Manufacturing of lasers and photodetectors on 100 mm InP in GaAs IC fabrication facility

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Abstract

The demand of photonics products has increased significantly due to growth in the data center market and other optical communication systems. In order to increase production volume it is necessary to manufacture optical devices (lasers and detectors) in a GaAs fabrication facility without a major capital investment. Highly reliable different types of lasers and photodetectors have been manufactured with high performance on 100 mm InP in a GaAs IC fabrication facility.

INTRODUCTION

Optical communication systems are being used not only in telecommunications but also in short distance high speed networks and data centers. Lasers and photodetectors are the most important components of any optical communication systems. Laser diodes transmit data (optical signal) through fiber. Photodetectors convert it back into an electrical signal. Semiconductor lasers are very compact, reliable and have a long life time. These laser diodes can be easily modulated and coupled to an optical fiber to transmit data. On the receiving side, p-i-n photodiodes made from InGaAs/InP lattice matched structures can detect the telecommunication bands at high speed. The explosive growth of internet traffic has increased the demand of these devices significantly. Therefore, it is necessary to manufacture these devices in high volume to satisfy market demand.

Generally these optoelectronic devices have been manufactured in dedicated fabrication facilities (2 or 3 inch) with relatively small volume. Youtsey et al. [1] have reported development of optical devices on 4 inch InP substrates using standard production tools in a GaAs IC manufacturing facility. However, those were not released for production. Global Communication Semiconductors Inc. has also manufactured photodiodes and semiconductor optical amplifiers but no lasers in the IC production environment [2]. In the last 3 years, MACOM has been developing high volume manufacturing processes for different types of lasers and photodetectors on 100 mm InP substrates using an existing GaAs IC manufacturing infrastructure. This has helped to reduce not only the development cost but also the manufacturing cost due to sharing of the fixed costs.

Optoelectronic devices based on InP contain InGaAs, InGaAlAs and InGaAsP epitaxial layers. GaAs based p-HEMT (high electron mobility transistor) devices contain AlGaAs, InGaAs, InGaP, AlAs epitaxial layers. The composition of the layers are different due to different lattice parameters (GaAs-5.6533 Å, InP-5.8686Å) and strain. The dopants in photonics devices are Si and Zn but for p-HEMT devices the dopant is Si. Because of the commonality between two families (InP and GaAs), with a few exceptions, several process modules such as photolithography, metal, dielectric layers, annealing and thinning were used to develop the manufacturing process of lasers and detectors using the same equipment. The coatings on the facets with different reflectivities were deposited in a separate tool. The wet chemical and dry etch processes were carried out in an isolated area with different tools to avoid cross-contamination. The same metrology and inspection tools were used to control the manufacturing process. This was possible due to larger critical dimensions for photonics devices than for GaAs IC devices.

FABRICATION OF LASERS

The epitaxial structures for the fabrication of lasers were grown by metalorganic chemical vapor deposition (MOCVD) on 100 mm n+ InP substrates. The structure consists of multiple quantum wells enclosed with graded index separate confinement heterostructure (GRIN-SCH) layers. A zinc doped InGaAs p-contact layer was grown on the top of the structure to reduce contact resistance. For distributed feedback (DFB) lasers an InGaAsP grating layer was grown on the p-side of the structure. The regrowth was carried out in a MOCVD system after creating the grating by a holography process.

The manufacturing process of ridge waveguide lasers was started with oxide deposition to create insulating pads underneath metal bond pads. The subsequent process steps were facet and ridge formation. The size of the ridge (length and width) depends on the design of the device for different applications. After passivation of the ridge, p-ohmic contact metal (Ti/Pt/Au) was deposited on the ridge and on the oxide pad. The wafers were annealed in a rapid thermal annealing system after back metal deposition on the n+ InP substrate. Different types of facet coating layers were deposited to modify the reflectivity of the facets. The design of the facet coating layers depends on the type of the lasers (FP, DFB) and modulation speed.

Fabry-Pèrot (FP) ridge waveguide lasers operating at a wavelength of around 1310 nm were manufactured successfully. These devices are directly modulated and can operate at different frequencies (2.5 Gb/s and 10 Gb/s) depending on the design. Distributed feedback lasers (DFB) with a single mode were also manufactured following the same process sequence with a few modifications in the facet coating layers. The speed of these devices is about 2.5 Gb/s.

FABRICATION OF PHOTODETECTORS

The epitaxial structure of p-i-n photodiode consists of four layers which are (i) a n+ InP bottom contact layer, (ii) a InGaAs i layer, (iii) an undoped InP layer and (iv) an InGaAs top contact layer. All the layers were grown by MOCVD on 100 mm semi-insulating InP substrates. The thickness of the i layer determines the speed and responsivity of the devices. A zinc diffused mesa process was utilized to manufacture p-i-n photodiodes. In the fabrication process, a silicon dioxide layer was used as a mask for selective zinc diffusion, which was carried out inside of a MOCVD reactor. Different wet chemical etch processes were developed to create an InGaAs ring contact layer and mesa structure. The wet chemical mesa etch process provided cylindrical mesas with smooth side walls, which helped to obtain lower dark current and capacitance. Ti/Pt/Au p- ohmic contacts were deposited on the InGaAs ring and AuGeNi/Au n- ohmic contacts were deposited on n+ InP. These contacts were annealed using a rapid thermal annealing system. Silicon nitride was used as a passivation layer as well as an antireflection coating. The thickness of the layer was designed to minimize reflection from the optical window on the device. A BCB layer around the mesa was used to reduce parasitic capacitance. Finally Ti/Pt/Au was deposited to form bond pads on the nitride layer and connect the anode and cathode of the devices to the bond pads. Photodetectors with 3dB band-widths of about 10 GHz and 25 GHz were manufactured using the same process flow but with different i layer thicknesses in the epitaxial structures.

CHARACTERISTICS OF LASERS

The fundamental characteristic of a laser diode is the relation between light output (L) and the injection current (I). Figure 1 shows the L-I curve of a 2.5 Gb/s FP laser device measured at 25 °C. No kinks in the curve indicate absence of any instabilities of the spatial and spectral modes. Threshold current (Ith) of the device is around 8 mA. The calibrated slope efficiency of the device is about 0.48 mW/mA. Figure 2 shows the emission spectrum of the laser observed at a current of about 28 mA. The different longitudinal modes in the spectrum are characteristic of a FP laser [3]. The center wavelength of the spectrum is about 1310 nm.

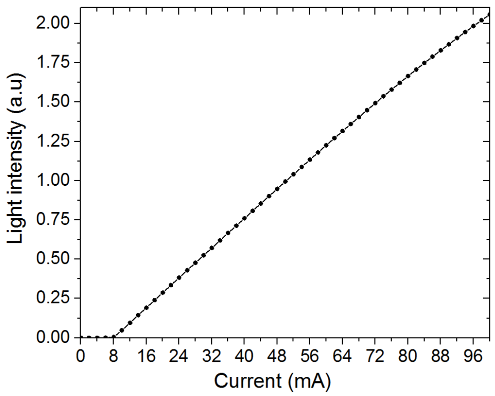

Fig. 1. L-I curve of a 2.5 Gb/s FP laser device.

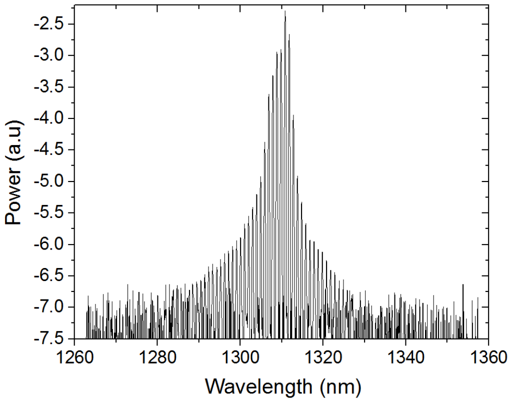

Fig. 2. Emission spectrum of a 2.5 Gb/s FP laser device.

Ridge waveguide 10 Gb/s FP lasers were also manufactured using a shorter ridge length and ridge width than 2.5 Gb/s FP laser devices. The center wavelengths of the devices are about 1310 nm. A boxplot of threshold currents for several 10 Gb/s FP devices from different lots is shown in Fig. 3. The average threshold current is about 6.5 mA at 25 °C. The small variation between wafers and lots indicates good quality of the epitaxial wafers as well as little variation in the process. The small signal optical modulation response was measured on a wafer using an Anritsu VNA and O/E calibration module. Figure 4 shows a series of frequency response curves with increasing bias current at 25 °C. The frequency response increases with the increase of emitted optical power as expected. The 3 dB bandwidth at a current of 45 mA is about 15 GHz. The resonance frequency of

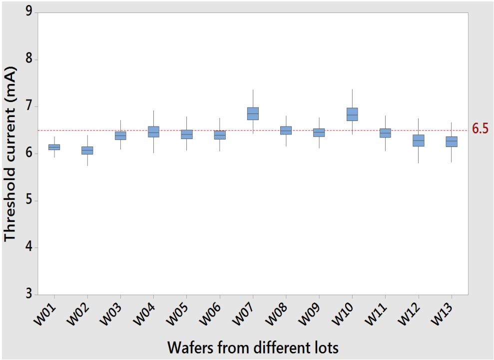

Fig. 3. Box plot of threshold current of 10 Gb/s FP laser devices at 25 °C.

relaxation oscillation was extracted by fitting the frequency response curves, and was found to be around 13.3 GHz. This is well above the requirement for 10 Gb/s operation.

The generation of single longitudinal mode lasers can be accomplished by suppressing unwanted lasing frequencies using an internal Bragg grating [4]. In a DFB laser the Bragg grating is placed along the optical path between the two facets. The two modes closest to the Bragg frequency have similar threshold gain. The reflection from one of the end facets of the laser device changes the gain margin, which enhances single mode emission. The spectrum of a 2.5 Gb/s DFB laser with single mode is shown in Fig. 5. The peak wavelength is about 1310 nm, which agrees well with the period of the grating. The side mode suppression ratio (SMSR) is defined as the ratio of the power of the side mode to the main mode. Figure 5 shows the side mode is suppressed by 46 dB. A box plot of wavelength of different wafers from multiple lots is shown in Fig. 6. A small variation in wavelength and high SMSR indicated good quality of the grating, epitaxial wafers and a stable process. The threshold currents and slopes of the devices at 25 °C are about 12 mA and 0.47 mW/mA, respectively.

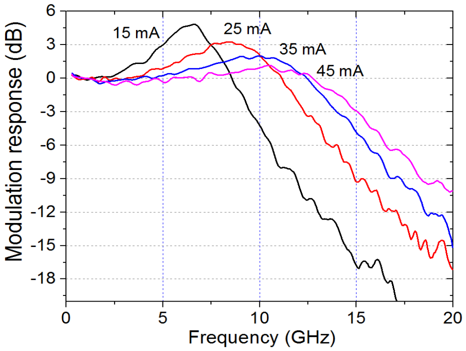

Fig. 4. Small signal response of 10 Gb/s FP laser.

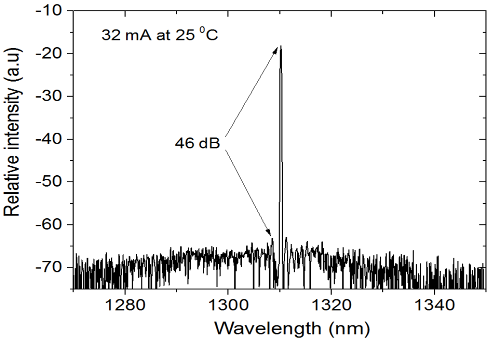

Fig. 5. Emission spectrum of a 2.5 Gb/s DFB laser device.

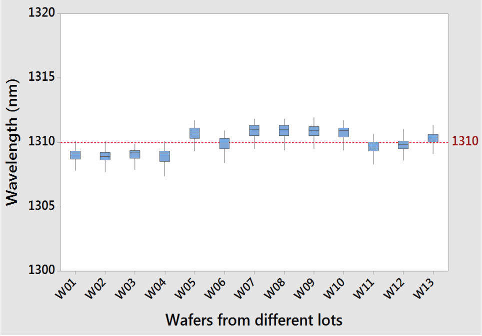

Fig. 6. Box plot of emission wavelength of 2.5 Gb/s DFB lasers at 25°C.

CHARACTERISTICS OF PHOTODETECTORS

Critical device parameters, such as capacitance, dark current and breakdown voltage of the photodiodes, were measured using a DC production test stand and a Keithley parameter analyzer. A box plot of capacitance for multiple wafers from different lots is shown in Fig. 7. The capacitance is around 160 fF at 5V and consistent across many lots. The dark current is about 0.1 nA at 5V. The responsivity of a photodetector is defined by the ratio of the photocurrent to the optical power. The responsivity was measured by directing 1330 nm laser light on to the device through an optical fiber and light wave probe, and was found to be around 0.98 mA/mW at 2V. The frequency response was measured using an Anritsu vector network analyzer, modulator and a laser (1330 nm). The 3 dB bandwidth of a 10 GHz p-i-n photodiode with 45 µm diameter at 5 V is around 10.2 GHz. Several devices were packaged in 2.5 GHz p-i-n TIA to measure sensitivity, and were found to be around -30 dBm. This indicates good quality of the devices.

Front illuminated 25 GHz p-i-n photodiodes were manufactured using the same process flow. Only the thickness of the i layer was thinner than the i layer of 10 GHz p-i-n devices. Photodetectors with different junction diameters and optical windows were fabricated to optimize the device structure for the specified performance. The capacitances of the devices with 30, 28, 26, and 24 µm junction diameters at 6 V are 135.1, 121.6, 109.3, and 97.6 fF, respectively. The decrease of the capacitances is primarily due to the decrease of the area of the device. The 3 dB bandwidth increased from 18.6 GHz to 24 GHz with the reduction of the junction diameter from 30 µm to 24 µm of the devices in GSG (ground signal ground) configuration. The 3 dB bandwidth was also measured on some devices with GS (ground signal) configuration with slightly lower capacitance. The variation of bandwidth as a function of capacitance is shown in Fig. 8. The increase of bandwidth is primarily due to reduction of the capacitance. It is evident that the junction capacitance of about 100 fF at -2.5 V is required to obtain 25 GHz band width. The frequency response of one of the devices with a 23 µm junction diameter and a 18 µm optical window is shown in Fig. 9. The 3dB band width is about 24.5 GHz at 2.5 V.

The average dark current at 5 V is about 0.32 nA. The lower dark current is primarily due to the high band gap InP cap layer [5], which reduces generation recombination current and diffusion current. This is also due to the zinc diffusion process which helps to keep the active junction inside the bulk of the device to reduce the surface leakage. The average breakdown voltage is about 30 V measured at 10 µA. The peak responsivity is around 0.8 mA/mW.

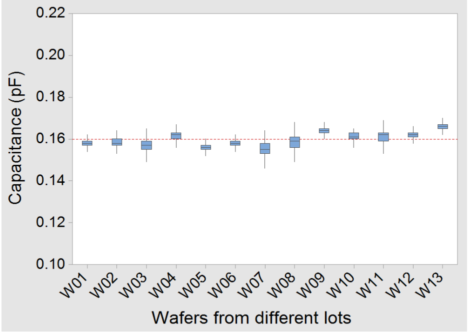

Fig. 7. Box plot of capacitance of 10 GHz p-i-n photodiodes.

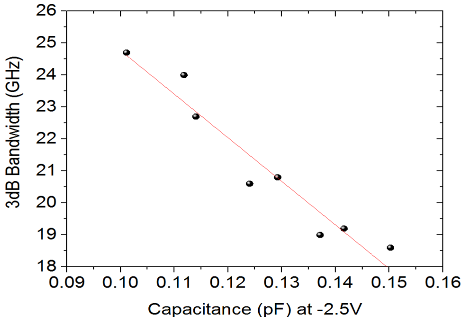

Fig. 8. Plot of bandwidth as a function of capacitance.

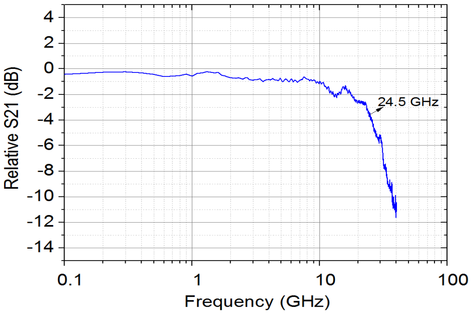

Fig. 9. High frequency response of 25 GHz p-i-n photodiodes.

CONCLUSIONS

FP lasers, DFB lasers and photodetectors with different frequencies were manufactured successfully in a GaAs IC fabrication facility. These devices showed high performance, good repeatability and passed the reliability test.

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ACRONYMS

IC: Integrated Circuit
DFB: Distributed Feed Back
FP: Fabry-Pèrot
SMSR: Side Mode Suppression Ratio
BCB: Bisbenzocyclotene