# Semiconductor optical amplifiers at 2.0-µm wavelength heterogeneously integrated on silicon

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**Abstract:** We report the first semiconductor optical amplifiers at 2.0-µm wavelength, heterogeneously integrated by bonding an InP-based active region to silicon. On-chip gain larger than 10 dB is observed at 20°C over a 40-nm bandwidth.

**OCIS codes:** (130.3120) Integrated optics devices, (230.4480) Optical amplifiers.

## 1. Introduction

Interests in the spectral region around 2.0-µm wavelength include the detection of molecules such as $CO_2$ and $H_2O$ for industrial process control and environmental monitoring [1-3]. It is also valuable for non-invasive blood glucose measurements [4], laser surgery [5] and represents a promising eye-safe transmission window for optical communications [6]. These applications have triggered the research and development of mid-infrared lasers with various specifications [7]. In particular, the recent demonstration of a 2.0-µm laser heterogeneously integrated on a silicon (Si) wafer [8] is an important step towards low-cost, high-volume and compact photonic integrated circuits (PICs). It leverages the very mature complementary metal–oxide–semiconductor (CMOS) fabrication infrastructures [9], which drive all electronic technologies. The reduced two-photon absorption in Si beyond 2.0 µm and its high Kerr coefficient also make it an attractive platform for future integration with broadband frequency combiners [10] and for parametric nonlinear optics [11-12].

Beside their primary purpose of light amplification, SOAs are basic building blocks for ultra-fast all-optical signal processing, such as wavelength converters, dispersion compensators and optical de-multiplexers [13]. SOAs heterogeneously integrated on Si and designed for 1.55-µm wavelength have recently attracted considerable attention [14-17], even though they were first demonstrated a decade ago [18]. Here we report, to our knowledge, the first 2.0-µm SOAs heterogeneously integrated on Si, which opens up new functionalities for advanced PICs.

## 2. SOA design and fabrication

The design of these 2.0-µm SOAs, as illustrated in Fig. 1, is based on our recently demonstrated 2.0-µm heterogeneously integrated Si lasers [8]. A 500-nm thick partially etched Si rib waveguide is photolithographically defined on an SOI wafer. Four InP-based InGaAs quantum wells are grown (by nLight) with metalorganic vapour phase epitaxy (MOVPE) and bonded to the SOI by plasma-assisted wafer bonding and annealed at 300ºC for 60 min. The InP substrate is removed by mechanical lapping and chemical wet etching. A III-V mesa is formed by methane/hydrogen/argon reactive ion etching (RIE) with a $SiO_2$ hard mask. This mesa is terminated on both sides by a low-reflection lateral tapering of the III–V material to a point, causing the hybrid active mode to couple into a passive Si waveguide mode. Under the III-V mesa, the width $W_{Si}$ of the etched part of the Si rib waveguide varies from 0.5 µm to 2.0 µm for different SOAs. Bottom contacts (Pd/Ge/Pd/Au) are deposited on *N*-InP and top contacts (Pd/Ti/Pd/Au) are deposited on *P*-InGaAs. A current channel is formed by proton implantation, with widths $W_c$ ranging from 4 µm to 6 µm. Devices are electrically isolated with $SiO_2$. The polished Si waveguide facets are antireflective (AR) coated with 1 pair of $Ta_2O_5/SiO_2$ layers with a nominal reflectivity below 0.1 %.

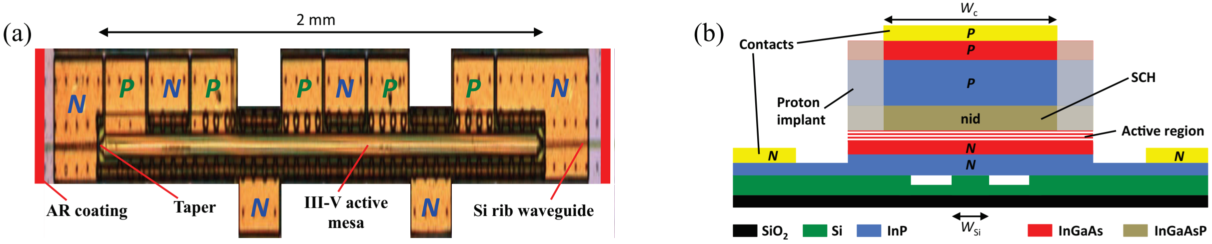

Fig. 1. (a) Top view micrograph of an SOA. The image width is magnified by 4. The *N*- and *P*- contacts are indicated. The 2-mm long III-V mesa terminates with tapers on both sides. Two thick red lines indicate the location of the AR coating layers. (b) Simplified cross-section schematic of the device below the mesa.

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## 3. Experiments and results

The SOAs are mounted on a temperature-controlled Copper stage fixed at 20°C by thermoelectric coolers and a water-cooling system. A source meter (Keithley 2400) is used to inject electrical current in the SOAs. The input light is provided by a 2-µm widely tunable laser (Newport Velocity TLB-6736) coupled into single-mode fibers and passed through an in-line polarization controller to select a TE mode as the input of the SOAs. The laser light is then split with a 5/95 coupler. An integrating sphere with an InGaAs photodiode power sensor (Thorlabs S148C) is connected to one arm of the coupler to monitor the intensity of the input light. Tapered lensed fibers inject and collect the light in and out of the SOAs. The amplified light is then coupled to an optical spectrum analyzer (Yokogawa AQ6375), from which the SOA output power and gain factor are extracted.

The coupling loss between the lensed fibers and the Si waveguide of the SOA is calibrated with the integrating sphere. An expected value of about 10 dB is extracted. The data presented in Fig. 2 are for an SOA with a 0.5-µm wide Si waveguide and a 6-µm wide current channel. Fig. 1(a) shows the measured on-chip gain of the SOA in the small-signal regime at a 2001-nm wavelength. Gain saturation is observed for currents around 330 mA. Fig. 1(b) shows the spectral variation of the small-signal gain at 330 mA. Values above 10 dB are observed over a bandwidth of 40 nm. The gain was also measured as a function of the input power at a fixed wavelength and a fixed current, showing a flat response and no saturation over the available range of input power (–40 dBm to –9 dBm).

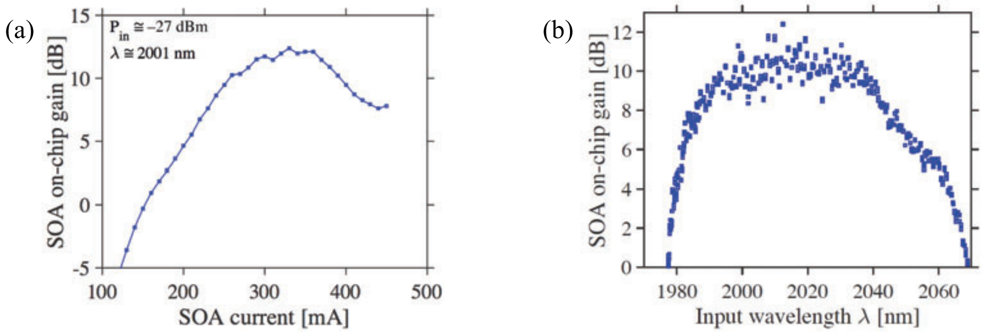

Fig. 2. SOA small-signal (input power $P_{\text{in}}$ = –27 dBm) characteristics. (a) On-chip gain factor measured as a function of the injected current near 2001 nm. (b) On-chip gain spectrum measured at 330 mA.

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