Spin-dependent transmission of polarized electrons through a ferromagnetic iron film

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Polarized electrons excited in a GaAs crystal by optical spin orientation are photoemitted after having passed through a thin ferromagnetic overlayer of iron. It is shown that the photoyield dpeends on the relative orientation of the spin magnetic moment of the photoelectrons with respect to the magnetization of the iron film. Close to the photothreshold, the transmission is about 1.7 times larger when the orientation is parallel compared to the case where it is antiparallel.

I. INTRODUCTION

Photoemission is an important tool for studying the electronic structure of solids. For primary photoelectrons energy and momentum parallel to the surface are conserved; accordingly, spectroscopic information is obtained by applying conservation laws alone without need for a microscopic model of the emission process.[1] In spin-polarized photoemission it is indispensable to know the relation between the measured polarization of the photoelectrons and the polarization of those initial states which contribute to the photocurrent.

A growing amount of evidence has accumulated that P generally undergoes a change during emission: the polarization measured in vacuum is generally different from the ground-state polarization of the electrons contributing to the photocurrent. In Refs. 2 and 3 the overlayer technique is used to show that unpolarized electrons from a nonmagnetically ordered substrate material become polarized after traversing a thin ferromagnetic film. Alternatively, in inverse photoemission it has been known for a long time[4] that the recombination radiation of an electron beam incident on a ferromagnet depends on the orientation of the spin polarization of the beam with respect to the magnetization pointing to a spin-dependent mean free path. Indeed, from an analysis of the experimental data presently available (see, also, Refs. 5–7), it is found that the spin-dependent inelastic mean free path is larger for majority electrons, i.e., those electrons which have their spin magnetic moment aligned parallel to the magnetization:[8] this results in the so-called polarization enhancement discussed in Ref. 3.

In this paper an experiment is presented which gives evidence for the spin-dependent transmission of photoelectrons through a ferromagnetic iron film. The characteristic feature of the experiment is that the test electrons which cross the ferromagnetic film are polarized. From an analysis of the spin dependence of the photoemitted current a ratio as large as 1.7 is obtained for the relative transmission of electrons having their spin magnetic moment parallel (antiparallel) to the magnetization of the iron film.

II. EXPERIMENT

The sample structure used is the following: polarized electrons are excited in a GaAs crystal using the method of optical spin orientation.[9] These polarized electrons can escape into vacuum after having traversed a magnetic iron layer with magnetization aligned along an external magnetic field perpendicular to the sample surface, see Fig. 1. The iron film is separated from the GaAs by an

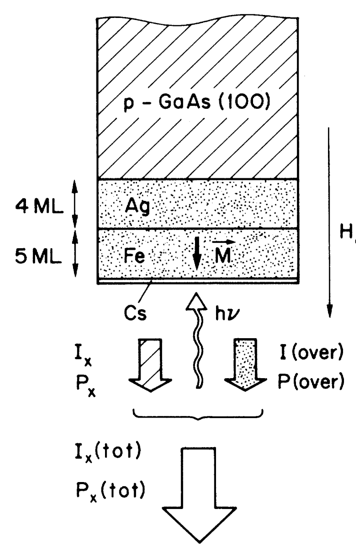

FIG. 1. Schematic of the sample structure: On the GaAs(100) substrate an Ag film with nominal thickness of 4 monolayers (ML) is deposited, followed by a 5-ML iron film. The photothreshold is lowered by cesium activation. The emitted current from the substrate is denoted by I_x, the polarization by P_x ($x=0,+,-$ for unpolarized, right-hand circularly polarized, left-hand circularly polarized light). The emitted current from the overlayer structure (Ag+Fe+Cs) is denoted by I (over), the polarization by P (over). The measured total intensity and total polarization are denoted by I_x(tot) and P_x(tot): they are composed of the emitted currents from the overlayer and the substrate. The magnetization **M** of the iron overlayer is aligned along the direction of the externally applied magnetic field. $h\nu$ indicates the direction of the light.

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intermediate buffer layer of silver. The purpose of the buffer layer is to prevent the interdiffusion and chemical reaction of Fe with GaAs.[10] Fe that is in direct contact with GaAs shows no magnetic order up to a thickness of about 15 monolayers (ML). In contrast, with the silver buffer layer the iron films are magnetic with a magnetization equal to the one found when depositing Fe on a Ag crystal.[11] Finally, cesium is evaporated on top of the structure in order to adjust the photothreshold to the desired value.

The GaAs(100) bulk crystal was mechanically polished to 0.1 μ and then inserted into the ultrahigh-vacuum chamber where it was Ar^+ sputtered (800 eV) and shortly annealed (1 min at 550 °C). The sharp low-energy electron-diffraction (LEED) pattern obtained after the surface preparation showed the well-known 6×4 reconstruction.[12] The Ag film deposited onto the GaAs is (110) oriented.[13] The LEED pattern of the Ag film becomes sharp only at thicknesses >10 ML. Most probably the reason is that very thin Ag films do not grow homogeneously on the GaAs surface.[13] In fact, scanning tunneling microscopy shows that Ag films grown on GaAs(110) and GaAs(100) consist of islands having lateral dimensions of typically 100 Å.[14]

The deposition of the Ag and Fe overlayers took place with the substrate at room temperature. The base pressure in the ultrahigh-vacuum chamber was 2×10^{-8} Pa. The magnetic field applied along the surface normal of the sample was generated by a superconducting coil. It was sufficiently large to saturate the iron film. The measurements have been carried out at a sample temperature of 220 K. Further details on the experimental setup can be found in Ref. 15. The polarization of the GaAs substrate electrons is due to the excitation with circularly polarized light across the band gap. A full account of this method of optical spin orientation is given in Ref. 11. The polarized GaAs electrons are emitted at low kinetic energy within 1 eV from photothreshold. At these energies the average inelastic collision causes an electron to be removed from the photocurrent,[16] which is a favorable feature for the observation of spin-dependent transmission effects. Note that the cesium submonolayer does not affect the polarization of the photoelectrons; numerous experiments confirm this explicitly for semiconductors[17] as well as ferromagnets.[15]

The aim of the experiment is to measure the total intensity I(tot) of all the emitted electrons as function of the polarization direction of the electrons excited in the GaAs-substrate crystal. The total photocurrent includes the contributions of all the layers. Since the inelastic mean free path in solids is of the order of 10 Å only, a noticeable contribution of the GaAs electrons to the photocurrent requires a careful choice of the thickness of the Fe and Ag layers. It turns out that five monolayers for both materials are about the optimum values for maximizing the polarization effect. Next we analyze how the polarization of the GaAs electrons affects the measured total intensity I(tot).

For any polarization of the light the number of electrons excited per unit time in GaAs is denoted by $n\uparrow$ ($n\downarrow$) for the two spin states. Spin up (down) means that the spin magnetic moment is directed parallel (antiparallel) to the surface normal of the sample. The total number of electrons excited in the GaAs is independent of the polarization of the light:

$$n\uparrow+n\downarrow=N_0 \ . \tag{1}$$

However, the ratio $q=n\uparrow/n\downarrow$ depends on the polarization of the light: for right-circularly polarized (rcp) light the ratio is $q_+=q$, for left-circularly polarized (lcp) light it is $q_-=1/q$. The number of up and down electrons expressed in terms of N_0 and q are

$$n\uparrow=N_0\frac{q}{1+q}, \quad n\downarrow=N_0\frac{1}{1+q} \ . \tag{2}$$

The aim of the experiment is to investigate whether the transmission of the substrate electrons through the Fe film is spin dependent. Denoting the transmission probabilities for electrons with spin-magnetic moment parallel (antiparallel) to the magnetization of the Fe layer by $\alpha\uparrow$ ($\alpha\downarrow$) the quantity to be determined is the ratio $r=\alpha\uparrow/\alpha\downarrow$.

Choosing the direction of the magnetization such that the $n\uparrow$ electrons have their spin magnetic moment aligned parallel to the Fe magnetization the photocurrent originating from the GaAs substrate is $I=n\uparrow\alpha\uparrow+n\downarrow\alpha\downarrow$. In particular,

$$\text{for unpolarized light, } q=1\text{: } I_0=\frac{1}{2}N_0(\alpha\uparrow+\alpha\downarrow) \ , \tag{3a}$$

$$\text{for rcp light, } q_+=q\text{: } I_+=\frac{N_0}{1+q}(q\alpha\uparrow+\alpha\downarrow) \ , \tag{3b}$$

$$\text{for lcp light, } q_-=\frac{1}{q}\text{: } I_-=\frac{N_0}{1+q}(\alpha\uparrow+q\alpha\downarrow) \ . \tag{3c}$$

When the polarization of the light is varied from rcp to lcp the relative change of the photocurrent originating from the GaAs substrate is

$$\frac{\Delta I}{I_0}=\frac{I_+-I_-}{I_0}=2\frac{(q-1)(r-1)}{(q+1)(r+1)} \ . \tag{4}$$

There is no change of the transmitted intensity of GaAs electrons if $\alpha\uparrow=\alpha\downarrow$ ($r=1$) or if the polarization obtained by optical pumping is zero ($q=1$).

The detected current I(tot) consists of the transmitted current from the GaAs and the current from the overlayer I(over). For rcp light $I_+(\text{tot})=I_++I(\text{over})$, for lcp light $I_-(\text{tot})=I_-+I(\text{over})$, for unpolarized light $I_0(\text{tot})=I_0+I(\text{over})$. The intensity I(over) of the electrons emitted by overlayer does not depend on the polarization of the light implying $\Delta I(\text{tot})=\Delta I$ and $I_0(\text{tot})=\frac{1}{2}[I_+(\text{tot})+I_-(\text{tot})]$. The relative change of the detected current upon reversal of the polarization of the light is

$$\frac{\Delta I(\text{tot})}{I_0(\text{tot})}=\frac{\Delta I}{I_0(\text{tot})}=\frac{I_+-I_-}{I(\text{over})+I_0} \ . \tag{5}$$

The spin-dependent transmission ($r\neq0$) is recognized by $\Delta I(\text{tot})\neq0$.

I_0(tot): the total intensity emitted with unpolarized light from the GaAs covered with the (Ag+Fe+Cs) overlayer. $I_+ - I_-$: the difference between the transmitted currents from the GaAs substrate due to reversal of the circular polarization of the light. $I_+ - I_-$ is equal to $I_+(\text{tot}) - I_-(\text{tot})$. *This is the effect of spin-dependent transmission.*

Further the ratio q of "up" and "down" polarized electrons emitted from the GaAs substrate into the overlayer must be known. This ratio is determined using a separate polarization measurement of the optically spin-oriented photoelectrons emitted from the GaAs substrate covered with Cs alone.

III. EXPERIMENTAL RESULTS

The polarization of the photoelectrons emitted by circularly polarized light from the GaAs-substrate crystal used is shown in Fig. 2. In the same figure the polarization is shown after having covered the crystal with a Ag film of 4 ML thickness. In both cases the photothreshold of the sample has been adjusted to 1.5 eV by depositing an appropriate amount of cesium on top of the whole structure.

Next the polarization of the optically spin-oriented electrons from GaAs after an additional film of Fe (5 ML thickness) has been deposited on top of the (GaAs+Ag) sample has been measured. No external magnetic field is applied, hence for unpolarized light $P_0(\text{tot})=0$.

Decisive for the experiment is the fact that the Fe film is ferromagnetic. The Fe film saturates at about 1 T, clearly below the demagnetizing field $4\pi M$. This is evident for considerable anisotropy perpendicular to the plane of the film. The perpendicular anisotropy in the system Fe/Ag(001) has been studied in detail.[11] The fact that the 5-ML Fe film is ferromagnetic proves that the Ag-buffer layer efficiently decouples chemically the Fe from the GaAs. When Fe is deposited directly on top of the GaAs the surface shows no ferromagnetic order at an Fe thickness of 5 ML. As already shown in previous experiments[11] the polarization of the photoelectrons emitted from the iron layer at $h\nu=2.15$ eV is identical to the polarization measured at $h\nu=1.5$ eV.

The experimental proof for spin-dependent transmission is presented in Figs. 3 and 4. In Fig. 3 a magnetic field of 1.6 T is applied to the system in order to assure that the Fe film is magnetically saturated. Then, the polarization of the light is varied from rcp to lcp in discrete steps by adjusting the variable Soleil-Babinet retarder. After having passed all optical components the intensity of the light incident on the sample surface was measured. The normalized photocurrent $I(\text{tot})$—the number of emitted electrons at constant light intensity at the sample surface—is then found to vary with the setting of the retarder, i.e., with the degree of circular polarization of the light. The photon energy was taken to be 1.5 eV, close to the photothreshold where the GaAs polarization is largest.

In Fig. 4 the relative change of the photocurrent $\Delta I(\text{tot})/I_0(\text{tot})$ is plotted at external magnetic fields $H=1.6$ T, $H=0$, and $H=-1.6$ T. $\Delta I(\text{tot}) = I_+(\text{tot}) - I_-(\text{tot})$, the + (−) subscript again refers to rcp (lcp) light. As before, the sense of the polarization of the light is defined with respect to the surface normal and not with respect to the direction of the magnetization. For $H=+1.6$ T and rcp light the GaAs photoelectrons

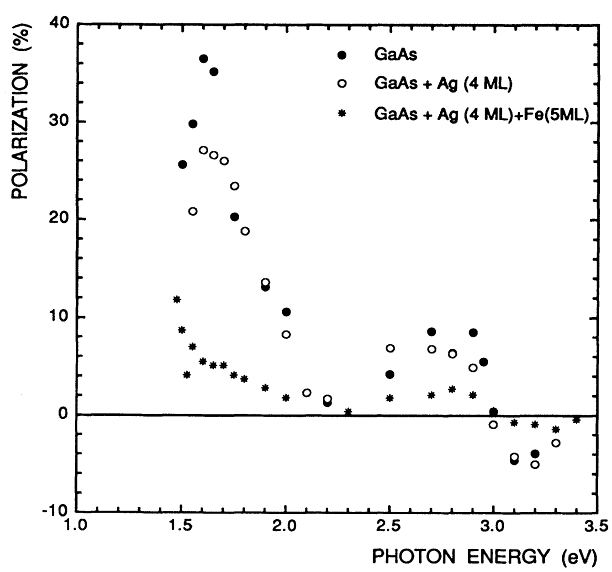

FIG. 2. Polarization of the photoelectrons emitted from strongly *p*-doped GaAs by circularly polarized light as function of the photon energy. Full circles: Cs-activated GaAs; Open circles: Cs-activated GaAs covered with 4-ML Ag. Stars: Cs-activated GaAs covered with 4-ML Ag and 5-ML Fe. No external magnetic field is applied and therefore the magnetic domains of the Fe film are not aligned.

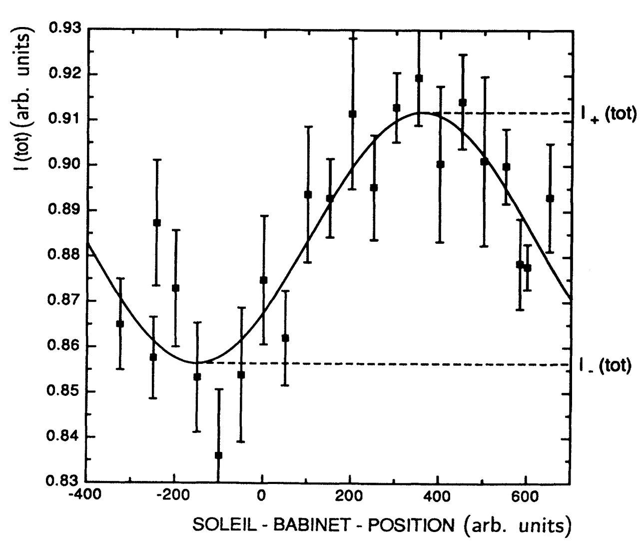

FIG. 3. Photocurrent $I(\text{tot})$ emitted from the Cs-activated GaAs substrate covered with 4 ML of Ag and 5 ML of Fe as a function of the degree of circular polarization of the light. At the position—150 of the Soleil-Babinet optical retarder the polarization of the GaAs electrons is antiparallel to the magnetization of the Fe film—[Intensity: $I_-(\text{tot})$], at +400 it is parallel [Intensity: $I_+(\text{tot})$]. The 5-ML Fe film is magnetically saturated in an applied field of 1.6 T.

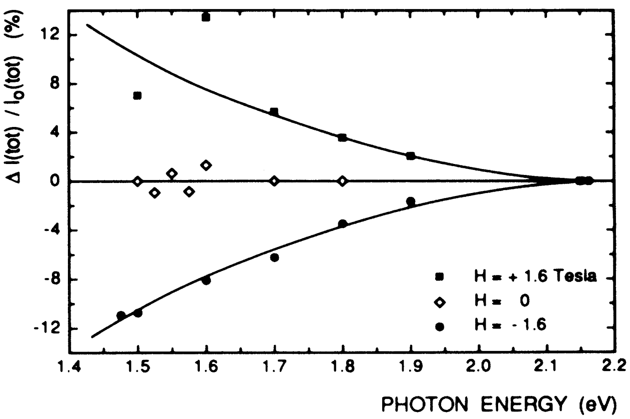

FIG. 4. Fractional change $\Delta I(\text{tot})/I_0(\text{tot})$ of the photocurrent upon switching the polarization of the light from rcp to lcp for applied magnetic fields $H=1.6$ T (full squares), $H=-1.6$ T (full circles), and $H=0$ (diamonds). At $H=1.6$ T and for rcp light the GaAs photoelectrons have their maximum polarization parallel to the magnetization of the Fe film.

have their maximum polarization parallel to the magnetization of the Fe film: therefore they give the maximum contribution to the photocurrent (full squares). After having reversed the magnetization by applying the field $H=-1.6$ T the GaAs photoelectrons have for rcp light their maximum polarization antiparallel to the magnetization of the Fe film: therefore, they give the minimum contribution to the photocurrent (full circles). When no magnetic field is applied, the photocurrent indicated by the zero line in Fig. 4 is independent of the polarization of the light (diamonds). With increasing photon energy the photocurrent through the magnetized Fe layer becomes less dependent on the polarization of the light. This is due to the fact that the polarization of the electrons excited in the GaAs decreases at higher photon energies.

From the information contained in Figs. 2–4, the ratio r of the transmission probability for up- and down-polarized GaAs electrons can be determined using Eq. (4). First, the ratio $\Delta I/I_0$ must be found. $\Delta I=\Delta I(\text{tot})$ can be read directly from Fig. 3 as the difference between the maximum and minimum of the total emitted current: $\Delta I_0(\text{tot})=0.055$ a.u. In order to determine $I_0=I_0(\text{tot})-I(\text{over})$, an additional relation between $I(\text{over})$ and I_0 can be set up.

For the unmagnetized overlayer the polarization of the photocurrent is entirely due to the optically oriented electrons emitted from the GaAs substrate. This polarization is shown in Fig. 3. With respect to the (GaAs+Cs) curve from Fig. 2 a reduction of the polarization occurs because of the admixture of unpolarized electrons from the overlayer. Again for $h\nu=1.5$ eV one finds from Fig. 2

$$\frac{I(\text{GaAs})P(\text{GaAs})}{I(\text{over})+I(\text{GaAs})}=0.12\ . \tag{6}$$

For the unmagnetized Fe film $I(\text{GaAs})=I_0$ independent of the polarization of the light. This follows from the fact that for the unmagnetized Fe layer there is no spin dependence of the transmitted GaAs current: $\alpha_0=\frac{1}{2}(\alpha\uparrow+\alpha\downarrow)$. Therefore,

$$I(\text{GaAs})=(n\uparrow+n\downarrow)\alpha_0=N_0\alpha=\frac{N_0}{2}(\alpha\uparrow+\alpha\downarrow)=I_0\ .$$

Then, with $P(\text{GaAs})=0.36$ at $h\nu=1.5$ eV (Fig. 2), the contribution of the overlayer to the photocurrent becomes

$$I(\text{over})=2I_0$$

or $I_0(\text{tot})=3I_0$. With $I_0(\text{tot})=0.88$ a.u. from Fig. 3, $I_0=0.29$ a.u. and $\Delta I/I_0=0.19$.

q is determined from Fig. 2: the polarization of the electrons emitted from GaAs+Cs by circularly polarized light is

$$P(\text{GaAs})=\frac{n\uparrow-n\downarrow}{n\uparrow+n\downarrow}=\frac{q-1}{q+1}\ .$$

At $h\nu=1.5$ eV, $P(\text{GaAs})=0.36$, therefore $q=2.125$. Now, all information to derive r from Eq. (4) is available. One obtains

$$\frac{\Delta I}{I_0}=0.19=2\frac{(q-1)(r-1)}{(q+1)(r+1)}=2\frac{1.125(r-1)}{3.125(r+1)} \tag{7}$$

giving

$$r=\alpha\uparrow/\alpha\downarrow=1.70\ . \tag{8}$$

This is the desired result.

Using the data displayed in Fig. 4 the ratio r is extracted at various photon energies. The values found are plotted in Fig. 5. Note that the transmission $\alpha\uparrow(\alpha\downarrow)$ refers to electrons with their spin magnetic moment parallel (antiparallel) to the magnetization of the Fe film.

From these intensity measurements it is concluded that the transmission of excited electrons through a magnetized Fe film is spin dependent. Majority electrons having their spin magnetic moments parallel to the magnetization have a substantially larger transmission probability.

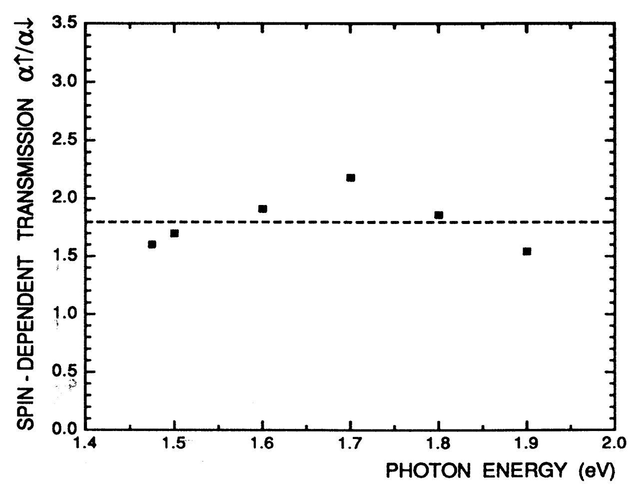

FIG. 5. Ratio of the transmission for majority and minority electrons through a ferromagnetic iron film.

It should be noted that all conclusions with regard to the spin-dependent transmission of electrons through a magnetized Fe film have been obtained from experimentally determined quantities. No adjustable parameters have been used.

IV. OUTLOOK

The transmission of polarized electrons through a magnetic Fe film is spin dependent. The origin of the spin-dependent transmission is not evident *a priori,* whether it is due to an interface effect or to a spin dependence of the inelastic mean free path in the Fe film. In principle, this problem could be decided by making measurements with Fe overlayers of different thickness. If the spin dependence of the transmission is an interface effect it should be insensitive to the thickness of the Fe layer. Unfortunately, the inelastic mean free path is so short that a systematic study of the spin dependence on the Fe thickness is hampered by the fact that the substrate emission becomes unmeasurably small for Fe layers more than a few monolayers thick. Therefore—as already noticed in Ref. 2—there is only a very restricted range of the thickness of the ferromagnetic films where meaningful experiments can be carried out.

Another problem to be addressed concerns the possibility of spin-dependent elastic scattering in ferromagnets. Evidently, elastic scattering has no influence on the transmitted intensity. Therefore, the spin-dependent change of the photocurrent discussed in this paper deals with inelastic scattering. However, a possible effect of spin-dependent elastic scattering on the polarization cannot be ruled out. Unfortunately, the effects are too small to be experimentally resolved by a polarization measurement with circular polarized light and with applied magnetic field. But, hypothetically, an experimental determination of elastic scattering is possible by applying the following procedure: from the intensity measurement the ratio $r=\alpha\uparrow/\alpha\downarrow$ is found. Then, the change of the polarization $\Delta P/P_0$ due to inelastic scattering is derived: if it turns out to be identical to the measured value $\Delta P/P_0$—provided the measurement can be done with sufficient accuracy—there is no evidence for elastic scattering. Otherwise, elastic scattering must be taken into account. It should be added that evidence for spin-dependent elastic scattering from paramagnetic moments has been found a long time ago.[18]

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