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An electron spin polarization detector: Spin-dependent absorption of a polarized electron beam

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The exchange interaction and the spin-orbit interaction are observed to cause a spin dependence of the absorption of a polarized electron beam in the amorphous ferromagnet $Ni_{40}Fe_{40}B_{20}$ and a W(100) single crystal respectively. The enhancement of the spin dependence, near the energy where the secondary electron yield is unity, is shown to provide a simple efficient detector of spin polarization.

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It was recently shown that when a polarized electron beam is incident on a ferromagnetic sample, the current collected, i.e., absorbed, by the sample depends on the relative orientation of the incident electron spin and the sample magnetization.[1] The cause of the spin dependence of the absorbed current was investigated and found to be primarily due to the spin-dependent elastic scattering of the incident beam. It was pointed out that a large spin-dependent absorption should also be observed owing to the spin-orbit interaction in scattering from high-Z materials such as W. Even a small spin dependence in the absorption, which could be due to either the exchange or spin-orbit interaction, was shown to be greatly enhanced at certain energies and to therefore provide a sensitive means to detect electron spin polarization.[1] It is the purpose of this letter to present the first measurements of the spin-dependent absorption due to the spin-orbit interaction in W and discuss specifically how the spin dependence due to either the exchange or spin-orbit interaction leads to a simple, compact, and efficient spin-polarization detector.

In scattering, spin-dependent effects usually represent only a small part of the total interaction, but can become dominant when the spin-independent effect is suppressed. The absorbed current I_a (number of electrons/sec) for an unpolarized incident electron beam goes to zero at E_0 (where the secondary electron yield is unity) and then becomes negative when there are more electrons leaving the sample than there are in the incident beam. The absorbed currents $i\uparrow\uparrow$ and $i\uparrow\downarrow$, when the spins of the incident electron beam are respectively parallel or antiparallel to the majority spin direction in the case of a ferromagnet, have separate zero intercepts at $E_0\uparrow\uparrow$ and $E_0\uparrow\downarrow$, respectively. At these energies the absorption process acts as a perfect spin filter. For example, at $E_0\uparrow\uparrow$ the absorbed current $i\uparrow\downarrow$ arises from antiparallel incident spins alone.

The spin-dependent absorption is characterized by the normalized asymmetry $A = (i\uparrow\uparrow - i\uparrow\downarrow)/(i\uparrow\uparrow + i\uparrow\downarrow)$, which is shown in Fig. 1 (a) as a function of the energy of the electron beam incident normally on the ferromagnetic metallic glass $Ni_{40}Fe_{40}B_{20}$. The individual currents $i\uparrow\uparrow$ and $i\uparrow\downarrow$ are shown along with $I_a = \frac{1}{2}(i\uparrow\uparrow + i\uparrow\downarrow)$ in Fig. 1 (b). A measure of the usefulness of this effect for a spin detector is the quantity $\Delta \equiv |E_0\uparrow\uparrow - E_0\uparrow\downarrow|$, which depends on the numertor of A and the slope of I_a. The measurements were made as described previously[1] by scanning the energy of the spin-polarization-modulated incident beam obtained from a GaAs polarized electron source.[2] The raw data plotted in Figs. 1 and 2 give an indication of the noise in the measurement.

A figure of merit[3] for this spin detector, which is analogous to the one used when counting statistics dominat traditional measurements of spin polarization by a Mott analyzer, is A^2I_a/I_0 where I_0 is the incident beam intensity. For a $Ni_{40}Fe_{40}B_{20}$ sample as in Fig. 1, we find $A^2I_a/I_0 = 0.003$ at $E_0\uparrow\downarrow$ and $E_0\uparrow\uparrow$, where $A = \pm 1$. This is to be compared to the figure of merit of 5×10^{-5} for a good Mott analyzer.[3]

The spin-orbit interaction has been shown to cause a very strong spin dependence in elastic scattering from a single crystals of W (Ref. 4–6) and Au.[7] This interaction also causes a large spin-dependent asymmetry in the absorbed-electron current when a polarized electron beam is incident on a W(100) crystal surface as shown in Fig. 2 for angles of incidence $\alpha = 0.4°$, 1.5°, 6.5°, and 14°. The quantity A of Fig. 2 is as defined above but now $\uparrow\uparrow(\uparrow\downarrow)$ corresponds to the incident spin parallel (antiparallel) to the scattering plane normal, $\hat{n} = (\mathbf{k}\times\mathbf{k}')/|\mathbf{k}\times\mathbf{k}'|$, where $\mathbf{k}$ and $\mathbf{k}'$ are the wavevectors of the incident and specularly scattered electron beam

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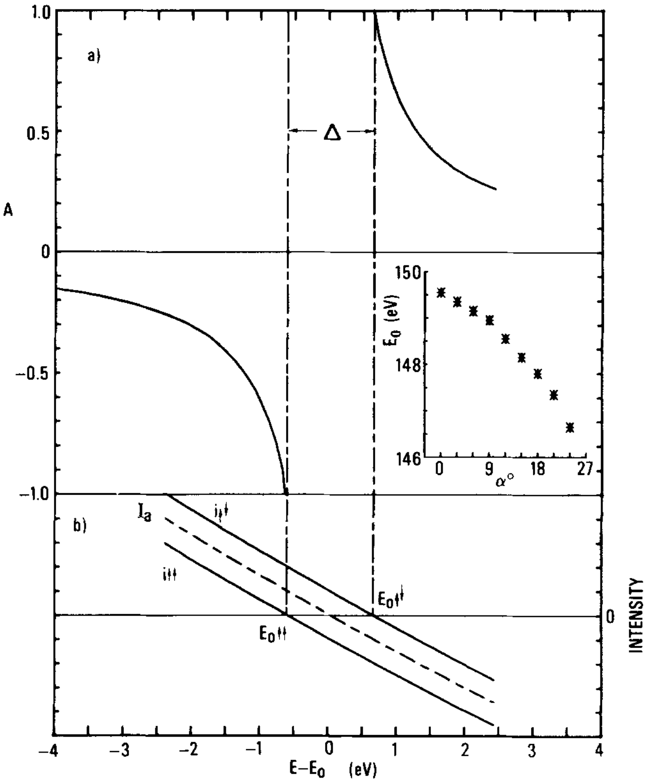

FIG. 1. (a) Exchange interaction induced asymmetry in the absorption of a polarized electron beam at normal incidence on $Ni_{40}Fe_{40}B_{20}$, where $E_0 = 149.55$ eV and $\Delta = 2.3$ eV. The inset shows the variation of E_0 with angle of incidence α. (b)The absorbed electron currents $i\uparrow\uparrow$ and $i\uparrow\downarrow$ are shown with the spin-averaged current I_a. At $E_0\uparrow\downarrow$, only electrons with spin parallel to the majority electrons induce a net absorbed current, i.e. $i\uparrow\downarrow = 0$.

respectively. At normal incidence $A = 0$. The sensitivity of A to angle of incidence α makes it possible to find $\alpha = 0$ to within less than 0.1°. The spin-dependent absorption is symmetric about normal incidence. That is, $A(\alpha) = A(-\alpha)$ when account is taken of the change in the normal to the scattering plane, $\hat{n}(\alpha) = \hat{n}(-\alpha)$. At only 6.5° from normal incidence the spin-dependent absorption is already greater than in the case of $Ni_{40}Fe_{40}B_{20}$ shown in Fig. 1. Note also that at these angles, parallel spins cause a larger absorbed current, giving curves which appear inverted from Fig. 1 (a). At $\alpha = 14°$, the spin dependence is very large as seen from the large $\Delta = 4.1$ eV and the slow decrease of A to either side of $E_0\uparrow\uparrow$ and $E_0\uparrow\downarrow$; at these energies the figure of merit $A^2 I_a / I_0 = 0.004$. The W(100) was cleaned and measured in the (1×1) phase as described previously.[6]

We consider now how this spin-dependent absorption, due either to the exchange or spin-orbit interaction, can be used as a detector. For example, referring to Fig. 1 (b), the absorbed current curve $I(E)$ due to a beam of polarization $P = -0.5$ would lie between the line I_a for zero polarization and the line $i\uparrow\downarrow$, which corresponds to $P = -1$. To the extent that $i\uparrow\uparrow$ and $i\uparrow\downarrow$ are linear, the zero intercept would fall halfway between E_0 and $E_0\uparrow\downarrow$. Note that as long as the energy variation of $i\uparrow\downarrow$ is known from a calibration measurement (it need not be linear), P can be determined from the zero intercept.

This type of spin analyzer is useful in a number of different modes of operation: (i) Measure the zero intercept of the

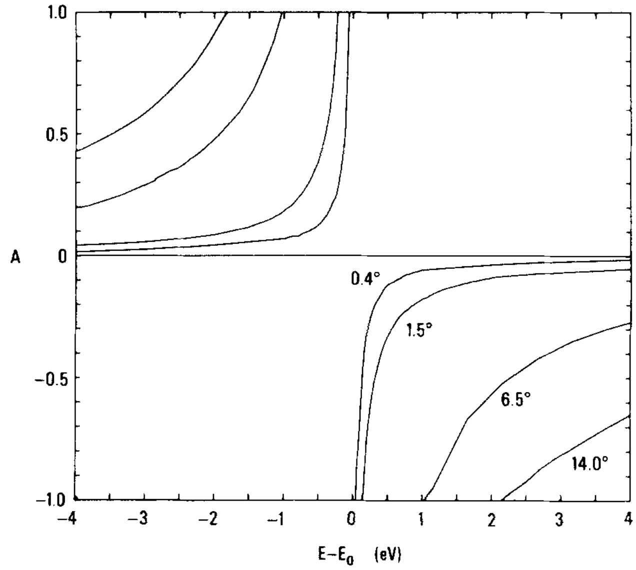

FIG. 2. Absorption of an electron beam incident on a W(100) surface, which is spin dependent as a result of the spin-orbit interaction, is shown at angles of incidence of 0.4°, 1.5°, 6.5°, and 14°. The corresponding E_0 are 206, 206.5, 216.9 and 222.5 eV, respectively, and the Δ are 0.1, 0.38, 2.1, and 4.1 eV, respectively.

unknown beam as described above. (ii). At the energy $E_0\uparrow\uparrow$ measure $I(E_0\uparrow\uparrow)$ and at $E_0\uparrow\downarrow$ measure $I(E_0\uparrow\downarrow)$. The polarization of the unknown beam is $P = (|I(E_0\uparrow\downarrow)| - |I(E_0\uparrow\uparrow)|)/(|I(E_0\uparrow\downarrow)| + |I(E_0\uparrow\uparrow)|)$.

(iii) If the direction of the polarization of the unknown beam can be reversed, it is possible to remain at one energy, say $E_0\uparrow\uparrow$ and measure both currents as required in the expression in (ii). In the case of the ferromagnetic detector, even if the incident polarization cannot be reversed, the majority spin direction of the detector can be reversed relative to the incident polarization by reversing the detector magnetization.

Other parameters are important in the application of spin-dependent absorption as a detector. The energy spread of the incident beam should be small compared to Δ. Absorption in W at 14° has an advantage of large Δ and a slowly varing A near $E_0\uparrow\uparrow$ and $E_0\uparrow\downarrow$. The incident electron beam which can be accepted by the detector is characterized by the conserved phase space producet $EA\Omega$, where E is the electron energy, A is the acceptable cross-sectional area of the beam at the detector, and Ω is the solid angle of the beam which can be accepted. The acceptable angular divergence of the beam at the detector depends on how rapidly E_0 changes with angle of incidence, which is shown for $Ni_{40}Fe_{40}B_{20}$ in the inset in Fig. 1(a). The shift of E_0 is less than ± 0.3 eV for a change in α of $\pm 4°$. Over the angular range plotted, Δ remains a constant 1.3 eV. In the case of W, both E_0 and Δ change significantly in the range $\alpha = 10°$–$20°$, so that for $\alpha = 14°$ the useful angular range is $\pm 1°$ about 14°, which is satisfactory for spin analysis of a low-energy electron diffraction beam. The relative insensitivity of E_0 and Δ to α for $Ni_{40}Fe_{40}B_{20}$ suggest that amorphous or polycrystalline samples may be advantages even when the spin dependence is due to the spin-orbit interaction.

The advantages of a detector based on spin-dependent absorption are its simplicity and high efficiency. No elecron multipliers are required as in a scattering-type detector, which adds to the simplicity but also means that single electrons cannot be detected. This is a disadvantage only for the weakest signals because of the high figure of merit of the absorption detector. Both the exchange interaction and the spin-orbit interaction provide a spin dependence useful for a polarization detector with comparable figures of merit. The choice is not between which interaction, but which target material is stable, easily prepared, and gives a high efficiency over the required acceptance phase space. We expect that this new type of spin detector based on the spin-dependent absorpton of electrons will find wide application.

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