Spin Polarized Semiconductor Lasers

P. Bhattacharya[a], and D. Basu

Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
University of Michigan, 1301 Beal Avenue, Ann Arbor, MI 48109-2122.
a) Email –pkb@eecs.umich.edu

Abstract: We have derived analytical expressions for threshold current reduction, output polarization, the gain anisotropy parameter and the spin laser frequency response taking into account the diffusion of spin polarized carriers from the ferromagnetic contact to the active region and spin-coupled laser rate equations. The validity of the derivations is endorsed by excellent agreement of these parameters from measurements done on spin-VCSELs.

I. INTRODUCTION

The ability to dynamically switch between orthogonal polarization states in spin-polarized semiconductor lasers with the bias current, which are otherwise difficult to predict, stabilize, or control [1], offers a novel and elegant technique for secure communication in a lightwave network. Other envisaged applications include reconfigurable optical interconnects, study of vitamins and asymmetric photochemical synthesis. Spin-polarized lasers also promise reduced threshold current [2], enhanced emission intensity and optical communication with enhanced bandwidth. For practical purposes the lasers have to be electrically injected and operate at high temperatures. To this end we have investigated the properties of quantum well and quantum dot spin vertical cavity surface emitting lasers (spin-VCSELs).

In electrically pumped spin polarized light sources, a non-equilibrium spin population is injected from a magnetic contact to the forward biased active region of a diode consisting of non-magnetic semiconductors. The active region can be a bulk semiconductor, or quantum structures such as quantum wells, wires, or dots. The selection rules for the conservation of angular momentum directly relate the spin orientation of the carriers transported to the active region to the polarization of photons emitted upon their radiative recombination (Fig. 1) .

While these relations hold for spontaneous emission, such as in a spin light emitting diode (LED), they do

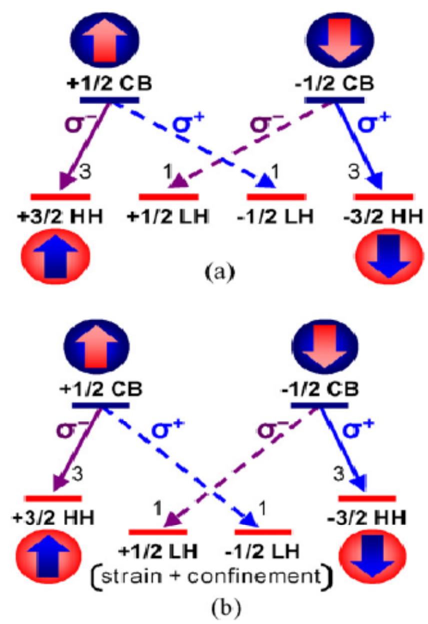

Fig 1: Electric dipole allowed radiative interband transitions and corresponding optical polarization for the cases of (a) bulk material with degenerate heavy- and light-hole bands and (b) a quantum well or a quantum dot in which epitaxial strain and quantum confinement have lifted the heavy- and light-hole band degeneracy.

not reflect the output polarization in a spin laser due to the non-linear dynamics and the spin polarization in the gain medium (active region), which gives rise to a large gain anisotropy at biases near threshold. As a result, the output polarization can be much larger than the spin polarization of the injected carriers. This together with emission intensity enhancement and threshold current reduction (Fig. 2) have been observed by us in quantum well spin lasers [3]. We have derived [4] the analytical form of the output polarization ${}_c$, threshold current $I_{th}(H)$, and the threshold current reduction $I_{th}/I_{th,0}$, as determined by gain anisotropy. In particular, we have highlighted the role of the diffusive transport of spin-polarized electrons from the ferromagnetic contact to the active

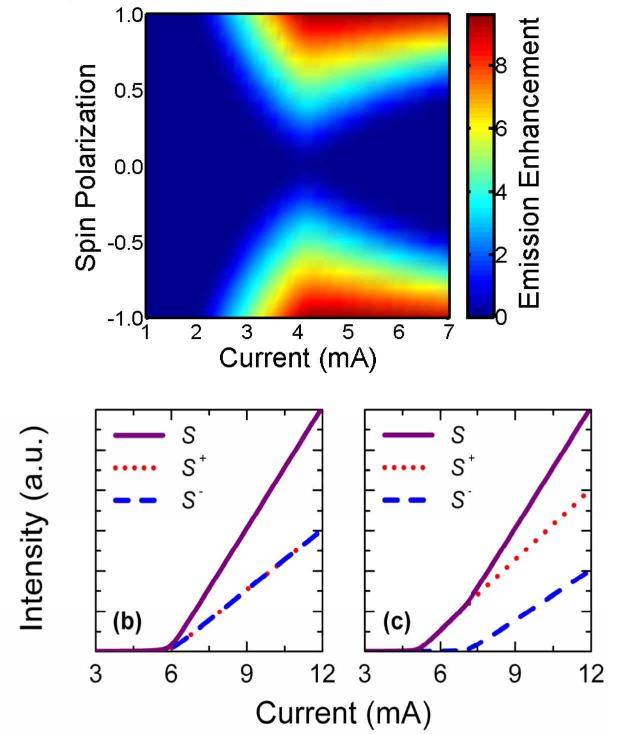

Fig 2: (a) Emission intensity enhancement predicted from the rate equation analysis for a 15 μm diameter Fe spin-polarized QW VCSEL for different values of injected spin polarization. (b) Theoretical light versus current characteristics for a spin-polarized QW VCSEL driven with 0% and (c) 19.8% spin-polarized pump currents. The solid line represents the total light intensity, S, which is the summation of the right-hand (S^-, dotted line) and left-hand circularly polarized (S^+, dashed line) modes.

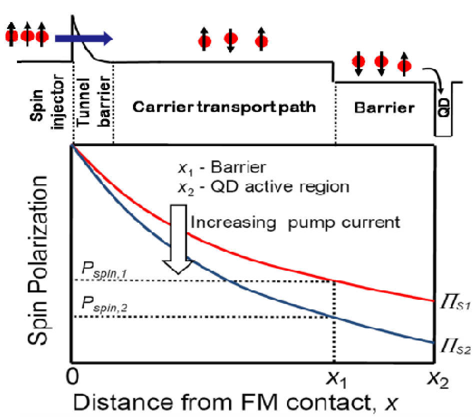

Fig 3: Schematic representation of the variation of carrier spin polarization with distance from ferromagnetic contact (MnAs) in a VCSEL in accordance with the spin diffusion equation. The barrier (cavity) is at distance x1, and the quantum dot region is at distance x2.

region (Fig. 3).

The quantum well (QW) and quantum dot (QD) laser heterostructures are grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs(001) substrate. VCSELs with mesa diameters of 15-30 μm are fabricated using the standard micro-fabrication techniques. The FM contact is realized with 10 nm Fe or 25 nm MnAs regrown by MBE.

The quantum well spin VCSELs exhibit a maximum threshold current reduction of 11 % and output degree of circular polarization of 23 % at 50 K . Quantum dot VCSELs can be operated at higher temperatures since the D'yakonov-Perel spin scattering process is inhibited in quantum dots due to discrete density of states and 3-dimensional carrier confinement. The QD spin VCSELs were operated at 200 K and at this temperature the maximum threshold reduction is 14 % and maximum circular polarization is also 14 % (Fig. 4). In addition we have demonstrated electrical

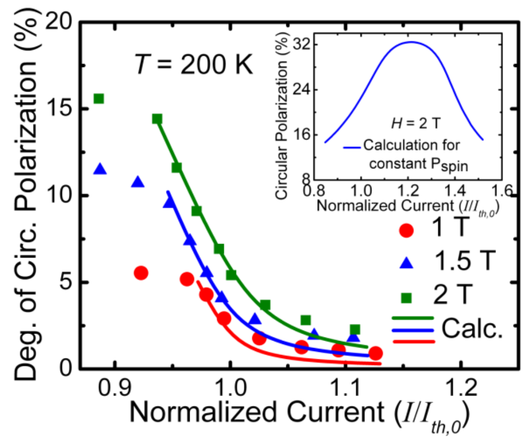

Fig. 4: Calculated and measured modulation of output circular polarization of InAs/GaAs QD spin VCSEL as a function of normalized pump current at different magnetic fields. The inset shows calculated polarization for constant pump current spin polarization, instead of the variation of P_{spin}.

modulation of the output polarization with peak modulation index of 0.6. All these results together with a model for high frequency response will be presented and discussed.

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