**Controlling magnetic fluctuation via cobalt permalloy co-sputtering in nano-wire structure.**

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**Abstract**

We observe enhancement of magnetic fluctuation intensity on NiFe-Co nano wire structure using Co-sputtering fabrication method. Co shows low increase of gilbert damping constant when it Co-sputtered with NiFe Compared with the other transition metals. Also Co interface layer was reported as enhancing spin hall conductivity between ferromagnet and heavy metal layer. Thus we measured enhancement of thermal fluctuation via micro-focus Brillouin light scattering (BLS) spectroscopy and lowering of threshold current of auto oscillation. Our result gives a chance to realization of low power operation in SOT based devices.

**Introduction.**

Spin torque nano oscillator (STNO) and spin Hall nano oscillator (SHNO) are known as the promising candidates for excitation of propagating spin wave­, and generator and detectorof ultra-tunable microwave. [1-3] Unlike conventional devices, which are based on semiconductors and utilize current flow for information processing, spin-based devices exploit electron spin to induce electric or magnetic signal. Recently, STNO and SHNO are reported as a nonlinear oscillator in neuromorphic computing due to their benefits from long lifetime, low energy operation and scalability below sub-micro size. [4,5]

STNO is the microwave generator, which induces the spin oscillation in a free layer using spin transfer torque from a fixed layer. In such device, the direct current, which flows in nano-structure, induces inevitable damage because of electro-migration and ohmic heating.[6] On the other hand, SHNO utilizes spin-Hall effect in the material with strong spin-orbit coupling. Spin-Hall effect is a relativistic spin-orbit coupling phenomenon, which induces electric charge current to generate transverse spin current.[4,7] In SHNO structure, the current flows through a heavy metal layer, underneath the free magnetic layer, and induces spin current out of the heavy metal layer. Then the spin current transfers the spin torque to excite the auto oscillation. SHNO has several advantages over STNO. For example, the structure of SHNO is relatively simple so that it allows direct optical measurement using magneto-optical techniques.[6,8] In addition, because of simple fabrication procedure, it is easy to implement synchronization of SHNO array for enhanced coherence.[9-11]

In general, current-induced spin-torque in SHNO play a key role as an anti-damping torque, which compensates natural damping completely when auto-oscillations occur.[8] And the threshold current density for auto oscillation is large, compare to STNO, because of the low efficiency of charge-to-spin current conversion.[12] Thus, near the threshold current, additional damping due to the scattering from nonlinear interaction between multi-modes emerges and it forbids ferromagnetic layer from onset of auto-oscillation.[23,26] To avoid the nonlinear scattering process, several experiments have been performed in spatially confined structures, which have discrete spin wave spectrum. For example, nano-gap spin Hall oscillator achieves auto oscillation by selectively suppressing modes except a mode which auto oscillate.[23] Nano-constriction spin Hall oscillator is also achieved auto oscillation using confinement of potential well in its bow tie structure.[8] These structure could avoid nonlinear scattering via process of minimizing the sample to reduce the number of mode from structure size.

Several studies have reported the efforts to enhance the performance of STNO or SHNO, such as high output power, low phase noise and energy efficiency. B. Divinskiy et al. showed the increase of oscillation amplitude by using CoNi nano constriction structure with multilayer perpendicular magnetic anisotropy (PMA). Z. Mohammad et al. demonstrated the enhancement of power density using mutual synchronization of multiple nano constriction structure.[11] In order to reduce the threshold current in SHNO, heavy metal of tungsten (W), instead of platinum (Pt), is used. [14] For the effective charge-to-spin conversion, modulation of thickness or interface of heavy metal is adopted via controlling of Pt thickness.[13]

Since co-sputtering (with what?) has advantages for the alloy formation in terms of uniformity and mass production, there are several studies utilizing co-sputtering.[15-19] One example is the significant enhancement of spin Hall transparency when Co is used as interface layer between heavy metal and ferromagnetic film. In addition, when transition metals are co-sputtered with Py(NiFe) and Co, the gilbert damping constant is found to be increased.[20] Considering these results, it is worthwhile to study the effects of Co co-sputtering with Py in SHNO.

We investigated the effects on magnetic fluctuation in a Py nano structure, when it is co-sputtered with Co, using micro-focused Brillouin light scattering spectroscopy(μ-BLS). We observed that Co reduces the threshold current for the excitation of magnetic wave in SHMO and enhances significantly the peak intensity in μ-BLS spectrum. Especially, for sputtering in a stoichiometric ratio of Py0.8Co0.2, the nanowire structure shows the threshold current, lower by about 27.6% than that of pristine sample.

**Experiment**

Figure 1(a) and (b) show a SEM image and schematic structure of nano-wire sample of 0.8 μm in width and 2 μm in length. The nano-wire is consisted of layer stack: Ta(1)/Pt(10)/Py1-*x*Co*x*(5)/Al2O3(5) where the number is thickness of each layer in the unit of nm. Pt layer is used as the heavy metal for the generation of spin hall effect. The Py1-*x*Co*x* layer is fabricated by co-sputtering of Co and Pt with the stoichiometric ratios of *x* = 0, 0.1, 0.2, 0.3 and 0.4. The actual Co ratio is determined by full name (XRR) measurement. The Ta and Al2O3 layers are a buffer layer above substrate and capping layer, respectively. AJA magnetron sputtering system with an initial base pressure of is used to fabricate samples without breaking vacuum in the whole processes.

Since μ-BLS system can detects the excitation of spin wave in local area, it is used to study the thermal fluctuation of spin wave in this study. The BLS system has 512nm Nd-YAG laser and the laser beam can be focused on a circular spot of 250 nm in diameter. External field of 1,500 Oe is applied in a right angle to saturated the magnetization of sample and maximize the STT effect.[22-24] Experiments are performed at room temperature.

**Results and Discussion**

Figure 2 shows the BLS spectrum intensity in terms of frequency, which is measured at the center of Py1-*x*Co*x* layer with various DC currents of 3.5, 4, 4.5, 5, and 5.5 mA and reshaped by Lorentzian line fitting. The observed BLS spectrum represents the thermally excited quasi-uniform ferromagnetic resonance mode. Integral intensity of BLS spectra, thus, indicates the total energy of magnetic fluctuation in the ferromagnetic layer.[21] The spectrum intensity increases as the current increases. Actually, it is hardly observed when the current is lower than 3.5 mA. The current, flowing through Pt-layer, would feel spin-Hall effect and, as a result, transfer spin-torque to the ferromagnetic layer. The enhanced magnetic fluctuation, induced by the transferred spin-torque, is observed by the increase of BLS spectrum intensity, as shown in Fig. 2. The spectrum shape, which is broader than that of spin-torque ferromagnetic resonance (ST-FMR), is likely due to contribution of non-uniform dynamical modes from spin transfer torque.[13] In the magnetic system in Fig. 1, only magnetic fluctuation of spin waves, rather than auto-oscillation, is observed in the current values in Fig. 2, due to geometry limitation. The application of larger current would induce another mode excitation, resulting in thermal mode hopping, which disturbs the system to get auto-oscillation regime.[8,25]

Although we do not observe auto-oscillation in the system in Fig.1 with the currents in Fig. 2, we can infers the threshold current for auto-oscillation using the current-dependence of BLS spectrum data.[13] According to the theory of nonlinear auto-oscillation,[26] inverse of total fluctuation intensity below threshold current regime should be linear to the current and the linear extrapolation can determine the threshold current of the system for auto-oscillation, i.e.,

where is the mean power of spectrum, and and are the bias and threshold current, respectively. Figure 2 shows the inverse of integrated intensity of BLS spectrum in terms of the bias current for the samples of Py1-*x*Co*x* (*x* = 0, 0.1, 0.2, 0.3, and 0.4). The line is the linear extrapolation of the five data points. The linear extrapolation for the samples gives the estimated threshold currents for auto-oscillation: 13.8 mA for Py1-*x*Co*x* (*x* = 0), 11.3 mA for Py1-*x*Co*x* (*x* = 0.1), 9.8 mA for Py1-*x*Co*x* (*x* = 0.2), 11.5 mA for Py1-*x*Co*x* (*x* = 0.3), 11.9 mA for Py1-*x*Co*x* (*x* = 0.4). This shows that the co-sputtering of Py1-*x*Co*x* () reduces noticeably the threshold current, i.e., 27.6% reduction of threshold current for Py1-*x*Co*x* (*x* = 0.2), compared to that for Py1-*x*Co*x* (*x* = 0). Slight increase of the threshold value, but still smaller than that for Py1-*x*Co*x* (*x* = 0), is observed with higher Co ratios.

Because the BLS signal is a result of quasi-ferromagnetic resonance due to the transferred spin-torque, its spectrum shape is fitted to Lorentzian approximation using the Kittel formula as

where is the gyromagnetic ration, is the maximum peak frequency of spectrum and is the effective magnetization. The field strength, , is the sum of the applied field and induced field due to the current, flowing in Pt layer. We estimate that about 80 % of current passes the Pt layer because the resistivity of Pt is quite lower than that of Py1-*x*Co*x* and the Pt layer is thicker by two times that that of Py1-*x*Co*x* layer. From the fitting, as shown in Fig. 2, effective magnetization is derived and plotted in terms of applied current for the samples, Py1-*x*Co*x* (*x* = 0, 0.1, 0.2, 0.3, and 0.4) in Fig. 4. Significant reduction of is observed in a sample of Py1-*x*Co*x* (*x* = 0.2), compared to that of Py. In particular, the current-dependence of reduction shows a clear nonlinear effect, which is related with the magnetic precession in Py1-*x*Co*x* (*x* = 0.2), manifested by the abrupt shift of frequency . The nonlinearity is an essential characteristics of auto-oscillation to enhance oscillation power and coherence between multiple oscillators using external microwave and mutual synchronization.

Fig 3. (b) shows shifts of center peak frequency with D.C current between 3.5mA and 5.5mA depending on Co composition and it shows their nonlinear characteristic which is variation of oscillation frequency depending on amplitude of oscillation[26]. Center frequency of samples shows red shifts as current increase due to joule heating and reduced effective magnetization[27,28] The shift increase most at Co 20% deposited sample. The fact increase of nonlinearity of oscillator has benefits since nonlinearity is important factor to enhance coherence and power of oscillation between multiple oscillator using external microwave source or mutual synchronization.[6,9]

Considering data qusai-ferromagnetic resonance which come from pure spin current results from spin hall effect, Data of BLS intensity graph fitted with lorentzian and we extract effective magnetization, Meff, of samples through kittel formula where γ is the gyromagnetic ratio, f0 is center frequency of lorentz fitted BLS intensity plotted with current, and H=|H0+HI|.

(2)

To get strength of total oersted field H including current induced magnetic field HI, we use conductive slab layer model[[29]]. More than 80% current pass Pt layer because the resistivity of Pt is quite low compare to Py and Py1-x Cox and thickness of Pt layer is twice thicker than ferromagnetic layer. Effective gilbert damping constant are determined using expression Derived from Landau-Lifshitz-Gilbert equation which consider demagnetization effects for in-plane magnetized ferromagnetic film.[30] Fig 4. (b) shows measured the effective magnetization Meff­ value of sample depending on Co composition as current increase. The value of M­eff reduced and it shows amplitude of precession of spin large because of spin torque from spin current and thermal effect. The reduction Meff is main nonlinear effect which is related with precession amplitude and nonlinear frequency shift.[31] we confirmed lowest Meff in Co 20% sample and which is corresponding to largest nonlinear frequency shift f0 in Fig 3. (b).

Fig 4. (a) shows effective gilbert damping constant αeff at peak current(5.5mA) and It is necessary to confirm variation on effective gilbert damping constant which results from Co-Py co-sputtering method. Values of αeff are a little larger than typical gilbert damping constant compare to value of Py which result from FMR measurement. This difference comes from spin wave excitation source between uniform external magnetic field and STT of pure spin current from heavy metal due to SHE. spin torque to non-uniform dynamical modes of ferromagnetic layer makes quasi-uniform ferromagnetic resonance(FMR) broadened. Values of shows tendency to increase as more current applied. Effective gilbert damping constant of Co 20% sample shows higher value than Py but lower than 30% and 40% composition. Considering reference paper which measured gilbert damping constant of Py-Co co-sputtered sample,increase of is acceptable.[20] we noted that threshold current is reduced comparing to Py sample though Py-Co Co-sputtering raise effective gilbert damping.

Although reducing threshold current of SOT based device is promising since it results by allowing low power operation and thermal stability, linewidth of signal and output power intensity is important factors. Fig 5. (a) shows FWHM of BLS intensity data at maximum amplitude(5.5mA) of BLS intensity depending on Co ratio. we note that linewidth of Py and Co 20% sample has similar value of linewidth although Co is added and show reduction of threshold current. Fig 5. (b) shows normalized peak intensity depending on Co ratio. We confirmed enhanced peak Co 20% composition about 23.3% comparing with Py only. however, from composition of Co 30% samples, intensity of peak shows abrupt suppression and it is below sample fabricated by Py only. we postulate the reason for this suppression is enlarged scattering and diminished efficiency of spin hall conductivity.

**Conclusion**

We report controlling magnetic fluctuation in nanowire structure fabricated by Py-Co co-sputtering method via BLS spectroscopy. we could infer reduction of 27.6% threshold current using magnetic fluctuation of samples at Co 20%.we also confirmed 23% enhanced intensity at peak without broadness of linewidth. We postulate that Co co-sputtering with Py enhance spin hall conductivity until 20 % of Co ratio and efficiency of it decrease as scattering increase after the ratio. From the application point of view, our result will benefit research studying nonlinear oscillator like in neuromorphic computing since it will reduce operation power of devices and enhance output power.



Fig 1.(a) SEM image of Nano wire structure. (b) Schematic of the experiment. Ta(1nm)/Pt(10nm)/Py1-xCox(5nm)/Al2O­3(5). (c) BLS Intensity spectra of Py80Co20 Nano wire Structure depending on D.C current from 3.5mA to5.5mA incremented in 0.5mA.



Fig 2.(a)~(e) inverse of BLS integral intensity of co-sputtered sample(Py1-xCox ,x=0,10,20,30,40) depending on D.C current. Each data is linear fitted and extrapolated



Fig3. (a). Threshold current extracted from extrapolation of inverse BLS intensity and (b) Center peak frequency at current 3.5mA and5.5mA depending Co composition (x=0,10,20,30,40)



Fig 4. (a). Effective Gilbert damping constant at peak(5.5mA) and (b). Effective magnetization constant depending on Co composition DC current from 3.5mA to5.5Ma incremented in 0.5mA step



Fig 5. (a). linewidth and (b). Peak amplitude depending Co composition at maximum amplitude(5.5mA) of BLS intensity.

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