ナノサイズ単一磁性体の磁化挙動

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磁気メモリーの高密度度化に伴い、その最小構成単位はナノサイズ領域に入りつつある。こうした状況では、個々のナノ磁性体の性質やスピンダイナミクスを定量的に把握することが、将来のデバイス設計・開発に不可欠である。これまで我々は異常ホール効果を利用した超高感度磁化検出法を開発し、単一ナノ粒子の磁気計測を可能にした。(Fig.1) この方法により $L1_0$FePt や Co/Pt 人工格子をはじめとする機能磁性材料のナノサイズ領域における磁化挙動を系統的に明らかにしてきた。そうした準静的測定に加え、実際のデバイスの高速動作を意識して高速パルス磁場に対する単一粒子(直径 120 nm) の応答を調べた。一例として保磁力の磁場印加時間依存性について調べた結果を Fig.2 に示す。ナノ秒から秒に及ぶ広い時間領域にわたり磁化反転は古典的な Neel-Arrhenius 則で説明でき、反転過程が熱揺らぎに支配されていることがわかる。

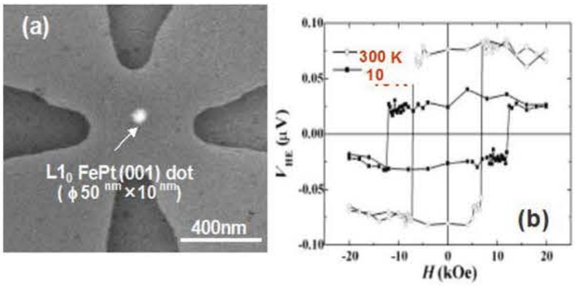

Fig.1　(a) **異常** Hall **効果測定に用いた** $L1_0$ FePt (001)**単結晶ドット**($^{\phi}$50 nm×^{t}10 nm)**と十字型電極の** SEM **像**, (b) (a)**の単一** FePt **ドットの温度** 10K, 300K **における磁化曲線**

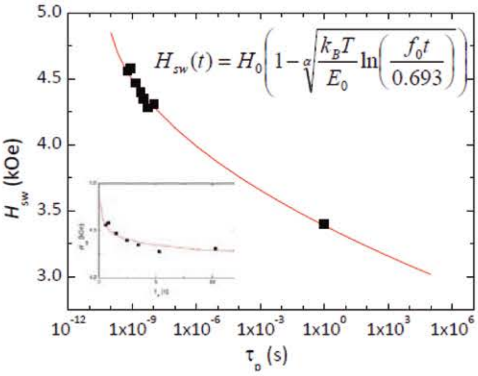

Fig.2 単一Co/Pt人工格子ドットの保磁力の印加磁場時間依存性.(赤線は Neel-Arrhenius 則)

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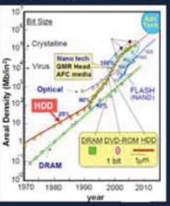
Outline

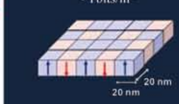
For future advancement in magnetic and spin electronic devices, it is essential to understand the magnetic behavior and spin dynamics of a single nanomagnet. However, no effective method has been available for detection of such extremely small magnetic moment. To overcome this difficulty, we have newly developed a highly sensitive magnetic detection technique utilizing the anomalous Hall effect (AHE). This technique has systematically revealed the magnetic behaviors of various magnetic materials in the nanoscale regime. In this article, we demonstrate how single nanomagnets of L1$_0$ FePt and Co/Pt multilayers behave depending on their size, especially focusing on the magnetization reversal process and the bistability condition necessary for digital memory use. In addition, we have also developed the nanoindentation technique using a scanning probe microscope for fabrication of nanostructures.

Background

Magnetic Recording (HDD) can realize highest data density and its value will reach **1 Tbits / in²** *within several years. Various spin tronice devices are also expected for future technologies.*



~ Tbits/in²



being comparable to characteristic length, such as

exchange length $L_{ex} \approx \sqrt{A}/M_s$

or

domain wall width $\delta_w \approx \pi\sqrt{A/K_u}$

How does such a tiny magnet behave in response to ***H*** , ***T***, etc ?

Theoretical prediction of micromagnetics

Critical boundary for coherent/incoherent rotation

$$L_{ex} = \frac{2q}{M_s}\sqrt{\frac{2A}{N_x}} \sim 35\ \mathrm{nm}$$

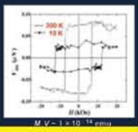
for L1$_0$ FePt particle with aspect ratio of 1/5

for $D \leq L_{ex}$ → coherent rotation

for $D > L_{ex}$ → incoherent rotation (curling or nucleation)

[A. Aharoni, Theory of Ferromagnetism (Cambridge Univ. Press); O. Kitakami et al. JJAP 40, 4019 (2001)]

Newly developed sensitive magnetic detection method using Anomalous Hall Effect (AHE)



$M \cdot V \sim 1 \times 10^{-14}$ emu

Developed AHE method ⇨ $\sim 10^{-15}$ emu (Co: 10 nm)

	VSM	SQUID	micro SQUID (Neel lab.)	AHE (present method)
Sensitivity	$\sim 10^{-4}$ emu	$\sim 10^{-7}$ emu	$\sim 10^{-15}$ emu	$\sim 10^{-15}$ emu
Max Field Max Temp	H_{max} = 20 kOe	H_{max} = 50 kOe	H_{max} = 90 kOe T_{meas} < 9 K	H_{max} = 90 kOe

[N. Kikuchi et al. Appl. Phys. Lett. 82, 4313 (2003)]

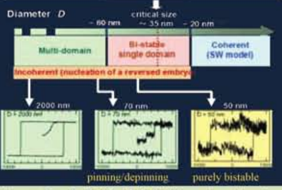
Magnetic behaviors of single crystal L1$_0$ FePt dots

Critical size for coherent / incoherent switching

$$D_c = \frac{2q}{M_s}\sqrt{\frac{2A}{N_x}} \sim 35\ \mathrm{nm} > \text{Experiment}\ \ 20\ \mathrm{nm}$$

M_s = 1250 G
A = 1 × 10^{-6} erg/cm

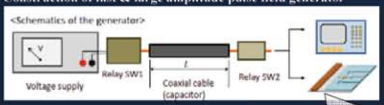
for aspect ratio of 5



For the first time, we have clarified that FePt dot behaves in a coherent manner when the dot size is smaller than nearly half the exchange length. ($D < L_{ex}/2$)

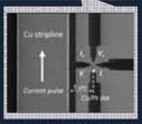
Magnetization dynamics in single nanomagnet

Construction of fast & large amplitude pulse field generator



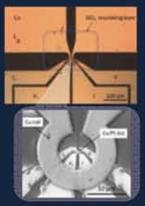
rise time < 0.4 ns
&
max H = 800 Oe (at I_p = 3.4 A)

This max H is insufficient to switch Co/Pt dot !!

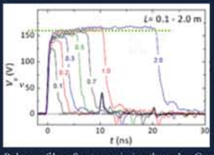


Cu line and AHE device with Co/Pt dot

Generation of *ns* pulse field



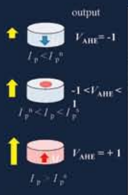
Optical & magnified SEM image of microcoil and AHE device with Co/Pt dot located at the crossing center.

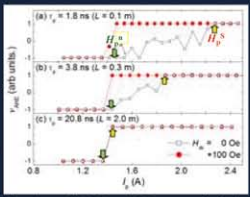


Pulse profiles after transmission through a Cu coil for various coaxial cable length L= 0.1 - 2.0m.

By varying the cable length L, we can control the pulse width from 1 ns to 20 ns, and its maximum field reaches 4.0 kOe.

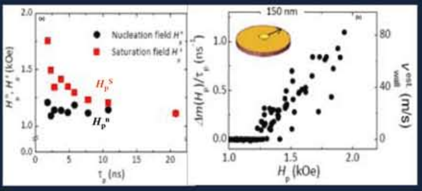
Switching experiment of [Co/Pt] dot by nanosecond pulse field





The positive pulse field with duration τ_p of 1.8, 3.8, and 20.8 ns was applied to the negatively saturated dot. For $I_p < I_p^n$, no change occurs (V_{AHE} = -1). For $I_p^n < I_p < I_p^s$, nucleation of a reversed domain occurs(-1 < V_{AHE} < +1). Further increase in the current gives the positive saturation (V_{AHE} = +1). We note that nucleation occurs within extremely short time of about 1ns, followed by its gradual expansion.

Nucleation & Wall dynamics in single [Co/Pt] dot

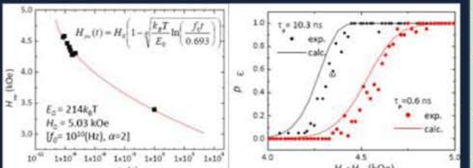


✓ Nucleation of a reversed embryo occurs less than 1 ns
✓ Domain wall velocity is proportional to field amplitude

velocity $V = \mu(H_p - H_n)$ μ **: mobility** (=130 m s^{-1} Oe^{-1})

✓ We can determin spin damping parameter α from μ

Thermal fluctuation of magnetiization in *ns* regime



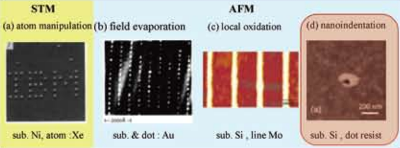
The classic Neel-Arrhenius model on thermal fluctuation reproduces the switching probability very well, indicating that

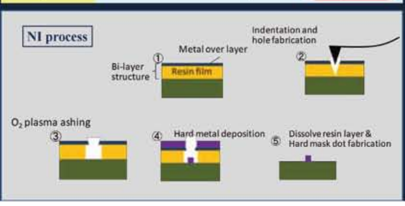
Neel-Arrhenius model is good approximation even in *ns* regime

Summary

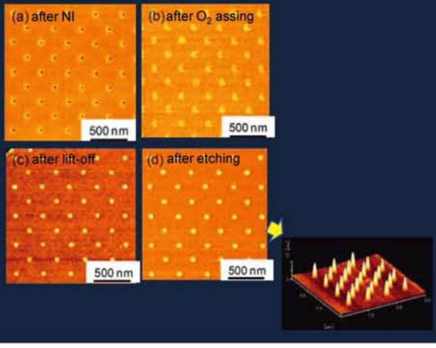
1. We have newly developed highly sensitive magnetic detection method utilizing the Anomalous Hall Effect (AHE) with sensitivity of 10^{-15} emu.
2. By means of the AHE method, we have successfully measured the magnetization curves of single nanomagnet and performed systematic study on L1$_0$ FePt and Co/Pt.
3. We have developed a fast pulse field generator being able to generate a pulse field with rise time less than 0.4 ns and amplitude of 4.0 kOe.
4. The ns switching experiment has revealed that magnetization switching proceeds via very rapid nucleation of a reversed embryo followed by its gradual expansion.
5. The classic Neel-Arrhenius model on thermal fluctuation reproduces the switching probability very well, indicating that Neel-Arrhenius model is good approximation even in *ns* regime

Development of SPM nanofabrication technique





Dot fabrication process



Dot fabrication process