

Optical characterization of a leaky-mode polysilicon photodetector using near-field scanning optical microscopy

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Abstract: Near-field scanning optical microscopy was used to characterize the light absorption capability of a leaky-mode coupled polysilicon photodetector fabricated for CMOS on-chip optical interconnects. The observed results are in good agreement with the modal calculations.

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1. Introduction

While optics is likely to impact chip-to-chip communications longer than ~ 10 cm in the near future, even many optical interconnect enthusiasts are skeptical about the prospects for on-chip optical interconnects. We are developing an optical clock distribution system for high-end processors using off-chip low-jitter sources that can be implemented in commercial CMOS as a platform for investigating on-chip optical interconnects [1]. To minimize barriers to adaptation of this technology, only materials already present in CMOS chips are being used to implement the necessary components. In particular, waveguide cores are constructed from SiN_x used for copper encapsulation; low-k dielectrics used between metal interconnect layers serve as the cladding, and polysilicon films currently used for resistors or gates are adapted for photodetectors. CMOS chips containing functioning optical waveguide H-trees and polysilicon based photodiodes have been fabricated. This paper presents initial characterization and modeling results on the waveguide coupled, leaky-mode polysilicon photodiodes which demonstrate power absorption in excellent agreement with simple modal projection and effective index calculations.

2. Fabrication

The waveguide and photodetector were fabricated in a commercial $0.35 \mu\text{m}$ CMOS technology at the Avago Technologies (formerly a part of Agilent) facility in Fort Collins. The MSM photodiode and waveguide structures, shown in cross-section in Fig. 1, is obtained by following a sequence of steps similar to those employed in conventional CMOS gate, dielectric, contact, and first layer metal deposition, etching, and chemical-mechanical polishing processes. Details will be provided at the presentation. The resulting leaky-mode coupled, polysilicon metal-semiconductor-metal photodiodes are 400 nm thick and contacted with tungsten filled vias. A 350 nm thick SiN_x ($n=1.8$) waveguide core is $0.5 \mu\text{m}$ wide and completely surrounded by of phosphosilicate glass (PSG, $n=1.45$). The relatively thin upper cladding (250 nm) allows a near-field scanning optical microscope (NSOM) to measure the optical intensity distribution along waveguides. After sawing, chips were edge polished to allow end-fire coupling of visible single mode fibers ($4/125 \mu\text{m}$ core/cladding diameter) to waveguides that lead to the detectors. A bias voltage creates an electric field oriented perpendicular to the direction of light propagation. The distance between the inner edges of the rows of contacts is restricted to a minimum of approximately $1.1 \mu\text{m}$ for the $0.35 \mu\text{m}$ design rules used here but scales with the CMOS technology generation to allow lower bias voltages in future devices.

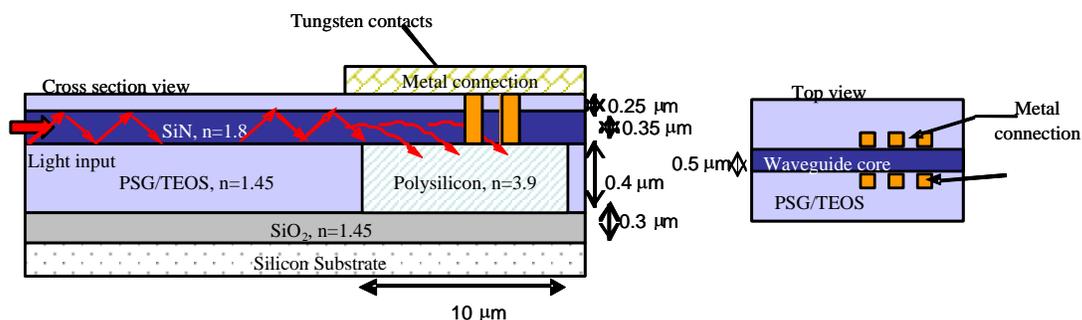


Fig. 1. Longitudinal cross-section of the waveguide and photodetector structure with top view shown in the inset.

3. Modal calculations

In order to analyze leaky-mode coupling to the photodiodes, propagation modes in both regions with and without the polysilicon layer were calculated using simple numerical eigenmode solutions. At a wavelength of 654 nm, the bound TE_{00} mode of the waveguide has a propagation constant $\beta_1=1.61k_0$, where k_0 is the wave vector in free space. When light enters the detection region, the original bound TE_{00} mode is projected onto a series of new modes, which are supported by the new index profile. Overlap integrals show more than 92% of the incident optical power is converted into a leaky silicon nitride mode with propagation constant $\beta_2=(1.65+i.00056)k_0$, where the absorption constant for polysilicon is taken as $\alpha=2400\text{ cm}^{-1}$. The imaginary portion of the propagation constant determines the dissipation rate of the optical power moving along the waveguide and coupling into the polysilicon. Based on these calculations, the estimated effective absorption coefficient for the leaky-mode coupled detector is $0.47\text{dB}/\mu\text{m}$. These calculations were made prior to the NSOM experiments described next.

4. Experimental results

In order to characterize the actual light absorption in the leaky-mode coupled photodetectors, a near-field scanning optical microscope (NSOM) from WiTec was used to measure the optical intensity along the waveguide. Fig 2(a) shows the intensity over a $10\ \mu\text{m} \times 25\ \mu\text{m}$ scanned area on the sample surface, and shows a strong intensity decrease in the detector regions where the light is absorbed by the polysilicon. In the waveguide before the detector, a Gaussian shaped optical field profile is observed, which corresponds to the guided TE_{00} mode. The intensity distribution along the centerline of the waveguide from both NSOM measurements and modal calculations are presented on a log scale in Fig. 2(b). An exponentially decaying intensity distribution was observed. Fitting the measured data with an exponential decay curve produces an estimated absorption coefficient of $0.55\text{dB}/\mu\text{m}$ in the optical intensity, which is in excellent agreement with the modal calculation result.

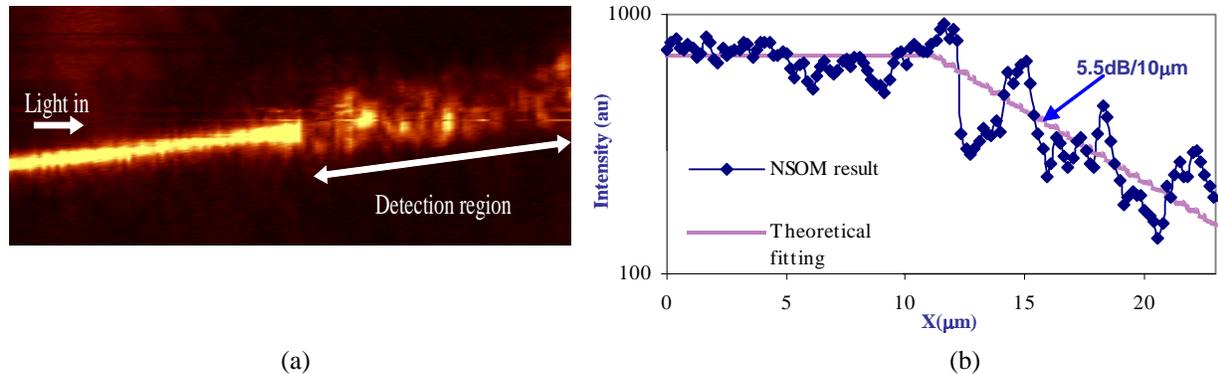
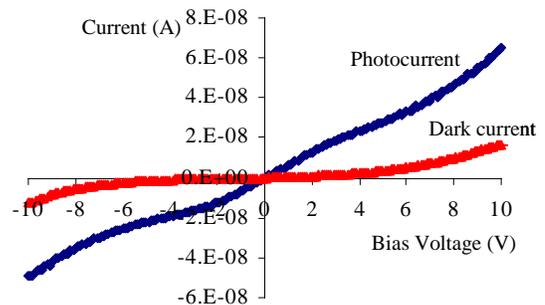


Fig. 2. (a) NSOM image over a $10\ \mu\text{m} \times 20\ \mu\text{m}$ scanned area on the sample surface and (b) log plot of intensity along center of the waveguide. Fitting the measured data with an exponential decay curve produces an estimated absorption coefficient of $0.55\text{dB}/\mu\text{m}$ in the optical intensity in excellent agreement with the modal calculation result. The oscillation may originate from multiple mode interference.

When biased, the photodetectors operated as expected and demonstrated an excellent on/off ratio at low bias. The measured DC response of a $10\ \mu\text{m}$ long photodetector with $1.14\ \mu\text{m}$ -contact spacing across a $0.5\ \mu\text{m}$ wide waveguide operated at a wavelength of 654 nm is shown in Fig. 3. The photocurrent response as a function of bias as well as the dark current is shown. At present, the low coupling efficiency from the visible single mode fiber with a mode field diameter 30-40 times larger than the waveguide makes it difficult to estimate the power in the waveguide and thus the detector responsivity. However, at low biases below 5V, the photocurrent to dark current ratio exceeds 10 despite the presence of grain boundaries in the polysilicon. A sub-linear response to light level modulation was observed. Additional photodetector characteristics will be presented at the conference. This work was supported by NSF under grant number ECS-0323493.



5. References

- [1] A.M. Raza, G.W. Yuan, C. Thangaraj, T. Chen, K.L. Lear, "Waveguide coupled CMOS photodetector for on-chip optical interconnects," The 17th Annual Meeting of the IEEE LEOS 2004, Vol. 1, pp. 152 - 153, Nov. 2004.