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High-Performance, Back-Illuminated InP/GaInAs Lateral PIN Photodiode

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Lateral structure photodiodes are important for developing simple-structure, high-performance monolithic receivers. We have fabricated high-performance interdigitated lateral InP/GaInAs PIN photodiode by introducing back-illumination structure. This PIN photodiode has exhibited, simultaneously, high quantum efficiency (85%), low dark current (<1 μA), low capacitance (0.25 pF) and high frequency response (3 GHz) characteristics.

1. Introduction

Interdigitated, lateral structure photodiodes are very important for fabricating high-performance monolithic photoreceivers, because they have electrodes on the same surface and therefore can be easily integrated with other devices and also they have inherently low capacitances. A number of papers on both PIN [1,2] and MSM(metal-semconductor-metal) [3,4] structures with GaInAs absorption layers have been published.

For achieving good receiver performance, photodiodes have to have low dark current, high quantum efficiency and high speed characteristics. Considering an application to coherent optical receivers [5], they are also required to exhibit good output linearity at high input power level and voltage-independent quantum efficiency. Lateral GaInAs PIN photodiode is expected to have greater possibility to fulfil these requirements than MSM photodiodes. Performance of previous lateral PIN photodiodes [1,2], however, has suffered from the degradation of the dark current because of the surface leakage current occurring in small bandgap p-n junction. Moreover, the quantum efficiency observed in previous PIN photodiodes was low because the absorption layer was shadowed by electrode fingers.

In this paper, we describe a lateral PIN photodiode with improved structure. The dark current has been reduced by introducing an InP-capped p-n junction structure. The quantum efficiency has been improved greatly by the use of back-illuminated structure. Fabricated photodiodes have also exhibited low capacitance and large bandwidth.

2. Fabrication

Figure 1 shows the structure of our lateral PIN photodiode with interdigitated electrodes. A 1 μm-thick undoped InP buffer layer, a 1.7 μm-thick undoped GaInAs photo-absorption layer and a 0.3 μm-thick n-InP cap layer ($n=1\times10^{16}$ cm^{-3}) were sequentially grown on a semi-insulating (SI) InP substrate with (100) plane. The p-n junction was formed by selective Zn diffusion at 500°C using a SiN

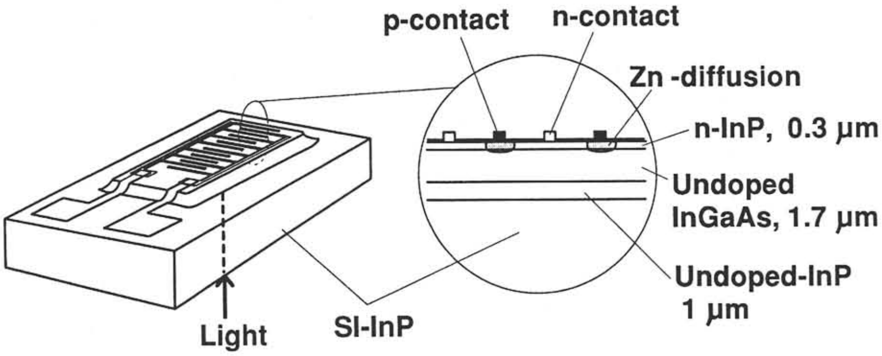

Figure 1. Structure of InP/GaInAs lateral PIN photodiode.

mask. The diffusion front was precisely adjusted at the InP-GaInAs interface in order to avoid speed limitation due to either carrier pile-up or diffusion current. For p-contact, Au/Zn/Au was alloyed at 430°C for 5 minutes. AuGe/Au for n-contact was alloyed at 380°C for 1 minute. The width of fingers was made as small as possible, to minimize the effect of electric field lowering below the fingers. This resulted in interdigitated contacts with fingers 1 µm wide and 3 µm apart. A mesa with a size of 80 x 100 μm^2 was formed for electrical isolation using Ar ion-beam etching technique with a photoresist mask. A SiN film was deposited for passivation and then Ti/Au bond-pads were formed. The substrate was thinned to 360 µm and another SiN layer was deposited on the bottom of the substrate as the antireflection coating.

3. Characteristics

Figure 2 shows the dark current as a function of the bias voltage. The dark-current is less than 10 nA up to 10 V above which tunnel current appears but the value is always below 1 µA up to 22 V. This has shown that the effect of surface leakage current is reduced by the introduction of the bandgap cap layer. Figure 3 shows the capacitance-voltage curve. The value of capacitance is only 0.25 pF at 22 V despite the

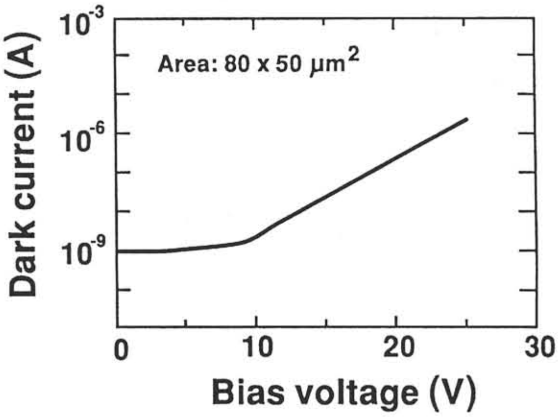

Figure 2. Dark current as a function of bias voltage.

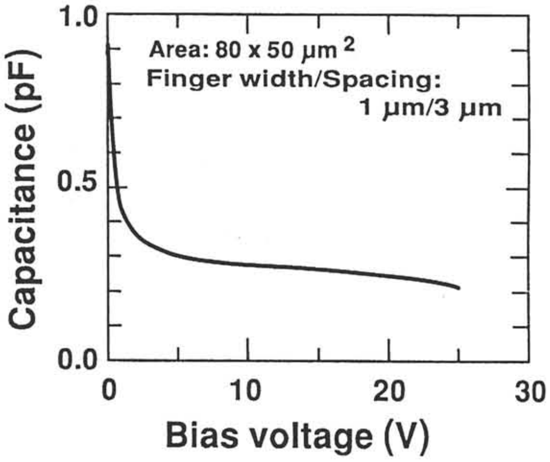

Figure.3. Capacitance-voltage characteristics.

large photosensitive area. This has shown at least 30% reduction of capacitance compared with conventional vertical structure PIN photodiodes with the same photosensitive area.

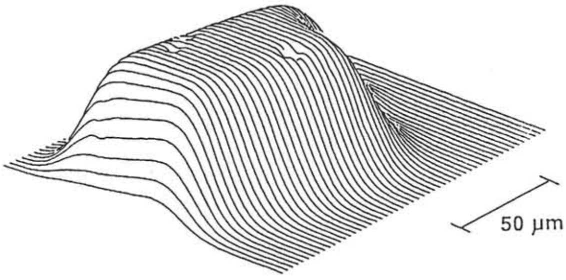

Figure 4. Photosensitivity profile of back-illuminated lateral PIN photodiode.

Figure 4 shows the photosensitivity profile measured by scanning a single mode fiber with back-illumination. The wavelength of light was 1.54 μm and the bias voltage was 10 V. Excellent uniformity has been observed. The size of uniform photosensitive part was 67 x 35 μm^2: this provides enough tolerance for fiber alignment. The quantum efficiency was independent of voltage and as high as 85%, which indicates complete collection of photocarriers generated in GaInAs layer, even below the contacts. The photocurrent output showed excellent linearity up to an input power level over 1 mW.

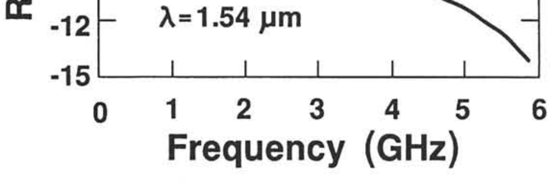

Figure 5. Frequency response of lateral PIN photodiode.

Figure 5 shows the frequency response characteristics measured using an intensity modulated DFB laser emitting at 1.54 μm. The frequency response characteristics depend strongly on the bias voltage. Comparing the strong voltage-dependence of the bandwidth with the week voltage-dependence of capacitance above 2 V, it is found that the bandwidth is dominated by the carrier transit time which is influenced by the two-dimensional electric field distribution below the electrode fingers. The -3 dB bandwidth becomes larger with the increase of the bias voltage, and at higher bias of 22 V transit time affect becomes negligible. A -3 dB bandwidth of 3 GHz at 22 V is consistent with the CR time-limited bandwidth which is given by the series resistance ($\sim$150 Ω) and the capacitance (0.25 pF) of the photodiode at 22 V. Further speed improvement can be expected for smaller contact spacing to decrease the carrier transit time and for lower series resistance to increase the CR time-limited bandwidth.

4. Conclusion

We have developed an InP/GaInAs lateral PIN photodiode with improved back-illuminated structure. This photodiode has exhibited, simultaneously, high quantum efficiency, low dark current and high frequency response ($\sim$3 GHz). These results indicate the applicability of the present structure to high-sensitivity monolithic receivers.

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