Effect of Mesa-Diameter on the 3-dB Bandwidth Enhancement of an InGaAs Photodiode with Inductive Signal Electrode

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***Abstract*— Backside-illuminated InGaAs photodiodes were fabricated using two types of high-impedance coplanar waveguide (CPW) transmission line with different signal electrode designs. The effect of mesa diameter on the enhancement of the 3-dB bandwidth of the fabricated photodiodes was then analyzed based on optical/electrical (O/E) frequency response measurements.**

Keywords—InGaAs, photodiode, bandwidth, mesa-diameter

I. Introduction

Vertically illuminated p-i-n photodiodes with InGaAs absorption layer have long been used in the production of high speed optical transceivers whose single-lane transmission rate is currently forced to increase up to 224 Gbps for deployment in high-performance data centers [1]. The transmission rate of the transceivers is primarily affected by the 3-dB bandwidth of the photodiodes. By the way, there is usually a tradeoff between the 3-dB bandwidth and the responsivity of the photodiodes. Therefore, it is required to develop technologies that increase the 3-dB bandwidth without reducing the responsivity. In case that the increase of the 3-dB bandwidth is limited by the resistance-capacitance (RC) time constant rather than the carrier transit time, the utilization of an inductive peaking phenomenon in which the optical/electrical (O/E) frequency response of a photodiode rise at an inductance-capacitance (LC) resonance frequency is helpful to increase the 3-dB bandwidth [2]. Previously, we reported that the 3-dB bandwidth of a backside-illuminated InGaAs photodiode with a modified uni-travelling carrier (MUTC) epitaxial layer structure can be significantly enlarged by optimizing the planar structure of the signal electrode constituting an inductive coplanar waveguide (CPW) transmission line [3]. In the report, the diameter of the cylindrical mesa that is formed by etching the epitaxial layer structure was fixed to 10 μm. In this study, we analyzed the effect of the mesa diameter on the 3-dB bandwidth enhancement using the frequency response measurement data of the InGaAs photodiodes with two types of high impedance CPW transmission lines using different signal electrode designs.

II. Fabrications

Photodiodes with a chip size of 500 μm x 400 μm were fabricated using a 2-inch semi-insulating InP wafer with a MUTC epitaxial layer structure. This epitaxial structure has an intentionally undoped 380 nm-thick i-InGaAs absorption layer and two 110 nm-thick p-InGaAs absorption layers whose Zn-concentrations are $3x10^{18}$ cm^{-3} and $9x10^{17}$ cm^{-3}, respectively. Photodiode fabrication starts with forming a circular Ti/Pt/Au ohmic contact metal electrode on a p-InGaAs top-contact layer, which is followed by the formation of a cylindrical photodiode mesa with target diameters of 6, 8, 10, 12, 15, 20, 25, 30 μm. Detailed photodiode fabrication processes can be found in our previous report [3]. There exists an aspherical InP lens with a lens diameter of 120 μm on the backside of the final photodiode chip. This monolithically integrated InP lens is for the ease of backside illumination.

III. Measurement Results

Scanning electron microscope (SEM) images showing the frontside of the fabricated photodiodes are given in Fig. 1. The photodiode in Fig. 1(a) has a straight signal electrode with a width and length of 20 and 75 μm, respectively, whereas all the photodiodes in Fig. 1(b), (c), and (d) have the same meandering signal electrode with a width and length are 5 and 475 μm, respectively. In addition, the mesa diameters of the photodiodes in Fig. 1(a) and (b) are 10 μm, while those in Fig. 1(c) and (d) are 20 and 30 μm, respectively. Since the meandering signal electrode is narrower and longer than the straight signal electrode, the former is expected to produce a larger CPW line inductance than the latter. On the other hand, the parasitic capacitance due to the CPW line is expected to be larger in the former than in the latter, since the former occupies a larger area than the latter. And, since the area of the semiring-shaped metal pattern that is connected to the two CPW ground electrodes increases in the order of mesa diameters of 10, 20, and 30 μm under the condition that the gap between the semiring-shaped metal pattern and the cylindrical photodiode mesa is constant, the junction capacitance of the photodiode mesa is also expected to increase in the order of mesa diameters of 10, 20, and 30 μm.

The O/E frequency responses of the fabricated photodiodes were measured at the bias of -2.5 V using a 67

GHz network analyzer and a C-band thin-film lithium niobate (TFLN) optical modulator with a electrooptic 3-dB bandwidth of 80 GHz. As known from the measurement data of Fig. 2, regardless of the kind of the signal electrode, the amplitude attenuation with increasing frequency becomes weaker as the mesa diameter decreases. And, the meandering signal electrode produces a flatter frequency response than the straight signal electrode at the region of the mesa diameter less than 12 μm. And, the former produces a steeper amplitude roll-off behavior than the latter at the same mesa diameter. Besides, Fig. 2 (b) clearly shows that a large 3-dB bandwidth, far exceeding our measurement limit of 67 GHz, can be achieved by reducing the mesa diameter of the photodiode with the meandering signal electrode to 6 or 8 μm.

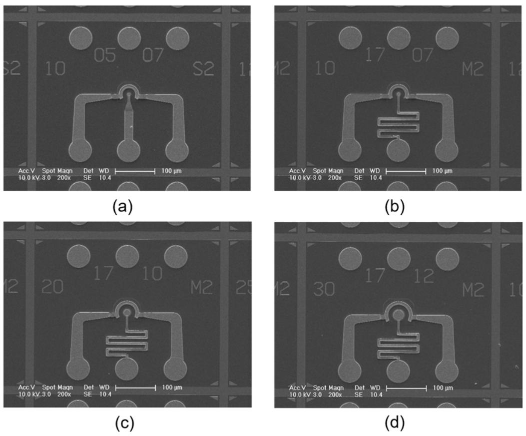

Fig. 1. SEM images showing the frontside of the fabricated photodiodes with (a) straight and (b, c, d) meandering signal electrode.

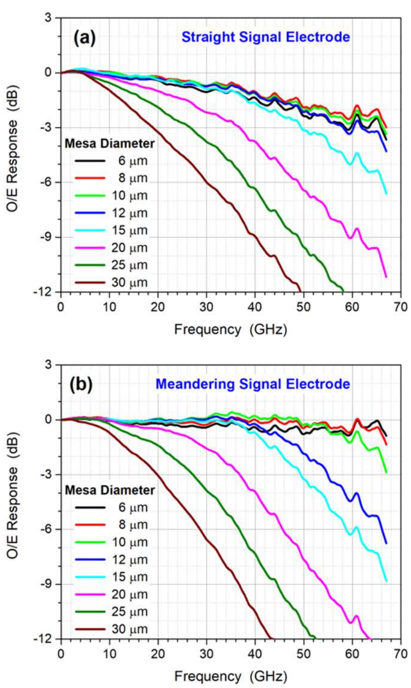

Fig. 2. Frequency response amplitude measurement data for the photodiodes with (a) straight and (b) meandering signal electrode.

Smith charts on the measured RF return loss (S11) reflectance data are given in Fig. 3. The frequency at which the impedance traces of Fig. 3 intersect the resistance axis can be regarded as the LC resonance frequency (f_R) of the photodiodes. Therefore, it can be known from Fig. 3 that the resonance frequency decreases, regardless of the kind of the signal electrode, as the mesa diameter increases. And, it is considered that the largest 3-dB bandwidth far exceeding 67 GHz is attributed to the optimum location of the resonance frequency, which is caused by both a large CPW line inductance due to the meandering signal electrode and the small junction capacitance due to the small mesa diameter of 6 or 8 μm.

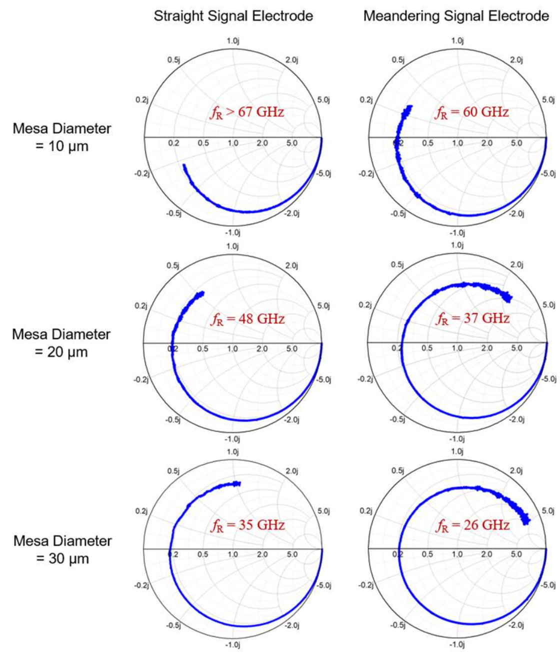

Fig. 3. Smith charts obtained from the S11 mesurement data for the photodiodes with (a) straight and (b) meandering signal electrode.

IV. Conclusion

In this study, we experimentally confirmed that the 3-dB bandwidth of a backside-illuminated MUTC InGaAs photodiode with a small mesa diameter of 6 or 8 μm can be significantly increased beyond 67 GHz by optimizing the planar structure of an inductive CPW signal electrode.

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