Magnetic tunnel junction based microwave detector

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We investigated the tunneling magnetoresistance change in magnetic tunnel junctions in the presence of external microwaves. The changing relative angle between the free layer and the pinned layer results in a rectification of the average resistance change. Due to its miniature size and its sensitivity to the microwave magnetic field, the magnetic tunnel junction could be utilized as a microwave power sensor with the ability to detect microwave frequencies. Studying microwave power and bias current dependencies reveals desired sensor features with linear responses and enhanced signal levels. © 2009 American Institute of Physics. [doi:10.1063/1.3231874]

In recent years, development of dynamics in magnetism and spintronics has attracted intensive interest in microwave related applications.1–5 Studies have been carried out through the two following complementary approaches: (i) high density dc current is injected into a hybrid magnetoresistive nanostructure to induce spin transfer torque, which precesses the magnetic layer to generate microwaves, serving as a microwave oscillator,6,7 (ii) microwaves are used to excite magnetization precession in a magnetoresistive device, which converts microwaves to a dc voltage or resistance signal,8,9 serving as a microwave detector. In various experimental demonstrations of the microwave detectors, single ferromagnetic strip rectification effect has been vigorously investigated. The induced voltage signal arises from both microwave-induced photoresistance and photovoltage effects. The former is due to the rectification of resistance and the latter is due to the coupling between rf current and alternating resistance. However, the signal level is relatively small due to a low anisotropic magnetoresistance value, typically less than a few percent. In this paper, a magnetic tunnel junction (MTJ) coupled with a coplanar waveguide (CPW) is used to detect microwaves. Due to the high tunneling magnetoresistance, the MTJ microwave sensor exhibits a much higher sensitivity to microwaves.

A MTJ is fabricated on top of a CPW by magnetron sputtering followed by standard lithography and etching-down procedure. A MTJ composed of Cu 100 nm/IrMn 15 nm/CoFe 6 nm/ AlOx 2.3 nm/ NiIrFe20 (Py) 20 nm/Cu 50 nm/Au 50 nm is patterned on the center line of the CPW so that microwaves can be efficiently fed into the NiFe layer. The size of the MTJ dot is 40 × 70 μm². Magnetization in the CoFe bottom layer is pinned by the antiferromagnetic layer IrMn along the z-axis, defined in Fig. 1. The free magnetic layer NiFe also exhibits a stress-induced anisotropy in the same direction. The experimental set up is shown in Fig. 1. Vector network analyzer supplies a microwave modulated by a 430 Hz ac signal. The microwave is then amplified with a nominal gain of 28 dB and fed into a CPW using a coplanar air probe. The CPW is shorted at the end in order to enhance the microwave magnetic field and minimize the microwave electric field.10 Helmholtz coils generate a tunable dc magnetic field from −100 to 100 Oe. A constant dc current bias is applied to the MTJ and a lock-in amplifier picks up the voltage signal corresponding to the rectification effect caused by the coupling of microwaves and the MTJ.

In the presence of microwaves, the magnetic free layer of the MTJ (NiFe) will precess and resonate at certain microwave frequencies in an external dc magnetic field. The relative angle between the magnetization of the free layer and the pinned layer deviates from parallel/antiparallel configurations, resulting in an increased/reduced average resistance. In order to model the resistance change, we take certain approximations: for the MTJ used in the experiment, the 6 nm CoFe layer pinned by an antiferromagnetic IrMn layer shows a large damping due to the interface roughness induced two-magnon scattering.11 The precession angle of CoFe is negligible compared to the precession of the free layer NiFe. Thus the time dependent resistance is determined by the longitudinal magnetization of the free NiFe layer, \[ R = R_p + \frac{1}{2}[1 - M_z(t)/M_z] \] for a parallel configuration.
rati on and $R = R_{AP} = [(R_{AP} - R_P)/2][1 + M_z(t)/M_s]$ for an antiparallel configuration, where $R_{AP}$ and $R_P$ are resistances at antiparallel and parallel configurations, respectively. $M_z$ is the saturation magnetization of NiFe, $M_s$ is the magnetization component along the external field direction, and $M_z(t) = \pm \sqrt{M_s^2 - (M_z(t) - M_s^2)}$. Here the out-of-plane magnetization precession component $M_z$ is much smaller than the in-plane precession $M_s$ due to the strong demagnetizing field. With a microwave power of 10 mW, the microwave magnetic field generated in the CPW is estimated to be 1 Oe (Ref. 14) and the precession angle is as small as 6°, assuming the susceptibility is about 1000. Since $M_z$ is much smaller than $M_s$, the changing voltage for parallel and antiparallel configurations can be written as

$$\Delta V = \pm \frac{I_d (R_{AP} - R_P)}{8M_s^2} h_{eff}^2 \chi[f, H]^2,$$

(1)

where $I_d$ is a dc current applied to the MTJ, $\chi$ is the microwave susceptibility of NiFe which can be derived from the Landau–Lifshitz–Gilbert equation, in which $f$ is the microwave frequency and $H$ is the external dc field,

$$\chi = \frac{\gamma M_s}{2} \left[ (H + H_a + M_s) + i \alpha f \right] \left[ (H + H_a + i \alpha f) - f^2 \right],$$

(2)

where $\gamma$ is the gyromagnetic ratio, which is typically 28 GHz/T, $H_a$ is the effective anisotropy field, and $\alpha$ is the damping constant.

Tunneling magnetoresistance (TMR) measured at 100 $\mu$A bias current is about 6%, as shown in Fig. 2(a). Figure 2(b) shows the microwave-induced voltage spectrum with 1 mW microwave input at different frequencies. The voltage curve resembles the ferromagnetic resonance (FMR) spectrum of NiFe and is proportional to $|\chi[f, H]|^2$, consistent with Eq. (1). The fitting based on Eqs. (1) and (2) for the voltage spectrum in parallel configuration are shown in green curves, with following extracted parameters: $M_s = 0.91 T$, $H_a = 16.1 Oe$, and $\alpha = 0.014 \pm 0.001$. The microwave magnetic fields from 1 mW nominal power input are extracted to be 0.38 Oe at 1.5 GHz, 0.37 Oe at 2 GHz, and 0.35 Oe at 2.5 GHz. The difference in magnitude is due to the frequency dependent loss and dimensional resonance in the transmission line. Opposite polarities of resonance peaks are also observed in parallel and antiparallel configurations, as predicted by Mecking et al.\textsuperscript{8} This suggests that the observed spectrum is due to a microwave-induced resistance effect instead of the bolometric effect. The voltage at resonance in an antiparallel configuration is slightly higher than the voltage in a parallel configuration. This may be due to that the pinned CoFe layer is closer to resonance condition in the antiparallel configuration. This mutual precession will decrease the resistance change in a parallel configuration, since the relative cone angle is reduced, while increasing the resistance change in an antiparallel configuration, where the relative cone angle is enhanced.

The microwave-induced voltage arising from the rectification effect is proportional to the square of the microwave magnetic field and thus, linear to microwave power. This makes MTJ sensor a potential microwave detector. Unlike a conventional rf diode, which rectifies the microwave voltage, the MTJ microwave detector is sensitive to the intensity of the microwave magnetic field. Due to the nature of ferromagnetic resonance, the MTJ sensor can distinguish the frequency of a microwave, although the frequency resolution is affected by its FMR linewidth, which is around 300 MHz for NiFe.\textsuperscript{18}

Microwave power dependence of induced voltage is measured at a frequency of 2 GHz and a fixed dc magnetic field of 44 Oe, which is the resonance field for NiFe at low microwave power. The sample used in this investigation has similar structure as the one used in Fig. 2, but with smaller CPW size. In order to cancel out the background signal, induced voltage is measured at both +80 and −80 $\mu$A bias current and the difference is taken. As shown in Fig. 3(a), the microwave-induced voltage increases with low input microwave power, with a dependence of $\Delta V \propto P_{RF}^{0.86}$, where $P_{RF}$ is the nominal power fed into the CPW. When the power increases, the induced voltage starts to level off due to the spin wave instability effect, in which the coherent precession mode couples to a chaotic spin wave mode and effectively reduces the average precession cone angle.\textsuperscript{19,20} Examples of microwave-induced voltage spectra are shown in Fig. 3(b). At higher powers, the spectrum is distorted and the peak voltage shifts toward a higher dc magnetic field.

According to Eq. (1), a high dc bias current could enhance the microwave-induced voltage. However, the bias is limited by the breakdown voltage of a MTJ, which is typically around 1 V.\textsuperscript{21} Higher bias current will also influence the tunneling rate in a MTJ and normally will result in a reduced TMR,\textsuperscript{22} which decreases the term $R_{AP} - R_P$ in Eq. (1), as shown in Fig. 4(a). The microwave-induced voltage difference at parallel and antiparallel resonances has the same pro-
file as the dc voltage difference, Fig. 4(b). The discrepancy at a high bias current is due to the thermal effect as it nears the breakdown voltage.

In summary, it is demonstrated that a significant voltage signal can be generated from a biased MTJ irradiated by microwaves, due to the rectification effect. The MTJ has a microwave-induced voltage proportional to microwave power, making it a microwave power detector. The MTJ inherits a ferromagnetic resonance feature from the magnetic layer, which is sensitive to the microwave frequency. On the other hand, it also results in a nonlinear high power response due to a spin wave instability effect. Bias current can be tuned to enhance the voltage response, sacrificing TMR and thermal stability. CoFeB/MgO/CoFeB based MTJ with much higher TMR and comparable free layer damping can replace the Alumina/Py based MTJ and improve the sensitivity by approximately ten times. Moreover, this detector senses the intensity of a microwave magnetic field, which can be tuned by changing the dimension of feed in waveguide with the same amount of power input. The detector should also be able to resist the high power microwave due to the absence of microwave electric field during the detection. In a miniature circuit, the MTJ has a larger resistance due to the current perpendicular to the plane configuration, which offers the advantage of a smaller thermal effect, compared to devices with current-in-plane configuration.

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FIG. 4. (a) Bias dependence of dc voltage differences between parallel and antiparallel conditions. The deviation from linear dependence indicates the decrease of TMR at high bias. (b) Bias dependence of microwave-induced voltage with input microwave at 2 GHz frequency and 1 mW nominal power. Differences in microwave-induced voltage at resonance in parallel and antiparallel conditions are taken in order to eliminate the background signal.