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InGaAs/InP p-i-n Photodiode with Extrinsic Pad Isolation Structure

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1. Introduction

A photodiode is an important component in optical transmission systems. One of the major trends in the development of photodiode is a large bandwidth-efficiency product [1]. The basic requirement for wide-bandwidth device is low capacitance. A desired device approach for wide-bandwidth p-i-n photodiode is to minimize extrinsic capacitance, while maintaining optimal thickness of absorption layer. The low capacitance p-i-n photodiodes, employing an air-bridged bondpad on a semi-insulating substrate [2] and a polyimide [3] respectively, have been reported. These approaches separate electrically the bondpad region from the intrinsic device area and then provide an effective reduction of parasitic capacitance. However, a systematic study on wet etching characteristics to isolate extrinsic pad area has not yet been investigated. In this work, the pad isolation structure based on etching characteristics of InGaAs and the pad design with a narrow feed line are described in detail and compared to the conventional pad.

2. Device Structure and Fabrication

The photodiode layer structure was grown using Si and C for n- and p-type dopants, respectively, on a semi-insulating InP substrate. It consists of a 100-nm InP n-type (4×10^{19} cm^{-3}) contact layer, a 430-nm undoped ($n < 2\times10^{15}$ cm^{-3}) InGaAs absorption layer, and 100-nm InGaAs p-type (2×10^{19} cm^{-3}) contact layer as shown in Fig. 1 (a). Using a semi-insulating InP substrate is to facilitate an isolation of the extrinsic pad [2]. Fig. 1 (a) shows a schematic cross section of the fabricated device, which is divided into the intrinsic photodiode area and the extrinsic pad area. P-contact in the intrinsic device region is connected to the extrinsic pad via a narrow feed line as shown in Fig. 1 (b). Selectively removing parasitic InGaAs and InP layers beneath the feed line makes possible to isolate the extrinsic pad from the intrinsic device area. The extrinsic pad isolation technology utilizes wet etching characteristics of the InGaAs layer. The etching profile and the lateral etch rate of the InGaAs layer depend on the crystal directions [4]. In order to investigate crystallographic orientation effects on the InGaAs layer, three types of Ti metal stripes are deposited on the InGaAs layer, which are aligned to [01-1], [011], and [010] directions on the (100) wafer (refer Fig. 2). For the crystal direction along the [010], there are little known factors about the etching profile. According to SEM observation, the nearly vertical profiles are obtained in this direction. The etching profiles exhibit undercut structures for type A, while they show overcut structures for type B and nearly vertical structures for type C. The lateral wet etching of the InGaAs layer on InP is performed using a selective etching solution with H_3PO_4: H_2O_2:H_2O = 1:1:10. The lateral etch rates are measured to be about 5.5 nm/sec, 2.4 nm/sec, and 3.2 nm/sec in the [010], [01-1], and [011] directions in the Fig. 3. The lateral etch rate in the [010] direction is founded to be approximately twice that in other directions. Using these wet etching characteristics, the extrinsic pad is designed to be connected to the P-contact with a bridge-like feed line, which is aligned along the [010] direction. The photodiodes are fabricated using a typical mesa process. Pt/Ti/Pt/Au metal layers are evaporated on p-type InGaAs for the ohmic contact. Next, the device mesa etching to InGaAs layers is carried out using selective etching solution. This process provides the electrical isolation between the active device area and the extrinsic pad area. Then, N-contact is deposited on n-type InP layer using evaporation of Ti/Pt/Au.

3. Result and discussion

Generally, a 3dB electrical bandwidth (BW) of the p-i-n photodiode is limited by both a carrier transit time and a RC time constant [1]. Unfortunately, the effects of two factors on frequency response cannot be optimized simultaneously. However, it is desired to reduce the device size as small as possible, while maintaining optimal thickness of absorption for wide-bandwidth photodiode. The transit time and parasitic limitations on the bandwidth of the photodiode are calculated theoretically as shown in Fig. 4. The 3dB electrical bandwidth (f_{3dB}) of the p-i-n photodiode is described by

$$f_{3dB} = \left(\frac{1}{f_T^{\,2}} + \frac{1}{f_T^{\,2}} \right)^{-0.5}$$

where f_T is the carrier transit time-limited bandwidth and f_{RC} is the RC time constant-limited bandwidth. The 3dB electrical bandwidth of the photodiode with a mesa diameter of 10 μm is mainly determined by the carrier transit time, while the bandwidth of those with more than a diameter of 20 μm is significantly dependent on the RC time constant. Therefore, it is expected to be effective in applying the extrinsic pad isolation to the device with more than a diameter of 20 μm.

In order to investigate effects of the bandwidth on extrinsic pad isolation, the devices with the pad isolation structure are compared to those of conventional pad structure. Fig. 5 shows the measured and calculated S_{11} versus frequency (0.5 ~ 18 GHz) of the device with extrinsic pad isolation structure. The small-signal equivalent circuit components shown in the inlet of Fig. 5 are extracted by optimization and fitting procedure. The extracted junction capacitance (C_j) of the device with the pad isolation structure is to be 83 fF, while its counterpart has a 112 fF. The pad isolation structure has the narrow feed line between the intrinsic device area and the extrinsic pad area, while the pad of the conventional structure is simply extended from the intrinsic device area as shown in the inlet of Fig. 6. The frequency response of these photodiodes is measured from 1 GHz to 16 GHz with a wavelength (λ) of 1.55 μm as shown in Fig. 6. Both devices with a diameter of 20 μm are measured at the reverse bias of 2 V. There is a difference of 0.8 dB at 16 GHz in the frequency response of both devices. Fig. 7 shows temporal response of both devices with the same diameter at the same bias and wavelength. The device with the pad isolation structure exhibits a full width at half maximum (FWHM) of 18 ps, while its counterpart has a 23 ps FWHM. Therefore, more enhanced characteristics such as 3dB bandwidth and FWHM in the devices using the extrinsic pad isolation demonstrates that effective removal of the parasitic capacitance around the extrinsic pad area can increase the frequency performance of the photodiodes.

4. Conclusions

Applying the extrinsic pad isolation technology in the InGaAs/InP p-i-n photodiodes demonstrates to enhance the frequency performance of the devices. In this technology, the design of the P-contact layout is based on wet etching characteristics of InGaAs, which significantly depend on the crystallographic orientation and allow more effective and easier pad isolation for the devices. The extrinsic pad isolation technology is promising for fabricating a low capacitance p-i-n photodiodes and obtaining high-speed characteristics.

Reference

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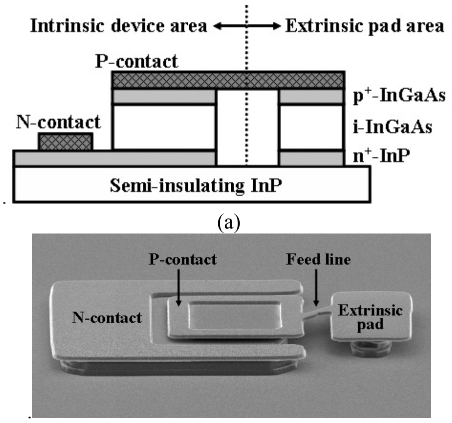

Fig. 1. A schematic cross section of the p-i-n photodiode with extrinsic pad isolation structure (a) and its SEM photograph (b).

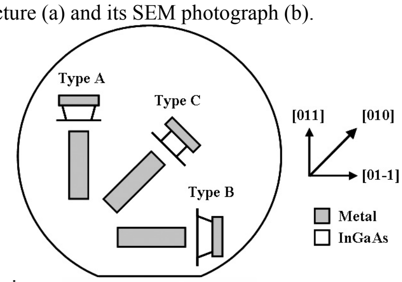

Fig. 2. Etching profiles of the InGaAs layer according to the crystal directions.

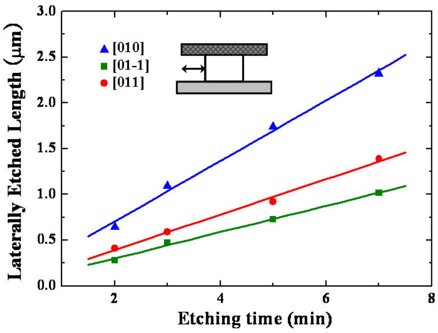

Fig. 3. Dependence of the laterally etched length to the InGaAs layer on etching time and crystal directions. The lateral etch rate of the InGaAs layer is characterized by measuring an amount of the undercut beneath the etch mask.

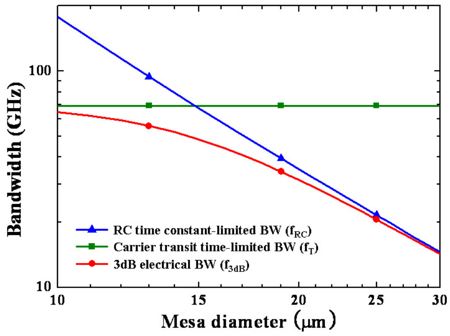

Fig. 4. Dependence of the calculated bandwidth on device mesa diameter.

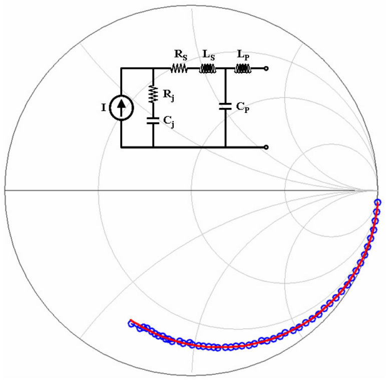

Fig. 5. Measured (circle) and calculated (solid line) S_{11} parameter of the device (diameter = 20 μm) with extrinsic pad isolation structure at a reverse bias of 2 V. The inset shows the equivalent circuit of the device.

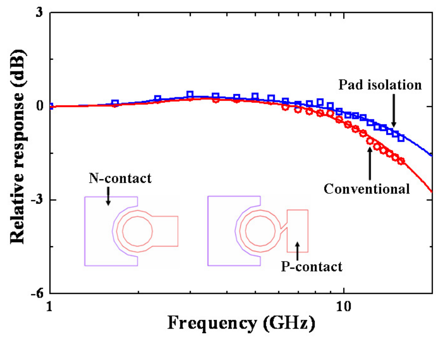

Fig. 6. Frequency response of the photodiodes (diameter = 20 μm) with pad isolation structure and conventional pad structure at a reverse bias of 2 V (dots are measured data and solid lines are calculated data).

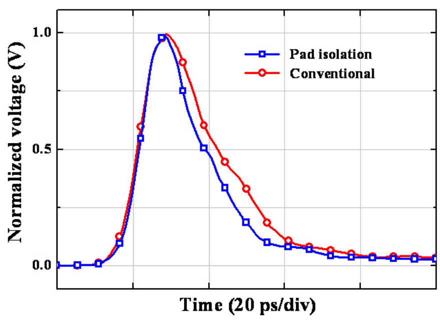

Fig. 7. Temporal response of the photodiodes (diameter = 20 μm) with pad isolation structure and conventional pad structure at a reverse bias of 2 V.