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Millimeter-Wave Detector Using Magnetic Tunnel Junctions With Perpendicularly Magnetized $L1_0$-Ordered FePd Free Layer

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Abstract

Spin-torque diode (STD) effect was investigated in small magnetic tunnel junctions (100 nm in diameter) utilizing $L1_0$-ordered FePd free layer. The STD spectra showed peaks at a milli-meter wave region, owing to the large perpendicular magnetic anisotropy in the free layer. The peak frequency was well fitted by Kittel's formula.

1. Introduction

Spin transfer torque provides us many useful phenomena such as magnetization switching [1], self-oscillation of the magnetization [2] and STD effect [3,4]. STD effect is a rectification effect of a radio frequency (rf) current, which caused by synchronizing the periodic change of the resistance and an injected r.f. current. Since the device size is nanoscale and the resonant frequency can be tuned by an external magnetic field, it has attracted much attention as a new diode detector beyond a conventional semiconductor diode. Many researchers concentrated their efforts on improving the diode sensitivity, and then very high diode sensitivity which exceeds that of a semiconductor diode has already been reported [5]. The other important task is to increase the detectable frequency to millimeter-wave region. One of the ways to realize a STD detector in the millimeter-wave region is to introduce the materials having large magnetic anisotropy such as $L1_0$-ordered alloys as a free layer material in magnetic tunnel junctions (MTJs). In our previous study, [6] 28 GHz was detected. In this study, a further high frequency region will be performed together with reducing the free layer thickness and decreasing the junction size to 100 nm.

2. Experimental Methods

The films consisting of MgO(001)-sub./Cr(40)/Pd(10)/FePd(2.0)/$Co_{40}Fe_{40}B_{20}$(0.5)/MgO(0.85)/$Co_{40}Fe_{40}B_{20}$(2)/Ru(0.85)/$Co_{75}Fe_{25}$(2)/IrMn(10)/Ta(5)/Ru(8) layers (in nm) were deposited by ultra-high-vacuumed (UHV) magnetron sputtering. 0.5-nm-thick CoFeB layer was inserted between FePd and MgO in order to improve interfacial roughness and to enhance TMR ratio [7]. After being annealed at 300ºC in a vacuum, the multilayers were microfabricated into small MTJs by using electron beam lithography and Ar ion milling. The diameter of the sample was 100 nm. Magnetoresistive properties were measured by d.c. two-probe method. The STD spectra were measured by using a modulation method with a signal generator and a lock-in amplifier under a perpendicular magnetic field without an external dc bias current. An r.f. current was injected through a bias-tee. An r.f. power was fixed at -16 dBm. All measurements were carried out at room temperature.

3. Results and Discussion

Fig.1 shows magnetoresistance curves measured under external magnetic field applied out-of-plane to the film (H_{OP}) and in-plane (H_{IP}). Under H_{OP}, magnetoresistance curve showed sharp resistance switching at $H_{OP} = \pm 2$ kOe. These facts indicated that the FePd/CoFeB free layer was perpendicularly magnetized. The resistance saturated at $H_{OP} = \pm 10$ kOe, which corresponds to the parallel configuration of the magnetizations in free and reference layer. TMR ratio, defined as $(R_{max}-R_{min})/R_{min}$, and resistance-area product (RA) were 18% and 4 $\Omega\mu m^2$, respectively. Under H_{IP}, the resistance changed continuously due to the change in FePd/CoFeB magnetization. By extrapolating the slope up to R_{min} at H_{OP} =10 kOe, effective perpendicular magnetic anisotropy (PMA) field ($H_{k\perp}{}^{eff}$) in FePd/CoFeB layer of 13.5 kOe was estimated.

Fig. 2(a) and (b) show the STD spectra under various H_{OP} in a low frequency region ($1< f <15$ GHz) and a high frequency region ($25< f <40$ GHz). All STD measurements were carried out after applying H_{OP} = -10 kOe in order to define the magnetic configuration of free layer. The spectrums were not subtracted by background noise. In the low frequency region, the peaks observed at 5 GHz were not obviously changed to H_{OP} (Fig. 2a). These peaks were thought to be due to the strongly coupled in-plane magnetized synthetic reference layer. The STD peaks were fitted by Kittel's equation as follows (Fig. 3a) :

$$f = \frac{\gamma}{2\pi}\sqrt{H_{k//}{}^{eff}\left(H_{k//}{}^{eff} - 4\pi M_s\right)\left\{1-\left(\frac{H_{OP}}{H_{k//}{}^{eff}}\right)\right\}} \qquad (1)$$

where, γ and $H_{k//}{}^{eff}$ are the gyromagnetic ratio and effective in-plane magnetic anisotropy field, respectively. The estimated $H_{k//}{}^{eff}$ was 14 kOe and that value was consistent with the $H_{k//}{}^{eff}$ of 15 kOe estimated from magnetization curves for reference layer (not shown). On the other hand, at the high frequency region, the observed peaks were apparently shifted to the high frequency region by the H_{OP} (Fig. 2b). The highest frequency was at 40 GHz, which in the millimeter wave region and higher than that of previous study. These higher frequencies might be realized by the reduction of the demagnetization factor nominal to the film plane due to the smaller junction size. The peak positions were fitted to Kittel's equation by simply taking into consideration of PMA change due to H_{OP} as follows (Fig.3b):

$$f = \frac{\gamma}{2\pi}(-H_{OP} + H_{k\perp}^{\ eff}) \qquad (2)$$

Therefore, the STD mode in this study was not non-linearity. The estimated $H_{k\perp}^{\ eff}$ was 12.7 kOe and this value was almost consistent with the $H_{k\perp}^{\ eff}$ of 13.5 kOe estimated from magnetoresistance curves (shown in Fig. 1). Therefore, STD signals observed in high frequency region were identified to be attributed to the FePd/CoFeB free layer. The signal observed at 40 GHz does not need an assist of the external magnetic fields. Zero field operation exploits the advantages of nanoscale devices and reduces power consumption by eliminating the need for a coil producing external magnetic field.

4. Conclusions

The STD measurements were performed in 100 nmφ-sized MTJs having $L1_0$-ordered FePd free layer. The STD signals in the millimeter-wave region were observed. Maximum frequency observed in this work was 40 GHz without external magnetic fields. By using Kittel's formula, observed millimeter-wave STD signals were found to be attributed to the large PMA in $L1_0$-ordered FePd.

Acknowledgements

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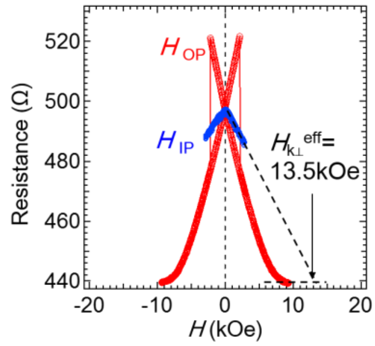

Fig.1 Magnetoresistance curves measured under external magnetic field applied perpendicular to the film plane (H_{OP}) and parallel to the easy axis of the reference layer (H_{IP}).

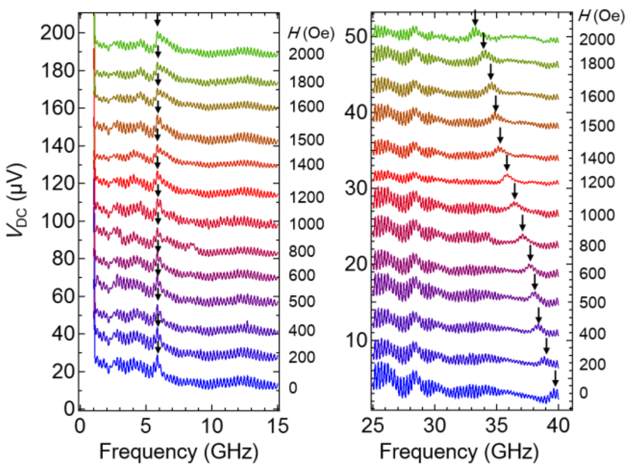

Fig.2 Typical STD spectra under various H_{OP} (a) in the low frequency region (1 < f < 15 GHz) and (b) the high frequency region (25 < f < 40 GHz).

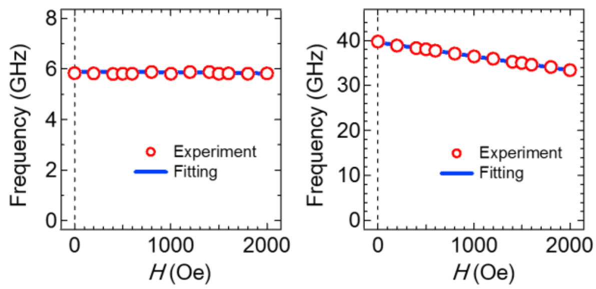

Fig. 3 Dependence of resonance frequency on external magnetic field (a) in the low frequency region (1 < f < 15 GHz) and (b) the high frequency region (25 < f < 40 GHz).