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Enhancement of terahertz electromagnetic wave emission from an undoped GaAs/*n*-type GaAs epitaxial layer structure

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We have investigated the emission of the terahertz electromagnetic wave from an undoped GaAs (200 nm)/*n*-type GaAs (3 μm) epitaxial layer structure (*i*-GaAs/*n*-GaAs structure), where the doping concentration of the *n*-GaAs layer is 3×10^{18} cm^{-3}. It is found that the first-burst amplitude of terahertz wave of the *i*-GaAs/*n*-GaAs sample is remarkably larger than that of a *n*-GaAs crystal, which means that the *i*-GaAs layer enhances the terahertz emission intensity. The first-burst amplitude of the *i*-GaAs/*n*-GaAs sample, by tuning the pump-beam energy to the higher energy side, exceeds that of an *i*-InAs crystal that is known as one of the most intense terahertz emitters. We, therefore, conclude that the *i*-GaAs/*n*-GaAs structure is useful to obtain intense terahertz emission. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2976436]

For the progress of terahertz range spectroscopy from the research stage to the application stage, it is required to develop convenient and intense terahertz electromagnetic wave emitters. Compound semiconductors with a surface electric field, by being irradiated by femtosecond-laser pulses, emit the terahertz electromagnetic wave originating from a surge current flowing in the surface depletion layer.[1,2] This phenomenon provides us a convenient terahertz emitter free from a device fabrication for an external applied bias. In the above terahertz emission mechanism, the doping concentration is a major factor determining the depletion-layer width and surface electric field, which are in the relation of trade-off on the doping concentration. In order to obtain intense terahertz emission, earlier works focused on searching a proper compound semiconductor and subsequently adjusted the doping concentration.[3–5] Moreover, external magnetic fields, which are of the order of 1 T, were used for enhancing the terahertz emission;[6–11] however, the terahertz spectroscopic system with the use of the magnetic field generator lacks the advantage of being convenient.

In the present work, we explore the feasibility of enhancing the terahertz emission intensity by the design of an epitaxial layer structure. We demonstrate that an undoped GaAs (*i*-GaAs)/*n*-type GaAs (*n*-GaAs) epitaxial layer structure is effective to enhance terahertz emission and that the emission intensity from the *i*-GaAs/*n*-GaAs sample can exceed the emission intensity from *i*-InAs that is known as one of the most intense terahertz emitters.

The present sample was an *i*-GaAs (200 nm)/*n*-GaAs (3 μm, 3×10^{18} cm^{-3}) structure grown on a 2°-off semi-insulating (001) GaAs substrate by metal organic vapor phase epitaxy, where the values in the parentheses denote the individual layer thickness and doping concentration. In order to clarify the sample characteristics, using a computational simulation on the basis of the Boltzmann–Poisson model,[12,13] we calculated the equilibrium potential structure and electron-density distribution in the *n*-GaAs (3×10^{18} cm^{-3}) and *i*-GaAs/*n*-GaAs samples, which are shown in Figs. 1(a) and 1(b), respectively. The parameters used in the calculations are the same as those used in Ref. 14. In Fig. 1(a), the solid line denotes the conduction-band energy as a function of distance from the surface, where the origin of the energy axis corresponds to the Fermi level (dashed line). The dashed-and-dotted line denotes the electron density as a

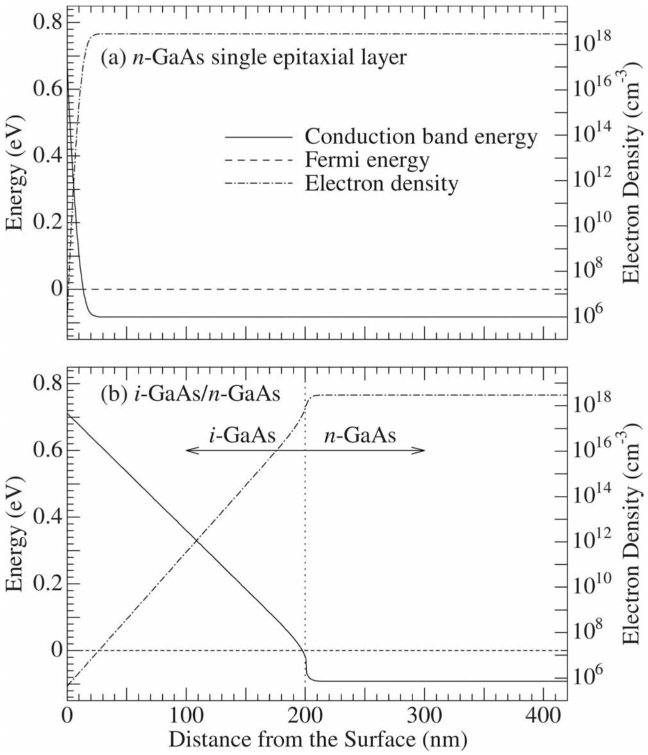

FIG. 1. Potential energy and electron density of each sample as a function of distance from the surface calculated on the basis of the Boltzmann–Poisson model. The solid and dashed lines indicate the conduction-band energy and Fermi level, respectively. The dashed-and-dotted line denotes the electron density calculated as a function of distance from the surface. (a) *n*-GaAs (3 μm, 3×10^{18} cm^{-3}) single epitaxial layer. (b) the *i*-GaAs(200 nm)/*n*-GaAs (3 μm, 3×10^{18} cm^{-3}) structure.

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function of the distance from the surface. As shown in Fig. 1(a), the conduction-band energy remarkably bends around the surface owing to the surface Fermi-level pinning. The thickness of the surface depletion region is estimated to be 13 nm from the electron-density distribution. The thin depletion layer originates from the fact that the whole epitaxial layer structure is highly doped to 3×10^{18} cm^{-3}. In contrast, as shown in Fig. 1(b), the conduction-band energy of the i-GaAs/n-GaAs sample has a finite potential slope in the whole i-GaAs layer with a thickness of 200 nm, which results from the fact that the i-GaAs top layer is free from doping. The i-GaAs layer has a uniform built-in electric field of 35 kV/cm. The electron velocity accelerated by the electric field saturates in the range of over 10 kV/cm in GaAs.[15] Therefore, the drift motion by the surface electric field in the i-GaAs/n-GaAs sample is comparable to that in the n-GaAs single epitaxial layer. Accordingly, the thicker depletion layer is advantageous to the terahertz emission. The sharp drop of the energy at the i-GaAs/n-GaAs interface is caused by the band-gap shrinkage of the n-GaAs layer due to the heavy doping. Corresponding to the potential structure, the i-GaAs layer is completely depleted, as shown in Fig. 1(b), which is effective to prevent terahertz emission from free carrier absorption. In addition, scattering of photogenerated carriers by background carriers is negligible in the i-GaAs layer. This is advantageous to the mobility of photogenerated carriers. Taking account of the fact that the depletion-layer thickness is 13 nm in the n-GaAs (3×10^{18} cm^{-3}) sample, the results of calculations suggest that the i-GaAs/n-GaAs structure is more suitable for the terahertz emitter than the uniformly doped epitaxial layer structure. We note that the appropriateness of the calculated potential structure has been confirmed using photoreflectance spectroscopy.[14] The time-domain terahertz emission signals from the sample were measured at room temperature with the use of laser pulses with a duration time of about 70 fs. The emitted terahertz beam was received by an optically gated bow tie antenna with a gap of 5.0 μm formed in a low-temperature-grown GaAs. The power of the gate beam was fixed to 4.0 mW. For reference samples, a (001) n-GaAs ($\approx 2\times10^{18}$ cm^{-3}) crystal and a (001) i-InAs crystal were examined.

Figure 2 shows the waveforms of the terahertz emission of the i-GaAs/n-GaAs, n-GaAs, and i-InAs samples at the pump-beam energies of 1.531, 1.589, and 1.621 eV. All the samples show an oscillation around the time delay of 0 ps, the so-called first burst. At first, it is obvious that the amplitude of the first burst of the i-GaAs/n-GaAs sample is larger by a factor of 10 than that of the n-GaAs crystal; namely, the i-GaAs layer actually enhances the emission intensity. Thus, it is concluded that the epitaxial layer structure plays an important role in enhancing the terahertz emission intensity.

Next, we discuss the pump-beam energy dependence of the terahertz emission, comparing the first-burst amplitude of the i-GaAs/n-GaAs sample with that of the i-InAs crystal. The increase in pump-beam energy corresponds to an increase in the absorption coefficient. The absorption coefficients of GaAs (InAs) at 1.531, 1.589, and 1.621 eV are 1.41×10^{-3} (6.95×10^{-3}), 1.77×10^{-3} (7.69×10^{-3}), and 1.96×10^{-3} (8.09×10^{-3}) nm^{-1}, respectively.[16] Accordingly, the increase in the pump-beam energy from 1.531 to 1.621 eV magnifies the absorption coefficient of GaAs (InAs) by 1.39 (1.16). In the present i-GaAs/n-GaAs sample, the penetration depth, which is the reciprocal of the absorption coefficient, is much longer than the i-GaAs layer thickness. Consequently, the increase in the absorption coefficient leads to the enhancement of the terahertz emission efficiency since the carrier number accelerated in the i-GaAs layer increases. The absorption coefficient of InAs is relatively insensitive to the change in the photon energy, because the fundamental transition energy of InAs (0.354 eV, Ref. 16) is much smaller than that of GaAs (1.424 eV, Ref. 16). The effect of increasing absorption coefficient on the terahertz emission intensity clearly appears in Fig. 2. At 1.531 eV, the first-burst amplitude of the i-GaAs/n-GaAs sample is slightly smaller than that of the i-InAs crystal, while, at 1.589 and 1.621 eV, the first-burst amplitudes of the i-GaAs/n-GaAs sample are markedly larger than those of the i-InAs crystal. It was reported that the terahertz emission intensity from GaAs is weaker by a factor of 10^{-1} than that of InAs.[7] Taking this report into account, we conclude that the i-GaAs/n-GaAs structure is a solution for enhancing the terahertz emission intensity.

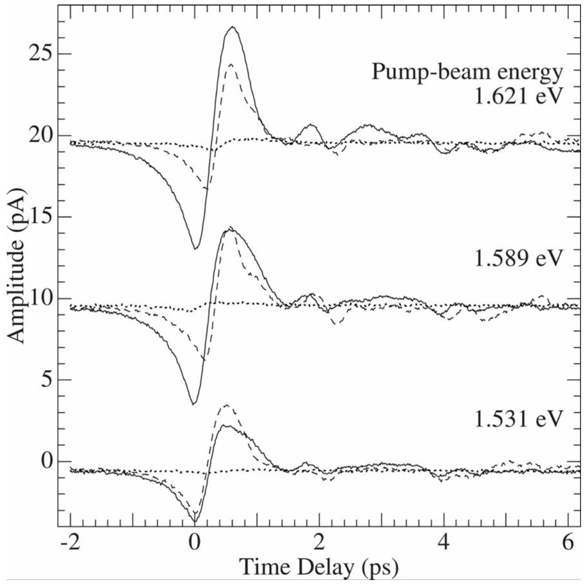

FIG. 2. Amplitude of the terahertz electromagnetic waveform as a function of time delay at room temperature. The solid, dotted, and dashed lines indicate the time-domain signals of the i-GaAs/n-GaAs, n-GaAs, and i-InAs samples. The pump-beam power was 20 mW, while the pump-beam energies were 1.531, 1.589, and 1.621 eV.

We also investigated the pump-power dependence of the terahertz emission from the i-GaAs/n-GaAs structure. Figure 3 shows the amplitude of the terahertz emission from the i-GaAs/n-GaAs sample illuminated by the pump beam with a photon energy of 1.621 eV as a function of pump-beam power. The inset of Fig. 3 shows that the first-burst amplitude at 20 mW is almost twice larger than that at 10 mW. In addition, the amplitude of the i-GaAs/n-GaAs sample shows an almost linear dependence on the pump-beam power. The linear dependence implies that the maximum pump-beam power of 20 mW is below the saturation level for the present i-GaAs/n-GaAs sample. Thus, the i-GaAs/n-GaAs sample has the ability of emitting stronger terahertz electromagnetic wave with the use of more intense excitation source.

In summary, we have investigated the terahertz emission from the i-GaAs(200 nm)/n-GaAs (3 μm, 3×10^{18} cm^{-3}) structure from the viewpoint of the feasibility of enhancing

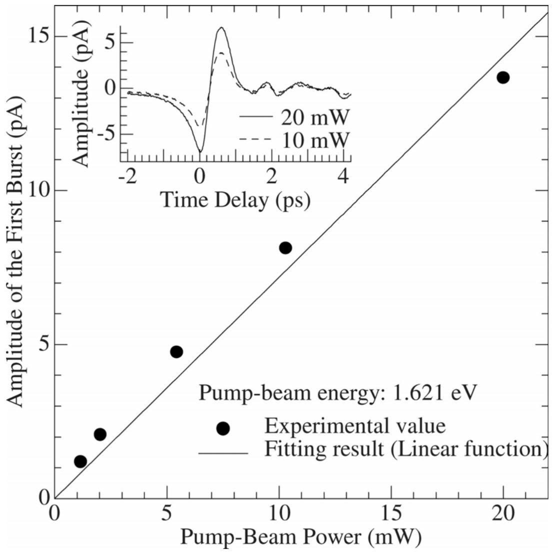

FIG. 3. First-burst amplitude of the terahertz emission from the *i*-GaAs/*n*-GaAs sample as a function of pump-beam power. The pump-beam energy was 1.621 eV. The closed circles indicate the experimental results, and the solid line depicts the fitting results. The inset shows the terahertz electromagnetic waveforms as a function of time delay of the *i*-GaAs/*n*-GaAs sample at the pump-beam power of 10 mW (dashed line) and 20 mW (solid line).

the terahertz emission by the epitaxial layer design. The numerical calculations indicate that the *i*-GaAs/*n*-GaAs structure is a suitable epitaxial layer structure for the terahertz emitter. From the terahertz emission measurement, it has been found that the first-burst amplitude of the *i*-GaAs/*n*-GaAs structure is larger by a factor of 10 than that of the *n*-GaAs crystal. In addition, at the pump-beam energies of 1.589 and 1.621 eV, the terahertz emission intensities of the *i*-GaAs/*n*-GaAs structure noticeably exceed those of the *i*-InAs crystal. From the results described above, we conclude that the design of the epitaxial layer structure is an important factor for enhancing the terahertz emission intensity and that the *i*-GaAs/*n*-GaAs structure actually enhances the terahertz emission.

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