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Response to "Comment on 'Electrically injected spin-polarized vertical-cavity surface-emitting laser' " [Appl. Phys. Lett. 88, 056101 (2006)]

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We thank Hägele and Oestreich[1] for a critical reading of our recent letter[2] reporting on an electrically injected spin-polarized vertical-cavity surface-emitting laser (spin-VCSEL). In their comment, Hägele and Oestreich's assert that electrical injection of spin-polarized holes in our structure is unlikely since the hole transit time from the spin aligner to the laser active region exceeds spin relaxation times reported in the literature and instead attribute the slight circular polarization to spin-dependent reabsorption. Clearly, considerable care must be taken in verifying spin injection from optical polarization measurements and in designing meaningful control experiments aimed at separating real from spurious contributions.

Our control experiment which compares the optical polarization between VCSELs containing magnetic and nonmagnetic layers does not eliminate a potential contribution from magnetic circular dichrosim (MCD), i.e., preferential absorption of one circularly-polarized component occurring in (Ga,Mn)As.[3] To investigate the severity of MCD in our previous experiment, we prepared a spin-VCSEL heterostructure for magnetophotoluminescence measurements using a portion of the original, unprocessed wafer. The sample was subjected to annealing and heat treatments mimicking those experienced during device fabrication. A dielectric $ZnSe/MgF_2$ dielectric Bragg reflector (DBR) stack was deposited by electron-beam evaporation to complete the spin-VCSEL heterostructure such that any light generated from radiative recombination in the quantum wells (QWs) would undergo numerous internal reflections before escaping. Our sample was mounted in a magneto-optical cryostat and illuminated by linearly polarized laser excitation, generating unpolarized carriers in the QW active region. The optical polarization of the photoluminescence (PL) was studied using a measurement geometry comparable to our previous electroluminescence (EL) experiment, collecting light along the surface normal and parallel to the direction of the applied magnetic field. Since this light travels an identical path in both experiments, the PL will exhibit all polarization effects which result from magneto-optical effects and not direct spin injection from the (Ga,Mn)As spin aligner. Figure 1 shows the degree of circular polarization for the PL and EL taken at $T=80$ K. It is apparent that MCD constitutes a sizable portion of the measured response as suggested by Hägele and Oestreich. However, the contribution is incomplete and a small ($\sim 1\%$) degree of circular polarization remains to be accounted, and we attribute the remaining $\sim 1\%$ polarization to injection of oriented hole spins.

As for the feasibility of hole spin transport over the sizable distance between the spin aligner and QWs, we make the following comments. Secondary mass ion spectroscopy analysis of our spin-VCSEL heterostructure has revealed that Mn impurities have diffused into and throughout the *p*-doped $Al_{0.8}Ga_{0.2}As/GaAs$ DBR pair (although to a small degree on the order of 10^{18} cm^{-3}) and may be contributing to direct spin injection at distances much closer to the active region than originally believed. We believe this diffusion occurs at elevated temperatures experienced during device fabrication, which includes a long duration (2.5 h) polyimide curing treatment as well as a 1 h, 250 °C anneal to enhance the ferromagnetic properties of the (Ga,Mn)As spin aligner. If we can assume that spin injection occurs from the bottom of the *p*-doped DBR, then a reasonable estimate of the time required for holes to transit the cavity, become captured within a QW, and recombine with an unpolarized electron thereby contributing to stimulated emission is ~ 3 ps.[4] This time is sufficiently short for some hole spins to retain their orientation even at elevated temperatures and might explain the existence of a small $\sim 1\%$ degree of circular polarization resulting from hole spin injection.

Second, Hägele and Oestreich contend that an unambiguous demonstration of successful hole spin injection has not been provided and further state that "edge emission from a quantum well at low temperature is always linearly polarized independent of hole or electron spin orientation" due to the orientation of QW optical dipole moments. We would like to note, however, that the same does not hold true for edge-emitting devices with quantum dot active regions for

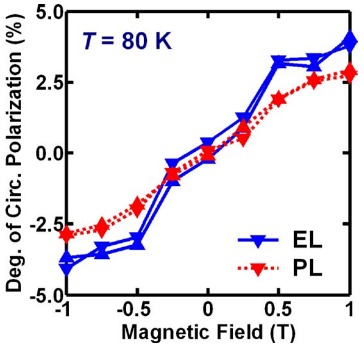

FIG. 1. Degree of circular polarization vs magnetic field for the EL and PL of the spin-VCSEL where ▲(▼) represents the case of ascending (descending) magnetic field.

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which hole spin injection from (Ga,Mn)As has been demonstrated.[5]

In summary, we have measured the contribution of MCD to the degree of circular polarization reported for our electrically injected spin-VCSEL. Though MCD provides the dominate contribution to the degree of circular polarization measured for our electrically injected spin-VCSEL, MCD does not account for all of the response, and we believe the remainder is attributable to hole spin injection. The spin-VCSEL design based on the principle of hole spin injection which we reported in Ref. 2 is clearly not optimal but was made as a first attempt in realizing a new device. We are currently investigating spin-laser designs incorporating alternative spin-aligner materials that should exhibit superior performance characteristics and in which problems related to the determination of electrical spin injection can be minimized.

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