# Front-Side-Illuminated InGaAs/InP Modified UTC-Photodiodes With Cliff Layer

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In microwave photonic applications, there is a growing need for analog optical links for systems such as phased arrayed radar and optical signal processing systems [1]. To reduce the loss and to increase the dynamic range of the microwave analog optical links, it is necessary to use photodiodes with high power handling capability and high linearity [2]. While space charge effects are one of the main factors limiting the high-power behavior in photodiodes [3], uni-travelling-carrier photodiodes (UTC-PDs) can effectively suppress the space-charge effect and increase the output current, by designing the structure so that only electrons contribute to the external photocurrent [4]. The UTC-PD bandwidth and output power performance can be further enhanced by an insertion of both an undoped optical absorption layer [5] and a charge-compensation layer [6][7], resulting in a modified UTC-PD (MUTC-PD) with cliff layer [7]. In this work, we have experimentally demonstrated the fabrication and characterization of a front-side illuminated InGaAs/InP MUTC-PD with cliff layer.

The heterostructure used to fabricate the InGaAs/InP MUTC-PD was grown on a semi-insulating InP substrate by MOCVD. As shown in Fig. 1, the heterostructure consists of a 50 nm p-type $GaAs_{0.5}Sb_{0.5}$ anode contact layer followed by a 100 nm p-type InP carrier blocking layer to prevent electrons from entering the anode contact. The use of GaAsSb for the anode provides a more favorable energy band alignment than with more conventional InGaAs contact layer. The light is absorbed in both a 700 nm thick graded p-type $In_{0.53}Ga_{0.47}As$ absorption layer and a 150 nm lightly n-doped $In_{0.53}Ga_{0.47}As$ absorption layer, and photogenerated electrons are collected using a 50 nm InP cliff layer, 900nm thick InP depletion layer and 20 nm thick n-type $In_{0.53}Ga_{0.47}As$ cathode contact layer. InP cliff layer serves to mitigate the space-charge effect at high photocurrent levels [7]. InGaAsP layers in the heterostructure are used to minimize the band discontinuity between InGaAs and InP. The device was fabricated by e-beam evaporation of Ti/Au anode contacts, mesa wet etching, thermal evaporation of AuGe/Ni/Au cathode contact, benzocyclobutene (BCB) sidewall passivation, reactive ion etching (RIE) of BCB vias, RF pad deposition (by e-beam evaporation) and optical window definition. The schematic cross-section of the fabricated device is shown in Fig. 2.

The dark current of the photodiodes has been measured experimentally from 0 V to 5 V. By measuring devices with areas ranging from 152 to 1128$\mu m^2$ (Fig. 3(a)), the dark current was found to linearly scale with the junction area, as shown in Fig. 3 (b). At a reverse bias of 5 V, the dark current density is $1.30\times10^{-2}$ A/cm$^2$. The voltage dependence of the photodiode capacitance was also measured; as shown in Fig. 4, the devices are fully depleted at around -7 V.

The responsivity of the devices under DC illumination at 1.55 μm was measured to be 0.24 A/W. No antireflection coating was used in these devices. Since the surface material $GaAs_{0.5}Sb_{0.5}$ produced a light reflectivity of 32.8% under normal incidence, the inclusion of an anti-reflection coating could enhance the photodiode responsivity to 0.36 A/W. The responsivity could be further enhanced using a back-side-illuminated structure, as the effective absorption length is doubled as a result of the reflection from the anode contact [8].

Fig. 5(a) shows the photodiode frequency response when biased at -8 V, for different optical illumination intensities. The 3 dB bandwidth of a 27 μm-diameter photodiode increases from 8.8 GHz to 12.8 GHz with an increase of photocurrent density from 1.7 A/cm$^2$ to $3.4\times10^2$ A/cm$^2$. This nonlinear bandwidth expansion arises because increased optical generation produces an increase in the internal electric field in the absorption region that accelerates the electrons, which enhances the high-speed performance of the photodiode [9]. Fig. 5(b) shows the inverse area dependence of the 3 dB bandwidth, for a photocurrent of approximately 100 μA. The RC time constant $\tau_{RC}$ and carrier transit time $\tau_{tr}$ were extracted by curve fitting. The carrier transit time $\tau_{tr}$ was found to be 8.91 ps, which includes the carrier diffusion time in the undepleted absorption layer as well as carrier drift time in the depletion region. This results in an effective velocity of $2.19\times10^7$ cm/s, consistent with expectations for transport in InP. The $\tau_{RC}$ was found to be 1.20 μs/cm$^2$. Since the load for these measurements was 50 Ω, the resulting capacitance was observed to be $2.39\times10^{-8}$ F/cm$^2$, which agrees well with the capacitance measurement of $2.03\times10^{-8}$ F/cm$^2$ at full depletion. These devices are promising for emerging RF photonics applications.

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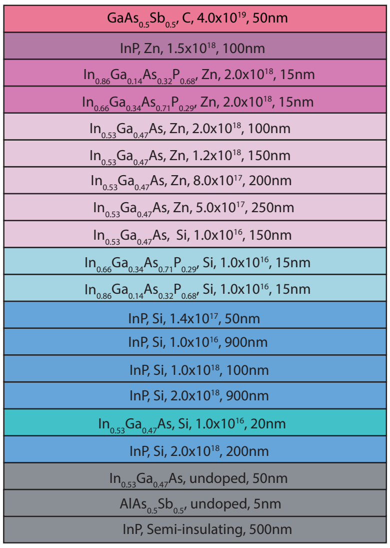



Fig.1. Heterostructure of InGaAs/InP MUTC-PD [7]

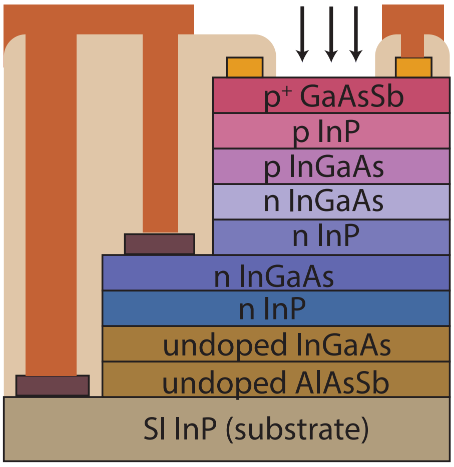
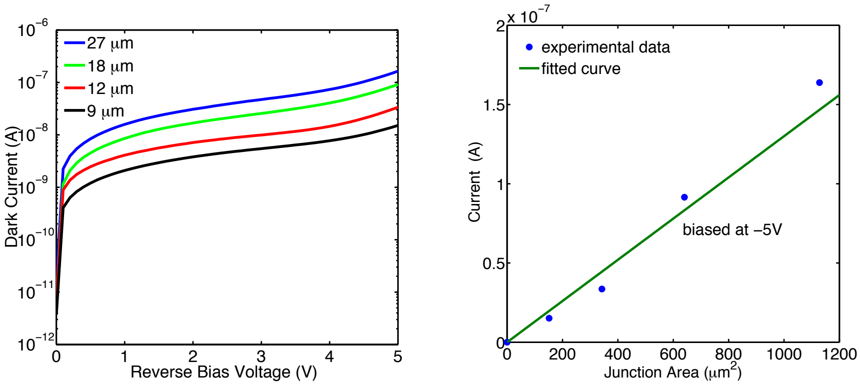



Fig.2 Cross-sectional schematic of front-side illuminated InGaAs/InP MUTC-PD fabricated in this work.




(a) (b)

Fig.3. Dark current (a) reverse bias dependence; (b) junction area dependence at -5V bias

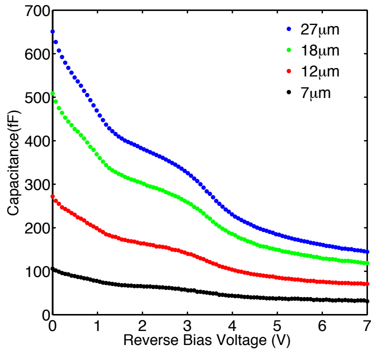
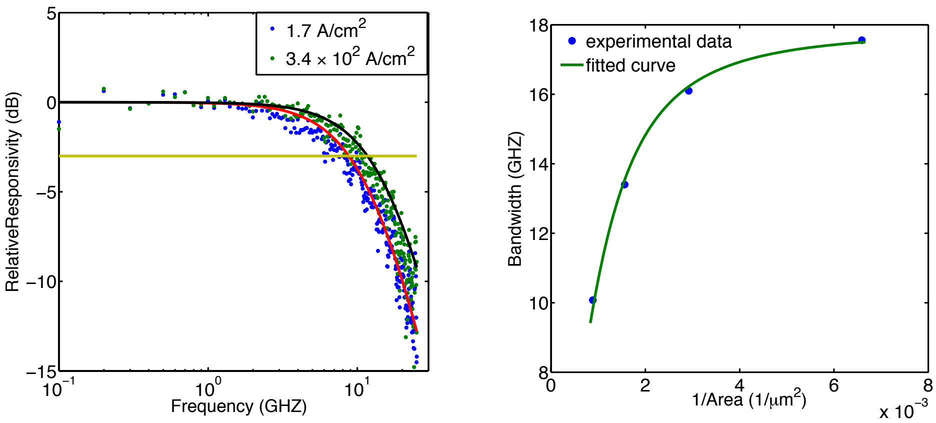



Fig.4. Capacitance-voltage (1 MHz) relationship for MUTC-PD in this work.




(a) (b)

Fig.5. A (a) Frequency response for 27um-diameter device at different photocurrent levels; (b) area dependence of 3 dB bandwidth for photocurrent of approximately 100 μA.