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RESEARCH ARTICLE

Time behavior of field screening effects in small-size GaAs photoconductive terahertz antenna

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Abstract The field screening effects in small-size GaAs photoconductive (PC) antenna are investigated via the well-known pump and probe terahertz (THz) generation technique. The peak amplitude of the THz pulses excited by the probe laser pulse as a function of the pump-probe time delay was measured. An equivalent-circuit model was used to simulate the experimental data. Based on the good agreement between the results of simulation and experiment, the time behavior of the radiation and space-charge fields was simulated. The results show that the space-charge screening dominantly determines the device response in the whole time, while the radiation filed screening plays a key role in initial time which strongly affects the peak THz field. The parameter analysis was performed, which may be valuable on the optimum design for the antenna as a THz emitter.

Keywords GaAs photoconductive (PC) antenna, field screening effects, terahertz (THz) emitter

1 Introduction

Since the initial observations of electromagnetic radiation in the terahertz (THz) frequency range in photoconductive (PC) antennas excited by ultra-fast laser pulses [1,2], considerable efforts were made to understand the mechanisms responsible for THz generation, for which was an efficacious method to investigate carrier transport and screening in PC antennas made on semiconductor [3–9]. This technique measures the THz radiation excited by the probe laser pulses; the pump pulses were used to inject electron-hole pairs prior to the probe pulses. Besides, an equivalent-circuit model was presented to investigate the screening effects in PC antennas and good agreements between simulation and experiment were obtained [6].

By the use of the pump and probe THz generation technique, PC antennas made by low temperature growth GaAs (LT-GaAs) were widely investigated [3–6], and the results demonstrate that two filed screening effects determine the device response: The screening of the applied bias field due to the space charge induced by the separation of the electrons and holes is as well as the screening of the local filed by the THz radiation. The time behavior of the radiation and space-charge fields was investigated and the results demonstrate that in the initial time the radiation field is very stronger than the space-charge field so that radiation field screening dominates the early response for a LT-GaAs PC H-shaped antenna with a 5-μm-wide PC gap [6]. For the PC antenna made by GaAs, the investigation on the time behavior of the two fields was missing [7–9]. Because the screening effect is the principal cause for saturation of THz emission observed when the emitters are driven hard with high-repetition-rate femtosecond (fs) laser pulses, this miss leads to that people do not fully understand the working process and characteristic of THz emitter made by GaAs.

In this paper, by using the pump and probe THz generation technique for a small-size GaAs PC strip-line antenna with a 50 μm spacing between lines, we measured the peak amplitude of the THz pulses excited by the probe laser pulse as a function of the pump-probe time delay under different pump powers. We used the equivalent-circuit model to simulate the measured data and to calculate the time behavior of the radiation and space-charge fields. Our results show that although the time behavior for our GaAs antenna is similar to that for the LT-GaAs antenna reported previously [6], quite difference between them was exposed: For the GaAs antenna, space-charge field is always stronger than radiation field so that the space-charge screening plays important role in the whole time process, while for the LT GaAs antenna in the

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initial time the radiation field is very stronger than the space-charge field so that radiation field screening dominates the early response [6]. Even so, the radiation field still plays a key role to affect the peak THz field for the GaAs antenna. Our results will be invaluable for designing and optimizing small-size PC THz emitters.

2 Experimental method and results

Figure 1(a) shows our experimental setup, which is similar to that described in Ref. [7]. The excitation source is a mode-locked Ti: sapphire laser (Coherent, Micra-5) providing 80 fs pulse width at a center wavelength of 800 nm and repetition rate of 80 MHz. The emitter antenna consists of two parallel 10 μm wide metal lines separated by 50 μm on a semi-insulating GaAs substrate. By using beam splitters, the laser pulse is divided into three beams (pump, probe and sampling). The pump (the sampling) pulse has a time delay 1 (time delay 2) relative to the probe pulse. The probe and pump pulses are focused on the emitter antenna. The pump pulse generates free carriers in the antenna and the probe pulse is chopped to generate a THz pulse. We can get the temporal evolution of the local filed between two electrodes in the antenna, the method is described as follows: Firstly, insert a beam dump after the time delay 1, change the time delay 2 and fix the time delay 2 when the THz filed is maximal; then, remove the beam dump, change the time delay 1 and monitor the THz filed.

Figure 1(b) displays the measured peak amplitude of the THz pulses excited by the probe laser pulse as a function of the pump-probe time delay under different pump powers. These traces reflect the response of the antenna to the two incident laser beams, which can be divided into four parts: The first, for large negative time delays, the probe pulse incidents on the antenna in advance of the pump pulse. From the causality principle, the pump pulse cannot affect the generation of the THz radiation by the probe pulse. As a result, constant THz amplitude is recorded. The second, for small negative time delays, the THz signals increase with the pump power, which can be interpreted for the cross-talk between the pump and probe pulses. The third, around $t = 0$ the THz signals have a sudden drop within about 0.5 ps, and the drop amount is proportion to the pump power. The last, at positive time delays, the THz signals continue to decrease but not too fast and recover slowly and incompletely. The decreasing time is related to the pump power. For the highest pump power, the decreasing time is about 10 ps. The lower the pump power, the longer the time. For the lowest power, the time is about 60 ps. An echo wave is detected around 50 ps.

3 Simulated method and results

According to the equivalent-circuit model [6,10], as shown in Fig. 2(a), the local electric field $E(t)$ in the antenna can be written as

$$E(t) = E_{\mathrm{b}} - E_{\mathrm{rad}} - E_{\mathrm{sc}}, \tag{1}$$

where E_{b} is the applied bias filed, E_{rad} is the radiation filed, and E_{sc} is the space-charge field. The radiation field can be represented by the voltage of the antenna impedance Z_{a}.

$$E_{\mathrm{rad}} = \frac{j(t)A}{d} Z_{\mathrm{a}} = \frac{e\mu_{\mathrm{e}} n_{\mathrm{f}}(t) E(t) A}{d} Z_{\mathrm{a}}, \tag{2}$$

where $j(t)$ is the current density flowing in the gap, A is the effective contact area of the PC gap, d is the width of the gap, e is electron charge, μ_{e} is the carrier mobility, and n_{f} is the carrier density. For the double-pulse pump, the time dependence of n_{f} can be expressed as

$$n_{\mathrm{f}}(t) = \frac{1}{2}\frac{\eta}{h\nu V}\exp\left(\frac{T_0^2}{4\tau_{\mathrm{c}}^2} - \frac{t}{\tau_{\mathrm{c}}}\right)\left\{J_{\mathrm{pump}}\left[1 + \mathrm{erf}\left(\frac{t}{T_0} - \frac{T_0}{2\tau_{\mathrm{c}}} + \frac{\tau}{T_0}\right)\right]\exp\left(-\frac{\tau}{\tau_{\mathrm{c}}}\right) + J_{\mathrm{probe}}\left[1 + \mathrm{erf}\left(\frac{t}{T_0} - \frac{T_0}{2\tau_{\mathrm{c}}}\right)\right]\right\}, \tag{3}$$

where η is the quantum efficiency, J_{pump} and J_{probe} are the pump and probe pulse energies, respectively, $h\nu$ is the photo energy of the laser at 800 nm, V is the active volume, T_0 is the pulse width, τ_{c} is the trapping time, and τ is the time delay between the pump and probe pulses.

The space-charge field is given by

$$E_{\mathrm{sc}} = \frac{P(t)}{\kappa\varepsilon}, \tag{4}$$

where κ is a screening factor, ε is the permittivity of the antenna material, and $P(t)$ satisfies the following equation:

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = -\frac{P(t)}{\tau_{\mathrm{r}}} + e n_{\mathrm{f}}(t)\mu_{\mathrm{e}} E(t), \tag{5}$$

where τ_{r} is the carrier recombination lifetime. From Eqs. (1), (2) and (4), we can get

$$E(t) = \left[1 + \frac{e\mu_{\mathrm{e}} Z_{\mathrm{a}} A}{d} n_{\mathrm{f}}(t)\right]^{-1}\left[\frac{V_{\mathrm{b}}}{d} - \frac{P(t)}{\kappa\varepsilon}\right]. \tag{6}$$

For our experiment, only the THz signal created by the probe pulse can be detected, so the simulation proceeds are taken as follows: At first, we used a fourth-order Runge-Kutta routine to solve Eq. (5) together with Eqs. (3) and (6) by setting $J_{\mathrm{probe}} \neq 0$ and $J_{\mathrm{pump}} = 0$, thus allowing us to get the reference THz waveform from a signal-pulse excitation for both pump and the probe pulse separately, identifying the optimal probe detection time by looking for the peak amplitude of the THz field for the probe pulse alone. Then, we used the same method to solve Eq. (5) together with Eqs. (4) and (6) by setting $J_{\mathrm{probe}} \neq 0$ and $J_{\mathrm{pump}} \neq 0$, thus allowing us to get the THz waveform from a double-pulse excitation. Finally, the THz signal can be obtained by

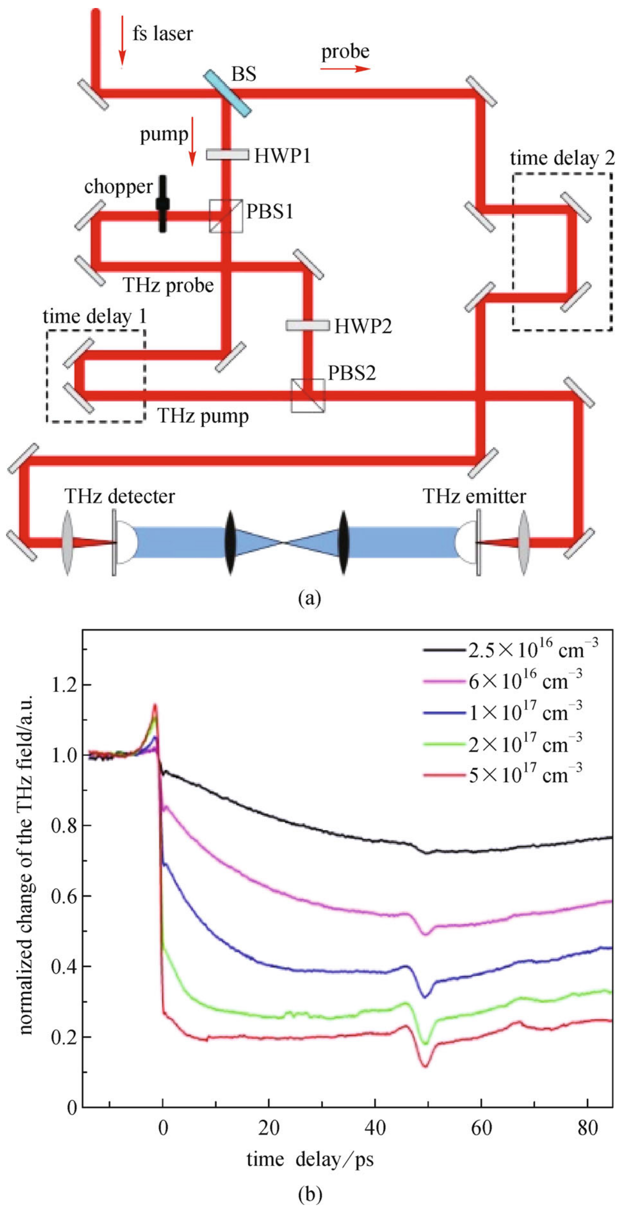


Fig. 1 (a) Experimental setup; (b) measured peak amplitude of the THz pulses excited by the probe laser pulse as a function of the pump-probe time delay under different pump powers. The power of the probe beam is set to 2 mW. The applied bias voltage is 55 V (field across the gap: 11 kV/cm). The displayed data normalized to 100% for $t = 0$. fs: femtosecond; BS: beam splitter; HWP: half-wave plate; PBS: polarization beam splitter

subtracting the amplitude of the reference THz waveform (pump only) from the amplitude of the computed double-pulse THz field.

Figure 2(b) shows the comparison of a measured curve to its calculated one for a fixed pump power. A very good agreement was achieved with values for the model parameters: $\kappa = 1500$, $\mu_e = 3000 \times 10^{-4}\,m^2/Vs$, $\tau_r = 320$ ps, $\tau_c = 15$ ps and $Z_a = 20\ \Omega$. By using these parameters, we simulated the sudden drop behavior of the peak THz field around $t = 0$ under different pump powers, as shown in Fig. 3, which are good agreed with the measured data.

Based on the good agreement of simulation and experiment shown in Figs. 2 and 3, it is justified to employ the model for a more detailed theoretical analysis. We paid our attention to the simulation of the time behavior of the space-charge and radiation fields under different pump powers. Figure 4 shows the calculated results for our GaAs antenna. As can be seen, the radiation field is always quite weaker than the space-charge field for our antenna with a 50 μm spacing between electrodes. For the LT-GaAs PC H-shaped antenna with a 5-μm-wide PC gap [6], however, in the initial time, the radiation field is very stronger than the space-charge field. It is easy to

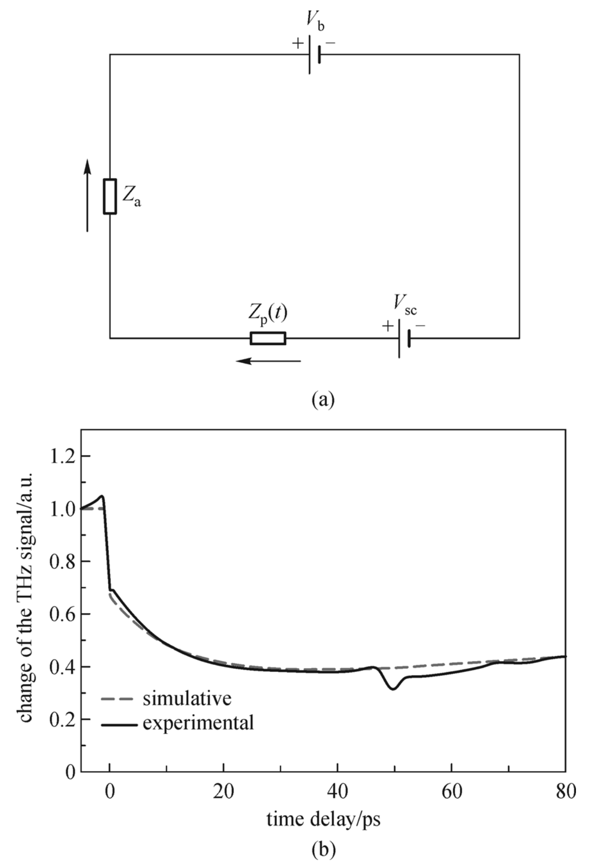


Fig. 2 (a) Schematically representing the equivalent circuit of GaAs antenna, four circuit elements in series with each other, V_b is the bias voltage of antenna, Z_a is the antenna impedance accounted for the THz radiation screening, $Z_p(t)$ models the time-varying impedance of the photo gap, and V_{sc} is the polarization induced by the separation of charge carries; (b) calculated and measured peak THz field as a function of the pump-probe time delay for fixed pump power at 10 mW

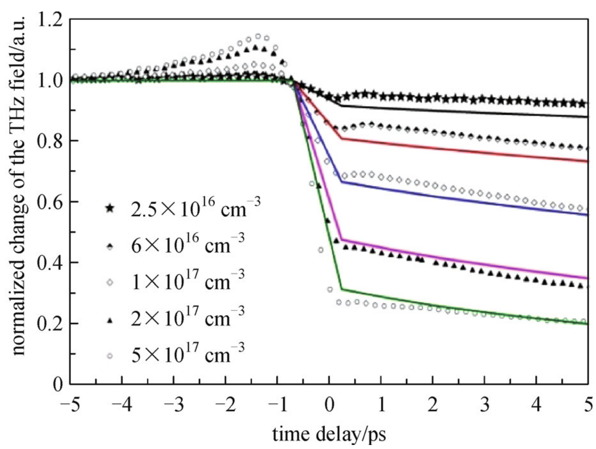


Fig. 3 Measured (solid curves) and calculated peak THz field around $t = 0$ under different pump powers

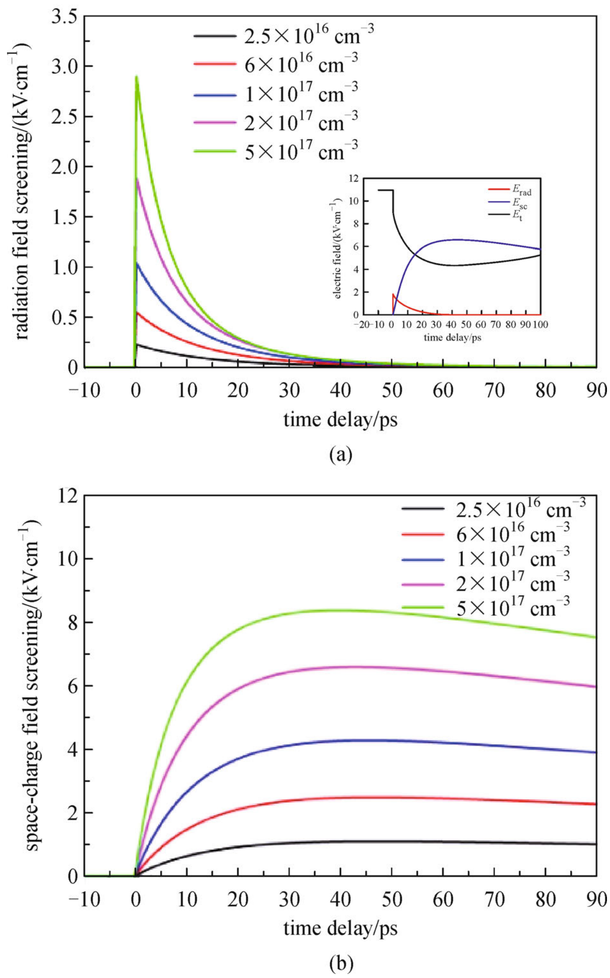
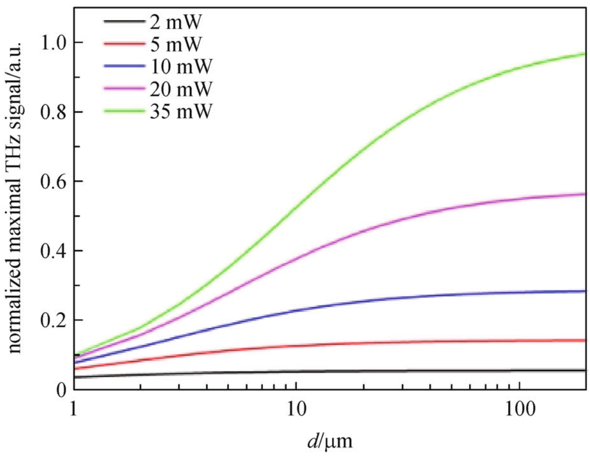


Fig. 4 Calculated time dependencies of (a) radiation field and (b) space-charge field under different pump laser powers. The inset in (a) shows the calculated temporal evolution of the local electric field in the antenna, plotted together with the radiation and space-charge fields for a fixed pump power at 20 mW. E_{rad} is the radiation field; E_{sc} is the space-charge field; E_t is the calculated temporal evolution of the local electric field in the antenna

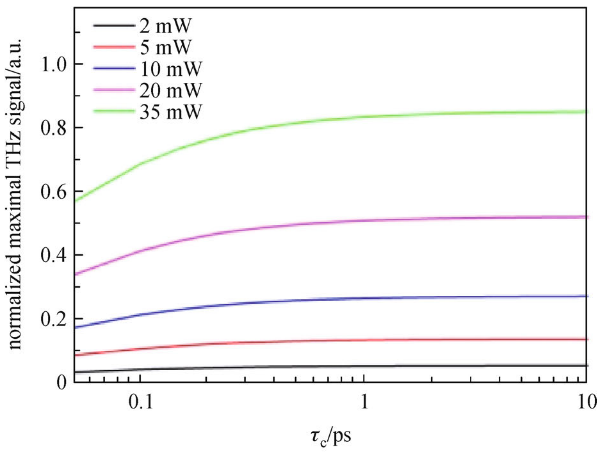
understand because the radiation field is inversely proportion to the spacing between two electrodes. Therefore, the space-charge field screening dominates the whole response for the GsAs antenna, while the radiation field screening dominates the early response for the LT-GaAs antenna. Both the radiation and space-charge fields are pump-power dependent. The higher the power is, the stronger the fields are, and the faster the radiation decays.

4 Discussion and conclusion

Based on the analysis above, we know the field screening effect is the important factor to affect the operating characteristic of a PC antenna as a THz emitter. The field screening effects depend on the geometrical parameters of



(a)



(b)

Fig. 5 Calculated normalized peak THz field changes with (a) the strip-line spacing d, and (b) the trapping time τ_c under different laser excitation powers

antenna, such as strip-line spacing d, and the material parameters of semiconductor, such as the trapping time τ_c. Figure 5 shows the calculated peak THz field changes with d and τ_c under different laser excitation powers. As can be seen, the peak THz field increases with d initially, and reaches saturation when d is large enough. The higher the laser power is, the larger the saturation value of d is. Comparing to d, the effect of τ_c is quite weak. Therefore, if the excitation level is quite high, taking a larger d is necessary.

The results shown in Fig. 5(a) is easy to understand, because the radiation field is inversely proportion to d, leading to the larger the d, the weaker the radiation field, and the stronger the peak THz field. When d is large enough, the radiation field will be weak enough, leading to the final saturation process to occur. It is worth noting that, for our GsAs antenna, the radiation filed screening plays a key role in initial time, leading to that d can strongly affects the peak THz field although the radiation field is much weaker than the space-charge field in the whole time range. As a contrast, we also calculated the d dependence of the peak THz field for large-area PC antenna (the results are not shown here), the saturation process is hard to occur because the radiation field is much stronger than the space-charge field in the initial time. Therefore, the parameter d is very important for the optimum design of a small-size PC THz antenna.

In summary, we investigated the time behavior of field screening effects in small-size GaAs PC THz antennas. The radiation filed screening plays a key role to affects the peak THz field, although the radiation field is much weaker than the space-charge field in the whole time range. These results are invaluable for designing and optimizing small-size PC THz emitters.

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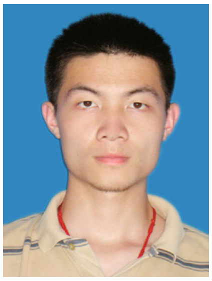
References

1. Auston D H, Cheung K P, Smith P R. Picosecond photoconducting Hertzian dipoles. Applied Physics Letters, 1984, 45(3): 284–286
2. Katzenellenbogen N, Grischkowsky D. Efficient generation of 380 fs pulses of THz radiation by ultrafast laser pulse excitation of a biased metal-semiconductor interface. Applied Physics Letters, 1991, 58(3): 222–224
3. Tonouchi M, Kawasaki N, Yoshimura T, Wald H, Seidel P. Pump and probe terahertz generation study of ultrafast carrier dynamics in low-temperature grown-GaAs. Japanese Journal of Applied Physics, 2002, 41(Part 2, No. 6B): L706–L709
4. Siebert K J, Lisauskas A, Löffler T, Roskos H. Field screening in low-temperature-grown GaAs photoconductive antennas. Japanese Journal of Applied Physics, 2004, 43(3): 1038–1043
5. Yano R, Gotoh H, Hirayama Y, Miyashita S. Systematic pump-probe terahertz wave emission spectroscopy of a photoconductive antenna fabricated on low-temperature grown GaAs. Journal of Applied Physics, 2004, 96(7): 3635–3638
6. Loata G C, Thomson M D, Löffler T, Poskos H C. Radiation field screening in photoconductive antennae studied via pulsed terahertz emission spectroscopy. Applied Physics Letters, 2007, 91(23): 232506-1–232506-3
7. Pedersen J E, Lyssenko V G, Hvam J M, Jepsen P U, Keiding S R, Sorensen C B, Lindelof P E. Ultrafast local field dynamics in photoconductive THz antennas. Applied Physics Letters, 1993, 62 (11): 1265–1267
8. Jacobsen R H, Birkelund K, Holst T, Jepsen P U, Keiding S R. Interpretation of photocurrent correlation measurements used for ultrafast photoconductive switch characterization. Journal of Applied Physics, 1996, 79(5): 2649–2657

9. Jepsen P U, Jacobsen R H, Keiding S R. Generation and detection of terahertz pulses from biased semiconductor antennas. Journal of the Optical Society of America B, Optical Physics, 1996, 13(11): 2424–2436
10. Loata G C. Investigation of low-temperature-grown GaAs photoconductive antennae for continuous-wave and pulsed terahertz generation. Dissertation for the Doctoral Degree. Frankfurt: Universitätsbibliothek Frankfurt am Main, 2007



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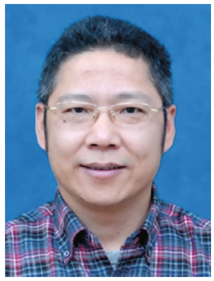

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