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Generation of THz Radiation from Resonant Absorption in Strained Multiple Quantum Wells in a Magnetic Field

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Optically excited THz-radiation from ten molecular-beam epitaxy (MBE)-grown strained multiple quantum wells (MQWs) on a (100)-oriented semi-insulating GaAs substrate is studied in a 1-T magnetic field. Wavelength-dependent THz-radiation clearly exhibits a resonance behavior at the excitation wavelength near 830 nm, the peak wavelength of photoluminescence (PL). We also observe and explain an emission spectrum from the MQW with slightly enhanced higher-frequency components compared to that of bulk GaAs. In the thin MQW sample, the THz emission is still significant. This indicates the possibility of designing MQWs as efficient THz emitters in the future.

KEYWORDS: THz-radiation, strained, multiple quantum wells, magnetic field, resonant absorption

THz radiation has become a powerful scheme for far-infrared spectroscopy and various imaging applications.1) Many materials and devices have been reported to generate THz radiation when excited by femtosecond laser pulses.2–7) On the other hand, THz radiations from electrically biased single quantum well or coupled double quantum wells have been reported. The radiation mechanisms are quantum beats by light-hole and heavy-hole excitons or charge oscillation between two electron states of the coupled system.8–10) Semiconductor microcavities have also been shown to generate THz-radiation from exciton absorption.11) The wavelength or power dependence of THz radiation fields by single12) and ten coupled quantum wells13) have been associated with the resonance absorption of excitons. The radiation intensity and oscillation decay time have also been studied as functions of excited charge carriers density in a superlattice structure.14) A tunable THz radiation at frequencies from 1.4 THz to 2.6 THz in a single quantum well from charge oscillation of excitons has been reported.12) The emission frequency from Bloch oscillations in an electrically biased superlattice structure can be tuned from 0.5 THz to more than 2 THz.15) By varying the applied field, anti-crossing of the emitted frequencies has also been observed in a superlattice.16) In these studies, the quantum wells or superlattices are biased by an electric field to generate THz radiation. It is well known that a magnetic field can be not only used to switch THz-radiation beams17) but also to generate higher average power of THz radiation.18,19) For a wide parabolic quantum well, a marked resonance enhancement of THz emission when the cyclotron frequency crosses the magneto-plasmon frequency was observed by varying the magnetic field.20) A magnetic field has also been used to observe the suppression of THz charge oscillation in double quantum wells at low temperatures.21) In this paper, we report an optically excited THz radiation from strained multiple quantum wells (MQWs) in a magnetic field, for the first time to our knowledge. Due to carrier screening of the strain-generated internal electric fields, strained QWs are expected to exhibit large 3rd-order optical nonlinear susceptibility, $\chi^{(3)}$.22) Through the optical rectification mechanism, materials with large $\chi^{(3)}$ are expected to emit higher THz power.23) Furthermore, a strain in the QW will bend its potential profile due to charge separation and thus increase the absorption at the band edge.24) Consequently, we also expect that THz-radiation power should also be enhanced as the pumping wavelength is tuned near the band edge.

The strained MQW sample consists of ten periods of 8-nm-thick $In_{0.11}Al_{0.09}Ga_{0.8}As$ wells separated by 10-nm-thick $Al_{0.3}Ga_{0.7}As$ barriers grown on a (100)-oriented semi-insulating GaAs substrate by molecular-beam epitaxy (MBE). The strain is estimated to be 0.8%. Its room-temperature photoluminescence (PL) spectrum is shown in the upper part of Fig. 1. A wavelength tunable, commercial mode-locked Ti: sapphire laser with a repetition rate of 82 MHz delivers nearly transform-limited 90 fs pulses at each wavelength for the excitation. The laser beam passes through a variable attenuator and is slightly focused onto the strained MQW sample at several incidence angles with its polarization parallel to the plane of incidence. The pumping spot size on the sample was approximately 1.5 mm in diameter to reduce the diffraction effect of the optically generated THz-emission power. The laser beam was mechanically chopped and the average excitation power was controlled to approximately 100 mW after the chopping. The sample was placed in the center of a 1 T permanent magnetic field, which was applied vertically to the incidence plane. THz radiation is thus generated by the Lorentz force with horizontal optical polarization.19) We estimate that the Cyclotron radius $r_c = 150 \times 10^{-10} m$. On the other hand, the Bohr radius is given by $r_B = 0.53\frac{n^2}{z} \times 10^{-10} m$, where the principle quantum number and atomic number, n and z, respectively, are integers. Thus, the cyclotron radius is about two orders of magnitude larger than the Bohr radius. The transmitted THz radiation through the sample was guided by two off-axis parabolic mirrors, each with a focal length of 20 cm, to a liquid-helium-cooled Si bolometer to detect the radiation power or passed through a Fourier transform polarizing interferometer to measure the THz-radiation spectrum. The chopping frequency was set to 205 Hz for the lock-in detection from the bolometer signal.

The excitation wavelength dependence of the THz-radiation power from the strained MQW sample with a variable incident angle is shown in the lower part of Fig. 1. Obviously, the resonance peak at 830 nm with a 0 degree incident angle

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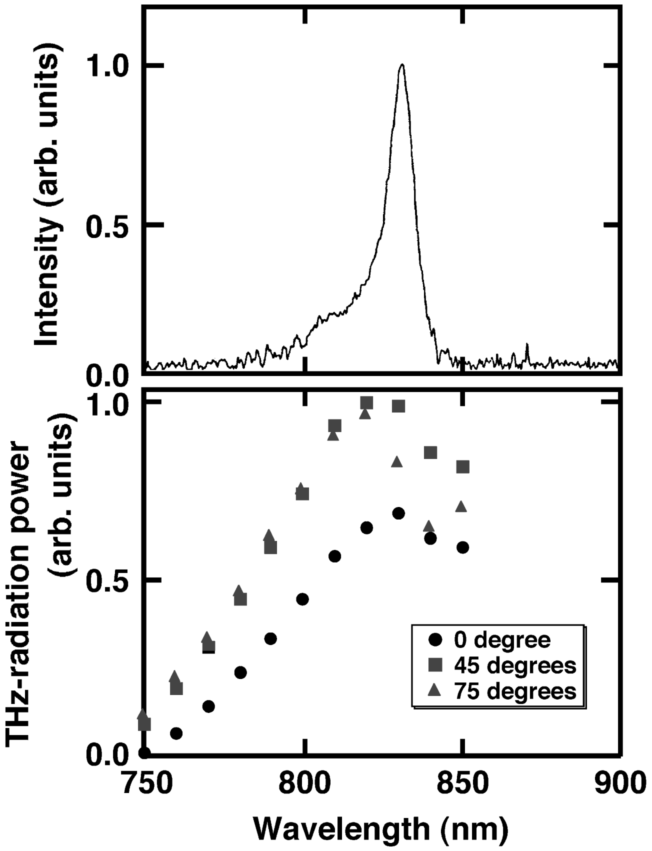

Fig. 1. Upper part: Photoluminescence spectrum of the strained MQW sample. Lower part: The wavelength dependence of THz-radiation power from strained MQW with variable incident angle. The circle indicates a 0 degree incident angle; the rectangle, 45 degree incident angle; triangle, 75 degree incident angle.

coincides with the PL peak. The sample can be observed to have a large nonlinear absorption at an excitation wavelength of approximately 830 nm. This phenomenon is probably due to the resonance of the lowest e-hh or e-lh state absorption effect. The peak shifts slightly to 820 nm and the THz-radiation power increases at shallow incident angles. For a 75-degree incident angle, THz radiation power is slightly lower than that at 45 degrees. This is possibly due to the larger injection area in the former case. As a result, the pumping intensity and the extent of nonlinear absorption are both reduced. The relationship between THz radiation power and excitation power for different incident angles is also shown in Fig. 2. The behaviors of the three cases are almost the same and all exhibit approximately quadratic dependence on the pumping power. A similar behavior was also observed previously for an InAs bulk emitter.18)

The wavelength dependence of THz radiation-power has also been measured in a semi-insulating GaAs (SI-GaAs) substrate with a 45 degree laser incident angle for comparison with the strained MQW as shown in Fig. 3(a). Note that the THz-emission power is still significant, even though the excitation energy is below that of the band gap, E_g ($\lambda > 830$ nm). This is a strong indication that the dominant emission mechanism is optical rectification, instead of the current surge effect. On the other hand, the THz-emission power decreased sharply when the excitation photon energy was tuned above E_g ($\lambda < 830$ nm). This is in contrast to that of bulk GaAs. Higher THz-radiation power in the GaAs sample was generated at a shorter pumping wavelength. Basically, the latter case can be explained in terms of the current surge effect25) from free carriers generated by the mentioned above band gap excitation, with a larger number of carriers being excited at shorter wavelengths. The maximum THz-radiation power from the SI-GaAs sample is about three times greater than that from our strained MQW, possibly due to the much thinner absorption region of the MQW. After design optimization, we expect that the MQW may generate greater THz-radiation power. The THz-radiation spectra (as shown in Fig. 3(b)) of the two samples were measured using a polarizing Michelson interferometer, with the laser at a 45 degree incident angle for greater THz radiation power. This setup also eliminates the interferometric structures of the spectra from rear-surface reflection. The excitation wavelength was tuned to either 750 nm or 820 nm to achieve the maximum THz-radiation power from GaAs or the strained MQW. We note that the higher-frequency portion of the spectrum is slightly enhanced in the strained MQW. This can be explained as follows. First, from the wavelength-dependence of the emitted THz power from the QW, we deduce that the dominant emission mechanism is optical rectification, instead of the current surge effect. This is in contrast to that of the bulk GaAs.

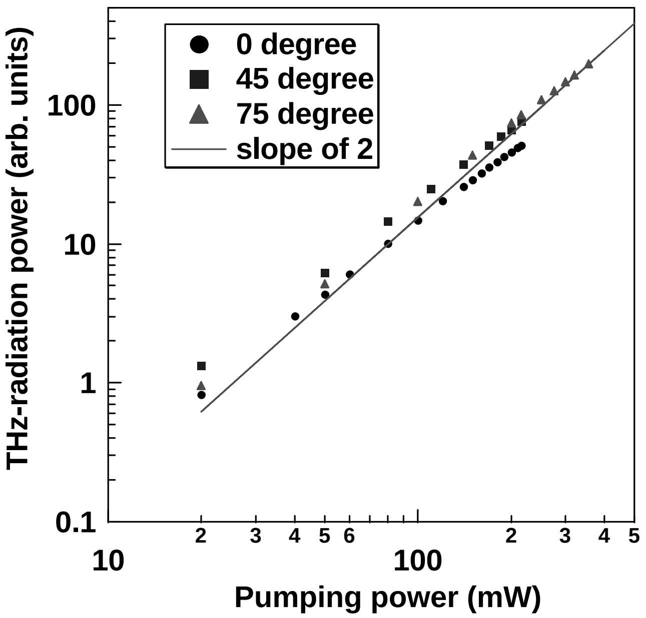

Fig. 2. The relationship between THz-radiation power and excitation power from strained MQW with variable incident angle. The circle indicates a 0 degree incident angle; the rectangle, 45 degree incident angle; triangle, 75 degree incident angle. The straight line has a slope of 2.

In general, the duration of the THz radiation due to carrier transport in GaAs is longer than that induced by purely optical rectification induced by transient (virtual) carriers.17) With a shorter decay time in its temporal waveform, we expect the blue portion of the THz spectrum because the QW should be blue shifted with respect to that of bulk GaAs. That is, the higher-frequency components of its spectrum would be enhanced. The main dips in the spectrum correspond to the interference effect of the substrate.

In conclusion, we report the optically excited THz radiation from ten MBE-grown strained MQWs on a (100)-oriented semi-insulating GaAs substrate in a 1 T magnetic field. The

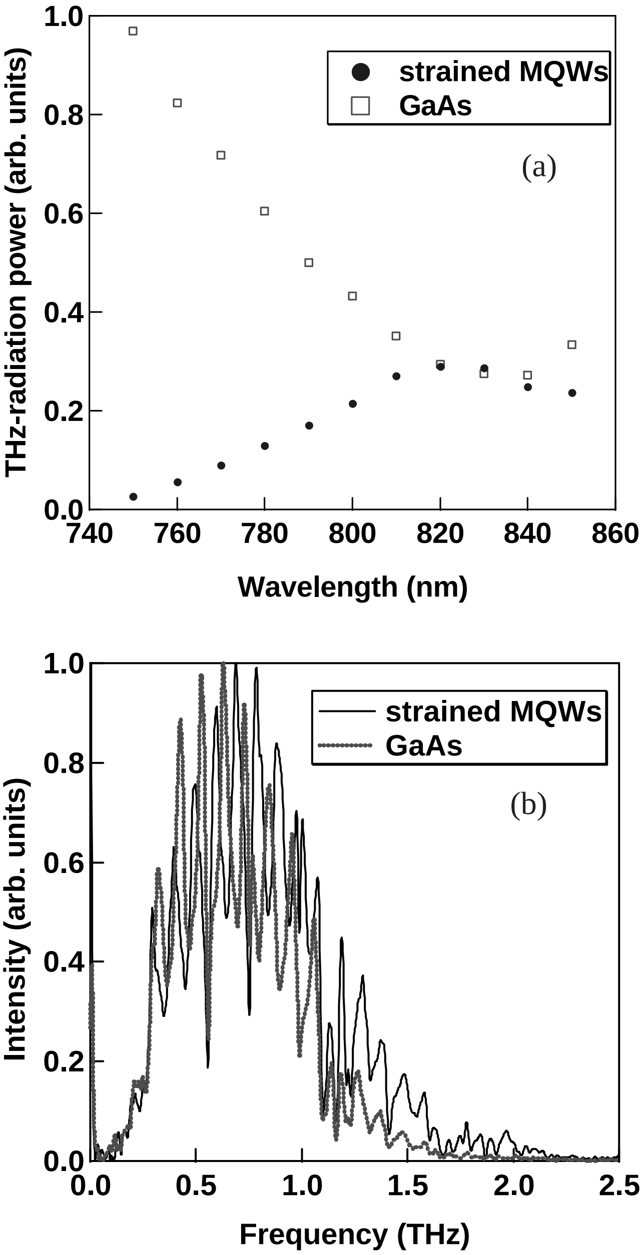

Fig. 3. (a) Wavelength dependence of THz-radiation power and (b) emitted spectrum obtained by Fourier transformation of the autocorrelation using a polarizing Michelson interferometer of the two different samples in a 1 T magnetic field with a 45 degree incident angle. The circle in (a) indicates the strained MQW, and the rectangle with a hollow, GaAs. The solid line in (b) indicates the spectrum of MQW, and the dash line, that of GaAs.

wavelength-dependent THz radiation clearly exhibits resonance behavior at the excitation wavelength near 830 nm, the peak wavelength of photoluminescence (PL). We also observe and explain an emission spectrum from the MQW with slightly enhanced higher-frequency components compared to that of bulk GaAs. In the thin MQW sample, the THz emission is still significant. This indicates the possibility of designing MQWs as efficient THz emitters in the future.

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1) D. M. Mittleman, S. Hunsche, L. Boivin and M. C. Nuss: Opt. Lett. **22** (1997) 904.
2) D. H. Auston: Appl. Phys. Lett. **43** (1983) 713.
3) X.-C. Zhang and D. H. Auston: J. Appl. Phys. **71** (1992) 326.
4) P. C. M. Planken, M. C. Nuss, W. H. Knox, D. A. B. Miller and K. W. Goossen: Appl. Phys. Lett. **61** (1992) 2009.
5) I. Brener, D. Dykaar, A. Frommer, L. N. Pfeiffer, J. Lopata, J. Wynn, K. West and M. C. Nuss: Opt. Lett. **21** (1996) 1924.
6) T. A. Liu, K. F. Huang, C. L. Pan, Z. Liu, S. Ono, H. Ohtake and N. Sarukura: Jpn. J. Appl. Phys. **38** (1999) L1333.
7) Z. Liu, S. Ono, H. Ohtake, N. Sarukura, T. A. Liu, K. F. Huang and C. L. Pan: Jpn. J. Appl. Phys. **39** (2000) L366.
8) M. C. Nuss, P. C. M. Planken, I. Brener, H. G. Roskos, M. S. C. Luo and S. L. Chuang: Appl. Phys. B **58** (1994) 249.
9) H. G. Roskos, M. C. Nuss, J. Shah, K. Leo, D. A. B. Miller, A. M. Fox, S. S. Rink and K. Köhler: Phys. Rev. Lett. **68** (1992) 2216.
10) M. S. C. Luo, S. L. Chuang, P. C. M. Planken, I. Brener, H. G. Roskos and M. C. Nuss: IEEE J. Quantum. Electron. **30** (1994) 1478.
11) M. Kusuda, S. Tokai, Y. Hokomoto, Y. Kadoya and M. Yamanishi: Physica B **272** (1999) 467.
12) P. C. M. Planken, M. C. Nuss, I. Brener, K. W. Goossen, M. S. C. Luo, S. L. Chuang and L. Pfeiffer: Phys. Rev. Lett. **69** (1992) 3800.
13) N. Sekine, K. Hirakawa and Y. Arakawa: Jpn. J. Appl. Phys. **37** (1998) 1643.
14) R. Martini, G. Klose, H. G. Roskos, H. Kurz, H. T. Grahn and R. Hey: Phys. Rev. B **54** (1996) 14325.
15) C. Waschke, H. G. Roskos, R. Schwedler, K. Leo, H. Kurz and K. Köhler: Phys. Rev. Lett. **70** (1993) 3319.
16) P. H. Bolivar, F. Wolter, A. Müller, H. G. Roskos, H. Kurz and K. Köhler: Phys. Rev. Lett. **78** (1997) 2232.
17) X.-C. Zhang, Y. Jin, T. D. Hewitt, T. Sangsiri, L. E. Kingsley and M. Weiner: Appl. Phys. Lett. **62** (1993) 2003.
18) N. Sarukura, H. Ohtake, S. Izumida and Z. Liu: J. Appl. Phys. **84** (1998) 654.
19) N. Sarukura, H. Ohtake, Z. Liu, T. Itatani, T. Sugaya, T. Nakagawa and Y. Sugiyama: Jpn. J. Appl. Phys. **37** (1998) L125.
20) D. Some and A. V. Nurmikko: Phys. Rev. B **50** (1994) 5783.
21) S. R. Andrews, P. G. Huggard, C. J. Shaw, J. A. Cluff, O. E. Raichev and R. Grey: Phys. Rev. B **57** (1998) 9443.
22) D. L. Smith and C. Mailhiot: Phys. Rev. Lett. **58** (1987) 1264.
23) S. L. Chuang, S. S. Rink, B. I. Greene, P. N. Saeta and A. F. J. Levi: Phys. Rev. Lett. **68** (1992) 102.
24) C. Knorr, O. Gfrörer, V. Härle, F. Scholz and A. Hangleiter: Semicond. Sci. Technol. **10** (1995) 1484.
25) X.-C. Zhang, B. B. Hu, S. H. Xin and D. H. Auston: Appl. Phys. Lett. **57** (1990) 753.