Annealing effects of 850 nm vertical-cavity surface-emitting lasers after proton irradiation

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ABSTRACT

A long-term annealing experiment was performed using 850 nm vertical-cavity surface-emitting lasers (VCSELs) irradiated with 10 MeV protons. Static parameters such as the threshold current, slope efficiency, and light output power were tested using annealing currents above and below the threshold. The experimental results indicated that these parameters gradually recovered with annealing time, and the degree of recovery was proportional to the annealing current. In addition, curve fitting was performed to obtain the direct relationship between the slope efficiency and annealing current. A comprehensive investigation of the annealing behavior of VCSELs is crucial for device applications in harsh radiation environments.

1. Introduction

Melngailis first proposed the idea of vertical laser emission [1]. The breakthrough research on the III–V oxidation process significantly improved the performance of vertical-cavity-surface-emitting lasers (VCSELs) [2, 3]. The compact laser design of VCSELs offers several advantages and possibilities in terms of performance, manufacturing, and packaging. In contrast to conventional edge-emitting lasers (EELs), VCSELs have low divergence, circular and non-astigmatic beams, low threshold currents, and high-efficiency high-speed modulation at low currents. Moreover, surface emission can achieve a dense 2-D integration of VCSELs [4, 5]. These advantages allow VCSELs to be adopted in a wide range of applications and achieve great commercial success in 3D recognition and data communication [6, 7].

Data communication is the driving force behind the significant advancement in the performance and reliability of VCSELs. Because of its high speed, small size, and lightweight optical interconnection, VCSELs have been gradually applied in the field of space and strong radiation. For example, the optical link upgrade of the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics (CERN) uses VCSELs [8]. Different from other environments, VCSELs in radiation-rich environment will have a serious impact on system performance and service life [9, 10].

Many studies have been conducted on the parameter degradation of VCSELs under radiation. The radiation sources used include gamma rays, neutrons, protons, electrons, and heavy ions [11, 12, 13, 14, 15]. Although the earlier studies qualitatively explored experimental rules, later studies examined the physical mechanism of GaAs/AlGaAs material degradation [16]. However, implantation annealing, which is a characteristic of GaAs-based devices, has not been adequately investigated. This is particularly true for long-term annealing with different injection currents. In this study, the long-term annealing effects of VCSELs was investigated based on the previously reported proton radiation effect [17]. Furthermore, the quantitative results of the slope efficiency versus annealing current presented in this paper can enable the accurate evaluation of the performance recovery of VCSELs.

The remainder of the manuscript is organized as follows. Section 2 of this article describes the experimental conditions of irradiation and annealing, as well as the test parameters and corresponding test equipment. Section 3 presents the annealing experiment results of the optical and electrical parameters under different annealing currents. The conclusions are presented in Section 4.

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2. Experimental methods

Multimode VCSELs with operating wavelengths of 850 nm were used in the experiment. A schematic of the VCSEL is shown in Figure 1. In this structure, 38.5 pairs of alternating refractive-index n-type distributed Bragg reflectors (DBR), three quantum wells (QW) and cladding layers, and 20.5 pairs of alternating refractive-index p-type DBRs were grown on an n-type GaAs substrate. The DBR and QWs were composed of Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As (50 nm/39 nm) and GaAs/Al_{0.3}Ga_{0.7}As (7.2 nm/8 nm), respectively. Adjacent DBRs used a 20 nm composition gradient, Al_{0.9-0.12}Ga_{0.1-0.88}. The thickness of the cladding layer above and below the quantum well was 114 nm. The irradiation experiment was performed at room temperature using an EN tandem electrostatic accelerator at Peking University. A flux of $6.4 \times 10^9$ p/cm$^2$ was used to accumulate the total fluence to $3.2 \times 10^{14}$ p/cm$^2$. The 10 MeV protons can completely penetrate the VCSEL up to the GaAs substrate, according to MULASSIS calculations [18]. The VCSELs were electrically and optically tested to ensure high parameter consistency. The output window at irradiation was perpendicular to the proton beam direction, and the package cap was removed to ensure that the degradation of the optical parameters was caused by proton irradiation rather than the degradation of the packaging window material. VCSELs annealing tests were then performed at 243 h, with annealing currents of (a) $I_{bias} = 15$ mA, (b) $I_{bias} = 20$ mA, (c) $I_{bias} = 25$ mA, and (d) $I_{bias} = 2.2$ mA (bias current below threshold current 2.3 mA).

We tested the voltage-current curve, light output power, and power intensity distribution curve, and calculated the series resistance, threshold current, and slope efficiency. The threshold current was calculated based on the coordinates of the current axis corresponding to the fitted intersection of the spontaneous emission of the LED mode and stimulated radiation of the laser mode. The fit of the laser mode data used the linear part of the L-I curve beyond the threshold owing to the thermal roll-over effects. As shown in Figure 2, the light output power and x-axis power intensity distribution of the far-field images were measured using scanning-slit optical beam profilers (BP-209-VIS). A high-sensitivity drive and temperature controller (IT4002QCL) was used during testing and annealing because of the temperature sensitivity of the VCSEL. A semiconductor parameter analyzer (4200A-SCS) was used to measure the voltage-current curve. The test time for each data point was less than 5 min to minimize the effect of annealing during the test. A schematic of the measurement setup is shown in Figure 3.

3. Results and discussion

3.1. Recombination enhanced defect reactions

Figure 4 shows the relationship between the L-I characteristics and the annealing time during the annealing process, in which the interruption of the L-I characteristics is attributed to the switching of the VCSEL operating mode. As shown in Figure 5, we observed a change in the operating mode before and after the current corresponding to the kink in the device. The effect of radiation on the L-I curve is primarily attributed to the displacement damage caused by proton irradiation. The...
interaction of protons with atoms in semiconductor lattices may cause atoms to shift from their positions in the lattice, resulting in vacancies, interstitials, antisites, and Frenkel pair defects. Moreover, primary knocking atoms may produce a displacement cascade to form complex defect clusters [19]. These defects in the lattice can act as non-radiative recombination centers, thereby reducing the carrier lifetime, which is related to spontaneous and stimulated emissions. Therefore, the threshold current of the VCSEL increases. The reduction in carrier lifetime can be obtained from the relationship between log(I) and V during spontaneous emission. The slope efficiency is expressed as

$$\eta = \frac{P_{\text{out}}}{I-I_{\text{th}}}$$  \hspace{1cm} (1)

where $\eta$ is the slope efficiency; $P_{\text{out}}$ is the output light power, and $I_{\text{th}}$ is the threshold current. Although the values of $P_{\text{out}}$ and $(I-I_{\text{th}})$ in Eq. (1) decrease simultaneously, the experimental results show that the degradation of $P_{\text{out}}$ is more significant than that of $(I-I_{\text{th}})$. Accordingly, the slope efficiency decreases. However, most of the defects are unstable and cause recombination owing to electrical implantation in actual work, which manifests as the annealing behavior of the parameters.

Recombination-enhanced defect reactions (REDR) are the primary reasons for parameter recovery after electric injection. Among the three main paths of energy liberation (Auger, radiative, and phonon emissions), multi-phonon emission is the main recombination mechanism of AlGaAs displacement defects [20]. The available thermal energy is insufficient to promote defect reactions at high temperatures. The energy released from carrier trapping during carrier injection enhances the subsequent trapping process. At high carrier densities, these energies may lead to a rapid increase in lattice vibrations that enhance the defect response [21]. As shown in Figure 4, the threshold current and slope efficiency were restored after positive-bias annealing.

### 3.2. Threshold current and slope efficiency

Directly modulated optical fiber communication changes the strength of the output light by controlling the injection current of the VCSEL, as shown in Figure 6. After proton irradiation, the degradation of the threshold and slope efficiency reduces the corresponding optical output power when modulating the power level “1”, which directly affects the current generated by the receiving photodiode, as indicated by the red curve in the figure. This results in an increase in the bit error rate (BER) of the optical fiber communication system, thereby causing system failure.

We determined the functional relationship between the threshold current and slope efficiency for different annealing currents and times, as shown in Figure 7 and Figure 8, respectively. The results indicated that these two parameters recovered rapidly in the first 20 h. This part may correspond to unstable point defects that are easy to compound; however, a small amount of recovery is observed after 20 h, which corresponds to vacancies and complex defect clusters that are difficult to recover. In addition, with an increase in the annealing current, the result of annealing is closer to that of the non-irradiated sample. Under an annealing current of 25 mA, the threshold current degraded by 8% when it was stable; however, the slope efficiency was infinitely close to the value before irradiation, which was different from the threshold current. Under the condition of high-injection annealing, the threshold current fails to recover completely owing to the unrecoverable defects that require carrier input compensation. The effect of these defects on the slope efficiency negligible at low currents owing to the recovery of most of the defects in the quantum well and their negligible influence on the overall reflectivity of the upper and lower reflective layers [22]. In addition, the data points obtained in the form of a pulse current...
minimized the influence of temperature. These factors make the slope efficiency close to the initial value. However, unrecoverable defects appear in the form of reducing the optical output power at a high injection current; this will be discussed in the next section.

Annealing below the threshold current requires a longer time, and the extent to which the final recovery is limited. We used the following formula to curve-fit the slope efficiency of annealing above the threshold current:

\[ \eta = \frac{60}{I_a} - \frac{0.3}{T} + 0.594 \]

where \( \eta \) is the slope efficiency, and \( I_a \) is the annealing current. The results indicated that the fitting curve corresponds well at different currents, indicating that the annealing result is directly related to the current. Annealing of other parameters also follows a law directly related to the current, but this quantitative law was not apparent because of the rapid saturation at 25 mA. For optical communication systems that operate in proton-rich environments for long periods of time, annealing is incomplete because of the low operating current.

### 3.3. Light output power and power intensity distribution

The light output power corresponding to the 23 mA current extracted from the L-I curve for different annealing currents is shown in Figure 9, and its recovery is consistent with the threshold current and slope efficiency. Notably, under an annealing current of 25 mA, the slope efficiency returns to the initial value, whereas the optical output power does not. When the optical output power is stable, it degrades by approximately 6%, which is close to the degradation degree of the threshold current. This is because the slope efficiency calculation uses the linear part after the threshold, and the effect of the junction temperature is not apparent at this time. As the junction temperature increases, the thermal roll-over mechanism causes the optical output power to gradually decrease [23]. We believe that the increase in the junction temperature is caused by the non-radiative recombination introduced by radiation, and the existence of defects causes carrier recombination to generate heat. This reduces the corresponding current when thermal rollover mechanisms occur. Even when the slope efficiency is restored to the ideal state, the light output power cannot be restored to the unirradiated value.

The annealing recovery of the power intensity distribution is shown in Figure 10. During the test, the scanning slit optical beam profilers were placed 5 mm from the VCSEL device. Unlike the Gaussian distribution curve of a single mode, the power intensity distribution exhibits a multimode state. Figure 11 shows the operating wavelength at 20 mA before and after irradiation, in which the optical cavity has a gain effect on multiple wavelengths. As the annealing time increased, the power intensity gradually recovered; however, the distribution of the curve was slightly different. Owing to the existence of defects, there were differences in the current density and operating wavelength at different annealing times. The slight difference in the curve profiles is attributed to the annealing-induced increase in the current density and recovery of the
operating wavelength. The wavelength shifted by 1.165 nm after irradiation and was accompanied by a decrease in the intensity. The red shift is attributed to changes in the optical cavity and DBR gain owing to temperature.

3.4. Electrical characteristics

Figure 12 shows the variation in the series resistance extracted from the V–I characteristics of the VCSEL with the annealing time and current. The series resistance of the VCSEL was determined using the DBR mirror. Owing to the non-radiative recombination center introduced by proton irradiation, a higher voltage is required to drive the device under the same injection current; thus, the series resistance increases. It can be observed from the figure that after annealing, a larger series resistance corresponds to a smaller annealing current, and there is no decreasing trend after 50 h. This also means that more defects are recovered at higher annealing currents.

4. Conclusions

In this study, a long-term annealing experiment was performed on VCSELs irradiated with 10 MeV protons. The experimental results indicated that the threshold current, slope efficiency, light output power, and power intensity distribution recovered with an increase in annealing time; the slope efficiency had a quantitative relationship with the annealing current above the threshold, and could be restored to the initial value under a high annealing current. Radiation-induced degradation and annealing recovery are attributed to the generation and recombination of non-radiative recombination centers. Furthermore, the performance recovery under different annealing currents was related to the defect type. A comprehensive study of the annealing behavior of VCSELs can potentially enable their application in environments with strong radiation.

Declarations

Author contribution statement

Jiawei Chen: Performed the experiments; Wrote the paper.
Yudong Li, Dong Zhou: Analyzed and interpreted the data.
Heini Maliya, Lin Wen: Contributed reagents, materials, analysis tools or data.
Qi Guo: Conceived and designed the experiments.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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