High-Efficiency Unitraveling-Carrier Photodiode with an Integrated Total-Reflection Mirror

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***Abstract*—A novel photodiode (PD) structure with an integrated total-reflection mirror which can enhance the quantum efficiency in back-illuminated geometry is proposed. Due to the diagonal propagation of the reflected light at the total-reflection mirror through the absorption layer, the efficiency is improved by about 50% from that of the normally irradiated case. By employing a unitraveling-carrier structure together with a thick absorption layer of 4700 A, the fabricated PD exhibits a high responsivity of 0.65 A/W, a high 3-dB bandwidth of 50 GHz, and a high-output voltage of 5 V, simultaneously.**

***Index Terms*—Efficiency, total reflection, unitraveling-carrier photodiode (UTC-PD).**

I. Introduction

A NEED for ultrafast photodetectors with a high-saturation output power has been emerging in various applications such as fiber-optic communication systems [1] and ultrafast measurements [2]. A combination of a high-saturation-power photodiode with an optical fiber amplifier enables us to eliminate the postamplification electronics, extend the bandwidth, and thus simplify the receiver configuration [2]. The unitraveling-carrier photodiode (UTC-PD) [3] is a promising solution for such a requirement, because it has both high-speed and high-saturation-power capability. A 3-dB bandwidth ($f_{3\,\mathrm{dB}}$) of 114 GHz and an output peak voltage (V_p) of 1.9 V (for a 25-Ω load) with a responsivity of 0.16 A/W have already been achieved [4].

A common constraint for the back-illuminated geometry is that the available quantum efficiency still decreases with an $f_{3\,\mathrm{dB}}$ increase due to the tradeoff between these parameters. The edge-coupled waveguide (WG) configuration is one approach to overcome this constraint. With a WG type UTC-PD, a responsivity of 0.4 A/W with $f_{3\,\mathrm{dB}}$ of 55 GHz and V_p of 1.3 V (for a 5-Ω load) was reported [5]. Another candidate is the edge-illuminated refracting-facet (RF) photodiode [6], which utilizes an angled irradiation on the absorption layer with a refracted light through an angled facet at the wafer edge. With an RF type pin-PD, a responsivity of 0.65 A/W with $f_{3\,\mathrm{dB}}$ of 42 GHz and V_p of 2.6 V (for a 50-Ω load) was reported [6]. Although these edge-coupled geometry PD's have high efficiencies, they need to be cleaved at [5] or close to [6] the illumination edge for the device fabrication. Thus, they are not compatible with on-wafer testing, which is especially important both for low-cost manufacturing and integration with other devices such as electric circuits [7].

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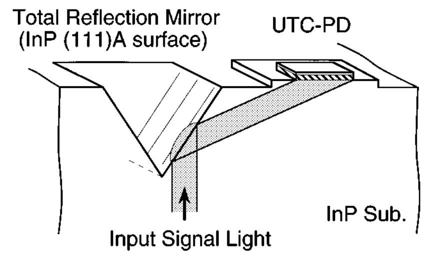

Fig. 1. Schematic drawing of the proposed photodiode with an integrated total-reflection mirror.

We propose a novel photodiode structure with an integrated total-reflection (TR) mirror which can enhance the quantum efficiency in back-illuminated geometry. A key aspect of the new PD is the diagonal propagation of the light through the absorption layer using the total-reflection on a (111)A facet mirror formed adjacent to the PD. The propagation length of the signal light in the absorption layer increases significantly, and this results in an efficiency that is about 50% greater than that in the normally irradiated case. By employing a unitraveling-carrier structure together with a thick absorption layer of 4700 A, we demonstrate PD's simultaneously exhibiting a high responsivity of 0.65 A/W, a high 3-dB bandwidth of 50 GHz, and a high-output voltage of 5 V.

II. Device Structure and Fabrication Process

Fig. 1 shows a schematic drawing of the proposed PD with an integrated total-reflection mirror. The V-groove shaped TR mirror is fabricated adjacent to the PD by wet chemical etching using HBr. Because of its chemical nature, the etching stops on the InP (111)A facet spontaneously, and the angle between the TR mirror and substrate surface is reproducibly defined at 54.7°. This angle satisfies the total reflection condition for the light coming vertically from the backside of the wafer when the surface side of the mirror is covered with a material (air in the present case) having a dielectric constant less than 2.59. The input signal light is reflected by the TR mirror, and irradiates the absorption layer diagonally. This increases the propagation length of the signal light in the absorption layer, and thus improves the efficiency. Considering the refraction at the hetero-interface below the absorption layer, the angle between the propagating light through the InGaAs absorption layer and the substrate surface is calculated to be 33.6°. Thus, the transfer length increase compared to the normally irradiated case becomes a

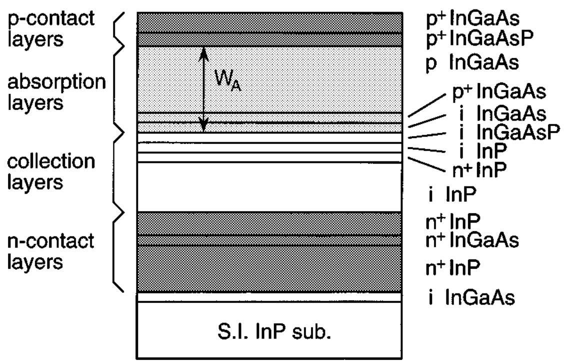

Fig. 2. Epitaxial layer structure of fabricated UTC-PD.

factor of about 1.8, and the efficiency increase is estimated to be a factor of about 1.4 to 1.5 depending on the absorption layer thickness (W_A) tested here.

The epilayers were grown on a (100) oriented semi-insulating (S.I.) InP substrate by low-pressure MOCVD. The p-type and n-type dopants were C and Si, respectively. Fig. 2 shows the layer structure of a fabricated InP–InGaAs UTC-PD with W_A of 4700 A. The absorption layer consists of p-InGaAs ($p = 1 \times 10^{17}$/cm^3, 4520 A), p$^+$InGaAs ($p = 2 \times 10^{18}$/cm^3, 80 A) and undoped InGaAs (100 A), and the collection layer consists of undoped InGaAsP (100 A), undoped InP (50 A), n$^+$InP ($n = 1.5 \times 10^{18}$/cm^3, 100 A) and undoped InP (1900 A). Here, the p-InGaAs absorption layer is lightly doped to 1×10^{17}/cm^3 so as to obtain the benefit from the self-induced field (self-bias effect) in the absorption layer [8]. In order to suppress current blocking at the absorption/collection layer interface, we used a step-graded bandgap profile, inserting an InGaAsP ($E_g = 1.05$ eV) layer between the InGaAs absorption and InP collection layers. The rest of the structure is similar to ones reported previously [4], [8]. For characterizing the high-speed device performance, hexagonally shaped double-mesa structure devices with an absorption area of 63 μm^2 were fabricated by wet chemical etching and lift-off processes. Each device was then integrated with a 50-Ω coplanar line on the S.I. InP substrate. The PD output electrode on the n-type layer is connected to the signal line so as to output a negative voltage signal, which is suitable for the direct drive of the digital circuit. The backside of the substrate was mirror-polished and antireflection coated after the devices were fabricated. The responsivity was measured in a broad-area device with an area of 2500 μm^2. Here, devices with several W_A values from 1800 to 4200 A were also tested. The pulse-photoresponse was measured by a pump-probe electrooptic sampling (EOS) technique [2] with a 1.55-μm incident pulse (a full-width at half-maximum (FWHM): 400 fs; repetition rate: 100 MHz) using an external CdTe probe chip.

III. Characterization of Fabricated TR-UTC-PD

Fig. 3 shows how the external quantum efficiency (or responsivity) changes depending on W_A at $\lambda = 1.55$ μm for fabricated broad-area PD's with and without TR mirrors. This comparison for each W_A was done in the same device by only changing the position of the input signal light, coming vertically from the backside of the wafer, at the TR mirror or at the absorption

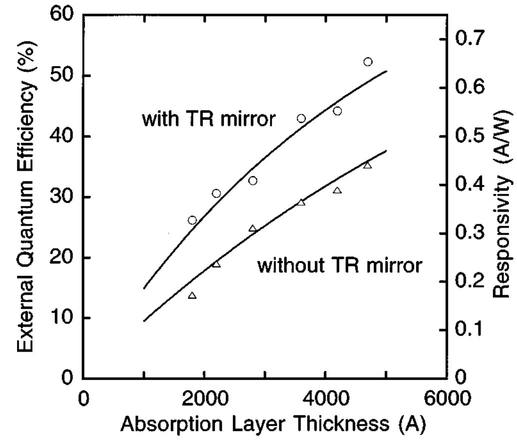

Fig. 3. Dependence of the efficiency on the absorption layer thickness for PD's with and without the total-reflection mirrors. The solid curves are the calculated tendencies.

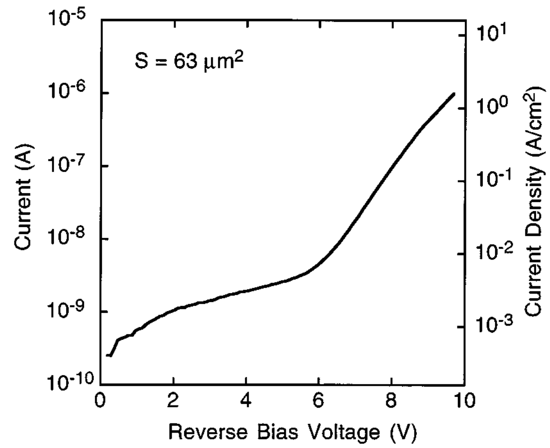

Fig. 4. Reverse biased I-V characteristics of a fabricated PD in a dark environment.

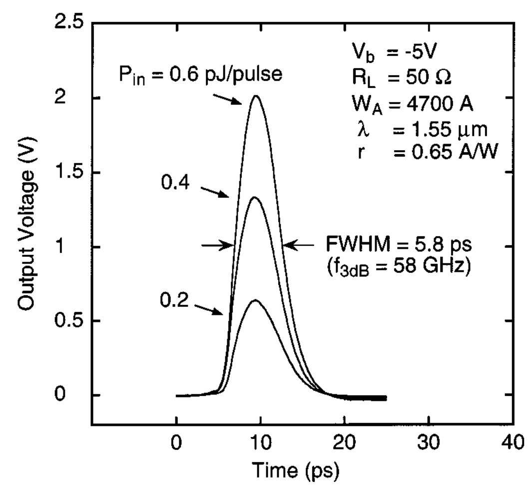

Fig. 5. Photoresponse of a TR-UTC-PD measured by an EOS technique.

area. While the efficiency showed a tendency to increase with increasing W_A, the efficiency for the PD with the TR mirror showed about 1.5 times higher values compared to the normally irradiated ones. The solid curves in the figure were calculated using the same material parameters such as the absorption coefficient [9] and refractivity [10] for both types of devices. Only the signal light propagation direction was different. The reasonable correspondence of these curves with the experimental results indicates that the efficiency is actually increased by the diagonal irradiation using the TR-PD structure. The responsivity for W_A of 4700 A was 0.65 A/W, which is the highest value ever reported for a UTC-PD. Fig. 4 shows the reverse biased I-V characteristics of a fabricated PD in a dark environment. The dark current is less than 10 nA (1.5×10^{-3} A/cm^2) when a reverse bias voltage is lower than 6.8 V. The breakdown voltage, defined as the voltage at a dark current of 10 μA, was 10.8 V. These values are reasonably high for a mesa structure PD with a thin collection layer thickness of 2150 A, and are suitable for practical high-output-power and wide-dynamic-range applications.

Fig. 5 shows a typical photoresponse of a TR-PD measured by the EOS technique at a bias voltage (V_b) of –5 V. The output peak voltage (V_p) increased linearly up to 2.0 V with increasing input power from 0.2 to 0.6 pJ/pulse where the output pulsewidth (FWHM) was maintained at less than 6 ps. The Fourier transform of the highest pulse response with a FWHM of 5.8 ps gives an $f_{3\,\mathrm{dB}}$ of 58 GHz. Fig. 6 summarizes V_p as a function of input power (P_{in}) with V_b as a parameter. Although V_p saturates at higher P_{in} values, it is clear that the region of the linear dependence of V_p on P_{in} expands with increasing V_b and exceeds 2 V for a V_b of –5 V. This wide linearity range is important for analog applications in the microwave photonics area. The saturation behavior is attributed to two mechanisms [3]. The first is the shift in the operating point to the lower reverse bias voltage. The second is the space-charge effect in the collection layer. Although these two mechanisms coexist, their degree of influence changes depending on V_b. When V_b is low, the former is prominent, because the bias point can easily move into the forward condition. On the other hand, when V_b is large, the bias voltage is kept negative. Thus, the space charge effect becomes relatively significant. For the present result, the output saturation is caused basically by the space charge effect even at the lowest V_b of –1 V, where the internal junction voltage is not deeply in the positive region because of a low series resistance of about 4 Ω. For the lower V_b cases in Fig. 6, the saturation occurs very sharply and the saturated V_p is very flat. On the contrary, more gradual saturation is seen for the higher V_b cases. This change is attributed to a difference in the carrier accumulation process in the collection layer, which depends on the diode bias voltage.

Fig. 7 shows the relationship between V_p and $f_{3\mathrm{dB}}$ with V_b as a parameter. The $f_{3\,\mathrm{dB}}$ increases slightly first and then decreases rapidly with increasing V_p. While more gradual decrease is seen for the higher V_b cases, the maximum available V_p with a necessary high $f_{3\,\mathrm{dB}}$ value increases with increasing V_b. The slight increase of $f_{3\,\mathrm{dB}}$ is attributed to the self-bias effect in the absorption layer, while the rapid decrease is associated with the output saturation explained above. A V_p of 1 V (typically required value for the direct drive of digital circuits) with an $f_{3\,\mathrm{dB}}$ of 40 GHz is obtained at V_b of only –1 V. Fig. 8 shows the relationship between V_p and V_b for specific $f_{3\,\mathrm{dB}}$ values. For higher-output-voltage applications, such as the direct driving of $LiNbO_3$ modulators and electroabsorption modulators, the fabricated PD provides the necessary high V_p of 5 V with a high $f_{3\,\mathrm{dB}}$ of 50 GHz, and an even higher V_p of 6 V with an $f_{3\,\mathrm{dB}}$ of 40 GHz, both with V_b of –10 V. These results demonstrate that a combination of the TR configuration with the UTC-PD structure is a promising way to realize a backside-illuminated geometry PD that exhibits high-efficiency, high-speed, and high-output voltage, simultaneously.

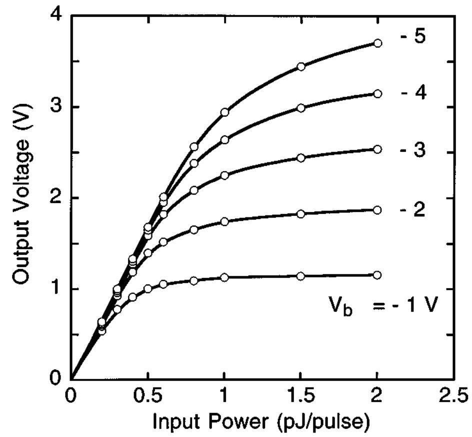

Fig. 6. Output peak voltage as a function of input power with bias voltage as a parameter.

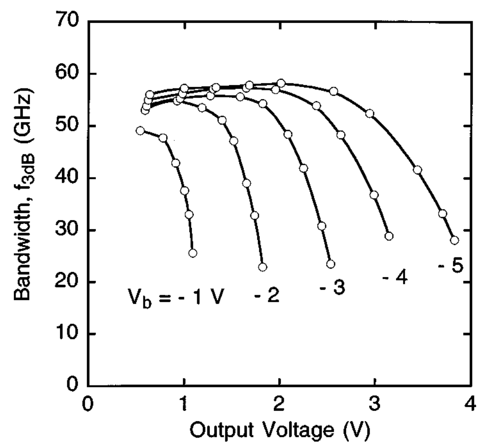

Fig. 7. Relationship between output peak voltage and 3-dB bandwidth with bias voltage as a parameter.

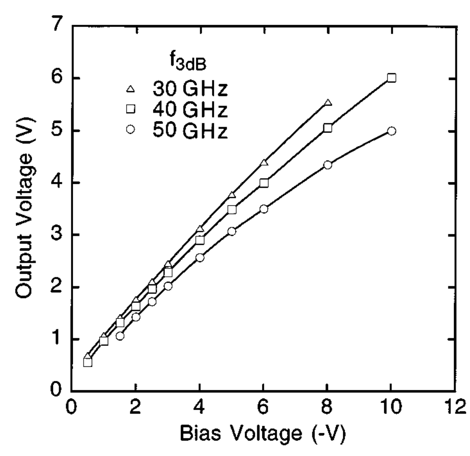

Fig. 8. Relationship between output peak voltage and bias voltage for specific $f_{3\,\mathrm{dB}}$ values.

IV. Conclusion

A novel back-illuminated photodiode with an integrated total-reflection mirror is proposed and characterized. With this configuration, the efficiency is improved by a factor of about 1.5 compared to the normally irradiated case. The dark current of the fabricated PD is less than 10 nA at reverse bias voltages of up to 6.8 V. The highest $f_{3\,\mathrm{dB}}$ obtained is 58 GHz with an output peak voltage of 2.0 V. The fabricated TR-UTC-PD with an absorption layer thickness of 4700 A simultaneously shows a high efficiency of 0.65 A/W, a high 3-dB bandwidth of 50 GHz, and a high-output voltage of 5 V. These results clearly demonstrate that the TR-PD structure is a promising way to improve the efficiency of backside-illuminated geometry PD without reducing its high-speed and high-output-voltage characteristics.

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