Thermal Anisotropy Modulation as a Major Source of Third Harmonic Magnetoresistance in Ni Thin Films

Yizi Feng[1], Haoran Chen[1], Tong Wu[1], Yunzhuo Wu[1], Le'an Li[1], Nan Jiang[1], Yizheng Wu*[1]

[1]Department of Physics, Applied Surface Physics State Key Laboratory, Fudan University, Shanghai, China

WU GROUP

Introduction

▶ Harmonic Voltage Measurement

Under a current excitation I,
the resistance may depend on the current

$$R(I) = R_0 + R_1 I + R_2 I^2 + \cdots$$

For sinusoidal current $I = I_0 \sin(\omega t)$,

$$V = IR(I) = R_0 I_0 \sin(\omega t) + R_1 I_0^2 \sin^2(\omega t) + R_2 I_0^3 \sin^3(\omega t) + \cdots$$
$$= V_{DC} + V_{1\omega}\sin(\omega t) + V_{2\omega}\cos(2\omega t) + V_{3\omega}\sin(3\omega t) + \cdots$$

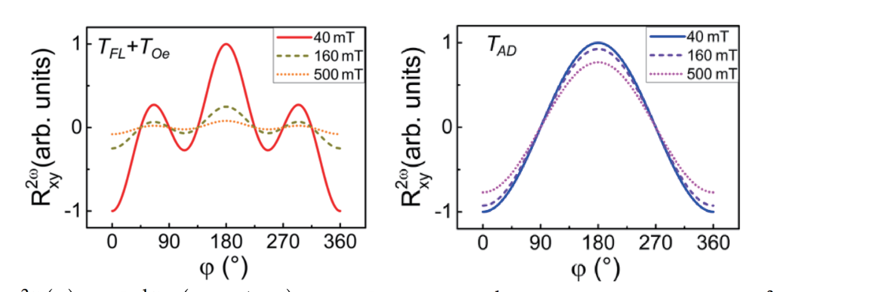
- V_{DC}: rectified voltage
- $V_{1\omega}$: first harmonic voltage
- $V_{2\omega}$: second harmonic voltage
- $V_{3\omega}$: third harmonic voltage
- ...

▶ Second Harmonic Measurement

a. Spin-orbital torque (SOT)

b. Unidirectional spin Hall magnetoresistance(USMR)

c. Thermal effects (anomalous Nernst effects、spin Seebeck effect...)



$$R^{2\omega}_{xy}(\varphi) = \{[R^{1\omega}_{AHE}(B_{DLT}/B_{eff}) + R_{VT}]\cos\varphi + [2R^{1\omega}_{PHE}(B_{FLT} + B_{Oe})/B_{ext}](2\cos^3\varphi - \cos\varphi)\}$$

Can Onur Avci et al, Physical Review B 90, 224427 (2014)

▶ Third Harmonic Measurement

a. SOT: nonlinear term of magnetization oscillation

b. SOT: nonlinear term of Spin Hall effect (NSHE)

c. Quantum geometry effects

d. Magnetoelastic effect

f. Thermally induced magnetization reduction

A new mechanism :thermally induced magnetocrystalline anisotropy variation

Thermal Effects in 3rd Harmonic Measurement: derivation

▶ Derivation

$$R = R(B,T_0) + \frac{\partial R(B,T_0)}{\partial T}\delta T = R(B,T_0) + \alpha\frac{\partial R(B,T_0)}{\partial T} I^2$$

for $I = I_0 \sin(\omega t)$:

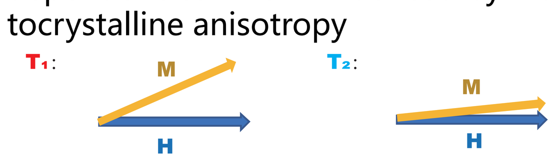
$$V = IR = I_0 R\sin(\omega t) + \alpha\frac{\partial R(B,T_0)}{\partial T} {I_0}^3 \sin^3(\omega t)$$
$$= \left(I_0 R + \frac{3}{4}\alpha\frac{\partial R(B,T_0)}{\partial T}{I_0}^3\right)\sin(\omega t) - \alpha\frac{1}{4}\frac{\partial R(B,T_0)}{\partial T}{I_0}^3\sin(3\omega t)$$

for $R_{xx} = R_0 + R_{AMR}\cos 2\varphi_M$ $\quad R_{xy} = R_{PHE}\sin 2\varphi_M$

$$\frac{\partial R_{xx}}{\partial T} = \frac{\partial R_0}{\partial T} + \frac{\partial R_{AMR}}{\partial T}\cos 2\varphi_M - 2R_{AMR}\sin 2\varphi_M\frac{\partial \varphi_M}{\partial T}$$

$$\frac{\partial R_{xy}}{\partial T} = \frac{\partial R_{PHE}}{\partial T}\sin 2\varphi_M + 2R_{PHE}\cos 2\varphi_M\frac{\partial \varphi_M}{\partial T}$$

The derivative ∂ϕ/∂T can exhibit rich angular dependencies when influenced by magnetocrystalline anisotropy



for in-plane uniaxial magnetocrystalline anisotropy: $E = M\cdot H - H_{Ku} M_s/2\sin^2\varphi_M$

$$\frac{\partial \varphi_M}{\partial T} = \frac{\partial H_{Ku}}{\partial T}\left\{\frac{\sin 2\varphi_M}{2H} + \frac{H_{Ku}}{2H^2}\sin 2\varphi_M\cos 2\varphi_M\right\}$$

for in-plane 4-fold magnetocrystalline anisotropy: $E = M\cdot H - H_{Kc} M_s/2\sin^2\varphi_M\cos^2\varphi_M$

$$\frac{\partial \varphi_M}{\partial T} = \frac{\partial H_{Kc}}{\partial T}\left\{\frac{\sin 4\varphi_M}{4H} + \frac{H_{Kc}}{4H^2}\sin 4\varphi_M\cos 4\varphi_M\right\}$$

▶ Results

Uniaxial Magnetocrystalline Anisotropy

$$R^{3\omega}_{xx} = R^{xx,3\omega}_0 + R^{xx,3\omega}_{\Delta MR}\cos 2\varphi_M - R^{xx,3\omega}_{\Delta H_{Ku}1}\sin^2 2\varphi_M - R^{xx,3\omega}_{\Delta H_{Ku}2}\sin^2 2\varphi_M\cos 2\varphi_M$$

$$R^{3\omega}_{xy} = R^{xy,3\omega}_{\Delta MR}\sin 2\varphi_M + R^{xy,3\omega}_{\Delta H_{Ku}1}\sin 2\varphi_M\cos 2\varphi_M + R^{xy,3\omega}_{\Delta H_{Ku}2}\sin 2\varphi_M\cos 2\varphi_M\cos 2\varphi_M$$

where

$$R^{xx,3\omega}_0 = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_0}{\partial T}$$
$$R^{xx,3\omega}_{\Delta MR} = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_{AMR}}{\partial T} \qquad R^{xy,3\omega}_{\Delta MR} = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_{PHE}}{\partial T}$$
$$R^{xx,3\omega}_{\Delta H_{Ku}1} = \frac{1}{4}\alpha {I_0}^2\cdot R_{AMR}\frac{\partial H_{Ku}}{\partial T}\frac{1}{H} \qquad R^{xy,3\omega}_{\Delta H_{Ku}1} = \frac{1}{4}\alpha {I_0}^2\cdot R_{PHE}\frac{\partial H_{Ku}}{\partial T}\frac{1}{H}$$
$$R^{xx,3\omega}_{\Delta H_{Ku}2} = \frac{1}{4}\alpha {I_0}^2\cdot R_{AMR}\frac{\partial H_{Ku}}{\partial T}\frac{H_{Ku}}{H^2} \qquad R^{xy,3\omega}_{\Delta H_{Ku}2} = \frac{1}{4}\alpha {I_0}^2\cdot R_{PHE}\frac{\partial H_{Ku}}{\partial T}\frac{H_{Ku}}{H^2}$$

4-fold Magnetocrystalline Anisotropy

$$R^{3\omega}_{xx} = R^{xx,3\omega}_0 + R^{xx,3\omega}_{\Delta MR}\cos 2\varphi_M - R^{xx,3\omega}_{\Delta H_{Kc}1}\sin 2\varphi_M\sin 4\varphi_M - R^{xx,3\omega}_{\Delta H_{Kc}2}\sin 2\varphi_M\sin 4\varphi_M\cos 4\varphi_M$$

$$R^{3\omega}_{xy} = R^{xy,3\omega}_{\Delta MR}\sin 2\varphi_M + R^{xy,3\omega}_{\Delta H_{Kc}1}\cos 2\varphi_M\sin 4\varphi_M + R^{xy,3\omega}_{\Delta H_{Kc}2}\cos 2\varphi_M\sin 4\varphi_M\cos 4\varphi_M$$

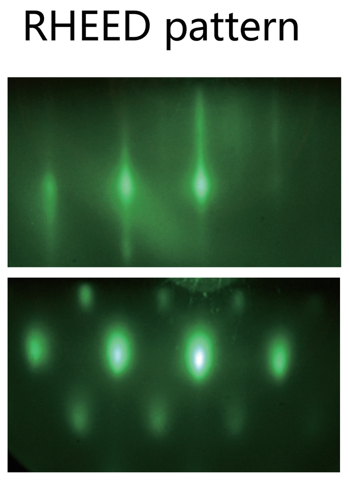
where

$$R^{xx,3\omega}_0 = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_0}{\partial T}$$
$$R^{xx,3\omega}_{\Delta MR} = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_{AMR}}{\partial T} \qquad R^{xy,3\omega}_{\Delta MR} = \frac{1}{4}\alpha {I_0}^2\cdot\frac{\partial R_P}{\partial T}$$
$$R^{xx,3\omega}_{\Delta H_{Kc}1} = \frac{1}{4}\alpha {I_0}^2\cdot R_{AMR}\frac{\partial H_{Kc}}{\partial T}\frac{1}{2H} \qquad R^{xy,3\omega}_{\Delta H_{Kc}1} = \frac{1}{4}\alpha {I_0}^2\cdot R_{PHE}\frac{\partial H_{Kc}}{\partial T}\frac{1}{2H}$$
$$R^{xx,3\omega}_{\Delta H_{Kc}2} = \frac{1}{4}\alpha {I_0}^2\cdot R_{AMR}\frac{\partial H_{Kc}}{\partial T}\frac{H_{Kc}}{2H^2} \qquad R^{xy,3\omega}_{\Delta H_{Kc}2} = \frac{1}{4}\alpha {I_0}^2\cdot R_{PHE}\frac{\partial H_{Kc}}{\partial T}\frac{H_{Kc}}{2H^2}$$

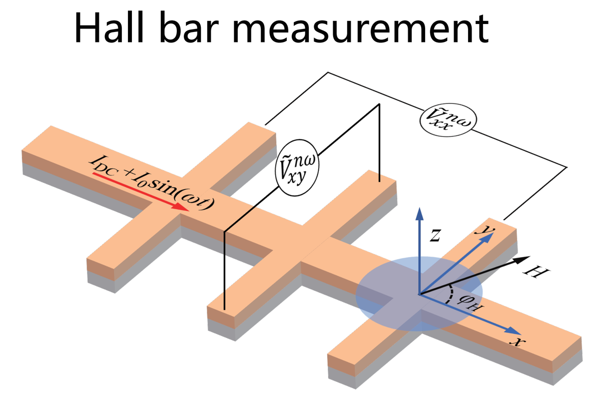
3rd Harmonic signal in Cr/Ni: 4 Fold Anistropy

MgO(001)/Cr(7nm)/Ni(7nm)

RHEED pattern

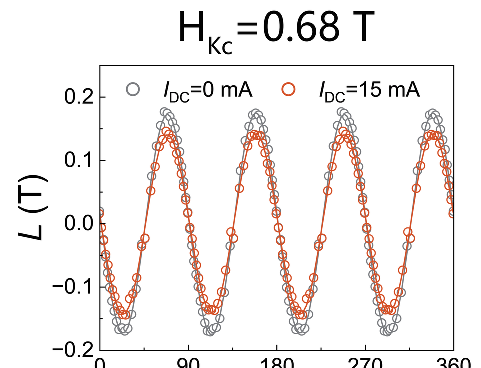


Hall bar measurement



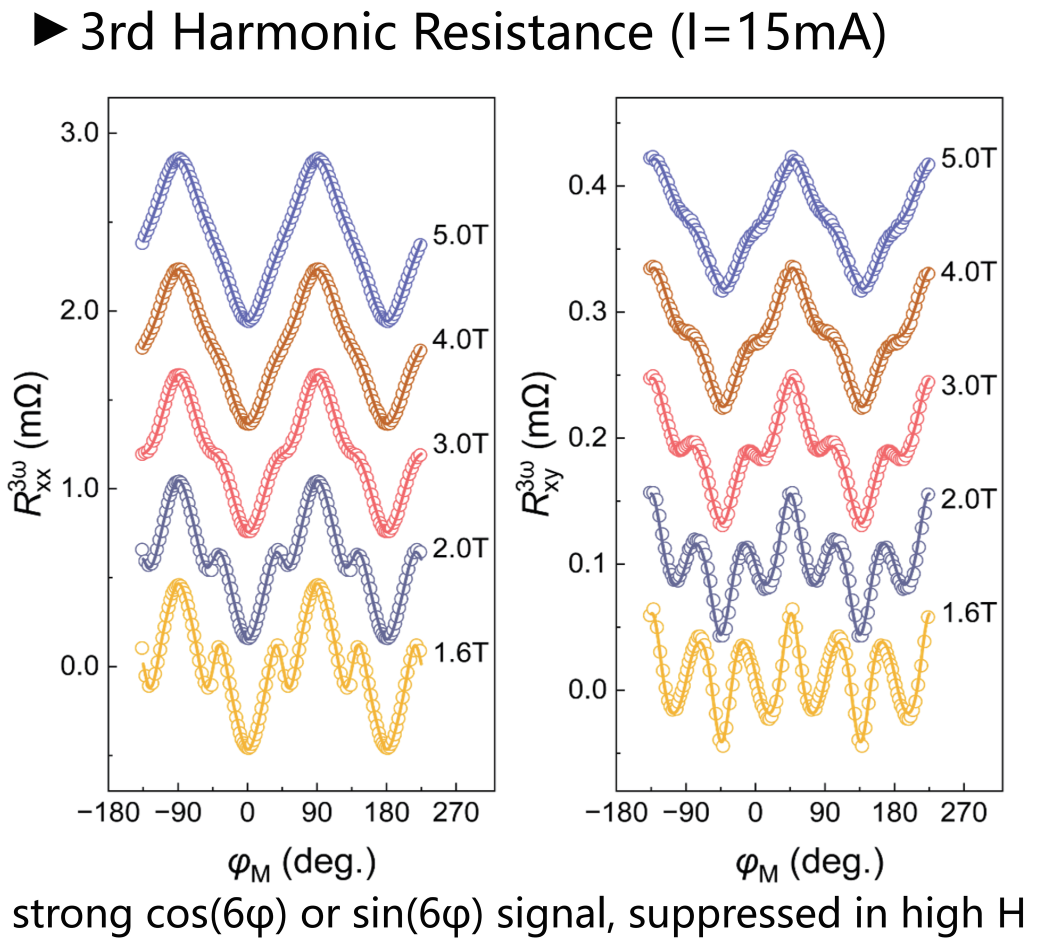
I is along the Cr(001)[100]

H_{Kc}=0.68 T

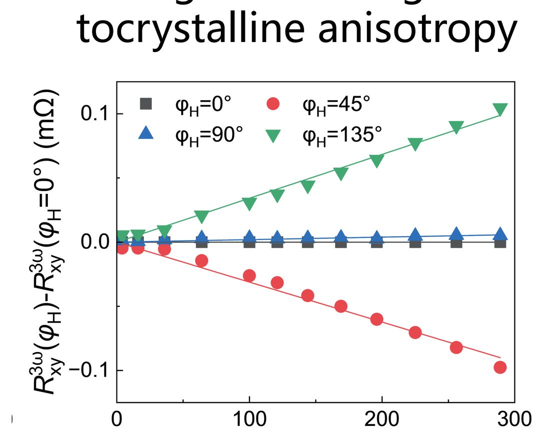


strong 4 fold magnetocrystalline anisotropy

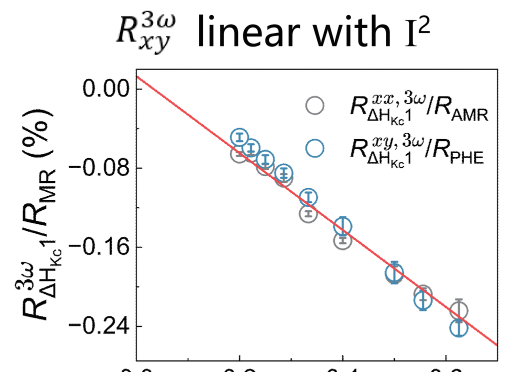
▶ 3rd Harmonic Resistance (I=15mA)



strong cos(6φ) or sin(6φ) signal, suppressed in high H



$R^{3\omega}_{xy}$ linear with I²



$R^{xx(xy),3\omega}_{\Delta H_{Kc}1}$ linear with 1/H

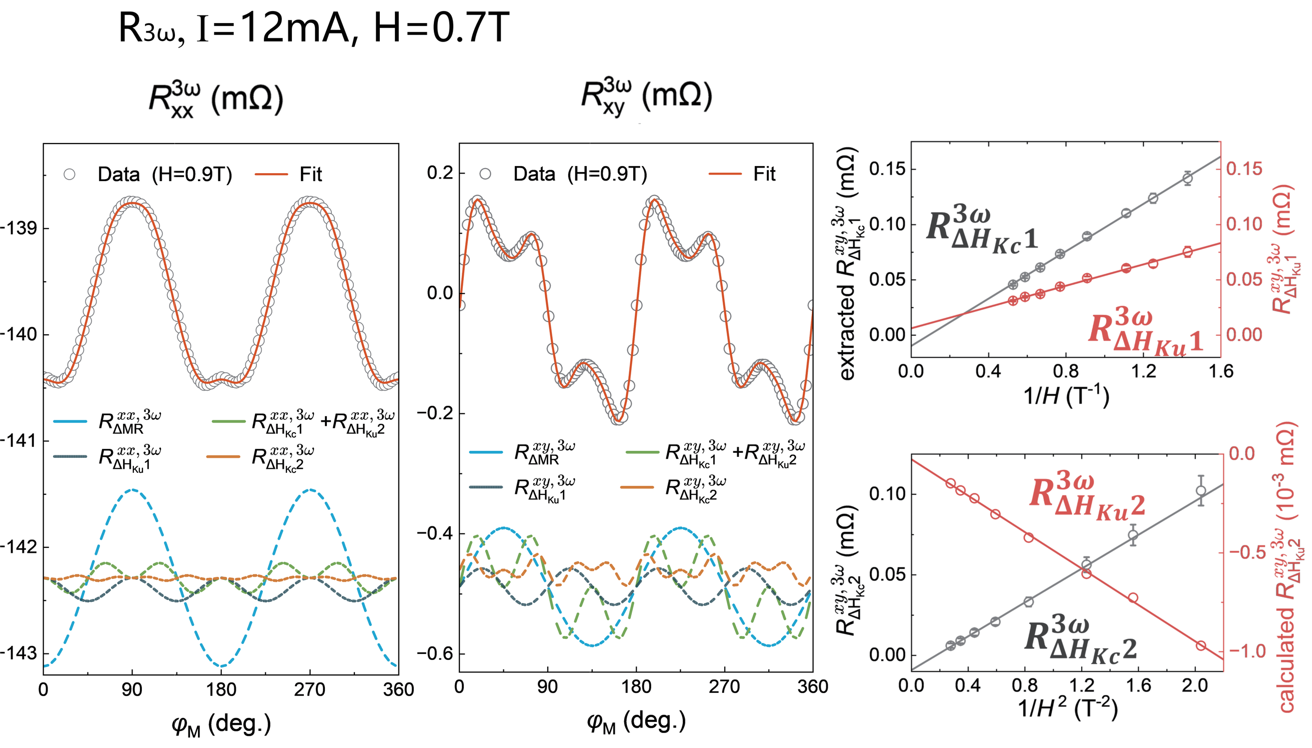
3rd Harmonic in Ni

▶ Single Crystal Ni

MgO(001)/Ni(10nm)

uniaxial anisotropy + 4 fold anisotropy √

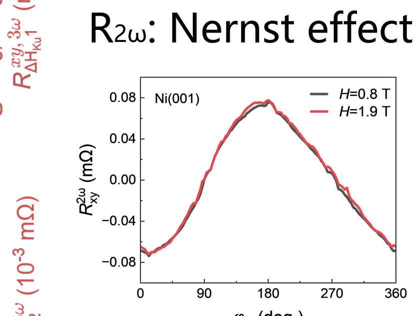
R3ω, I=12mA, H=0.7T



both $R^{3\omega}_{\Delta H_{Kc}}$ and $R^{3\omega}_{\Delta H_{Ku}}$ dominate

different field scaling

R2ω: Nernst effect



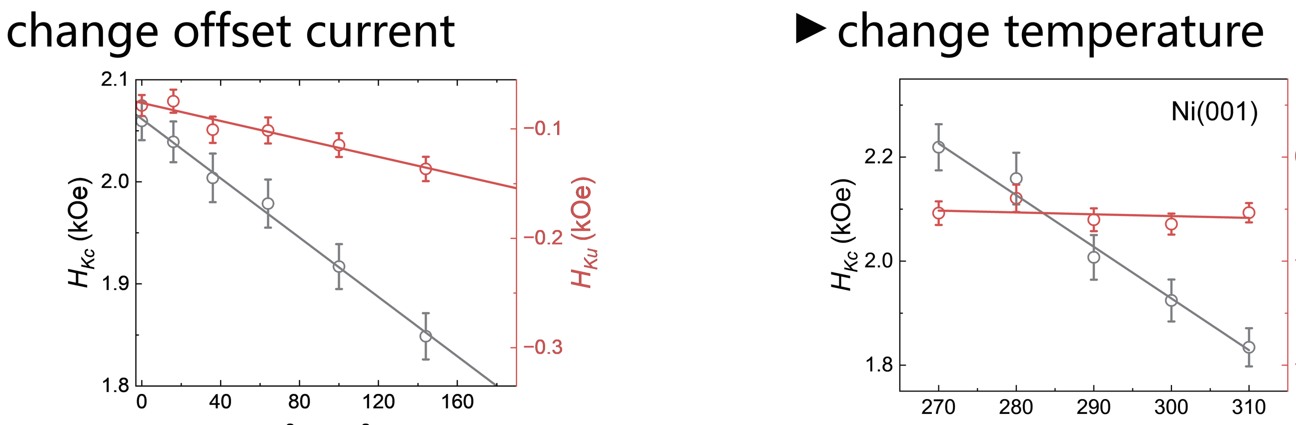
No obvious SOT signal ✕

Anisotropy measurement

$I = I_{DC} + I_0\sin(\omega t)$, I_0=2mA

H_{ku}: Uniaxial Anisotropy Field H_{kc}: 4-fold Anisotropy Field

▶ change offset current ▶ change temperature



★ $H_{ku} \propto I^2_{DC}$, independent of sample temperature

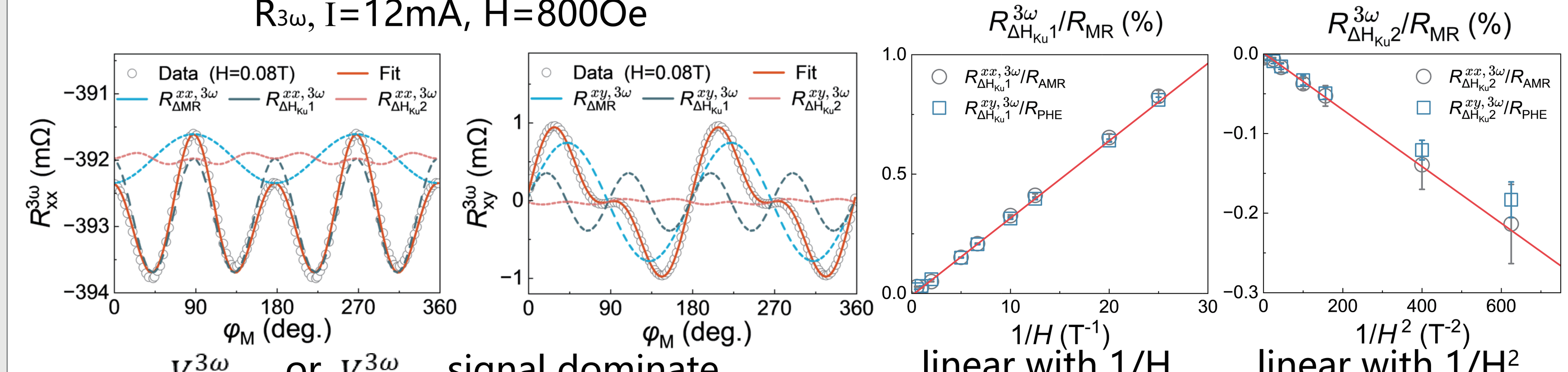
$H_{kc} \propto I^2_{DC}$ and temperature

▶ Poly Ni

Al2O3(0001)/SiO2(4nm)/Ni(10nm)

uniaxial anisotropy √

R3ω, I=12mA, H=800Oe



$V^{3\omega}_{xx,HI,1}$ or $V^{3\omega}_{xy,HI,1}$ signal dominate

linear with 1/H

linear with 1/H²

Summary

- ▶ Third-harmonic voltage in Cr/Ni and Ni systems
- ▶ New mechanism identified: thermally induced magneto-crystalline anisotropy variation
- ▶ Third-harmonic voltage depends on the type of magneto-crystalline anisotropy in this mechanism
- ▶ Thermal effects must be carefully considered in third-harmonic measurements