Design and measurement of a reversely biased SOA as high-speed photodetector

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*A reversely biased Semiconductor Optical Amplifier (*SOA*) structure is investigated for its use as a high-speed waveguide pin-photodetector (*WGPD*). The layer stack of the* WGPD *is chosen such that it can be integrated with* SOA *and passive waveguide devices. The optical attenuation of the Q(1.55) absorbing layer embedded between two Q(1.25) layers is measured for a number of* SOA *lengths at the wavelength range of 1520 nm to 1570 nm. The quantum efficiency and 3-dB bandwidth of the* WGPD *for various lengths, p-mesa widths and absorption layer thicknesses are determined.*

Introduction

The integration of the three basic components of optical integrated circuits, passive waveguides, semiconductor optical amplifiers (SOAs) and photodetectors is a significant challenge for researchers [1]. Monolithic integration of the photodetector with a SOA provides the advantage of having higher external quantum efficiency, compensation of on-chip optical loss and fiber-to-chip coupling loss. In addition, the components are self-aligned and the packaging costs can be reduced.

Among the different types of the photodetectors, the pin-WGPD is a suitable choice for the monolithic integration with passive waveguides as well SOAs, since a double-heterostructure pin-WGPD has a cross-sectional structure very similar to SOA and passive waveguide. In literature, integration of the WGPD with SOA and passive waveguide devices such as arrayed waveguide gratings (AWG)and spot-size converters has been reported. Wake *et al.* [2] have presented the first monolithically integrated optical preamplifier with a pin-photodetector on InP substrate with a gain of 20 dB and a bandwidth of 35 GHz. The first integration of an arrayed waveguide grating, a SOA, and an array of photodetectors with a 3.5 GHz bandwidth and a responsivity of 0.5 A/W was reported by Zirngibl [3]. Mason *et al.* [4] demonstrated a 40 Gb/s photonic integrated receiver including a beam expander, SOA, and a pin-photodetector with –17 dBm sensitivity.

In this paper, we describe the use of an SOA structure as a reversely biased pin-WGPD. The SOA's were previously used in a wavelength convertor and in a ring laser [5, 6]. Several static measurements and simulations are carried out on a number of SOA structures with various lengths and reversed bias voltages, to determine the efficiency and bandwidth of the SOA used as a WGPD at a wavelength around 1.55 μm .

Photodetector structure

Fig. 1(left) shows a cross section of the side-illuminated pin-WGPD on an InP substrate. The absorbing layer is a non-doped InGaAsP layer with a bandgap wavelength of λ_g = 1550 nm, Q(1.55), embedded in two non-doped quaternary confinement layers Q(1.25). To form a pin-junction, absorbing layers are surrounded by p- and n-InP cladding layers. A highly p-doped InGaAs contact layer is placed on top of the p-InP cladding layer.

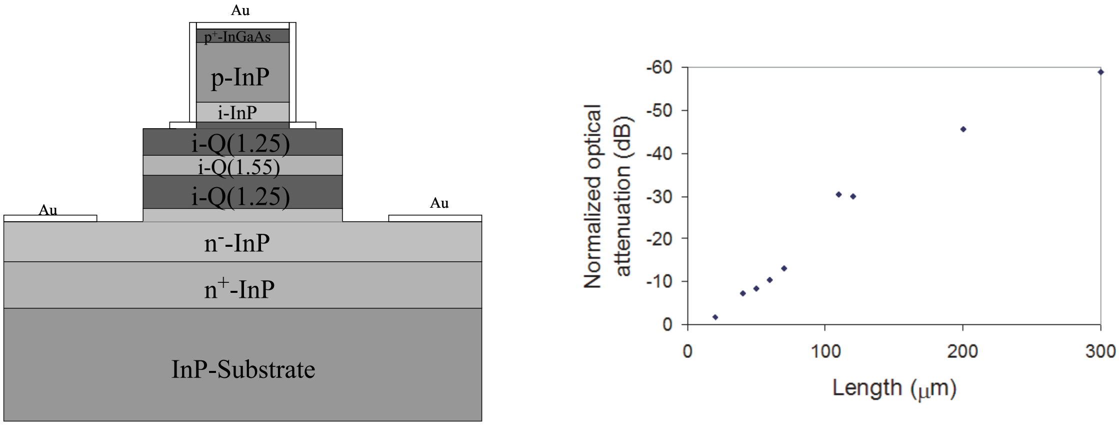

Figure 1: (left) Cross-section of the WGPD. (right) Measured optical attenuation vs. length of the SOA at a wavelength of 1550 nm.

This layer provides a very low-resistance between the p-InP cladding layer and contact metallization layer. In order to have a low-resistance path for the electrons and holes in the n- and p-InP cladding layers and, at the same time, a low-optical attenuation path through the optical waveguide, the layers are gradually doped to reduce the overlap between the optical field and high-doping level regions.

Measurement of the absorption

The three most important features of the WGPD are efficiency, bandwidth, and monolithic integration with passive waveguides. One of the important parameters in the determining the length of WGPD is the optical attenuation in the absorption layer. In order to determine the optical attenuation of the absorption layer, the optical transmission of several reversely biased SOAs was measured as a function of the SOA length. All SOA's were 2 μm wide and had an 120 nm thick Q(1.55) absorption layer. They were butt-coupled to passive waveguides and the total length of the active and passive parts was 3700 μm. For the measurements, optical power from the spontaneous emission spectrum of an EDFA was launched into the SOAs and the remaining power at the output was measured. The excess loss compared to a waveguide with no active section can be attributed to the absorption by the active layer. In fig. 1(right) the normalized optical attenuation as a function of SOAlength is shown. The absorbed optical power in the SOA at a wavelength 1550 nm was found to be about $\alpha = 950$/cm, almost independent of the reverse bias voltage at this wavelength. Using this value, the internal quantum efficiency of the SOA versus the active layer thickness and the SOA-length for a 2 μm wide p-mesa is simulated (see fig. 2(left)). It shows that for a 120 nm thick active layer, 2 μm width of the p-mesa and 90 μm detector length, an internal quantum efficiency of 90% is attainable. The internal quantum efficiency versus wavelength for a 60 μm long detector at three different reverse bias voltages is presented in fig. 2(right), demonstrating that with increasing bias voltage, the dependence of the optical absorption on wavelength is reduced.

Modelling of the WGPD

The 3-dB bandwidth of the WGPD is restricted by both the *RC* and carrier transit time. If we assume that these limitations are independent of each other, a small-signal equivalent-

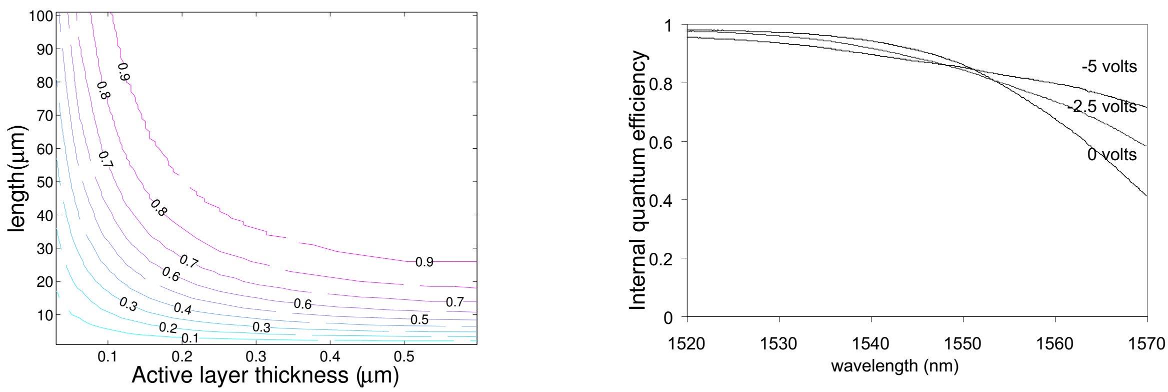

Figure 2: (left) Internal quantum efficiency as function of the active layer thickness and length for a SOA with 2 μm wide and 500 nm waveguide layer. (right) Internal quantum efficiency as function of the wavelength at reversed bias voltage of 0, –2.5 and –5 volts.

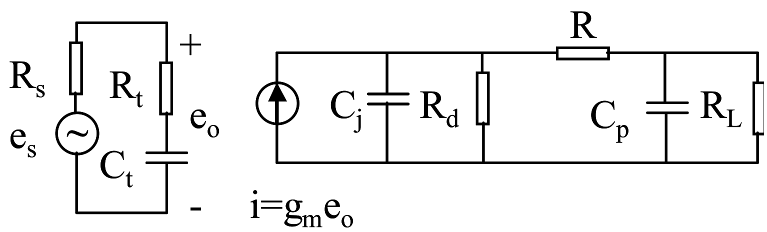

Figure 3: Small-signal equivalent-circuit model of the pin-WGPD.

circuit model of the WGPD comprising the *RC* and transit time elements is extracted to determine the device bandwidth (fig. 3). In this model, the elements of C_j, R_d, R and R_L are junction capacitance, dark current, series and load resistances, respectively. We model the transit time of the carriers across the depletion region (τ_h) as an *RC*-time, with R_t and C_t the equivalent elements determined as $1/(2\pi R_t C_t) = 3.5/(2\pi\tau_h)$ [7]. In addition, we assume that the input optical ac-signal is approximated as an ac-voltage e_s with a resistance of R_s. $e_o(\omega)$ is the delayed voltage of input signal $e_s(\omega)$ due to the transit time delay of electrons and holes flowing through the cladding layers and g_m is a constant adjusted to the opto-electronic conversion quantum efficiency [8].
The 3-dB bandwidth of the WGPD calculated with this model is shown in fig. 4(left) for various depletion layer thicknesses and detector lengths of 10, 60, and 300 μm. The 3-dB bandwidth of the devices peaks at the point where the transit time bandwidth and *RC*-bandwidth are equal. In fig. 4(right), the 3-dB bandwidth of the WGPD versus the detector length and p-mesa width is shown, which illustrates that a bandwidth of 40 GHz is feasible for a 90 μm long device, with a 2 μm p-mesa width and a 120 nm thick active layer.

Conclusion

We have investigated the use of a SOA structure in reverse bias as a high-efficiency and high-speed WGPD. Devices with a 120 nm thick active layer measuring 2×90 μm^2 show sufficient absorption for reaching an internal quantum efficiency of 90%. The model we

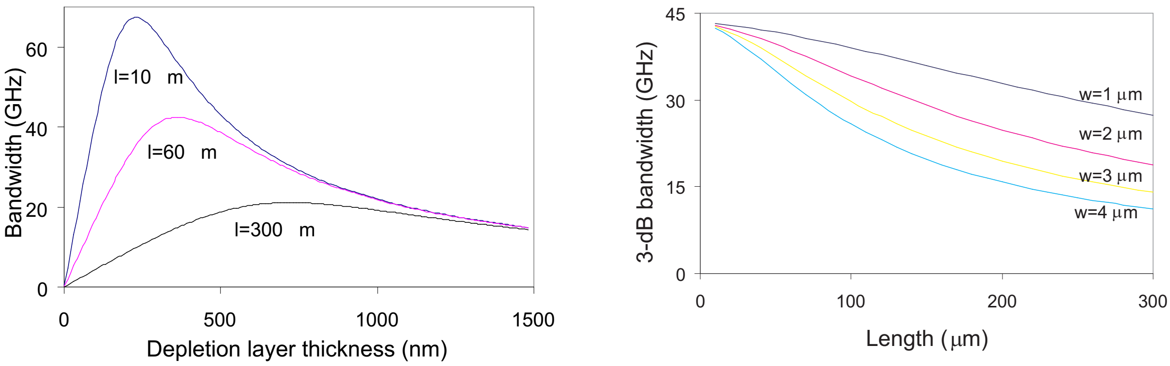

Figure 4: (left) Calculated bandwidth vs. depletion layer thickness for three different lengths and 2 μm width and a 500 nm depletion layer thickness. (right) Bandwidth vs. length for a WGPD with 90 μm length and a depletion layer thickness of 500 nm.

developed predicts a 3-dB bandwith of 40 GHz for this device. Because of the chosen structures, integration of passive waveguide devices with SOAs and high-speed WGPDs is possible, which enables the realisation of a wide range of photonic devices and circuits.

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