Extended Abstracts of the 2002 International Conference on Solid State Devices and Materials, Nagoya, 2002, pp. 540-541

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# Lasing Characteristics of InGaAs/InGaAsP MQW PnpN Optical Thyristor Operating at 1.565 μm

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## 1. Introduction

Recently, a great deal of interest has been focused on digital optical switching devices, which are essential elements for the optical systems such as interconnection, self-routing, and neural network. As an optical switching device, optical thyristor has many advantages such as fast response, low switching energy, low power consumption, high ON/OFF contrast, and good expandability to 2-D monolithic arrays [1], [2]. Most of all, optical thyristor not only operates as an optical switch but also emits light. This feature distinguishes it from other optical switches such as self-electrooptic effect device (SEED) and EAM. In many applications, however, relatively slow switching speed from the "on" to the "off" state is the major limiting factor in optical thyristor. In the conventional thyristors, excess majority carriers in the center layers of the ON-state thyristor cannot be depleted immediately, because they are confined and vanished only by very slow recombination process (~msec). This serious slow-switching problem has been overcome by fully depleted optical thyristor (DOT), in which excess carriers in the center n- and p-layers are fully depleted by applying a reverse-bias pulse [2]. When an negative voltage pulse is applied, the center layers of DOT are fully depleted, and the excess carriers can be swept out less than a few tens of pico-second. In other words, DOT is a simple and fast two-terminal optical device. As an effort to achieve faster switching speed and lower switching energy, various device structures of optical thyristor have been reported [3]. However, most of DOT studies have been focused on GaAs-based surface-normal structures for optical interconnection purpose. The possible usage of DOTs for advanced optical communication has been overlooked. The double-heterostructure optoelectronic switch (DHOS) was demonstrated for the first time in the InP/InGaAsP material system by Simmons et al. [4]. This structure employed very thin n-type charge sheet layer. On the other hand, our structure can be completely depleted by reversely biasing the P-n junction. This makes the waveguide-type depleted optical thyristor (WDOT) distinct from other heterostructure devices using an InP/InGaAsP material system. PnpN fully depleted optical thyristor has potential applications in advanced optical communication systems such as optical code division multiple access (CDMA) system and optical asynchronous transfer mode (ATM) system [5]. In optical CDMA, WDOT can be used as a fast hard-limiter enhancing the peak to side-lobe ratio. Moreover, in optical ATM it can be used as a fundamental packet-switching device with both logical and relational functions. To the best of our knowledge, the fabrication and measurement for InGaAs/InGaAsP MQW waveguide-type depleted optical thyristor laser diode (WDOT-LD) have not been reported. In this study, we have fabricated the WDOT-LD with InGaAs/InGaAsP MQW structure.

## 2. Experiment

MQW PnpN structures were grown on InP substrates by MOCVD in the following order: an $N^+$ -InP layer (500nm, $1\times10^{18}$ $cm^{-3}$), a P -InP layer (300nm, $2\times10^{17}$ $cm^{-3}$), a six quantum wells p -InGaAs layers (7nm, $1\times10^{17}$ $cm^{-3}$) with barrier p -1.25Q layer (10nm, $1\times10^{17}$ $cm^{-3}$), single quantum well InGaAs undoped layer (6nm) with barrier 1.25Q undoped layer (10nm), a six quantum wells n -InGaAs layers (7nm, $1\times10^{17}$ $cm^{-3}$) with barrier n -1.25Q layer (10nm, $1\times10^{17}$ $cm^{-3}$), an N -InP layer (300nm, $2\times10^{17}$ $cm^{-3}$), a $P^+$ -InP layer (500nm, $2\times10^{18}$ $cm^{-3}$), an $P^+$ -InGaAs contact layer (100nm, $1\times10^{19}$ $cm^{-3}$). For the full depletion, the thickness and doping concentration of the center layers should be designed carefully. For low reverse full-depletion voltage, the center layers should be as thin as possible. In contrast to the fact that thin center layers may degrade the optical sensitivity in a surface-normal structure, thin light-absorbing center layers do not affect on the optical sensitivity in a WDOT for the advanced optical communication systems. Nonetheless, if the center layers are too thin, the nonlinear s-shape current-voltage (I-V) characteristic of optical thyristor cannot be obtained. Therefore, the n- and p-layers of the WDOT were made up of the carefully designed layer thickness and doping concentration. The design was performed by using the finite difference method [6]. For the optical waveguide definition, selective wet etching techniques instead of reactive ion etching were used to diminish possible ion damage in the optical guiding layers. The etch depth was about 0.9 μm for the waveguide to reach active layer. Then, the ridge waveguide width is 6 μm. Silicon nitride, deposited by plasma enhanced chemical vapor deposition, was used to electrically isolate p and n contact. The P+ -ohmic contact was made using a lift-off process of Ti/Pt/Au, and N+ -layer was contacted with Ti/Au after lapping InP substrate up to 200 μm.

### 3. Results and Discussion

Fig. 1 shows the measured nonlinear s-shape current-voltage (I-V) characteristics of an MQW WDOT-LD The ridge waveguide was cleaved to a length of 300 μm. In a forward bias, the optical thyristor clearly shows the nonlinear s-shape I-V characteristics with three distinct states; the low-current OFF-state, the high-current ON-state, and the negative differential resistance region. In the OFF-state, the device has a high-impedance up to switching voltage of 4.6314 V. On the other hand, it has low-impedance in the ON-state voltage of 0.5935 V.
And then, the switching and holding current are respectively 10 μA, 20 μA. Fig. 2 shows the CW light output of an MQW WDOT-LD under various temperatures for a length of 300μm. Threshold currents at the temperature of 25 °C and 10 °C are 111 mA and 72.5 mA, respectively. The lasing wavelength is centered at 1.565μm at a bias current equal to 1.41 times threshold.

### 4. Conclusions

We have demonstrated, for the first time, WDOT-LD with InGaAs/InGaAsP MQW structure. The waveguide type PnpN optical thyristors clearly show the nonlinear s-shape I-V and lasing characteristics. We obtain a sufficient switching voltage and very low current. WDOT has been shown lasing characteristics. This has been considered as enhancing of switching time. It is believed that our experimental results propose the potential applications in advanced optical communication systems such as CDMA and ATM system.

### Acknowledgments

The work done by KIST has been partially supported by Advanced Photonics Technology Project of the Korean Ministry of Science and Technology.

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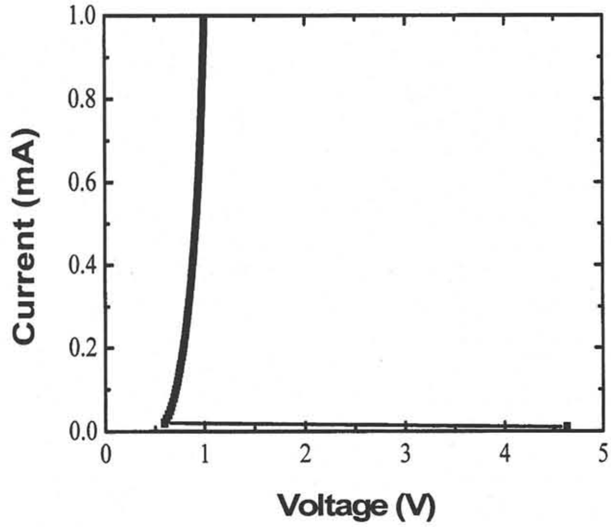


Fig. 1 The nonlinear s-shape current-voltage (I-V) characteristics of an MQW waveguide optical thyristor with device length L=300 μm.

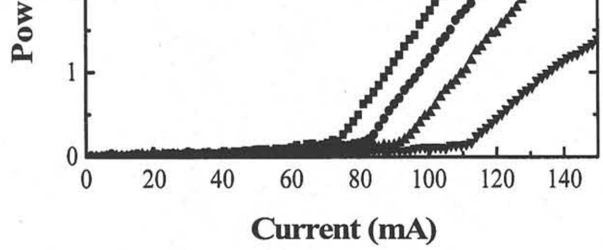


Fig. 2 The output power of MQW WDOT-LD operating at various temperatures.