**Controlling magnetic fluctuation using 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[1,2], and generator and detector[3] of ultra-tunable microwave. 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 (SHE) in the material with strong spin-orbit coupling. Spin hall effect is a relativistic spin-orbit coupling phenomenon that unpolarized electrical current generates transverse spin current.[4,7] SHNO uses the spin current as source of oscillation. In SHNO structure, Charge current je which passes heavy metal results in spin polarized current with out-of-plane direction,z,and it transfer torque to ferromagnetic layer above heavy metal layer. SHNO has several advantages over STNO. For example, since charge current doesn’t pass ferromagnetic layer directly, SHNO is more stable structure. 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] One of drawbacks in SHNO is the fact that SHNO needs large current density, compare to STNO, because of the low charge to spin current conversion ratio.[12]

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. [13] For the effective charge to spin conversion, modulation of thickness or interface of heavy metal is adopted via controlling of Pt thickness.[14] (Read this phase to see the changes are right. Rearrange the references)

Since co-sputtering 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 the magnetic fluctuation in a Py nano wire, when it is Co co-sputtered, using micro-focus 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**

Fig 1.(a) and (b) show SEM image and schematic of width 800nm length 2μm. nanowire sample. Overall stack of layer is Substrate/Ta(1nm)/Pt(10nm)/Py1-xCox(5nm)/Al2O3(5nm)(x=0,10,20,30,40).We used AJA magnetron sputtering system to fabricate samples. The base pressure is 1.0 x10-9torr. Pt layer is used as heavy metal to generate spin hall effect. We co-sputtered Py and Co with 5nm thickness. Portion of Co within ferromagnetic layer is 0,10,20,30,40% respectively. Ta functions as seed layer below Pt layer and Al2O3 is capping layer above ferromagnetic layer to prevent oxidation. Overall procedure is done without breaking vacuum of sputtering system. Ratio between Py and Co is determined by growth rate using XRR measurement. Since brillouin light scattering spectroscopy(BLS) can detect spin wave dynamic in local area, various studies utilize it to study sub-micrometer structure.[21] In this experiment ,BLS is used to measure thermal fluctuation intensity of spin wave. 512nm Nd-YAG laser has beam diameter 250nm and we measured BLS intensity with laser spot at center of 800nm width and 1.7 nano wire. Magnetization of sample is saturated using external field which is set to 1500Oe and angle between D.C current and external field is 90º for efficiency of STT.[22-24] Experiments are performed with room temperature.

**Result**

Fig 1. (c) is BLS intensity plot of 800nm nano wire sample. BLS spectra is characterized by a lorentzian line shape. The BLS intensity of selected frequency is proportional to square of the dynamic magnetization of selected frequency. Integral intensity of BLS spectra indicates total energy of magnetic fluctuation in ferromagnetic layer [21]. Spin current which result from charge current passing heavy metal transfers torque to ferromagnetic layer. Thus magnetic fluctuation enhanced as current increase and followed by increase of BLS intensity as Fig1. (c). Measured data show thermally excited quasi-uniform ferromagnetic resonance mode and its shape is broader then the other measured data using ST-FMR due to contribution of non-uniform dynamical modes from ferromagnetic layer[14]. We observed only magnetic fluctuation and range of applied D.C current is below threshold current regime due to limitation of geometry. Total fluctuation intensity will be suppressed as applied current close to threshold current. Increased temperature causes additional mode excitation and results in thermal mode hoping which disturbs the system from getting into auto-oscillation regime[8,25].

Generally, in SHNO, spin current-induced torque increases as D.C current applied and SOT plays a role of anti-damping torque which compensates natural damping completely when auto-oscillation occurs[8]. Near the threshold current, additional damping which is originated from nonlinear scattering from nonlinear interaction between multi-modes emerges and it forbids ferromagnetic layer from onset of auto-oscillation.[23,26] To avoid nonlinear scattering process, several studies experimented on spatially confined structures which have discrete spin wave spectrum. For example, nano-gap spin hall oscillator achieved auto oscillation by selectively suppressing modes except a mode which auto oscillates[23] and nano-constriction spin hall oscillator achieved using confinement of potential well resulting from its bow tie structure[8]. These structure could avoid nonlinear scattering via process of miniaturizing the sample to reduce the number of modes that structure has.

In this experiment, the structure has multi-mode. Thus if we apply D.C. current near threshold current, it goes though nonlinear scattering process and it couldn’t achieve auto oscillation. Although we can’t observe auto-oscillation directly, Without direct measurement of auto-oscillation mode , one can infer threshold current using BLS data of sub-threshold current regime.[14]According to theory of nonlinear auto oscillator and studies[26], inverse of total fluctuation intensity below threshold current regime is plotted linearly and extrapolation of this linear plot could determine threshold current of the system.

(1)

is inverse mean power, I is a bias current and ITh is threshold current. Plotting output power as a function of current in below auto oscillation regime offers precise value of threshold current, ITh ,even in strong thermal fluctuation of system.[26] Figure 2 Fig 2. (a)~(e) show inverse of BLS integral intensity of co-sputtered sample depending on current. Linearly fitted graph extrapolated to determines threshold current of each composition (Py1-xCox, x=0,10,20,30,40). Threshold current is reduced when Co is co-sputtered with Py. Especially at Co ratio 20%(x=20) shows threshold current reduction 27.6% comparing with Py sample. In Fig 3. (a), we confirmed that ratio of Co larger than 20% results in increase of threshold current gradually. This might result from scattering effect due to Co and it is more dominant than enhancement of spin hall toque[20].

Fig 3. (b) shows shifts of center peak frequency with D.C current from 3.5mA to 5.5mA depending on Co composition and it shows their nonlinear characteristic which represents 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 increases most at Co 20% deposited sample. We should note the increase of nonlinearity from Py and Co co-sputtering since nonlinearity is important factor to enhance coherence and power of oscillation between multiple oscillators using external microwave source or mutual synchronization.[6,9]

Considering plot of BLS spectra is qusai-ferromagnetic resonance which results from pure spin current results from spin hall effect, we extracted effective magnetization, Meff, of samples through kittel formula where γ is the gyromagnetic ratio, f0 is center frequency of BLS intensity.

(2)

To get strength of total oersted field H including current induced magnetic field HI, H=|H0+HI|, we used conductive slab layer model[[29]]. More than 80% current passes Pt layer because the resistivity of Pt is quite low comparing with Py and Py1-x Cox and thickness of Pt layer is twice thicker than ferromagnetic layer. Effective gilbert damping constant was determined via expression which is derived from Landau-Lifshitz-Gilbert equation considering demagnetization effects for in-plane magnetized ferromagnetic film.[30] Fig 4. (b) shows value of effective magnetization Meff­ depending on Co composition as current increase. The value of M­eff is reduced and it shows that amplitude of precession of spin become large due to 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 ,depending on Co composition 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 from ST-FMR measurement. This difference results from spin wave excitation source between uniform external magnetic field and STT of pure spin current from heavy metal due to SHE[14]. Spin torque from pure spin current excites non-uniform dynamical modes of ferromagnetic layer which makes BLS spectra broad. 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 raises effective gilbert damping.

Although reducing threshold current of SOT based device is promising since it could allow the devices to low power operation and thermal stability, linewidth of signal and output power intensity should be considered as important factors either. 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 its threshold current was reduced. 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 the composition of Co 30% samples, intensity of peak shows abrupt suppression and its value is below sample fabricated by Py only. We postulate the reason for this suppression is enlarged scattering from Co co-sputtering 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 expect 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 diminished due to additional Co composition which contributes to increase of effective gilbert damping. From the application point of view, our results will benefit research studying nonlinear oscillator like neuromorphic computing since it could 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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