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A High-Speed, High-Sensitivity Silicon Lateral Trench Photodetector

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Abstract

We report a novel silicon lateral trench photodetector that decouples the carrier transit distance from the light absorption depth, enabling both high speed and high responsivity. The photodetector, fabricated with fully VLSI compatible processes, exhibits a 3-dB bandwidth of 2.5 GHz at 3.0 V for a light source of 670 nm. An external quantum efficiency of 68% is achieved at 845nm wavelength. A photoreceiver with a wire-bonded lateral trench detector and BiCMOS trans-impedance amplifier demonstrates excellent operation at 2.5 Gb/s data rate and 845 nm wavelength with only a 3.3 V bias.

Index terms:

Photodetector, photodiodes, silicon, optical receivers, and optoelectronic devices

Introduction

Conventional silicon-based photodiodes with vertical p-*i*-n layers have intrinsic limitations at wavelengths in the optical communication range (*i.e.* 850 nm), resulting from the trade-off between carrier transit distance and light absorption depth due to the low absorption coefficient of silicon [1]. The bandwidths of interdigitated metal-semiconductor-metal (MSM) detectors [2,3] and lateral p-i-n photodiodes formed by diffusion or ion-implantation [4,5] are still limited by the absorption layer thickness. This is so because the electric field intensity decays rapidly below the shallow or surface electrodes. Using a very thin silicon-on-insulator (SOI) substrate, a very high bandwidth has been reported, however with a significant reduction of responsivity [3]. By optimizing the active layer thickness of SOI substrates, lateral p-*i*-n photodiodes have been demonstrated with 1-2 GHz bandwidths and 18-25% peak external quantum efficiencies [5].

In this paper, we present a novel lateral p-*i*-n photodiode with deep trenches, creating a uniform electric field and thus enhancing the collection of photocarriers far below the surface. Detectors in the present work were fabricated with fully VLSI-compatible processes, in contrast to the MSM trench structure [6]. A 3-dB bandwidth of 2.5 GHz at 670 nm and 3 V has been obtained. The responsivity is 0.47 A/W at 845 nm, corresponding to an external quantum efficiency of 68%. With a wire-bonded lateral trench detector (LTD) and a trans-impendence amplifier, successful operation at a 2.5 Gb/s data rate using 845 nm light source has been achieved at low voltage of only 3.3 V. To the authors' knowledge, these devices have the best overall function (highest speed–responsivity at low bias) among silicon-based photodetectors.

Device Structure and Fabrication

The trenches of a lateral trench photodiode are filled alternately with n^+ and p^+ polycrystalline silicon and layered out as interdigitated fingers with 3.3 μm spacing. The total active area is a circle with diameter of 75 μm. The schematic of the cross-section is illustrated in Fig. 1. In a normal light incidence configuration, photocarriers generated in the silicon region between the deep trenches are collected laterally in a uniform electric field. Thus with sufficiently deep trenches, photocarrier transit time may be independent of the light absorption depth in this structure. Therefore, in principle, the speed of the detector is determined by the finger spacing only, if the capacitance induced by the deep trenches is negligible.

LTDs presented in this paper were fabricated on a p-type (100) silicon substrate with a resistivity of 11-16 Ω·cm. The detailed process flow can be found elsewhere [7] and is summarized as follows. The fabrication starts with deep trench (~ 7 μm) formation through a thin silicon nitride layer into the silicon substrate by reactive ion etching. The trench width at the top surface is approximately 0.35 μm. To fill the trenches with n^+ and p^+ polysilicon sequentially, borosilicate glass (BSG) was used as a sacrificial material. First, BSG was deposited to fill all trenches and was subsequently planarized by chemical-mechanical-polishing (CMP) down to the silicon nitride layer. Using a patterned hard mask, BSG was stripped from every other trench. Fig. 2a shows the cross-sectional SEM picture of a device at this point of fabrication. *In-situ* phosphorus-doped amorphous silicon (a-Si) with a concentration of about 10^{20} cm^{-3} was then deposited. The top surface of the trenches was exposed afterwards. The BSG in the remaining trenches was then stripped off, the cross-sectional SEM being shown in Fig. 2b. *In-situ* boron-doped a-Si (~$6x10^{20}cm^{-3}$) was deposited and then planarized. Complete trench fill has been achieved even with a high aspect ratio (~1:20) during amorphous silicon deposition. Finally, devices were annealed at high temperature to crystallize the a-Si into polysilicon, activate the dopants, and drive the dopants from the trenches into the silicon substrate, forming junctions away from the trench sidewalls. Fabrication of CMOS or BiCMOS circuits can resume at this point for fully integrated receivers. In this work, only discrete photodetectors with silicide and metal contacts on top of each trench were implemented. No anti-reflection coating was used.

Experimental Results

Fig. 3 shows the dark and photocurrent of a typical LTD under reverse bias. Extremely low dark current of 1.5 pA is obtained at 5 V. The breakdown voltage is 27 V. The capacitance of the device is 1.04 pF at 5 V, of which 0.48 pF is due to the large metal probing pad and can be reduced by an optimized back-end process. The measured responsivity at 845 nm is 0.47 A/W, corresponding to an external quantum efficiency of 68%.

The frequency response of the LTD was measured using small-signal modulation of a semiconductor laser, with results as shown in Fig. 4. For a wavelength of 670 nm, the 3-dB bandwidth is 2.5 GHz at 3.0 V, with a slight increase at a larger bias. Combined with other experiments with different polysilicon annealing conditions, it is believed that the speed of the LTDs in this work is transit-time limited. Higher bandwidth can be obtained by optimizing the finger spacing. For a light source of 845 nm, a low frequency tail is observed (Fig 4b). At this wavelength, about 63% of the light is absorbed in the silicon below the 7 μm deep trenches. Of these carriers, some are transported via slow diffusion in the undepleted region and some move slower in the depleted region under the trenches due to relatively lower electrical field. These slow carriers contribute to the ~4 dB drop in response at ~100 MHz. With deeper trenches, the low frequency response for long wavelength can be improved. For a limited trench depth, the slow carriers can also be blocked using a buried oxide [8]. Ignoring the response tail at $f<100$MHz for 845 nm light source, the signal drops by 3 dB at 2 GHz (Fig. 4b).

To evaluate the detector performance for photoreceivers, a discrete LTD was wire-bonded to a BiCMOS trans-impedance amplifier. An 845nm wavelength laser source was modulated with a

2.5 Gb/s and 2^7-1 pseudo-random-bit-sequence (PRBS) input. The detail of the measurement has been discussed elsewhere [9]. The measured eye-diagram is shown in Fig. 5. Because of the implementation of an AC coupling capacitor in the trans-impedance amplifier, the receiver exhibits excellent performance in spite of the low frequency tail. At a bit-error-rate (BER) of 10^{-9} and a bias of 3.3 V, the sensitivity is –17.1 dBm. Error-free operation (BER<10^{-10}) up to 6.5 Gb/s is observed. To the authors' knowledge, this is the fastest silicon-based optical receiver ever reported. With a fully integrated LTD and amplifier, we expect excellent operation up to 10 Gb/s [10].

Conclusion

Novel silicon lateral trench photodetectors that are compatible with CMOS processing have been demonstrated. The trench structure decouples the carrier transit distance from the light absorption depth. The LTDs exhibit high-speed, high responsivity and excellent operation at 2.5 Gb/s and 3.3 V bias for light source at 845 nm. The performance and the process compatibility of the silicon LTD make possible the fabrication of silicon monolithic receivers for fiber-optic data links.

Acknowledgments

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Figure Captions

Fig. 1 Schematic of the cross-section of an lateral trench detector.

Fig. 2 Cross-sectional SEM pictures of LTD when (a) BSG is etched away from every other trench, (b) BSG is completely stripped off after n^+ amorphous silicon depositon and polishing.

Fig. 3 Measured dark and photo current from a typical LTD under reverse bias. Extremely low dark current is achieved.

Fig. 4 Frequency response of an LTD at (a) 670 nm and (b) 850 nm wavelength.

Fig. 5 Eye diagrams of a discrete LTD wired to a BiCMOS trans-impedence amplifier at 3.3 V and 2.5 Gb/s rate with a light source of 845 nm.

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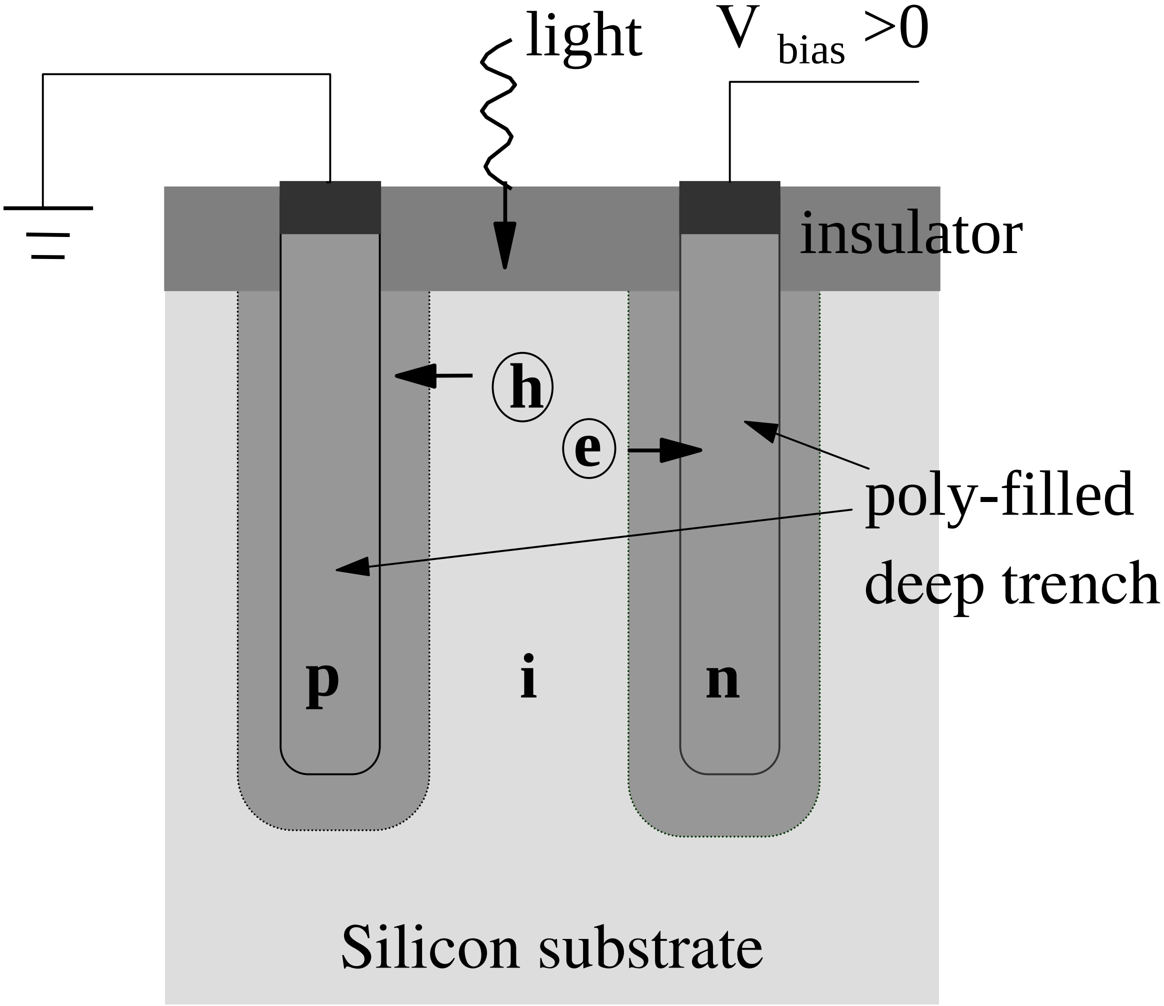

Fig. 1

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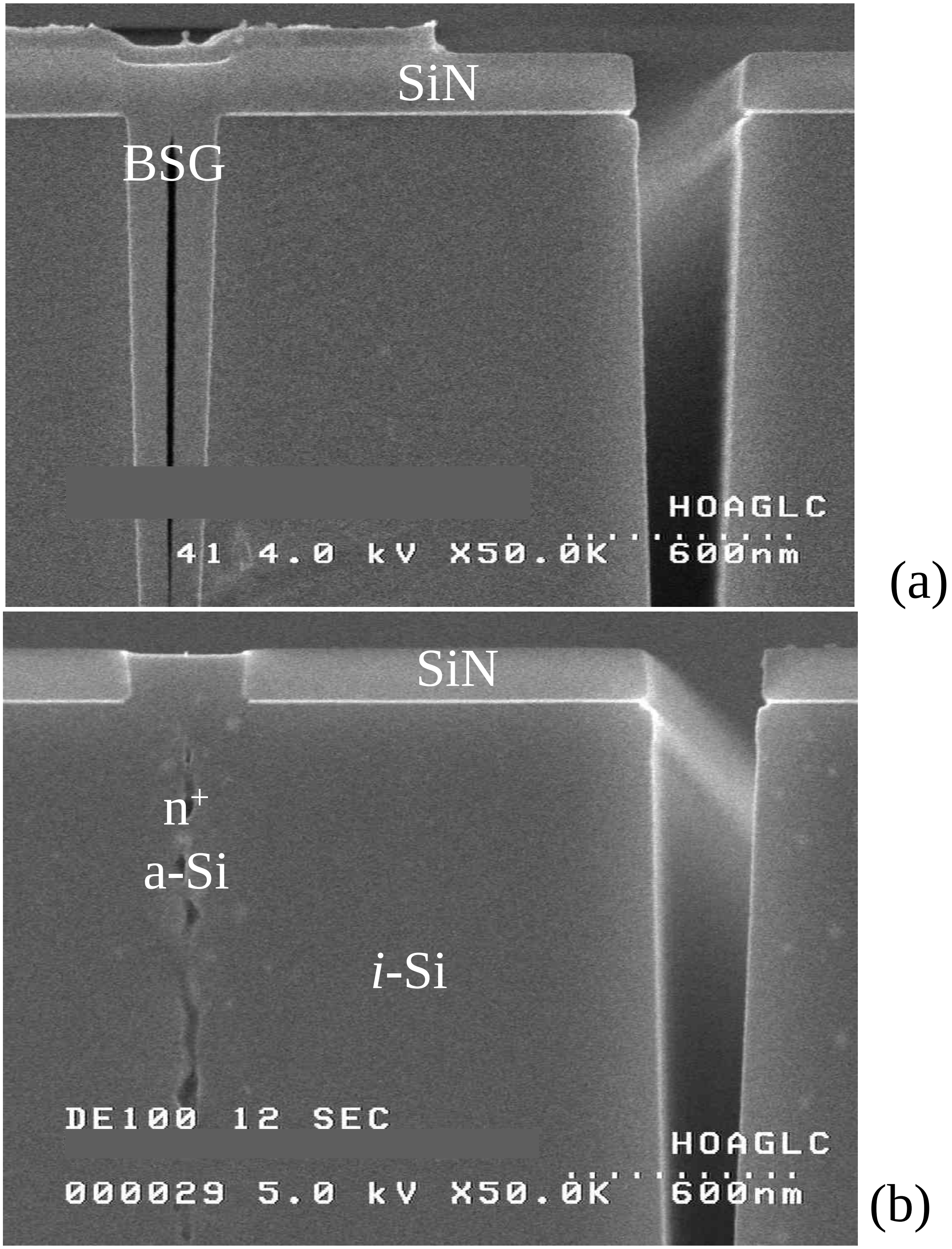
SiN
BSG
[redacted]
HOAGLC
41 4.0 kV X50.0K 600nm
(a)
SiN
n^+
a-Si
i-Si
DE100 12 SEC
[redacted]
HOAGLC
000029 5.0 kV X50.0K 600nm
(b)

Fig. 2

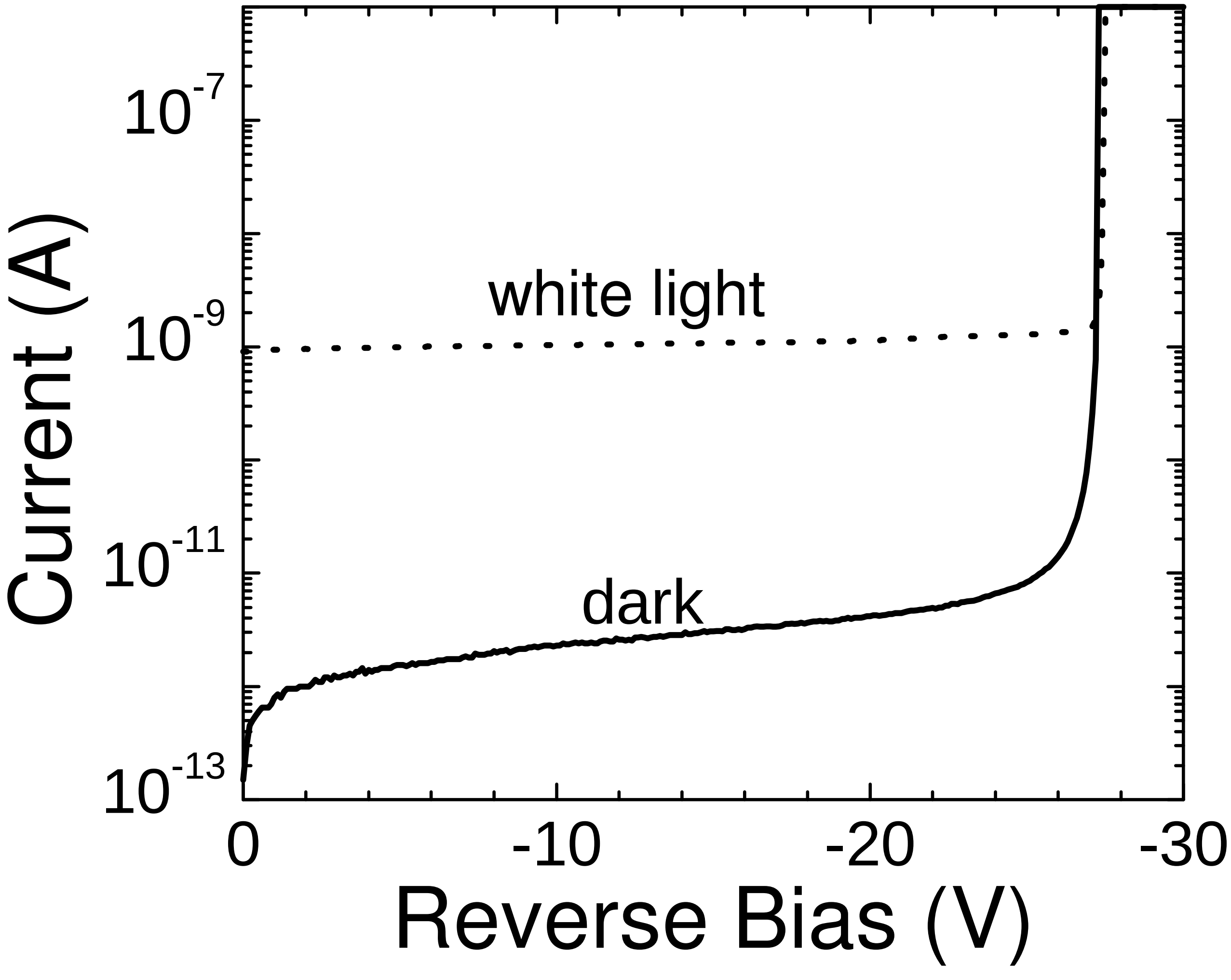
white light
dark
Current (A)
10^{-7}
10^{-9}
10^{-11}
10^{-13}
0
-10
-20
-30
Reverse Bias (V)

Fig. 3

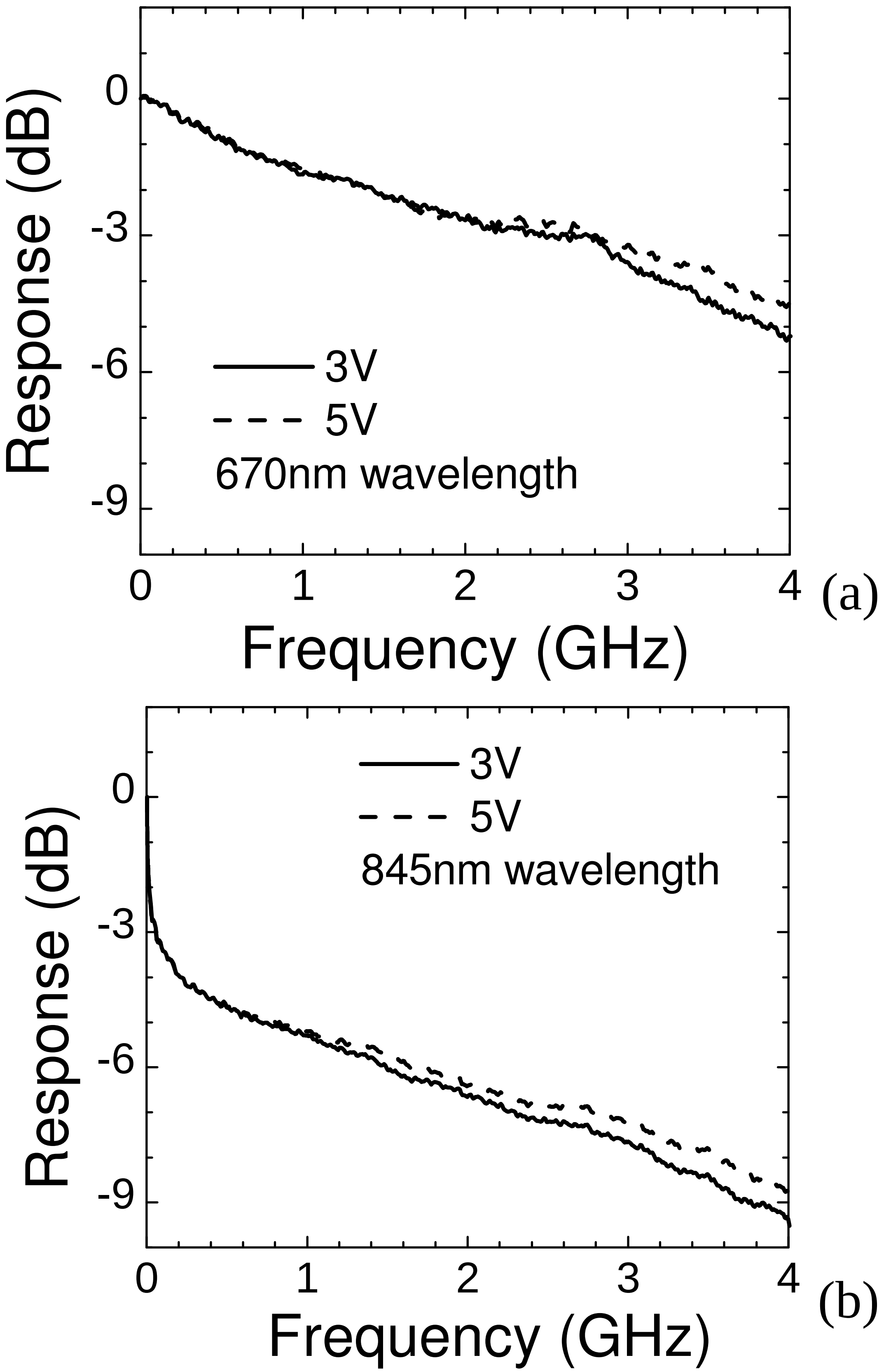

Fig. 4

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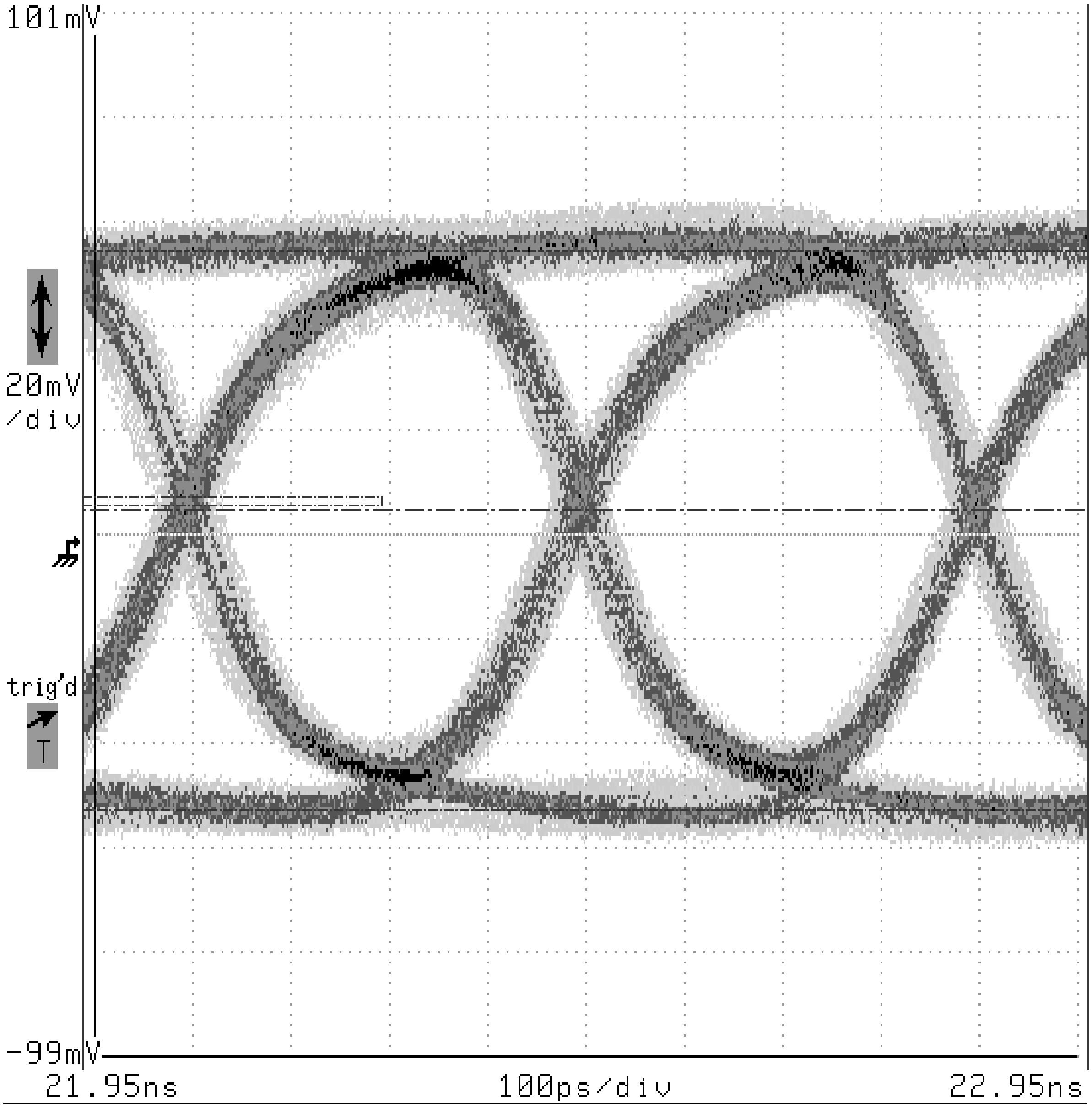

Fig. 5

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