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Strong emission of THz radiation from GaAs microstructures on Si

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Remarkably strong emission of terahertz radiation from illuminated GaAs microstructures on a Si substrate is reported. The peak–to–peak amplitude of terahertz radiation from the sample is 9 times larger than that of THz radiation from a semi-insulating GaAs wafer. The spectral width of the sample is larger than that of a semi-insulating GaAs wafer; in particular, the spectral amplitude increases at higher frequencies. The presented GaAs microstructures on a Si substrate can be suitable for practical and efficient THz sources required in various THz applications.
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I. INTRODUCTION

Terahertz (THz) time-domain spectroscopy has been used to investigate molecular motions in gaseous or liquid states and carrier dynamics in various materials, such as, semiconductors, dielectrics, etc.[1–4] THz radiation enables direct observation of low-energy modes of materials, such as, molecular rotations, phonons, polaritons, and charge and spin waves by resonance excitation.[5] THz emission spectroscopy is a powerful method to investigate sub-picosecond responses with femtosecond optical pulses. In particular, charged states at the surface of a semiconductor are directly related with the radiated THz waveform.[6–9]

Semiconductors illuminated by a femtosecond laser beam can emit THz radiation. A transient current by drift and diffusion of photo-carries in the semiconductor can induce THz radiation. The amplitude of the THz radiation is proportional to the time derivative of the current, while the waveform of the THz radiation in time is closely related to the increasing and decaying features of the current. Therefore, the properties of THz radiation from semiconductors with ordered or disordered structures are different from those of THz radiation from bare semiconductors as the structures influence the movement of photo-carriers. For example, introduction of nanostructures on a Ge wafer can enhance the amplitude of THz radiation without changing the spectral bandwidth.[10] Disordered nanostructures on a GaAs wafer can broaden the spectral bandwidth.[11]

The properties of THz radiation emitted from GaAs microstructures with sizes of a few micrometers are worth studying as micrograins and rich defect states of the microstructures can increase the transient current and lead to a fast current decay. Therefore, it is expected that the illuminated GaAs microstructures can emit strong THz radiation with a large spectral bandwidth. Furthermore, the GaAs microstructures can be easily grown on a Si substrate by the molecular beam epitaxy (MBE) method without costly fabrication processing, such as, lithography and dry etching.[12]

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Therefore, GaAs microstructures on a Si substrate can be a good candidate for a cheap and efficient THz radiation source.

In this paper, the properties of THz radiation from illuminated GaAs microstructures on a Si substrate are reported. The peak–to–peak amplitude of the THz radiation from the GaAs microstructure on the Si substrate is 9 times larger than that of THz radiation from a semi insulating (SI) GaAs wafer; it is even comparable with that of THz radiation from an *n*-type InAs wafer. The spectral width of the sample is larger than that of a SI GaAs wafer; in particular, the spectral amplitude increases at higher frequencies. The remarkable enhancement of THz radiation is also observed in other samples grown under different conditions. Therefore, GaAs microstructures on a Si substrate can be utilized as an efficient THz radiation source.

II. EXPERIMENTAL DETAILS

In the MBE growth of GaAs microstructures on a SI Si (111) substrate, a self-catalyzed vapor–liquid–solid (VLS) growth technique was used.[12] Prior to the sample growth, the substrate was thermally cleaned at 650 °C for 10 min without any group-III or group-V overpressure to remove native oxide. The substrate surface was then exposed to Ga molecular beam flux by opening a Ga shutter for 2 min at the same temperature. The Ga molecular beam flux corresponded to a growth rate of 1.7 Å/s. The Ga shutter and As valve were then simultaneously opened to grow GaAs microstructures at 650 °C for 1 h. The temperature was intentionally chosen to grow GaAs microstructures by delaying the formation of nanowires.[13]

Figure 1(a) shows a top-view scanning electron microscopy (SEM) image of a GaAs-microstructure sample. Figure 1(b) shows a close-up SEM view of a part of Fig. 1(a). The area

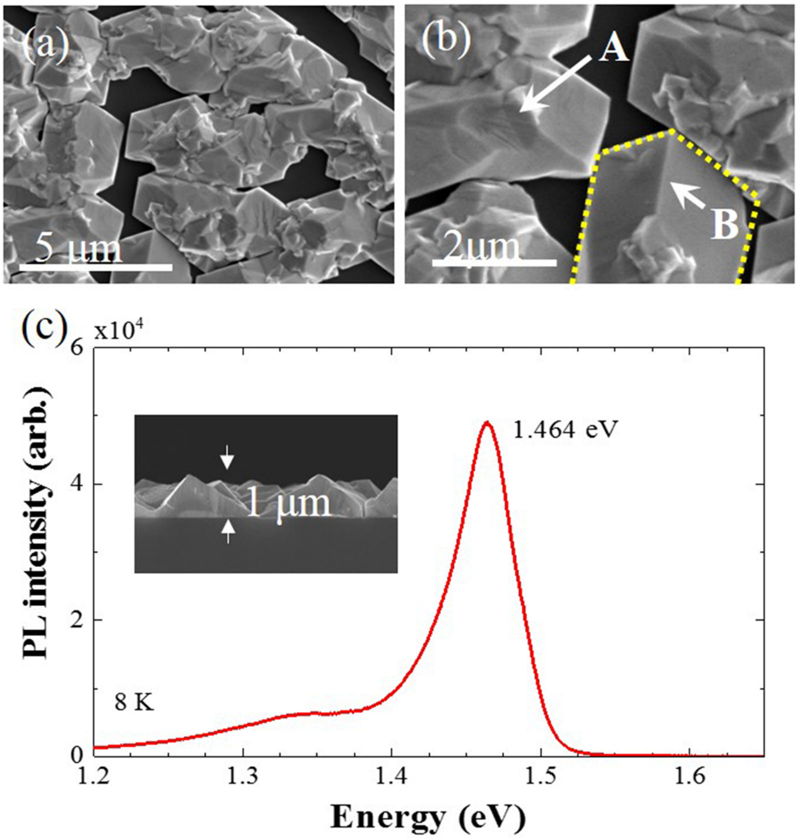

FIG. 1. (a) Top-view SEM image of a GaAs-microstructure sample. (b) Close-up SEM image of a part of (a). The area indicated as "A" shows step-bunching, an evidence of step-flow crystal growth, while the straight line indicated as "B" shows a facet of a WZ crystal. (c) Low-temperature PL spectrum of the sample. The emission peak is observed at 1.464 eV. The inset shows a cross-section SEM image of the sample.

indicated as "A" shows step-bunching, an evidence of step-flow crystal growth, while the straight line indicated as "B" shows a facet of a wurtzite (WZ) crystal.[14] A cross-section SEM view of the sample is shown in the inset of Fig. 1(c).

Figure 1(c) shows a low-temperature (8 K) photoluminescence (PL) spectrum of the sample. A Nd:YVO$_4$ laser (532 nm) with an excitation power of approximately 1.38 mW and 150/mm grating were employed in the PL spectrum measurement. A 570-nm long-pass filter was used to block the laser line. It is well known that WZ GaAs exhibits PL emission at 1.467 eV at low temperature.[15] The sample has a PL peak at 1.464 eV; therefore, the measured PL spectrum confirms that the sample has a WZ crystal structure.

The THz radiation from the sample was measured with a standard THz time-domain spectroscopy setup. A femtosecond Ti:sapphire laser (Mai Tai, Spectra-physics) beam with a center wavelength of 800 nm, pulse width of 100 fs, and repetition rate of 80 MHz was employed. It was split to two beams to generate and detect THz radiation. For the generation, the laser pulse irradiated the sample at an angle of 45°. For the detection, an electro-optic sampling method was used.[16] Using two parabolic mirrors, the generated THz radiation was focused onto a 2-mm-thick ZnTe (110) crystal. The irradiating power of the femtosecond laser beam was fixed at 1 W, while the output voltage of one of the balanced detectors was fixed at 300 mV. All measured data were acquired under dry air at room temperature.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show waveforms of THz radiation from the GaAs microstructure on the Si substrate and SI-GaAs wafer in time and frequency domains, respectively. The amplitude

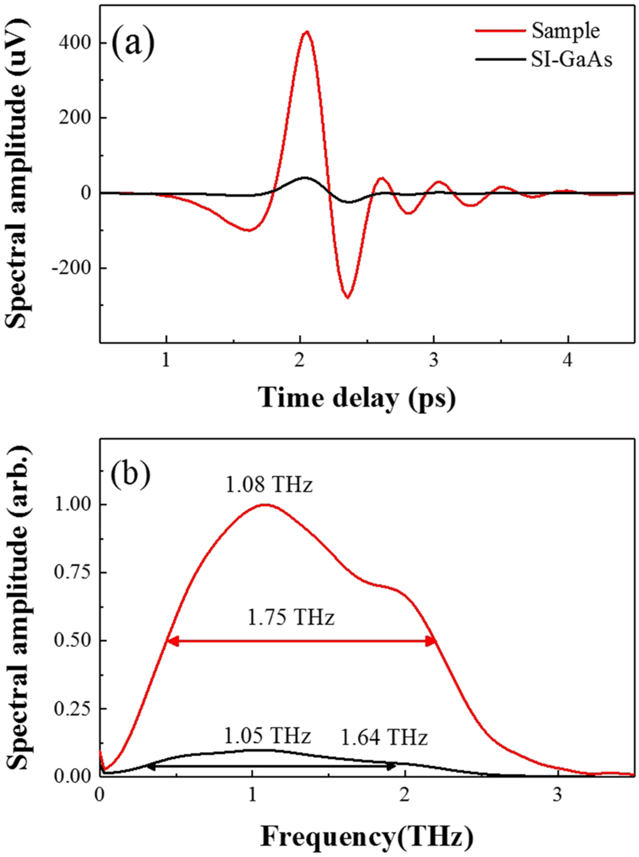

FIG. 2. (a) Time-domain and (b) frequency-domain waveforms of the emitted THz radiations from the sample and SI-GaAs wafer.

of THz radiation generated from a transient current in an illuminated semiconductor is simply expressed as:

$$E_{THz}(t) \propto \frac{\partial J(t)}{\partial t} = \frac{\partial N(t)}{\partial t} e\mu E_s, \tag{1}$$

where $J(t)$ is the transient current, $N(t)$ is the density of photo-carriers, e is the charge of electron, μ is the carrier mobility, and E_s is the built-in surface field.[17] In the time domain, the peak–to–peak amplitude of THz radiation from the sample is approximately 9 times larger than that of the SI-GaAs wafer. The waveforms normalized to the peak amplitudes imply that the decay of $N(t)$ in the sample is faster than that of $N(t)$ in the SI-GaAs wafer, while their increase characteristics of $N(t)$ are approximately equal (Figure S1, supplementary material, SI). In the frequency domain, the peak frequency of the sample, 1.08 THz, is slightly higher than that of the SI-GaAs wafer, 1.05 THz. The full width at half-maximum of the sample, 1.75 THz, is larger than that of the SI-GaAs wafer, 1.64 THz. It is worth noting that the normalized spectral amplitudes at higher frequencies in the sample are larger than those in the SI-GaAs wafer (Figure S2, supplementary material, SI). The shortened decay time of $N(t)$ in the sample might be attributed to the micrograins and rich defect sites. In general, the micrograins and rich defect sites create various defect states including deep defect states to trap free electrons and holes in diffusion. Thus they can reduce the mobility and nonradiative recombination lifetime of carriers.[17]

A Hall measurement at room temperature was performed to obtain the mobility and carrier concentration of the sample, yielding values of 2,010 $\mathrm{cm^2/V \cdot s}$ (the sample is n-type) and 9.85×10^{17} $\mathrm{cm^{-3}}$, respectively. The mobility is approximately 0.25 times that of a typical GaAs, while the carrier concentration of the sample is comparable to that of a typical doped semiconductor.[18,19]

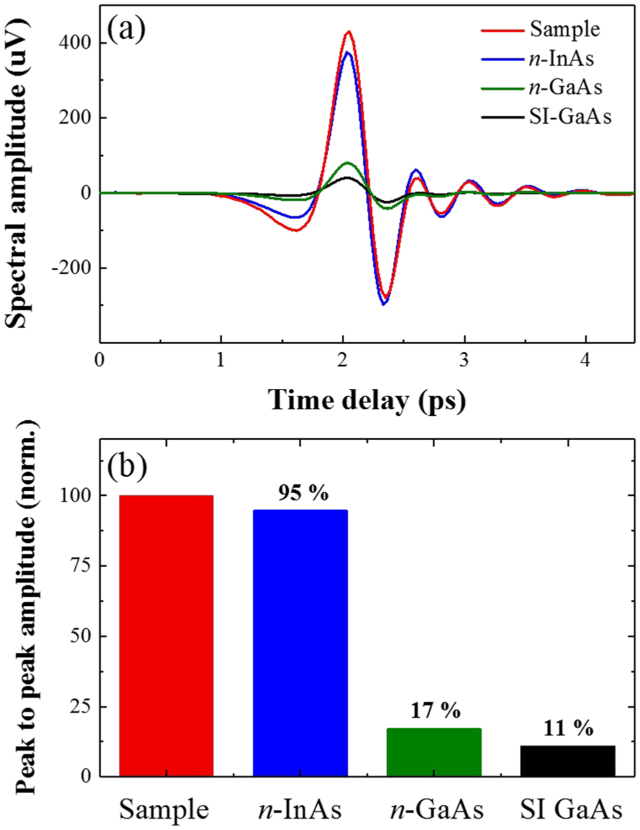

FIG. 3. (a) Time-domain waveforms and (b) histograms obtained from the peak–to–peak amplitudes of THz radiation from the sample and n-type InAs, n-type GaAs, and SI-GaAs wafers.

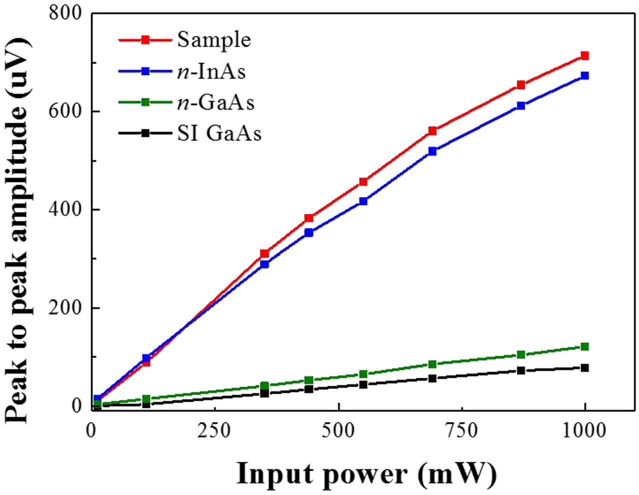

FIG. 4. Dependences of the peak–to–peak amplitudes of THz radiation from the sample and *n*-InAs, *n*-GaAs, and SI-GaAs wafers on the input power.

As the built-in surface field is proportional to the slope of the band bending on the surface caused by the difference between the Fermi energies of surface and bulk states, the surface field of a doped semiconductor is larger than that of an un-doped semiconductor. Therefore, it is worth comparing the emission of THz radiation of the sample with those of *n*-type semiconductors including an *n*-type InAs enabling to emit strong THz radiation.[20]

Figures 3(a) and 3(b) show the time-domain waveforms and histograms, respectively, obtained from the peak–to–peak amplitudes of THz radiation from the sample and SI-GaAs, *n*-type GaAs, and *n*-type InAs wafers. The values are normalized to the peak–to–peak amplitude of the sample. It should be emphasized that the peak–to–peak amplitude of the sample is even slightly larger than that of the *n*-type InAs wafer, while the mobility of a typical InAs wafer is approximately 30,000 cm^2/V·s, which is approximately 15 times that of the sample.[17] This might imply that the built-in surface field of the sample is significantly larger than that of the *n*-type InAs wafer. It has been reported that strong THz emission from nanostructured semiconductors and GaAs grown Ga-rich on GaAs substrates is caused by an enhancement of the built-in surface field on the surface.[21,22] The time-domain waveforms and the peak–to–peak amplitudes of THz radiation from the sample and SI

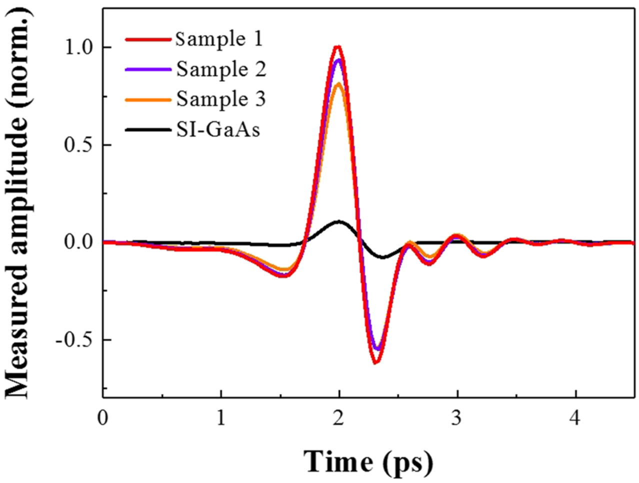

FIG. 5. Time-domain waveforms of the three different samples and SI-GaAs wafer.

GaAs, *n*-type GaAs, and *n*-type InAs wafers are also compared to those of a *p*-type InAs wafer, which is well-known as a highly efficient THz source (Figure S3, supplementary material).

Figure 4 shows the dependences of the peak–to–peak amplitudes of THz radiation from the sample and SI-GaAs, *n*-type GaAs, and *n*-type InAs wafers on the input power of the femtosecond laser with a central wavelength of 800 nm; approximately linear dependences on the input power are observed. The linear power dependence of the peak–to–peak amplitudes implies that the surge current is the main contribution to the THz emission.[17,23] The difference between the values of the sample and *n*-type InAs wafer increases with the input power and saturates above an input power of 600 mW (Figure S4, supplementary material, SI).

In order to confirm the strong emission of THz radiation from GaAs microstructures on a Si substrate, three samples were grown with different As/Ga gas pressure ratios of $r = 15\%$ (sample 1), 20% (sample 2), and 25% (sample 3). When $r < 15\%$, for example, $r = 10\%$, GaAs microstructures were not properly formed on a Si substrate. Figure 5 shows the time-domain waveforms of THz radiation from the three different samples and SI-GaAs wafer. The amplitudes of THz radiation were normalized to the peak amplitude of the sample 1. The samples exhibit remarkable enhancements of THz radiation, compared with the SI-GaAs wafer. The intensities of THz radiation from the samples increase with the gas pressure ratio.

IV. CONCLUSIONS

THz radiation from illuminated GaAs microstructures on a Si substrate was investigated. The peak–to–peak amplitude of terahertz radiation from the sample is much larger than that of THz radiation from a GaAs wafer. The THz radiation from the sample exhibited an enhanced spectral amplitude in the higher-frequency range. The properties of THz radiation from the sample may be understood by a fact that micrograins and rich defect sites can increase the photo-carriers and reduce the nonradiative recombination lifetime. The GaAs microstructures on a Si substrate emitting strong THz radiation with an enhanced high-frequency spectrum can be suitable for practical and efficient THz sources required in various THz applications.

SUPPLEMENTARY MATERIAL

See supplementary material for some figures that support our conclusion.

ACKNOWLEDGMENTS

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