Transparent In-line Optical Power Monitor Integrated with MOS Optical Phase Shifter using InP/Si Hybrid Integration

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Abstract *We demonstrate a transparent in-line optical power monitor using an InP-based phototransistor monolithically integrated with an InP/Si hybrid MOS optical phase shifter. The trap-mediated photodetection and amplification by phototransistor enables photodetection down to -44 dBm with an optical insertion loss of <0.25 dB. ©2023 The Author(s)*

Introduction

Si programmable photonic integrated circuits (PICs) offer many promising applications, such as computation and sensing [1]. In a programmable PIC, numerous 2×2 Mach-Zehnder interferometers (MZIs) with optical phase shifters are commonly used to reconfigure the functionality of a PIC. The splitting ratio of the MZI can be electrically tuned with optical phase shifters by controlling the optical phase of the propagating light in a Si waveguide. Therefore, accurate control of phase shift values at each phase shifter is necessary to reconfigure PICs for specific purposes. However, fabrication variations or environmental temperature change inevitably induce phase errors into a PIC. Thus, the phase values need to be accurately calibrated by optical power monitoring and feedback control.

One promising method to calibrate phase shifters to compensate for phase errors, in terms of simplicity and ease of integration, is monitoring the output optical power of each MZI directly. A non-invasive monitoring method called CLIPP [2] uses the conductance change of a Si waveguide under light propagation to directly measure the optical power in Si waveguides, and real-time power monitoring and feedback control have been successfully demonstrated [3]. Although this method is attractive in terms of low-loss power monitoring and ease of integration with complementary metal-oxide-semiconductor (CMOS) compatibility, the least measurable optical power is relatively high, and the signal readout system requires complex electronic circuits. To solve these issues, we have proposed a metal-oxide-semiconductor field-effect-transistor (MOSFET)-based phototransistor called photoFET with ultrathin InGaAs membrane [4]. Although this InGaAs-based photoFET enables the direct detection of an extremely weak light owing to the ultrahigh responsivity, the measured insertion loss was still high (>1 dB) for the use as a practical power monitoring in PICs.

In this paper, we propose a transparent in-line optical power monitor based on a waveguide-coupled photoFET using an ultrathin InP membrane, which can be monolithically integrated with an energy-efficient InP/Si hybrid MOS optical phase shifter [5, 6]. As shown in Fig. 1, an n-type InP membrane is bonded on a p-type Si rib waveguide with Al_2O_3 gate dielectric. For a photoFET, the InP membrane with source/drain contacts works as a transistor channel. The trap-mediated absorption in the InP channel enables photodetection even using a wide-bandgap InP. Owing to the transistor gain achieved by effective gating through a Si waveguide, a weak incident light can be detected with a minimal insertion loss. Here, we experimentally demonstrate an InP-based waveguide-coupled photoFET and successfully monitor the output of an MZI monolithically integrated with an InP/Si hybrid MOS optical phase shifter.

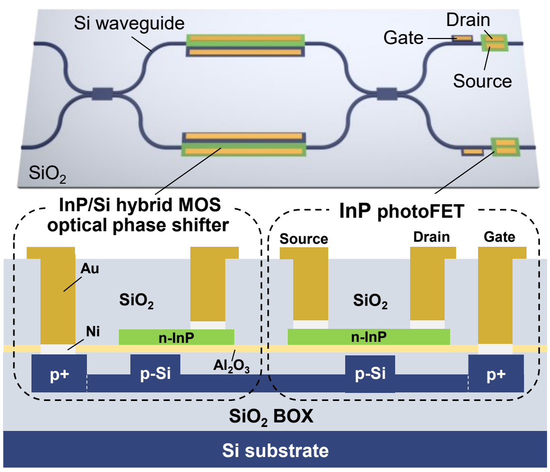

Fig. 1: A schematic of InP phototransistor integrated with InP/Si hybrid MOS optical phase shifter.

Device fabrication

An InP photoFET and an InP/Si hybrid MOS optical phase shifter were monolithically

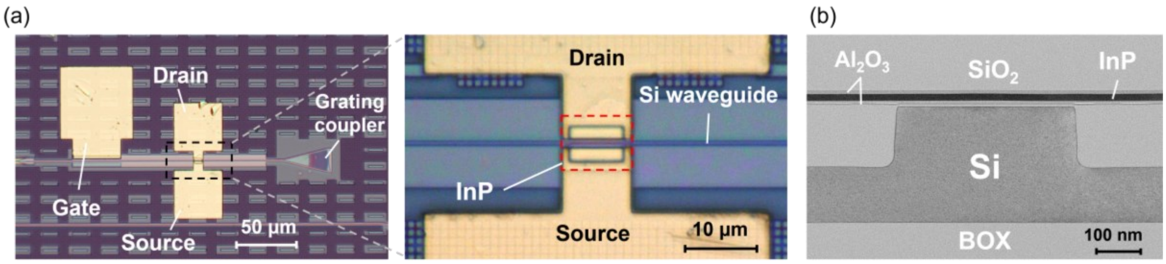

Fig. 2: (a) Plan-view microscopy images and (b) TEM image of InP photoFET.

fabricated as follows. After bonding a 20-nm-thick n-InP (N_D = 5×10^{17} cm^{-3}) layer on an SOI wafer including a 300-nm-thick p-type Si rib waveguide via 8-nm-thick Al_2O_3, InP mesas were defined by electron-beam (EB) lithography and reactive ion etching (RIE). Subsequently, 8-nm-thick Al_2O_3 and 650-nm-thick SiO_2 layers were deposited for surface passivation. Finally, contacts for n-InP were formed by a Ni/Au metal stack through EB evaporation and lift-off process. Figures 2(a) and (b) show the plan-view microscopy images and cross-sectional transmission electron microscopy (TEM) image of an InP photoFET, respectively.

FET characteristics

We first measured the electrical characteristics of fabricated devices without light injection. Figure 3(a) shows the drain current (I_d) – drain voltage (V_d) characteristics at different gate voltages (V_g) ranging from -1 V to 2 V for a representative device with a channel length of 50 µm and a channel width of 1 µm. I_d saturated with the increase in V_d, suggesting a good operation as a transistor. Figure 3(b) shows I_d–V_g characteristics at V_d = 0.5, 1 V. We observed a drain current on/off ratio of approximately 10^4, suggesting that the Si waveguide gating effectively controls the transistor channel.

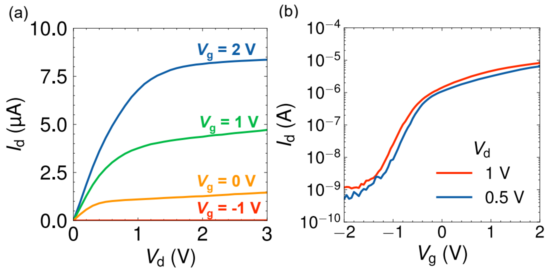

Fig. 3: (a) I_d–V_d characteristics at different V_g from -1 V to 2 V. (b) I_d–V_g characteristics at V_d = 0.5 V, 1 V.

Photoresponse

We characterized the photoresponses of a 10-µm-long InP photoFET with a continuous-wave (CW) light at 1550 nm wavelength from a tunable laser source. The light was injected into a photoFET via a grating coupler, and the input power was controlled by an optical attenuator. By the cutback method, the propagation loss of a Si waveguide and the insertion loss of a grating coupler were estimated to be 1.6 dB/cm and 2.6 dB, respectively. Figure 4(a) shows I_d–V_d characteristics under various input light powers. Note that the input power is defined as the light power injected to the photoFET here. Even with a weak light of -44.0 dBm, a clear photocurrent was observed, showing a better sensitivity than that of CLIPP [2]. Figure 4(b) illustrates the responsivity as a function of the incident light power, showing a nonlinear relationship. The photogating effect is dominant when the transistor is in the on state, i.e., $V_g \geq 0$ V [7]; as a result, the responsivity becomes 1.7 A/W at an incident light of <1 µW, indicating the amplification of photocurrent by phototransistor.

Subsequently, the tunable laser was directly modulated by an electrical waveform generator to measure the time response of a 50-µm-long photoFET. Note that the rise time and fall time of the modulated input light signal was within 1 µs. When V_g is -1 V and V_d is 1 V, the rise time and fall time of the photoFET were 69 µs and 104 µs, respectively, which is sufficiently fast as a power monitor for applications such as monitoring the spritting ratio of MZI for the calibration.

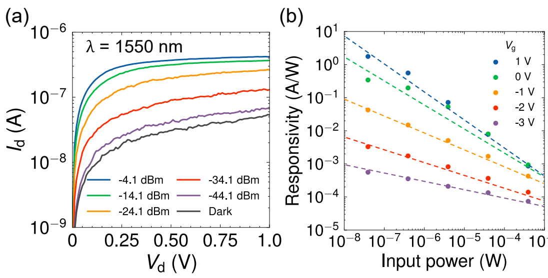

Fig. 4: Photoresponses of a 10-µm-long InP photoFET under 1550-nm-wavelength light injection. (a) I_d–V_d characteristics at V_g = 0 V. (b) Responsivity as a function of injected light power at V_d = 1 V.

Insertion loss

We measured the transmission of InP photoFETs and evaluated the insertion loss at 1310 nm and 1550 nm wavelengths, as shown in Fig. 5. Note that the insertion loss of a grating coupler and the propagation loss of the Si waveguide were subtracted for the evaluation. The insertion loss of ultrathin-InGaAs-based photoFETs is also shown as a reference. The fitting results show that the insertion loss per unit length of an n-InP photoFET is 0.017 dB/μm at 1310 nm wavelength and 0.023 dB/μm at 1550 nm wavelength, which are significantly smaller than the 0.12 dB/μm of InGaAs photoFETs. The optical loss induced by the optical mode mismatch is negligibly small owing to the ultrathin InP channel [5]. As a result, the insertion loss of the 10-μm-long photoFET shown in Fig. 4 is <0.25 dB, suggesting the proposed InP photoFETs can be used as transparent in-line optical power monitors at infrared wavelengths. From this result, the internal quantum efficiency was calculated to be 2700 % when the incident light was -44 dBm and V_g = 1 V due to the amplification of the phototransistor. Part of the insertion loss is expected to originate from the light absorption by metal contacts due to misalignment. Therefore, the insertion loss can be further reduced by improving the fabrication process.

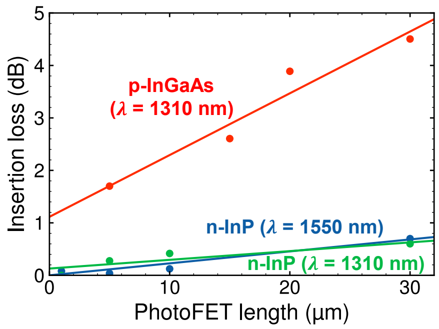

Fig. 5: Insertion loss of InP photoFET as a function of the device length at 1310 nm and 1550 nm wavelengths.

Monolithic integration with MOS phase shifter

An InP photoFET and a 1×1 asymmetric MZI with an 875-μm-long InP/Si hybrid MOS optical phase shifter were monolithically integrated, as shown in Fig. 6(a). To evaluate the charcteristcs of the optical phase shifter, the transmission spectum at diffrent gate voltages were measured. Note that the voltage applied to InP (V_{InP}) was 0 V here. As shown in Fig. 6(b), a clear wavelength shift of the resonance peak was observed due to the electron accumulation at the InP MOS interface. At a wavelength of 1564.8 nm, where the resonance peak at V_g = 0 V was observed, the transmission changed from -38.4 dBm to -16.6 dBm when V_g was changed from 0 V to 5 V.

To demonstrate the operation of an InP photoFET as an in-line optical power monitor, CW light at a wavelength of 1564.8 nm was injected to the MZI. Here, V_g was set to -1 V to reduce the dark current while maintaing relatively large photocurrent, and V_g was shared by the phase shifter and the photoFET. Therefore, V_{InP} was offset by -1 V to apply a specific voltage to the phase shifter. We changed the voltage applied to the phase shifter ($V_g - V_{InP}$) and measured the transmission of the MZI and the drain current of the photoFET. As shown in Fig. 6(c), the photocurrent clearly increases with the increase in the transmission of MZI, sucessufully demonstrating that the proposed photoFET can be used as an in-line optical power monitor.

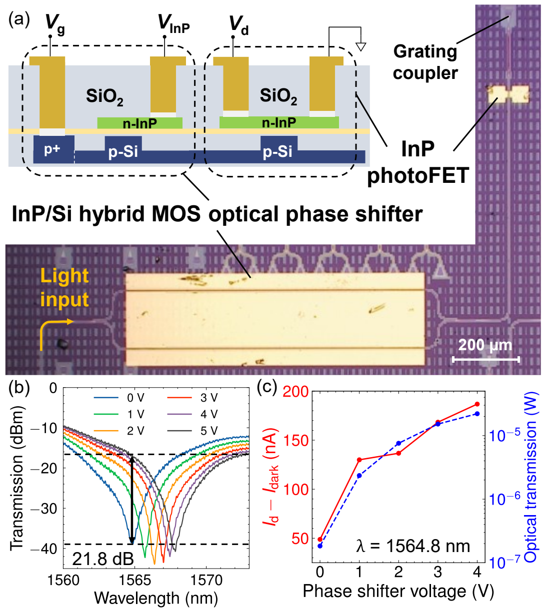

Fig. 6: (a) A Schematic and a microscopy image of a monolithically integrated InP photoFET and MZI with InP/Si hybrid MOS optical phase shifter. (b) Measured transmission spectra of the phase shifter at different V_g. (c) I_d and optical transmission at V_d = 1 V as a function of the voltage applied to the optical phase shifter.

Conclusions

We proposed a transparent in-line optical power monitor using an InP-based phototransistor. The detection of light down to -44 dBm was achieved with <0.25 dB insertion loss owing to the trap-mediated photodetection and the amplification by phototransistor. Furthermore, we monolithically integrated the phototransistor with an InP/Si hybrid MOS optical phase shifter, demonstrating the direct optical power monitoring of the output light intensity of the MZI over two orders of magnitude. This result is promising for energy-efficient PICs using III-V/Si hybrid integration.

Acknowledgements

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