Noise Analysis and Optimization of Terahertz Photoconductive Emitters

Lei Hou, Wei Shi, and Suguo Chen

***Abstract*—The electromagnetic noise generated by terahertz photoconductive emitters was investigated, and the intensity of noise spectrum was analyzed by statistical method. The relationship between the noise of the emitter and the resistivity as well as carrier lifetime of the antenna material was obtained. And the effect of carrier lifetime and mobility of antennas on the THz generation efficiency was investigated. Based on those results, GaAs:O material was fabricated by an ion implantation technique to obtain the required performance. The signal-to-noise ratio of the GaAs:O emitter was remarkably improved compared with a SI-GaAs emitter at the same experimental condition.**

***Index Terms*—GaAs:O, Photoconductive antenna, signal-to-noise ratio (SNR), terahertz.**

I. Introduction

IN 1984, Auston [1] first demonstrated that the terahertz (THz) radiation could be generated by a femtosecond laser illuminating a biased photoconductive (PC) antenna. And this method has been widely used in both THz time-domain spectroscopy (TDS) systems and THz imaging systems now. An integrated THz system includes a THz emitter, a THz detector the related optical parts and control electric circuits, and one of its important parameters is the signal-to-noise ratio (SNR). Some researchers have increased the sensitivity of a THz TDS system by optimizing optical systems [2] or improving the sensitivity of detectors [3]. In addition, extensive efforts have been taken to improve the THz output power of a PC antenna to increase the SNR including optimizing antenna structures [4], employing antenna array [5], [6], using more effective substrate (LT-GaAs [7] or ion implanted GaAs [8], [9]), improving electric field distribution [10], [11], and so on. However, a few works were focused on the noise generated by PC emitters [12], [13]. If the noise power and the THz radiation power are enlarged with the same times, the SNR of the THz system does not change. In this paper, the noise generated by PC emitters was investigated and the SNR of a THz TDS system was remarkably improved by using an oxygen ion implanted GaAs (GaAs:O) antenna.

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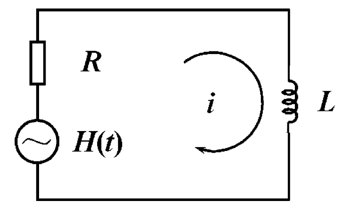

Fig. 1. *RL* net with a heat noise *H*(*t*), which is the equivalent circuit of a PC emitter.

II. Noise Spectrum Analysis

Generally, the noise of a THz TDS system comes from lasers, PC emitters, and THz detectors. In this paper, we focused on the noise generated by PC emitters. The noise of PC emitters can be classified as thermal noise (Johnson noise) and generation-recombination noise (shot noise).

A. Thermal Noise

When the photoexcited carriers move from the cathode to the anode across the surface of a photoconductor in the presence of an applied electrical field, the thermal motion of carriers will cause a fluctuation of electrodynamic potential across the PC antenna.

Fig. 1 is an equivalent circuit of a PC emitter, which is an *RL* net with a thermal noise source *H*(*t*) attached on the resistor (*R*), and its Langevin equation is presented as follows [14]:

$$L\frac{di}{dt} + Ri = H(t) \tag{1}$$

where *i* represents the current in the circuit; *R* and *L* are the resistance and the inductance of a PC emitter.

In the interval of $0 \le t \le T$, the following Fourier series was used to solve (1)

$$\begin{cases} H(t) = \sum\limits_{-\infty}^{\infty} \alpha_n \exp(j\omega_n t) \\ i(t) = \sum\limits_{-\infty}^{\infty} \beta_n \exp(j\omega_n t) \end{cases} \tag{2}$$

α_n and β_n are Fourier factors, $\alpha_n = (1/T)\int_0^T H(t) \exp(-j\omega_n t)dt$, $\beta_n = (1/T)\int_0^T i(t)\exp(-j\omega_n t)dt$, and $\omega_n = 2\pi n/T (n = 0, \pm 1, \pm 2, \ldots)$. Due to $d/dt = j\omega_n$, the relationship between α_n and β_n is obtained by substituting (2) into (1):

$$\beta_n = \frac{\alpha_n}{j\omega_n L + R}. \tag{3}$$

The spectral intensity of thermal noise $S_H(f)$ and the spectral intensity of current fluctuation noise $S_i(f)$ are expressed as

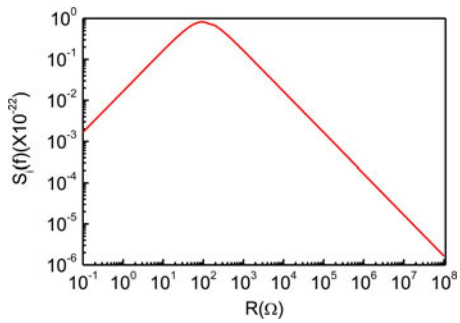

Fig. 2. Relationship between $S_i(f)$ and the resistance of PC emitter.

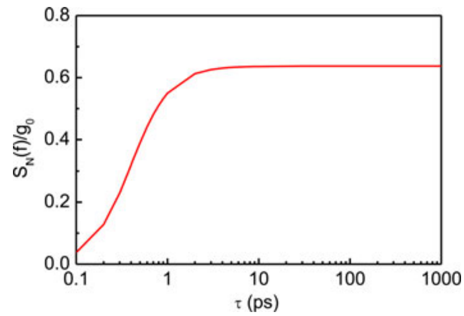

Fig. 3. Relationship between $S_N(f)/g_0$ and carrier lifetime.

follows:

$$\begin{cases} S_H(f) = \lim_{T\to\infty} 2T\overline{\alpha_n \alpha_n^*} \\ S_i(f) = \lim_{T\to\infty} 2T\overline{\beta_n \beta_n^*} \end{cases} \tag{4}$$

where α_n^* and β_n^* are the complex conjugates of α_n and β_n.

H(*t*) is a white noise source, $S_H(f)$ equals to $S_H(o)$, and $S_H(o)$ is the spectral intensity of low-frequency thermal noise. So the $S_i(f)$ can be indicated as follows:

$$S_i(f) = \frac{S_H(o)}{R^2 + \omega^2 L^2}. \tag{5}$$

According to the Nyquist theorem [15], the relationship of $S_H(o) = 4kTR$ and $S_i(f)$ is represented as

$$S_i(f) = \frac{4kTR}{R^2 + \omega^2 L^2}. \tag{6}$$

According to (6), the $S_i(f)$ is determined by the antenna's resistance and inductance at the temperature of *T* and at the frequency of ω. When the antennas are with the same structure, their inductance will be a constant, but their resistance is determined by the antenna materials at the same exciting power. Therefore, we evaluated the $S_i(f)$ of antennas with different resistances at 1 THz. In the calculation, L is supposed as $5/\pi$ nH [16], so $\omega L = 100$. Fig. 2 shows the relationship between $S_i(f)$ and antenna resistance at 1 THz. $S_i(f)$ first increases with the increase in resistance and reaches its maximum when the antenna resistance is 100 Ω, and then it decreases with the increase of antenna resistance. Because the dark resistance of a GaAs PC antenna is normally larger than 10^6 Ω, the larger the resistance of the antenna, the smaller the $S_i(f)$.

B. Generation-Recombination Noise

Generation-recombination noise is the fluctuation of voltage on a PC emitter caused by the generation and recombination of carriers. The fluctuation of carriers can be described as

$$\frac{d\Delta N}{dt} = -\frac{\Delta N}{\tau} + H(t) \tag{7}$$

where ΔN is the fluctuation of total carriers and τ is the carrier lifetime. Using the same method, we obtained the equation of spectral intensity of generation-recombination noise, which is represented as

$$S_N(f) = 4\overline{\Delta N^2}\frac{\tau}{1+\omega^2\tau^2}. \tag{8}$$

$\overline{\Delta N^2} = g_0\tau$ can be deduced, and g_0 is the generation rate of electrons. To the same antenna material, g_0 is a constant at the degenerate state. As a result, (8) is expressed as

$$S_N(f) = 4g_0\frac{\tau^2}{1+\omega^2\tau^2}. \tag{9}$$

Fig. 3 shows the relationship between the $S_N(f)/g_0$ and the carrier lifetime at the frequency of 1 THz. The shorter the carrier lifetime, the weaker the $S_N(f)$. When the carrier lifetime is larger than 5 ps, the $S_N(f)$ is saturated.

III. THz Generation Efficiency

Based on the current surge model of large-aperture PC antennas, the far field THz radiation is expressed as [17]

$$E_r(r,t) = -\frac{A}{4\pi\varepsilon_0 c^2 r}\frac{(d\sigma_s(t-|r-r'|/c)/dt)}{[\eta_0\sigma_s(t-|r-r'|/c) + (1+\sqrt{\varepsilon})]^2} \tag{10}$$

where η_0 is the impedance of free space (377 Ω), ε is the relative permittivity of GaAs, ε_0 is the permittivity in vacuum, E_b is the biased electric field, *c* is the speed of light in vacuum, *A* is the effective area of the PC antenna, *r'* is the position of the antenna center, *r* is the position of detector, and $\sigma_s(t)$ is the surface conductivity. $\sigma_s(t)$ is defined as

$$\sigma_s(t) = \frac{e(1-r)}{\hbar\omega}\int_{-\infty}^{t} dt'\mu(t-t')I_{\mathrm{opt}}(t')\cdot\exp(-(t-t'))/\tau_c \tag{11}$$

where *e* is the electronic charge, *r* is the optical reflectivity of the photoconductor, $\mu(t)$ is the time-varied carrier mobility, $I_{\mathrm{opt}}(t)$ is the time-varied optical intensity, $\hbar\omega$ is the photon energy, and τ_c is the lifetime of the photon-generated carrier.

In order to accurately simulate the temporal waveform of THz pulse emitted from a GaAs large-aperture PC antenna, we should know the carrier's kinetics in GaAs. From the kinetic equation of electrons in an external electric field, the time-varied mobility can be expressed as

$$\mu(t) = \frac{e\tau_s}{m_e^*}\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right] \tag{12}$$

where τ_s is the average scattering time, which is the average time interval between two successive scatterings of one electron drifting in the electric field.

The laser source used to illuminate a PC antenna is a femto second (fs) pulsed laser and the distribution of optical intensity changing with time is a Gaussian-shaped pulse [18]

$$I_{\mathrm{opt}}(t) = \frac{F}{2\sqrt{\pi}\Delta t}\exp\left(-\frac{t^2}{\Delta t^2}\right) \tag{13}$$

where F is the full excitation fluence, and $\sqrt{\ln 2}\Delta t$ is the full width at half-maximum (FWHM) of the laser.

Concerning the current surge model, we know that the THz generation efficiency is affected by the carrier lifetime and the mobility of antenna materials. Fig. 4(a) shows the effect of carrier lifetime on THz intensity. In the calculation, the FWHM of excitation laser is 100 fs, the average scattering time of carriers is 0.1 ps, the corresponding mobility is 2621 cm^2/V·s, and the carrier lifetimes are 0.3 and 300 ps, respectively. Based on the result, the THz intensity from the antenna with the carrier lifetime of 0.3 ps is 2.13 times higher than that of the antenna with the carrier lifetime of 300 ps. In addition, the THz waveform from the antenna with 0.3 ps lifetime has a large negative peak of the waveform, which is caused by the fast recombination of electrons and holes after the laser beam disappears. Fig. 4(b) indicates the effect of carrier mobility on THz intensity. In the calculation, the FWHM of fs laser is 100 fs, the carrier lifetime is 100 ps, and the mobilities of two antennas are 200 and 5000 cm^2/V·s, respectively. According to the result, the THz generation efficiency of the antenna with larger mobility is slightly higher than that of the antenna with smaller mobility. Although the difference of their mobility is 25 times, the ratio of their THz intensity is 1.17:1. From the calculation, it is found that the carrier lifetime plays a key role on the THz generation efficiency of PC antennas.

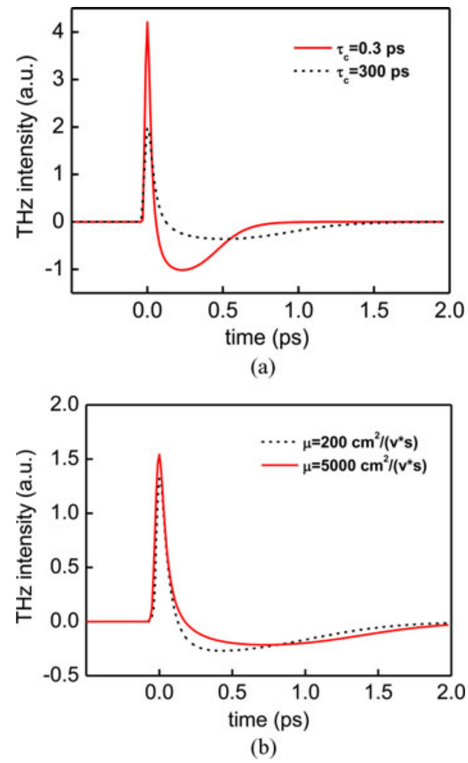

Fig. 4. (a) Effect of carrier lifetime on THz intensity. (b) Effect of carrier mobility on THz intensity.

IV. EXPERIMENT

From the foregoing analysis, we can draw the conclusion that a good antenna material should have high resistivity to restrain thermal noise and have short carrier lifetime to suppress generation-recombination noise and improve THz generation efficiency. Semiinsulating (SI) GaAs is most commonly employed as antenna substrate, and its resistivity can be higher than 10^7 Ω·cm. However, its carrier lifetime is several hundreds of picoseconds. LT-GaAs is regarded as the most outstanding PC material, it can be processed to obtain the resistivity of larger than 10^7 Ω·cm and the carrier lifetime of less than 1 ps. However, these excellent characteristics are difficult to be reproduced from sample to sample because the quality of the material depends critically on both the growth temperature and the post-growth thermal annealing conditions [19]. Recently, some ion-implanted GaAs materials were used as the antenna materials, and these materials exhibit good structural as well as electrical properties, ultrafast optoelectronic response, and good repeatability by precisely controlling the ion implantation dose, the ion energy, and the thermal annealing conditions [20]. In this paper, the oxygen-ion-implanted GaAs (GaAs:O) was fabricated, and the good performance of a GaAs:O antenna was demonstrated by comparing with a SI-GaAs antenna with the same structure at the same conditions.

A commercial high-resistivity ($>10^7$ Ω·cm), (110)-oriented, SI-GaAs substrate was used as the starting materials. Oxygen ion was implanted in SI-GaAs by Rutherford backscattering spectrometry facility with a 2-MV tandem accelerator. Normally the absorption depth of GaAs for 800-nm wavelength is close to 1 μm. Multiple implants using different energies were performed to achieve a relatively uniform defect distribution over the implantation depth of 1 μm. The energies corresponding to dosage are 500 keV/1.5 $\times$ 10^{14}/cm^2, 800 keV/1.5 $\times$ 10^{14}/cm^2, and 1200 keV/6 $\times$ 10^{14}/cm^2. After the implantation process, the rapid temperature annealing (RTA) was executed under N_2 gas environment and a GaAs cap was used to prevent As ion desorption. The parameter of RTA is 550 °C for 60 s. The resistivity and carrier lifetime of GaAs:O are 5 $\times$ 10^8 Ω·cm and 0.3 ps, respectively.

The electrode pattern is two parallel strip lines with the gap of 20 μm, which were fabricated on the substrate by the conventional photolithography technique. The mixture of Ni/Au–Ge/Au was deposited on the SI-GaAs and GaAs:O substrates by e-beam evaporation and was metalized by RTA. Accurately controlling the RTA time and temperature, we prepared the SI-GaAs antenna and GaAs:O antenna with AuGeNi alloy ohmic contact electrodes. Meanwhile, two metal pads were deposited on the substrate beside the electrodes as heat sink to remove the heat generated by laser and current [21]. Those antennas were measured using a TDS system. A mode-locked laser based on an Er-doped fiber oscillator (Femtolite-100 IMRA) was used to generate excitation laser pulses with the wavelength of 800 nm and the repetition rate of 75 MHz. The laser pulse width was less than 150 fs. The power of the pump beam was 50 mW. The emitter was biased with a 70-kHz square wave voltage with the duty

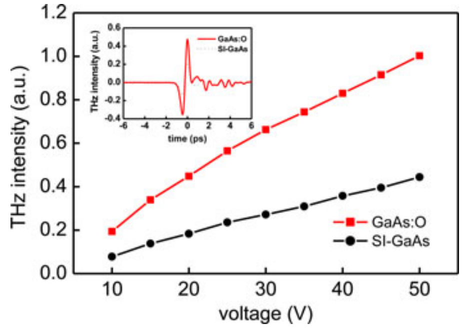

Fig. 5. Peak values of THz intensity generated by 20-μm-gap GaAs:O antenna and SI-GaAs antenna at different bias voltages. The inset shows THz time-domain waveforms of GaAs:O antenna and SI-GaAs antenna biased at 40 V and excited by 50-mW pump intensity.

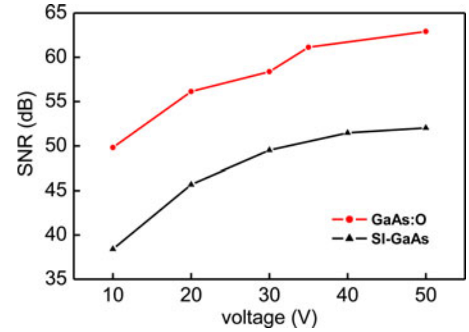

Fig. 6. SNR of GaAs:O antenna and SI-GaAs antenna at different bias voltages and the same excitation power of 50 mW.

cycle of 50%. The emitter was fast switched by the transmit light to generate transient current and produce the broadband THz radiation. The THz beam from the emitter was collimated and focused on a 1-mm-thick ZnTe crystal by a pair of off-axis parabolic mirrors. A probe pulse of 5 mW traveled collinearly with the THz pulse through a ZnTe crystal. The THz pulse modified the optical refractive index of the probe pulse by means of the linear electrooptic (Pockels) effect and thereby induced the ellipticity of the probe polarization. By measuring this ellipticity as a function of delay with respect to the THz pulse, we retrieved the time dependence of the electric field of the THz pulse. In all experiments, the time constant of the lock-in amplifier was 300 ms.

V. Performance of GaAs:O Antenna

A. THz Generation Efficiency

The THz time-domain waveforms generated from the GaAs:O antenna and the SI-GaAs antenna are shown in the inset of Fig. 5. The bias voltage for both antennas was 40 V. The peak to peak values of THz intensity generated by the GaAs:O antenna and the SI-GaAs antenna are 0.83 (a.u.) and 0.36 (a.u.), respectively, so that the intensity of THz wave from the GaAs:O antenna is 2.3 times higher than that of the SI-GaAs antenna at the same bias electric field. Fig. 5 shows the peak values of THz intensity generated by the GaAs:O antennas and the SI-GaAs antennas at different bias voltages, and the THz intensity from the GaAs:O antenna is about 2.2–2.5 times stronger than that of the SI-GaAs antenna at the same bias voltage.

The carrier lifetimes of GaAs:O and SI-GaAs are 0.3 and 300 ps, respectively, tested by an optical pump-optical probe experiment. According to the current surge model, because GaAs:O has an extremely short lifetime, the derivative of conductivity is larger than that of SI-GaAs. Therefore, the derivative of current ($dJ_s(t)/dt$) of GaAs:O is larger than that of SI-GaAs when laser illuminates antennas. After the laser pulse vanished, the current in antennas decreases because of the recombination of electrons and holes, and the $dJ_s(t)/dt$ of GaAs:O is also larger than that of SI-GaAs due to its small lifetime. As a result, GaAs:O antenna has higher THz generation efficiency.

B. Signal-to-Noise Ratio

Then, the SNRs of the GaAs:O antenna and the SI-GaAs antenna were investigated. The time-domain THz waveforms with enough long noise background before their main peaks were scanned. The SNR is defined as the ratio of peak-to-peak value of THz intensity to the root-mean-square of the first quarter of noise background. Fig. 6 shows the SNR of GaAs:O and SI-GaAs antennas at different bias voltages. The SNR of the GaAs:O antenna is 3–3.7 times higher than that of the SI-GaAs antenna. Furthermore, the THz intensity from the GaAs:O antenna is about 2.2–2.5 times higher than that of the SI-GaAs antenna, which means that the root-mean-square of noise from the GaAs:O antenna is less than that of the SI-GaAs antenna. The dark resistances of the GaAs:O antenna and the SI-GaAs antenna are 42 and 2.9 MΩ, respectively. According to Fig. 2, the spectral intensity of current fluctuation noise of the SI-GaAs antenna is 14.5 times higher than that of the GaAs:O antenna at 1 THz. Meanwhile, the spectral intensity of generation-recombination noise of the SI-GaAs antenna is three times higher than that of the GaAs:O antenna based on the results of Fig. 3. Hence, the GaAs:O antenna has lower noise and higher SNR.

VI. Conclusion

The noise generated by a PC emitter includes thermal noise and generation-recombination noise. And a good antenna material should have high resistivity to restrain the thermal noise and have short lifetime to suppress the generation-recombination noise. Meanwhile, the antenna with shorter carrier lifetime has higher THz generation efficiency. GaAs:O material was fabricated by ion implantation technique to approach the required performance. Its resistivity is 5×10^8 $\Omega\cdot$cm and its carrier lifetime is 0.3 ps. The SNR of the GaAs:O antenna is 3–3.7 times higher than that of the SI-GaAs antenna with the same structure under the same experimental conditions.

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REFERENCES

[1] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting Hertzian dipoles," *Appl. Phys. Lett.*, vol. 45, pp. 284–286, May 1984.

[2] Y. Takeshi, S. Eisuke, and A. Tsutomu, "Asynchronous optical sampling terahertz time-domain spectroscopy for ultrahigh spectral resolution and rapid data acquisition," *Appl. Phys. Lett.*, vol. 87, p. 061101, Aug. 2009.

[3] Y. Gao, M. Chen, S. Yin, P. Ruffin, C. Brantley, and E. Edwards, "Terahertz enhancement from terahertz-radiation-assisted large aperture photoconductive antenna," *J. Appl. Phys.*, vol. 109, p. 033108, Feb. 2011.

[4] J. T. Darrow, B. B. Hu, X.-C. Zhang, and D. H. Auston, "Subpicosecond electromagnetic pulses from large-aperture photoconducting antennas," *Opt. Lett.*, vol. 15, pp. 323–325, Jun. 1990.

[5] M. Awad, M. Nagel, H. Kurz, J. Herfort, and K. Ploog, "Characterization of low temperature GaAs antenna array terahertz emitters," *Appl. Phys. Lett.*, vol. 91, p. 181124, Nov. 2007.

[6] A. Dreyhaupt, S. Winnerl, T. Dekorsy, and M. Helm, "High-intensity terahertz radiation from a microstructured large-area," *Appl. Phys. Lett.*, vol. 86, p. 121114, Mar. 2005.

[7] S. Kono, M. Tani, P. Gu, and K. Sakai, "Detection of up to 20 THz with a low-temperature-grown GaAs photoconductive antenna gated with 15 fs light pulses," *Appl. Phys. Lett.*, vol. 77, pp. 4104–4106, Oct. 2000.

[8] T. A. Liu, M. Tani, M. Nakajima, M. Hangyo, and C. L. Pan, "Ultrabroadband terahertz field detection by photoconductive antennas based on multi-energy arsenic-ion-implanted GaAs and semi-insulating GaAs," *Appl. Phys. Lett.*, vol. 83, pp. 1322–1324, Jul. 2003.

[9] K. J. Chen, Y. T. Li, M. H. Yang, W. Y. Cheung, C. L. Pan, and K. T. Chan, "Comparison of continuous-wave terahertz wave generation and bias-field-dependent saturation in GaAs:O and LT-GaAs antennas," *Opt. Lett.*, vol. 34, pp. 935–937, Mar. 2009.

[10] W. Shi, L. Hou, and X. Wang, "High effective terahertz radiation from semi-insulating-GaAs photoconductive antennas with ohmic contact electrodes," *J. Appl. Phys.*, vol. 110, p. 023111, Jul. 2011.

[11] H. Zhang, J. K. Wahlstrand, S. B. Choi, and S. T. Cundiff, "Contactless photoconductive terahertz generation," *Opt. Lett.*, vol. 36, pp. 223–225, Jan. 2011.

[12] M. van Exter and D. R. Grischkowsky, "Characterization of an optoelectronic terahertz beam system," *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 11, pp. 1684–1691, Nov. 1990.

[13] L. Duvillaret, F. Garet, and J.-L. Coutaz, "Influence of noise on the characterization of materials by terahertz time-domain spectroscopy," *J. Opt. Soc. Am. B*, vol. 17, pp. 452–461, Mar. 2000.

[14] A. van der Ziel, *Noise. Sources, Characterization, Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1971, pp. 15–16.

[15] H. Nyquist, "Thermal agitation of electric charge in conductors," *Phys. Rev.*, vol. 32, pp. 110–113, Jul. 1928.

[16] A. Mar, G. M. Loubriel, F. J. Zutavern, M. W. O'Mallty, W. D. Helgeson, D. J. Brown, H. P. Hjalmarson, A. G. Baca, R. L. Thornton, and R. D. Donaldson, "Doped contacts for high-longevity optically activated, high-gain GaAs photoconductive semiconductor switches," *IEEE T. Plasma Sci.*, vol. 28, no. 5, pp. 1507–1511, Oct. 2000.

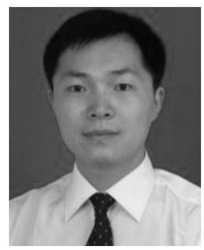
[17] J. T. Darrow, X.-C. Zhang, D. H. Auston, and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas," *IEEE J. Quantum Electron.*, vol. 28, no. 6, pp. 1607–1616, Jun. 1992.

[18] T. Zhang and J. Cao, "Temporal characterization of THz pulses generated by larger aperture photoconductive antennas," *Chin. J. Rare Metals*, vol. 28, pp. 588–589, Jun. 2004.

[19] B. Salem, D. Morris, Y. Salissou, V. Aimez, S. Charlebois, M. Chicoine, and F. Schiettekatte, "Terahertz emission properties of arsenic and oxygen ion-implanted GaAs based photoconductive pulsed sources," *J. Vac. Sci. Technol. A*, vol. 24, pp. 774–777, May/Jun. 2006.

[20] B. Salem, D. Morris, V. Aimez, J. Beerens, J. Beauvais, and D. Houde, "Pulsed photoconductive antenna terahertz sources made on ion-implanted GaAs substrates," *J. Phys: Condens. Matter*, vol. 17, pp. 7327–7334, Nov. 2005.

[21] W. Shi, L. Hou, Z. Liu, and T. Tongue, "Terahertz generation from SI-GaAs stripline antenna with different structural parameters," *J. Opt. Soc. Amer. B*, vol. 26, pp. A107–A112, Sep. 2009.



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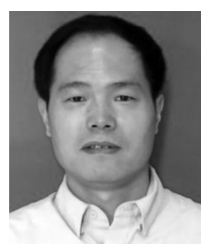

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