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Photon-Microwave Conversion in Semiconductors by Optical Carrier Control

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Original scientific paper

The ultrafast carrier dynamics in the optically excited semiconductors is studied by observing the THz radiation. We developed the pump and probe THz beam generation system with variable sample temperature control, and employed it to examine the ultrafast carrier scattering processes. The results proved that the THz beam generation, especially pump and probe method, is a powerful tool to study the ultrafast phenomena. We propose the new model to explain the ultrafast carrier dynamics just after photon arrivals in low-temperature-grown GaAs, which includes the intervalley scattering process.

Key words: femtosecons laser, terahertz radiation, ultrafast carrier dynamics, low-temperature-grown GaAs, pump and probe terahertz emission

1 INTRODUCTION

Femtosecond (fs) optical pulses can excite terahertz (THz) radiation from various kinds of photoswitches [1–3]. As the THz radiation generally originates due to the photo-excitation of carriers followed by their acceleration, the THz waveforms in time-domain contain a number of information to understand carrier dynamics in an optically excited system. However, there still remains uncertain picture of the carrier dynamics in relation to the photon-microwave conversion mechanism [1].

In the present work, the optically-excited carrier dynamics in semiconductors, which plays an important role of the THz beam excitation is discussed based on the THz emission properties. A pump and probe THz beam excitation technique is employed to observe ultrafast carrier dynamics in femtosecond time domain.

2 THz RADIATION

2.1 Radiation from a semiconductor photoswitch

According to classical electromagnetic dynamics, the far-field electric field E_{THz} of the electromagnetic wave radiated from a small dipole antenna is given by

$$E_{\mathrm{THz}} \propto \frac{\partial J}{\partial t}, \qquad (1)$$

where J is the current. Suppose that a photoconductive switch consists of a semi-insulating GaAs substrate and photoswitch with an illumination area of 10 μm by 10 μm, connected to a dipole antenna, and the antenna is DC-biased to store electrostatic energy.

The transient response after a femtosecond laser illumination of the photoswitch can be described by the following formulas [4]:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -\frac{n}{\tau_r} + G \qquad (2)$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{v}{\tau_s} + \frac{q}{m}E \qquad (3)$$

$$E = E_b - \frac{P}{\alpha\varepsilon} \qquad (4)$$

$$\frac{\mathrm{d}P}{\mathrm{d}t} = -\frac{P}{\tau_r} + J, \qquad (5)$$

where n is the carrier density, G is the generation rate of the carrier, τ_r is the recombination lifetime, v is the carrier velocity averaged over the carrier distribution, q is the charge of the electron, τ_s is the momentum relaxation time, m is the effective mass of the electron, E is the local electric field, E_b is the applied electric field, P is the polarization induced by the spatial separation of the electron and hole, ε is the dielectric constant of the substrate, and α, taken as 3 here, is the geometric factor of the materials. By neglecting the contribution of the holes, then the transient THz waveform can be determined by

$$E_{\mathrm{THz}} \propto \frac{\partial J}{\partial t} \propto ev\frac{\partial n}{\partial t} + en\frac{\partial v}{\partial t}. \qquad (6)$$

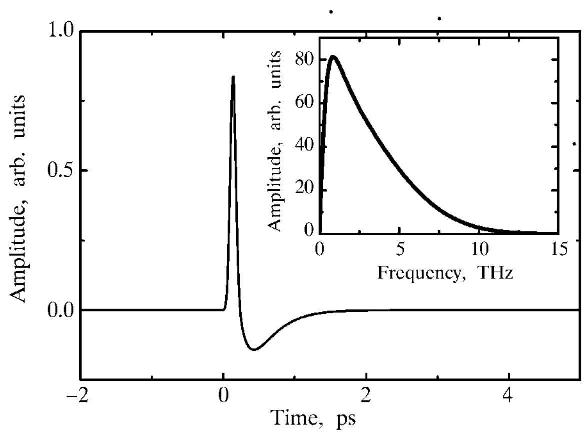

Fig. 1 Calculated THz radiation waveform emitted from a photoconductive SI-GaAs with a dipole antenna. The inset shows the corresponding a frequency spectrum

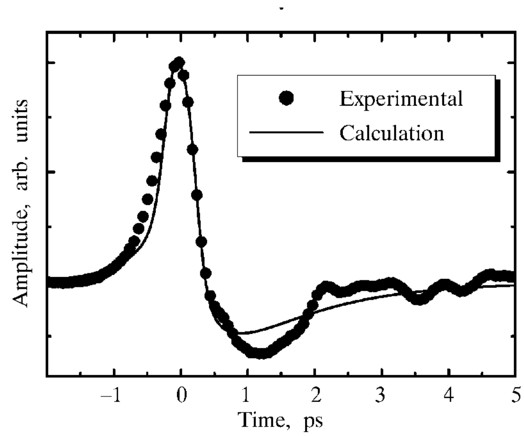

Fig. 2 THz radiation waveform from a prepared SI-GaAs photoconductive switch excited with a laser power of 2 mW and a bias voltage of 6 V. The solid line is a fit to the data calculated by the convolution between expected excitation waveform and optical response function of the LT-GaAs detector

Figure 1 shows an example THz waveform calculated assuming parameters of τ_r of 100 ps, τ_s of 30 fs, and an optical pulse width of 150 fs. The result suggests that the ultrashort electromagnetic pulse can be emitted from the dipole photoconductive antenna.

2.2 Experimental Procedures

Typical experimental setup (See Fig. 3) has been described previously [2]. Briefly, a mode-locked Ti:sapphire laser excited with a cw Ar ion laser is used to produce 50 fs (FWHM) light pulses, with a center wavelength of around 780 nm and at a repetition rate of 82 MHz. The fs light pulses were focused by an objective lens onto the center of the photoconductive switch. THz radiation emitted from the opposite side through the substrate is collimated and focused by a pair of off-axis paraboloidal mirrors onto the detector through a Si hemispherical lens. A photoconductive switch made of low--temperature-grown GaAs (LT-GaAs) is used as a detector. The detector was triggered by fs probe pulses separated from the pump beam by a beam splitter. The integrated photocurrent is lock-in detected. The THz waveforms in the time domain are monitored by changing the delay time between the pump and probe pulses.

2.3 THz radiation

Figure 2 shows a typical radiation waveform emitted from SI-GaAs photoswitches. The THz beam pulse width is much wider than that calculated as in Figure 1. Generally the radiated THz pulse is distorted by several factors such as the optical responsibility of the detector. The solid line in Figure 2 is a fit to the data, calculated by the convolution between the waveform given in Figure 1 and the appropriate optical response function in the detector photoswitch. This suggests that although the THz waveform originates in the ultrafast carrier transport, the distortion by the unclear factors prevents us to utilize it as a tool for the investigation method of the ultrafast carrier dynamics.

3 PUMP & PROBE THz RADIATION

3.1 Pump & Probe THz Radiation

Pump and probe THz excitation technique has been employed to investigate the carrier dynamics in GaAs by several groups [5–7], and they observed the ultrafast carrier behavior. However, the reports have been limited in a small number, and the rela-

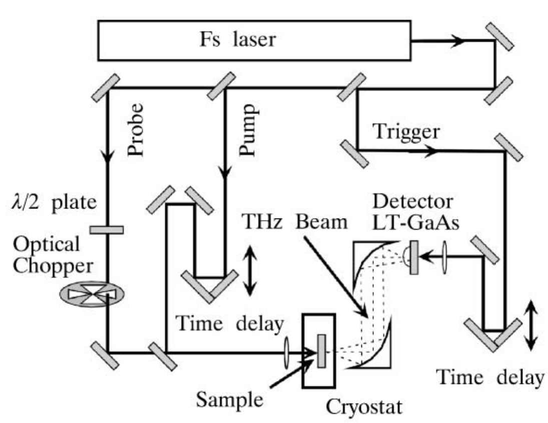

Fig. 3 Experimental setup for the generation and detection of the pump and probe THz beam. This is the same system for the conventional THz beam generation and detection except the pump optical path

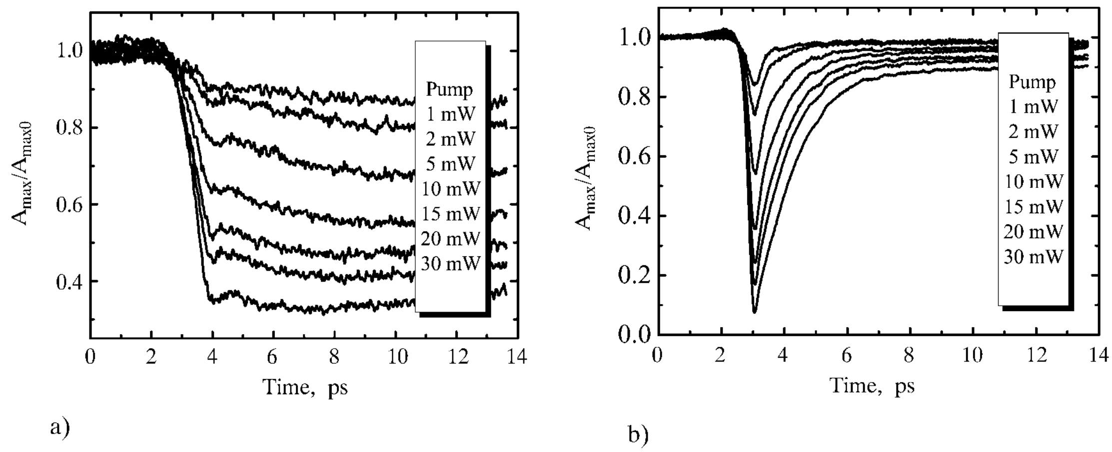

Fig. 4 Normalized maximum amplitude of the probe THz beam as a function of time delay emitted from (a) the SI-GaAs, and (b) LT-GaAs photoswitches. The switches are biased at a voltage of 6 V, *and a probe laser power is 1* mW *and 2* mW *for SI-GaAs and LT-GaAS, respectively*

tionship between the observable and the carrier dynamics still remains unclear. In the present work, we built a new system for the pump and probe THz radiation measurement with the temperature controllable sample holder, and applied it to study the carrier dynamics in SI-GaAs and LT-GaAs.

3.2 Pump & Probe THz Radiation System

Figure 3 shows the experimental setup for pump and probe THz beam excitation and detection. The fs optical pulses are separated into three beams; pump, probe, and trigger beam. We measure the THz radiation waveform excited by the probe beam. After fixing the delay time between the probe and trigger beams at the maximum amplitude of the waveform, its dependence on the delay time between the pump and probe beams is monitored at various excitation conditions.

3.3 Results and Discussion

General Auger recombination time in GaAs is in the order of 10 to 100 ps. Thus the time that the probe THz amplitude recovers to the initial values is expected to the same order. Figure 4 (a) shows the normalized maximum amplitude of the probe THz beam emitted from the SI-GaAs photoswitch as a function of the delay time between the pump and probe beams. The maximum amplitude after the pump beam arrival decreases with increasing probe laser power, which is attributed mainly to the screening effect. The amplitude has not recovered in this time region as expected.

LT-GaAs is well known to have an ultrashort carrier lifetime as short as 300 fs [8]. This relaxation dynamics is also clearly observable in the pump and probe THz beam generation properties as shown in Figure 4 (b). However, one can recognize the slow component in the relaxation dynamics, which increases with increasing pump laser power. Namely the results indicate that the pump and probe THz signals contain the information for the several scattering processes during the relaxation of the excited carriers.

In order to study the relaxation dynamics, the temporal signals were analyzed. When we analyze the relaxation time constants by calculating fits to the data on the assumption that the relaxation mainly originates in the three processes, the time constants strongly depend on the excitation power. The results indicate that there exist four main relaxation processes at least, which has been mentioned by many reports. Thus the fits to the relaxation part of the data are calculated based on the following formula,

$$F = A \cdot e^{-t/\tau_a} + B \cdot e^{-t/\tau_b} + C \cdot e^{-t/\tau_c} + D \cdot e^{-t/\tau_d}, \qquad (7)$$

where A, B, C, D, τ_a, τ_b, τ_c, and τ_d are the fitting parameters with a condition that $A+B+C+D=1$.

The relaxation times for τ_a, τ_b, and τ_c, are estimated to be 0.26, 0.85, and 1.25 ps, respectively, assuming that $\tau_d = 100$ ps [9], regardless of the excitation power. Figure 5 shows the laser power dependence of the contribution ratio of the relaxation processes. The laser powers can be transferred into the carrier generation density as depicted in Figure 5 assuming an absorption depth of 1 μm in the 1 μm-thick-LT-GaAs layer, and a power-reflection efficiency of 0.3 at a wavelength of 800 nm.

It has been reported that the LT-GaAs grown at around 250 degrees has the mid-gap-state (MGS) density of about $10^{18}/cm^3$ [9]. Our data shown in Figure 5, suggest that τ_a, and τ_b are closely related

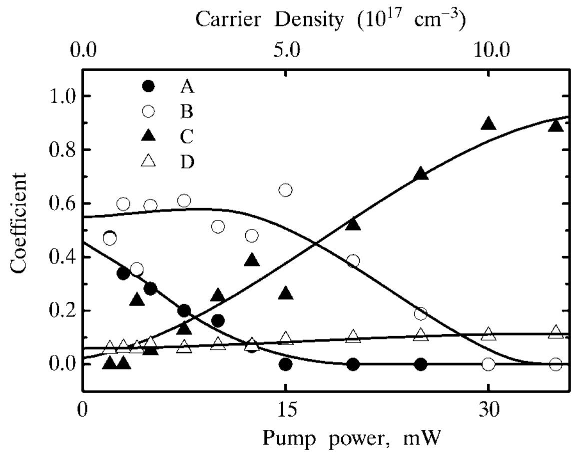

Fig. 5 Coefficient A, B, C, and D, as a function of laser power. Solid lines are only a guide to the eyes

to the scattering with mid-gap-state. The results suggest that at relatively low excitation power, the scattering with MGS plays an important role in the carrier dynamics, which becomes less important with increasing carrier generation density.

This quantitative evaluation of the optically excited carrier dynamics in LT-GaAs leads to a new scattering model. Figure 6 shows the schematic band structure of GaAs including the important scattering processes. At the initial coherent regime, the photons excite the electrons into the high energy level, followed by the momentum randomization at the excited level. Then they start relax into the lower energy state. Generally the fastest scattering process, corresponding to τ_a-process here, is attributed to the hot-carrier relaxation by the scattering with MGS as identified as τ_2 in Figure 6 [9]. However, the decrease in the contribution ratio of the scattering processes explained by τ_a, and τ_b disagrees with the model proposed so far. Here we propose the model that the scattering processes explained by τ_a, τ_b, τ_c, and τ_d correspond to the processes referred to as τ_1, τ_2, τ_3, and τ_4 in Figure 6, which can quantitatively explains the present data. The intra-valley scattering time via LO phonon scattering is reported about 110 fs. The difference between that time and estimated τ_b is provably attributed to the long effective relaxation time in the Γ-valley; the relaxation is governed by the multiple-scattering processes to lose the hot-electrons' high energy. The decrease in the scattering amplitude for τ_2 may originate the band filling effect at the Γ-valley.

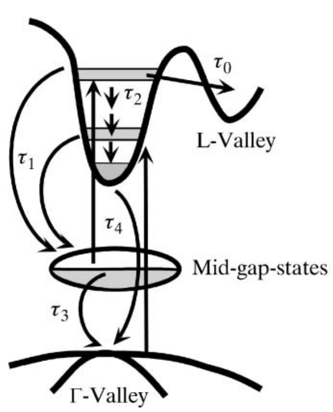

Fig. 6 Schematic band diagram for LT-GaAs including mid-gap-states as a part of the band. The key excitation and decay processes are indicated

At high electric field or high density excitation regime, the intervalley scattering defined by τ_0 is also important because the carriers excited from the As precipitates or the ones accelerated in the Γ-valley can get easily into the L-valley. We observed that the intervalley scattering plays an important role in the optically excited SI-GaAs while emitting THz radiation. This will be reported in detail elsewhere.

4 CONCLUSION

In the conclusion, the ultrafast carrier dynamics in the optically excited GaAs while exciting the THz beam is studied by observing the THz radiation. We developed the pump and probe THz beam generation system with variable sample temperature control, and employed it to examine the ultrafast carrier scattering process. The results proved that the THz beam generation, especially pump and probe method, is powerful tool to study the ultrafast phenomena. We propose the new model to explain the ultrafast carrier dynamics just after photon arrivals in LT-GaAs, which includes the intervalley scattering process.

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Fotonsko-mikrovalna konverzija u poluvodičima kontrolom vala nosioca u optičkom području. Proučavana je dinamika ultrabrzog nosioca u optički pobuđenim poluvodičima promatranjem generiranja zraka u THz području. Razvijen je sustav za generiranje THz zrake pumpe i probe s temperaturnom kontrolom varijabilnim uzorkom. Sustav je korišten za ispitivanje procesa raspršenja ultrabrzog nosioca. Rezultati ukazuju na činjenicu da je generiranje THz zraka, a posebno metoda pumpe i probe, snažan alat za proučavanje ultrabrzih pojava. Predložen je novi model za objašnjenje dinamike ultrabrzog nosioca, upravo nakon upada fotona GaAs dobiven pomoću niskotemperaturnog procesa. Model sadrži proces raspršenja među energetskim pojasevima.

Ključne riječi: femtosekundni laser, zračenje u terahercnom području, dinamika ultrabrzih nosilaca, GaAs dobiven pomoću niskotemperaturnog procesa, emisija vala pumpe i probe u terahercnom području

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