An efficient low-energy electron-spin-polarization analyzer

M. Erbudak
Laboratorium für Festkörperphysik, ETHZ, CH-8093 Zürich, Switzerland
N. Müller
Universität Osnabrück, Fachbereich 4, D-4500 Osnabrück, Germany

(Received 13 November 1980; accepted for publication 20 January 1981).

The spin-orbit coupling in the scattering of electrons at the surface of a gold crystal induces a spin-dependent absorption of electrons. A huge spin dependence of the absorbed current is observed, which promises the realization of an electron-spin-polarization analyzer with an efficiency of over 10^{-2}.

PACS numbers: 34.80. – i, 29.75. + x, 71.170.Ej, 79.20.Hx

Recently, a novel electron-spin-polarization analyzer has been proposed,[1] which is much superior compared to scattering experiments used today.[2] The principle of this new detector is the spin dependence of electron absorption in a ferromagnetic metal. Here, we demonstrate that a still stronger spin-dependent absorption is produced by the spin-orbit coupling in the diffuse backscattering of electrons from a gold target. The spin asymmetry A in the absorption is ± 1, if the electrons are spin polarized along the normal of the plane of incidence and if they hit the surface of a gold crystal at an appropriate angle α. We have measured absorption currents up to 1% of the primary beam intensity and hence the figure of merit[2] for detection of electron spin polarization $A^2 I/I_0 = 10^{-2}$ compared to $< 10^{-4}$ for the best conventional device. Therefore this new detector is the first step towards a new generation of electron spin detectors, which promises a much easier access to spin-dependent phenomena in many branches of physics.

The surface of a gold (110) crystal is cleaned in vacuum ($p = 4\times 10^{-9}$ Pa), as described previously.[3] Electrons from a GaAs cathode[4] – initially with zero polarization – are focused on the surface with an intensity $I_0 = 10^{-8}$ A at such an energy E_0 that the current absorbed by the gold crystal is zero. This situation occurs when the number of primary electrons I_0 hitting the surface and the number of backscattered electrons I_S leaving it are exactly equal. A typical I-V characteristics around E_0 is displayed in the inset of Fig. 1 as a broken line. For a well-defined azimuthal orientation ϕ of the crystal with respect to the plane of incidence spanned by the incoming electrons and the surface normal, we have found that E_0 varies with the polar angle of electron incidence α. The deviations of $E_0(\alpha)$ from cosine law[5] is attributed to crystalline effects, such as diffraction and channelling. For the case where the electrons impinge in an azimuth normal to the "chains" of the surface net (the scattering plane is normal to the $1\bar{1}0$ direction $\phi = 90°$)[3], $E_0(\alpha)$ is shown in the upper part of Fig. 1. Since the behavior of $E_0(\alpha)$ is observed to be symmetric around $\alpha = 0$, it is displayed only for positive values of α. E_0 is relatively smooth for $|\alpha| \leqslant 15°$ and $|\alpha| \geqslant 49°$. At a given α and corresponding E_0 we then have used spin-polarized electrons alternating the polarization of the incident beam from 0.23 to -0.23. At each polarization setting a finite absorption current was detected. This externally meassured current is denoted $I_\uparrow$ ($I_\downarrow$) for the case when the spin of the incident electron is parallel (antiparallel) to the normal of the plane of incidence. The resulting spin-dependent current difference $I = I_\uparrow - I_\downarrow$ thus obtained is plotted as function of α on the lower part of Fig. 1. Both the ordinate of Fig. 1 and the $I_\uparrow$-V and $I_\downarrow V$ characteristics in the inset are extrapolated to polarizations of ± 1. The α values are determined with an absolute error of 0.5° and resettability of 0.1°; the energy spread in the electron beam is 0.2 eV. There was, however, a noisy background in the current mea-

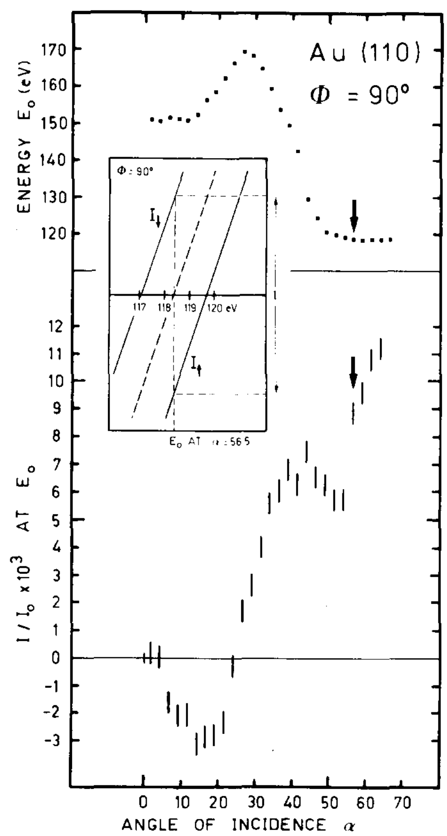

FIG 1. The zero-current energy of unpolarized electrons striking the gold crystal with an angle of incidence α (upper figure) and the resulting spin asymmetry I/I_0 in the absorption for fully polarized electrons. $\phi = 90°$ means that the chains of the (110) surface are perpendicular to the plane of incidence. The inset shows the I-V characteristics of the current absorbed by the target if the incident beam is fully polarized ($I_\uparrow$ and $I_\downarrow$) and unpolarized (broken line).

surement which is responsible for the error bars in I/I_0, as explained below. The GaAs photocathode is operated at a fixed potential of -240 V and electrons are extracted by accelerating them towards ground potential. By means of proper electron optics and applying a bias to the target $(-240 + E_0)$, the desired scattering energy is achieved. However, the resulting leakage current from the sample to ground puts limitations in the present arrangement on the usable ranges of the electrometer for the current detection, producing some uncertainties in I. Still, it is obvious that enormous spin dependences appear in the observed current. The arrows in Fig. 1 at $\alpha = 56.5°$ mark E_0 and I/I_0 values used in the inset. The polarization-dependent absorption relative to the primary beam intensity is very high at large angles, drops to zero at $\alpha = 24°$ and changes sign. At $\alpha = 0°$, I is zero. The same behavior with opposite sign, however, is obtained for the negative values of α. A similar spin-dependent absorption spectrum is measured for $\phi = 0°$, i.e., plane of incidence parallel to the chains,[5] as displayed in Fig. 2.

The physical phenomenon responsible for the observation described above is the spin-orbit coupling of electrons when they elastically scatter at the gold surface. Depending on their spin orientation, they are subject to different scattering potentials and therefore, the zero-current energies $E_{\uparrow o}$ and $E_{\downarrow o}$ are different. For $\phi = 90°$ and $\alpha = 56.5°$, $E_{\uparrow o} = 117.1$, $E_o = 118.4$, and $E_{\uparrow 0}$=119.7. Hence, at E_0, for an electron with its spin parallel to the normal of the plane of incidence there is a finite absorption , whereas when the electron spin is antiparallel to the normal more electrons leave the target than are incident on it. At any energy the spin-dependent asymmetry can be given as$(I_\uparrow - I_\downarrow)(I_\uparrow + I_\downarrow)^{-1}$ which is usually a very small fraction. At E_o, however, the polarization-independent portion vanishes and A diverges. Depending on the spin orientation of the incident electrons, the measured current is positive or negative. At $E_{\uparrow o}$ and $E_{\downarrow o}$, A resumes values of ± 1. That the spin-orbit coupling is the responsible cause for the observation described here, is shown by the appearance of the mirror symmetry of the crystal surface as an antisymmetry of I/I_o profile with respect to α and $-\alpha$ and its being zero for $\alpha = 0°$ where a complete spatial symmetry is achieved with respect to the incoming and outgoing electrons.

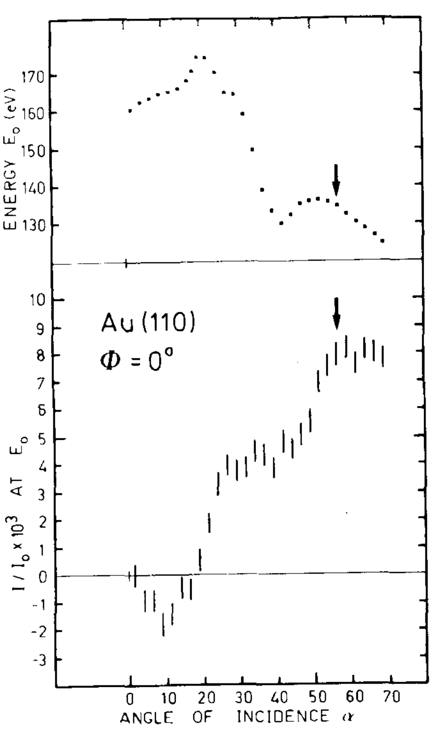

FIG. 2. E_o and I/I_o profiles as a function of α at $\phi = 0°$ (chains in the plane of incidence).

We want to point out that a device for measuring electron spin polarization based on these principles can be realized with moderate effort. A beam of electrons with unknown polarization $\pm P$ can be steared on a clean gold crystal to hit the surface under a preselected set of angles, e.g., $\pm 56.5°$. Two absorption currents thus measured at the gold target must be symmetrized (cf. inset of Fig. 1) around zero by adjusting the incident beam energy. The difference between these two symmetrical currents $(I = I_\uparrow - I_\downarrow)$ is then a direct measure of the spin polarization of the incident beam; a fully polarized beam would yield I/I_o values shown in Figs. 1 or 2 depending on the polar and azimuth orientation of the target.[6] The exact values of E_o are very sensitive to the cleanliness of the surface, which affects the work function and hence the number of secondaries produced. The energy spread of the incident beam will influence the resolving power of this device. As seen in Fig. 1 (inset), $E_{\uparrow o} - E_{\downarrow o} = 2.6$ eV for $\phi = 90°$ and $\alpha = 56.5°$. There will, however, be no problem if the energy spread of the beam is much below this value as is the case in many electron detecting spectroscopies. For $\phi = 0°$ and $\alpha = 56.5°$, we have obtained $E_{\uparrow o} - E_{\downarrow o} = 2.2$ eV. A comparison between Figs. 1 and 2 suggests a favorable operation at $\phi = 0°$ and $|\alpha| \geqslant 56.5°$, which yields a relatively constant I/I_o value. For some experimental conditions, an operation at $\phi = 90°$ and $|\alpha| \geqslant 49°$ can be utilized if the constancy of E_o with respect to α is crucial. In either case, this device will have a figure of merit of 10^{-2} for detection of spin polarization, which is much superior to the currently used polarization detectors.

The main features of the spin-orbit interaction, like those described here, are dictated by the properties of the single atom, which are only to a certain extent modulated by the crystalline environment and by the chemical bonds. The scattering properties of a polycrystalline sample are in fact very similar to those of the isolated atom, as was shown for mercury.[7] Therefore, in a practical detector for electron spin polarization one can use a polycrystalline target instead of a well-defined single crystal.

The authors are much indebted to H. C. Siegmann for suggesting this experiment and making Ref. 1 available prior to publication. We also would like to thank M. Landolt for fruitful discussions and MPI für Plasmaphysik in Garching for the crystal manipulator. This work was supported by the Schweizerische Nationalfonds.

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

R. J. Celotta, D. T. Pierce, H. C. Siegmann,[a] and J. Unguris [b]
National Bureau of Standards, Washington, D. C. 20234

(Received 20 November 1980; accepted for publication 20 January 1981)

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.

PACS numbers: 79.20.Hx, 71.70.Ej, 75.50.Kj

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 $A^2 I_a/I_0$ where I_0 is the incident beam intensity. For a $Ni_{40}Fe_{40}B_{20}$ sample as in Fig. 1, we find $A^2 I_a/I_0 = 0.003$ 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

[a]Permanent address: Laboratory for Solid State Physics, Swiss Federal Institute of Technology, CH-8093, Zurich, Switzerland.
[b]NBS-NRC Postdoctoral Fellow 1980-81.