

## Viewpoint

## Spins Jump Another Threshold

Andre Petukhov

*Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA*

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*New theoretical tools could take spintronic lasers to the next phase of their evolution.*Subject Areas: **Optics, Spintronics****A Viewpoint on:****Mapping between quantum dot and quantum well lasers: From conventional to spin lasers**

Jeongsu Lee, Rafał Oszwałdowski, Christian Gøthgen, and Igor Žutić

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In a semiconductor spin laser, the laser action is driven by a current of charge carriers in the laser cavity, while the polarization of the stimulated emission is defined by the spins of the carriers. Such lasers are one of the most promising outcomes of research in spintronics [1, 2], but the theoretical tools needed to describe them can be fairly complex, making it difficult to have an intuitive feel for how best to improve upon existing designs. Now, a paper appearing in *Physical Review B* from Jeongsu Lee and colleagues at the State University of New York (SUNY) in Buffalo [3] proposes a simple description of spin lasers based on quantum dots. Their mathematically transparent models will be helpful for developing fast and efficient optical communication schemes that rely on circularly polarized light.

The heart of a spin laser is a device called a vertical cavity semiconductor laser (VCSEL), which is essentially a very small (micrometer size) mesalike pillar of semiconductor material that emits light in the direction  $z$ , perpendicular to the base material (substrate) on which it is grown. Stimulated emission takes place in the “active region” of the VCSEL. Here, an electron in the semiconductor’s conduction band undergoes a transition to an empty state in the valence band (a hole), producing a photon and leaving the active region. This process is called radiative electron-hole recombination. To replenish the electron and hole population, the charge carriers must be injected (“pumped”) into the active region by electrical current. At a threshold injection value, a population inversion is achieved, where the number of conduction-band electrons exceeds the number of electrons remaining near the top of the valence band. When this occurs, the laser-cavity losses are overcome and laser action begins. The current that must be injected for this lasing action to occur—the threshold current—determines the power needed to run the laser. If it is too high, the laser may be impractical for certain applications.

The active region of a VCSEL can be based on quan-

tum wells or dots, which are semiconductor heterostructures in which the charge carriers are confined in one or all three dimensions, respectively. The selection rules for optical transitions in these structures depend on the spins of the participating carriers. Let’s define spin up as the spin projection parallel to  $z$ . To a good approximation, a conduction-band spin-up electron can recombine only with a spin-down hole. In this act, a photon of left circular polarization is emitted. Conversely, a spin-down electron recombines with a spin-up hole, emitting a right-hand circularly polarized photon. (In reality, the electrons may flip their spins without emitting light, and this spin relaxation can limit many spin-laser characteristics.)

Within this simple picture, VCSELs host two lasing modes, with opposite circular polarizations. The modes have equal intensities when the spins of the injected carriers are unpolarized. Interesting effects appear, however, when the laser is supplied by spin-polarized electrons, that is, by a current that contains more electrons with spin up than down (or vice versa). This idea was first used in spin-based light-emitting diodes [4], but now has new implications for lasers. As shown in Fig. 1, the threshold current is smaller when the injected electrons are spin polarized.

The threshold reduction is achieved not through some improvement of the laser structure, but through limiting the “wasteful” equal feeding of the two modes. The first experiments that showed this relied on the optical, rather than electrical, injection of carriers [5]. More recently, a group led by P. Bhattacharya demonstrated electrical injection, first into a quantum well and next into a quantum dot VCSEL [6, 7]. In both cases, threshold reduction, albeit modest, was found.

On the theoretical front, several groups have been developing models, which can be utilized for spin lasers [8–10]. The group at SUNY Buffalo focused on formulating simple rate equations, sufficiently transparent to

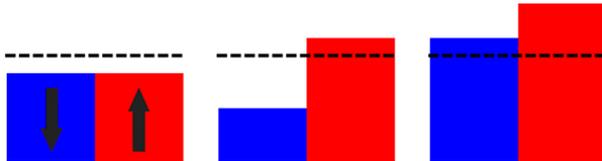


FIG. 1: In a spin laser, the threshold current density for lasing to occur depends on the polarization of the current. The current density for electrons with spin up (red) and down (blue) is denoted by the rectangles' heights; dashed line shows the threshold current required for lasing in a "spin-unpolarized" laser. (Left) The densities of spin-up and spin-down electrons are equal,  $n_{\downarrow} = n_{\uparrow}$ , and none of the two subpopulations reaches the threshold. (Middle) If the same current density is injected, but the current contains spin-polarized electrons ( $n_{\downarrow} < n_{\uparrow}$ ), it is possible to reach a lasing threshold. This current is the first threshold. Injecting even more electrons with the same spin polarization (right), leads to the second threshold. (APS/A. Petukhov)

explain the role of important parameters, such as the spin relaxation times of electrons and holes. These equations are essentially a bookkeeping approach, in that they track how electrons and holes turn into photons. For the simplest description of a quantum well conventional laser, only two such equations are needed: one for electron density  $n$  and one for stimulated photon density  $S$ . This simplicity results from the fact that  $n_{\uparrow} = n_{\downarrow} = n/2$  (as in the left side of Fig. 1), and similarly for the hole densities  $p_{\uparrow,\downarrow}$ , so there is no need to keep track of left- and right-hand polarized emission,  $S_{\pm}$ . It is also usually assumed that there are as many electrons as holes in a charge-neutral active region, independently of the (possibly time-dependent) injection current. These assumptions keep the equations simple.

When modeling quantum dot spin lasers, however, Lee *et al.* realized that, with the rather large number of necessary nonlinear rate equations, the problem could really only be solved numerically. But often, one wants a fairly simple way to study trends—say, how changing one parameter qualitatively affects the laser's performance—without a full-blown solution. There are two reasons why quantum dot lasers are more complicated than quantum well lasers. First, as they argue, there is a difference in how they are modeled. In a quantum dot laser, a model has to explicitly account for two spatial regions: the quantum dot itself and a very thin layer of material on which the dot resides. Electrons are injected into this so-called wetting layer, before they enter the quantum dot. Second, for spin-polarized injection, one needs to consider separate equations for the photon densities of opposite polarizations. Similarly, spin-up and spin-down electrons in the wetting layer and in quantum dots have their own equations, which are coupled by spin-relaxation terms, adding another complication.

As a simplification, the authors propose a mapping scheme that allows them to describe a quantum dot spin laser with four equations, similar to ones used for a quan-

tum well spin laser. This is done at the expense of introducing the so-called gain saturation term, commonly used in the modeling of semiconductor lasers. This term is controlled by a constant called the gain compression factor  $\epsilon$ . Lee *et al.* propose to use two values of  $\epsilon$ . One value is for the static regime, when the current driving the laser does not change in time, the other one is for modulated injection. Observing this distinction, the authors show that the quantum dot spin lasers can be described by relatively simple equations. For example, these equations can be used to calculate an analytical solution for the first threshold for any spin polarization of the injected electrons.

Together with other theoretical works, this development makes it possible to model spin VCSELs very efficiently, and could help drive the experimental search for better materials and structures with which to make them. However, the future of these lasers may depend on improvements in the device engineering. So far, the electrical injection of spin-polarized electrons requires an external magnetic field that is directed normal to the VCSEL substrate. This results from intricacies of the spin VCSEL growth procedure, during which a thin injector multilayer forms on the semiconductor mesa. This layer polarizes the spins of the injected current. Without a magnetic field, the magnetization of this layer, and thus the spins of the injected electrons have zero (average) projections on  $z$ . VCSELs requiring an external magnetic field to operate are impractical for most applications, so one solution is to find materials for these leads that are magnetized along  $z$  without an external field. Efforts to integrate such materials into light-emitting diodes have been promising [11], so there is good reason to believe they will be found for VCSELs, too.

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## About the Author

### Andre Petukhov



Andre Petukhov is a professor of physics and department head at the South Dakota School of Mines and Technology in Rapid City, SD. His scientific interests include spintronics, theory of nanoscale electronic materials and devices, quantum information processing, and electronic structure and transport properties of solids with emphasis on spin-dependent phenomena in magnetic semiconductors. He is an adjunct professor at Case Western Reserve University in Cleveland, OH. He also worked as a summer faculty and sabbatical visitor at the Naval Research Laboratory in Washington, DC, and NASA Ames Research Center. Before joining the faculty at the South Dakota Tech, he worked as a senior research associate at Case Western Reserve University. He obtained his Ph.D. degree in solid-state physics at the St. Petersburg State Polytechnical University, Russia (Leningrad Polytechnic Institute) in 1981.