High-Speed and High-Power Performances of LTG-GaAs Based Metal–Semiconductor–Metal Traveling-Wave-Photodetectors in 1.3-μm Wavelength Regime

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***Abstract*—In this letter, we demonstrated ultrahigh bandwidth and high output power performances of low-temperature-grown (LTG) GaAs-based metal–semiconductor–metal traveling wave photodetectors (MSM TWPDs) in the long wavelength regime ($\sim$1300 nm). Ultrahigh bandwidth (1.3-ps pulsewidth with 234 GHz transformed 3-dB electrical bandwidth) was achieved with long-absorption-length (70-μm) devices due to the improved microwave property in the MSM TWPDs and their high velocity-mismatch bandwidth. Under high optical power illumination, these 70-μm-long MSM TWPD devices also exhibited superior output power-bandwidth-product performance due to their large absorption volumes. To the best of our knowledge, the demonstrated peak-output-voltage-bandwidth product (3.55 V, 160 GHz, 568 GHz-V) is the highest among the reported photodetectors for long optical communication wavelength (1.2 μm–1.6 μm) applications.**

***Index Terms*—Low-temperature-grown GaAs, metal–semiconductor–metal photodetectors, p-i-n photodetector, self-alignment, traveling-wave photodetectors, ultrahigh bandwidth photodetectors.**

LOW-TEMPERATURE-GROWN GaAs (LTG-GaAs) based photodetectors (PDs) merit a lot of attentions due to their short response time, high electrical bandwidth [1], [2], low dark current, and their ability to integrate with other microwave devices such as antenna [3]. However, the wide absorption band gap ($\sim$800 nm) of LTG-GaAs restricts its applications from long wavelength (1300–1550 nm) optical communications. In the long wavelength regime, several picosecond response time has been obtained from LTG-InGaAs-based PDs, which is much longer than the sub-picosecond response time of LTG-GaAs-based PDs in the shorter wavelength regime [4], [5]. Recently, several research groups had demonstrated LTG-GaAs-based p-i-n/n–i–n, and metal–semiconductor–metal (MSM) high-speed PDs by using vertical-illuminated or edge couple traveling wave structure in the long optical communication wavelength regime [6]–[8]. The below band-gap photon-absorption in LTG-GaAs is achieved by utilizing mid-gap defect state to conduction band transitions. However, with a much smaller below-bandgap absorption constant than the normal band-to-band absorption constant [7], the achieved quantum efficiency is extremely low ($\sim$0.6 mA/W) with traditional vertical-illuminated PDs structure [8]. Regarding edge couple p-i-n/n-i-n traveling wave PDs structure, the problem of low efficiency can be overcome by properly increasing the device absorption length. Besides, the available maximum output power in these low-modal-absorption and long-length PDs also has the potential to be improved significantly [9]. Although the available maximum output power increases with the device absorption length, the electrical bandwidth will degrade seriously due to serious microwave loss, low velocity mismatch or R-C limited bandwidth in p-i-n-based waveguide structure [9][10].

In this letter, we demonstrate ultrahigh bandwidth and high peak power performances of long-absorption-length MSM traveling wave photodetectors (MSM TWPDs) [11] with LTG-GaAs absorption layer under long wavelength excitation ($\sim$1300 nm). With an absorption length of 70-μm, the responsivity of the LTG-GaAs-based MSM TWPDs was found to be greatly improved to $\sim$13 mA/W under 18-V bias. Greater bandwidth performance than a comparison (40 μm-absorption-length) p-i-n TWPD was also observed due to enhanced microwave velocity and low microwave loss in MSM microwave guiding structure [10]. The 70 μm-absorption-length MSM TWPDs showed a transient impulse response which has full-width-half-maximum (FWHM) less than 1.3 ps with a corresponding 234-GHz 3-dB electrical bandwidth, even in the high output peak photocurrent regime ($\sim$25 mA, 50-Ω load). Combined with the capability of suffering high bias voltage without breakdown, these MSM TWPDs demonstrated excellent peak-voltage-bandwidth product performance. Compared with state of the art InP-based unitraveling carrier photodetector (UTC-PD) in long-wavelength regime [12]–[14], our transient measurement results exhibit better peak voltage-bandwidth product performances (3.55 V, 160 GHz, 568 GHz-V).

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The structure of the measured MSM-TWPDs are similar to previously reported MSM TWPDs [11] except for a modification in the optical waveguide structure for the purpose of better optical wave guiding in long wavelength regime, and the modified thickness for each epi-layer from top to bottom is 500 nm for LTG-GaAs, 100 Å for AlAs, 400 nm for $Al_{0.2}Ga_{0.8}As$, 1 μm for $Al_{0.3}Ga_{0.7}As$, and 3 μm for $Al_{0.7}Ga_{0.3}As$. All samples were annealed in MBE chamber at 600 °C with detail fabrication processes given in [11]. The waveguide width is 2 μm with a device absorption length of 70 μm for complete absorption. We employed a Cr^{4+}: forsterite laser operating at 1230 nm, which mimics the telecommunication wavelength of 1300–1550 nm, as the light source for dc (direct current) IV and transient electrooptical (EO) sampling [15] measurements. Our previous studies had shown that LTG-GaAs has similar carrier dynamics for the excitation wavelength of ~1230 and ~1550 nm [16]. We have also performed a comparison measurement in an LTG-GaAs-based p-i-n TWPD [10] with the same measurement setup in order to investigate the microwave behavior of MSM TWPD. The comparison p-i-n TWPD has a 40-μm device absorption length, 0.9-μm waveguide width, and 250-nm LTG-GaAs active layer thickness. The waveguide width of the comparison p-i-n TWPD is narrower than its MSM counterpart (0.9 μm versus 2 μm) due to that the microwave performance of p-i-n waveguide is more easily degraded with increased waveguide width than that of the MSM structure [10]. The growth and annealing condition of LTG-GaAs photoabsorption layer was the same as that of the MSM TWPDs. The device responsivity under 70-pJ/pulse excitation (including coupling and reflection loss) was ~11 mA/W at 5-V bias for p-i-n TWPD and with the same value at 15-V bias for MSM TWPD. The breakdown voltages of MSM and p-i-n TWPDs were around 20 and 7 V, respectively. With increased bias voltage up to 18 V in the MSM TWPDs, its responsivity (external quantum efficiency) can be further increased to ~13 mA/W. The quantum efficiency of MSM TWPDs could be further improved by longer device absorption length and wider waveguide width, while the later implied better coupling efficiency [10]. Compared with previously reported LTG-GaAs-based vertical-illuminated MSM PD (MSM VPD) under long wavelength excitation [8], our obtained quantum efficiency was already over twenty times better. This significant improvement in quantum efficiency was due to long absorption length with the edge-coupled structure and the self-aligned fabrication process [10].

The transient impulse responses and corresponding bandwidth performances of this device were measured by an EO sampling system [15] driven by the 1230 nm Cr^{4+}: forsterite laser. The optical pulsewidth (FWHM) of the mode locked Cr^{4+}: forsterite laser was 130 fs with 110-MHz repetition rate. With the EO measured impulse response, the peak output photocurrent can be calculated from the area of each impulse response, the measured average photocurrent, and the repetition rate of mode-locked laser. In order to ensure that the measured devices were excited in the linear regime without bandwidth saturation, the input optical power was reduced to the level that the shape of measured impulse response was independent of input optical power, which corresponded to ~30-mA peak photocurrent for both the MSM TWPDs and the comparison p-i-n TWPD. Fig. 1 shows the measured impulse response of the MSM TWPD with an obtained impulse response FWHM less than 1.3 ps. The peak current was around 25 mA with 50-Ω load and 4-V bias voltage, and the transformed 3-dB electrical bandwidth of 234 GHz was shown in the inset of Fig. 1. Take p-i-n TWPD as a comparison, within the same peak output photocurrent regime (~28.7 mA), the comparison p-i-n TWPD showed a ~1.5-ps response time with 200 GHz transformed 3-dB electrical bandwidth (Fig. 2). Although the MSM TWPD had a longer device length (area), it still showed better bandwidth performance due to its superior microwave guiding property [10]. This measurement result thus confirmed our previous theoretical study [10] that the bandwidth of long-absorption length TWPD can be improved by MSM structure.

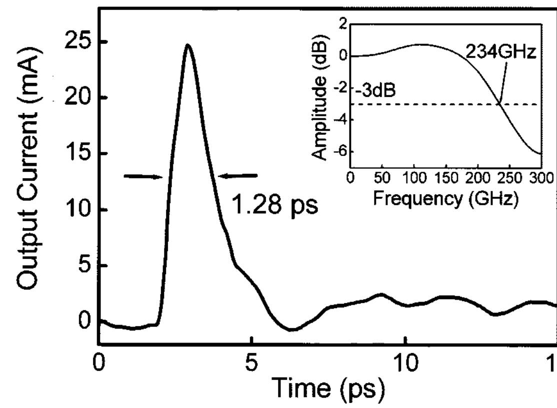

Fig. 1. EO measured transient response of a 70-μm-long MSM TWPD. Inset shows its corresponding frequency domain response with fast-Fourier transform.

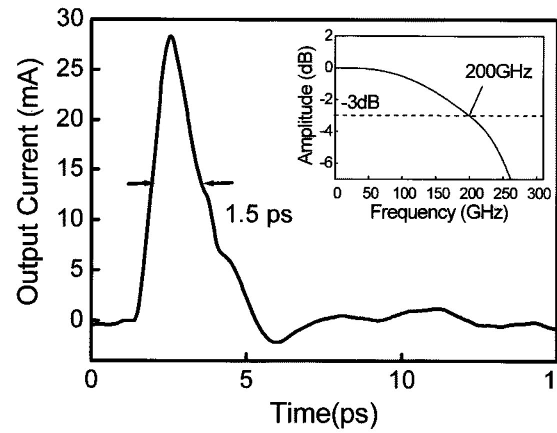

Fig. 2. EO measured transient response of a 40-μm-long p-i-n TWPD. Inset shows its corresponding frequency domain response with fast-Fourier transform.

The ultrahigh-speed performance observed in the low-modal-absorption and long-device-length LTG-GaAs-based MSM TWPD implies its high output power/bandwidth product advantage. Compared with the high-power InP-based UTC-PD [12]–[14], our device shows a better product value between bandwidth and peak-output-voltage. The peak output voltage (or power) and the electrical bandwidth of an ultrahigh speed photodetector are usually two tradeoff parameters, which also

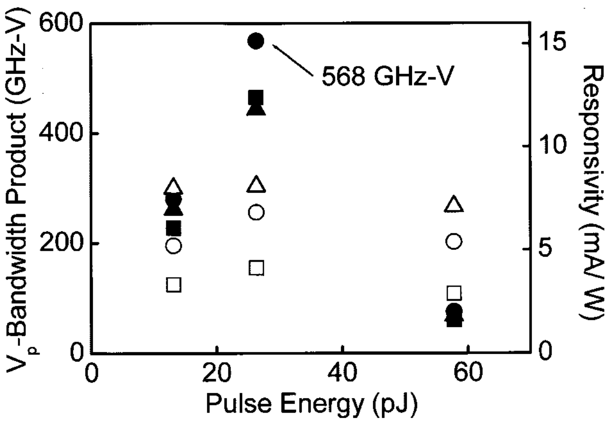

Fig. 3. V_p (output peak voltage)-bandwidth product (solid symbols) and responsivity (open symbols) versus optical excitation energy for different bias voltages. The maximum peak voltage bandwidth product corresponds to 160-GHz bandwidth and 3.55-V peak output voltage at 10-V bias voltage (indicated by arrow). Solid (open) squares, solid (open) circles, and solid (open) triangles correspond to the V_p-bandwidth product (responsivity) at bias voltages of 5, 10, and 15 V, respectively. The obtained responsivity increased with bias voltage. The responsivity under 15-V bias with a 70-pJ excitation energy is 11 mA/W (not shown).

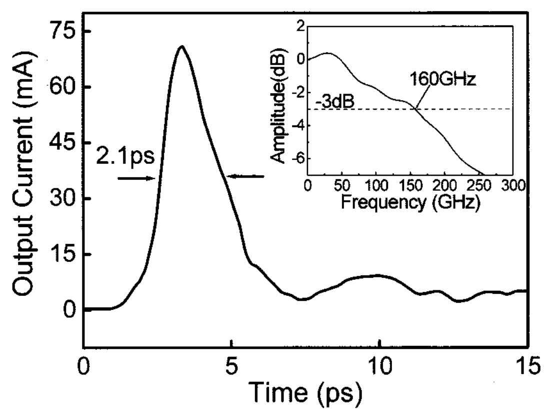

Fig. 4. EO measured transient response of a 70-μm-long MSM TWPD corresponding to the best V_p-bandwidth product condition. Inset shows its corresponding frequency domain response with fast-Fourier transform.

depend on the applied bias and the illuminated optical power. In order to explore the best combinations of bias point and illuminated optical power level for the best power-bandwidth product performance in our device, we measured the impulse response and peak output photocurrent under different bias and different input optical pulse energies. Fig. 3 plots the V_p (output peak voltage)-bandwidth product and responsivity versus input pulse energy for different bias levels of measured MSM TWPDs. The peak output voltage was calculated by multiplying the peak photocurrent with a 50-Ω load. The best operation points for the input optical pulse energy and bias voltage are about 28 pJ/pulse and 10 V, respectively. The maximum V_p-bandwidth product of 568 GHz·V corresponds to a 160-GHz 3-dB electrical bandwidth and a 3.55-V peak output voltage (with 71-mA peak current and 50-Ω load), with its corresponding impulse and frequency responses shown in Fig. 4.

In summary, we have demonstrated the ultrahigh-speed/bandwidth and high-power performances of a novel LTG-GaAs-based long-absorption-length MSM TWPD under long wavelength excitation ($\sim$ 1300 nm). Ultrahigh bandwidth (1.3-ps pulsewidth with 234 GHz transformed 3-dB electrical bandwidth) was achieved with long-absorption-length (70 μm) devices due to the improved microwave property in the MSM TWPDs and their high velocity-mismatch bandwidth. Under high-power illumination, these 70-μm-long MSM TWPD devices also exhibit superior power-bandwidth-product performance due to their large absorption volumes, superior microwave guiding structure, short carrier trapping time of LTG-GaAs, and the ability to suffer high bias voltage without breakdown. To the best of our knowledge, the demonstrated peak-output-voltage-bandwidth product (3.55 V, 160 GHz, 568 GHz·V) is the highest among the reported photodetectors for long optical communication wavelength (1.2 –1.6 μm) applications.

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