Effect of inserting Ni and Co layers on the quantum well states of a thin Cu film grown on Co/Cu(001)

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The effect of Ni and Co inserting layers on the quantum well (QW) states of a Cu film grown on Co/Cu(001) is systematically investigated using angle-resolved photoemission spectroscopy. For electron energy $E-E_F<-0.5$ eV, we find that both Ni and Co inserting layers behave similarly to serve as a potential-energy barrier to divide the Cu film into two Cu QWs. For energy near the Fermi energy, the Ni and Co inserting layers have different effects on the Cu QW states while the Co thin layer still perturbs the Cu QW states, the Ni inserting layer behaves as if it were a Cu layer, especially at the Fermi energy, even up to 10 ML thickness. Such different effects of the Ni and Co inserting layers are attributed to their different electronic band matching with the Cu energy band. The first-principles calculation confirms that the electron reflectivity near the Fermi level is indeed very different at the Cu/Ni and Cu/Co interfaces, supporting the experimental results.

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I. INTRODUCTION

Electrons in an atomically flat metallic thin film are confined in the normal direction of the film surface to form quantum well (QW) states.[1–3] The formation of QW states could modulate the density of states near the Fermi level to result in a thickness-dependent oscillation of many physical properties such as magnetic interlayer coupling,[4–6] magnetoresistance,[4,7] work function,[8] gas desorption energy,[9] electron-phonon interaction,[10] and superconducting transition temperature,[11] etc. It is now well recognized that a profound study of the QW states provides a great opportunity to nanostructure research for the purpose of manipulating various physical properties of a thin film.

The QW states should be modulated not only by the film thickness but also by the QW structure. In fact, semiconductor multi-QW systems have been designed and synthesized to control physical properties such as electron spins for the next generation spintronics technology.[12,13] For metallic thin-film systems, most of the QW studies have been focused on single QW structures and thus have not reached their full potential. Noting that many new phenomena stem from the electronic interaction between different layers, it is expected that the interaction between different QWs has the potential of generating new properties not available in a single QW structure.

The face-centered-cubic (fcc) Cu/Co(001) system is one model system for the study of QW states in metallic thin films. The Cu QW states in both occupied[14–16] and unoccupied states[17–19] have been extensively studied, and are well described by the phase accumulation model.[20–22] For example, the QW states in the Cu/Co(001) system are found to be spin dependent due to the spin-dependent energy band of the Co(001) substrate.[23,24] By measuring the momentum-resolved QW states, the physical origin of the long- and short-period oscillations of the magnetic interlayer coupling in Co/Cu/Co sandwiches, as well as the relationship between the two oscillations, have been unambiguously identified.[16,25] For a multi-QW system with two Cu QWs separated by a thin Ni (or Co) barrier layer, preliminary experiments demonstrated that the electron wave function in one Cu QW can tunnel across the thin barrier layer to interact with the wave function of another Cu QW,[26,27] and the phase accumulation model is also applied successfully to such multi-QW systems.[27] Moreover, for the multi-QWs system with two Cu QWs separated by a Ni/Cu/Ni QW, the two Cu QWs are shown to interact resonantly at the middle Cu QW energy levels.[28] On the other hand, inverse photoemission experiments show that above the Fermi level, the Cu QW-state energy is greatly shifted by a Ni capping layer,[29] implying that the QW states extend to the entire Ni+Cu film instead of being confined to the Cu film by the Ni layer above the Fermi level. This result indicates that the Ni layer can no longer be regarded as a featureless energy barrier for the Cu QW states above the Fermi level. Although the results from multi-QW systems demonstrate qualitatively the interaction between different Cu QWs, it is unclear how the interaction between two QWs depends on the electronic structure of the inserted barrier layer.

In this paper, we revisited the system of two Cu QWs separated by a Ni (or Co) layer. We find that in the normal direction, the Ni and Co layers (as thin as 2 ML) serve as an energy barrier to separate the Cu film into two QWs for electron energy below −0.5 eV. Near the Fermi level, however, the Ni and Co inserting layers have very different effects on the Cu QW states. For a Co inserting layer, the Co layer maintains its energy barrier role to make the Cu film behave as two QWs even for Co as thin as 1.3 ML. For a Ni inserting layer, we find that above −0.3 eV the Ni layer behaves as if it were a Cu layer, making the Cu/Ni/Cu structure behave as a single QW structure, even up to 10 ML Ni. The observed difference is attributed to the different band matching at the Cu/Ni and Cu/Co interfaces. The first-principles calculation shows that electron propagation experiences a negligible reflection at the Cu/Ni interface above −0.4 eV in the normal direction, explaining our experimental result that the Cu/Ni/Cu structure behaves as a single QW under this condition.

II. EXPERIMENT

In experiments, metallic double QWs are created by inserting a thin Ni or Co layer (as an energy barrier) between two Cu films, and information on electron quantization is usually obtained by angle-resolved photoemission spectroscopy (ARPES) measurements. A Cu(001) single crystal was prepared by mechanical polishing with the diamond paste down to 0.25 μm followed by electrochemical polishing. The Cu crystal was then cleaned *in situ* with cycles of Ar-ion sputtering at 1.0 keV and annealing at ~600 °C. The Co, Ni, and Cu films were deposited by molecular-beam epitaxy at room temperature. An 8 ML Co film was first grown on Cu(001) to serve as a base layer. Double Cu QWs of Cu/Co/Cu and Cu/Ni/Cu were then grown on top of the 8 ML Co base layer by growing the two Cu films into cross wedges. The layer-by-layer epitaxial growth nature has been confirmed in the literature among the Cu, Co, and Ni growths in the (001) orientation.[30,31] The evaporation rate was monitored by a quartz thickness monitor and had a typical value of ~1–2 Å/min. Literature values of the layer spacing is used with 1.8 Å layer spacing for Co and Cu and 1.7 Å layer spacing for Ni.[31] The ARPES measurement was performed at beamline 7.0.1.2 of the Advanced Light Source of the Lawrence Berkeley National Laboratory. Thickness-dependent measurements were systematically performed on the double-wedged sample by directing the photon beam (50×100 μm) to different positions on the sample. During the ARPES measurement, 83 eV photon energy was used to select the electronic states near the belly of the Cu Fermi surface.[14] QW states derived from the *sp* band with Δ_1 symmetry are thus selected under this measurement geometry. During the ARPES measurement, the ΓX direction is determined by measuring the angular distribution of the QW states at the Fermi energy (E_F) with an accuracy better than 0.3°.

III. RESULTS AND DISCUSSION

We first discuss the result of double QWs of Cu/Ni (2 ML)/Cu grown on Co/Cu(001). Figure 1(a) shows the schematic drawing of the sample. With this double-wedged sample, a scan along the horizontal direction (parallel to BD) retains the total Cu thickness but varies the position of the Ni layer inside the overall Cu film, and a scan along the AC direction will fix the Ni-layer position in the center of the Cu/Ni/Cu sandwich but varies both inner and outer Cu-film thickness in an identical way. According to the previous report,[26] in the extreme limit of a total transparency of the Ni layer to the electron wave propagation, the Cu/Ni/Cu should

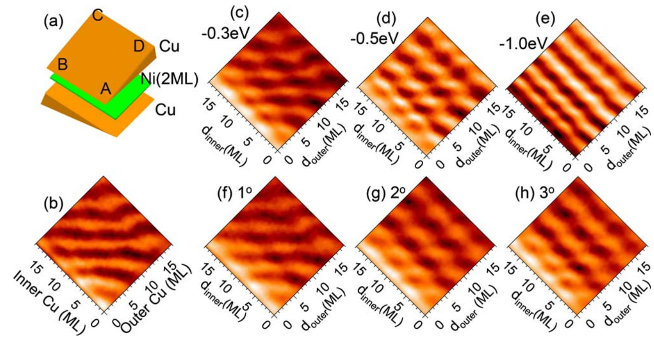

FIG. 1. (Color online) (a) Schematic drawing of the cross-wedged Cu/Ni/Cu sample. (b) Photoemission intensity at the Fermi level along [001] direction. [(c)–(e)] Photoemission intensity at −0.3, −0.5, and −1.0 eV along [001] direction. [(f)–(h)] The photoemission intensity at the Fermi level at different off-normal angles of 1°, 2°, and 3° along [110] direction.

behave as a single QW such that the QW states of the Cu/Ni/Cu film should have little dependence on the Ni position. In the opposite extreme limit that the Ni layer fully isolates the two Cu QWs, the QW states in the two Cu layers should interact very weakly with each other, such that the surface sensitive ARPES measurement should pick up only the QW states of the outer Cu layer. In general, when the situation lies between the above two extreme limits, the interaction between the two Cu QW states will result in a modulation of the QW electron density by the Ni position.

Figures 1(b)–1(h) show the photoemission intensity of the Cu/Ni/Cu sample at different electron energies and at different emission angles at the Fermi level E_F (defined as zero energy). Here the energy and angular windows for the photoemission spectra are ~50 meV and ~0.2°, respectively. Figure 1(b) depicts the photoemission intensity at the Fermi level along the normal direction of the film. Obviously the photoemission intensity oscillates as a function of the total Cu-film thickness along the AC direction due to the QW states in the whole film structure. However, for a fixed total Cu thickness, the photoemission intensity has little dependence on the Ni-layer position. This result is slightly different from the previous report,[26] which showed a modulation of each QW-state intensity at E_F along the BD direction, i.e., a modulation of the QW-state intensity by the 1 ML Ni position inside the Cu QW. In our experiments, the Ni inserting layer has 2 ML thickness, which should have a stronger modulation effect than the 1 ML Ni on the Cu QW states, but apparently we observe little intensity change at the E_F along the BD direction. These different results are attributed to the lower angular resolution of earlier photoemission measurements that actually integrated a wider angular range than the present measurements. This is evidenced in Figs. 1(f)–1(h), which show the detailed photoemission intensity at E_F at different emission angles (e.g., different $k_\parallel$ along ⟨110⟩ direction). The modulation effect of the Ni position on the QW photoemission intensity appears even at an off-normal direction to be just 1° ($k_\parallel$=0.08 Å^{-1}) and becomes stronger at greater off-normal angles. This explains the earlier result reported in the previous paper.[26]

The absence of the QW-state intensity modulation by the Ni position at E_F is further revealed by an energy-dependent

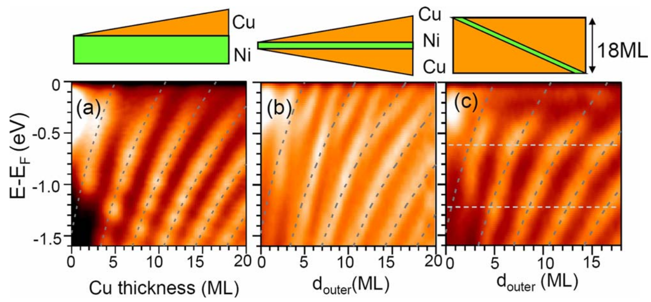

FIG. 2. (Color online) Photoemission spectra as a function of Cu thickness of (a) Cu/Ni(8 ML)/Co(001), (b)Cu/Ni(2 ML)/Cu/Co(001), and (c) Cu(d)/Ni(2 ML)/Cu(18 ML-d)/Co(001). Schematic drawings on top of the spectra show the structure of the samples. The gray dashed lines are fitting result using Eq. (1) for a single Cu QW. The horizontal dash lines in (c) are guide lines to show the QW energy levels of the entire Cu/Ni/Cu sample.

study of the QW states [Figs. 1(c)–1(e)]. We find that the modulation effect of the Ni-layer position on the QW states becomes visible only below −0.3 eV. For energy below −1.0 eV, the QW photoemission intensity depends mainly on the outer Cu-film thickness, showing that the 2 ML Ni inserting layer decouples almost completely the inner and outer Cu QWs below −1.0 eV. This result shows that at normal emission the 2 ML Ni inserting layer behaves as an energy barrier to separate the overall Cu film into two Cu QWs only below −0.3 eV. Above −0.3 eV, the Ni layer behaves as a Cu layer, having virtually no effect in separating the overall Cu film into two Cu QWs.

The effect of the Ni inserting layer was also studied by taking the energy spectra at different Cu thicknesses (Fig. 2). Figure 2(a) shows the result from a Cu/Ni(8 ML)/Co(001) sample. The QW-state intensity at lower energy reaches a maximum at discrete Cu-layer thicknesses, showing the "layer-by-layer" growth quality of the Cu film on a Ni(001) surface. The position of the QW states in Cu/Ni(001) can be fitted using the phase accumulation method in which the quantization condition is given by[20]

$$2(k_{BZ}-k_{\perp})d_{\mathrm{Cu}}-\Phi=2\nu\pi, \quad \nu \text{ is an integer number}. \tag{1}$$

Here, k_{BZ} is the Brillouin-zone vector and $k_{\perp}$ is the electron wave vector along the [001] direction. Φ is the total phase gain of the electron wave function upon reflections at the Cu/vacuum and Cu/Ni interfaces. As shown by the dashed lines in Fig. 2(a), the QW-state position is well fitted by Eq. (1) with the use of the bulk Cu energy band and a linear energy dependence of the phase.

Figure 2(b) shows the energy spectra along the AC line in Fig. 1(a). Similar to the previous report,[26] the Ni layer at the center of the Cu film separates the Cu film into a symmetric double QW system. At low energy ($E<-0.5$ eV), the 2 ML Ni barrier almost completely isolates the two Cu QWs to result in degenerate QW states in the two Cu wells. Under this condition, only the QW states in the outer Cu film are observed by ARPES, as evidenced by the same QW positions as in the Cu/Ni(001) single QW system. At higher energy, the degeneracy of the QW states in the two Cu wells is lifted by the overlap of the QW wave functions from the two Cu films across the Ni barrier layer. Since the QW states in the two Cu films interact strongly above $E>-0.3$ eV, it is not surprising to see that the QW state with index ν in the outer Cu layer at lower energy evolves continuously into the QW states with indices of 2ν and $2\nu+1$ of the overall Cu film at higher energy.

Although the results of Figs. 2(a) and 2(b) can be understood qualitatively, we have ignored the detailed electronic structure of the Ni layer. In the phase accumulation model, the effect of the Ni layer comes from its energy gap, which serves as an energy potential barrier to confine the Cu electrons.[20] This model actually simplifies the role of Ni by assuming that the phase at the Cu/Ni interface changes from $-\pi$ to 0 as the energy increases across the Ni energy gap and takes the value of zero above the energy gap. The Ni layer then becomes a featureless energy barrier that is independent of the Ni electronic structure above the energy gap. To explore the effect of Ni electronic structure on the Cu QW states, we turn our attention to the scan along the line BD in Fig. 1(a), where the total Cu-film thickness is fixed but the Ni position varies within the Cu film. At low energy [Fig. 2(c)], we find that the measured QW states are the same as in a single Cu/Ni(001) system. Noticing that ARPES only probes the outer Cu film, the above result shows that 2 ML Ni is thick enough to separate the Cu film into two isolated QWs. For energy above −0.3 eV, however, the QW states are suddenly dimmed and no longer evolve with the Ni position. This result is consistent with the result of Fig. 1 that the Ni layer under this condition behaves as part of the Cu film so that the QW states should be determined by the overall Cu/Ni/Cu structure in the way that

$$2(k_{BZ}^{\mathrm{Cu}}-k_{\perp}^{\mathrm{Cu}})d_{\mathrm{Cu}}+2(k_{BZ}^{\mathrm{Ni}}-k_{\perp}^{\mathrm{Ni}})d_{\mathrm{Ni}}-\Phi-\Phi_{\mathrm{Ni}}=2\nu\pi. \tag{2}$$

Here Φ_{Ni} is the total phase gain for an electron traveling across the two Cu/Ni interfaces. Then the QW states under this condition should be determined by the total Cu and Ni thicknesses and are independent of the Ni position. We notice that the photoemission intensity recovers above −0.1 eV, showing that there exists a QW state at E_{F} in this Cu/Ni/Cu film, consistent with the result of Fig. 1(b). It should also be noted that the photoemission intensity at ~ −0.6 and ~−1.2 eV is stronger than at other energies [indicated by the dashed horizontal lines in Fig. 2(c)]. This result indicates that the 2 ML Ni film cannot completely isolate the two Cu QWs, instead, it permits a weak overlap of the electron wave functions from the two Cu QWs to result in a resonance of the QW photoemission intensity of the top Cu layer. The energy positions are different from the QW states of 18 ML Cu/Ni(001) but close to the QW-state position of 20 ML Cu/Ni(001). This is because the 2 ML Ni film has to be considered as a part of the whole quantum well. The existence of these states extending into the whole quantum well has been verified by the first-principles calculation.[32]

Next, we studied the dependence of the QW states on the thickness of the Ni inserting layer. A double-wedged sample of Cu/Ni was grown on top of a Cu(10 ML)/Co(8 ML)/Cu(001) film [Fig. 3(a)]. If the Ni layer were thick enough to

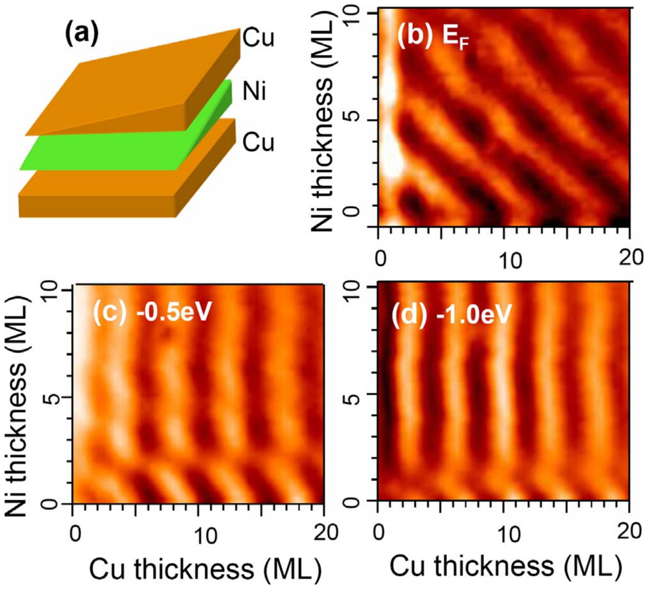

FIG. 3. (Color online) (a) Schematic drawing of the Cu/Ni/Cu(10 ML)/Co(001) sample. [(b)–(d)] Photoemission intensity as a function of the Cu and the Ni thicknesses at the energy of (b) E_F, (c) −0.5 eV, and (d) −1.0 eV.

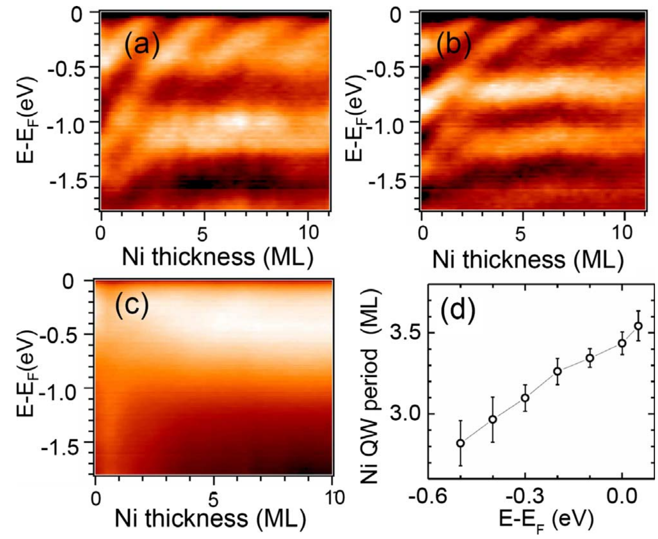

FIG. 4. (Color online) Energy spectra as a function of the Ni thickness in (a) Cu(10 ML)/Ni(d)/Cu(10 ML)/Co(001), (b) Cu(20 ML)/Ni(d)/Cu(10 ML)/Co(001), and (c) Ni(d)/Co(001). (d) The Ni QW oscillation periodicity derived from (a)

separate the electron wave functions of the two Cu films, the intensity of the QW states should then oscillate with the outer Cu-film thickness only and be independent of the Ni-film thickness. Otherwise the QW states should depend on both the Cu- and the Ni-film thicknesses. Figure 3(b) shows the photoemission intensity at E_F as a function of Cu and Ni thicknesses. It is obvious that the QW states depend on both the Cu and Ni thicknesses, showing that the QW states extend into the whole Cu/Ni/Cu structure, even for $d_{Ni} > 10$ ML. However, for energy below −0.5 eV, the QW states vary only with the outer Cu thickness for $d_{Ni} > 2$ ML, showing that 2 ML Ni is thick enough to effectively isolate the electrons in the two Cu films for $E < -0.5$ eV.

The effect of the Ni inserting layer on QW states was further studied by taking the energy spectra as a function of Ni thickness in a Cu/Ni/Cu film where both the outer and inner Cu-film thicknesses are fixed, as shown in Figs. 4(a) and 4(b). For $d_{Ni} < 2$ ML, the QW states evolve with the Ni thickness in the entire energy range, showing that the QW states in the two Cu films are coupled together across the Ni layer. For $d_{Ni} > 2$ ML, the QW states at $E < -0.5$ eV are independent of the Ni thickness, confirming our previous conclusion that the two Cu QWs are separated by the Ni layer ($d_{Ni} > 2$ ML) at $E < -0.5$ eV. However, for energy above −0.5 eV, the QW-state energy increases with the Ni-film thickness, showing that the QW states under this condition are determined by the overall Cu/Ni/Cu structure. It is interesting that no QW states were observed from the measurement of the Ni/Co/Cu(001) sample [in Fig. 4(c)]. The reason is that the d-band electrons dominate the photoemission intensity in a Ni film so that the QW states of the Ni sp-like electrons[33] are overwhelmed by the stronger d-band photoelectrons in the Ni/Co/Cu(001) sample. A Cu overlayer effectively filters out the Ni d-electron emissions, thus manifesting the Ni sp-like QW states. The oscillation periodicity of the QW states was determined and is shown in Fig. 4(d). It should be pointed out that the observed QW states extend to the whole Cu/Ni/Cu structure, thus it should not be interpreted as being localized within the Ni film. Therefore, the QW states should be described by Eq. (2). From the oscillation periodicity of the photoemission intensity with the Ni-film thickness, we estimate that the k_F of Ni sp band is $\sim 0.71 k_{BZ}$.

The above result shows that the Ni electronic structure plays an important role in the QW states of the Cu/Ni/Cu structure near the Fermi level. To further explore this fact, we studied the effect of a Co inserting layer on the Cu QW states as a comparison. Figure 5(a) shows the photoemission intensity at E_F along the normal-emission direction from Cu/

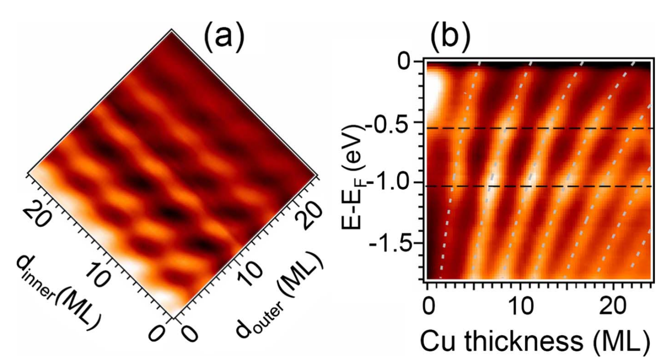

FIG. 5. (Color online) (a) Photoemission intensity as a function of the Cu thickness at E_F along the normal-emission direction from Cu(d_{outer})/Co(1.3 ML)/Cu(d_{inner})/Co/Cu(001). (b) Photoemission spectra as a function of the Cu thickness in Cu(d)/Co(1.3 ML)/Cu(24 ML-d)/Co(001). The gray dashed lines are the single QW states measured from the sample Cu(d)/Co(001), and the horizontal dash lines in (b) are guide lines to show the QW energy levels of the entire Cu/Co/Cu sample.

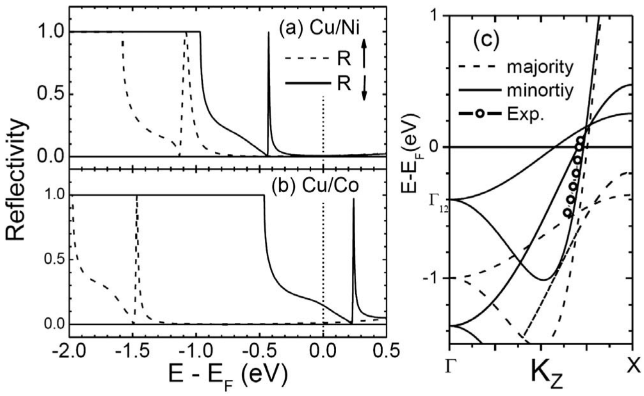

FIG. 6. The energy-dependent electron reflectivity at (a) Cu/Ni(001) interface and (b) Cu/Co(001) interface with majority (dashed line) and minority (solid line) spins. (c) The calculated Ni energy bands for majority (dashed) and minority (solid) electrons. The circles are experimental results based on Eq. (2). Here the Fermi level was adjusted to match the Γ_{12} energy of the experimental value of −0.4 eV (Refs. 43 and 44).

Co(1.3 ML)/Cu/Co/Cu(001). The sample has the same structure as shown in Fig. 1(a). In contrast to the result of Cu/Ni(2 ML)/Cu shown in Fig. 1(b), a clear modulation of the Co-layer position on the QW photoemission intensity is observed at E_F in the Cu/Co(1.3 ML)/Cu sample, showing that the Co inserting layer has a stronger perturbing effect on the Cu QW states than the Ni inserting layer near the Fermi level. The modulation effect of the Co inserting layer was found to be stronger for the lower-energy QW states.[28] Figure 5(b) shows the photoemission intensity as a function of the outer Cu thickness with the total Cu thickness fixed at 24 ML [along the BD direction in Fig. 1(a)]. The result is very different from the corresponding Cu/Ni/Cu case near the E_F [Fig. 2(c)] but is almost identical to the single QW case of Cu/Co(8 ML)/Cu(001). This result indicates that 1.3 ML Co is thick enough to separate the Cu film into two Cu QWs whereas the Ni inserting layer behaves as a Cu layer at E_F to connect the two Cu layers to form a single QW. The higher photoemission intensities in the energy range of −0.55 and −1.05 eV are attributed to the resonance effect with the QW states of the inner Cu layer, showing that the 1.3 ML Co still permits certain degree of the Cu-electron propagation across the Co layer.

To understand the different effects of the Ni and Co inserting layers on the Cu QW states, we studied the electron reflectivity at the Cu/Ni and Cu/Co interfaces by calculating the scattering matrix using a recently developed first-principles method.[34] The detailed description of the theoretical method can be found in Ref. 35. When the Ni or Co layer can be regarded as an effective energy barrier, the electron should be partially reflected at the Cu/Ni or Cu/Co interface. During the calculation, the Cu, Ni, and Co were treated as half-infinite thick layers, with the electron wave traveling from the Cu side to the Ni or Co side. Since minority-spin electrons dominate the QW states in the Cu/Co(001) system,[23,24] here we only discuss the calculated result for minority-spin electrons. Figure 6 presents the energy dependence of the electron reflectivity at the Cu/Ni(001) and Cu/Co(001) interfaces for the normal incidence of a Cu electron. The common feature for the electron reflectivity at the Cu/Ni and Cu/Co interfaces is that the minority-electron reflectivity decreases from full reflection to a small value as the energy increases from the Ni and Co minority-electron energy gap toward the Fermi level. If compared to the Cu/Co case, the calculated minority-electron reflectivity at the Cu/Ni interface is much smaller above the Ni energy gap and becomes virtually zero at the Fermi level. The sharp peak in the calculated reflectivity comes from the Fano resonance due to the flat energy dispersion at the Γ_{12} point, which can be regarded as a localized state. The Fano resonance originates from the quantum-mechanical interference between a discrete energy state and a degenerate energy continuum,[36–38] and it is usually identified by a detailed line-shape analysis of electronic transport[39,40] and optical spectra,[41,42] thus it is irrelevant for the current measurement.

Our experimental results can then be fully explained by the above theoretical calculation. Above the Γ_{12} point of the minority-electron band, the near zero electron reflectivity at the Cu/Ni interface allows the extension of the electron wave function to the entire Cu/Ni/Cu structure to form a QW state, i.e., the Cu/Ni/Cu in this case behaves as a single Cu film (e.g., the Ni layer could be treated as a Cu layer). The electron reflectivity at the Cu/Ni interface above the Fermi level is also near zero according to the calculation. This explains the inverse photoemission result that the QW states in this case extend throughout the Ni+Cu film.[29] In contrast, the finite electron reflectivity below the Γ_{12} energy makes the Ni layer an effective energy barrier to confine the electron in the outer Cu film to form QW states in the subwell. For the case of Cu/Co, the higher Co minority Γ_{12} energy than the Fermi energy generates an appreciable amount of the electron reflectivity at the Cu/Co interface below the Fermi surface, and thus should lead to a partial confinement of the electrons in the outer Cu layer to form QW states in the subwell.

From the calculation result, the Γ_{12} energy value is roughly the crossing point for defining the role of the Ni or Co inserting layer in the Cu QW states; the Ni or Co inserting layer behaves as an energy barrier below the Γ_{12} energy and as a Cu film above the Γ_{12} energy. In our experiments, from the fact that a 10 ML Ni layer cannot separate the electrons of two Cu QWs above −0.3 eV and that 2 ML Ni behaves as an effective electron barrier below −0.5 eV, the

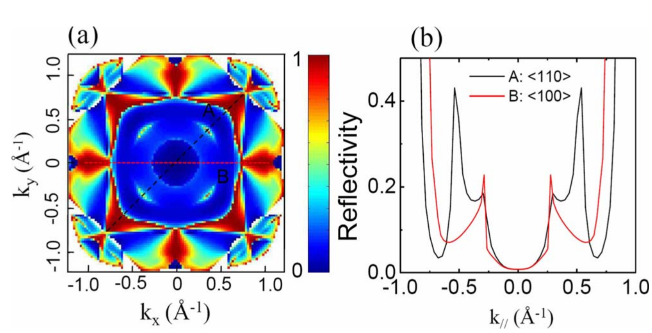

FIG. 7. (Color online) (a) The contour of calculated minority-electron reflectivity at the Cu/Ni(001) interface in k space. (b) The line scan of the electron reflectivity along ⟨110⟩ and ⟨100⟩ directions.

Γ_{12} energy is estimated to be ~ -0.4 eV, consistent with a previous experimental value of ~ 0.4 eV.[43,44] It is well known that the first-principles calculation cannot determine the Fermi level accurately so technically we have adjusted the calculated Fermi level in Fig. 6 to match the Γ_{12} energy of the experimental value -0.4 eV. In the experiment, the energy dispersion of the minority-electron band can be determined from the QW periodicity in Fig. 4 using Eq. (2) [shown in Fig. 6(c)]. The experimental energy dispersion is close to the calculated *sp* minority energy band.

The angular condition for the QW states in the Cu/Ni/Cu structure can also be understood by the theoretical calculation. Figure 7(a) shows the contour of the electron reflection in *k* space, and Fig. 7(b) shows the electron reflection as a function of $k_{\parallel}$ along the [110] and [100] directions. The electron reflection is very small only around the Γ point but develops rapidly away from the Γ point, in agreement with the experimental results.

IV. SUMMARY

In summary, we investigated the interaction of two Cu QWs across a thin Ni or Co film. We find that the Ni inserting layer behaves as a Cu layer in the Cu/Ni/Cu structure above -0.3 eV but as an energy barrier below -0.3 eV. On the other hand, the Co inserting layer always behaves as an energy barrier below the Fermi level. Theoretical calculations show that the different roles of the Ni and Co inserting layers in the Cu QW states are due to their different minority Γ_{12} energy values relative to the Fermi surface. From the QW-state oscillation periodicity, the Fermi wave vector k_F of fcc Ni was estimated to be $\sim 0.71 k_{BZ}$, which is consistent with the theoretical band-structure calculation.

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