High-Speed Low-Temperature-Grown GaAs p-i-n Traveling-Wave Photodetector

Yi-Jen Chiu, *Student Member, IEEE,* Siegfried B. Fleischer, and John E. Bowers, *Fellow, IEEE*

***Abstract*—WE report a novel type of p-i-n traveling-wave photodetector utilizing low-temperature-grown GaAs (LTG-GaAs). The devices show a record impulse response time (530-fs full-width at half-maximum, ∼560 GHz −3-dB bandwidth) which agrees with theoretical estimates. The effects of various limiting factors on the device performance were analyzed theoretically and compared with measurements obtained by electrooptic characterization of our devices. Calculations indicate that the device speed is dominated by the short carrier lifetime. DC external quantum efficiencies as high as 8% were obtained.**

***Index Terms*—Current distribution, electrooptic measurements, low-temperature grown GaAs, photodetector, p-i-n photodiodes, semiconductor device, traveling-wave devices, ultrafast electronics.**

LOW-TEMPERATURE-GROWN GaAs (LTG-GaAs) has attracted a lot of interest recently because of its potential for optoelectronic devices applications. Due to the short carrier trapping time in LTG-GaAs, photodetectors can be made with a picosecond or subpicosecond response [1]–[3]. Vertical metal–semiconductor–metal (MSM) photodetectors have very low fabrication cost and can be designed for low capacitance resulting in high-speed performance. Such MSM photodetectors, however, suffer from a limited bandwidth-efficiency product. Edge-coupled traveling-wave photodetectors (TWPD), both of MSM and p-i-n type [4]–[6], have been demonstrated with high speed and high bandwidth-efficiency product. The tradeoff between efficiency and bandwidth can be eliminated in the TWPD. Impedance matching of the TWPD to the load circuit make it possible to overcome the *RC*-limit inherent to lumped element designs. In this work, we improved the processing in the previous work [5] and successfully fabricated a p-i-n TWPD with low-temperature-grown GaAs (LTG-GaAs) as the absorption layer (i-layer), thus combining the advantages of the TWPD with the short carrier lifetime in the LTG-GaAs material. The fabricated devices showed a subpicosecond response ranging from 530- to 1.1-ps FWHM. The measured impulse responses agree well with theoretical predictions which indicate that the fast response time is primarily caused by the short carrier trapping time in LTG-GaAs intrinsic region.

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The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106 USA.

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The material was fabricated by MBE. The epilayers were grown on a semi-insulating GaAs substrate using a As2 to Ga pressure ratio of 12. The p-i-n structure was grown at high temperatures except the LTG-GaAs i-layer (170 nm) which was grown at 215 °C and subsequently in-situ annealed at 590 °C for 10 min. The n- and p-layers (600 nm $Al_{0.2}Ga_{0.8}As$) were deposited at 570 °C. The device fabrication followed standard p-i-n processing steps including RIE etching, metallization for the p- and n-contacts, and polyimide passivation. The details of material growth and processing are reported in [5]. In [5], there is considerable misalignment between the n- and p-contacts, which caused excess capacitance. The photolithography was improved and the speed was enhanced by around 50%.

Pump-probe electrooptic sampling was used to measure the impulse response. The optical pulses were obtained from a modelocked Ti:sapphire laser with ∼150-fs pulsewidth and ∼100-MHz repetition rate. A $LiTaO_3$ crystal was utilized to detect the electrooptic signal [7]. The detectors were biased at −3 V for these measurements. To ensure that the devices were operated in the linear regime, the optical power level was lowered until the signal shape was independent of input power.

Fig. 1(a) shows the electrooptical impulse response, which exhibit pulsewidths as short as ∼570-fs FWHM (top). The FWHM of this measured impulse response is comparable to the finite optical pulsewidth. The detector response was, therefore, deconvolved to account for the induced broadening. After this correction a FWHM of only 530 fs (the dotted bottom curve) was obtained. Fig. 1(b) shows the corresponding Fourier transform of the measured and corrected signals. The −3-dB bandwidths are 520 and 560 GHz, respectively. DC photocurrent measurements revealed external quantum efficiencies as high as 8% (without AR coating).

To gain further insight into the device performance, we adopted a simple model to describe the device response. Three important aspects that determine the device performance were included in the simulation. 1) The distributed nature of the TWPD was modeled as a series of photodetectors. After the optical excitation the pulse travels through the detectors and a distributed photocharge is generated that excites a microwave pulse which is collected at the output. 2) To model the electrical transmission line properties an equivalent circuit model was used [8], [9]. It included transmission line losses and dispersion. 3) The detector was analyzed in its linear operation regime (i.e., without power-dependent, carrier-screening effects), in agreement with the experimental conditions. Neglecting nonlinear effects leads to a linear rate equation for the local material response which is solved by a

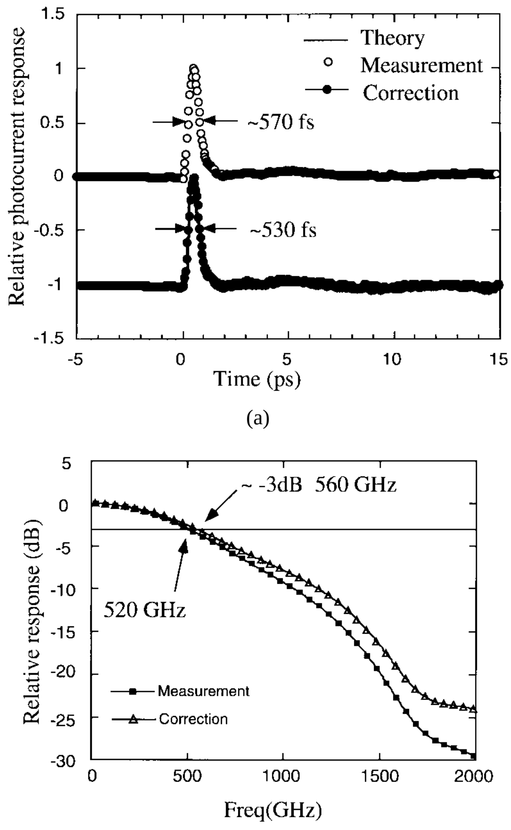

Fig. 1. (a) The top curve is the measured electro-optical response. The bottom curve (dot) show the response after deconvolving the finite pulsewidth of optical excitation, and the bottom solid curve is theoretical prediction. (b) The corresponding Fourier transform of the measured and corrected signals.

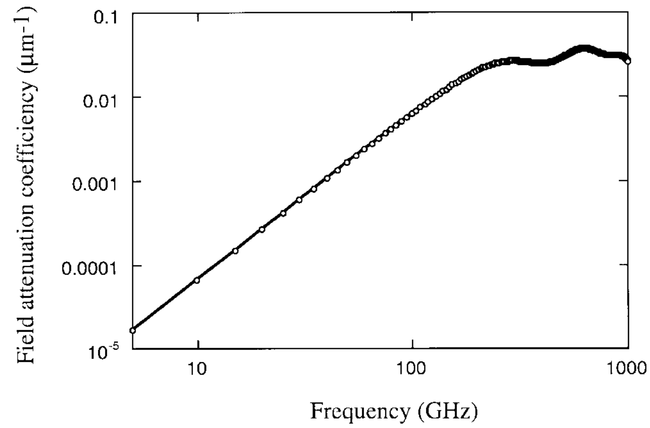

Fig. 2. The microwave field attenuation coefficient versus the frequency.

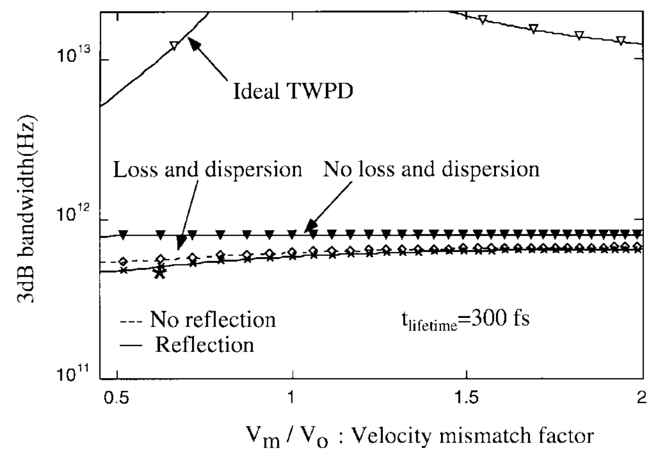

Fig. 3. The −3-dB bandwidth with velocity mismatch factor ($v_m/v_o, v_m$: Microwave velocity; v_o: Optical velocity). The "*" point is the experiment results.

simple exponential decay [10]. LTG-GaAs material grown and annealed under identical conditions as the material used for the fabrication of the detectors showed a ~300-fs decay rate in pump-probe measurements. The LTG-GaAs carrier lifetime was thus assumed to be 300 fs in the modeling. The total detector response which accounts for the distributed nature of the photocurrent, was then obtained by integration (see [11]). Device dimensions of 1 μm width, 10 μm length, and 0.17 μm thickness of LTG-GaAs were modeled in agreement with the fabricated structure.

Several factors affect the impulse response of traveling-wave photodetectors, namely the loss and dispersion of the microwave transmission line, the velocity mismatch between optical and electrical waves, the reflection at the input end of the microwave waveguide, the intrinsic material response (carrier life time), and the carrier transit across the active region.

The attenuation of the microwave signal on the traveling-wave transmission line was determined by comparing the measured impulse response of photodetectors with 25 and 10-μm length. Fig. 2 shows the results of this measurement. The field attenuation coefficient was found to be below 0.02 μm^{-1} for subterahertz frequencies. For detectors with a length in the range of 5–20 μm, the microwave loss is therefore below 2 dB up to several hundreds of GHz. The modal optical absorption coefficient is around 0.5 μm^{-1} limiting the region of interaction between optical and electrical waves to about 6 μm. This length is short enough to neglect the velocity mismatch [4]. This is further illustrated in Fig. 3, which shows the bandwidth dependence as a function of the velocity mismatch ratio (V_m/V_o: microwave velocity relative to optical velocity). The top curve of Fig. 3 shows an ideal TWPD (ignoring microwave loss, dispersion, reflection at the input and carrier lifetime) which gives optimal performance when velocity matched ($V_m/V_o = 1$). However, once the carrier lifetime is included, the response is almost flat for a large range of velocity mismatch ratios (V_m/V_o:0.5–2). Other factors (loss, dispersion and reflection) also have only little effect on the resulting bandwidth.

The absorption layer thickness of 170 nm suggests a carrier transit time considerably slower than both the 500-fs photocurrent response and the 300-fs carrier lifetime. Consequently, the detectors fast response is primarily determined by short carrier lifetime. For comparison the mark "*" in Fig. 3, it shows our experiment result consistent with the theoretical predictions.

Fig. 4 summarizes the calculated impulse response as a function of the effective carrier lifetime. The *RC*-imposed bandwidth limit is also shown on the bottom of Fig. 4, where a vertical structure with the same active area and i-layer

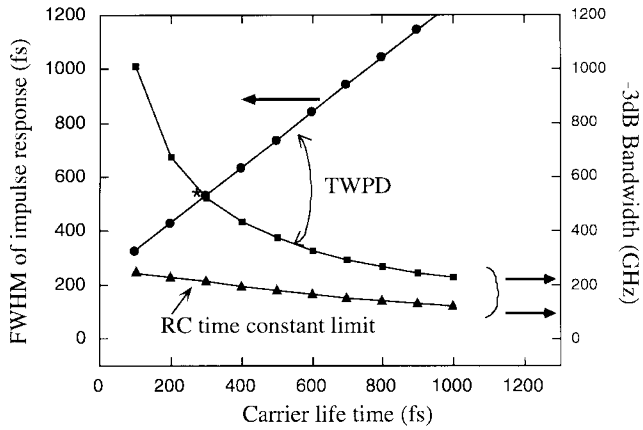

Fig. 4. The calculated impulse response versus the effective carrier lifetime. The top two curves are the TWPD response for time response (FWHM) and frequency response (−3 dB bandwidth). The bottom is *RC*-imposed bandwidth limit. The measured response is marked with a "*" in Fig. 4.

thickness was assumed. The measured response is marked with a "*" in Fig. 4. The large improvement in bandwidth of the TWPD compared to an *RC*-limited lumped-element detector proved that this limitation was overcome in the TWPD. This is particularly evident in the short carrier lifetime regime.

The low dc quantum efficiency (∼8%) is due to the tradeoff between efficiency and bandwidth. Since the photodetector efficiency is proportional to the ratio of carrier lifetime to transit time acrose the absorption layer, the bandwidth is increased at the expense of efficiency.

In summary, we have demonstrated a novel type of p-i-n photodetector which incorporates low-temperature grown GaAs. The device shows a subpicosecond impulse response and the device performance was found to be much improved by the short carrier lifetime.

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