Spin polarization of secondary electrons from amorphous 3*d* metallic ferromagnets

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It is shown that the spin polarization of secondary electrons from Fe-Ni–based metallic glasses ($Fe_{82}B_{12}Si_6$, $Fe_{60}Ni_{20}B_{20}$, $Fe_{44}Ni_{37}B_{19}$) in the energy range of 10–20 eV directly reflects the bulk magnetization of the material. All samples show a strong spin-polarization enhancement at low secondary energy (<10 eV). No additional structure is observed for these amorphous materials, contrary to single crystals where the spin polarization is affected by band-structure (low-energy electron diffraction) effects.

Measuring the spin polarization of secondary electrons from ferromagnets has, over the last few years, evolved into a powerful tool for studying the magnetism of surfaces.[1] When combined with highly focused primary excitation sources, "magnetic imaging" can be achieved with a lateral resolution of 100 Å. This so-called secondary-electron microscopy with polarization analysis (SEMPA) has become an important and exciting technique for measuring the domain structure at the surface of a ferromagnet.[2] For a quantitative interpretation of these kinds of data, the relation between surface magnetic moment and measured spin polarization has to be established.

After the first successful experimental demonstration —on a rather ill-characterized surface— that secondary electrons from magnetic samples are indeed spin polarized,[3] it was generally thought that the spin polarization of low-energy secondary electrons simply reflects the net magnetization of the material. Detailed energy-resolved measurements showed that the spin polarization of secondary electrons exhibits unexpected interesting features.[4] Below about 10 eV secondary energy, a strong enhancement of the spin polarization over the bulk magnetization is common to all 3*d* ferromagnets studied so far. This effect has been explained in terms of Stoner excitations by Glazer and Tosatti,[5] or as being due to a strong spin dependence of the inelastic mean free path by Penn, Apell, and Girvin.[6]

Above 10 eV the spin polarization levels off into a "plateau," showing only a weak general decrease with increasing energy. For single-crystal surfaces additional structures have been observed to be superimposed on this plateau.[1] These structures have recently been explained by Tamura and Feder[7] as being due to band-structure [low-energy electron diffraction (LEED)] effects. There has been some discrepancy in the literature about the absolute spin-polarization value of the plateau. In some cases, the plateau value closely resembled the bulk magnetization, while in others significantly smaller values were found (see Ref. 1). In this Brief Report, it is shown that for a series of 3*d* amorphous ferromagnets with varying magnetizations, the measured spin polarization between 10 and 20 eV energy equals the bulk magnetization of the material within the experimental uncertainty of the measurement (i.e., 1%–2%).

The experiments were performed in an ultrahigh-vacuum apparatus described in detail elsewhere.[8] The samples were ribbons, clamped together to form circular loops, and could be magnetized by a current pulse through a small coil wrapped around them. The samples were cleaned by noble-gas-ion sputtering (up to several hours) at room temperature without any subsequent annealing, in order to avoid recrystallization and possible surface-segregation effects. The excitation source was a commercial LEED gun, run at 400-eV primary energy. The electrons impinged on the surface 30° off normal while the secondary electrons were collected normal to the surface. After passing through a hemispherical energy analyzer ($\Delta E = 200$ meV) the spin polarization was measured in a high-energy (100 kV) Mott detector. A negative bias of 30 V was applied to the samples in order to suppress any low-energy stray electrons not originating from the sample and to more efficiently collect the secondary electrons.

Figure 1 shows the results obtained for the three different samples. The lower panel shows the typical intensity distribution curve of secondary electrons (for the $Fe_{82}B_{12}Si_6$ sample), strongly peaking at zero energy. The intensity curve did not vary significantly for the three samples. The three upper panels of Fig. 1 show the spin-polarization spectra. All three samples show the same general features: strong enhancement of the spin polarization below 10 eV, followed by a plateau where the spin polarization is almost constant over a large energy range. No significant structures like those found in single crystals are superimposed on this plateau. The spin-polarization values of these plateaus (i.e., between 10 and 20 eV) are 22%, 19%, and 15%, respectively. These values *quantitatively* agree with the known bulk magnetizations of these samples[9] within the absolute accuracy of the measurements (estimated to be between 1% and 2%). I believe that this quantitative agreement can be expected at least for all 3*d* ferromagnetic samples, where no magnetic surface reconstruction takes place and the changes in surface magnetic moments are relatively small. This then also im-

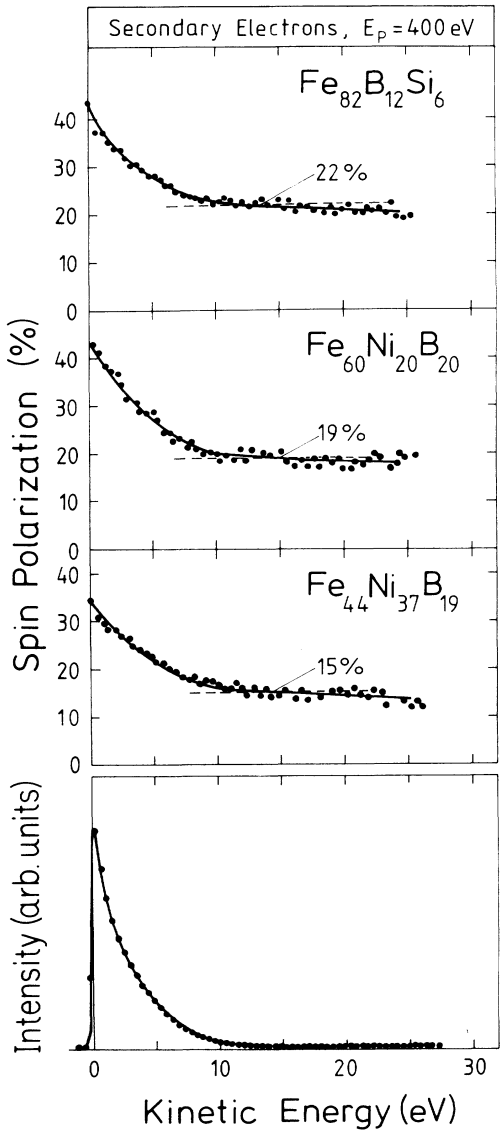

FIG. 1. Intensity distribution curve (lower panel) and spin polarization spectra of secondary electrons from three different amorphous ferromagnetic samples. The solid lines are guides to the eye. The broken lines and the numbers give the "plateau" value, i.e., the spin polarization around 15 eV energy.

plies for the present samples that the composition at the surface is essentially bulklike. In cases where much lower spin-polarization values have been found (see Ref. 1), this could be due to incomplete magnetization of the sample, surface contamination, and miscalibration of the spin polarimeter.

Finally, I want to mention two practical aspects of the present work. First, SEMPA can, in principle, be done in a quantitative way, i.e., measuring absolute magnetization. For this purpose, an energy spectrum between, e.g., 10 and 20 eV kinetic energy should be taken in order to find the real plateau-polarization value for single-crystalline or polycrystalline samples. In this way, structures in the polarization due to diffraction effects can be accounted for. An energy resolution of a few eV would be good enough. Of course, this type of operation implies a large loss in sensitivity because of the loss in intensity and the reduced polarization values at higher kinetic energies, so that for a more qualitative application, i.e., imaging of domain structures, the operating mode which collects essentially all secondary electrons might be advantageous. Second, an amphorous sample like $Fe_{82}B_{12}Si_6$ can be used as a "calibrated" spin-polarized electron source. The measured spin-polarization values are very reproducible;[10] it is relatively easy to clean these samples as compared to single crystals. Sputtering with Ar or Ne, at 2 kV, and 10 μA for 1 h at room temperature was sufficient to get a clean sample, which did not change anymore with further sputtering. No annealing was done after sputtering. Unfortunately there was no sensitive Auger equipment (cylindrical mirror analyzer) available during the measurements to check surface cleanliness and composition. This type of source is not as involved as, e.g., the GaAs source, and is at least as reproducible.

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[9]See, e.g., F. E. Luborsky, in *Ferromagnetic Materials*, edited by E. P. Wohlfarth (North-Holland, Amsterdam, 1980), Vol. 1.
[10]Actually, this sample was used as a first test sample in the new spin-polarized electron spectrometer at the University of California, Irvine. With no difficulty and in very little time, we were able to reproduce quantitatively the results presented in this paper. D. L. Abraham and H. Hopster (unpublished).