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Compact amorphous-silicon visible-light monitor integrated in silicon nitride waveguides

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***Abstract*—This work reports on the realization of an amorphous silicon visible-light detector integrated in Si_3N_4 waveguides. The device is very compact (< 40 µm), has a responsivity of about 10 mA/W and a sensitivity of -40 dBm.**

Keywords—optical waveguides, amorphous silicon, integrated detectors, visible light, photonic integrated circuits

I. Introduction

Visible-light is a spectral region of much interest for many applications such as imaging, metrology, biosensing, nanomedicine and quantum optics. In this wavelength range, Silicon Nitride (SiN) is one of the most established high-index-contrast photonic platforms, offering a good tradeoff between low propagation loss and high integration scale [1]. In order to make photonic integrated circuits evolve towards more complex programmable architectures [2], it is necessary to monitor the working point of the photonic device by means of on-chip in-line light detectors.

Amorphous silicon (a-Si) is widely used in the visible range for the realization of opto-electronic devices, such as in photovoltaic applications. In integrated optics, a-Si is employed to realize optical waveguides for the near-infrared range where it is almost transparent, but in the visible range it is still largely unexploited. The integration of an a-Si detector on a lithium niobate waveguide on silicon has been recently demonstrated at 850 nm wavelength [3]. In this work, we exploit the photoconductivity of an a-Si film deposited as a coating layer of a SiN waveguide to realize a compact in-light photodetector operating in the red-light range. A sensitivity down to -40 dBm with a responsivity of 10mA/W is demonstrated.

II. Assessment of a-Si Photoconductivity

The a-Si layer was deposited with a Silane based PECVD deposition: the presence of SiH_4 will ensure the hydrogenation of the a-Si film, at the base of the photoconductive properties of amorphous the Silicon films [4]. An optimization process was performed in order to maximize the absorption coefficient of the a-Si film in the entire visible range of wavelengths in order to achieve the highest photoconductive response of the material. Material deposition was carried out with an RF power of 50W at 13.56MHz, a chamber pressure of 500 mTorr and a substrate temperature of 300°C.

The photoconductivity of the a-Si thin film at a wavelength $\lambda = 660$ nm was assessed by means of the vertically-illuminated test device shown in Fig 1(a). The Au/Cr electrodes were realized through a lift-off process, by using direct laser writing lithography followed by a thermal evaporation process. As shown in Fig. 1(b), the light beam is vertically shone on the photoconductive film from a single-mode optical fiber, while two metallic probes are used to feed the device electrodes with the bias voltage and to read the light-dependent current through a lock-in read-out scheme. The I-V characteristics was firstly measured in DC in dark condition, this measurement providing a dark conductivity of the a-Si film of about 10^{-7} S/cm. Upon illumination see [Fig. 1(c)], we observed a dynamic range in the measured power intensity higher than 40 dB (from -50 dBm to -10 dBm), this change being responsible for a variation of more than three orders of magnitude in the a-Si conductivity (quantified in about 10^{-4} S/cm for -9 dBm input power). The slight sublinearity in the current-power characteristic is due to the reduction of the free-carrier lifetime in the a-Si film at high carrier generation rate, that is at higher photon flux) [4].

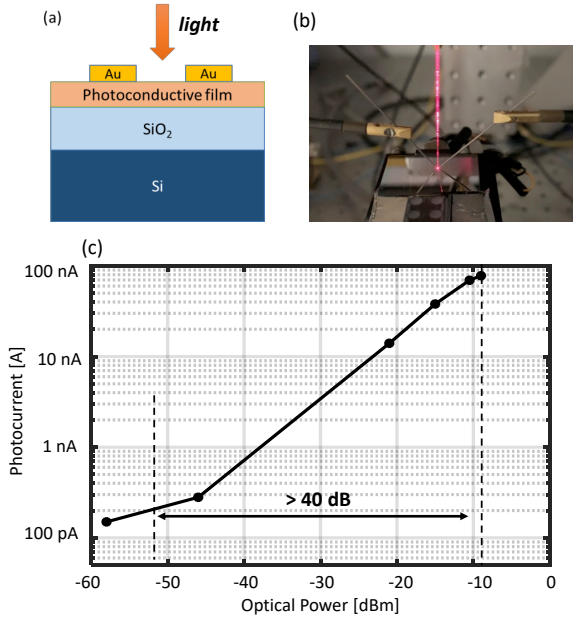

Figure 1. (a) Schematic of the vertically-illuminated device for the assessment of a-Si photoconductivity. (b) Photograph of the experimental setup. c) Photocurrent measured in vertically-illuminated test devices (electrode size 200 µm x 200 µm, electrode spacing 20 µm) for increasing optical power at a wavelength of 660 nm (red light).

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This effect is responsible for a reduction of the responsivity at higher optical power; however, at maximum optical power of -9 dBm, a photocurrent of 80 nA is measured (20 μm electrode spacing, 8V applied voltage) resulting in a responsivity of about 5 mA/W, which is close to recently reported results for a-Si photoconductors [3].

III. A-SI DETECTOR INTEGRATED IN Si_3N_4 WAVEGUIDES

Figure 2(a) schematically shows the longitudinal geometry of the a-Si detector integrated in Si_3N_4 waveguide. The hydrogen silsesquioxane (HSQ) upper cladding of a buried channel waveguide (Si_3N_4 core 400 nm x 200 nm) is locally lowered in order to enable the deposition of a thin film of a-Si at a suitable spacing from the waveguide in order to introduce a controllable absorption of the guided light. Electromagnetic simulations based on the beam propagation method (BPM) show that the evanescent coupling between the fundamental transverse electric (TE) mode and a 200 nm thick a-Si film coating layer at a distance of 200 nm provides 4 dB absorption over 100 μm propagation length. Figure 2(b) shows a top view micro-photograph of a fabricated device. Selective removal of the HSQ upper cladding was performed by direct laser writing optical lithography followed by reactive ion etching in CHF_3/O_2 mixture. Once deposited, the a-Si is then patterned by direct laser writing optical lithography and then dry etched in SF_6/O_2 mixture. On top of the a-Si film a pair of electric contact pads (4 μm spacing, 15 μm width) were fabricated by lift-off technique using a direct laser writing optical lithography followed by the deposition of 150 nm of gold with a small adhesion layer of chromium. The bonded pads are kept as far as possible in order to avoid unwanted capacitances, while the two golden paths are kept very close in order to minimize the resistive path of the current in the a-Si.

The laser source is butt-coupled to the waveguide device by using a horizontal alignment optical setup. The optical fiber has a mode field diameter of about 3.5 μm (+/-0.5) providing a coupling loss of about 10 dB/facet with the optical waveguide if no mode adapters are realized at the waveguide termination. In order to reduce the parasitic capacitances due to the electrical probes, the sample was wire bonded to an electrical. Figure 2(c) shows the measured photocurrent versus the frequency of the lock-in read-out electronics for different optical power in the detector region. The plateau in the low-frequency side of the curves provides the light dependent change of the photocurrent due to the photoconductivity of the a-Si film, whereas the high frequency behavior is dominated by the parasitic capacitance between the metallic pads. The black line provides a reference dark current of 65 pA (at 8 V applied voltage). When the light beam is switched on, a photocurrent of about 4 nA is measured (red line), with an estimated power at the sensor of –30 dBm. and an absorption of 2 dB. This photocurrent corresponds to a responsivity of about 10 mA/W, that is similar to the one we obtained for the vertically illuminated device. The maximum frequency of the detector is currently set by the parasitic capacitance limiting the operational bandwidth to 1 kHz at -30 dBm, which is however in line with typical monitoring operation but that can be used down to almost -50 dBm with longer reading time

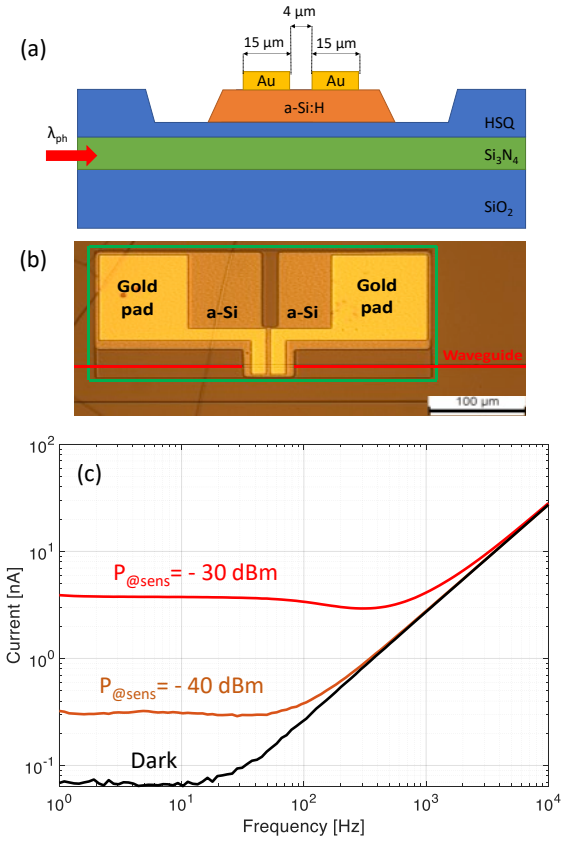

Figure 2. (a) Schematic of the a-Si detector integrated in a Si_3N_4 waveguide; (b) Top view photograph of a fabricated device; (c) Measured photocurrent versus the frequency of the electrical lock-in read-out for increasing optical power at the detector: dark condition (black curve), -40 dBm (brown), and – 30 dBm (red curve).

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