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**Invited**

# Photonic Integrated Circuits Fabricated by Bandgap-Energy-Controlled Selective MOVPE Technique

Tatsuya Sasaki, Masayuki Yamaguchi and Keiro Komatsu[1]
Optoelectronics and High Frequency Device Research Laboratories, NEC Corporation
34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan
Phone: +81-298-50-1536, Fax: +81-298-50-1106, E-mail: sasaki@optd.cl.nec.co.jp
[1]Present affiliation: ULSI Device Developement Labs., NEC Corp., 2-9-1 Seiran, Otsu, Shiga 520, Japan

## 1. Introduction

Recently, demands on high transmission capacity for long-haul optical transmission systems have much increased. Wavelength division multiplexing (WDM) is one of the most practical approach. Different wavelength laser diodes are key devices. For optical networks, photonic switching will play an important role, because it can handle over Gb/s-capacity unit paths and can be reconfigured with optical cross-connection. Semiconductor optical amplifiers (SOAs) are very attractive as gate elements for such systems.

We have developed selective MOVPE technique for fabrication of various photonic integrated circuits (PICs), because it can achieve simultaneous formation of active/passive waveguides of semiconductor optical components such as laser diodes, amplifiers, modulators and optical waveguides[1]. Since waveguide layers are selectively grown on typically 1.5 $\mu$ m-wide spacing between a pair of $SiO_2$ mask stripe, waveguide structure can be directly formed without semiconductor etching process. This narrow-stripe selective MOVPE technique has advantage in precise wavelength control of DFB-LDs. Waveguide thickness modulation using this technique is also effective for integration of a spot-size-converter (SSC)[2][3].

In this paper, our recent demonstration of photonic devices, such as wavelength-controlled DFB LDs for WDM systems and SSC-integrated SOA Gates for photonic switching systems, are presented.

## 2. Wavelength-controlled DFB LDs for WDM Systems

For WDM systems, light sources with different lasing wavelengths and uniform lasing characteristics are strongly required. Fabrication of such LDs on a single wafer is very attractive from the viewpoint of cost reduction, because the number of wafer to be grown drastically decreases.

We have demonstrated 40-channel different wavelength DFB-LDs on one wafer [4]. Figure 1 shows our concept. Different pitch of gratings were formed on an n-InP wafer by electron-beam lithography. Newly developed field-size-variation technique[5] enabled fine pitch control of a 0.0012nm step. Forty-channel different pitch gratings from $\Lambda_1$=235.98nm to $\Lambda_{40}$=247.68nm by a 0.3nm step were formed. Then $SiO_2$ mask stripes were formed on the wafer. The mask stripe width was varied from $Wm_1$ =24.0 $\mu$ m to $Wm_{40}$=35.7 $\mu$ m so as to adjust the gain-peak wavelength of a selectively grown active layer to the lasing wavelength for each channel. A compressive-strained MQW active layer was selectively grown on a 1.5 $\mu$ m wide spacing between a pair of mask stripe. Finally, the MQW active layer was buried with a p-InP cladding layer. Both facets were coated with AR films. The cavity length was 300 $\mu$ m.

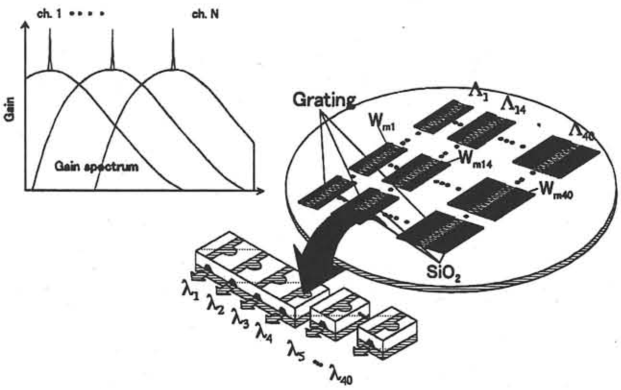


Fig. 1 Wavelength-controlled DFB LDs on one wafer.

Figure 2 shows measured distribution of lasing wavelength and gain-peak wavelength for 40-channel. Over 75nm lasing wavelength span with 1.95nm spacing was achieved. The standard deviation for lasing wavelength was 0.62nm. Fine lasing wavelength control was achieved, resulting from both fine control of grating pitch by the field-size-variation technique and fine control of waveguide structure by the narrow-stripe selective MOVPE technique.

Wavelength detuning between the lasing wavelength and the gain-peak wavelength was less than 10nm for each

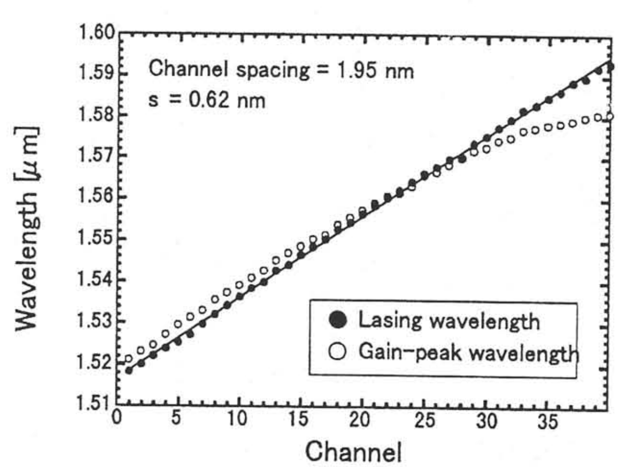


Fig 2. Distribution of lasing wavelength and gain-peak wavelength for 40-channel DFB LDs.

channel. Stable single mode operations with more than 35dB side mode suppression ratio were obtained. Average threshold current for the 40-channel LDs was 8.9mA. Maximum threshold current was as low as 12mA. These uniform characteristics show bandgap energy of the MQW layer can be controlled precisely by the narrow-stripe selective MOVPE technique.

### 3. SSC integrated SOA Gates for Photonic Switching

SOAs have several features such as high extinction ratio, broad bandwidth, low power consumption and compactness. Therefore, SOA array integrated with a passive splitter is one of the key devices for photonic switching systems. We have demonstrated a polarization-insensitive SOA gate [6]. In the hybrid switch matrices, which consists of SOAs and a planar waveguide circuit or single mode fiber (SMF) array, easy assembling is strongly required for cost reduction and matrix size expansion. SSC-integrated SOA gate is attractive, because low coupling loss and large assemble tolerance are expected without any lenses. We have presented a SSC-integrated SOA gate fabricated by the narrow-stripe selective MOVPE technique[7].

Figure 3 shows a schematic structure. The SOA consists of an 350 $\mu$ m-long active region, 250 $\mu$ m-long SSC regions, and window regions at both end facets. A thickness-tapered core layer at the SSC region was simultaneously grown with an InGaAsP bulk active layer at the active region. Nearly square dimension of the active layer (420nm wide and 270nm thick) provides polarization insensitive operation with high optical gain. To obtain large layer thickness variation, we introduced atmospheric pressure selective MOVPE[8]. Almost three times thickness variation was obtained between the active layer (Wm=30 $\mu$ m) and the core layer at the end of the SSC regions (Wm=4 $\mu$ m).

Measured far field pattern shows 13-14$^\circ$ FWHM which is much smaller than that of 40$^\circ$ for a conventional SOA without SSC. Measured minimum coupling loss between the SOA and a flat-ended SMF was as low as 3dB, and 1dB loss increase tolerance in the transversal direction was $\pm 3$ $\mu$ m.

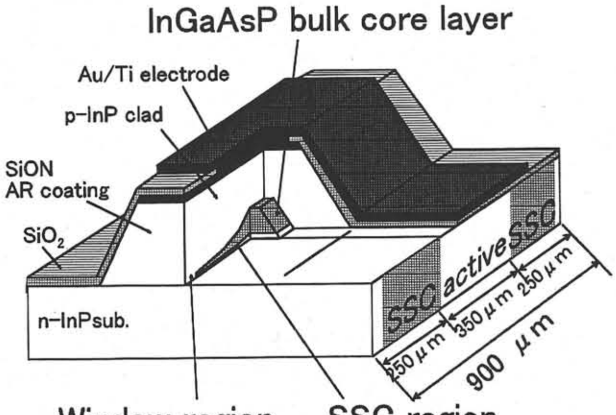


Fig. 3 Schematic structure of a SSC-integrated SOA gate.

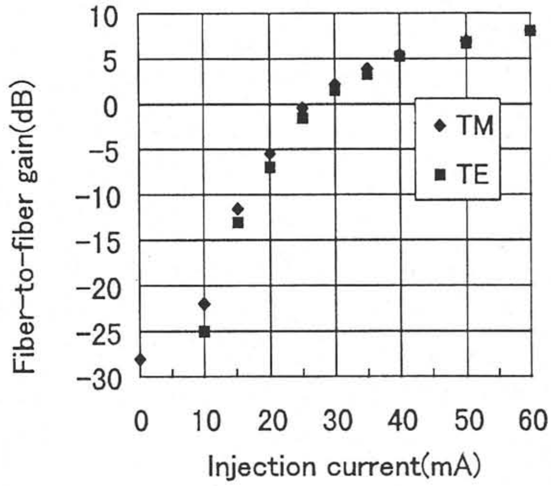


Fig. 4 Measured fiber-to-fiber gain characteristics.

Figure 4 shows fiber-to-fiber gain characteristics. Insertion-loss-free operation was obtained at 27mA injecton current. Polarization sensitivity was sufficiently small. This SSC integrated SOA with large coupling tolerance and low power consumption will be applied to large-scale optical matrix switch for optical cross-connection systems.

### 4. Conclusions

The bandgap-energy-controlled narrow-stripe selective MOVPE technique is effective for fabricating wavelength-controlled LDs and SSC-intregrated SOA gates with high device performance. The selective MOVPE is a promising device fabrication technology for future optical communication systems.


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