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Spin-Dependent Absorption of Electrons in a Ferromagnetic Metal

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It is found that the current collected by a ferromagnet placed in an electron beam depends on the orientation of the incident electron spin. At certain energies, only electrons with spins parallel or antiparallel to the net surface spin density cause a net target current. The spin dependence is caused by the influence of the exchange interaction on the elastic scattering. Inelastic scattering measurements show that the spin dependence of the production of secondary electrons is small.

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When low-energy electrons strike a metal, a variety of elastic and inelastic scattering phenomena occur. In the case of a ferromagnet, the interaction between the primary electron and the ordered net spin density of the sample electrons gives rise to a spin-dependent exchange interaction.[1,2] By using a primary beam of spin-polarized electrons and a ferromagnetic target, it is now possible to measure directly the effects of the exchange interaction in the elastic and inelastic channels. We present measurements to show that the effect of the exchange interaction is generally of the order of 10^{-2} of the spin-averaged interaction, for primary-electron energies E_0 of 2–500 eV. However, the exchange interaction can have a dominant effect on the net current absorbed by the sample at certain primary energies; either $i_a^{\uparrow\uparrow}$ or $i_a^{\uparrow\downarrow}$ can be finite while the other is zero, where i_a is the net absorbed electron current (number of electrons per second) and $\uparrow\uparrow$ ($\uparrow\downarrow$) means the polarization of the incident beam is parallel (antiparallel) to the majority-spin direction in the sample. To elucidate the mechanism behind this striking phenomenon, we present the first measurements of the spin-dependent asymmetry in inelastic scattering and secondary production. These suggest that the primary cause of the spin-dependent absorption is the spin-dependent interaction in elastic scattering. Through these results we demonstrate that polarized electron scattering presents a simple way to study various elastic and inelastic processes in a ferromagnetic electron gas and to obtain information on surface magnetic properties. Furthermore, the spin dependence of the absorbed current provides a new principle for detecting the spin polarization of an electron beam much superior to the complicated and inefficient methods in use or proposed.[3,4]

Spin-dependent electron scattering from a ferromagnetic surface was first measured by Celotta *et al.*[5] on Ni(110) with use of the spin-polarized electron beam emerging from a GaAs photocathode. In the present experiment, the spin-polarized electron beam is incident normal to the surface of the ferromagnetic glass, $Ni_{40}Fe_{40}B_{20}$. The electrons scattered from the sample are measured with a movable Faraday cup with an energy analyzing element to obtain the elastically scattered current $i_s(E_0)$ or the inelastically scattered current $i_s(E)$. The current absorbed by the sample, i_a, can be measured by a meter connected to the sample. An advantage of using a metallic glass is that it can be easily magnetized[6]; this leads to minimal stray magnetic fields outside the surface. The sample is a $16\times2\times0.03$ mm^3

strip and is magnetized parallel to the long polished surface by pressing it firmly against the polished poles of a horseshoe-shaped electromagnet. The saturation magnetization of the sample is 2.2 Bohr magnetons per formula unit ($NiFeB_{0.5}$) at room temperature.

To test the influence of any remaining small stray fields produced by the electromagnet or the surface roughness of the sample, the dependence of i_s and i_a on the sample magnetic field direction was measured with an unpolarized electron beam. The influence of stray fields was smallest for incident- and scattered-electron directions close to the normal of the sample surface. In this case, on reversing the field, we observed no change of either i_a or i_s down to $E_0 = 2$ eV. The electron beam[7] had a polarization of 36%, a diameter of 1 mm and hit the sample in the middle.

After mild Ar^+ bombardment (500-eV ions) at glancing incidence, Auger spectroscopy detected Ni and Fe in a ratio of 1:1. This is in agreement with Chuang and Wandelt,[8] who found that Fe and Ni have very similar sputtering cross sections. The boron concentration was typically approximately half that of Ni and Fe as expected. Oxygen, which appeared to reduce the spin-dependent effects, could be removed by ion bombardment. The main residual surface contaminant was carbon, the surface concentration of which was comparable to boron. This formed a very stable surface on which the spin-dependent measurements were made.

The spin-dependent asymmetry in the absorbed current defined as $A = (i_a^{\uparrow\uparrow} - i_a^{\uparrow\downarrow})/(i_a^{\uparrow\uparrow} + i_a^{\uparrow\downarrow})$, is shown in Fig. 1 as a function of the energy E_0 of the primary-electron beam. The asymmetry A is generally small but passes through $A = -1$ at $E_0 = E_0^{\uparrow\uparrow} \cong 148.9$ eV where $i_a^{\uparrow\uparrow}$ is zero, goes to $-\infty$, and returns from $+\infty$ passing through $A = +1$ at $E_0 = E_0^{\uparrow\downarrow} \cong 150.2$ eV. This means, for example, that at 150.2 eV only parallel incident spins give rise to a net absorbed current. The spin averaged absorbed current $I_a = \frac{1}{2}(i_a^{\uparrow\uparrow} + i_a^{\uparrow\downarrow})$, which would be observed with an unpolarized beam, is displayed near the divergence of A. We see that $I_a = 0$ at $E_0 \cong \frac{1}{2}(E_0^{\uparrow\uparrow} + E_0^{\uparrow\downarrow})$. Since $2I_a$ is the denominator of A, this *formally* explains the divergence. *Physically* the change of sign of I_a on increasing E_0 is due to the increasing number of secondary electrons that leave the sample in addition to the elastically and inelastically backscattered primaries.[9] As the cross section for secondary-electron production increases, an energy is reached where the current leaving equals

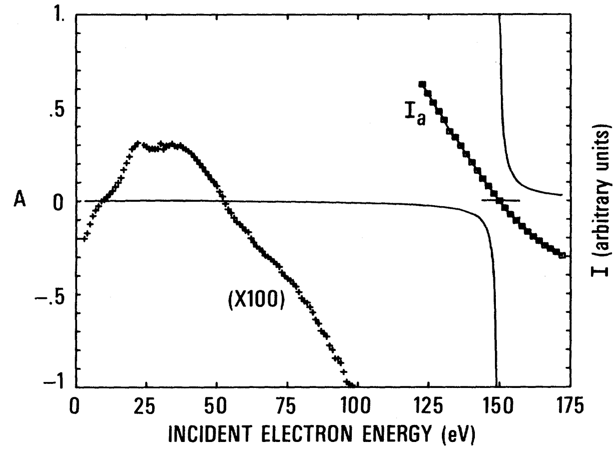

FIG. 1. Spin asymmetry $A = (i_a^{\uparrow\uparrow} - i_a^{\uparrow\downarrow})/(i_a^{\uparrow\uparrow} + i_a^{\uparrow\downarrow})$ of the absorption of electrons in $Ni_{40}Fe_{40}B_{20}$ vs electron energy in electron volts at room temperature is given by the solid line and below 100 eV magnified 100× by the +. The spin-averaged $I_a = \frac{1}{2}(i_a^{\uparrow\uparrow} + i_a^{\uparrow\downarrow})$ absorbed by the sample is shown by the squares near the energy where it changes sign. $\uparrow\uparrow$ ($\uparrow\downarrow$) denotes preferred spin direction in primary-electron beam parallel (antiparallel) to the majority-spin direction in the sample.

that incident on the sample so that no electrons are collected. For the spin-polarized ferromagnetic case, there are *two* such energies, one for parallel spins ($E_0^{\uparrow\uparrow}$) and the other for antiparallel spins ($E_0^{\uparrow\downarrow}$). It has been pointed out by several authors that spin-dependent effects may become dominant whenever the intensity approaches zero.[3] Here I_a changes sign, making a very small initial spin asymmetry increase to 100% in a very convenient energy range. In addition, at $E_0^{\uparrow\downarrow}$ and $E_0^{\uparrow\uparrow}$ the values of $i_a^{\uparrow\uparrow}$ and $i_a^{\uparrow\downarrow}$, respectively, are still quite large, namely about $10^{-3} i_0$, where i_0 is the intensity of the primary beam. The absorption measurement can therefore provide a simple, compact, efficient detector of spin polarization.[10]

At $E_0 \leq 25$ eV, A was measured by maintaining a constant beam energy, but applying a retarding voltage to the sample. This reduces the effect of stray magnetic fields. When the magnetization of the sample was reversed, we obtained the same values for $A(E_0)$, down to $E_0 = 2$ eV, a strong test for the absence of asymmetries introduced by the apparatus. For $E_0 \leq 100$ eV, A is of the order of 10^{-3}, and shows interesting structure, especially the change of sign at $E_0 = 55$ eV and $E_0 = 9$ eV. At the lowest energies, this ferromagnet prefers to absorb minority-spin electrons.

The absorbed current equals the incident current minus the elastically and inelastically scattered electrons and the true secondary electrons which leave the sample. Thus, one expects a spin-dependent absorption, $A \neq 0$, either because (i) the production of secondary electrons, (ii) the elastic scattering, or (iii) the inelastic scattering of primary electrons is spin dependent. In order to isolate the origin of the spin dependence we have measured the number of electrons $N(E)$ backscattered from the sample into the Faraday cup at an energy E when bombarding with a primary beam of energy E_0. Simultaneously, we have also determined the spin asymmetry $S(N(E))$ in the scattering or production of those electrons. We define $S(E) \equiv S(N(E)) = [N^{\uparrow\uparrow}(E) - N^{\uparrow\downarrow}(E)]/[N^{\uparrow\uparrow}(E) + N^{\uparrow\downarrow}(E)]$, where $N^{\uparrow\uparrow}(E)$ $[N^{\uparrow\downarrow}(E)]$ is the number of electrons scattered to the Faraday cup at an energy E when the spin of the primary electron beam is parallel (antiparallel) to the majority spins in the sample. Figure 2 shows $N(E)$ and $S(E)$ for an incident energy $E_0 = 97$ eV. We see that $S(E)$ is largest for the elastic scattering, decreases with increasing energy loss, changes sign around $E = 40$ eV, and finally is zero for $E \rightarrow 0$, where a large number of true secondaries are produced. It follows that the main factor determining the spin dependence of the net absorbed current is not the production of secondaries. The small wiggles in both $N(E)$ and $S(E)$ are generated by noise and do not have physical meaning. The zero intercept in $S(E)$ is determined within about 10 eV.

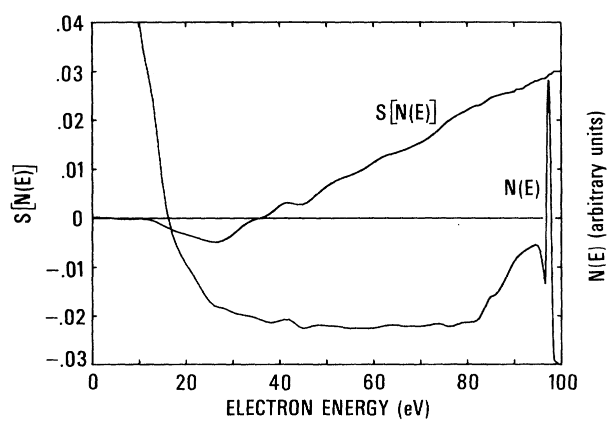

FIG. 2. Number $N(E)$ of electrons scattered from the sample at an energy E into the Faraday positioned in backscattering direction at 14° from the sample normal. The elastic peak, some loss structure, and part of a large peak of true secondaries can be seen. The spin dependence $S(E) = [N^{\uparrow\uparrow}(E) - N^{\uparrow\downarrow}(E)]/[N^{\uparrow\uparrow}(E) + N^{\uparrow\downarrow}(E)]$ in the production of an electron with energy E is also shown.

Initial measurements of the spin asymmetry in the elastically scattered current as a function of energy show that it crosses zero at approximately the same energies as $A(E_0)$ and is opposite in sign. That is, at energies where parallel spins are absorbed by the sample more strongly, antiparallel spins are scattered more strongly. This is consistent with our conclusion that the spin dependence of the net absorbed current is not due to a spin dependence of secondary production, and strongly suggests that instead it is due to the spin dependence of the elastic scattering.

A detailed understanding of $N(E)$ requires a theory for the inelastic scattering events and the subsequent rediffusion to the surface. However, it is known[9] that the following are reasonable approximations: (1) Inelastically scattered primary electrons occur predominantly at $E_0 > E > \frac{1}{2}E_0$; (2) true secondary electrons excited from the valence bands occur at $E < \frac{1}{4}E_0$; (3) most inelastic collisions need to be followed or preceded by elastic collisions so that the electron is redirected to the surface and can escape since inelastic scattering is predominantly in the forward direction. With these assumptions, one can reach some understanding of $S(E)$. The fact that $S(E)$ changes sign at about 40 eV, near the energy at which the spin dependence of the elastic scattering changes sign, suggests that the primary electrons retain their spin polarization in the inelastic collisions and are redirected to the surface by spin-dependent elastic events. Thus, $S(E)$ is mainly determined by elastic scattering. Also, no particular structure is observed in $S(E)$ at a loss energy of 5–10 eV where there is a damped surface-plasmon peak in $N(E)$. This observation supports the predictions of Helman and Baltensperger[11] that spin dependence of plasmon production is very small.

The absence of spin dependence in secondary-electron production has a bearing on current theories of the spin dependence of the inelastic mean free path in a ferromagnet. In the model of Feder[1] which was used to interpret spin-polarized photoemission measurements of Bringer *et al.*,[12] it was postulated that inelastic scattering occurs only between electrons of opposite spin orientation, that is, an up-spin electron only excites a down-spin electron. This yields[1] a ratio of the cross sections for electron-hole pair production of $\sigma^{\uparrow}/\sigma^{\downarrow} = n^{\downarrow}/n^{\uparrow}$, where $n^{\uparrow}$ $(n^{\downarrow})$ in the density of majority (minority) spins. This model makes a definite prediction for $S(E)$ of the low-energy true secondary electrons created predominantly by electron-hole pair production. Together with our observation that inelastically scattered electrons retain much of their spin polarization, the expected scattering asymmetry of the secondary electrons is $S(E) = (n^{\downarrow} - n^{\uparrow})/(n^{\downarrow} + n^{\uparrow}) \cong -0.1$ since $n^{\uparrow} - n^{\downarrow} = n_B$ is the Bohr-magneton number and $n^{\uparrow} + n^{\downarrow}$ is the total number of valence electrons per formula unit. The value of $S(E)$ predicted by this model is in contradiction to our observed values of $S(E)$ for true secondary electrons. The spin dependence of the inelastic mean free path is much smaller than predicted by the model of Feder[1] and Bringer *et al.*[12] The small values of spin-dependent mean free paths recently calculated by Rendell and Penn[13] for Fe, Co, and Ni are consistent with the present observations.

In summary, we have found that the net current absorbed by a ferromagnet is spin dependent and that the spin dependence is related to that of the elastically scattered electrons. A measurement of the spin-dependent asymmetry of inelastic scattering shows that secondary production is not spin dependent. The measurement of absorbed current offers a simple way of detecting electron-spin polarization and of obtaining information on surface magnetization.

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