An efficient waveguide photodetector fabricated in an InP-based amplifier layer stack

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This article describes the fabrication and characterization of a waveguide pin-photodetector (WGPD) based on butt-joint integration of a passive waveguide and photodetector. The WGPD is fabricated in a layer stack that is designed to be used for an optical amplifier, which now acts as a detector by reversely biasing the pin-diode. The device is fabricated in active-passive material with a technology that uses two epitaxial regrowth steps. The static and high-frequency behavior of the photodetector are characterized and demonstrate a very low dark current of 20 nA at -4 V and an internal efficiency of more than 65% for a 60 μm long device at -5 V bias voltage around a wavelength of 1.5 μm. The output reflection coefficient shows more than 20 GHz bandwidth for a 70 μm long device.

Introduction

One of the main goals for the research on photonic integrated circuits (PIC) is to monolithically integrate passive components, light emitters, semiconductor optical amplifiers (SOA), and photodetectors, making advantage of compactness, low cost, and low optical on-chip and coupling losses. Essential work on the monolithic integration of the passive and active components was carried out before by Nagarajan's group, that fabricated a 40×40 Gb/s transmitter and receiver by integrating arrayed waveguide gratings (AWGs), SOAs, and pin-photodetectors [1, 2]. In that case, the active layer was based on quantum well and on bulk material for the transmitter and the receiver, respectively. It is a great challenge for researchers to realize transmitters and receivers in a common layer stack with low on-chip optical attenuation and also for RF-frequencies up to and beyond 40 GHz. In our previous work, we demonstrated that a reversely biased SOA can be used as a pin-photodetector at RF-frequencies [3]. In this article we report the structure, fabrication scheme and measurement results of WGPDs on semi-insulating (SI)-InP substrate.

Device structure and fabrication

Figure 1 shows a schematic structure of a deeply-etched edge-illuminated WGPD on SI-InP substrate. The pin-WGPD is monolithically integrated with a passive waveguide. The structure of the WGPD is formed by an epitaxial growth of the layers on a SI-InP substrate. The absorbing layer is quaternary InGaAsP, non-intentionally doped, with a bandgap wavelength of 1.55 μm, Q(1.55), and a thickness of 120 nm. The active layer is surrounded by two undoped confinement layers Q(1.25) with a thicknesses of 140 nm and 190 nm to decrease the barrier height and to establish the optical confinement. The p- and n-doped layers are InP material with a graded doping level to reduce the optical loss in the cladding layers and to make a low resistance path for electrons and holes. The n-InP buffer layer is graded with doping levels of $5 \cdot 10^{17}$ and $1 \cdot 10^{18}\,/\mathrm{cm}^3$ for 200 and 900 nm and the p-doped layer is graded with doping levels of $1 \cdot 10^{17}$, $3 \cdot 10^{17}$, $5 \cdot 10^{17}$ and $1 \cdot 10^{18}\,/\mathrm{cm}^3$ for 50, 200, 300, and 1000 nm thicknesses, respectively. A highly p-doped InGaAs layer on top of the p-InP cladding layers is used for obtaining good ohmic contacts. The p- and n-electrodes were designed based on a coplanar waveguide (CPW) structure.

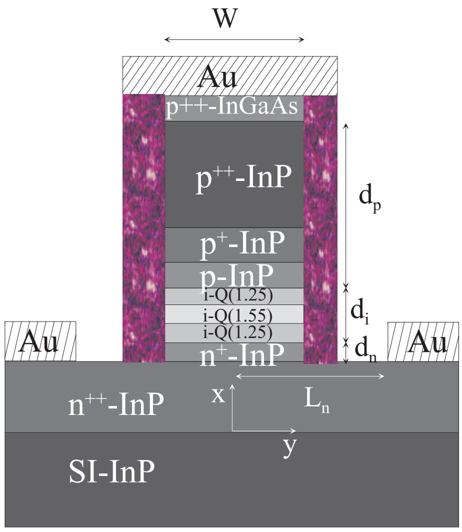


Figure 1: Schematic structure of the WGPD.

The structure of the passive waveguide consists of a 500 nm n-Q(1.25) guiding layer with a doping level of $6 \cdot 10^{16}\,/\mathrm{cm}^3$ and an n-InP cladding layer identical to the WGPD, and the p-InP cladding layers with the doping level of n.i.d., $3 \cdot 10^{17}$, $5 \cdot 10^{17}$ and $1 \cdot 10^{18}\,/\mathrm{cm}^3$ for 50, 200, 300, and 1000 nm thicknesses, respectively.

The monolithic integrated passive waveguide and WGPD were fabricated in a MOVPE grown layer stack. After growth, the passive waveguide and the WGPD were etched in several steps using reactive ion etching (RIE) process. Then polyimide layers were spun and baked to planarize the surface and passivate the sidewalls of the photodetectors. The polyimide was etched back using CF_4/O_2 gases to create contact openings for the WGPDs. Ti/Pt/Au metallization was applied by e-beam evaporation. Finally, a 1.5 μm thick layer of Au was electroplated to have low RF-attenuation.

Characterization

Static and RF-measurements were carried out on the WGPDs. The static characterization includes measurements of the dark current and of the responsivity of the photodetectors at different biasing voltages and wavelengths. The RF-measurements are carried out to determine the 3-dB bandwidth of the photodetectors through the output reflection coefficient (S_{22}) and RF-responsivity.

Static measurement — The dark current of the WGPDs was measured by sweeping the bias voltage from -4 V to 0.5 V, as shown in figure 2 for 40, 60, 500, and 1000 μm long devices. The dark current is less than 20 nA at bias voltages down to -4 volts.

The static responsivity of the photodetectors was determined by launching an optical power of -10 dBm from a tunable laser and measuring the photocurrent through two needles placed on the p- and n-electrodes of the reversely biased WGPD using a Keithly source-current meter. The wavelength of the tunable laser was swept from 1440 to 1600 nm. By considering the optical fiber and connector losses of 0.5 dB, fiber-chip coupling loss of 4 dB and having previously evaluated a passive waveguide loss of 2 dB/cm,

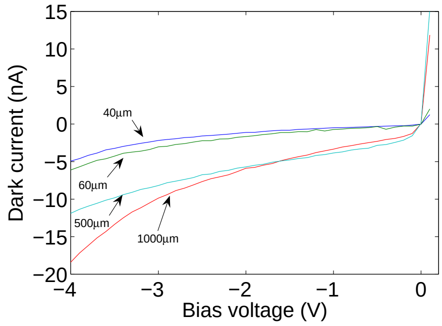
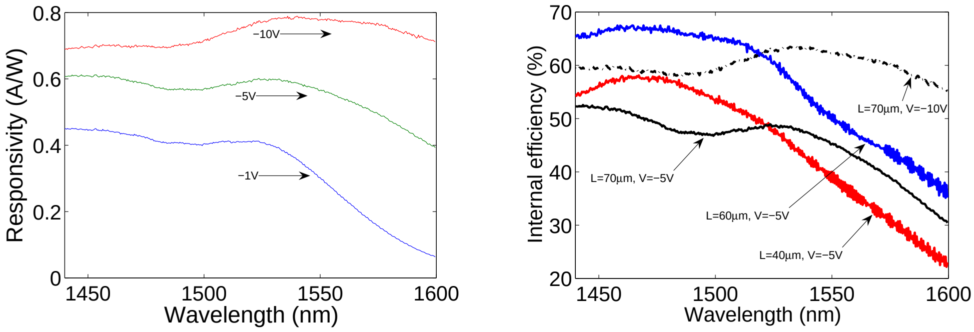


Figure 2: Dark I-V curves for several photodetectors.



(a) (b)

Figure 3: (a) Internal responsivity as a function of wavelength for a 70 μm long photodetector at bias voltages of -10, -5, and -1 volts. (b) Internal efficiency as a function of wavelength for several WGPDs and bias voltages.

the PD internal responsivity was determined. The internal responsivity of a 70 μm long WGPD is shown in figure 3-a at biasing voltages of -1, -5, and -10 V. As it can be observed in the figure, the responsivity decreases after the bandgap wavelength of absorber (Q1.55), 1.55 μm, as it is also described in [3]. By increasing the reverse voltage from -5 to 10 V, the depletion layer broadens and more photons are absorbed, which results in a higher responsivity.

The internal efficiency as a function of wavelength for 40, 60 and 70 μm long photodetectors is shown in figure 3-b. Moreover, a responsivity increase of 5% can be noticed for a 70 μm long photodetector when increasing the bias voltage from -5 to -10 V, thus causing a broadening of the depletion layer.

RF-measurements — The electrical response of the WGPDs was measured to evaluate the 3-dB bandwidth of the photodetectors. The output reflection coefficient of the WGPDs was measured with a lightwave component analyzer in the frequency range of 130 MHz to 20 GHz. To evaluate the device RF performance, the parasitic effects caused by RF-cables, bias-tee, adaptors and RF-probe were de-embedded by following standard measurement methods reported in [4] .

The output reflection coefficient $|S_{22}|$ of several photodetectors was measured at a bias voltage of -5 V, as shown in figure 4, and a 3-dB cut-off point above 20 GHz for the short devices (70 and 110 μm) and below 20 GHz for the long PDs (400 and 900 μm) was

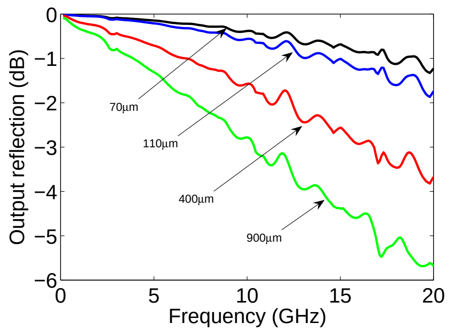


Figure 4: Output reflection coefficient vs. frequency for several photodetectors at -5 V bias voltage.

registered.

Conclusions

We realized WGPDs that have been characterized to evaluate the dark current, efficiency and 3-dB bandwidth. The measurement results demonstrate a very low dark current, about 20 nA at -4 bias voltage, and more than 65% internal efficiency for a 60 μm long device at -5 V bias voltage and 1.5 μm wavelength. The output reflection coefficient shows a bandwidth of more than 20 GHz for 70 and 110 μm long detectors.

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