High bandwidth surface-illuminated InGaAs/InP uni-travelling-carrier photodetector

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Uni-traveling-carrier photodiodes (UTC-PDs) with ultrafast response and high saturation output are reported. A gradient doping layer and a narrow InP cliff layer were introduced to enhance the saturation and bandwidth characteristics. We measured the dark current, photo response, bandwidth, and saturation current of the fabricated UTC devices. For a 15-μm-diameter device, the dark current was 3.5 nA at a reverse bias of 1 V, and the 3-dB bandwidth was 17.2 GHz at a reverse bias of 5 V, which are comparable to the theoretically values. The maximum responsivity at 1.55 μm was 0.32 A/W. The saturation output current was over 19.0 mA without bias.

Keywords: surface-illuminated uni-traveling-carrier photodiode, InP substrate

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1. Introduction

With the development of modern optical communication, the ever-increasing requirement for high performance optical receivers eventually pushes the carrier frequencies above 100 GHz, where limited solutions are currently available. High saturation output current and high bandwidth photodetectors used in various optical communication systems and for ultrafast measurements have attracted growing interest. In 1997, Ishibashi reported a high-speed and high-saturation uni-traveling-carrier photodiode (UTC-PD) for photo detecting.[1] Recently, the III–V UTC-PDs have been used in wireless communications, spectroscopic measurement systems, and imaging systems.[2]

The main structure difference between the UTC photodiode and the conventional PIN photodiode is that the absorption layer and the space-charge region are separated in the InP/InGaAs UTC-PDs, as shown in Fig. 1. In the conventional PIN photodiode, electrons and holes photo-generated in the depletion absorption layer produce space charge, resulting in field modulation and possible limitations in current densities during high frequency operation. The holes with much lower drift mobility and velocity contribute dominantly to the space charge, and can be more easily decelerated by the induced field modulation. In the UTC-PDs, the majority carriers are holes with short relaxation time in the p-type absorption layer, thus the photon-generated holes are easily recombined with electrons in the absorption layer. The photo-generated electrons drift/diffuse to the depletion region under the self-induced field in the absorption layer, and their velocities overshoot under the applied field in the carrier collecting layer. Therefore, only high-velocity electrons are used as active carriers, which shortens the transition time and delays the onset of the space charge effect for high current operation.[1,3]

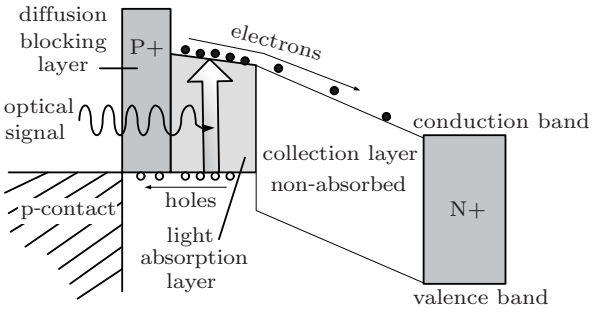


Fig. 1. Band diagram of uni-traveling-carrier photodiode.

The highest speed top-illuminated UTC photodiode reported was fabricated by Nippon Telegraph and Telephone Corporation (NTT) Photonics Laboratories in 2000. The device with 5 μm^2 active area demonstrated a bandwidth up to 310 GHz and a responsivity as low as 0.07 A/W.[6] Reducing the size and the thickness of the absorption layer was the major reported approach to get a higher bandwidth.[4–6] Our research group also carried out studies on UTC photodiodes. In 2010, the space-charge-screening effect in the carrier concentration and the space electric field in the UTC photodiode were analyzed based on the drift–diffusion model.[7] In 2012, we demonstrated that the saturation characteristics were enhanced obviously by introducing a cliff layer and a gradually doped absorption layer, and the collapse of the electric field in the absorption layer led to the saturation.[8] However, those two works just focused the theoretical and simulation analysis of the devices. In this paper, we report our recent experimental

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study of top illuminated uni-traveling-carrier photodiodes and give a comparative analysis.

2. Device fabrication

The UTC photodiodes studied in this paper were grown on semi-insulating InP substrates by metal-organic chemical vapor deposition (MOCVD). The UTC-PD structure parameters are shown in Table 1. The doping levels are 2×10^{18} cm^{-3} and 2×10^{17} cm^{-3} on the barrier side and the collector side, respectively. The absorption layer consists of un-doped 35-nm-thick $In_{0.53}Ga_{0.47}As$ and 665-nm-thick grading doped P-$In_{0.53}Ga_{0.47}As$. The doping difference generates a step-like potential profile in the conduction band, which can help the electrons diffuse more rapidly into the collector. The collection layer is an intrinsic 600-nm-thick InP layer. Here, a heterojunction transition layer was inserted to lower the potential spike produced at the absorption layer/collection layer interface, and improve the electric intensity on the InGaAs side to accelerate the electrons traveling through the heterojunction barrier.[8] The diffusion-block layer is a 700-nm-thick P-$In_{0.78}Ga_{0.22}As_{0.47}P_{0.53}$ layer.

Table 1. Epitaxial structure of UTC-PD.

Material	Thickness/nm	Doping/cm^{-3}	
P-$In_{0.53}Ga_{0.47}As$	20	$>5\times10^{18}$	P$^+$ contact layer
P-1.2 μm-$In_{0.78}Ga_{0.22}As_{0.47}P_{0.53}$	700	$>5\times10^{18}$	
P-$In_{0.53}Ga_{0.47}As$	665	grading from 2×10^{17} to 2×10^{18}	absorption layer
U-$In_{0.53}Ga_{0.47}As$	35	intrinsic	
U-1.3 μm- $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$	10	intrinsic	
U-1.08 μm- $In_{0.87}Ga_{0.13}As_{0.28}P_{0.72}$	10	intrinsic	heterojunction transition layer
N-InP	10	5×10^{17}	
N-InP	600	1×10^{16}	collection layer
N-InP	750	$>5\times10^{18}$	N$^+$ contact layer
N-$In_{0.53}Ga_{0.47}As$	20	$>5\times10^{18}$	
Buffer		buffer	
S.I.-InP substrate	350		

A double mesa structure was defined by ultraviolet lithography followed by dry etching in an inductively coupled plasma (ICP) etcher. In the first mesa process, the diodes were patterned. A controlled etch stop in the n$^+$-InP layer was necessary, since the thickness of the n$^+$ layer must be as large as possible to achieve a small series resistance. Then a second mesa etching step down into the S.I.-InP subtract was performed to define the n contact. The metal contacts were formed by depositing and patterning an Ni/Ge/Au metal stack on the top mesa for p-type Ohmic contact and an Au/Zn/Au metal stack on the second mesa for n-type Ohmic contact. A plasma enhanced chemical vapour deposition (PECVD) oxide was used to passivate the mesa. The devices were fabricated on circular mesas with diameters of 15 μm, 20 μm, 40 μm, 60 μm, and 80 μm, respectively.

3. Characterization of UTC-PDs

As we know, the most relevant figures of merit for a photodetector are the dark current, the responsivity (in units of A/W), the response speed (in terms of response time or bandwidth in hertz), and the saturation current (maximum output current). Here we present our experimental results on these characteristics and a comparative analysis.

3.1. Dark current

Figure 2 shows the *I*–*V* characteristic of UTC photodetectors. Under −1 V bias, dark currents of 3.5 nA, 3.8 nA, 4.0 nA, 4.3 nA, 8.0 nA were obtained for the devices with diameters of 15 μm, 20 μm, 40 μm, 60 μm, 80 μm, respectively, As we know, the dark currents in junction photodiodes are relevant to the generation in the space charge region, diffusion from the quasi-neutral regions, and surface leakage.[9] And the surface leakage is most important for our vertical mesa device structure. Thus, an anisotropic etched profile, a smooth and residue-free surface, and an appropriate passivation are very important for the UTC-PD to reduce the sidewall leakage current.

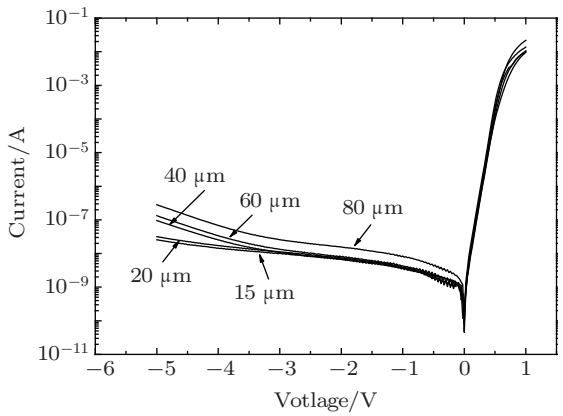


Fig. 2. Dark currents of UTC photodetectors with diameters of 15 μm, 20 μm, 40 μm, 60 μm, and 80 μm.

3.2. Responsivity

The responsivity R at normal incidence can be expressed as[9]

$$R = \frac{\lambda}{1.24}\eta = \frac{\lambda}{1.24}(1-\theta_{\rm R})\eta_{\rm in}(1-{\rm e}^{-\alpha W_{\rm a}}), \quad (1)$$

where λ is the vacuum wavelength of the incident radiation (in units of μm), η is the quantum efficiency (the conversion efficiency of photons to electrons), $\theta_{\rm R}$ is the reflectivity at the input interface, $\eta_{\rm in}$ is the internal quantum efficiency, α is the optical absorption coefficient (in units of $\rm cm^{-1}$), and $W_{\rm a}$ is the thickness of the absorption layer. We assume $\alpha = 7.5\times10^3$ $\rm cm^{-1}$ for $\rm In_{0.53}Ga_{0.47}As$.[10] When the thickness of the absorption layer is 0.7 μm and the input optical wavelength is 1.55 μm, the responsivity of the UTC photodetector can be expressed as

$$R = \frac{\lambda}{1.24}\eta \approx 0.507(1-\theta_{\rm R})\eta_{\rm in}. \quad (2)$$

Thus, the responsivity of the UTC-PD is less than 0.5, which is limited by the thickness of the absorption layer and the input optical wavelength.

In the experiment, the photocurrent of the UTC-PD was measured with a monochromatic light source (wavelength 1.55 μm and optical power 0.5 mW). The light was normal incident on the top surface of the device. Figure 3 shows the typical *I*–*V* characteristics of the UTC photodiode of 15 μm in diameter with and without illumination. The responsivity was about 0.2 A/W, which is related to the area of the effective aperture of the device. For the 30-μm-diameter UTC-PD, the responsivity was increased to 0.32 A/W and the quantum efficiency was 25%. According to formula (2), the responsivity can be increased by the optimization of the antireflection coating material and the thickness. Moreover, a waveguide or backside-illuminated[11] UTC device structure also can increase the responsivity efficiently.

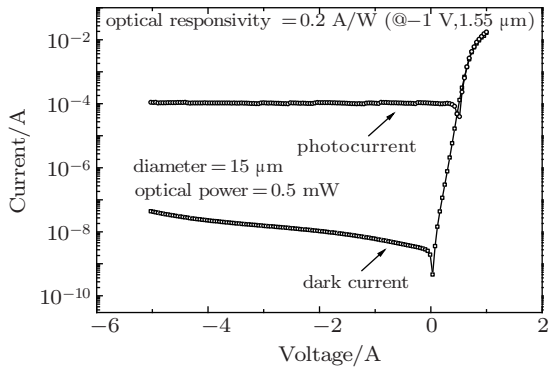


Fig. 3. The responsivity of UTC photodetectors of 15 μm diameter.

3.3. The 3-dB bandwidth

The UTC-PD is basically a PIN-PD with an active grading doped p-type absorption layer and an un-doped wide-gap carrier-collection layer (Fig. 1). In the absorption layer, electrons and holes are generated by photo excitation. Holes as the majority carriers respond quickly with dielectric relaxation time, and electrons as the minority carriers diffuse (and drift) into the collection layer. The doping gradient in the absorption layer introduces a band gap gradient and yields a potential gradient, which can be incorporated to generate a quasi-field to effectively accelerate the electrons. The wide-gap diffusion block layer is placed on the p-contact side of the absorption layer to avoid the back diffusion of electrons toward the anode, as shown in Fig. 1. Since holes are the majority carriers with negligible dielectric relaxation time, their transport is a collective motion, thus the absorption layer response is primarily determined by the electron transport. High mobility and high drift velocity of electrons are essential in minimizing the absorption layer traveling time. Moreover, due to the electron velocities overshoot in the collection layer, the collection layer traveling time can be much smaller than that in the absorption layer in a typical structure with similar absorption and collection layer thicknesses ($W_{\rm a} \sim W_{\rm c}$). The overshoot velocity of electron in the collection layer is about one order of magnitude larger than the hole saturation velocity. This difference provides a much higher carrier-transport-limited bandwidth for the UTC-PD. Thus, the operation speed of the UTC device is determined by the electron transit time in the absorption and the collect layers, which also can be proved by the following theoretical calculations.

The bandwidth of the UTC photodiode is mainly limited by the *RC* delay of the device and the carrier transit time in the active region. The 3-dB bandwidth can be obtained approximately via the following equation:

$$f_{\rm 3dB} = \frac{1}{\sqrt{f_{\rm t}^{-2} + f_{RC}^{-2}}}. \quad (3)$$

Here, the *RC* bandwidth f_{RC} can be calculated by

$$f_{RC} = \frac{1}{2\pi RC} = \frac{2W_{\rm a}}{r\varepsilon_{\rm i}\pi^2 D^2} f_{RC} = \frac{1}{2\pi RC} = \frac{2W_{\rm a}}{R\varepsilon\pi^2 D^2}, \quad (4)$$

where $W_{\rm a}$ is the thickness of the absorption layer, $\varepsilon_{\rm i}$ is the permittivity of the intrinsic layer, and D is the mesa diameter. Based on the drift–diffusion model and the small-signal model, the transit-time-limited bandwidth $f_{\rm t}$ is given by[3]

$$f_{\rm t} = 1/(2\pi\tau_{\rm a}) = 1/[2\pi(W_{\rm a}^2/3D_{\rm e} + W_{\rm a}/v_{\rm th})], \quad (5)$$

where $D_{\rm e}$ is the electron diffusion coefficient, $v_{\rm th}$ is the thermionic emission velocity, and $W_{\rm a} = W_{\rm c}$ is assumed. In the calculations, we assume thermionic emission velocity $v_{\rm th} = 2.5\times10^7$ cm/s[1] and electron diffusion coefficient $D_{\rm e} =$ 300 $\rm cm^2/s$.[12] When the thickness of the absorption layer is 0.7 μm, the transit-time-limited bandwidth is 19.3 GHz. Moreover, we assume an intrinsic Si collection layer thickness of 0.7 μm, a mesa diameter of 15 μm, a permittivity

of 12.5 for InP,[11] and take the 50 Ω cable impedance into account. Then, we obtain a 114 GHz *RC*-limited bandwidth. Consequently, an f_{3dB} of 18.7 GHz can be attained in the UTC photodiode with 15 μm diameter. Therefore, the f_{3dB} of UTC-PDs is basically determined by the traveling time, and W_a is a decisive structure parameter for the bandwidth of the UTC photodiode.

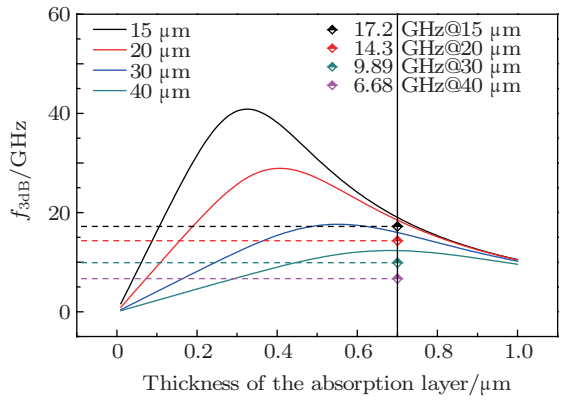


Fig. 4. (color online) The theoretical predicted value and measured result of the frequency response for UTC photodetectors with different diameters under 1.55 μm illumination.

The optoelectronic frequency response was measured on-wafer with a network analyzer in the range from 0.8 GHz to 20 GHz. The theoretically predicted values and the measured results of the frequency response for the UTC photodetectors with diameters of 15 μm, 20 μm, 30 μm, 40 μm under 1.55-μm illumination are shown in Fig. 4. A 17.2 GHz of 3-dB bandwidth was achieved for the device with a 15 μm diameter at bias voltage −5 V, which is slightly lower than the theoretically predicted value of 18.7 GHz. It is found that the thickness of the absorption layer has a significant influence on the 3-dB bandwidth of the UTC device. To attain high speed operation of the UTC photodiode, it is essential to decrease the thickness of the absorption layer, however, it also results in the decreases of quantum efficient and responsivity. Therefore, in order to get high bandwidth and high responsivity simultaneously, waveguide and backside-illuminated UTC-PDs are better choices.[13]

3.4. Saturation

Under high carrier injection, mobile space charge accumulates in the depletion layer of photodiodes, which decreases the electric field and bends the energy band of the PDs. Then, the decrease of the electric field drastically reduces the carrier velocity, enhances the charge storage, and eventually deteriorates the linearity of response and results in an output saturation current.[14] The saturation situations are similar between the UTC-PD and the PIN-PD. However, for the UTC-PD, the space charge consists of only electrons whose velocities are much higher than those of holes. Therefore, the photocurrent does not saturate until the current density becomes an order of magnitude higher than that for the PIN -PD. Figure 5 illustrates the band diagrams of the saturation processes for the UTC-PD and the conventional PIN-PD.

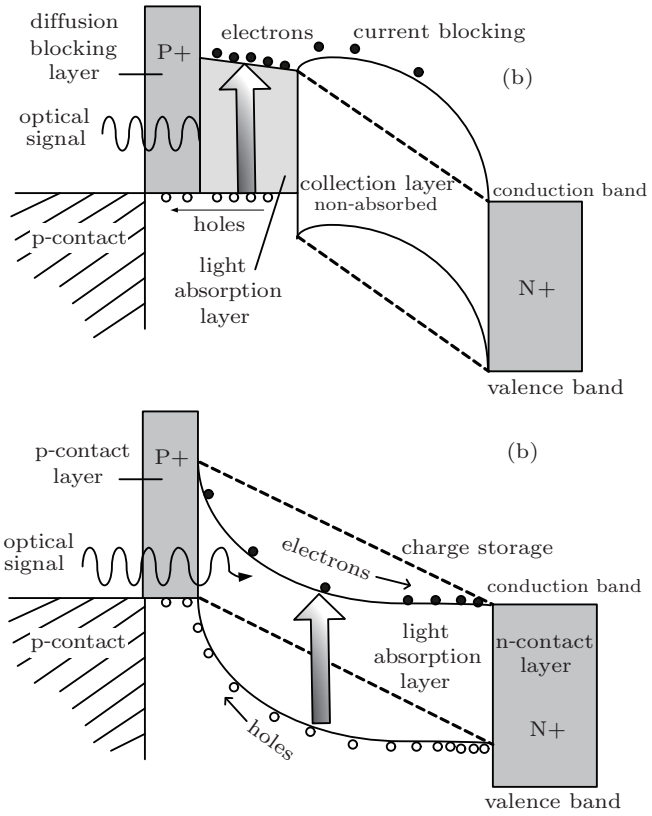


Fig. 5. Band bending at high photo-current density operations: (a) UTC-PD, (b) PIN-PD.

Beyond a critical current density J_{max}, the field modulation starts to lower the carrier velocity and results in saturation. Such J_{max} values at steady states can be estimated using carrier saturation velocities v_e^s/v_h^s and the critical electric fields E_e^c/E_h^c. The corresponding critical carrier densities are simply calculated by solving the Poisson's equation as follows:[3]

$$n_c - N_D = \frac{2\varepsilon[-V_{bias} + V_{bi} - E_e^c W_c]}{qW_c^2}, \tag{6}$$

$$p_c = \frac{6\varepsilon[-V_{bias} + V_{bi} - E_h^c W_c]}{qW_c^2}, \tag{7}$$

where N_D is the background donor density in the collection layer, ε is the dielectric constant, V_{bias} is the applied voltage, and V_{bi} is the built-in voltage. The critical current density J_{max} can be approximated by

$$J_{max}(\text{UTC}) = qn_c v_e^s, \tag{8}$$

$$J_{max}(\text{PIN}) = qp_c v_n^s. \tag{9}$$

If we assume $v_e^s = 4 \times 10^7$ cm/s for InP and $v_h^s = 5 \times 10^6$ cm/s for InGaAs, the maximum current output of the UTC-PD is 3 times higher than that of the PIN-PD.[1]

The current–voltage characteristics were measured at different incident optical powers under the illumination of

1.55 μm. Light from a wavelength fixed laser source was amplified by an erbium-doped optical fiber amplifier (EDFA) and then coupled into a detector through a plane fiber probe with a beam diameter of 9 μm. The maximum output optical power from the EDFA was 120 mW. Because of the connector coupling loss, the fiber loss, and the coupling loss between the fiber and the device, actually the light reaching the top surface of the detector was almost 100 mW. Without bias, no compression of the DC photocurrent was observed and the output optical current was 19.0 mA.

4. Conclusion

We have investigated high output and fast response heterostructure photodiodes by utilizing UTC to simultaneously decrease the junction capacitance, transmission line impedance, and carrier transit time. The devices were grown on InP substrates by MOCVD. With an output voltage of −1 V, the 15-μm-diameter device showed a dark current of 3.5 nA, a responsivity of 0.2 A/W under the illumination of 1.55 μm, and a 3-dB bandwidth up to 17.2 GHz, which are similar with the theoretical results obtained via small signal analysis. The measurement with DC excitation showed that the saturation power of the photodetector was above 100 mW of the optical power, and the maximum output current was above 19.0 mA. Compared with the conventional PIN detectors, the UTC-PDs have the advantages on the bandwidth and output current. In the future, we will investigate the waveguide or backside-illuminated UTC device structure to increase the responsivity and bandwidth simultaneously.

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