Optically-pumped dilute nitride spin-VCSEL

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Abstract: We report the first room temperature optical spin-injection of a dilute nitride 1300 nm vertical-cavity surface-emitting laser (VCSEL) under continuous-wave optical pumping. We also present a novel experimental protocol for the investigation of optical spin-injection with a fiber setup. The experimental results indicate that the VCSEL polarization can be controlled by the pump polarization, and the measured behavior is in excellent agreement with theoretical predictions using the spin flip model. The ability to control the polarization of a long-wavelength VCSEL at room temperature emitting at the wavelength of 1.3 µm opens up a new exciting research avenue for novel uses in disparate fields of technology ranging from spintronics to optical telecommunication networks.

OCIS codes: (160.6000) Semiconductor materials; (140.7260) Vertical cavity surface emitting lasers; (250.7260) Vertical cavity surface emitting lasers; (140.5560) Pumping; (260.5430) Polarization; (230.5440) Polarization-selective devices.

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1. Introduction

GaInNAs/GaAs active regions provide important advantages for developing 1.3 um vertical-cavity devices such as monolithic integration with GaAs/AlAs distributed Bragg reflectors (DBR) and improved temperature behavior. Examples of devices include VCSELs [1, 2], vertical external cavity surface-emitting lasers (VECSELs) and vertical-cavity semiconductor optical amplifiers (VCSOAs) [3].

In parallel, the study of the physical properties of spin-injected VCSELs is a current area of considerable research interest. The goal is to develop optoelectronic devices whose emitted polarization can be controlled via the generation (either electrically or optically) of spin-polarized carriers. These "spintronic VCSELs" offer many attractive advantages, including enhanced intensity and polarisation stability as well as a reduced threshold current [4–6], and have potential applications in cryptographic communications and reconfigurable optical interconnects [7]. The generation of spin oriented carriers in VCSELs can be induced using both electrical and optical techniques. Electrical spin-injection of VCSELs has received considerable experimental interest in recent years [7, 8]; however the high magnetic fields and low temperatures required to achieve circularly-polarized lasing as well as the higher complexity of wafer design and growth is a current practical challenge. On the other hand, optical pumping can also be used to generate spin oriented carriers in VCSELs allowing control of the polarization of the light emitted by these devices. This represents a novel way of balancing their inherent polarization properties and a route to study the fundamental physics of the devices. Optically pumped spin injected VCSELs have recently been investigated theoretically [9] and experimentally for short wavelength VCSELs [10–12]. It has been demonstrated that the output polarization of these VCSELs can be controlled with the pump polarization and that the degree of polarization of the emission is higher than that of the pump. However, we are not aware of any work with devices operating at the longer wavelengths typically used in long distance optical communication systems.

In this work, we present the first experimental investigation on the optical spin-injection of a dilute nitride 1300nm-VCSEL. Furthermore, our experiments have been performed with the device operated at room temperature and under continuous-wave (CW) optical pumping. The measurements were performed with a novel setup in two forms: an all-fiber arrangement and a basic free-space setup. The use of fiber components requires a means of calibrating the polarization in the all-fiber part of the setup, and so we present an experimental protocol to do this. We demonstrate experimentally that the polarization of the VCSEL's emitted light can be effectively controlled by that of the optical pump and that a large degree of circular polarization can be achieved at the VCSEL output when circularly polarized pumping is used. The spin flip model is used to model the behavior and gives excellent agreement with the experimental results.

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2. Experimental setup

2.1 Device structure

The VCSEL-wafer used in this work was grown by a solid source molecular beam epitaxy (MBE) reactor equipped with a radio frequency plasma source for nitrogen incorporation. The layer structure is presented in Fig. 1a. The top and bottom Bragg stacks, respectively, contained 16 and 20.5 GaAs/AlAs pairs, and the 3-λ cavity contained five groups of three quantum wells (QWs) positioned approximately at the antinodes of the optical field. Each 7nm $Ga_{0.67}In_{0.33}N_{0.016}As_{0.984}$ QW was sandwiched between 2 nm $Ga_{0.75}In_{0.25}N_{0.017}As_{0.983}$ strain mediating layers, which had higher band gap and smaller lattice mismatch with respect to the substrate than the QWs. The bottom DBR ensured a high enough reflectivity, of about 99.8%, while employing a relative small amount of layers. This is beneficial in terms of overall growth time and stability of fluxes ensuring correct phase matching for the top DBR grown at the end. The latter had even less pairs to ensure sufficient output from the laser; the simulated reflectivity for the top DBR was in the range of 99.2%. Using a higher reflectivity would enable to reduce the number of QWs and pumping level, but would also decrease the operation bandwidth. As shown in Fig. 1b, photoluminescence (PL) and reflectivity spectra measured on the as-grown VCSEL wafer indicated good alignment of the PL spectral peak with the cavity resonance so that lasing was expected at a wavelength close to 1300 nm.

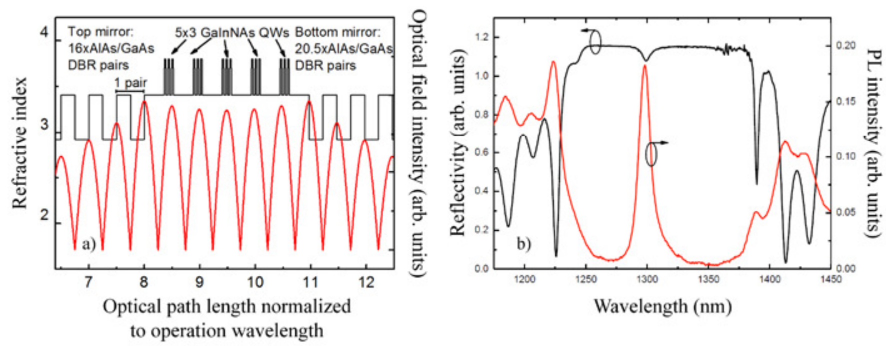

Fig. 1. a) Optical design of the VCSEL structure. The GaInNAs QWs are surrounded by GaInNAs strain mediating layers. b) VCSEL reflectivity and photoluminescence spectra.

2.2 Spin-injection

Figure 2a illustrates the novel experimental setup used to investigate optical spin-injection. This consisted mostly of commercial pigtailed fiber-optic components spliced together, using 980 nm single-mode fibers (HI 1060). A commercial 980nm laser was used to optically pump the VCSEL wafer. The pump was driven by a 1 A CW current source and followed by an isolator, a polarization controller and a 90/10 coupler to allow power monitoring. The light from the pump was focused onto the wafer using a long-focal length lens-ended fiber with a spot diameter of the order of 10 µm. The VCSEL wafer was pasted onto a silicon carrier wafer mounted in a custom temperature-controlled copper mount. A window in the mount allowed the part of the pump which was transmitted through the VCSEL and silicon wafers to be directed towards the head of a free-space polarimeter. Measurements of the pump polarization with the wafers either in place or removed gave the same results despite the high transmission losses of the wafers at 980 nm.

Optical emission from the VCSEL was collected by the lens-ended fiber. 10% of this light was used for analysis via the aforementioned 90/10 coupler. A 1300 nm isolator which blocked the 980 nm light reflected by the wafer was used to remove the pump. A second 90/10 coupler was then used to direct part of the 1300nm VCSEL light to an Optical

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Spectrum Analyzer (OSA) and an in-line polarimeter to perform a relative measurement of the VCSEL polarization. The wafer mount was kept at a constant temperature of 20°C.

It was found that the polarization of the VCSEL was very dependent on the pumping conditions in terms of alignment and, for example, the VCSEL could sometimes exhibit polarization switching when pumped with linear polarization. Thus great care was taken when setting up the system and the measurements presented in part 3 were obtained under conditions where no polarization switching occurred. Figure 3 presents the L-I curve of the VCSEL and its spectrum at full pump power.

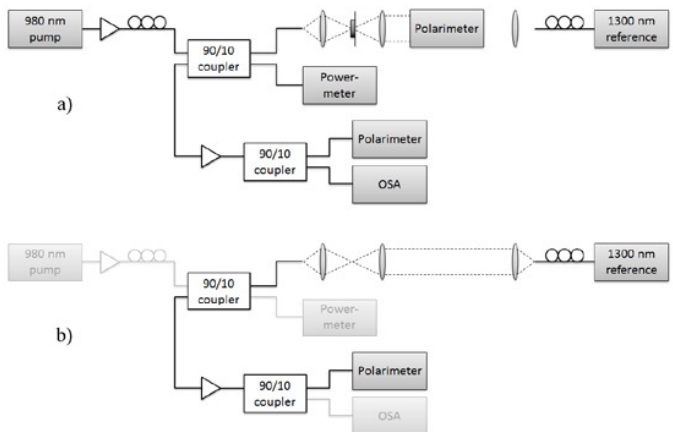

Fig. 2. a) Setup used for the investigation of spin-injection of the 1300nm-VCSEL wafer. b) Characterization of the polarization change in the part of the setup shown in black.

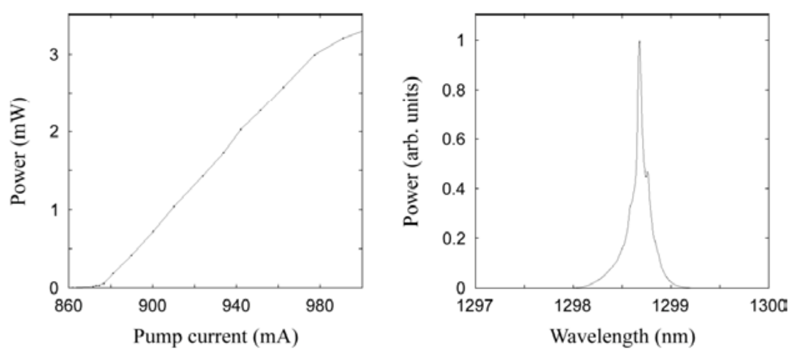

Fig. 3. L-I curve (left) and spectrum of the VCSEL (right) for a pump current of 1 A.

2.3 Setup characterization

The use of fiber components reduces the number of critical alignments when compared with a free-space set up, since only the position of the wafer with respect to the lens-ended fiber affects the operation of the VCSEL. Once established, pigtailed components such as couplers and isolators can also be easily added to the setup. However, knowledge of the change in polarization induced by the fiber setup is necessary to be able to relate measurements of the polarization performed at different points. The characterization consisted of injecting a reference 1300 nm light source of known polarization into the setup, so that it followed the same optical path as the VCSEL light, and measuring its polarization at the end of the setup.

Figure 2b shows the system setup allowing characterization of the polarization change induced between the lens-ended fiber and the in-line polarimeter. Light from a 1300 nm laser was collimated and injected in the setup with the wafer removed. The polarization was set with a polarization controller to several arbitrary states ranging from circular right to circular

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left. Each polarization state was first verified by inserting the head of the free-space polarimeter in the collimated beam, facing towards the reference laser. With the polarimeter head removed from the collimated beam, the corresponding relative polarization at the end of the setup was then measured with the in-line polarimeter.

The transformation of the polarization between the lens-ended fiber and the in-line polarimeter corresponds to a three-dimensional rotation on the Poincaré sphere. The value of the three rotation angles were identified from the different pairs of absolute and relative polarizations of the reference light. The measurement of the polarization of the VCSEL described in part 2.2 was then rotated with the angles derived. As the whole fiber setup was mostly left untouched, calibrations of the setup made on different days gave similar values for the three rotation angles used to analyze the data.

3. Results

The property studied when investigating spin-injection is the ellipticity of the polarization; the ratio between the degree of circular polarization *DOCP* and the total degree of polarization *DOP*. Practically, a polarimeter measures the vector $\{S_1, S_2, S_3\}$ and the ellipticity is directly equal to the experimental value of S_3 [13]. Because of the two different directions of observation of the polarization of the pump and the VCSEL, right-handed VCSEL polarizations are observed for left-handed pump polarizations [6] and the ellipticity is in fact equal to the negative of S_3 found from the measurements of the polarization of the VCSEL. Figure 4a presents the measured relation between the polarization of the pump and that of the VCSEL. The VCSEL mount was kept at a temperature of 20°C, the pump was driven at 1 A and the power reaching the wafer was estimated to be around 180 mW.

Figure 4 shows that the polarization of the VCSEL can be controlled with that of the pump. Studies of spin-VCSELs generally focus on pulsed excitation of the device in order to reach polarization degrees very close to 1 [12]. The achievement of a significant ellipticity at room temperature under CW operation of the pump was demonstrated for shorter-wavelength devices biased close to threshold [11]. Our results show that ellipticities up to 0.7 could be achieved with the 1.3 µm CW room temperature VCSEL biased well above threshold.

To compare with theory a four-level model, the spin flip model (SFM), was used to investigate the dependence of the VCSEL polarization on that of the pump. The SFM equations are conventionally written in terms of the right- and left-circularly polarized complex fields, denoted respectively by $\bar{E}_+$ and $\bar{E}_-$, and two populations of electrons, those with spin-down and spin-up, with corresponding normalised densities n_+ and n_-, respectively. The ellipticity of the VCSEL output is then given by $(|\bar{E}_+|^2 - |\bar{E}_-|^2)/(|\bar{E}_+|^2 + |\bar{E}_-|^2)$. According to the SFM [9, 14, 15], recombination of spin-down and spin-up electrons in a QW VCSEL produces two lasing transitions for right- and left-circularly polarized electric fields. The spin relaxation process for electrons is characterized by a decay rate γ_s, whereas spin relaxation of holes in the valence band is assumed to be instantaneous. In addition, circularly-polarized pump components (η_+,η_-) are included in order to account for polarized optical pumping [16], so that the ellipticity of the pump is given by $((\eta_+ - \eta_-)/(\eta_+ + \eta_-)$. The SFM rate equations were solved numerically using the Runge-Kutta method by the solver ode45 in MATLAB with a variable time step. The key model parameters are $\kappa = (2\tau_p)^{-1}$ and $\gamma = \tau_n^{-1}$ where τ_p and τ_n are the photon and electron lifetimes, respectively, α the linewidth enhancement factor, γ_p the birefringence rate, γ_s the spin relaxation rate, γ_a the gain anisotropy or dichroism rate, and the total pump rate $\eta = \eta_+ + \eta_-$. A best fit of the theory with the experimental S_3 was found using the following model parameters: $\kappa = 250$ ns^{-1}, $\gamma = 1$ ns^{-1}, $\gamma_p = 5$ ns^{-1}, $\gamma_s = 105$ ns^{-1}, $\gamma_a = 0$, $\alpha = 2$ and $\eta = 1.5$. The value of γ used here is consistent with the high quality of the active material and with the recombination rates reported from pressure and temperature measurements in 1300 nm GaInNas VCSELs [17]. Figure 4a shows the excellent agreement with experiment obtained from the SFM modeling for output polarization versus pump polarization.

The theory was also able to reproduce well the saturation of the VCSEL polarization for nearly circular pump polarizations. Figure 4b shows that although the parameter fitting was performed solely on S_3 very good agreement was found between theory and experimental data in the Poincare sphere. Here the theoretical data was rotated by 180° around the S_2-axis to match the circular and linear polarizations of the experiment.

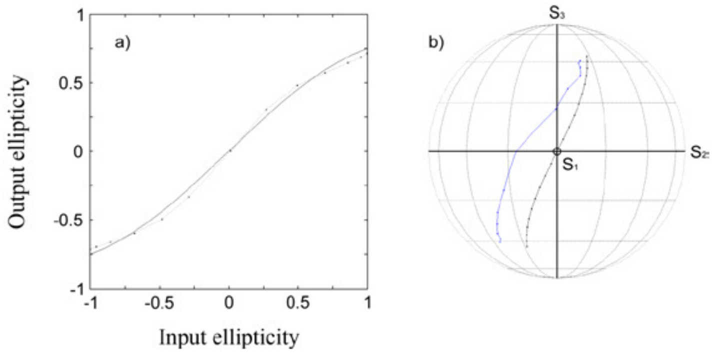

Fig. 4. a) VCSEL (output) ellipticity as a function of the ellipticity of the CW pump (input). The dotted line shows the experimental data while the solid line shows theoretical results. b) Experimental (in blue) and theoretical (black) Stokes vector in the Poincaré sphere. The VCSEL is biased well above threshold and kept at 20°C.

A relatively fast spin relaxation rate was used here in comparison with other studies where values of γ_s usually range from 1 to 100 ns^{-1} [7, 12, 18]. Measured values of the spin relaxation rate for as-grown GaInNAs QWs in the literature are typically in the range from 0.5 ns^{-1} [19] to 13 ns^{-1} [20]. However, a large increase in relaxation rate has been reported after annealing [19]. Since the active region of a VCSEL is effectively annealed during the growth of the top Bragg stack, this may result in an increased spin relaxation rate of the order of that used in the simulation here. Stable operation with a fast spin relaxation rate requires a slow birefringence rate as dictated by the conditions for linear polarization stability derived in [15]. While a closer agreement between the experimental and theoretical ellipticities was found with lower values of γ_s and a large γ_p, in such a case polarization switching was predicted with linear pump polarization which was in disagreement with the experimental data.

5. Conclusion

We report the first room temperature optical spin-injection of a GaInNAs/GaAs 1300 nm VCSEL under CW pumping. We show that the polarization of the VCSEL was controlled by that of its pump and that a large degree of circular polarization can be achieved for circular pump polarizations. The measurements were performed with a setup mostly constituted of fiber components following a novel experimental protocol, and very good agreement was found with theory. The results reported in this work offer exciting prospects for novel applications of VCSELs in different fields including spintronics and optical networks where polarization could be accurately controlled offering a novel medium for data encoding.

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