve in fig 2 shows many side peaks. The side peaks are not visible for blue curve as the main peak height is too large compared to the side peaks. We found experimentally that the side peak separation is inversely proportional to the feedback delay. The best linewidth obtained on sample B is shown in fig 3. A magnetic field of 58 Oe, -2.7 mA dc current and amplifier gain of 24 dB were employed to obtain this data. This data shows that we obtained highly coherent oscillations exhibiting linewidths as narrow as 200 kHz at ~ 2.5 GHz, resulting in a very large *Q* factor of 12800.

We carried out micromagnetic simulations incorporating the feedback effect using Mumax3 software. The simulations have revealed that the magnetization oscillations of various parts of the sample are phase-locked due to the feedback effect i.e. the entire sample can oscillate coherently like a single domain magnet giving rise to high power and low line width. Analytical calculation based on universal oscillator model also support the experimental data. Further our calculations indicate that if we increase the TMR ratio of our devices and decrease the width of the CPW, we can observe the oscillations without using the amplifier i.e. the MTJ itself can provide enough gain to sustain oscillations.

4. Conclusions

We have demonstrated coherent microwave emission from a magnetic tunnel junction by using feedback effect. We could obtain a quality factor, exceeding 10000. Novel physical effects and better oscillators can be obtained from devices with interplay of both spin torque and feedback effect.

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