

Carrier Dynamics and Enhanced Terahertz Generation in GaAs Photoconductive Emitters with Microstructures

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Surface states are expected to play a key role in broadband terahertz (THz) emitters, where photoexcited carrier distributions are confined within about 1 μm of the surface. Optical pump and THz probe spectroscopy was used to study the dynamics of nonequilibrium charge carriers in both textured and non-textured GaAs substrates. Our findings show that the textured surface acts as an antireflective layer, greatly boosting the infrared pump laser's coupling efficiency into the semi-insulating GaAs substrate. Additionally, texturing introduces a trap-assisted recombination pathway, speeding up carrier relaxation and thus reducing Joule heating. Under the same pumping and bias field conditions, the coarse-textured GaAs photoconductive antenna shows nearly 7.85 times stronger THz emission amplitude than the non-textured device, along with improvement in signal-to-noise ratio. At a fixed bias field, higher pump power increases photogenerated carrier density, causing bias field screening and subsequent saturation of THz emission. At fixed pump power, when the bias field reaches $\sim 2.5 \text{ kV/cm}$, both THz emission and photocurrent spectra show a clear kink, signaling intervalley scattering from the Γ valley to the $L(X)$ valleys under high electric fields.

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Terahertz (THz) radiation occupies a critical region of the electromagnetic spectrum ranging from 0.1 to 10.0 THz, bridging the gap between microwave electronics and infrared optics. This unique spectral position enables distinctive capabilities in imaging, communication, and spectroscopy.^[1–5] However, designing efficient THz emission devices remains challenging. Primary THz generation methods include photoconductive antenna (PCA) emission,^[6–13] optical rectification,^[14–17] and spintronic emitters.^[18–22] Among these, PCA emitters, relying on electronic acceleration in semiconductors, are particularly effective in producing high-power broadband THz radiation. The emitted THz field depends critically on substrate materials, electrode geometry, optical pump lasers, and bias voltages.^[23–26]

PCAs have established THz time-domain spectroscopy (TDS) as an important tool for material and chemical analysis.^[27–31] With the rise of compact commercial THz-TDS systems, developing cost-effective, high-efficiency PCA substrates has become a key focus. For THz PCA, the fundamental requirements are that carriers generated by the incident laser have shorter lifetime, higher electron mobility, and high resistivity. Various methods have been explored to enhance photo-absorption and reduce the carrier lifetime of semi-insulating materials like GaAs; strategies such as ion implantation,^[32]

chemical passivation,^[33,34] epitaxial growth,^[35] and plasmonic metasurfaces have been explored.^[36,37] However, most physical doping methods incur high costs and low productivity. In contrast, femtosecond laser ablation offers a rapid, low-cost alternative for tailoring optoelectronic properties without complex fabrication.^[38–40]

This technique generates new electronic surface states and diverse micro/nano-textures by controlling femtosecond pulse trains or gas environments.^[41,42] Notably, ablated GaAs exhibits strong absorption below the bandgap,^[38,43] which is attributed to micron-scale periodic ripples that excite surface plasmon polaritons.^[44–46] These structures act as antireflection layers, boosting photo-absorption.^[38,47] The capability to control doping levels, photo-absorption properties, and carrier lifetimes through femtosecond-laser-ablation opens new pathways for enhancing THz optoelectronic devices.

THz generation in semiconductors occurs when a femtosecond laser pulse with photon energy exceeding the bandgap E_g ($E_g = 1.42 \text{ eV}$ for intrinsic GaAs at 300 K) photoexcites carriers. The THz electric field $E_{\text{THz}}(t)$ generated from a THz PCA can be correlated with the time derivative of the photo-conductivity,^[2,48]

$$E_{\text{THz}}(t) \propto \frac{d[e\mu N(t)]}{dt} E_{\text{mol}}, \quad (1)$$

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where e is the elementary charge constant, μ is the mobility, and $N(t)$ is the charge carrier density. E_{mol} is the local electric field given by^[49]

$$E_{\text{mol}} = E_{\text{bias}} - \frac{P_{\text{sc}}}{\eta\varepsilon}. \quad (2)$$

Here, P_{sc} is the space-charge polarization created by the carrier separating due to the applied bias field E_{bias} , $\varepsilon = 12.9\varepsilon_0$ is the dielectric constant of GaAs, and η is the antenna geometrical factor. Due to the hole effective mass ($m_{\text{h}}^* = 0.34m_{\text{e},0}$) being significantly larger than the electron effective mass ($m_{\text{e}}^* = 0.067m_{\text{e},0}$), hole mobility is substantially lower. Consequently, electrons dominate the surface conductivity. After photoexcitation, the devices exhibit sub-linear emission behavior with increasing applied electric field, which arises from Joule heating P_{H} induced by high current densities. P_{H} is approximated by^[48]

$$P_{\text{H}} \approx \frac{\tau}{T_0} \frac{E_{\text{bias}}^2 N_0 e \mu A}{d}, \quad (3)$$

where T_0 is the pump pulse period, N_0 is the initial carrier density, d is the electrode spacing, and A denotes the cross-sectional area, which is defined as the product of electrode width and depth of charge-carrier penetration. Thus, shortening charge-carrier lifetime τ reduces the steady-state photocurrent, thus mitigating Joule heating. Traditionally, this is achieved by photo-injecting carriers into material regions with high-density surface states, where surface recombination shortens the τ ,

$$\frac{1}{\tau} = SR + \frac{1}{\tau_{\text{b}}} \approx SR, \quad (4)$$

where S is the surface recombination velocity, R is the surface-area-to-volume ratio, and τ_{b} is the bulk charge-carrier lifetime of the material ($\tau_{\text{b}} \approx 2$ ns for GaAs).^[50,51] Textured semiconductor surfaces can effectively shorten charge-carrier relaxation time.

In this work, we employ time-resolved optical-pump THz-probe (OPTP) spectroscopy to investigate ultra-fast carrier recombination dynamics in femtosecond-laser-ablated semi-insulating gallium arsenide (SI-GaAs) substrates. We further demonstrate that the surface engineered with microstructures can enhance THz emission. The textured surface plays a dual role: it maximizes the coupling of infrared radiation into SI-GaAs and introduces abundant defect sites to promote electron-hole recombination. Experimental results confirm that the coarse-textured GaAs THz PCA exhibits a 7.85-fold higher THz emission amplitude with a higher signal-to-noise ratio (SNR) compared to its non-textured counterpart. These findings not only shed critical light on the fundamental physical mechanisms underlying GaAs-based THz PCAs but also establish a foundation for optimizing device performance in practical applications.

An experimental optical setup for femtosecond-laser ablation of textured surfaces on SI-GaAs substrates is illustrated in Fig. 1(a) [see Section 1 of the Supplementary Materials (SM) for details]. The femtosecond pulse laser

generates an 800-nm pulse train (120 fs pulse width, 1 kHz repetition rate). A neutral-density filter was used to attenuate the laser power to 300 mW. A focusing lens focuses the laser onto the GaAs substrate. The laser focus moved at a scanning speed of 4 mm/s, with row spacing of 20 μm . After femtosecond laser ablation, the GaAs surface forms periodic stripe structures with different texturing degrees. Coarse-textured SI-GaAs was fabricated in ambient air (20 $^{\circ}\text{C}$, 30% humidity), while fine-textured SI-GaAs was fabricated in a nitrogen atmosphere (1 atm) within a sealed chamber.

Figure 1(b) shows top-view scanning electron microscopy (SEM) images that reveal the coarse-textured surface has a transverse period of ~ 900 nm, compared to ~ 600 nm for the fine-textured SI-GaAs. The non-textured SI-GaAs retains a flat, smooth surface. Side-view SEM images obtained by tilting samples at 45° are presented in Fig. 1(c), which reveal height differences. The coarse and fine textures have heights of approximately 860 nm and 570 nm, respectively. During laser processing, a nitrogen atmosphere, with superior cleanliness and lower humidity than ambient air, minimizes oxidation and contamination, resulting in smoother, cleaner surfaces. In contrast, atmospheric oxygen reacts with the material to form oxides, resulting in rougher surfaces or the formation of an oxide layer.^[52]

Using the atomic force microscope (AFM) measurements, we obtained the horizontal and vertical topographic profiles to determine the roughness of the surfaces. Figures 2(a)–2(c) presents three-dimensional AFM views of GaAs substrates. The root mean square (RMS) roughness of three samples was measured as 199.90 nm, 71.92 nm, and 4.39 nm for coarse-, fine-, and non-textured GaAs substrates, respectively. The diffuse reflectance and transmittance of coarse-, fine-, and non-textured GaAs are shown in Figs. 2(d) and 2(e). The optical absorption of GaAs substrates can be extracted from $A = 1 - R - T$, where A , R , and T are the fractions of power for absorbed, reflected, and transmitted beams respectively, as shown in Fig. 2(f). The coarse-textured GaAs exhibits an $\sim 20\%$ enhancement in absorption at 780 nm (above the bandgap) and $\sim 43\%$ enhancement in absorption at 1200 nm (below the bandgap) compared to the non-textured GaAs substrate.

As shown in Fig. 1(d), identical antennas were fabricated on SI-GaAs substrates. Photolithography and electron-beam evaporation were used to fabricate the heat sink and electrode structures. The parallel conductive stripe-line electrodes have a width of 100 μm and a gap of 150 μm . After annealing, the electrodes form ohmic contacts with the GaAs wafer. The wafer was then mounted onto a printed circuit board, with the cathode and anode connected separately to enable bias voltage application via a SubMiniature version A connector. The textured GaAs substrates did not affect the fabrication of antennas. The electrical properties of the devices were characterized using a custom-built current-voltage (I - V) measurement platform.

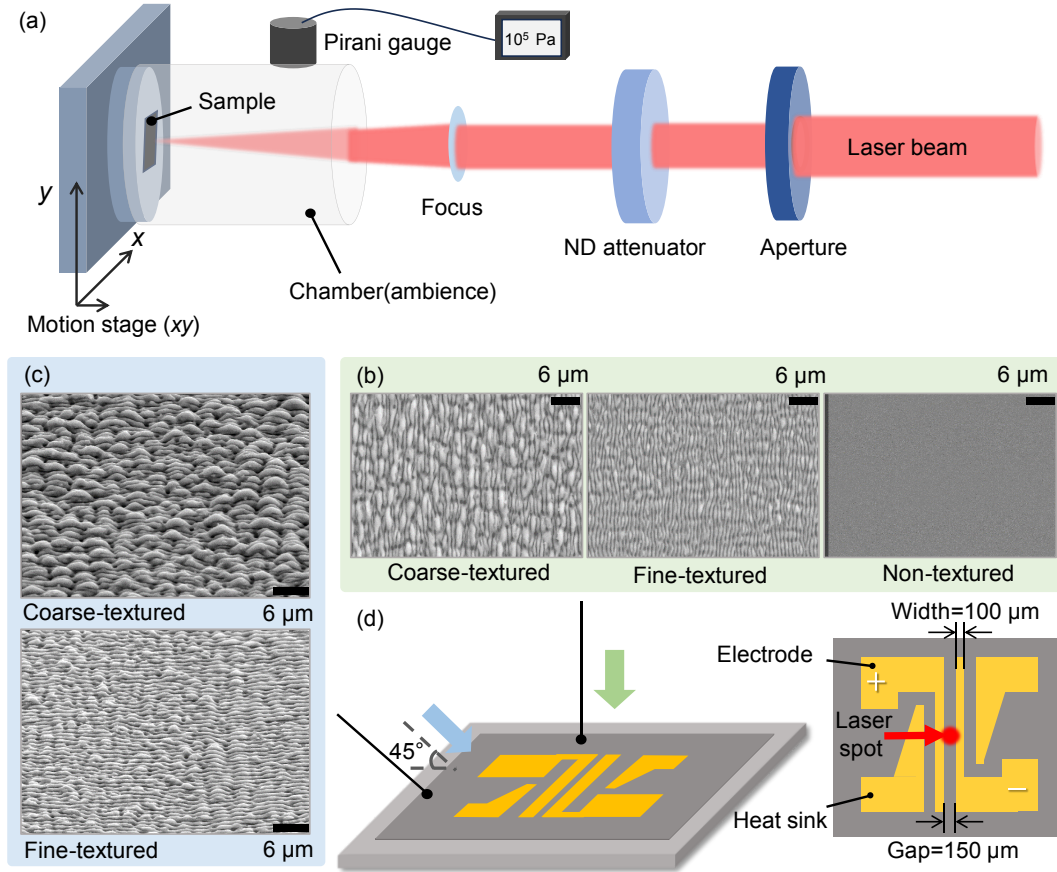


Fig. 1. (a) Schematic of the setup for femtosecond laser processing experiment used to fabricate micro/nano structures on semiconductor surfaces. (b) SEM images showing the surface characteristics of coarse-textured, fine-textured, and non-textured GaAs substrates. (c) Side-view images of the sample surface at a 45° tilt. (d) Schematic of the THz PCA emitter fabricated on textured SI-GaAs substrate.

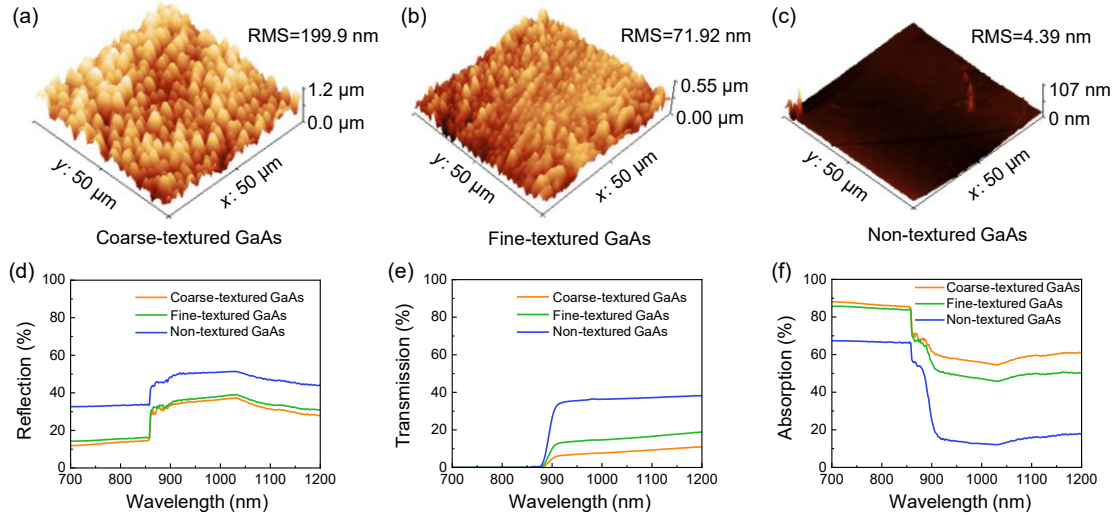


Fig. 2. Isometric views of AFM topographies for (a) coarse-textured GaAs, (b) fine-textured GaAs, and (c) non-textured GaAs. (d) Optical reflection spectra. (e) Optical transmission spectra. (f) Optical absorption spectra of coarse-, fine-, and non-textured GaAs.

Since the substrate carrier lifetime significantly affects THz generation efficiency,^[53,54] we first investigate the ultrafast charge carrier dynamics of textured and non-textured GaAs using an OPTP setup (see Section 2 of the SM for details). Figure 3(a) shows typical photo-induced

transient changes in THz transmission $\Delta T(t)/T_0$ as a function of pump-probe time delay t for coarse-, fine-, and non-textured SI-GaAs substrates. $\Delta T(t)/T_0 = [T(t) - T_0]/T_0$, where T_0 and $T(t)$ represent the THz peak values before and after photoexcitation, respectively.^[55,56] $\Delta T(t)/T_0$

can be described by^[48]

$$\frac{\Delta T(t)}{T_0} \propto -\Delta\alpha(t)e^{-\Delta\alpha(t)\delta} - \Delta n(t)e^{-\Delta\alpha(t)\delta}, \quad (5)$$

where $\Delta\alpha(t)$ represents the free-carrier absorption (FCA), $\Delta\alpha(t) = \frac{\omega N(t)e^2}{c\epsilon_0 m n_b} \frac{\omega/\tau_r}{\omega^4 + (\omega/\tau_r)^2}$, $\Delta n(t)$ represents the free-carrier dispersion (FCD), $\Delta n(t) = -\frac{N(t)e^2}{2\epsilon_0 m n_b} \frac{\omega^2}{\omega^4 + (\omega/\tau_r)^2}$, where m denotes the effective mass, n_b stands for background refractive index, ω is the angular frequency of the probe beam, and τ_r indicates the momentum relaxation time. In Fig. 3(a), $\Delta T(t)/T_0$ is negative, indicating that FCA dominates over FCD. Under the thin-film approximation, $\Delta\sigma(t) = \frac{1+n}{Z_0\delta} [\frac{1}{1+\Delta T(t)/T_0} - 1]$, where $n = 3.57$ is the THz refractive index of GaAs substrate, $\delta \approx 1 \mu\text{m}$ is the pump penetration depth and $Z_0 = 377 \Omega$ is the impedance of free space.^[50,57,58] A direct comparison of the $\Delta\sigma(t)$ for coarse-, fine-, and non-textured SI-GaAs substrates shows that the coarse-textured substrate exhibits the highest photoconductivity under the same pump fluence of $79.5 \mu\text{J}\cdot\text{cm}^{-2}$. This phenomenon is attributed to enhanced light absorption in the coarse-textured surface. The groove ridges and ripples increase the effective light-absorbing area, thereby improving absorption performance

like an anti-reflection layer. This observation is further supported by our optical measurement in Fig. 2(f).

In Fig. 3(b), the normalized $-\Delta T(t)/T_0$ curves are fitted with an exponential decay function to extract the charge-carrier relaxation time. The relaxation time of non-textured GaAs exceeds 1500 ps, consistent with the reported lifetime of approximately 2 ns in the literature.^[50,51] For fine- and coarse-textured GaAs substrates, the charge-carrier relaxation times are determined to be 960 ps and 338 ps, respectively. This trend can be explained by the fact that microstructures enhance surface roughness, inducing numerous surface defects that act as scattering centers for carrier transport. These results indicate that coarse-textured GaAs not only exhibits higher photoconductivity than non-textured GaAs but also has a shorter relaxation time constant. As described by Eq. (4), the textured semiconductor surface increases the optically excited surface area and reduces the charge-carrier relaxation time τ by defect-assisted recombination. By using AFM analysis, we estimated that the ratio R between coarse-textured and fine-textured GaAs is 1.66. According to Eq. (4), we can obtain that the surface recombination velocities S are calculated to be 2.3 nm/ps and 1.3 nm/ps for coarse-textured and fine-textured GaAs, respectively.

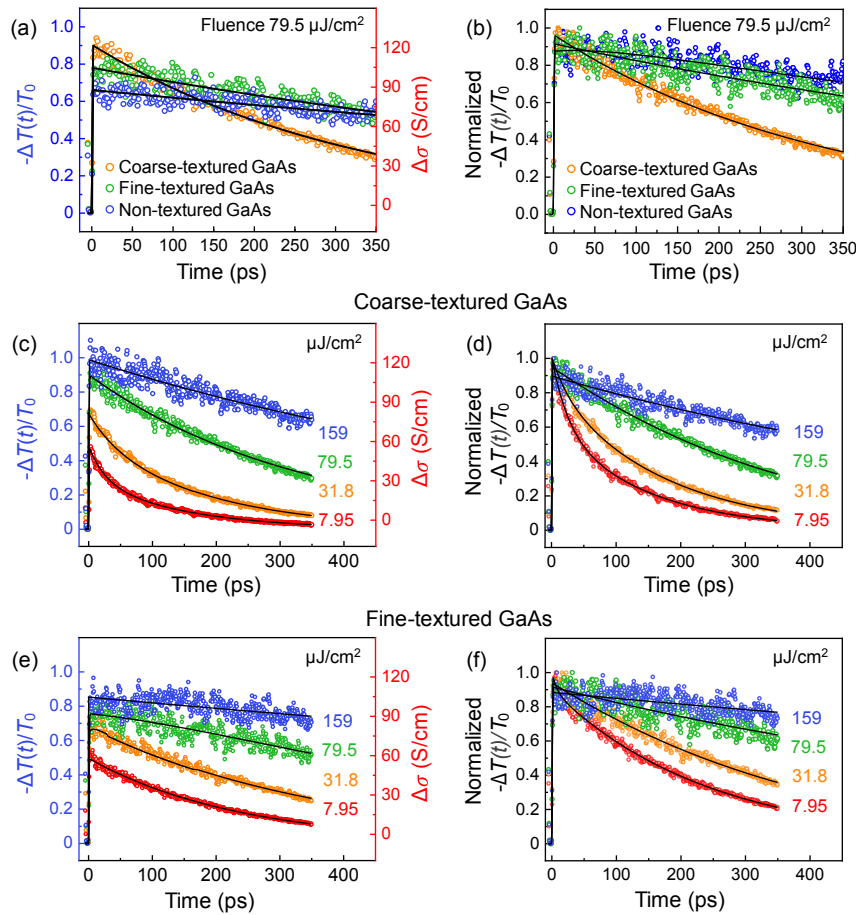


Fig. 3. (a) Both the $-\Delta T(t)/T_0$ and $\Delta\sigma(t)$ curves for coarse-textured, fine-textured, and non-textured SI-GaAs substrates excited by a pump fluence of $79.5 \mu\text{J}\cdot\text{cm}^{-2}$. (b) Normalized $-\Delta T(t)/T_0$ corresponding to (a). (c) Both the $-\Delta T(t)/T_0$ and $\Delta\sigma(t)$ of coarse-textured GaAs under pump fluences ranging from 7.95 to 159 $\mu\text{J}\cdot\text{cm}^{-2}$. (d) Normalized $-\Delta T(t)/T_0$ corresponding to (c). (e) Both the $-\Delta T(t)/T_0$ and $\Delta\sigma(t)$ of fine-textured GaAs under pump fluences ranging from 7.95 to 159 $\mu\text{J}\cdot\text{cm}^{-2}$. (f) Normalized $-\Delta T(t)/T_0$ corresponding to (e).

Figures 3(c) and 3(e) plot $-\Delta T(t)/T_0$ and $\Delta\sigma(t)$ of coarse- and fine-textured SI-GaAs substrates under varying pump fluences. The rise time remains constant across all pump fluences. Photoconductivity increases with pump fluence, which is consistent with the generation of THz pulses from the THz PCA (discussed later). Figures 3(d) and 3(f) show the normalized $-\Delta T(t)/T_0$ curves at different pump fluences, revealing that the decay slows down and exhibits a linear trend as pump fluence increases. Exponential fitting of these $-\Delta T(t)/T_0$ curves indicates that for coarse-textured GaAs, the relaxation time constant increases from 147 ± 2 ps to 814 ± 17 ps, while for fine-textured GaAs, it rises from 237 ± 1 ps to 2485 ± 169 ps as pump fluence increases from 7.95 to $159 \mu\text{J}\cdot\text{cm}^{-2}$. This behavior aligns with the expected surface states filling effect, which suppresses carrier recombination.^[59,60] Conversely, high photocarrier density excitation enhances Joule heating, leading to more pronounced thermal diffusion, an issue that could degrade the performance and stability of THz PCAs.

Next, we performed a comparative study on the time-domain THz emissions of non-textured, fine-textured, and coarse-textured GaAs-based THz PCAs. All devices were excited under identical conditions. The THz emission was detected in the far field via electro-optical sampling using a 1-mm-thick ZnTe crystal (see Section 3 of the SM for details). Figures 4(a)–4(c) show THz transients generated by coarse-, fine-, and non-textured GaAs-based THz PCAs under a bias field of 3 kV/cm with optical pump powers of 10, 20, and 40 mW, respectively. Among the three types of GaAs-based THz PCAs, the coarse-textured device exhibits the highest peak-to-peak THz amplitude, followed by the fine-textured and non-textured devices.

The SNR of the time-domain spectrum was calculated using the formula

$$\text{SNR} = 20 \log \left(\frac{S_{\text{signal}}}{\sqrt{S_{\text{noise}}}} \right), \quad (6)$$

where S_{signal} denotes the THz peak-to-peak amplitude and $\sqrt{S_{\text{noise}}}$ is the RMS value of the time-domain signal noise.^[61] The SNR data is presented in the insets of Figs. 4(a)–4(c). Both coarse and fine textured devices exhibit higher SNR values than non-textured devices, indicating their greater potential for practical applications. Figure 4(d) shows the frequency-domain spectrum obtained by fast Fourier transform from Fig. 4(c). The noise level was determined from signals acquired without THz emission, revealing a system bandwidth of approximately 3 THz.

Figure 4(e) plots the peak-to-peak amplitude of THz emission $E_{\text{THz}}^{\text{peak}}$ as a function of optical pump power F_p . $E_{\text{THz}}^{\text{peak}}$ increases with F_p , indicating that an increase in the number of highly mobile excited carriers enhances the photocurrent amplitude within the device. The data can be well described by a saturation formula,^[8,62] $E_{\text{THz}}^{\text{peak}}(F_p) = B \times F_p / (F_p + F_{\text{sat}})$, where B is the magnitude of the THz radiation and F_{sat} is the saturation optical pump power. The solid lines in the figure reproduce the saturation behavior of THz generation. The fitted F_{sat} values are approximately 16.49 mW and 28.34 mW for coarse- and fine-textured GaAs PCAs, respectively. This saturation effect can be attributed to both screening of the bias field and Joule heating effects caused by the high density of photocarriers.^[23,63] The textured GaAs exhibits a higher saturation power, which demonstrates mitigation of space-charge screening and reduction of carrier lifetime.

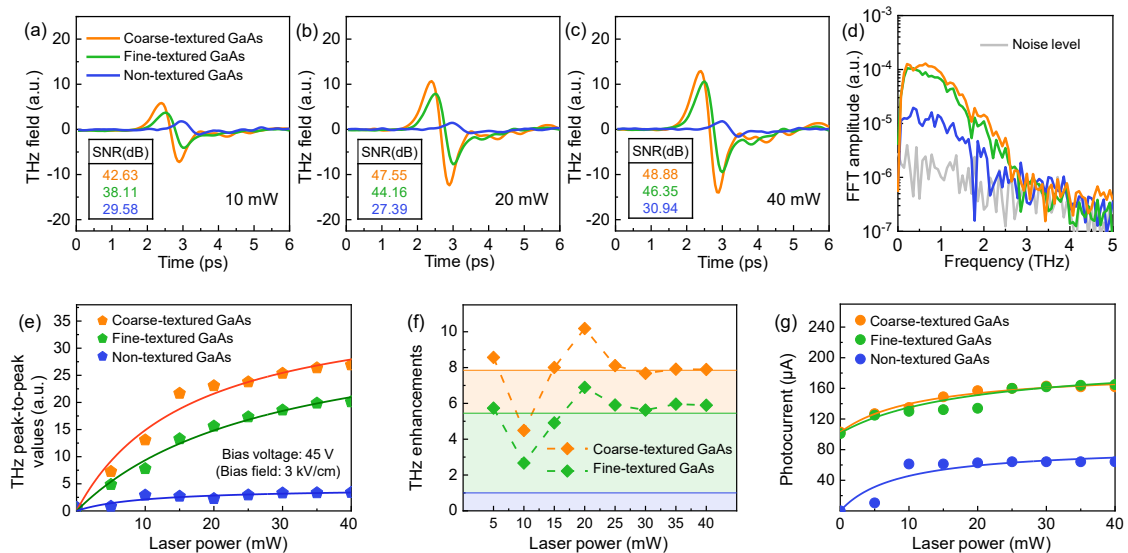


Fig. 4. Time-domain THz waveforms generated from coarse-textured (orange), fine-textured (green), and non-textured (blue) GaAs-based THz PCA under a bias field of 3 kV/cm, with pump laser powers of (a) 10 mW, (b) 20 mW, and (c) 40 mW. Insets show the corresponding SNRs of TDS. (d) Frequency domain spectrum of (c) after fast Fourier transform. (e) Peak-to-peak amplitude of THz radiation measured at different laser powers. (f) THz enhancements of coarse-textured and fine-textured GaAs THz PCA, calculated as the ratio of the THz generation of textured devices to that of the non-textured device. (g) Photocurrents measured as a function of pump laser power, where circles represent experimental data points.

Table 1. Comparison of radiation performance for different optimization strategies of THz PCAs. Parameters λ is the laser wavelength, P is the excitation laser power (pump fluence), V_{bias} is the bias voltage, and g is the gap between the antenna electrodes.

Strategies	Semiconductor materials	THz enhancements	Conditions λ (nm)/ P (mW)/ V_{bias} (V)/ g (μm)	References
Plasmonic modes	SI-GaAs	~ 2.3 times	522/45/40/30	[66]
Surface passivation	SI-GaAs	~ 4.2 times	800/160/-/-	[34]
Epitaxial growth	LT-GaAs	~ 1.8 times	800/90/142/50	[67]
Surface patterning (polishing film)	SI-InP	~ 1.1 times	780/50/50/-	[48]
Surface patterning (laser ablation)	SI-GaAs	~ 1.65 times	800/10 mJ·cm ⁻² /10/50	[43]
Surface patterning (laser ablation)	SI-GaAs	~ 7.85 times	780/40/45/150	This work

Figure 4(f) shows the THz enhancement ratios derived from Fig. 4(e), defined as the ratio of THz emission from textured PCAs to that from the non-textured device. Results indicate 7.85-fold and 5.45-fold enhancements in THz generation for coarse- and fine-textured PCAs, respectively. This improvement primarily originates from enhanced light absorption by textured surfaces: substrate microstructures increase the specific surface area, enabling stronger interaction between the pump laser and SI-GaAs.^[28,64,65] Additionally, textured devices exhibit reduced Joule heating compared to non-textured counterparts. Figure 4(g) shows photocurrents measured under identical excitation and bias conditions, revealing a clear correlation between the photocurrents of textured PCAs and THz generation, which aligns with the principle that higher photocurrent enhances THz emission. It is important to note that the photocurrents measured are DC currents, which capture the average photocurrent. In contrast, the observed THz emission is dominated by the ultrafast photocurrent generated during optical excitation.

Table 1 summarizes recent typical optimization strategies for semiconductor-based PCAs. The THz enhancement is defined as the ratio of the THz signal amplitude after design optimization to that of the reference signal. E. Isgandarov *et al.* studied free-space THz emission from PCAs nano-decorated with gold nanoparticles. A maximum enhancement of ~ 2.3 times was achieved.^[66] The periodic plasmonic structures (tens to hundreds of nanometers) enhance both light-matter interaction and local electric fields, boosting THz radiation. However, nanoscale fabrication complexity increases production costs.

C. Headley *et al.* improved the stability and performance of THz photoconductive switches by combining (NH₄)₂S surface passivation with Si₃N₄ encapsulation. This strategy enhances absorption and increases resistance to prevent breakdown. The Si₃N₄-passivated GaAs sample showed a 4.2 times enhancement compared to the untreated reference.^[34] In addition, epitaxial growth, primarily based on molecular beam epitaxy technology, is used to fabricate LT-GaAs and superlattice structures.^[49,67] These engineered substrates exhibit shorter carrier lifetimes and higher surface-state recombination efficiency, with performance tunable via growth parameters (e.g., thickness, annealing temperature). L. Hou *et al.* fabricated an LT-GaAs antenna that exhibited 1.8 times higher

THz intensity than its SI-GaAs counterpart under identical structures and experimental conditions.^[67]

Collier *et al.* investigated THz enhancement on coarse- and fine-textured surfaces of InP substrates, and achieved ~ 1.1 times THz emission enhancement while significantly reducing Joule heat via shortened carrier lifetime and modulated photocurrent.^[48] Madéo *et al.* reported a femtosecond-laser-ablated GaAs-based THz emitter, which exhibited a 1.65-fold THz enhancement at high optical power compared to non-ablated counterparts.^[43] Our work achieves a 7.85-fold enhancement in THz radiation via femtosecond laser ablation, which is better than the reported strategies, with additional advantages of low cost and ease of operation.

Figures 5(a) and 5(b) show the time-domain waveforms of THz radiation emitted from coarse- and fine-textured THz PCAs under different bias fields (E_{bias}) with an optical pump power of 40 mW. The differences in THz emission amplitude E_{THz} between the two devices under identical E_{bias} stem from their distinct surface textures. Figure 5(c) summarizes the peak-to-peak THz amplitude $E_{\text{THz}}^{\text{peak}}$ as a function of E_{bias} . $E_{\text{THz}}^{\text{peak}}$ increases with E_{bias} and gradually saturates when E_{bias} is below ~ 2.5 kV/cm, consistent with the expected carrier accumulation behavior in the Γ valley. Notably, when E_{bias} exceeds ~ 2.5 kV/cm, $E_{\text{THz}}^{\text{peak}}$ continues to rise, with a distinct kink appearing in the $E_{\text{THz}}^{\text{peak}}$ curve around this threshold. To confirm this kink is not an artifact, we also measured the photocurrents of textured and non-textured GaAs-based THz PCAs in Fig. 5(d). The photocurrents exhibit similar behavior and validate the kink's signature.

THz emission is directly determined by the time-varying velocity of charge carriers,^[9]

$$E_{\text{THz}}^{\text{peak}}(E_{\text{bias}}) \propto \frac{\partial v_e}{\partial t} = \frac{eE_{\text{bias}}}{m_{\Gamma}^*}, \quad (7)$$

where m_{Γ}^* denotes the effective electron mass in the Γ valley. Equation (7) predicts that $E_{\text{THz}}^{\text{peak}}(E_{\text{bias}})$ is proportional to E_{bias} as long as m_{Γ}^* remains constant. In Fig. 5(e), we plotted $E_{\text{THz}}^{\text{peak}}(E_{\text{bias}})/E_{\text{bias}}$ as a function of E_{bias} . The data suggests a significant change in electron effective mass around 2.5 kV/cm, which aligns with the Gunn threshold (~ 3 kV/cm in GaAs).^[26,50,58] The change in $E_{\text{THz}}^{\text{peak}}(E_{\text{bias}})/E_{\text{bias}}$ can be attributed to carrier intervalley transport, as illustrated by the semi-classical band diagram in Fig. 5(f).

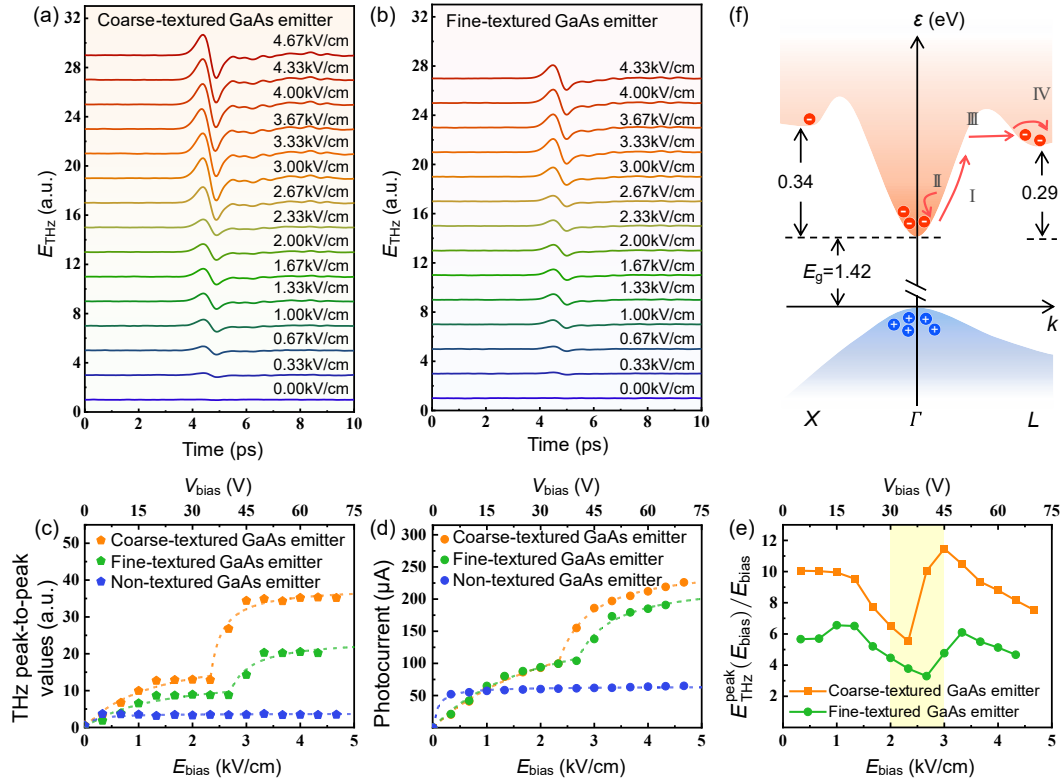


Fig. 5. Time-domain THz waveforms of (a) coarse-textured and (b) fine-textured GaAs-based THz PCAs under various applied bias fields E_{bias} . (c) Peak-to-peak amplitudes of the THz electric field as functions of E_{bias} . (d) Photocurrents of textured and non-textured GaAs-based THz PCAs, the dashed line serves as a guide for the eye. (e) $E_{\text{THz}}^{\text{peak}}(E_{\text{bias}})/E_{\text{bias}}$ plotted against E_{bias} . (f) Schematic illustration of the ε - k dispersion in GaAs at $E_{\text{bias}} = 0$ kV/cm.

GaAs has a band gap of ~ 1.42 eV between the top of the valence band and the bottom of the conduction band's Γ valley. The pump pulse directly excites electrons into the Γ valley, where they accelerate efficiently under F due to their small effective mass of $m_{\Gamma} = 0.067m_0$. The motion of electrons in k -space can be described by four processes. Process I: electrons are accelerated from the bottom of the Γ valley. For E_{bias} below ~ 2.5 – 3 kV/cm, photoexcited carriers lack energy for intervalley scattering (L and X valleys lie 0.29 eV and 0.46 eV above Γ , respectively). In high-purity materials with low excitation densities, carriers in the Γ valley undergo ballistic acceleration and carrier-phonon interactions. The main electron-lattice coupling here refers to polar-optical scattering with longitudinal-optical phonons (Process II), causing carrier diffusion and thermalization in the Γ valley on a picosecond timescale. Process III: when E_{bias} exceeds the Gunn threshold, electrons gain energy comparable to the Γ - L intervalley gap, scattering into the satellite L valley with a larger effective mass of $0.55m_0$. Higher fields also enable some electrons to transfer into the X valley. Process IV: steady state is reached via deformation potential scattering within the $L(X)$ valley.^[26,68] Carriers in L and X valleys have lower mobility due to their large effective masses, explaining why $E_{\text{THz}}^{\text{peak}}(E_{\text{bias}})/E_{\text{bias}}$ decreases when E_{bias} exceeds ~ 2.5 kV/cm.

In summary, we demonstrate enhanced THz generation in SI-GaAs PCA emitters using femtosecond laser-ablated microstructures. By engineering coarse and fine textures on the GaAs surface, these microstructures serve dual functions: they act as antireflective layers to boost infrared pump laser coupling efficiency and introduce trap-assisted recombination pathways to shorten carrier relaxation time and mitigate Joule heating. Under identical pumping and bias conditions, the coarse-textured THz PCA exhibits a higher THz emission amplitude than the non-textured counterpart. We also observe saturation in THz emission at high pump powers, which is attributed to both screening of the bias field and Joule heating effects. Additionally, a distinct kink in THz and photocurrent spectra at ~ 2.5 kV/cm indicates intervalley carrier transfer from the Γ to $L(X)$ valleys under high electric fields. These findings provide valuable insights for optimizing GaAs-based THz PCAs to achieve efficient and broadband THz emission. Future work could involve fabricating various metasurfaces that can be fabricated on textured GaAs substrates. Specifically, physical effects such as electromagnetically induced transparency,^[28] bound state in the continuum,^[64,65] and exceptional point^[69,70] can be used to enhance light-matter interaction, thereby further improving the radiation efficiency of THz waves.

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