Polarization control of vertical-cavity surface-emitting lasers by electro-optic birefringence

Min Soo Parka) and Byung Tae Ahnb)
Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology, 373-1 Koosung-dong, Yusung-gu, Taejon, 305-701, Korea

Byueng-Su Yoo, Hye Yong Chu, and Hyo-Hoon Park
Telecommunications Basic Research Laboratory, Electronics and Telecommunications Research Institute, Taejon, Korea

C. J. Chang-Hasnain
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California

(Received 20 August 1999; accepted for publication 17 December 1999)

Polarization of vertical-cavity surface-emitting lasers (VCSELs) grown on (001) GaAs substrate has been controlled by electro-optic birefringence. Birefringence was induced at the top distributed Bragg reflector by applying an electric field along the [001] direction. The cavity resonance of the polarized light along the [110] or [110] direction shifted to shorter and longer wavelength, depending on the direction of the applied electric field. By varying the direction and strength of the electric field, we actively controlled the polarization of VCSELs. The dominant polarization mode occurred along the [110] direction for the negative electric field, and along the [110] direction for the positive electric field. © 2000 American Institute of Physics. [S0003-6951(00)04207-8]

Vertical-cavity surface-emitting lasers (VCSELs) emit two orthogonally polarized lights along two specific crystal directions. In order to apply VCSELs to polarization-sensitive systems such as magneto-optic disks or coherent detection systems, VCSELs with a single preferential polarization are required in the operation current range. However, most VCSELs without intentional polarization selectivity show orthogonal polarization states at and above the threshold and unstable polarization switching with increasing current. There have been many attempts to control the polarization by introducing the optical gain or loss anisotropy to VCSELs. A single dominant polarization mode could be achieved by using techniques such as anisotropic transverse cavity,1,2 tilted pillar structure,3,4 misoriented substrate,5 and non-(001) GaAs substrate.6,7 Because the gain or loss of devices fabricated with these models was fixed, however, changing the dominant polarization mode was impossible after the fabrication was finished. In this letter, we present a polarization control method using electro-optic birefringence.

VCSELs based on (001) GaAs substrate generally do not have birefringence since the refractive index of GaAs is isotropic. The most popular way to change the refractive index is to apply an electric field to the material along a specific crystal direction. Valle et al. theoretically investigated the polarization properties of VCSELs with the refractive index anisotropy in the entire structure.8,9 They showed the polarization could be controlled by the model gain difference originated from the carrier distribution. Here, we apply an electric field to the top distributed Bragg reflector (DBR) along the [001] direction. This made the refractive index of GaAs and AlAs anisotropic. Therefore, cavity resonances in the [110] and [110] directions are different. With this scheme, we can actively control the polarization of VCSELs by varying the direction and strength of an applied electric field. The polarization mode with a larger optical gain will be dominantly emitted.

The schematic of the fabricated VCSEL grown on (001) GaAs substrate by molecular beam epitaxy (MBE) is shown in Fig. 1. The bottom DBR consists of Si-doped 23 pairs of GaAs/AlAs with Al0.3Ga0.7As grading layers. The 2λ-thick undoped active region consists of InGaAs/GaAs three quantum wells placed at the antinode positions of standing wave. The top DBR is an n-i-p structure. The Be-doped p-type layers are composed of a λ/4-thick AlAs as an oxidation layer for current confinement and a 3λ/4-thick GaAs as a p-contact layer for current injection. The undoped region

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a)Present address: Hyundai MicroElectronics Co., Ltd., Research Center, Cheongju-si, Korea.
b)E-mail address: btahn@cais.kaist.ac.kr
sustaining an applied electric field is 15.5 pairs of GaAs/AlAs DBR. A Si-doped n-type GaAs layer follows for phase matching and a top contact in the end. The epitaxial structure is designed at 950 nm wavelength for bottom emission through the substrate. The injected current flows between the p contact and the bottom n contact. Current flow is confined by an oxidized AlAs layer placed just above the active region. The p contact is grounded to control the direction of an electric field applied between the top contact and the p contact. Contact pads are fabricated at the top contact and the p contact to avoid unwanted birefringence that may possibly arise from the stress by the probe touch.

When an electric field $E$ is applied along the [001] direction, the refractive indices along [110] and [110] directions $n_{[110]}$ and $n_{[110]}$ can be calculated from the following relation:  

$$n_{[110]} = n_0 - \frac{n_0^3}{2} r E,$$

$$n_{[110]} = n_0 + \frac{n_0^3}{2} r E,$$

where $n_0$ is the refractive index in the absence of an electric field, and $r$ is the electro-optic coefficient of GaAs (1.3422 × 10^{-12} m/V) or AlAs (0.8 × 10^{-12} m/V). When an electric field is applied, the cavity resonance of the polarized light along the [110] or [110] direction shifts to a shorter and longer wavelength, depending on the direction of the applied electric field. For a positive electric field, the cavity resonance of the [110] polarization mode (H mode) shows a blue shift, while that of the [110] polarization mode (V mode) shows a red shift. The cavity resonance difference between the two polarization modes linearly increases with increasing the electric field strength. For a negative electric field, the cavity resonances shift to the reverse direction. The reflectivity change of the top DBR by the applied electric field is very small at around the cavity resonance so that the loss change can be ignored for the selection of a dominant polarization mode. We expect that the electro-optic birefringence results in the gain difference between $H$ and $V$ modes due to their different cavity resonances, and this is the main factor in changing the polarization property.

We measured the light–current ($L–I$) characteristics at various electric fields. The diameter of the top DBR was 12 μm. The two polarization modes were simultaneously measured by a polarized beam splitter at room temperature without a heat sink. The threshold currents ranged from 1.8 to 2.5 mA and the light output power was about 100 μW. The cavity resonance at low injection current was 940 nm. This is somewhat distant from the calculated cavity resonance of 950 nm. The high threshold current and low output power may be attributed to this disagreement. The dominant polarization mode in the absence of an electric field was randomly oriented along either [110] or [110]. This means the epitaxial wafer has no specific polarization selectivity.

Figure 2 shows the typical $L–I$ characteristics resolved into each polarization mode with the voltage applied at the top contact. The output powers of $H$ and $V$ modes ($P_h$ and $P_v$) are easily changed by the applied voltage variation. In the absence of an electric field, the $P_v$ is slightly larger than the $P_h$. When the applied voltage is positive, the $P_h$ decreases and the $P_v$ increases as shown in Fig. 2(b). As the applied voltage increases up to 10 V, the $P_h$ is completely suppressed in Fig. 2(c), resulting in the increase of the polarization suppression ratio (the ratio of a large output power to a low output power). In Fig. 2(d), on the other hand, the $P_h$ increases and the $P_v$ decreases as the applied voltage is negative. Further increase of the negative voltage makes the $H$ mode the dominant polarization mode [Fig. 2(e)], opposite to the result of Fig. 2(c). This tendency was observed for most measured devices. From this result, we can consider that the polarization of VCSELs has been successfully controlled by applying the electric field on the top of the DBR and that it can be actively controlled by varying the direction and strength of the electric field. The field strength needed to change the polarization differed from $10^2$ to $10^3$ V/cm. This may be because the devices can have different resident birefringence generated during the fabrication process. We can see a slight decrease in the total output power as the electric field increases. Since the gain curve is not changed during the application of the electric field, we think that the thermal effect by the high electric field is responsible for the decrease.

Figure 3 shows the emission spectra of the device shown in Fig. 2 measured at various applied voltages by monochromator with a 0.1 nm resolution. The device was biased at 4 mA. The emission spectrum measured in the absence of an electric field represents the $V$ mode. The $H$ mode is not seen because the full width at half maximum of the spectrum is too wide to separate the two polarization modes. For the +10 V applied voltage, the emission spectrum shifts to a longer wavelength. This is caused by the shift of the cavity resonance by the applied electric field.
wavelength because the $V$ mode shows a red shift as discussed previously. For the $-10$ V applied voltage, the emission spectrum also shows a small red shift. Referring to Fig. 2(d), we can see the emission spectrum represents the $H$ mode, which shows a red shift under a negative electric field. Therefore, the emission spectrum appears to show a red shift for both electric field applications.

The above results can be explained by the variation of the cavity resonances in the presence of an electric field. We think the power partition between $P_h$ and $P_v$ found in Fig. 2(a) is attributed to the magnitude of the optical gain due to the different cavity resonances, which are not yet identified in these devices. The $P_v$ is larger than $P_h$ for the device without applying an electrical field. Therefore, the resonance of the $V$ mode will be located near the spectral gain maximum, compared to that of the $H$ mode. For a negative electric field application, the gain of the $H$ mode increases and thus the output power increases, while that of the $V$ mode decreases and thus the output power decreases. Further increase of the electric field reverses the gain magnitude and the output powers of the two polarization modes. For a positive electric field application, gain difference between the two polarization modes is larger and the polarization suppression ratio increases. The same interpretation is available for the case when $P_h$ is larger than $P_v$. It was reported that the spectral alignment of the cavity resonance to gain spectrum was important for selecting a dominant polarization mode.\(^{11}\) Due to the poor resolution of monochromator, we could not confirm the cavity resonance splitting associated with the two polarization modes. To prove how far the two polarization modes are separated and how the two polarization modes shift under an electric field application, more precise spectrum analyses are under investigation.

The shift of the gain curve by temperature can affect the control behaviors since the polarization states can be controlled by the spectral alignment of the cavity resonance to gain spectrum. In particular, the electric field-induced polarization control will be sensitively changed at the crossing point of the gain maximum to the cavity resonance. We, however, think that the selection of the polarization state will be possible by controlling the bias voltage even near the gain crossing region. In addition, the relatively large gain offset to the resonance position will prevent the polarization changes. If the cavity structure is designed in a way that the cavity modes are always placed at one side of the gain curve distant from the gain maximum, there will be a decrease in the output power due to the low optical gain. Though this power loss is inevitable, it will not be a major problem in the operation current range and it can be minimized through the cavity design.

In conclusion, the polarization of VCSEL has been successfully controlled by electro-optic birefringence. Birefringence is induced at the top of DBR by applying an electric field along the [001] direction. The dominant polarization mode occurs along the [110] (or [110]) direction for the negative (or positive) electric field application. By varying the direction and strength of the electric field, we can select a wanted polarization mode with some degree of freedom.

This work was partially supported by the Ministry of Information and Communications, Korea.

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