Spin Polarization of Injected Electrons

LaBella *et al*. (*1*) claimed 92% spin polarization for electrons injected into gallium arsenide [GaAs(110)] from a Ni scanning tunneling microscope (STM) tip, which, they asserted, emitted 100% spin-polarized electrons. Such a claim, if substantiated, would constitute a development of great importance for the emerging field of spintronics: It would suggest that the field is rapidly closing in on the goal of injecting electrons with 100% spin polarization, a key to device applications. For reasons discussed below, however, we believe that the actual injected electrons had a spin polarization of much less than 92% and that emission of 100% spin-polarized electrons from the Ni tip would not be expected.

The measured polarization of the emitted light in the LaBella *et al*. study, 11.5%, is connected to the spin polarization of the injected electrons by three conversion factors: (i) the ratio of the detected light polarization to the emitted light polarization; (ii) the ratio of the emitted light polarization to the polarization of the electron spin density; and (iii) the ratio of the polarization of the electron spin density to the polarization of the injected current. By ignoring the refraction of the light when it leaves the GaAs, LaBella *et al*. (*1*) both missed the first correction factor and overestimated the second. The final conversion factor depends strongly on material parameters that LaBella *et al*. did not determine and that vary quite strongly in existing measurements.

Because the index of refraction for GaAs is 3.4, light that was collected at an angle of 60° in these experiments was emitted at angle of 14.8°. From the Fresnel formulae, the circular polarization decreases slightly on refraction, so the polarization of the emitted light would have been a factor of 1.06 greater than the measured light polarization. The circular polarization of the emitted light is related to the spin polarization of the electron density through matrix elements that give a factor of two divided by the cosine of the emission angle; this results in a conversion factor of $2/\cos(14.8°) = 2.07$. The total conversion factor between the measured light polarization and the spin polarization of the electrons at recombination is thus $2.07 \times 1.06 = 2.19$. Ignoring refraction led LaBella *et al*. to use a factor of $2/\cos(60°) = 4.0$. Thus, the measured electron spin polarization at recombination was 25.2%, rather than the 46% that they claimed.

The polarization of the electron spin density at recombination would have been less than the polarization of the injected current because of spin-flip scattering. The authors used values for the recombination and spin-relaxation lifetimes based on published results, which, through equation 1 in (*1*), gave an injected electron spin polarization a factor of two larger than the recombination polarization. However, the lifetimes depend on doping, temperature, and sample quality. Consequently, different groups using different samples will obtain different values. Without reliable spin and electron lifetime values that pertain to the sample investigated, we do not believe that the factor-of-two-larger value for the injected electron polarization claimed by LaBella *et al*. is justified. Rather, we believe it would be more appropriate for them to claim a measured spin polarization of 25.2% and to point out that the injection polarization is likely to be larger, possibly by a factor even greater than two, but also possibly by a factor much closer to one.

It is not surprising that the injected electron spin polarization that can be inferred from the measured circular polarization of the emitted light is not close to 100%. The authors assert that the Ni(110) STM tip emits 100% spin polarized electrons because along the ξ direction in Ni, the density of spin-up states at the Fermi level is zero. Indeed, both the spin-up and spin-down Σ_1 bands cross the Fermi level in mid-zone. In the photoemission measurements referenced by LaBella *et al*., selection rules suppressed photoemission from the Σ_1 states and hence achieved 100% spin polarization. These selection rules do not apply to tunneling; furthermore, at the tunneling voltages used in the experiment, both the spin-up and spin-down states below the Fermi level are accessible for tunneling. As a consequence, it was incorrect to assert that the tunneling current from the Ni(110) tip was 100% polarized.

In summary, we believe that an electron spin polarization at recombination of 25.2% can be inferred from these experiments and that it is difficult to say definitively by how much the actual electron polarization upon injection exceeded that number.

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References

1. V. P. LaBella *et al*., *Science* **292**, 1518 (2001).

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Response: We thank Egelhoff *et al*. for carefully scrutinizing our recent study (*1*). We agree with their comment that light emitted from the GaAs sample refracts and that we overlooked this in our conversion factors. Refraction affects the polarization of the light in two ways. First, using the index of refraction of GaAs at 100 K (3.27), a detector oriented at 60° to the surface normal actually measures emissions coming from an angle of 15.4° to the surface normal. Including the selection rules, this results in a conversion factor between the optical polarization and electron polarization at the time of recombination of 2.07, as Egelhoff *et al*. assert. Second, because of the Fresnel effect (a 1.06 conversion factor), the measured polarization is reduced from the true value. These combined results yield a conversion factor of 2.19 between the measured optical polarization and the electron spin polarization at the time of recombination, not a factor of 4.0 as originally published, as Egelhoff *et al*. correctly point out. Thus, the measured optical polarization of 11.5% results in an electron spin polarization at the time of recombination of 25.2%, not 46%.

Egelhoff *et al*. further comment that we should be concerned about the accuracy of the spin-relaxation lifetime. It is true that we did not measure the spin-relaxation lifetime for the sample studied in (*1*). As we noted there, however, a published value for spin-relaxation lifetime of 2.5×10^{-10} s exists for GaAs at a temperature of 77 K and an acceptor doping concentration of 10^{19} (*2*). If that result also applied to our sample, then the polarization at the time of injection was 50.4% (not the 92% reported). Of course, if that result were not applicable to our sample, then the polarization at the time of recombination may have been as low as 25.2%.

Finally, we agree with the observation by Egelhoff *et al*. that the polarization state of tunneling electrons may be different from that of photoemitted electrons.

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References

1. V. P. LaBella *et al*., *Science* **292**, 1518 (2001).
2. L. G. E. Pikus, A. N. Titkov, in *Optical Orientation*, F. Meier, B. P. Zakharchenya, Eds. (Elsevier, New York, 1984), p. 121.

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