Nonlinear Behaviors of Low-Temperature-Grown GaAs-Based Photodetectors Around 1.3-μm Telecommunication Wavelength

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***Abstract*—We observed distinct bandwidth degradation behaviors in low-temperature-grown GaAs (LTG-GaAs)-based traveling-wave photodetectors (PDs) under $\sim$1300-nm telecommunication wavelength operation. Compared with the bandwidth degradation behaviors of different excitation wavelengths ($\sim$800 and $\sim$1550 nm) in LTG-GaAs-based PDs, the saturation behaviors at the studied wavelength are more serious and can be attributed to "hot electron" effect of photogenerated carriers. The disclosed unique material properties of LTG-GaAs are important for its applications in ultrafast optoelectronics and understanding its carrier dynamics with the defect states.**

***Index Terms*—Bandwidth saturation, metal–semiconductor–metal (MSM) devices, photodetector, traveling wave devices.**

IN RECENT years, there has been sustained interest in low-temperature-grown GaAs (LTG-GaAs)-based photodetectors (PDs) due to their ultrashort response time [1], high electrical bandwidth [2], [3], and their ability to integrate with other microwave devices such as antenna [4]. However, the absorption band-gap ($\sim$870 nm) of LTG-GaAs restricts its applications from long-wavelength (1300–1550 nm) optical communications. Recently, several research groups have demonstrated the optical pump–probe measurements of LTG-GaAs materials [5] and high-speed high-output-power performances of LTG-GaAs-based p-i-n/n-i-n PDs and metal–semiconductor–metal (MSM) photoconductor in the $\sim$1550-nm wavelength regime [6]–[9]. The below band-gap photoabsorption in LTG-GaAs can be achieved by utilizing mid-gap defect state to conduction band transitions [6], [7] or two-photon absorption [8], [9].

In this letter, we report distinct nonlinear behaviors of LTG-GaAs-based MSM traveling-wave PDs (TWPDs) under $\sim$1300-nm wavelength excitations by an electrooptical (EO) sampling technique. The investigated device has previously demonstrated ultrahigh-speed and record-high peak-output-power bandwidth product performances among all long-wavelength (1300–1560 nm) PDs [10]. The EO measured impulse current response in the $\sim$1300-nm wavelength regime shows a significant broadening, indicating pronounced bandwidth degradation, compared with that in the $\sim$800-nm wavelength regime when increasing the photogenerated carrier densities. Since the absorbed photon energy ($\sim$1 eV) at $\sim$1300-nm wavelength is much higher than the subband-gap energy ($\sim$0.7 eV) between the conduction and the defect state Fermi surface [11]; the observed distinct nonlinear behaviors are possibly originated from slowed relaxation of hot electrons and the ensuing carrier lifetime increase. By contrast, the hot carrier effects under 800- or 1550-nm wavelength excitation are not so pronounced due to the fact that the excitation photon energies are close to the energies of band-to-band and midgap-states-to-conduction band transitions, respectively.

The measured MSM TWPDs at 1300- and 800-nm wavelengths in this study are the same as those in [3] and [12]. The measured modal absorption constants of the studied devices at 800, 1230, and 1550 nm are 830, 430, and 200 cm^{-1}, respectively, with corresponding effective device-absorption lengths of 24 and 12 μm for 1230- and 800-nm wavelength, respectively. The modal absorption constants were obtained by comparing photocurrents from different absorption-length devices [7]. For the following discussion, we choose 70-μm-long and 12-μm-long devices for 1300- and 800-nm studies, respectively. We employed a mode-locked femtosecond Ti : sapphire and a Cr^{4+} : forsterite laser operating at 800 and 1230 nm as the light sources for the time-resolved EO sampling measurement, which is similar to the system described in [13]. The top-view of measured MSM TWPD can be found in [12]. Fig. 1 shows the EO measured impulse current responses under 800- [Fig. 1(a)] and 1230-nm [Fig. 1(b)] excitations. Traces A–D are the results under different illumination intensities. Also shown beside the traces are the corresponding collected carrier densities, which can be obtained by dividing the collected charges by the device absorption volumes. In Fig. 1(a), under the condition of higher collected carrier densities compared with those of

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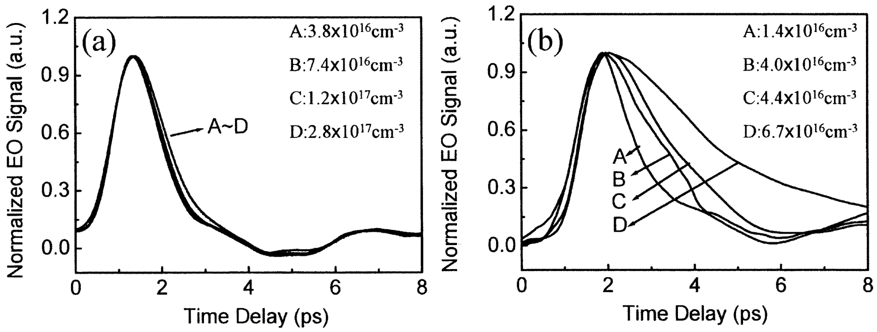

Fig. 1. Normalized EO sampling traces of LTG-GaAs-based MSM TWPDs under (a) 800-nm wavelength and (b) 1230-nm wavelength short pulse excitations under different illumination intensities. DC biases were fixed at 10 and 5 V for (a) and (b), respectively. The input pulse energy densities of Traces A–D in (a) are 0.13, 0.286, 0.54, 1.43 mJ/cm^2 and in (b) are 0.22, 0.45, 0.587, 1 mJ/cm^2.

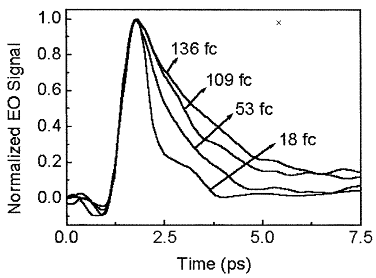

Fig. 2. Normalized EO sampling traces of LTG-GaAs-based p-i-n TWPDs under 1230-nm wavelength short pulse excitations under a fix dc bias voltage of 5 V under different illumination intensities.

Fig. 1(b), there is no obvious broadening in the measured EO traces even with the highest collected carrier density (Trace D). However, the traces measured at 1230 nm [Fig. 2(b)] show serious broadening with increased collected carrier densities. The full-width at half-maximum (FWHM) of the measured impulse response increases from 1.4 ps in Trace A to 3.1 ps in Trace D. The observed nonlinear behavior is opposed to the general design concept of high-speed/power PDs, which are made to achieve less electrical bandwidth degradation in high output-power regime by reducing the optical modal absorption constant and increasing the device absorption length.

We also performed EO sampling measurements with LTG-GaAs-based p-i-n TWPDs under different illumination intensities with the 1230-nm light and compared the results with their performances under 800-nm excitations, to make certain if the observed distinct broadening behavior $\sim$1300 nm is a special feature due to our specific structure of MSM TWPDs. As shown in Fig. 2, the broadening phenomenon remains the same in LTG-GaAs-based p-i-n TWPDs under 1230-nm excitations. The corresponding collected charges were listed in the figure in order to compare with previous 800-nm data from the same device [14]. The measured p-i-n TWPD transient responses broaden severely with increased collected charge over 50 fC under 1230-nm excitation while the previous study [14] showed very little broadening in the 800-nm excited EO traces in the same device under the same bias within the same range of collected charge (from 10 to 140 fC).

The photoabsorption mechanism plays an important role in the observed distinct nonlinear behaviors of our LTG-GaAs-based TWPDs under 1230-nm excitation. There are several possible linear or nonlinear transition processes in LTG-GaAs under subband-gap excitations [15]. In order to clarify the dominant photoabsorption processes in LTG-GaAs under 1230-nm illumination, we measured the transmission of a LTG-GaAs sample under different optical illumination power by the same mode-lock Cr^{4+} : forsterite laser with the same focused optical beam diameter size ($\cong 2.6$ μm) as in EO sampling measurement. The growth and annealing conditions of the measured LTG-GaAs sample is the same as those of the photoabsorption layers in the measured MSM TWPDs and p-i-n TWPDs, which were grown at 210 °C and annealed at 600 °C in a molecular beam epitaxy chamber. In order to avoid the undesired two-photon absorption from GaAs substrate during measurements, the substrate was removed by the mixed solution of citric acid and hydrogen peroxide (5 : 1), which has etching selectivity between AlGaAs and GaAs. The linear proportionality of the measured transmitted optical power to the pump power at $\sim$1230-nm wavelength excitation indicated that the dominant photon-absorption process in our prepared samples and devices is transitions from midgap defect states to conduction band [15].

According to the dominant photoabsorption process between midgap defect states to conduction band under 1230-nm excitation, the broadening behaviors in EO sampling measurement can, thus, be attributed to hot electrons [16] and the associated hot phonons and intervalley scatterings in the conduction band. For 1230-nm subband-gap excitation, carriers in the mid-gap states can be excited into the Γ valley with high excess energy ($\sim$300 meV), which is close to the offset energy ($\sim$310 meV) of L valley relative to the Γ bottom. These hot electron effects should reduce the electron capture rate back to the defect states and cause the broadened response of the carrier-lifetime-limited devices. Based on the above discussion, our observed hot carrier phenomenon should also take place in LTG-GaAs-based devices under normal excitation with a photon energy much larger than the band-gap energy. Serious bandwidth degradation behaviors of LTG-GaAs-based photomixer have been previously observed under $\sim$585-nm excitation [17].

Fig. 3 shows the measured impulse FWHM of MSM TWPDs under 1230-nm excitation versus dc bias at three different optical illumination powers. The FWHM of the measured impulse responses increases with excitation powers and bias voltages. We exclude the coulomb-barrier lowering effect [18] from the

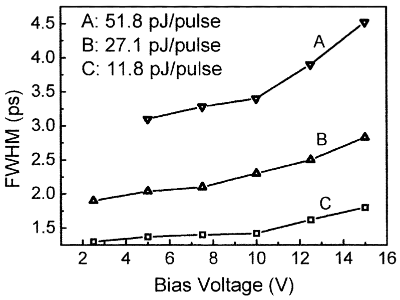

Fig. 3. FWHM of the measured impulse responses of LTG-GaAs-based MSM TWPD under 1230-nm excitation versus dc bias voltages with different optical excitation energies. The densities of optical pumping energy for Traces A–C are 1, 0.5, and 0.23 mJ/cm^2, respectively.

dominant response broadening effect, because the electric field in the optical guiding mode center of MSM TWPDs is not high enough to induce significant coulomb-barrier lowering effect. We calculated the two-dimensional electric field distribution between interdigitated metal electrodes by solving the electrical potential. According to the previous report, the coulomb-barrier lowering effect in LTG-GaAs will increase carrier lifetime when the magnitude of electric field is higher than 4.4×10^4 V/cm [18]. However, for the case of our MSM TWPD structure, the external applied bias voltage must be over 20 V to achieve this electric field magnitude. The coulomb-barrier lowering effect is, thus, responsible for the response broadening effect of our devices over 24 V reported in a previous paper [19]. The observed lifetimes in this report are also too short compared with the observed long lifetime under the coulomb-barrier lowering effect. With a higher carrier density, the space charge screening effect could also reduce the local electric field and reduce the coulomb-barrier lowering effect [3]. However, as we can see from Fig. 3, with a higher carrier density, the response broadening effect is getting worse, thus, indicating a different mechanism. Faster electron scattering in k-space with higher electron density that quickly moves the electrons out of their photoexcited region should result in a slower capture process. It is especially interesting to notice the lifetime broadening threshold of $\sim$10 V (20 kV/cm) in Fig. 3. Under such a high electric field, photogenerated electrons will be forced to undergo intervalley scatterings and be swept into L valley (Gunn effect) easily. The carrier capture rate, thus, reduced and resulted in the observed response broadening. The observed bias-dependent response broadening effect is more serious compared with that under 800-nm excitation [3], due to the fact that the heavy-mass holes also play an important role in the 800-nm responses.

In conclusion, we have observed distinct bandwidth degradation behaviors in LTG-GaAs-based TWPDs under $\sim$1300-nm operation. Compared with the bandwidth degradation behaviors of LTG-GaAs-based PDs under different wavelength excitations ($\sim$800 and $\sim$1550 nm), the saturation behaviors at the studied wavelength are more serious and can be attributed to hot electron effect of the photogenerated electrons. The disclosed unique material property of LTG-GaAs is important for its applications in ultrafast optoelectronics and understanding its carrier dynamics with high-density defect states.

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