Detection of terahertz waves using low-temperature-grown InGaAs with 1.56 μm pulse excitation

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The authors have investigated the dc and terahertz-detection characteristics of the photoconductive antennas made on low-temperature-grown (LTG) $In_xGa_{1-x}As$ ($0.4<x<0.53$). It was found that the resistivity of the LTG $In_{0.4}Ga_{0.6}As$ can be as high as 700 Ω cm, with which the resistance of the antenna becomes higher than 3 MΩ. Terahertz waves were detected by the antennas with the pulse excitation at 1.56 μm, with a spectral range exceeding 3 THz, and a dynamic range of about 55 dB. The results also indicate that the photocarrier dynamics depend on the In content. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2712503]

In terahertz time-domain spectroscopy, photoconductive (PC) antennas exhibiting ultrafast response and high resistivity are often used as an emitter and/or detector. Conventionally, PC antennas have been made on low-temperature-grown (LTG) GaAs and operated with light pulses whose center wavelength is around 0.8 μm. Recently, aiming at the connection between the terahertz and telecommunication technologies, efforts have been made to shift the excitation wavelength to the 1.5 μm regime.[1–3] To realize PC antennas operable with 1.5 μm light, the band gap of the material should be reduced so as to enable efficient photoexcitation. Though LTG $In_xGa_{1-x}As$ with $x\sim 0.3$ has been shown to work quite well at 1.06 μm excitation,[4] there is no well-established PC material suitable for 1.5 μm excitation yet.

$In_{0.53}Ga_{0.47}As$, which is lattice matched to an InP substrate, has been widely used in optoelectronic devices as a semiconductor material working in the 1.5 μm range. Unlike LTG GaAs, however, $In_{0.53}Ga_{0.47}As$ exhibiting high resistivity and short lifetime of the photo-excited carriers is difficult to realize.[5,6] Though Be doping has been reported to reduce the residual carrier density and the lifetime through the compensation of donor states formed by the antisite As (Refs. 7–11) and the suppression of As precipitate formation,[11] the resulting resistivity is not very high.[8,9] As alternatives, $In_{0.53}Ga_{0.47}As$ with ion implantation[1–3,12] or with ErAs nanodots[13,14] have been investigated and proven to work rather well as terahertz antennas. Yet, there have been no reports on terahertz generation or detection at 1.5 μm excitation using PC antennas made on LTG InGaAs. In this letter, we report that Be doped bulk LTG InGaAs can be used as a PC material for terahertz detection at 1.5 μm excitation. In particular, we show that the decrease of In content down to $\sim$0.4 leads to a remarkable increase of the dark resistance (700 Ω cm) and to an improvement of the terahertz detection performance.

We grew LTG $In_xGa_{1-x}As$ layers of 1.6 μm thickness by molecular beam epitaxy directly on semi-insulating InP substrates. The growth parameters were as follows: Substrate temperature T_G, 180 or 280 °C (thermocouple reading scaled using the values at the de-oxidation temperature of GaAs); arsenic flux (gauge reading), $\sim 2\times 10^{-5}$ Torr; growth rate, $\sim$1 μm/h; and Be doping density, $\sim 7\times 10^{17}$ cm^{-3}. The In content x was estimated from the In to Ga flux ratio using the value at which $In_{0.53}Ga_{0.47}As$ is grown, and was chosen to be 0.40, 0.47, or 0.53. The band gaps of the InGaAs layers were evaluated from the absorption spectra to be about 1540, 1620, and 1660 nm for $x=0.40$, 0.47, and 0.53, respectively. These values of the band gap are close to those expected from the x values, taking into account the influence of strain. We should mention that values of the growth temperature, the In content, and the band gap wavelength are not very accurate, but they give a correct impression of the relative magnitude. The surfaces of the 180 °C grown layers were milky, while those of the 280 °C grown layers were mirror-like, though small structures were observed in the microscope images. An apparent x dependence of the roughness was not found. After the growth, annealing was performed *ex situ* at a temperature T_A ranging from 400 to 650 °C for 1 h in a H_2 ambient with a GaAs capping. Then the PC antennas having a dipole gap and a width of 5 and 10 μm, respectively, were formed, and finally the InGaAs layers were mesa etched, leaving the region around the dipole gap.

The terahertz detection measurement was performed using a standard time-domain setup, where the terahertz waves emitted from a PC antenna were collimated and focused to a detector antenna with a pair of off-axis parabolic mirrors and hyperhemispherical Si lenses. The light source was a mode-locked pulse fiber laser (IMURA B-200; center wavelength of $\sim$1.56 μm, pulse width of $\sim$60 fs, and repetition of $\sim$50 MHz). In the present work, we used a PC antenna made on LTG GaAs as the terahertz emitter, which was excited by the second harmonic (0.78 μm) of the laser pulses. The same laser was also used in the measurement of voltage-current characteristics of the antennas.

Figure 1 shows the carrier (electron) concentration n, the mobility μ, and the resistivity ρ obtained in Hall measurements without illumination as functions of the annealing temperature T_A. The results on the layers of $x=0.53$ grown at 280 °C and annealed at 650 °C are not included in the figure since it became p type. Here, some distinct features can be noticed. First, n of the layers grown at 280 °C are lower than those at 180 °C. Second, μ for $T_G=280$ °C is obviously higher ($\sim$1000 cm^2/V s) than those (40–100 cm^2/V s) for $T_G=180$ °C, and they are relatively flat against the change of

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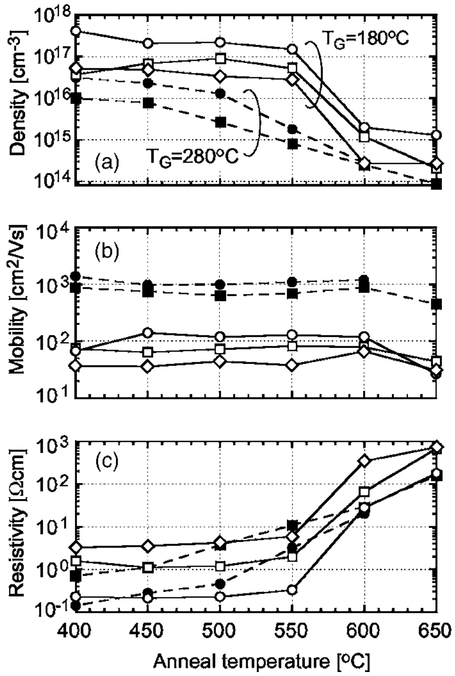

FIG. 1. Carrier (electron) density, mobility, and resistivity of the LTG $In_xGa_{1-x}As$ as functions of the annealing temperature. The open and filled symbols correspond to the growth at 180 and 280 °C, respectively, and the circles, squares, and diamonds show the values of x=0.53, 0.47, and 0.40, respectively. The lines are guides for the eyes.

T_A. Third, the layers grown at 280 °C show gradual decrease (increase) in $n(\rho)$ with increasing T_A, whereas the growth at 180 °C results in a steep decrease (increase) in $n(\rho)$ at T_A =600 °C. Finally, $n(\rho)$ gets lower (higher) with the decrease of x. As a result of these, the resistivity as high as 700 Ω cm was realized at T_A=650 °C in the layers of x=0.40 and 0.47 grown at 180 °C. The T_G dependence of n at low T_A and the reduction of n by annealing at high T_A are qualitatively consistent with the previous reports,[7,9] where the results were explained by the activation of Be as acceptors,[7] though the activity of Be atoms is more complicated than a simple picture.[10] Hence, the x dependence of n found here could be also explained by that of the Be activation, though the situation is even more complicated because of the presence of strain, and further study is necessary to elucidate the details.

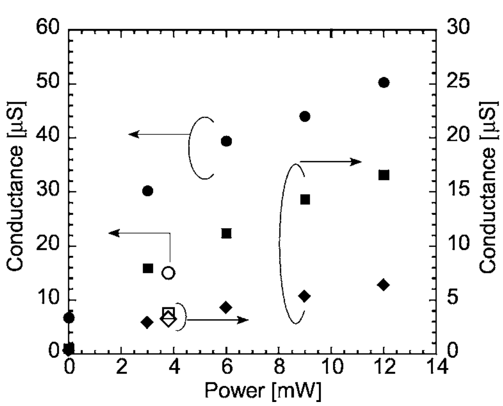

FIG. 2. Conductance of the PC antennas made on the $In_xGa_{1-x}As$ grown at 180 °C and annealed at 650 °C as functions of the excitation power. The circles, squares, and diamonds correspond to x=0.53, 0.47, and 0.40, respectively. Filled and open symbols are the values under 1.56 and 0.78 μm excitations, respectively.

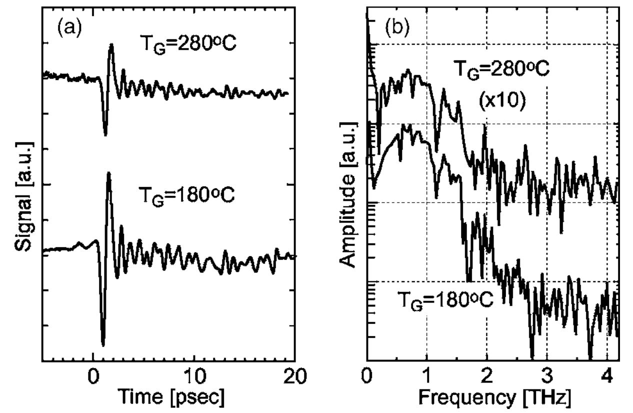

FIG. 3. Time-domain traces and their amplitude spectra of the terahertz signals detected by the antennas made on the $In_{0.53}Ga_{0.74}As$ grown at 180 and 280 °C. The annealing temperature was 600 °C. The time-domain traces were vertically shifted for clarity.

Shown in Fig. 2 are the dc (average) conductance, evaluated at the bias of 1 V, of the PC antennas made on the InGaAs layers grown at T_G=180 °C and annealed at T_A =650 °C as functions of the power of the laser pulses. The dark (0 mW) conductance is very low ($G \sim 0.3\ \mu\Omega^{-1}$) in the antennas of x=0.40 and 0.47 in comparison with that of x =0.53, as expected from the Hall measurement. The dark resistance ($R \sim 3$ MΩ) as well as the resistivity (700 Ω cm) mentioned above are more than an order of magnitude higher than those realized in the ion-implanted InGaAs.[2,3] In the antennas of x=0.47 and 0.53, the photoinduced conductance under 1.56 μm excitation (filled symbols) is roughly twice that under 0.78 μm excitation (open symbols), consistent with the ratio of the photon flux, indicating that the band gap is well below the photon energy. On the contrary, in x =0.40, the conductance under 0.78 μm excitation and that under 1.56 μm excitation are very close, indicating that the band gap of this material is close to the photon energy for 1.56 μm. These results are consistent with the band-edge wavelength evaluated from the absorption spectrum. Interestingly, under 0.78 μm excitation, for which the difference in absorption coefficient between the antennas may be neglected, the photoconductance of the antennas of x=0.40 and 0.47 are obviously lower than that of x=0.53. This may imply that the recombination time of the photocarriers is shortened by the decrease of x, in addition to the reduction of the mobility.

Now let us discuss the terahertz detection performance. Figure 3 shows the time-domain traces and their amplitude spectra of the terahertz signals detected by the antennas made on the $In_{0.53}Ga_{0.47}Aa$ layers grown at 180 or 280 °C and annealed at 600 °C. The bias voltage and the excitation power for the emitter were 30 V and 5 mW, respectively, and the excitation power for the detector was 3.8 mW. Though the terahertz signals were detected by both the antennas, the peak amplitude is obviously higher in the 180 °C grown antenna, in spite of the mobility (120 cm^2/V s) and photoconductance (100 μS, not shown) lower than those (1160 cm^2/V s and 230 μS) of the 280 °C grown antenna. On the other hand, the noise floor, which we confirmed to be dominated by the detectors themselves, is lower in the 180 °C grown antenna. Hence, we concluded that the growth temperature should be as low as 180 °C. Regarding the annealing temperature, though the results are not shown here,

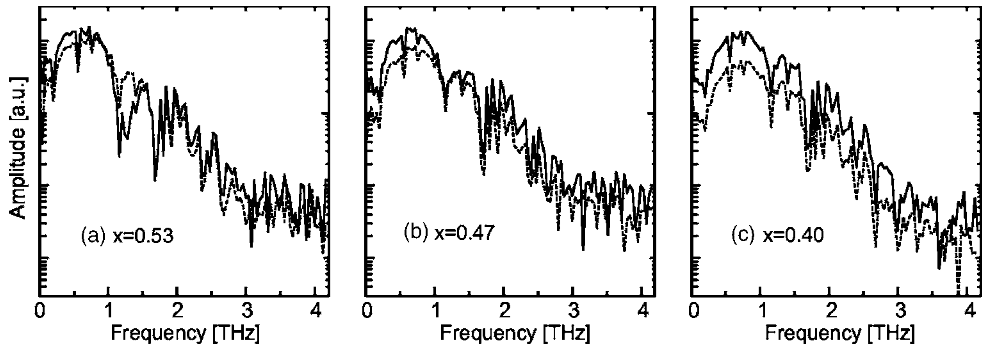

FIG. 4. Amplitude spectra of the terahertz signals detected by the antennas made on the LTG $In_xGa_{1-x}As$ layers: (a) $x=0.53$, (b) $x=0.47$, and (c) $x=0.40$, all grown at 180 °C and annealed at 650 °C. The dotted and solid curves correspond to the 3 and 12 mW excitation, respectively.

we found no significant difference between $T_A=600$ and 650 °C for all cases of x, but the signal was weak and the noise floor was high in the antennas of $T_A=550$ °C.

Next, we focus on the In content x. Depicted in Figs. 4(a)–4(c) are the amplitude spectra obtained with the antennas of $x=0.53$, 0.47, and 0.40, respectively, for the two excitation conditions of 3 and 12 mW. The bias voltage and the excitation power for the emitter were 30 V and 9 mW, respectively. In all cases, terahertz signals were measured quite well with the spectral range exceeding 3 THz. However, if we take a closer look at the spectra, we notice several important differences. At 3 mW excitation, the peak amplitude decreases with the decrease of x, which may be ascribed to the inefficiency of the photoexcitation in the large band gap material. Nevertheless, at 12 mW excitation, the peak amplitude gets very close. This is because the peak amplitude does not increase efficiently with the increase of the excitation power, particularly in the antenna of $x=0.53$, in spite of the increase in the photoconductance, as shown in Fig. 2. On the other hand, the noise amplitude is obviously low in the antenna of $x=0.40$. As a result, the best peak-to-noise ratio ($\sim$55 dB) was obtained in the antenna of $x=0.40$ at 12 mW excitation.

Another interesting feature can be noticed if we compare the amplitude $A_{1\sim2\ \mathrm{THz}}$ in 1–2 THz with that $A_{0.7\ \mathrm{THz}}$ around 0.7 THz, where the spectra take their peak values. Obviously, the ratio $A_{1\sim2\ \mathrm{THz}}/A_{0.7\ \mathrm{THz}}$ is higher in the antenna of $x=0.40$ than in that of $x=0.53$. In particular, in the antenna of $x=0.53$, the increase of the excitation enhances the amplitude in the low frequency regime, $\sim$0.4 THz, but suppresses those at around 1.2 THz. Though the reason for the suppression is not clear, it could be due to the absorption of the terahertz waves by the photoexcited carriers in the antenna. A weak but similar tendency is seen in the antenna of $x=0.47$. On the contrary, in the case of $x=0.40$, the amplitude is enhanced almost equally over the whole frequency range. Future investigations are expected to elucidate the details of the photocarrier dynamics in LTG $In_xGa_{1-x}As$.

In summary, we have presented the dc and terahertz-detection characteristics of the PC antennas made on Be doped LTG $In_xGa_{1-x}As$. It was shown that low carrier concentration and high resistivity can be realized by the growth at $\sim$180 °C and the annealing at $\sim$650 °C, particularly in the low x cases. Terahertz signals with the spectral range exceeding 3 THz were detected in the PC antennas under the excitation at 1.56 μm. The antenna of $x=0.40$ showed the lowest noise floor and unsaturated increase in the peak amplitude up to 12 mW excitation, resulting in the peak-to-noise ratio of 55 dB. The terahertz-detection characteristics suggest that the relaxation processes of the photoexcited carriers are quite dependent on x.

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