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

ByungRo Kim1, S. Hwang1 Seungha Yoon2, Songhee Han3, and B. K. Cho\*1

1School of Materials Science and Engineering, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Buk-gu, Gwangju 61005, South Korea

2Nano Photonics Group, Korea Institute of Industrial Technology, 6, Cheomdangwagi-ro 208-gil, Buk-gu, Gwagju 61012, South Korea

3Division of Navigation Science, Mokpo National Maritime University, Mokpo 58628, Republic of Korea

**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 In-plane Charge current je passing heavy metal results in out-of-plane spin polarized current z and it transfer torque to free layer. (Rewrite it. I do not catch what you want to describe.) 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] One of drawbacks in SHMO 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. [14] For the effective charge to spin conversion, modulation of thickness or interface of heavy metal is adopted via controlling of Pt thickness.[13] (Read this phase to see the changes are right. Rearrange the references)

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 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 use 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-sputter Py with Co 5nm thickness and Co takes portion in ferromagnetic layer is 0,10,20,30,40% respectively. Ta is 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 detects spin wave dynamic in local area, various studies utilize it to study sub-micrometer structure.[21] BLS is used to measure thermal fluctuation intensity of spin wave. 512nm Nd-YAG laser with beam diameter 250nm and measure 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 current and external field is 90º for efficiency of STT.[22-24]Experiment are performed with room temperature.

**Result**

Fig 1. (c) is BLS intensity plot of 800nm Nano wire sample. BLS spectra fitted with lorentzian line shape. 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 STT[13]. 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). we observed only magnetic fluctuation and current regime of the fluctuation is below threshold current regime due to limitation of geometry. Total fluctuation intensity will be suppressed as current close to threshold current because increased temperature cause additional mode excitation and result in thermal mode hoping which disturbs the system get to auto-oscillation regime[8,25].

Generally, In SHNO, Spin current-induced torque increases as D.C current applied and SOT play a role of anti-damping torque which compensates natural damping completely when auto-oscillations occur[8]. Near the threshold current, additional damping which 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 experiment on 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] 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 miniaturize the sample to reduce the number of mode from structure size.

In this experiment the structure has multi modes thus suffer nonlinear scattering process thus couldn’t achieve auto oscillation. Although we can’t observe auto-oscillation directly, Without direct measurement of auto-oscillation mode , one can infers threshold current using BLS data of sub threshold current regime.[13]According to theory of nonlinear auto oscillator and studies[26],Inverse of total fluctuation intensity below threshold current regime change linearly and extrapolation of this linear plot can determine threshold current of the system

(1)

is inverse mean power, I is 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] Fig 2. (a) ~(e) show inverse of BLS integral intensity of co-sputtered sample depending on current. linearly fitted graph extrapolated to determine threshold current of each composition (Py1-xCox, x=0,10,20,30,40). Threshold current reduced when Co is co-sputtered with Py. Especially at Co ratio 20%(x=20) shows threshold current reduction 27.6% compare to Py sample. In Fig 3. (a) we confirm that ratio of Co larger than 20% results in increase of threshold current gradually. This may imply scattering effect from Co more dominant than enhancement of spin hall toque[20].

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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