Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 553-556

D-4-4

Switching Characteristics of InGaAs/InP MQW Voltage-Controlled Bistable Laser Diodes

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Voltage-controlled optical bistability in $In_{0.53}Ga_{0.47}As/InP$ multiquantum well (MQW) laser diodes is demonstrated for the first time by using the quantum confined Stark effect (QCSE) and saturable absorption of a two-dimentional exciton. The MQW bistable laser is fabricated from a wafer grown by gas source molecular beam epitaxy. It consists of a 280μm long injected gain region and a 20μm long voltage controlled saturable absorption region. Optical bistability is obtained in a wide range of control voltages from +0.7V to -0.6V. Switching operation is achieved by injecting a set light pulse and applying reverse bias reset voltage to the saturable absorption region. Turn-on time is 300psec with input light of 6mW and turn-off time is 500psec with -0.5V applied voltage pulse.

1. Introduction

Optical bistable devices will be key elements in future telecommunication switching and optical data processing systems. Optical bistable laser diodes are superior to passive type devices for their lower switching power(1), larger tolerance in wavelength(2) and large optical gain. Conventional bistable laser diodes, which consist of a gain region and a less injected loss region, have been studied for optical time-division switching systems(2),(3). However, turn-off time of the bistable laser is limited by the recovery time of the saturable absorber, which is several nsec for a general switching condition. To overcome this problem, some efforts(4) have been made to reduce the carrier lifetime of the absorption region. In early experiments, voltage-controlled optical bistability was demonstrated by Tarucha *et al.* (5) in GaAs/AlGaAs MQW laser diodes. A decrease in carrier lifetime in this device is expected by applying reverse bias voltage to the saturable absorption. However, self-sustained intensity pulsation sometimes occurs because of the large gain coefficient in the absorption region of GaAs/AlGaAs MQW laser diodes. There are no reports of demonstrating voltage-controlled effects in the switching response.

In this letter, we report on the bistability of the $In_{0.53}Ga_{0.47}As/InP$ MQW laser diode and its switching operation by injecting a set light pulse and applying reverse bias reset voltage.

2. Device Structure

All the samples for this study were grown by gas source molecular beam epitaxy (GSMBE) developed by Panish for the quaternary system of InGaAsP(6). An ultra-high-vacuum (UHV) system was evacuated with a 2200*l*/sec liquid-nitrogen-trapped turbomolecular pump and a titanium sublimation pump with cryopanel. Atomic beams of Group III elements of Ga/In and dopant beams of Si/Be were generated by effusion cells. The beams were controlled with shutters in the same way as conventional solid source MBE. The AsH_3 and PH_3 flow rates were regulated with thermal mass flow meters and hydrides were decomposed into the dimers of As_2 and P_2. The cracking process of hydrides was to heat the gases to 950°C at the inlet port of the UHV system by using the high temperature gas cell (HTGC). The cracking temperature was selected by observing mass

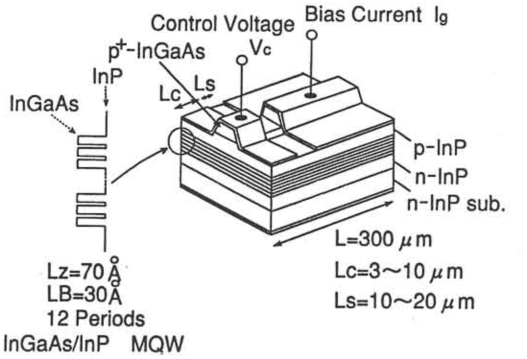

Fig.1 Schematic view of InGaAs/InP MQW bistable laser diode

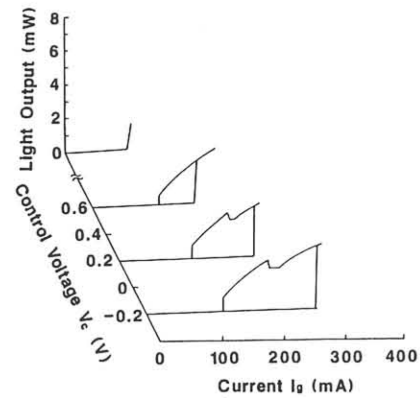

Fig.2 Light output vs. bias current into the gain region I_g as a parameter of the control voltage V_c

spectroscopic analysis of the decomposition.

The MQW laser structure was grown on [100] oriented Sn-doped InP substrates. The grown layers consist of 1 μm thick InP (Si-doped, cladding), 12 periods of 70 Å thick $In_{0.53}Ga_{0.47}As$ and 30 Å thick InP, 2 m thick InP (Be-doped, cladding) and 0.2 μm thick $In_{0.53}Ga_{0.47}As$ (Be-doped, contact layer). The growth temperature was 530°C. Although the quantum well number was a bit larger than conventional MQW laser diodes, the threshold current density was as low as 1.5 kA/cm^2 for 700 μm-long broad-area laser diodes. A schematic view of the MQW bistable laser is shown in Fig.1. 8 μm wide ridge structure was formed by chemical etching. The mesa height was about 2 μm. The two segmented electrodes were formed by removing the InGaAs contact layer. Isolation resistance was 1 kΩ. The cavity length L and width of the saturable absorption region (L_c+L_s) were 300 μm and 20 μm, respectively. The longer electrode is for the gain region and the shorter for the saturable absorption region where control voltage is applied. The threshold current was 100 mA when the two electrodes were directly connected.

3. Characteristics of MQW Bistable Laser

3.1 Lasing Characteristics

Figure 2 shows the characteristcs of light output as a function of bias current into the gain region I_g with various control voltages applied to the saturable absorption region V_c. The gain region was pumped by current pulse (10 kpps, 1 μsec width).

The curve with no hysteresis represents the characteristic when the two electrodes are directly connected. The lasing wavelength with no control voltage applied is longer than the excitonic peak wavelength due to bandgap shrinkage effect. So loss in the saturable absorption region is small. In case of applying control voltage, the two-dimensional exciton in the saturable absorption region works as a saturable absorber and causes hysteresis. With increasing reverse bias voltage, the wavelength of the two-dimentional excitonic peak shifts to longer wavelengths and absorption increases. Therefore, turn-on current, turn-off current, and the hysteresis width ΔI increases with decreasing V_c. Turn-on and turn-off current as a function of control voltage V_c is shown in Fig.3. Optical bistability was obtained in a wide range of control voltages V_c from +0.7V to -0.6V. The measured ΔI was 68 mA at Vc=+0.6V and 218 mA at Vc= -0.6V. When control voltage Vc becomes larger than +0.7V, hysteresis disappears. This is different from the characteristics of conventional inhomogeneous-current-injection-type bistable lasers.

Figure 4 shows experimental data of the bistable region, lasing and non-lasing region against bias current I_g and control voltage V_c. The upper and lower lines represent turn-on and turn-off conditions, respectively. The lasing region located above the upper line can be divided into three parts: A stable region (relaxation oscillation damps gradually with time), pulsation region I (relaxation oscillation continues during bias current pulse) and pulsation region II (self-sustained pulsation occurs). With small control voltage V_c, self-sustained pulsation occurs because the differential gain coefficient becomes large.

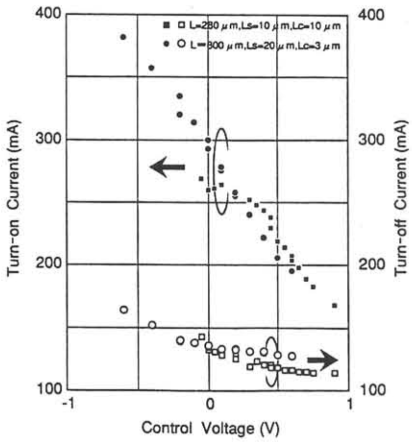

Fig.3 Turn-on and turn-off current vs. control voltage

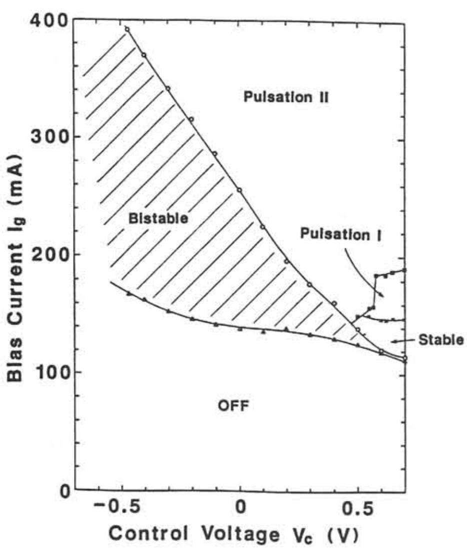

Fig.4 The experimental data of the bistable region, lasing and non-lasing region against bias current I_g and control voltage V_c

3.2 Switching Operation by Control Voltage

Switching operation was observed when applying bipolar voltage to the saturable absorption region as shown in Fig.5. Set-on and set-off voltage was +0.4V and -0.7V, respectively. They are superimposed on +0.2V bias voltage. Both set-on and set-off pulse width were 10 nsec. The rise time and fall time were less than 200 psec. Turn-on time decreases with increasing set-on voltage. This is because the difference of the cavity loss between bias state and on state becomes larger for large set-on voltage and then the difference of the inversion population also increases. Turn-on time was less than 200 psec. Turn-off time decreases with decreasing control voltage V_c (increasing reverse bias voltage) . It was 600 psec with control voltage V_c of -5V.

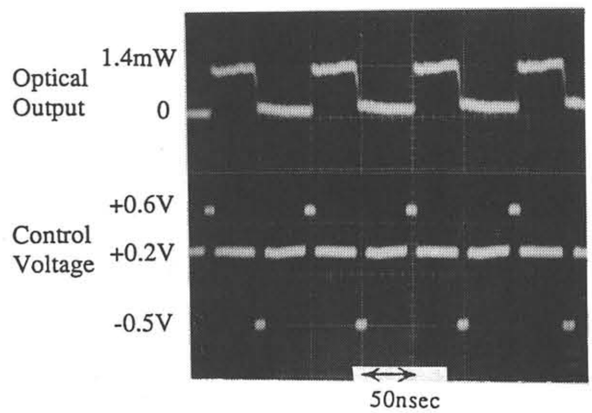

Fig.5 Switching operation by applying bipolar voltage to saturable absorption region

3.3 Switching Operation by Light Injection

Switching operation by injecting a set-on light pulse was also obtained. Figure 6 shows the experimental set-up for light injection. A laser diode as a light source was directly modulated by a pulse generator (rise time and fall time less than 200 psec). Input light wavelength was 1.47 μm, which was 30Å shorter than that of the bistable laser. Set-on light was injected into the gain region and pulse duration was 10 nsec. The bias current into the gain region I_g (10 kpps, 1 μsec width) was biased to 2 mA below electrical turn-on current. Switching operation is shown in Fig.7. Set-on light power measured in front of the bistable laser facet was 2.8 mW. A 5 nsec-duration -0.5V pulse was applied to the saturable absorption region as the set-off pulse with +0.2V bias voltage. Turn-on time decreases with increasing injected light power. Turn-on time of 300 psec was obtained when set-on light power was 6 mW. It can be reduced by setting optimum bias current. Figure 8 represents turn-off time versus control voltage V_c.

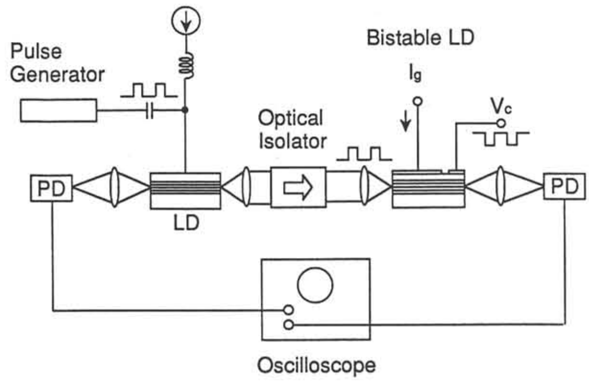

Fig.6 Experimental set-up of light injection

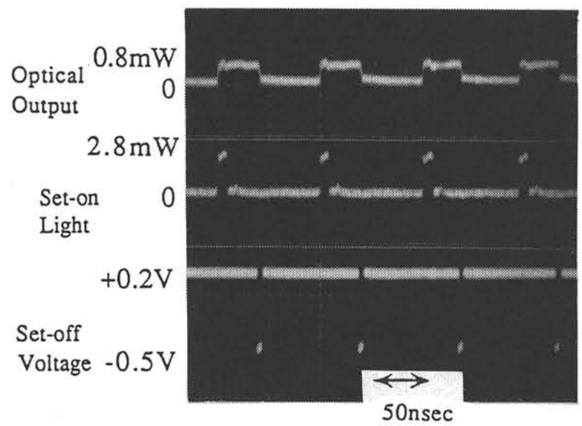

Fig.7 Switching operation by injection set-on light pulse and applied control voltage

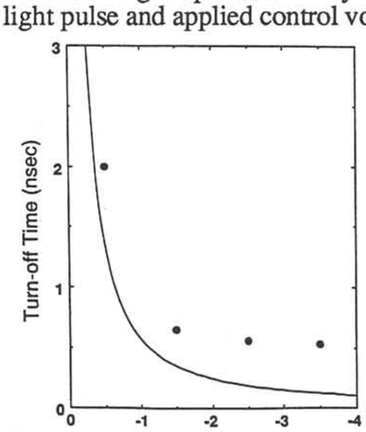

Fig.8 Turn-off time vs. control voltage V_c

The solid line shows the calculation results by solving rate equations. The ratio of the differential gain coefficient in the gain region to that in the saturable absorption region of 0.7, and the radiative recombination time in the saturable absorption region of 10 nsec were used in the calculation. Turn-off time decreases with increasing reverse bias voltage. This was the same as mentioned in **3.2.** Turn-off time was saturated 500 psec with control voltage V_c of less than -3.5V. Less than 100 psec turn-off time was estimated from the calculation results. On the other hand, the stray capacitance of the device was measured to be 5 pF. Therefore, the turn-off time of this laser was considered to be limited by the stray capacitance in the saturable absorption region. Less than 100 psec switching speed is thought to be possible by reducing the stray capacitance.

4. Conclusion

In summary, we believe that this is the first demonstration of the voltage-controlled operation of $In_{0.53}Ga_{0.47}As/InP$ MQW bistable laser diodes. Switching operation by a set-on light pulse and subnanosecond turn-off time by applying reverse bias set-off voltage was obtained. The MQW bistable laser is promising for a high-speed optical memory device because it has a higher relaxation oscillation frequency and larger gain coefficient than the conventional DH structure.

Acknowledgement

The authors would like to thank Dr. Takayuki Sugeta for his support and encouragement throughout this work. They also thank Mr. Shinichi Iida for his contribution to the fabrication process.

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