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Room Temperature Laser Oscillation with Circular Polarization in Spin VCSELs

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1. Introduction

Controlling both electron charge and spin in semiconductors has been attracting much attention because of its potential applications to spin-polarized LEDs and lasers, spin transistors and quantum computers, etc. Vertical-cavity surface-emitting lasers (VCSELs) demonstrate circularly polarized lasing and threshold reduction by injecting spin polarized electrons, and these features become pronounced by a high degree of spin polarization and a long electron spin relaxation time τ_s. Quantum wells (QWs) on (110) GaAs have a longer τ_s than that on (100) GaAs since the D'yakonov-Perel' mechanism, which is the dominant spin relaxation mechanism in zinc-blende semiconductors at room temperature (RT), is significantly suppressed.

We grew GaAs/AlGaAs [1] and InGaAs/GaAs [2] MQWs on (110) GaAs substrates by MBE. τ_s in the (110) InGaAs/GaAs MQWs was measured to be 2.8±0.3 ns at 77 K [2], which was almost ten times longer than that in (100) QWs (230 ps at 70 K). Carrier lifetime τ_c was measured to be 420 ps. At RT, τ_s and τ_c were 440±50 and 40 ps, respectively. We fabricated a (110) VCSEL structure based on InGaAs/GaAs MQWs and demonstrated circularly polarized lasing by optical spin injection [2]. A difference in the laser thresholds for the two lasing modes (σ+ and σ-) and a high degree of circular polarization, 0.94, were observed at 77 K. Gigahertz switching of lasing circular polarizations was also obtained [3].

In this paper, recent progress in spin-VCSELs is reviewed.

2. Room Temperature Circularly Polarized Lasing in an Optically Spin Injected VCSEL[4]

A VCSEL structure shown in Fig.1(a) was fabricated on a (110) GaAs substrate. It consists of distributed Bragg reflectors (DBRs) and a 2λ-cavity that includes $Al_{0.15}Ga_{0.85}As$ spacers and nine GaAs/$Al_{0.15}Ga_{0.85}As$ QWs with 10-nm wells and 10-nm barriers. Three QWs were assigned to every three antinodes of the optical field. A SEM image of the cross-sectional view of the VCSEL is shown in Fig. 1 (b), in which defects were not observed. A reflectance spectrum of the VCSEL wafer is shown in Fig. 1 (c). The peak reflectivity was estimated to be higher than 99% from the width of the stop-band of the spectrum. The VCSEL was optically pumped at RT. The pump light was

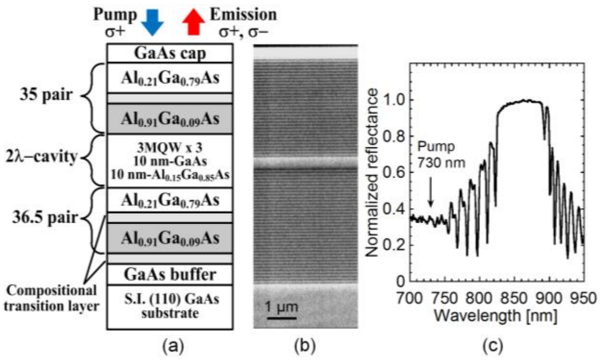

Fig. 1 (a) Schematic structure of (110) VCSEL, (b) cross-sectional SEM image and (c) reflectance spectrum.

right-circularly polarized (σ+) optical pulses at a 730-nm wavelength (shown by the arrow in Fig. 1 (c)) to excite the carriers in the spacers, well layers, and barrier layers. The spin-polarized electrons in the conduction band were generated by the σ+ pump pulses via the optical selection rules in the Faraday geometry.

Fig. 2 shows the σ+ and σ- components of the VCSEL output intensities. The σ+ and σ- modes start lasing at an excitation intensity I_{ex} of about 3.3 and 3.7 kW/cm^2, respectively (shown by the arrows). The degree of circular polarization P_c $\{=(I_{\sigma+} - I_{\sigma-})/(I_{\sigma+} + I_{\sigma-})\}$ is also plotted in Fig. 2. The P_c remained almost constant (~ 0.2) below the threshold for the σ+ component. Then, the P_c dramatically increased up to 0.9 when the I_{ex} was increased to 3.7 kW/cm^2 and reached a maximum value of 0.96 at 4.0 kW/cm^2. This means that almost circularly polarized lasing was achieved at RT.

We investigated the emission wavelength dependence of the lasing polarization at RT [5]. Lasing was observed in

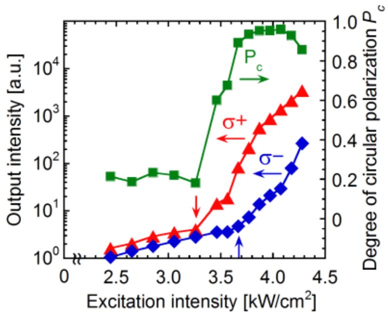

Fig. 2 VCSEL output intensities (σ+ and σ- components) and P_c against excitation intensity at RT.

the one circularly polarized mode over a wide wavelength range from 838 to 857 nm, in which a degree of circular polarization higher than 0.8 was maintained. The thicknesses of the MBE-grown layers vary throughout the wafer, which leads to a wide-range variation in the cavity wavelength λ_c, but with very little change in the transition wavelengths of the active layers. Thus, we can investigate the effects of the λ_c detuning from the e-hh transition wavelength on the lasing polarization using a single wafer. The thresholds I_{ex} for the σ+ and σ- modes are summarized in Fig. 3. The calculated transition wavelengths for the e-lh and e-hh transitions of the ground states are 843 and 853 nm, respectively. We observed σ+ circularly polarized lasing for all the λ_c. It should be noted that we observed lasing in the σ+ mode even at a λ_c of 843 nm.

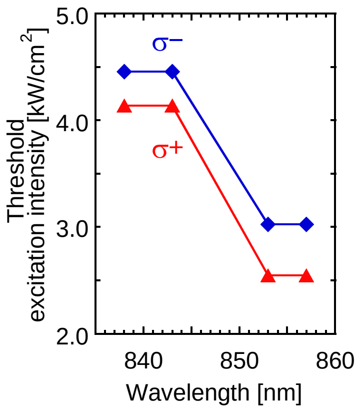

Fig. 3 Threshold excitation intensity (σ+ and σ- polarizations) as a function of emission wavelength.

3. Carrier Lifetime and Electron Spin Relaxation Time in Micro-Post QWs [6]

We demonstrated 1-GHz switching of the lasing circular polarizations in a (110) VCSEL by optical spin injection [3]. To faster switch the lasing circular polarizations, shortening the τ_c while preserving the long τ_s is a straightforward solution. Fabricating post structures with dry-etching shortens τ_c due to the surface non-radiative recombination at the etched sidewall. However, the effect of dry-etching on τ_s has not been well understood. We demonstrated that the long τ_s in (110) QWs is preserved even when the sidewall boundaries with fast surface recombination are introduced and τ_c is drastically shortened.

The sample has an undoped (110) GaAs/AlGaAs MQW. It consists of twenty periods of 9-nm-thick GaAs QWs. The ECR-RIE with a gas mixture of Cl_2 and N_2 was used for the etching. The sample was illuminated by circularly polarized pulses at 77 K. The excitation wavelength was tuned to 730 nm, which excited both the transitions from the heavy hole and light hole bands in the MQW but no transition in the barrier layers.

Fig. 4 summarizes the measured τ_c and τ_s in relation to post size d. When d is smaller than about 10 μm, the measured τ_c was found to be approximately proportional to d.

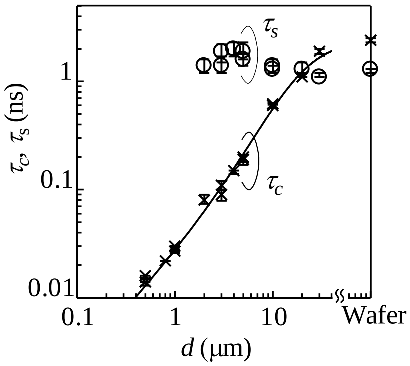

Fig. 4 Size dependence of τ_c and τ_s for (110) GaAs/AlGaAs QW micro-posts. Solid line is a fitted curve for τ_c.

By contrast, τ_s can be essentially constant for our (110) MQW. The reflection and scattering at the sidewalls may be reduced due to the large non-radiative surface recombination velocity. Therefore, it is natural that the measured τ_s did not show clear d dependence. Our rate equation analysis indicates that (110) QW micro-posts with the long τ_s and shortened τ_c can be used for faster switching, about 20 GHz, of lasing circular polarizations in spin-VCSELs.

QWs with a long τ_s and a short τ_c may find a number of applications in spin-photonic devices in which spin-relaxed electrons deteriorate the device performances.

4. Conclusion and Future Perspective

Recent progress in our research on optically injected spin-VCSELs based on (110) QWs was reviewed. Realization of electrically injected spin-VCSELs at RT will be the next target. Although (Ga, Mn) As [7], Fe [8], and MnAs [9] were used as spin injectors, the operation at RT has not been achieved. Ferromagnetic electrodes which can inject high density spin current into VCSELs and confinement of the spin current to small active regions of VCSELs will be the key technologies.

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