Interfacial Roughness Facilitated by Dislocation and a Metal-Fuse Resistor Fabricated Using a Nanomanipulator

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ABSTRACT: Granular magnetic systems consisting of magnetic nanoparticles embedded in a nonmagnetic metallic matrix have emerged as an attractive building block for nanodevices. A key challenge for building interface-based nanodevice applications, such as magnetic memory devices, is to clearly know about the influences of interfacial roughness on the scattering of conduction electrons. Here, we demonstrate a granular magnetic system composed of Co and Cu nanoparticles and further link the atomic structure of the Co/Cu interface to the scattering mechanism of conduction electrons. The multiple scattering is caused by the dislocations at the rough interface, which lead to a reduction of conduction efficiency and an increase of energy consumption.

These dislocations mostly originate from the lattice defects on the surface of nanoparticles, the lattice mismatch of two crystal structures, and the different surface energies. Based on the negative effects of a rough interface on electronic transport, we first develop a nanometal-fuse resistor, which could hopefully be used in the protection circuits of nanodevices. Our results may open up the possibility of implementing the low-dimensional granular magnetic materials in nanodevice applications.

KEYWORDS: granular magnetic systems, interface, dislocation, nanowire, nano metal-fuse resistor, aberration-corrected transmission electron microscopy

INTRODUCTION

The study of granular magnetic systems composed of magnetic nanoparticles embedded in a nonmagnetic metallic matrix has experienced growing interest in the last decade.^{1–11} Their giant magnetoresistance effect (GMR) attracts continuous attention because of potential magnetic recording and magnetic nanosensing applications.^{4,12–15} The main generation mechanism of GMR is the spin-dependent scattering of conducting electrons at interfaces between the magnetic particles and the nonmagnetic metallic matrix.¹² Therefore, a detailed description of the interface is necessary to understand the GMR behavior. A number of experiments and model calculations have been already performed to elucidate the interface impact on GMR.^{12,16,17} It is proved that GMR is determined by the interfacial area and the corresponding structure.¹⁷ However, few studies focus on the interfacial structure between the magnetic particles and the nonmagnetic metallic matrix on the atomic scale. The atomic observation of the interfacial structure requires an extremely high spatial technique. An aberration-corrected transmission electron microscope (Cs-corrected TEM) and a scanning transmission electron microscope (Cs-corrected STEM) equipped for performing electron energy-loss spectroscopy (EELS) and energy-dispersive X-ray analysis (EDX) have recently made significant

progress in terms of space and time resolution, and achieved a surprisingly high spatial resolution below 0.5 Å and readily realized a direct imaging and electronic-state detection of individual atoms and even chemical bonds.¹⁸ In this work, we employ a Cs-STEM with EELS and EDX to identify the GMR mechanism involving the influence of interfacial roughness on the scattering of conduction electrons.

A Co/Cu granular magnetic system is a good example model for studying the correlation between the interfacial structure and electron scattering because of its large GMR effect¹⁴ and small lattice mismatch (<2%).¹⁹ As illustrated in Figure 1a, [001]-Co and [001]-Cu developed in a Co/Cu system are well matched. In addition, previous reports²⁰ found that it is very difficult to produce a solid solution using Co and Cu, which can be attributed to a lower surface energy of Cu (1.52 J·m⁻²) than that of Co (2.16 J·m⁻²). Those investigations indicate that the Co/Cu system preferentially forms a well-defined interface.

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Figure 1. DFT calculations were employed to explore the interfacial structure and the scattering mechanism between the Co and the Cu grains. (a) Interfacial structure of Co and Cu along the [001] orientation with a good lattice matching. (b) Co atoms have easy access to the Cu crystalline structure with the Cu grain surface of the existing lattice defects. (c) Energy dependence on the number of substitution atoms in Cu/Co systems. (d) Charge redistribution, defined as $\rho_{\text{Co/Cu}} - \rho_{\text{Cu}} - \rho_{\text{Co}}$, in the Cu/Co system without Cu atom substitution. (e) Charge redistribution in the Cu/Co system with one Cu atom substituted by a Co atom. (f,g) Diagrams of magnetic moment changes of Cu atoms at the interface.

The interfacial structure has a great effect on the local geometry of the magnetic moment and the hybridization between the Co and Cu 3d bands, which directly causes the transformation of the atomic magnetic moment and GMR response at the Co/Cu interfaces. Thus, the interfacial structure of the Co/Cu system studied here has a considerable significance because of its wide range of properties such as electrical properties,^{21,22} magnetic properties,¹⁹ and energy

storage,²³ and practical application in gas sensors²⁴ and spintronics.²⁵

In this work, magnetic Co/Cu granular nanowires were chosen to explore the influence of a rough interface on electron scattering because of their small size¹⁸ and because their atomic structure can be observed using a Cs-STEM.²⁶ Our measurement and density functional theory (DFT) calculation results revealed that the formation of a rough interface between Co and Cu grains originates from the dislocation (see details in the later part) and the conduction electrons are largely scattered on the interfaces, which then leads to a dramatic resistivity increase of the Co/Cu nanowires. Utilizing single Co/Cu nanowires, we successfully developed a metal-fuse resistor (MFR) device for an in situ scanning electron microscope (SEM), and its resistivity and maximum current density were measured to be $1.75 \times 10^{-8} \Omega \cdot \text{m}$ and $4.7 \times 10^{11} \text{ A} \cdot \text{m}^{-2}$, respectively, which can be well used to protect nanodevices and nanosensors from a large pulse current.

RESULTS AND DISCUSSION

The Co/Cu granular magnetic nanowires were grown by template synthesis (see the nucleation mechanism analysis in Supporting Information).^{27–31} It was found that the crystal structure of Co is a fcc structure, which is epitaxially determined by that of Cu. In addition, the deposition overpotential of Cu ions is lower than that of Co ions,³² easily inducing the lattice defects on the surface of Cu grains, in which the defect sites could be occupied by Co atoms during the crystal growth. However, it is very difficult to replace Cu atoms by Co atoms in a perfect Cu single crystal (see Figure 1c–g for a detail discussion), because of which a thin interface was formed between Co and Cu grains under our experimental conditions, as illustrated in Figure 1b.

To explore the interfacial structure and the scattering mechanism between Co and Cu grains, DFT calculations were employed, as shown in Figure 1c–e. Figure 1c presents the

Figure 2. The morphology, crystal structure, chemical composition of the Co/Cu granular magnetic nanowires analyzed by SEM and TEM. (a) SEM image of the nanowires dispersed on an $\text{SiO}_2(200 \text{ nm})/\text{Si}$ with free-standing formation after the template dissolved. (b) TEM image of four nanowires with a 55 nm uniform diameter. (c) EDX spectrum measured from a bundle of Co/Cu nanowires. (d) HAADF-STEM image of the scanned area of the elemental mapping. (e–g) EDX elemental mappings of Co $K\alpha$, Cu $K\alpha$, and their combination, respectively. (h) SAED pattern of four NWs taken from the area marked by a dashed circle in (b).

Figure 3. High-resolution STEM images of the interface at different positions and the EELS scan line spectra. (a) Cs-STEM image of the two nanoparticles along the [110] orientation inside the nanowires, and the insets of the lower right-hand corner and the lower left-hand corner are the collection of two line scan spectra taken across the two nanoparticles using the EELS line scan, of which the collected positions are marked by the dotted line in (a) and zoomed in the inset, the upper image is the crystalline structure of the interface. (b,e) Cs-STEM image of the two nanoparticles along the [110] orientation at different positions. (c,f) FFT images of (b,e), respectively. (d,g) IFFT images of the (111) plane marked in (c,f), respectively.

energy dependence on the number of Co–Cu atomic interchange along the [001] direction, of which the system consists of a $4 \times 4 \times 1$ Cu unit cell (marked by blue balls) and a $4 \times 4 \times 1$ Co unit cell (marked by red balls). We found that the energy of the system increases with an increase in the number of Co/Cu atoms that interchange. Because of swapping either one atom or more atoms shown in the insets of Figure 1c, the energy of the system becomes far higher than that without interchange of atoms (see the inset in the lower left of Figure 1c). This result indicates that the Co/Cu atomic interchange is very hard. Meanwhile, the lattice defects on the surface of Cu grains are easily generated during the electrodeposition, because of which a thin interface is formed between Co and Cu grains. Figure 1d,e show charge redistribution, defined as $\rho_{\text{Co/Cu}} - \rho_{\text{Cu}} - \rho_{\text{Co}}$, where $\rho_{\text{Co/Cu}}$ is the charge density of the Co/Cu system with/without atomic interexchange, and ρ_{Cu} (ρ_{Co}) is the charge density of the Cu (Co) surface. The red color represents the electron accumulation and the blue color represents the electron depletion. The d orbital of Co located in the blue area and the p orbital of Cu in the red area in Figure 1d (without atomic interchange) indicate that the d orbital of Co loses electrons and the p orbital of Cu gains electrons at the interface. Because of the charge redistribution, Cu atoms at the interface have

induced magnetic moments, whose calculated data of are shown in Table S1 and the corresponding the schematics are presented in Figure 1f,g. Two layers of Cu atoms at the interface have different magnetic moments and in the opposite direction under zero external magnetic field, causing a large scattering of conduction electrons. As the number of the Co/Cu atomic interchange increases, electron gain and loss at the interface increases (Figure 1e), causing that the magnetic moment direction of Cu atoms away from the interface is inverted as shown in Figure 1g. Therefore, the scattering mechanism with the conduction electrons at the interface causes the formation of magnetic moments of Cu atoms.

The morphologies of Co/Cu granular magnetic nanowires were observed on the nanoscale using a SEM and a TEM. Figure 2a shows a representative SEM image of the Co/Cu NWs dispersed on a free-standing SiO_2 (200 nm)/Si after the dissolution of the template. Quantitative analysis reveals that the average diameter of the Co/Cu NWs is 52 nm and that of the length is about 30 μm . The length-to-diameter ratio was therefore calculated to be about 577. The TEM image (Figure 2b) further shows that individual Co/Cu NWs have a uniform diameter of 55 nm, which is the same as the above SEM observation with error. Besides, it is clearly seen that the Co/Cu NW is composed of tiny grains. The statistics of the

average sizes are shown in Figure S2, the average sizes of these Cu and Co grains are obtained to be 5 and 12 nm. In order to obtain the chemical composition of the NWs, the chemical analysis of the nanowires was performed by using energy dispersive X-ray (EDX). Figure 2c shows the corresponding EDX spectrum measured from the Co/Cu nanowires. As expected, both Cu and Co peaks of the nanowires appear. Quantitative analysis of the EDX spectrum indicates a 73:27 atomic ratio of Co/Cu, inferring a $\text{Co}_{73}\text{Cu}_{27}$ composition under our experimental conditions. This result is in agreement with the results of the analysis of the CV curves (see Supporting Information for details), verifying the rapid nucleation and growth of Co under a -1 V depositional potential. In addition, the Al and O peaks on the EDX spectrum (Figure 2c) come from the residue of dissolved alumina, and the Ni and C peaks correspond to the carbon-coated nickel grid, which were confirmed by EDX of an empty carbon-coated nickel grid. To further verify the distribution of two elements within the nanowires, EDX maps of the cobalt and copper elements were obtained. Figure 2d shows a high-angle annular dark field (HAADF)–STEM image of the single nanowire, which was used for the chemical analysis. Figure 2e,f display the corresponding EDX elemental maps of Cu ($K\alpha$ at 8.048 keV) and Co ($K\alpha$ at 6.980 keV), respectively. It is seen that the Cu and Co elements were uniformly distributed throughout the whole nanowires. In order to well understand the distributions of two elements within a single nanowire, the mapping images of Cu $K\alpha$ and Co $K\alpha$ were combined as shown in Figure 2g. The EDX spectrum and elemental mapping results only confirm that the individual nanowire is composed of the Co and Cu elements.

The crystal structures of the Co and Cu grains in the NWs were further analyzed using the selected-area electron diffraction (SAED) technique. Figure 2h shows a typical SAED pattern of four NWs taken from the area marked by a dashed circle in Figure 1b. The rings can be indexed to two sets of lattice planes. The sky-blue one can be well indexed to be an fcc structure of (111), (200), (220), (311), (222), and (400) planes with a 3.61 Å lattice constant, which come from the Cu nanograins. The red one can be well indexed to be an fcc structure of (111), (200), (220), (311), and (222) planes with a 3.54 Å lattice constant, which is attributed to the Co nanograins. This result discloses that the nanowires consist of the fcc Co and fcc Cu nanograins. Because Co is typically a hcp structure, the fcc structure of Cu nanograins is deduced to have an induced effect on the crystalline growth of Co nanograins, fitting with the crystallite growth controlled by the incorporation of metal atoms into the lattice interface.³³ Therefore, the lattice defects on the Cu nanoparticle surface and the lattice mismatch between Co and Cu should induce a rough interface, which causes a large scattering with the conduction electrons at the interfaces between the Co and Cu nanograins. However, the interfacial roughness cannot be evaluated by using the SAED technique because the interface is made up of several atomic layers and the incident diameter of the SAED beam is more than 50 nm.

In order to obtain the accurate interfacial information, a Cs-STEM equipped with EDX and EELS was employed. Figure 3a shows a representative atomic-resolution HAADF–STEM image of the two Co and Cu grains inside the NW, in which chemistry analyzed by the EELS line scan is given in the lower right-hand and the lower left-hand corner. The two spectra were collected from the two lines scanned by red and blue

dotted lines on 12 and 5 nm grains (the insets in Figure 3a are the magnification of the scanning positions), respectively. It is clearly seen that the Co signal (Co $L_{2,3}$ edge) oscillates along the red-dotted line while the Cu signal (Cu $L_{2,3}$ edge) remains constant on 12 nm grains. In contrast, the Cu signal oscillates along the blue-dotted line while the Co signal remains constant on 5 nm grains. This result further confirms that the Co/Cu NW consists of 12 nm Co and 5 nm Cu nanograins. It is proved that the growth rate of Co is faster than that of Cu, which is previously speculated through the analysis of the CV curve and the EDX spectrum. From the atomic resolution HAADF–STEM image projected along the $[110]$ orientations of the Co and Cu grains (Figure 3a), both reveal that the individual Co or Cu nanograins are monocrystals with a fcc structure. The interplanar distances were measured to be 0.206 ± 0.003 and 0.203 ± 0.003 nm, matching with the (111) planes of fcc Cu and Co, respectively. Meanwhile, it is clearly seen that Co and Cu grains have an epitaxial growth along the $[001]$ orientation and form a close-packed structure as previously reported,³⁴ which proves that the mechanism of the nucleation and growth of Co/Cu nanowires is controlled by the incorporation of metal atoms into the lattice interface under our deposition conditions. The interface between the Co and Cu grains was marked by yellow-dotted lines in Figure 3a. The thickness of the interfaces is about 0.57 nm (about three atomic layers) and a dislocation is clearly displayed (as shown in the top crystal structural illustration in Figure 3a). To further investigate the interfacial atomic structure, the other two atomic HAADF–STEM images from the different positions were obtained along the $[110]$ orientation, as shown in Figure 3b,e. The interplanar distances were measured to match with the (002) planes of fcc Cu and Co, further verifying that the Co grains epitaxially grow along the Cu $[001]$ orientation on the nanoscale as mentioned above. However, Co(111) and Cu(111) have a lattice mismatch (about 2%)¹⁹ and the Co surface energy is larger than that of Cu, the dislocations are therefore very easily formed between the Cu and Co grains and the rough interfaces are induced to generate. Figure 3b,e clearly show two irregular rough interfaces between the Cu and Co grains marked by the yellow-dotted lines. To well display the dislocations, the inverse fast Fourier transform (IFFT) technique was employed. Figure 3c,f show the FFT images of Figure 3b,e, while Figure 3d,g show the corresponding IFFT images of the diffraction points from the (1–11) and (–11–1) planes masked by green-dotted circles in Figure 3c,f, respectively. It is shown that the dislocations induce lattice distortions, while the lattice distortions possess the same size and morphology as the interface marked in Figure 3b,e. This phenomenon indicates that the dislocation is the main reason to form the rough interface, consistent with the previous reports.^{35,36}

The mechanism for the formation of dislocation is suggested as follows (Figure 4): the surface of the Cu grain has a number of lattice defects, which are rapidly occupied by Co atoms during the crystal growth; while it is very difficult for the Co atoms to remain stable because of the lattice mismatch and the large difference in surface energy between the Cu and Co, which induce the stress at the interface; the stress then causes the Co atom to have a deviation from the Cu lattice position and finally forms a dislocation as shown in the inset of Figure 3a; the rough interface is then generated and further leads to the large scattering of conduction electrons and the increase of resistivity. Based on the above experimental results and

Figure 4. Mechanism of the formation of a rough interface. The surface of Cu nanoparticles has a number of lattice defects, which are rapidly occupied by Co atoms during the crystal growth. However, it is very difficult for Co atoms to remain stable because a lattice mismatch and the larger difference of surface energy between the Cu and Co, which induce a stress in the interface and cause the Co atomic deviation from the Cu lattice position. Dislocations are then formed and a rough interface is facilitated.

and an increase of resistivity in the interface. It is inferred that the 55 nm single Co/Cu nanowire has a large resistivity, and can be chosen as the material of the MFR.^{37,38} A 10.71 μm long Co/Cu nanowire was manipulated onto two Pt electrodes to make a MRF nanodevice, which was accomplished using a SEM-nanomanipulator system. Figure S3 presents the detailed fabrication process, in which the dedicated nanomanipulators were used to press the two bottoms of the Co/Cu nanowire on the Pt electrodes and measure the electrical property of the MFR nano-device. Figure 5b,d show a representative SEM image of the MFR nanodevice and the enlarged joint, respectively. It is clearly seen that the nanowire bottom has been mechanically pressed into the Pt electrode, which has formed a good ohmic contact. The electrical property of the MRF nano-device was subsequently measured using the in situ SEM-nanomanipulator system. The voltage–current curve of the MRF nano-device shown in Figure 5f reveals a linear relationship, indicating a successful fabrication of the MRF nanodevice and proving the reliability of the device fabrication method. Quantitative calculation gives a total resistance (R_T) of 1775.2 Ω . In order to obtain the intrinsic resistance of the MRF nanodevice, the tip-to-tip contact resistance (R_i) of the nichrome probes (the inset of Figure 5g) was measured. A 60.3 Ω value was detected (Figure 5g). Therefore, the intrinsic resistance of the MRF nano-device is determined to be 1714.9 Ω after the calibrated tip-to-tip contact resistance (60.3 Ω) (R_i) is subtracted (see more details in our previous reports³⁶). According to the classic resistivity formula $\rho = RS/L$ (where R is the intrinsic resistance, S is the cross-sectional area, and L is the length),^{39,40} the resistivity of the MRF nano-device can be calculated to be $3.39 \times 10^{-7} \Omega \cdot \text{m}$, which is bigger than that of standard bulk Co and Cu ($6 \times 10^{-8} \Omega \cdot \text{m}$ ⁴¹ and $1.75 \times 10^{-8} \Omega \cdot \text{m}$ ⁴² at the room temperature, respectively). This result again

analysis, it can be inferred that the dislocations cause scattering of the conduction electrons in the Co/Cu NW. According to the above analysis, the influences of interfacial roughness on the scattering of conduction electrons are illustrated in Figure 5a. When the conduction electrons collide with the interface between the Co grain and the Cu grain, the electrons lose additional momentum gained from the electric field and show a random direction inside the interface. This effect leads to a large scattering of the conduction electrons

Figure 5. SEM images and electrical properties of the MRF nano-device. (a) Diagram of the scattering of the conduction electrons in the interface. (b) SEM image of the MRF nano-device. (c) SEM image of the MRF nanodevice after Co/Cu nanowire was fused. (d) Enlarged view of the nanowire bottom in the fabricated MRF nanodevice showing the pressed effect by the nanomanipulator. (e) Enlarged view of the breakpoint after the Co/Cu nanowire was fused. (f) I – V curve of the MRF nanodevice. (g) I – V curve of the tip-to-tip contact. Inset, the corresponding SEM image of the tip-to-tip contact. (h) The record time–current curve showing the failure of the MRF nanodevice.

proves that the roughness of the interfaces can cause a large scattering of the conduction electrons. In addition, the maximum current density ($J_{\max}$) is also an important parameter to evaluate the performance of the MRF nano-device, and is obtained by measuring the failure current of the MRF nano-device.⁴⁰ A 0.753 mA failure current was measured as shown in Figure 5h. This curve shows that the MRF nano-device resistance at the point of failure increases rapidly, indicating that a Joule heating breakdown mechanism occurs. $J_{\max}$ is calculated to be 4.7×10^{11} A/m². Figure 5c,e show the images before and after the fuse blew, revealing that the MRF nanodevice works properly. This result indicates that the Co/Cu NW can be well used as a fuse material for nanodevices and nanosensors.

CONCLUSION

In conclusion, we have comprehensively analyzed the atomic structure of the interfaces in Co/Cu nanowires using a Cs-STEM with the assistance of EDX and EELS techniques. Dislocations are found to mainly lead to a rough interface via the mechanism of nucleation and growth by incorporating metal atoms into the lattice interface, which also causes the large scattering of the conduction electrons and the increase of resistivity. A single Co/Cu nanowire is then used to make a MRF nanodevice, whose resistivity and maximum current density are measured to be 1.75×10^{-8} Ω ·m and 4.7×10^{11} A·m⁻², respectively. Our work not only discloses the mechanism of interfacial roughness on the scattering of conduction electrons, but also shows that granular magnetic systems can be well applied for building interface-based nanodevices and nanosensors.

EXPERIMENTAL METHOD

Preparation of Nanowires. Co/Cu granular magnetic nanowires were synthesized by electrochemical deposition into anodic alumina templates with 50 nm diameter pores. A gold layer was sputtered onto one side of the template to serve as the working electrode in a standard three-electrode electrochemical cell. The reference electrode was a saturated calomel electrode and the counter electrode was a graphite rod. The electrodeposition electrolyte was composed of 0.5 mol/L CoSO₄·7H₂O, 0.005 mol/L CuSO₄·7H₂O, and 0.6 mol/L H₃BO₃. Voltammetric experiments were used to determine the optimal electrodeposition potentials of the Co/Cu granular magnetic nanowires. It can be seen that a reduction peak appeared at -0.16 V and a sharp increase of cathodic current occurred at 0.98 V, which are related to the onset of Cu and Co deposition, respectively. Therefore, an electrodeposition potential of -1 V was constantly set for 1800 s to deposit Co/Cu granular magnetic nanowires. The electrodeposition electrolyte was continuously agitated throughout using a magnetic stirrer. Typical curves showing the time dependence of current density during the deposition of Co/Cu granular magnetic nanowires is shown in Figure S1d.

Calculation Methods. First principles calculations were performed in the framework of DFT as implemented in the Vienna Ab initio Simulation Package^{43,44} with projector augmented wave potentials and generalized gradient approximation of Perdew–Burke–Ernzerhof. The energy cutoff for the plane-wave basis set was 520 eV, and the total energy was converged to 10^{-5} eV. The crystal geometry was optimized without any symmetry constraints until all residual forces on each atom became less than 0.01 eV Å⁻¹. The Brillouin zone sampling was done using a Gamma mesh of $5 \times 5 \times 1$ k-points. We constructed a slab model using a $4 \times 4 \times 1$ unit cell, which consists of 5 layers Cu and 5 layers Co in the (001) direction, and a 22 Å vacuum.

SEM and TEM Characterization. Co/Cu granular magnetic nanowires completely released from the templates by using 0.1 M

sodium hydroxide solution were dispersed on an SiO₂ (100 nm)/Si and holey carbon-film-coated grids for SEM and STEM analysis, respectively. The morphology, atomic structure, and chemistry of the nanowires were analyzed using a SEM (Tescan MIRA 3) and an aberration-corrected scanning transmission electron microscope (Cs-STEM, FEI Titan Cubed Themis Z operated at 300 kV) equipped for EDX analysis (Super-X), electron energy loss spectroscopy (EELS, Gatan GIF 965), HAADF, and scanning transmission electron microscopy (STEM).

MRF Nanodevice Fabrication. The electrodeposited Co/Cu granular magnetic nanowires were dispersed on Si/SiO₂ (200 nm) wafers. To fabricate a MRF nano-device, the individual nanowires were assembled into the lithography patterns using our dedicated nanomanipulators within a SEM. The detailed procedures are as follows: a single nanowire was pushed to release from the substrate wafer by using a nanomanipulator and lifted from the substrate via van der Waals force; then the nanowire was precisely placed between two Pt electrodes; finally, the two bottoms of the nanowire were mechanically pressed into Pt electrodes and the MRF nanodevice was then fabricated.

Electrical Property Measurement of the MRF Nanodevice. The electrical property of the MRF nano-device was simultaneously measured with an *in situ* SEM by using dedicated nanomanipulators manufactured by our group. After two conductive nichrome probes were tightly punched on the Pt electrodes, a scanning voltage from -0.01 to 0.01 V was applied to the MRF nanodevice to measure its resistivity. Maximum current density was measured by applying a rapidly increasing current to the MRF nanodevice.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsami.0c02745>.

Nucleation mechanism and preparation of Co/Cu granular magnetic nanowires (Figure S1); magnetic moment calculation of Cu atoms in the interface by DFT (Table S1); statistics of Co and Cu grain size analyzed using the STEM image (Figure S2); and fabrication of the MRF nanodevice (Figure S3) (PDF)

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Author Contributions

J.Z. designed the experiments, prepared the specimens, characterized, analyzed, and interpreted all data, and wrote the paper. Y.P. designed the experiments, provided overall guidance, supervised the TEM measurements, characterized, analyzed, and interpreted the data, and wrote the paper. R.C. performed the DFT calculations. X.L. and H.M. grew the Co/Cu granular magnetic nanowires and fabricated the MRF nanodevice together. X.Z. and X.D. performed the TEM measurements together. J.Z. drafted the paper and all authors commented on the manuscript. C.G., Y.H., and A.K. discussed the data. K.T. performed the DFT calculations and wrote the DFT part of the manuscript. X.Z. analyzed the magnetic data and discussed the content.

Notes

The authors declare no competing financial interest.

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