Characterization of optical loss and carrier lifetime in integrated III-V/SOI distributed feedback lasers

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Characterization of heterogeneously integrated III-V/SOI distributed feedback (DFB) lasers is reported. Based on the measurement results, the taper used to couple the light from the III-V active section to the Si waveguide underneath can lead to an optical loss of about 1 dB per taper. Moreover, heterogeneously integrated lasers based on an InAlGaAs multi-quantum wells (MQWs) active region have at least 50 % shorter carrier lifetime than their InGaAsP counterparts.

introduction

As data rates between processors in modern information processing systems increase, the unprecedented required bandwidth and low power consumption go beyond the capability of the conventional copper interconnects. To address these needs, silicon photonics can be a viable alternative by offering optical interconnects in those advanced electronic systems. It provides advantages in producing integrated circuits (ICs) with higher capacity, lower cost optical interconnects as well as solving electrical interconnect limits in datacenters and supercomputers. It also facilitates the scaling of photonics to high levels of integration with improved performance and better process control at low cost. Moreover, the significant performance of silicon photonics in wavelength division multiplexing (WDM) and scaling to > 1 Tb/s is of great importance [1,2].

There have been lots of progress in developing integrated optical platforms in silicon photonics including passive elements as well as high speed and large bandwidth photodetectors. However, an efficient and reliable integrated laser source has still remained a technology challenge. Due to the indirect bandgap of the silicon, which makes it a very inefficient light source, making an efficient light emitter is the most challenging issue in silicon photonics [3].

The main fabrication procedures of heterogeneously integrated laser diodes on the silicon photonics platform include direct growth on a Si substrate, direct or adhesive bonding, and micro-transfer-printing [4-5]. Some demonstrations of the direct epitaxial growth of III-V compound semiconductors on Si have been reported in [3-4,6]. Regarding the epitaxial growth, the high density of the threading dislocations (TDs) caused by mismatch of lattice constants and thermal expansion coefficients, makes it difficult to achieve high quality layers for efficient lasing. The mentioned phenomenon is a challenging issue in semiconductor lasers with multi quantum wells (MQWs) active region. On the other hand, quantum dot (QD) materials are promising for direct growth on Si, because they have a large tolerance to TDs and work efficiently even in high temperature conditions[3]. However, MQW materials show better performance than QDs in optical interconnects because of their modal volume properties. Consequently, other on-chip devices such as very compact micro-disk lasers as well as vertical cavity surface emitting lasers (VCSELs) with low power consumption and low output power, distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers exhibiting high speed modulation bandwidth and output power up to a few milliwatts have been unveiled mainly by bonding and recently micro-transfer-printing techniques. The developed laser diodes are mainly focused on datacom/telecom applications and operate around the optical fiber communication wavelengths of 1300 nm or 1550 nm. Recently, direct modulation of a III-V-on-silicon DFB laser has been demonstrated at 56 Gb/s [7]. The reported threshold current is about 32 mA and the laser active section is 340 µm long. Despite the good performance, the demonstrated device still needs to be optimized in terms of having much smaller footprint, lower threshold current and higher differential efficiency in order to be an efficient source for low power consumption and low cost transceivers. Other configurations based on external modulation even generate higher bit rates up to 80 Gbps NRZ-OOK [8] and 100 Gb/s Electro-absorptive duobinary [9], but at the expense of larger footprint and extra power consumption.

This paper investigates carrier lifetime characteristics of the MQW active regions used in the devices already developed in our previous works. These MQW structures are mostly based on typical compound semiconductors such as InGaAsP and InAlGaAs grown on InP substrate. Subsequently, in view of the optimization of the device structure for the low power consumption, an experimental study has been performed on the losses of the III-V cavity.

Carrier lifetime characterization

In order to measure the carrier lifetime, first the subthreshold RF reflection coefficient (S_{11}), from which the laser input impedance ($Z_{in}=V/I$) can be extracted, is measured. Here, I is the modulated current and V denotes the corresponding frequency dependent voltage between the contacts. Then the differential carrier lifetimes can be found by fitting the real part of the measured input impedance to the following relation:

$$\mathrm{Re}(Z_{in})=R_s+R_d/(1+\omega^2\tau^2) \qquad (1)$$

where, impedances R_s and R_d are frequency independent series component as well as frequency and bias dependent component, respectively [10]. According to our measurements on carrier lifetimes in various DFB lasers, it is observed that Al-containing MQWs have at least 50% faster recombination for the carriers. Figure. 1 shows the measured lifetime of about 0.33 ns for the InAlGaAs MQW at a bias current of 2 mA while a value of 0.78 ns is obtained for the InGaAsP MQW in the same measurement.

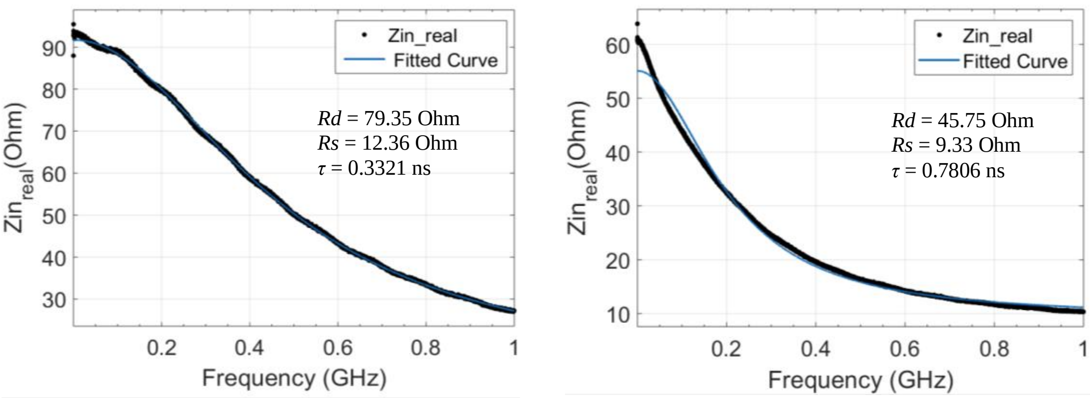

Figure 1. The real part of the measured input impedance of a III-V/SOI DFB laser and the fitted curves at a bias current of 2 mA. InAlGaAs MQW DFB lasers (left) and InGaAsP MQW DFB lasers (right).

Figure. 2 indicates the carrier recombination time as a function of the bias current for two different MQWs active regions in heterogeneously integrated DFB lasers.

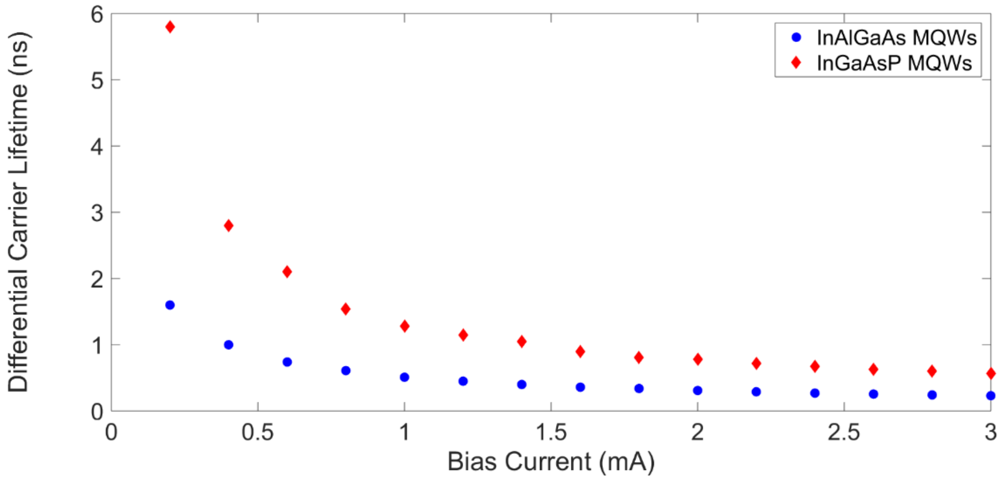

Figure 2. Measured differential carrier lifetime as a function of bias current for InAlGaAs and InGaAsP MQWs.

Optical loss characterization

Concerning the optimization of the device structure for the low power consumption, we also performed an experimental study on the losses of the III-V cavity. Due to the specific configuration of such devices, incorporating tapered waveguides on both III-V and Si substrate is crucial to facilitate the coupling of light from the III-V active region to the Si waveguide underneath. In order to measure the optical loss of the III-V cavity and that of the taper sections, it is necessary to accurately measure the transparency currents of similar lasers with different lengths. Then, the optical loss can be obtained by measuring a fiber to fiber transmission at the transparency currents of the laser diodes with various lengths. To achieve this, we assume that the transmission (T) of a laser diode with the length L is obtained as follows:

$$T = T_1 . T_2 . e^{-\propto_{int} L} \quad (2)$$

here, T_1 and T_2 represent the transmission from the two taper sections incorporated in each side of the laser, and $\propto_{int}$ denotes the intrinsic loss coefficient which mainly originates in scattering and intervalence band absorption (IVBA) in the III-V layers. The setup for the transparency current measurement is depicted in Figure. 3. The transparency current as a function of pump wavelength is measured for two DFB lasers with the length of 300 and 500 μm as shown in Figure. 4. Our measurement results on different structures show 1 to 3 dB loss per taper section and the intrinsic loss of 20 to 40 cm^{-1}.

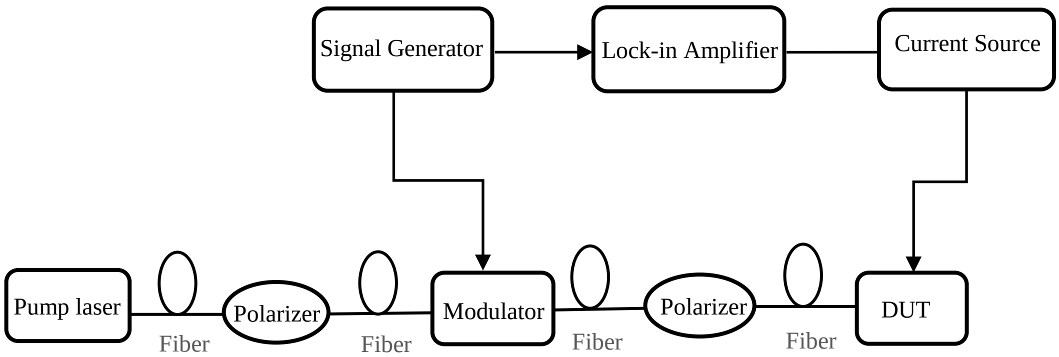

Figure. 3. Block diagram of the setup for the transparency current measurement.

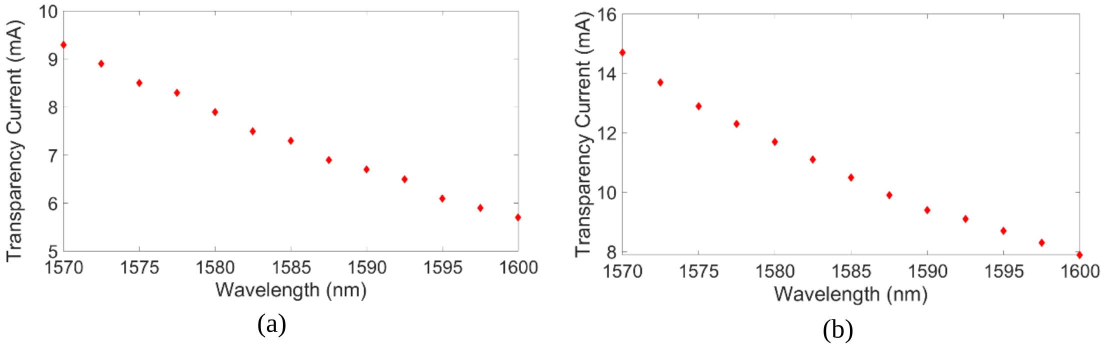

Figure. 4. The measured transparency currents versus wavelength for two heterogeneously integrated DFB lasers with a length of a) 200 µm, b) 400 µm

Conclusion

In this paper, first we have studied the carrier recombination time in heterogeneously integrated III-V/SOI DFB lasers. Our experimental results show that InGaAlAs based MQW lasers have 50 % shorter carrier lifetime in comparison to their InGaAsP counterparts. This specific characteristic of these materials makes them a promising candidate for high speed applications. Subsequently, our experimental results on fiber to fiber transmission at the transparency currents of various laser diodes indicate about 1 dB loss per taper section.

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