# Nanomanufacturing of High Energy Product Tetragonal-FeCo Nanostructures ( NSF-CMMI-1332658 )

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## INTRODUCTION

**Background**: High-performance rare earth magnets, such as Nd-Fe-B and SmCo, have been developed because of growing demand for green energy technologies. A peak energy product has been reached at about ~56 MGOe during the past 10 years. However, due to the cost and very limited supplies of rare earth magnets, great efforts in material science and technology have been made globally on their potential substitutions.

**Project achievement**: Tetragonal FeCo nanostructures are becoming particularly attractive because of their high magnetocrystalline anisotropy (MAE) and magnetization achievable without rare-earth element. Yet, controlling their metastable structure, size and stoichiometry is a challenging task. In this study, we demonstrate AuCu templated FeCo shell growth followed by thermally induced phase transformation of AuCu core from face-centered cubic to $L1_0$ structure, which triggers the FeCo shell to transform from the body-centered cubic structure to a body-centered tetragonal phase. High coercivity, 846 Oe, and saturation magnetization, 221 emu/g, are achieved in this tetragonal-FeCo structure. Beyond a critical FeCo shell thickness, confirmed experimentally and by lattice mismatch calculations, the FeCo shell relaxes. The shell thickness and stoichiometry dictate the magnetic characteristics of the tetragonal-FeCo shell. This study provides a general route to utilize phase transformation to fabricate high performance metastable nanomagnets, which could open up their green energy applications.

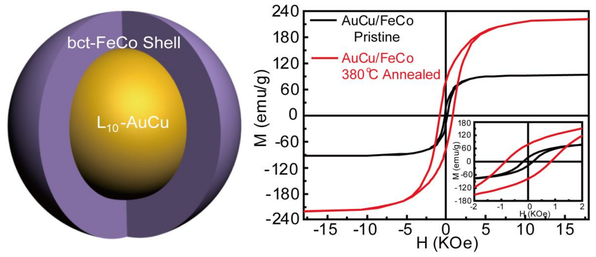



**Figure 1**. Phase transformation induced tetragonal FeCo nanostructures, exhibiting high magnetocrystalline anisotropy due to the lattice distortion through thermal treatment.

**Project product**:

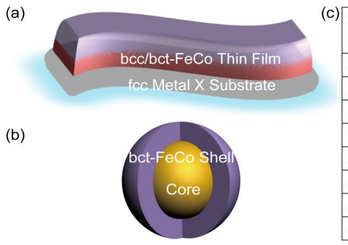
1. Gong, M.; Kirkeminde, A.; Skomski, R.; Cui, J.; Ren, S. Q.* Template-Directed FeCo Nanoshells on AuCu. ***Small***, 10, 4118 (2014).

2. Kirkeminde, A.; Ren, S. Q.* Interdiffusion Induced Exchange Coupling of L10-FePd/α-Fe Magnetic Nanocomposites. ***Nano Letters***, 14, 4493 (2014).

3 . Gong, M.; Kirkeminde, A.; Wuttig, M.; Ren, S.Q.* Phase Transformation Induced Tetragonal-FeCo Nanostructures, ***Nano Letters***, DOI:10.1021/nl5030485 (2014).

## RESULTS: Nanomanufacturing of High Energy Product Tetragonal-FeCo Nanostructures

The tetragonal distortion realized within the FeCo epilayer could enable a large MAE, due to the in-plane expansion from the lattice-mismatched interface. A list of lattice-matched metal substrates with FeCo is shown in the Figure 2, where the Bain-strain lattice correspondence with the FeCo phase makes AuCu a prime candidate for an epitaxial growth template for the FeCo shell. Our hypothesis for this study is to test that the lattice expansion due to $L1_0$ ordering transformation of AuCu core could enable the tetragonal distortion of FeCo shell, leading to a large MAE.




(c)

| fcc Metal X | $a_{fcc}$ [nm] | $a_{bcc\ FeCo}$ [nm] | $\frac{a_{fcc}\sqrt{2} - a_{bcc\ FeCo}}{a_{fcc}\sqrt{2}}$ |
|---|---|---|---|
| Ni | 0.350 | 0.2856 | -0.15382 |
| Cu | 0.362 | | -0.11558 |
| Pt | 0.392 | | -0.0302 |
| Rh | 0.380 | | -0.06273 |
| Ag | 0.409 | | +0.01262 |
| Au | 0.411 | | +0.01742 |
| AuCu | 0.387 | | -0.04351 |
| AuCu($L1_0$) | 0.285 | | -0.10038 |

**Figure 2.** The schematic design route of FeCo thin film growth on fcc metal substrate (a), and bct FeCo shell growth on the core metals. (c) Lattice mismatch table between metal templates and FeCo.

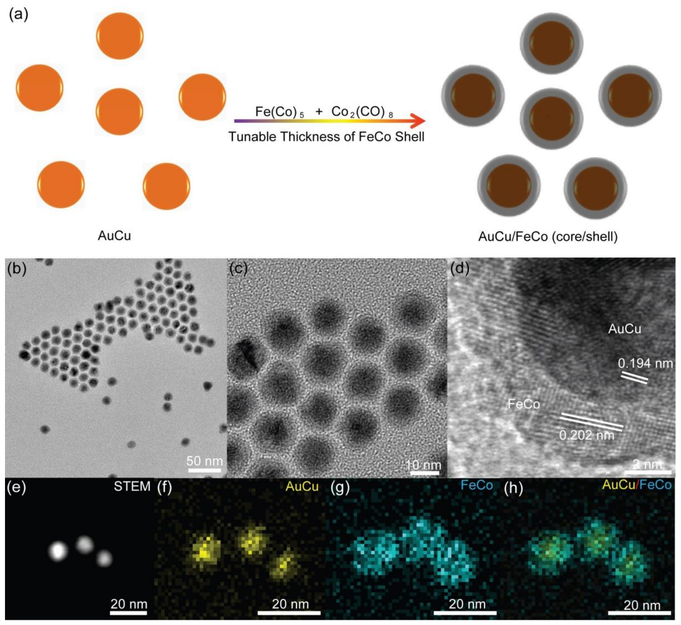



**Figure 3.** (a) Illustration of AuCu/FeCo (core/shell) nanocrystal synthesis. (b-d) TEM and high-resolution TEM (HRTEM) images of AuCu/FeCo (core/shell). (e) STEM elemental mapping images of AuCu/FeCo core/shell nanocrystals, (f) AuCu core elemental mapping images in yellow, (g) FeCo shell elemental mapping images in blue, and (h) Combined AuCu/FeCo core-shell elemental mapping image.

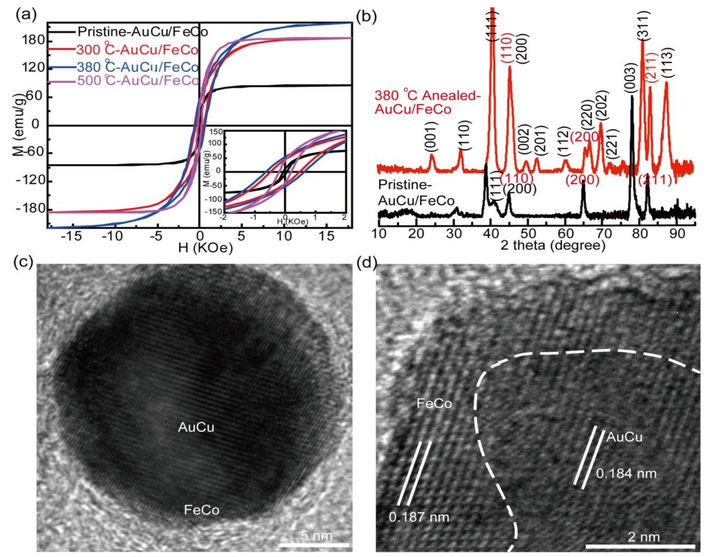



**Figure 4.** (a) Magnetic-Hysteresis loops of L10-AuCu/FeCo core/shell nanocrystals with an overall Fe:Co ratio at 47:53 under different annealing conditions. The inset shows the annealing temperature dependent coercivity of $L1_0$-AuCu/FeCo. (b) XRD patterns of AuCu/FeCo core/shell nanocrystals: pristine and after 380oC annealing. The black and red labeled peaks represent AuCu and FeCo diffraction peaks. (c and d) TEM and HRTEM images of $L1_0$-AuCu/tetragonal-FeCo nanocrystals annealed at 380ºC.

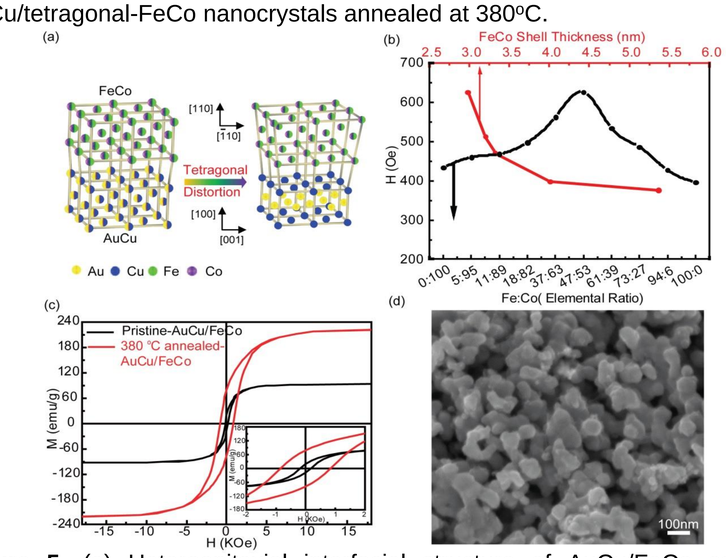



**Figure 5.** (a) Heteroepitaxial interfacial structure of AuCu/FeCo core/shell systems: pristine (left) and after 380ºC annealing (right). (b) The coercivity depends on the FeCo shell thickness and stoichiometry. (c) M-H loops of AuCu/FeCo with an overall Fe/Co ratio at 53:47. The inset shows the annealing temperature dependent coercivity of L10-AuCu/FeCo. (d) SEM image of AuCu/FeCo core/shell particles at 53:47 annealed at 380ºC.

## CONCLUSION AND ACKNOWLEDGEMENT

A versatile templating and phase transformation approach is reported to manufacture tetragonal FeCo nanomagnets. The novelty of this approach is that a tetragonal FeCo shell can be induced by the $L1_0$ phase transformation of the AuCu templating core under mild thermal annealing. The structure evolution of the AuCu core dictates the tetragonal distortion of the FeCo shell, leading to its tunable magnetic characteristics. The close lattice match between the $L1_0$ ordered AuCu core and tetragonal (110) FeCo shell forms a stable interface. This work provides a general route to synthesize heteroepitaxial $L1_0$-AuCu/tetragonal-FeCo nanomagnets. This synthetic effort could be expanded to other magnetic composite systems which will allow the fabrication of high energy density magnets for magnetic storage and green energy applications. **ACKNOWLEDGEMENT**: This work was funded by National Science Foundation under Award Number NSF-CMMI-1332658.