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Effect on polarization control in 850 nm vertical cavity surface emitting laser fabricated by H^+ ion inclined implantation using tungsten wire as mask

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Abstract

Polarization character measurements on VCSEL devices, fabricated by ion inclined implantation with various parameters using tungsten wire as mask, were performed. The effect of polarization mode control was observed in these devices with square injected current aperture formed by distributed ion during implantation. Moreover, the effect depended on the size of the square injected current aperture. The device with highest polarization mode suppression ratio (PMSR) up to 14 dB was obtained, which kept the operation of linear polarization state at $3.4I_{th}$ injected current. The further optimization to obtain the better polarization control effect is available. What the most valuable is that the mechanism of polarization control effect is completely self-formed during device processing. Furthermore, this method is the simplest technique to apply in industry, as much as we know.

Keywords: VCSEL; Ion implantation; Polarization control

1. Introduction

Vertical cavity surface emitting laser (VCSEL) is widely applied in the areas of optical communication, optical storage [1] and optical interconnection [2] because of its many advantages compared with edge emitting laser (EEL). Device and module based on VCSEL are provided on the market. However, in many cases, the light emit from VCSEL is required as the linear polarization mode in the operating current region, which have received much attention as a problem over recent years. It resulted from the cylinder current injection and isotropy at transverse direction of the device structure. Many measures on VCSEL have been proposed to control the polarization mode, such as etching relief on the surface [3,4], electric-optical effect [5], structure epitaxy on non-(0 0 1) substrate [6], asymmetric current injection [7], and so on [8]. Most of these methods, in which the anisotropy was induced to control the polarization, are too complicated to apply in industry. Thus, there is no measure taken on the common VCSEL products on market, which are fabricated by ion implantation or selective oxidation, as much as we know. Most of the VCSEL products on market showed the polarization characteristic of ellipse.

In previous reports, we proposed a new ion implantation technique to fabricate the VCSEL device without any photography and lift-off steps, which is simple enough to apply in the industry. Using tungsten as mask during the implantation, we obtained the devices of high difference quantum efficiency [9] and low threshold current of 1.4 mA [10], respectively. In this letter, the polarization

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characteristic of the devices fabricated with different parameters during implantation was investigated. The result showed that polarization control effect depended on the anisotropy induced by the size of square current aperture owing to this technology. In our cases, the device with polarization mode suppression ratio up to 14 dB was obtained. The further optimization on the parameters in implantation was available to improve the polarization control capability. The most important is that the structure of polarization control is self-formed during processing. Furthermore, this fabrication method was the simplest and suitable for the industry.

2. Device structure and fabrication

The VCSEL structure, shown in Fig. 1, consisted of a 30.5 pair n-doped quarter-wave $Al_{0.1}Ga_{0.9}As/AlAs$ stack as the bottom distributed Bragg reflector (DBR), three 8 nm GaAs quantum wells in the center of a one-wave $Al_{0.25}Ga_{0.75}As$ spacer and a 16.5 pair p-doped quarter-wave $Al_{0.1}Ga_{0.9}As/AlAs$ stack as the top DBR, all grown by metal organic chemical vapor deposition (MOCVD) on an n^+-GaAs substrate. Graded layers, with the thickness of 25 nm and formed with variable duty cycle superlattices, were used between each $Al_{0.1}Ga_{0.9}As$ and AlAs heterointerface to reduce the series resistance. A p^+-$Al_{0.1}Ga_{0.9}As$ layer with the thickness of 12 nm was grown subsequently as ohmic contact layer. The DBR reflectivity spectrum and the cavity mode position of our wafer were measured, which indicated that the cavity mode wavelength was about 835.79 nm and mode width was 1.3 nm. The cavity mode located at the center of high reflectivity region of DBR basically.

The devices with different size of square current aperture were fabricated by two procedures, respectively. One was mentioned in previous report [9]. In that case, the tungsten wire with the diameter of 20 and 12 μm was used, respectively. The other would be illustrated as follows.

Tungsten wires, whose diameter was 20 and 12 μm, respectively, and spacing was 300 μm, were adopted to cover on the wafer as mask at first. The tungsten wires were aligned with the wafer cleavage plane. We deposited a Cr–Au with the thickness of about 150 nm before the first implantation to avoid the wafer to be dirtied and improve ohmic contact. Subsequently, H^+ implantation inclined at a large angle at opposite direction of the perpendicular direction of the wafer surface was performed. Our purpose was to reduce the current injection aperture and make the H^+ distribute perfectly around the active region. The perfect distribution was that a waist shape would be obtained around the active region so that the current could inject the active region along the infundibular routeway. In our experiment, the inclined angle was 17°. The energy of H^+ implantation was 450 keV, and injection dosage was $1 \times 10^{15}\ cm^{-2}$ each time. The wafer was rotated 90° before the last two implantations. Then the tungsten was vertical to the trace of it for the first time. In the last two implantations, the inclined angel was still 17°, the implanting energy was 410 keV, and the dosage was $1 \times 10^{15}\ cm^{-2}$. The decrease of implanting energy was to shape a thick insulation layer around the active region. Subsequently, we deposited a Cr–Au with the thickness of 150 nm as electrode. The deposition of Au–Ge–Ni layer as n-electrode and annealing to recover the destroyed lattice near the surface were performed when the fabrication finished. The procedure of fabrication was shown as Fig. 2. The square, which was shaped by two across rectangular in the center of the device, was light window surrounded by electrode. After simple cleavage, the single device was obtained. Using this fabrication technology, the VCSEL array would also be obtained so long as we adjusted the space of tungsten wire and appended the separation-etching step at last.

Based on the technology using tungsten wire as mask during implantation, the devices were marked by the calculated size of square light aperture according to the procedure, shown in Table 1. Among them, the samples A and C were fabricated by two times ion implantation while samples B and D was fabricated by four times ion implantation.

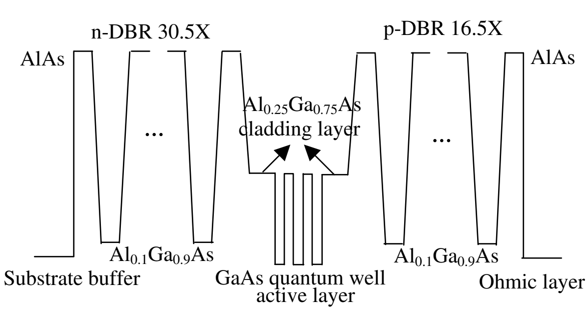

Fig. 1. The schematic of VCSEL epitaxial wafer structure.

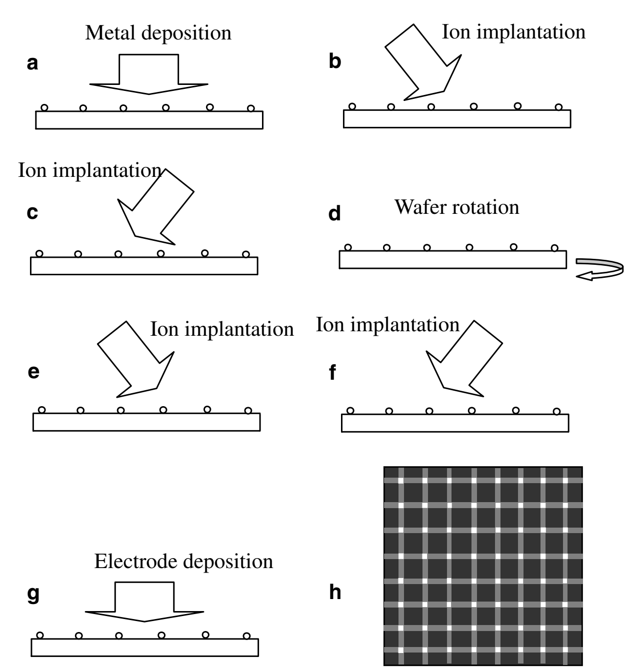

Fig. 2. The procedure of fabrication using tungsten wire as mask.

Table 1
The sample marked by the size of injected current aperture

Size (μm)	20	17.5	12	9.5
Mark	A	B	C	D

3. Results and discussion

Devices with batch low threshold current of about 1.5 and 2.0 mA, respectively, which was equivalent to the threshold current of selective oxidation products, were obtained according to the size of injected current aperture. The threshold current decreased first and increased later with the size of aperture decreasing, as shown in Fig. 3. It was because that the injected current transverse expanded as well as the loss of mirror enhanced rapidly if the current aperture decreased beyond a certain value. Series resistance changed around 150 and 250 Ω, depending on the total implanted ion dose. The output light power decreased when the size current aperture decreased. The surface of a real device after fabrication was shown as an inset figure.

The polarization resolved light powers versus normalized injected current with different current aperture were measured, which was shown in Fig. 4(a)–(c). In order to compare with them, we also gave the polarization characteristic of selective oxidation product (provided by Department of Optoelectonics of AXT Co. Ltd.) in Fig. 4(d).

Fig. 4(a) showed the light power versus normalized injected current when the size of current aperture was A. The device was operating with linear polarization state of 0° along [1 1 0], which was the diagonal of the square current aperture, till the injected current was above $1.36I_{th}$. The polarization mode suppression ratio (PMSR) was 4 dB. The intensity of 90° polarization mode along $[1\bar{1}0]$ increased when the current continued increasing. Thus, the total output light showed the polarization state of ellipse whose major axis was [1 1 0]. The intensity of 90° polarization mode would be more than that of 0° polarization mode at $1.5I_{th}$ injected current. At that time, the major axis of the ellipse polarization shifted to orthogonal direction. The shift would occur again with the increase of the current. In conclusion, the "threshold current" was $1.36I_{th}$ when ellipse polarization existed. In the case that the size of the current aperture was B, the device showed a good linear polarization mode of 0° under the whole linear operation region. The PMSR was up to 14 dB when the polarization state of ellipse appeared at injected current of $3.44I_{th}$ and the light output power began to saturate as shown in Fig. 4(b). Fig. 4(c) showed the case when the size of current aperture was C. The character of polarization control was between those of (a) and (b). The "threshold current" was about $2.3I_{th}$ when the polarization of ellipse existed. The PMSR was up to 14 dB too. The polarization direction of major axis of the ellipse shifted to orthogonal under injected current of about $4I_{th}$. Compared with Fig. 4(b), the effect of polarization control did not improve, though the calculated size of current aperture was smaller than that of sample B. When the technology of two times ion implantation was used, we had to perform the implantation by inclined 10° angle in order to avoid the existence of tunnel effect, which resulted in the inclined light output wave-guide in the device structure. This kind of inclined wave-guide possibly influenced the effect of polarization control partly. The polarization resolved light power of sample D versus current was not obtained because the intensity of output light was not strong enough to be detected. The measurements on selective oxidation product were also carried out for comparison. Since there was no additional measure to control the polarization state in the selective oxidation device with circular current aperture, the result showed polarization of ellipse with the PMSR of about 3 dB, when injected current was just above the threshold.

In the measurement, the direction of extremum of polarization resolved light output power always existed along the diagonal of the square current aperture formed by our technology using a tungsten wire as mask during implantation. The results showed that effect of polarization control existed in the devices. Furthermore, this effect depended on the size of the current aperture. The measurements on batch devices fabricated by us gave the similar results. It was well known that, for implanted VCSEL device, the current restricted layer was formed by damaged crystal lattice during ion implantation. In our device structure, the implanted ion shaped square injected current aperture during four times ion implantation. The aperture was located just above the active region. Current was injected into active region along the square aperture. When laser started to oscillate, a resonance cavity was defined by p- and n-DBRs in the longitudinal direction. While in the transverse direction, carriers decreased the refractive index of the injected region, which surrounded the center of light field. It provided definition to the light field in the transverse direction. Therefore, a dynamic resonance cavity with a square cross section was formed. It equaled to inducing

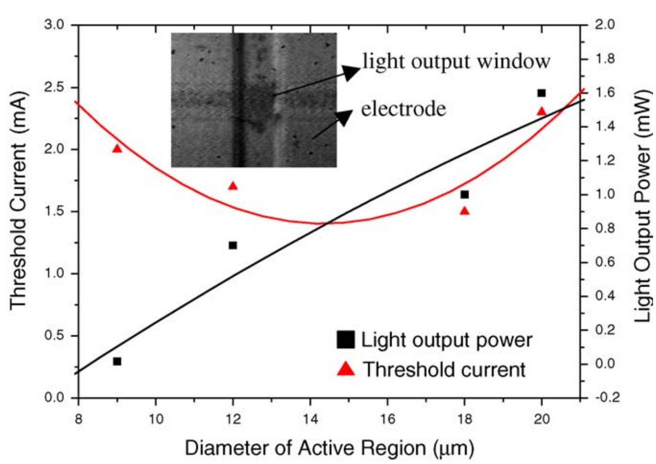

Fig. 3. The trend of threshold current and output power versus current with various size of current aperture Inset figure: picture of a real device surface taken by CCD.

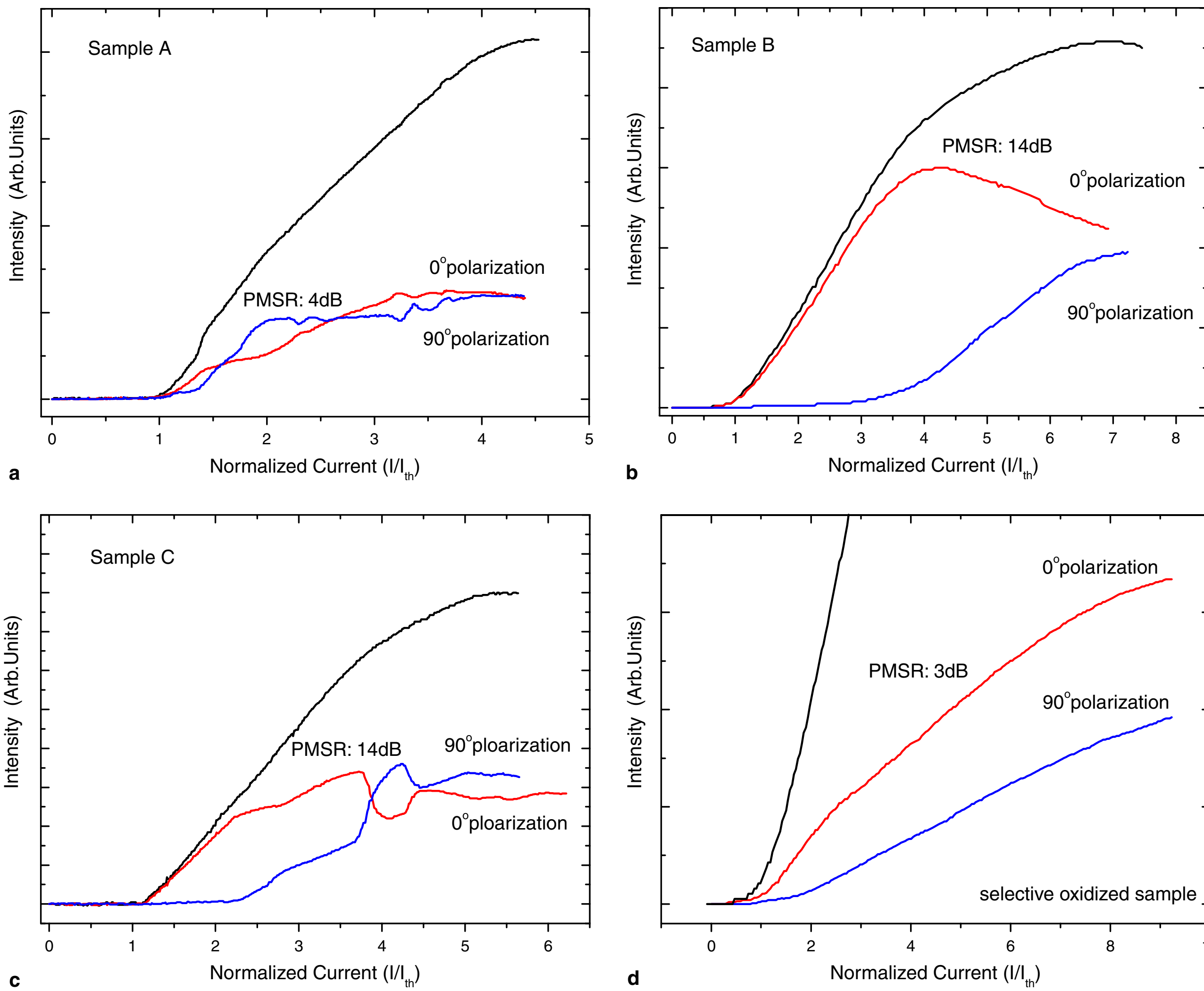

Fig. 4. The curve of polarization resolved light output power versus injected current: (a) the case of sample A, whose size of current aperture was about 20 μm in calculation; (b) the case of sample B; (c) the case of sample C; (d) the case of selective oxidation product provided by company.

an anisotropy restriction in transverse direction in relation to the circular light field in the active region. As a result, the polarization of output light was controlled and a linear polarized mode was obtained. In comparison to the other reported methods on polarization mode control, an important advantage of our method is that this mechanism on polarization controlling was completely self-formed during device processing. Fig. 5 showed the spectra of sample B under different injected current. The spectra proved that the device emit a stable linear polarized mode till the injected current of $3.1I_{th}$. After that, device began to come into saturation. The device showed a trend of multi-mode operation. Accordingly, an ellipse polarized mode switch on. Usually, when the size of the injected current aperture versus the active region decreased, the induced anisotropy increased, so that the effect of polarization control was improved. However, the effect of polarization control did not improve continuously with the narrowing of injected current aperture. It should be noticed that device with a small injected current aperture was easy to come into saturation. When the saturation happened, the cross section of

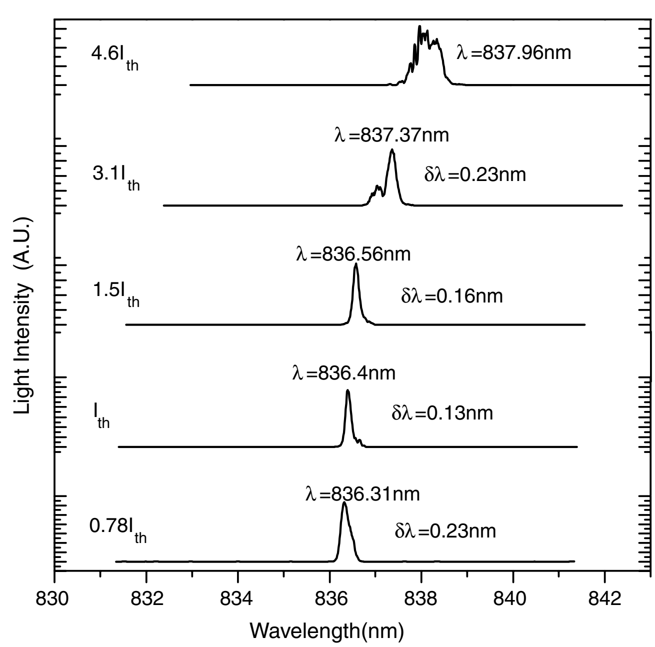

Fig. 5. Spectra of sample B under different injected current.

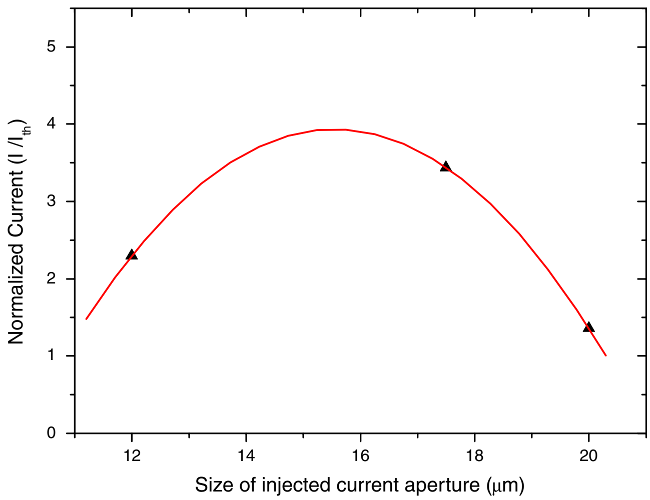

Fig. 6. Normalized current at which ellipse polarized mode switch on versus size of current aperture.

dynamic resonance cavity shifted to circle-shape due to high carrier density. The effect of polarization control weakened. Furthermore, the light output power would also decrease with the decrease of size of injected current aperture. In Fig. 6, the curve of maximum injected current, at which ellipse polarized mode switch on, versus to the size of current aperture was given. The further optimization to obtain the better polarization control effect was available according to our results.

4. Conclusion

Using tungsten wire as mask, we fabricated the 850 nm VCSEL devices by various parameters during ion implantation. Measurements of polarization resolved light output power versus injected current on them were performed. The results showed the effect of polarization control in this kind of device with square injected current aperture, depending on the size of current aperture. The device with highest PMSR up to 14 dB was obtained, which kept the operation of linear polarization state at $3.4I_{th}$ injected current. The further optimization to obtain the better polarization control effect is available. The most valuable is that this mechanism on polarization control is completely self-formed during device processing. And, this fabrication method is the simplest technique to apply in industry, as much as we know.

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