Ultrahigh-Power-Bandwidth Product and Nonlinear Photoconductance Performances of Low-Temperature-Grown GaAs-Based Metal–Semiconductor–Metal Traveling-Wave Photodetectors

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***Abstract*—Maximum-output-power and bandwidth performances are usually two tradeoff parameters in the design of high-speed photodetectors (PDs). In this paper, we report record high-peak output voltage ($\sim$ 30 V) together with ultrahigh-speed performance (1.8 ps, 190 GHz) observed in low-temperature-grown GaAs (LTG-GaAs)-based metal-semiconductor-metal (MSM) traveling-wave photodetectors (TWPDs) at a wavelength of 800 nm. Ultrahigh-peak output power and ultrahigh-electrical bandwidth performances were achieved due to superior MSM microwave guiding structure, short carrier trapping time, and the capability to take high bias voltage ($\sim$ 30 V) with a LTG-GaAs layer. Under such a high bias voltage, a significant nonlinear photocurrent increase with the bias voltage was observed. The nonlinear photoconductance and ultrahigh-output power-bandwidth performances opens a new way in the application of high-performance optoelectronic mixers and photomixer devices.**

***Index Terms*—Metal–semiconductor–metal (MSM), nonlinearities, photodetectors (PDs), traveling-wave devices.**

THE TWO major trends in the development of ultrahigh-speed photodetectors (PDs) are improving bandwidth-efficiency product and obtaining high-output power-bandwidth product [1]. For the PDs with high-output power-bandwidth product, they can find applications in low-cost photoreceiver circuits without electrical amplifiers [1], microwave photonics systems [2], and optoelectronic generation of high-power microwaves and millimeter waves [3]. Maximum-output-power and electrical bandwidth performances are two tradeoff parameters in the design of high-speed PDs [1]. By reducing optical modal absorption constants and increasing photoabsorption lengths (volumes) in edge-couple PD structures, the device's output power can increase significantly [4], [5]. However, in these high-power PDs, the electrical bandwidth would decrease seriously due to R-C or velocity mismatch bandwidth limitations and serious high-frequency microwave loss [6]. There are two major ways to increase the product performance of output current (power) and electrical bandwidth. One is to distribute the photocurrents along edge-coupled PDs, such as the velocity matched distributed photodetector (VMDP) [7]; the other is to increase the carrier velocity using a unitraveling carrier PD [8]. In this letter, we report record-high peak output voltage-bandwidth product performance ($\sim$ 30 V, 190 GHz, 5.7 THz-V) of low-temperature-grown GaAs (LTG-GaAs)-based MSM traveling wave photodetector (MSM-TWPD) [9] under high optical excitation energy ($\sim$ 71 pJ/pulse) and a high bias voltage level (30 V), which was measured using an electrical–optical (EO) sampling station based on a femtosecond Ti:sapphire laser at 800 nm. By utilizing the MSM microwave guiding structure, a large photoabsorption volume can be achieved without obvious electrical bandwidth degradation [6]. The serious space charge screening effect under high-power illuminations in most high-power PDs has also been reduced with LTG-GaAs photoabsorption layer due to its short carrier trapping time and the fact that most of the collected photogenerated carriers are from the regions near metal contacts where least space charge screening effects occur [1], [10]. The capability to take high dc bias voltages (30 V) in a MSM-TWPD also reduces the external circuit saturation effect [10] and improves its maximum output peak voltages. Compared with the maximum allowable bias voltage of molecular beam epitaxy (MBE) annealed MSM-TWPDs [11], the demonstrated rapid thermal annealing (RTA) annealed devices show superior capability to take even higher bias voltages and to deliver even higher output powers. Under such a high dc bias voltage, a significant nonlinear photocurrent increase has also been observed, which are possibly originated from carrier capture-time increasing [12] or avalanche breakdown effects.

The cross-sectional schematic diagram and top view of the measured MSM-TWPDs are similar to those of the devices previously reported in [9]. The samples were annealed in a RTA chamber at 600 °C with the rest of the fabrication processes similar to those in [9]. The absorption length and waveguide width of the measured device are 12 and 2 μm, respectively, and the corresponding photoabsorption volume is about 12 μm^3, which

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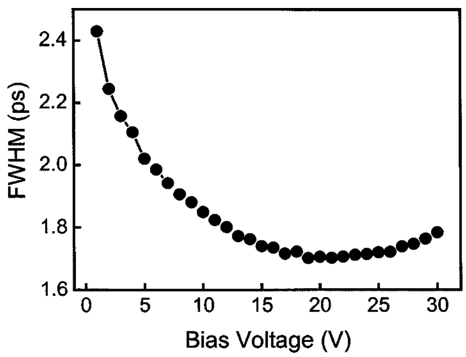

Fig. 1. FWHM of the measured transient responses of a 12-μm-long MSM TWPD under different bias voltages with a fixed optical excitation energy (71 pJ/pulse).

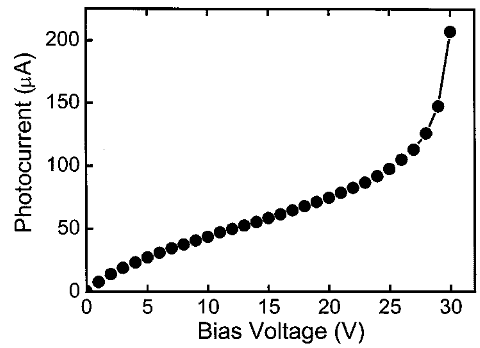

Fig. 2. Measured average photocurrent versus bias voltage with a fixed optical excitation pulse energy of 71 pJ.

is much larger than the general absorption volumes of ultrahigh-speed PDs ($\sim$ 1 μm^3) [7]. Larger photoabsorption volume can release the required high density of photogenerated carriers for high output currents and, thus, reduce the high-density induced space charge screening effect [1], [10]. Regarding with the traditional p-i-n TWPD structure, larger photoabsorption volume can be achieved by increasing the device absorption length and waveguide width. However, the electrical bandwidth will degrade more significantly because of serious high-frequency microwave losses and lower velocity mismatched bandwidths [6]. With respect to MSM-TWPD, by utilizing the MSM microwave guiding structure, the propagation microwave mode would be "quasi-TEM mode," which has a higher microwave velocity and a lower microwave loss compared with the "slow wave mode" in a p-i-n structure [13]. The superior microwave guiding property of the quasi-TEM mode will ensure that the electrical bandwidth performance is less sensitive to the device absorption length and higher power bandwidth product performances can, thus, be expected. Compared with the traditional high-power/bandwidth MSM VMDPs [7], the electrical bandwidth of our structure is not limited by the Bragg cutoff frequency [14], which is a non-negligible problem in VMDPs when the device bandwidth is over 200 GHz.

We employed a mode-locked Ti:sapphire laser as the light source for the impulse response EO sampling measurements, which has a center wavelength at 800 nm. The full-width at half-maximum (FWHM) of the optical pulses was 100 fs with a 100 MHz repetition rate. Fig. 1 shows the FWHM of the EO measured electrical impulse response versus bias voltage in the high optical excitation energy regime ($\sim$ 71 pJ/pulse). The bias voltage was varied from 1 to 30 V. Compared with the MBE annealed MSM-TWPD with a similar geometric size, the maximum allowable bias voltage improves from $\sim$ 20 to $\sim$ 30 V. This improvement is possibly originated from different defect densities or defect distributions due to different annealing approaches. Higher output power from RTA annealed MSM-TWPD could, thus, be expected, because the maximum peak output voltage is limited by the dc bias voltage, which could be saturated by the peak output voltage signal [11]. The response FWHM was found to decrease with increased bias voltage when the bias voltage was below 20 V. However, when the bias voltage was over 20 V, the measured response FWHM increased with bias voltage slightly. In the high optical excitation regime, the dominant nonlinear response in the LTG-GaAs active layer would be a combination effect, due to defect saturation and space charge screening [11], [16]. In order to reduce the space charge screening effect and the thus-induced broadening of impulse response, higher bias voltage (with higher external applied electric field) is needed. This might be responsible for the reduction of response FWHM with increased bias up to 20 V. However, when the bias voltage was higher than 24 V or even up to 30 V, the response FWHM increased again. Fig. 2 shows the measured average photocurrent versus bias voltage. When the bias voltage was over 24 V, a significant rise of photocurrent was also observed. The observed increase of photocurrent and response FWHM with high bias voltage (over $\sim$24 V) suggests the increase of carrier lifetime [12] that is possibly due to Coulomb barrier lowering, electric field induced carrier heating and intervalley scattering that causes increased carrier capture time, or even avalanche breakdown effects. The bias dependent behaviors under lower optical excitation energies are almost similar to our previous report [11], where the bias voltage for the fastest impulse response decreases with the optical excitation energy. For example, with an optical excitation energy of 27 pJ/pulse, the fastest impulse response occurred with a bias voltage of 10 V. However, with a bias voltage over 24 V, a significant nonlinear rise of photocurrent is always observed even with lower optical excitation energies. The nonlinearity in photocurrent versus bias voltage (photoconductance) of this demonstrated device implies its potential in the application of ultrahigh-frequency optoelectronic mixers [15], [16]. By properly choosing the dc bias point and injecting microwave or millimeter-wave signals from local oscillators to this demonstrated device, the incoming modulated sinusoidal optical signals can be distorted due to this nonlinear photoconductance. The component of up or down converted photogenerated signals can, thus, be collected from the harmonics of the distorted signals.

Fig. 3 shows the EO measured impulse response under 30 V bias voltage and its corresponding frequency response by utilizing a Fourier transform technique, which shows a 190 GHz electrical bandwidth. We calculated the peak output voltage (V_p), which was about 30 V with $\sim$ 500 mA peak output photocurrent, by utilizing the collected photogenerated charge per pulse ($\sim$ 2100 fC), the area of the measured impulse response, and the characteristic impedance ($\sim$ 60 Ω) of integrated CPW transmission line [9]. The corresponding

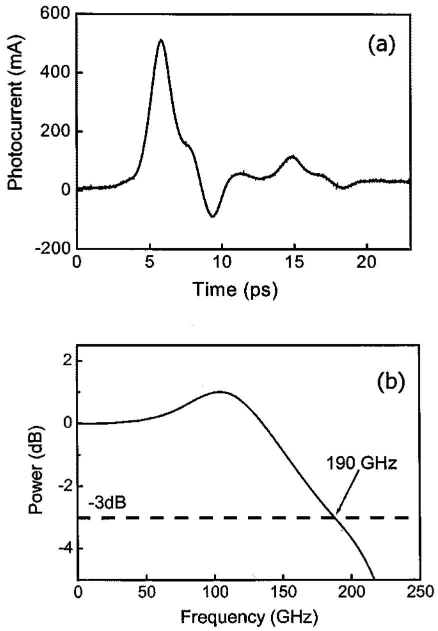

Fig. 3. (a) EO measured transient response of a 12-μm-long MSM TWPD with a high optical excitation energy (71 pJ/pulse) and a fixed high bias voltage (30 V). (b) Its corresponding frequency domain response by use of fast-Fourier transform technique, which shows a 3-dB electrical bandwidth of 190 GHz.

quantum efficiency (including coupling loss) under this operation condition is $\sim 4.5\%$. The dc bias voltage (also 30 V) thus limited the maximum output peak voltage due to external circuit saturation effects. The obtained V_p ($\sim$ 30 V) and electrical bandwidth (190 GHz) product (5.7 THz-V) is the highest among all the reported ultrahigh-speed PDs, including LTG-GaAs-based p-i-n TWPDs ($\sim$ 1400 fC, 6 ps) [17], MBE-annealed MSM-TWPD ($\sim$ 1600 fC, 1.5 ps, 220 GHz, 4.4 THz-V) [11], InGaA-based vertical p-i-n PD ($\sim$ 7.2 ps, 68 fC) [17], GaAs-based p-i-n TWPD ($\sim$ 5.5 ps, 59 fC) [18], unitraveling carrier PD (UTC-PD, $\sim$ 3.1 ps, 115 GHz, V_p: 1.92 V) [8], and VMDP ($40 \sim 50$ GHz, V_p: 2.5 V) [7]. This excellent power-bandwidth product of MSM TWPD is not only due to its superior MSM microwave guiding structure but also due to the short carrier trapping time and the capability of suffering high bias voltage in LTG-GaAs photoabsorption layer. Although the short carrier trapping time will sacrifice the quantum efficiency in LTG-GaAs based PDs, only the photogenerated carriers that are near the surface of metal contacts can be collected. Thus most of the collected carriers travel through extremely short distances where stronger electric field exists with less space charge screening effect, comparing with other parts of the active region [1], [10].

In conclusion, a record performance of output power-bandwidth (5.7 THz-V) product has been demonstrated by using RTA annealed MSM-TWPD under high-power 800 nm wavelength excitation and high bias voltage (30 V). The ultra-high bandwidth and high-power performances of our demonstrated devices can find applications in the microwave photonic systems [2], high-power photomixers [3], and photoreceiver circuits without electrical amplifiers [1]. Nonlinear photoconductance behavior under such high dc bias voltage has also been observed. This nonlinear relation between bias voltage and photocurrent also implies the application of MSM-TWPD in ultrahigh-frequency optoelectronic mixers [15], [16] or in fiber-optic/millimeter-wave linking systems [19].

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