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High-Photocurrent and Wide-Bandwidth UTC Photodiodes with Dipole-Doped Structure

Q. Q. Meng, H. Wang, C. Y. Liu, K. S. Ang, X. Guo, B. Gao, Y. Tian, C. M. Manoj Kumar, and J. Gao

***Abstract*—InP-based uni-traveling-carrier photodiodes (UTC-PDs) with novel dipole-doped structure to achieve high photocurrent as well as wide bandwidth are demonstrated in this work. The dipole-doped layers in combination with a 22-nm-thick undoped InGaAs setback layer were employed at the InGaAs/InP absorption and collection interface to reduce the current blocking effect. A high photocurrent of 160 mA with 1.9 GHz 3-dB bandwidth from a 70-µm-diameter top-illuminated UTC-PD is achieved. A large 3-dB bandwidth of 62.5GHz, which is estimated with an equivalent circuit model, has also been obtained from a 12-µm-diameter UTC-PD device. The results demonstrate that the dipole-doping can serve as an effective alternative to the quaternary InGaAsP layer at InGaAs/InP interface for InP-based UTC-PD to suppress the current blocking and reduce the complexity in epi-layers growth and device fabrication.**

***Index Terms*—Dipole-doped layer, high speed, photocurrent, uni-traveling-carrier photodiodes (UTC-PDs), 3-dB bandwidth.**

I. INTRODUCTION

HIGH-photocurrent and high-speed photodiodes (PDs) have attracted intensive research interests for the application of CATV network, photonic analog-to-digital converter and optical links to phased array antenna [1, 2]. To meet the requirements for both high photocurrent and high speed operation, various types of photodiodes have been investigated. Conventional PIN-PD [3] is one of the simplest PD structures which is used for a wide range of applications. In a conventional PIN-PD structure, both electrons and holes are photo-generated in the depletion layer. The holes with much lower drift mobility and velocity, contribute dominantly to the space charge and can result in the degradation of device performance, especially under high power illumination [1].

Hence, Ishibashi *et al.* [1] proposed a new type of photodiode - uni-traveling-carrier photodiode (UTC-PD) which could achieve high speed and high photocurrent operation simultaneously. Compared to PIN-PD, the UTC-PD has a unique mode of operation where only faster electrons serve as the active carriers, which can reduce the space charge effect and lead to much higher current and higher speed operations [4]. Due to this advantage, UTC-PD has attracted a great research attention for very promising high-photocurrent and high-speed devices. For a typical UTC-PD which has an p-type doped InGaAs absorption layer and a wide InP collector, to suppress the current blocking and improve the device bandwidth and power/current handling capability, InGaAsP compositional graded quaternary structures are employed at the InGaAs/InP heterostructure interface to smooth the bandgap discontinuity. However, the presence of compositional graded InGaAsP layers at InGaAs/InP interface could result in the complexity and difficulty in the material growth and subsequent device fabrication. In this work, UTC-PDs with novel dipole-doped InGaAs/InP structure without using InGaAsP quaternary are reported. The dipole-doped UTC-PDs have demonstrated good figure of merit (FOM) with high photocurrent as well as high speed performance. The use of dipole-doped interface may ease the material growth and device fabrication without compromising the device performance.

II. DEVICE STRUCTURE AND FABRICATION

Table I shows the detailed layer structure comparison between the conventional UTC-PDs with InGaAsP quaternary structure [5] (left column) and the UTC-PDs with novel dipole-doped structure developed in this work (right column). Both structures are similar, with the exception at the InGaAs/InP interface, where it has been highlighted. Generally, InP-based UTC-PD consists of a p-type narrow-bandgap InGaAs light absorption layer and an n-type wide-bandgap InP carrier collection layer. The abrupt energy barrier at InGaAs/InP absorption/collection interface can block electron flow, cause a buildup of stored charge, degrade DC performance at high current densities and also limit the high-speed performance. To overcome this problem, compositional graded InGaAsP layers were normally inserted between the InGaAs absorption and InP collection layers [5, 6]. However, the insertion of the InGaAsP layers often results in the difficulty in growth process as well as results in the complexity of device fabrication.

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TABLE I. STRUCTURE COMPARISON BETWEEN CONVENTIONAL UTC-PD AND NOVEL DIPOLE-DOPED UTC-PD

Conventional InGaAs/InP UTC-PD with InGaAsP quaternary structure			**InGaAs/InP UTC-PD with novel dipole-doped structure**		
Layer	**Thickness (nm)**	**Doping (cm^{-3})**	**Layer**	**Thickness (nm)**	**Doping (cm^{-3})**
InGaAs	30	p:1×10^{19}	InGaAs	30	p:1×10^{19}
InP	200	p:1×10^{19}	InP	200	p:1×10^{19}
InGaAs	50	p:2×10^{18}	InGaAs	50	p:2×10^{18}
InGaAs	100	p:1×10^{18}	InGaAs	100	p:1×10^{18}
InGaAs	300	p:5×10^{17}	InGaAs	300	p:5×10^{17}
InGaAs	15	undoped	InGaAs	22	undoped
InGaAsP	15	n:5×10^{16}	InGaAs	8	p:1×10^{18}
InGaAsP	15	n:5×10^{16}	InP	8	n:1×10^{18}
InP	5	n:5×10^{17}	InP	13	n:1×10^{17}
InP	200	n:5×10^{16}	InP	200	n:5×10^{16}
InP	600	n:5×10^{18}	InGaAs	30	n:5×10^{18}
S. I. – InP substrate			InP	600	n:5×10^{18}
			S. I. – InP substrate		

In our UTC-PD structure, novel dipole-doped layers, in combination with a 22-nm-thick undoped InGaAs setback layer were employed at the InGaAs/InP absorption and collection interface to reduce the current blocking effect. The dipole-doped layers consist of an 8-nm-thick InGaAs layer and an 8-nm-thick InP layer, both of which have been p- and n-type doped with the concentration of 1×10^{18} cm^{-3}. The dipole-doped UTC-PD structures used in this work were grown by molecular beam epitaxy (MBE). Beryllium was used for the p-type dopant and Silicon for the n-type.

Figure 1 shows the band diagram simulation of a UTC-PD with and without dipole-doped structure, which has been obtained by using a 1-D simulator. The solid line and dashed line represent the the band profiles with and without dipole-doped structure, respectively. The inset also presents the enlarged conduction band diagram near the InGaAs/InP heterointerface. It is noted that, by incorporating a dipole-doped structure, the effective energy barrier at the InGaAs/InP interface can be reduced by ~0.2 eV. Not only the energy barrier is reduced, which facilitates the electrons easily thermionic emission across, but also the thickness of the triangular well is reduced, which could enhance electrons tunnel through the junction barrier. Therefore, the reductions on the barrier height and thickness may substantially suppress the current blocking.

Top-illuminated dipole-doped UTC-PDs with double cylindrical mesas of different diameters varied from 12 to 80 μm were fabricated using standard processing techniques. Overall, 7 optical masks, 35 structures including complete UTC-PDs and test structures, have been taped-out for fabrication of UTC-PDs. The 1st p-mesa wet etch stopped at the n-InGaAs to define the active area. The 2nd n-mesa wet etch was terminated at the semi-insulating substrate. A Ti/Au/Ni metal stack was used for both p- and n-metal non-alloy ohmic contacts. After BCB via opening, GSG (Ground-Signal-Ground) contact pads and a dielectric-supported connection to the top p-contact layer were fabricated for high-speed measurements. The responsivity and high speed response characteristics of the fabricated dipole-doped UTC-PDs have been tested with an Agilent Lightwave Component Analyzer (LCA), incorporated with an Erbium Doped Fibre Amplifier (EDFA). The modulated light coming out from the LCA is amplified by the EDFA and coupled into the devices under testing. As an example, a device under testing for responsivity and high speed performance is shown in the inset of Fig. 2. The left port of the device is connected with microwave probe and the optical fibre is used to couple the pumping light. In fact, the modulation index achieved using an LCA maybe a little over-estimate the photocurrent compared to a signal generated by an heterodyne set-up.

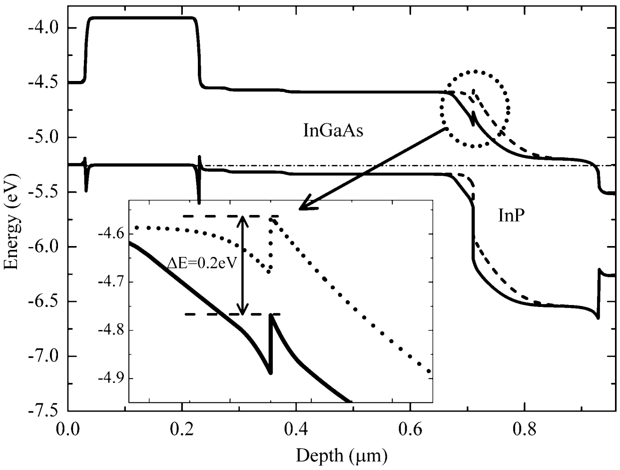

Fig. 1. Comparison between energy band profiles of a UTC-PD with (solid line) and without (dashed line) dipole-doped structure. Inset: Conduction band discontinuity at the InGaAs/InP (absorption/collection) interface.

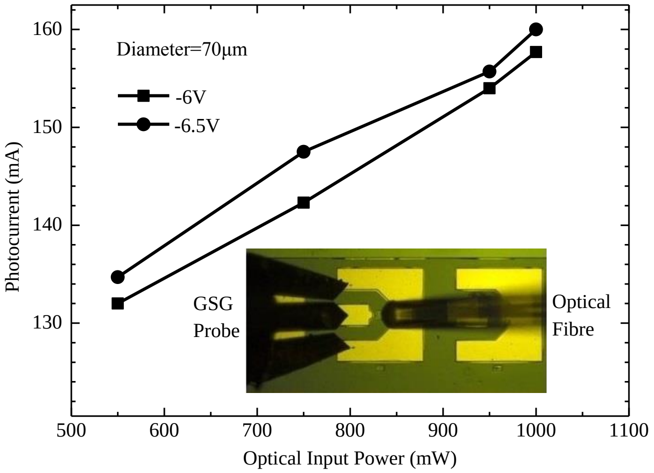

Fig. 2. Measured photocurrent of a top-illuminated 70-μm-diameter dipole-doped UTC-PD under reverse bias of 6V and 6.5V with input optical power of 550mW, 750mW, 950mW and 1000mW. Inset: A device under testing.

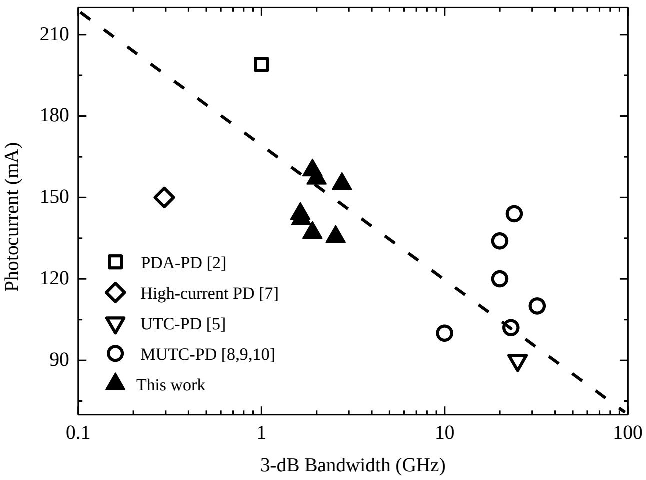

Fig. 3. High photocurrents reported for various PDs.

III. RESULTS AND DISCUSSION

Dipole-doped UTC-PDs with different diameters were measured with photocurrent and S-parameters under different reverse biases and optical pumping power conditions at 1.55 μm wavelength. The measured photocurrent of a top-illuminated 70-μm-diameter dipole-doped UTC-PD as a function of optical power under different reverse-bias voltages are shown in Fig. 2. The photocurrent increases with the increase of the input optical power. A high photocurrent of 160 mA is achieved with a 1.9 GHz 3-dB bandwidth under 6.5 V reverse bias voltage. No saturation of photocurrent was observed. The measurement was limited by the maximum power (1000 mW of our EDFA). With higher optical pumping power, even higher photocurrent should be anticipated.

The comparison of the FOM of the dipole-doped UTC-PDs with other high-photocurrent and high-speed PDs reported in the literature [2, 5, 7-10] is shown in Fig. 3. It can be seen that the UTC-PDs with a dipole-doped InGaAs/InP interface are on par with other high-current PDs, in which InGaAsP quaternary layers are used to smooth the conduction band discontinuity. The result suggests the effectiveness of using dipole-doping to minimize the current blocking and space charge effects. This can be further validated by the measurement of 3-dB bandwidth for the dipole-doped UTC-PDs. If the presence of conduction band discontinuity at InGaAs/InP interface resulted in a significant electron pile-up and current blocking at the InGaAs/InP interface, the carrier transport from InGaAs absorption region to InP collector would be slowed down. Poor frequency response of the device should be expected.

Fig.4 (a) shows typical frequency responses as a function of biasing voltage measured from a 12-μm-diameter dipole-doped UTC-PD when the optical input power is 100mW. The device exhibits a large 3-dB bandwidth, which is far beyond 20 GHz (limitation of measurement equipment) and it is estimated to be around 62.5 GHz at a photocurrent of 7.33mA with an equivalent circuit model when the reverse bias is 6 V. Fig. 4 (b) shows frequency responses as a function of input power measured from a 12-μm-diameter dipole-doped UTC-PD under the reverse bias of 5V. The device demonstrates good 3-dB bandwidths more than 20GHz nearly at all the optical input power levels. It is worth mentioning that, by replacing the InGaAsP ternary layer with a simple dipole-doped structure, the device speed performance is not compromised at all. The high photocurrent and large bandwidth in our UTC-PDs clearly demonstrate that the use of dipole-doping can effectively reduce the barrier height at InGaAs absorber and InP collect interface, which facilitates the electrons' thermionic emission and tunneling across the InGaAs/InP junction [11, 12].

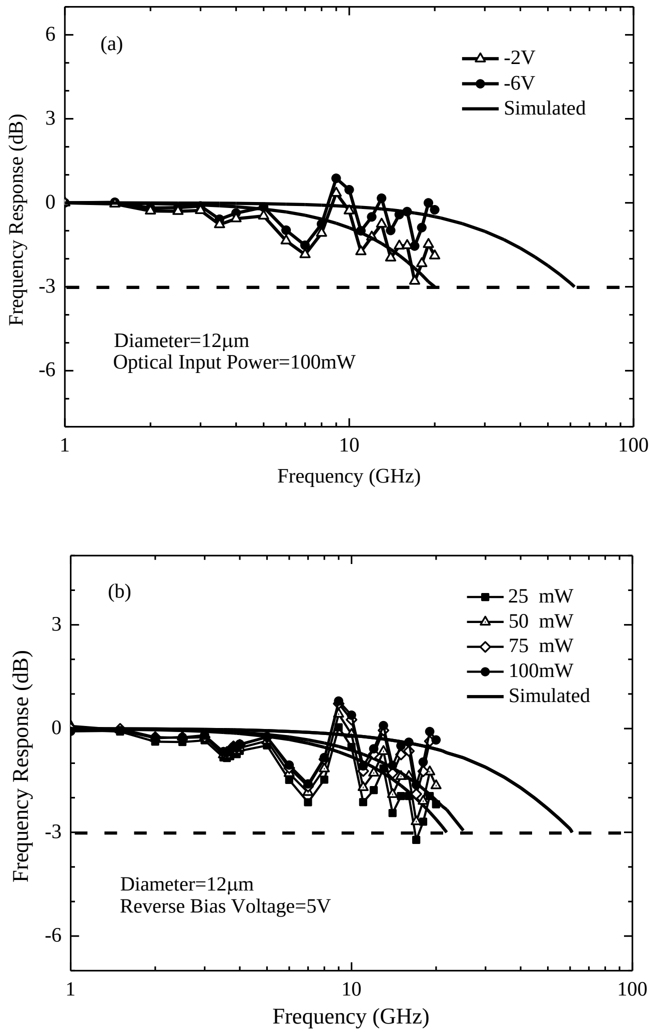

Fig. 4. (a) Measured (line with symbols) and simulated (solid line) frequency responses of a 12-μm-diameter UTC-PD with dipole-doped structure under -2 V and -6 V bias when the optical input power is 100mW. (b) Measured (line with symbols) and simulated (solid line) frequency responses of a 12-μm-diameter UTC-PD with dipole-doped structure under -5V bias when the optical input power is 25mW, 50mW,75mW and 100mW, respectively.

IV. CONCLUSION

In this paper, UTC-PDs with novel dipole-doped structure have been presented for the first time. The devices with high photocurrent and large bandwidth were demonstrated. The results suggest that the simple dipole-doping can serve as an effective alternative to the quaternary InGaAsP layer at InGaAs/InP interface for InP-based UTC-PDs to suppress the current blocking and reduce the complexity in epi-layers growth and ease device fabrication.

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