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Fundamental oscillation up to 1.08 THz in resonant tunneling diodes with high-indium-composition transit layers for reduction of transit delay

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Abstract: Fundamental oscillations up to 1.08 THz with the output power of 5.5 microwatts was achieved in GaInAs/AlAs resonant tunneling diodes (RTDs) at room temperature. The graded emitter, thin barriers, and high-indium-composition transit layers were introduced to reduce the tunneling and transit delays. The first two of these structures are the same as those in RTDs oscillating at 1.04 THz reported recently, and the last structure provided for further reduction of the transit time and increase in frequency due to suppression of the Γ–L transition and increment of the launching velocity.

Keywords: resonant tunneling diodes, terahertz oscillator
Classification: Electron devices, circuits, and systems

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DOI: 10.1587/elex.9.385
Received January 19, 2012
Accepted February 06, 2012
Published March 10, 2012

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1 Introduction

The terahertz (THz) frequency range has been receiving considerable attention because of its many applications, such as ultrahigh-speed wireless communications, spectroscopy, and imaging [1]. For these applications, compact and coherent solid-state sources are key components. Resonant tunneling diodes (RTDs) [2, 3, 4, 5, 6, 7, 8] are candidates for the source and have the highest frequency at room temperature among electron devices until now.

We reported a fundamental oscillation at 1.04 THz using GaInAs/AlAs RTDs [7]. In these RTDs, structures that can reduce the tunneling time and the transit time across the collector depletion region were introduced. For the reduction in tunneling time, thin barriers were adopted. For the transit time, a possibility of its increase due to the electron transition between the Γ and L bands in the collector region was discussed. The graded emitter was proposed and introduced to suppress this transition with a reduced electric field.

However, because the suppression of the Γ–L transition by the graded emitter was not sufficient, the effect to improve the delay time was small. The reduction of the transit and tunneling times by structure optimization is effective for further increase in oscillation frequency. For the reduction in tunneling time, thinner barriers are effective. For the reduction in transit time, introduction of a material with larger Γ–L separation for the suppression of the Γ–L transition, low effective mass in transit layer, and increment of the launching velocity by the large launching energy at the exit of the tunneling barrier are considered to be effective.

DOI: 10.1587/elex.9.385
Received January 19, 2012
Accepted February 06, 2012
Published March 10, 2012

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In this study, as a preliminary experiment, we introduced the transit layers with increased indium composition for the reduction in transit time. GaInAs layers with high indium composition are considered effective in reducing transit time due to large Γ–L separations, low effective mass and high launching energy. A fundamental oscillation up to 1.08 THz was achieved using this structure at room temperature. From the comparison between the measured and theoretical results, the collector transit velocity was estimated to be slightly increased by the addition of the high-indium-composition layers.

2 Device structure

In the device structure, a GaInAs/AlAs double-barrier RTD on a semi-insulating InP substrate is located at the center of the slot antenna. The length of the slot antenna is 20 μm. To apply a DC bias voltage to the RTD and generate a high-frequency standing wave in the slot simultaneously, metal-insulator-metal reflectors were placed at the both ends of the slot. A resistor made of a bismuth film was connected in parallel to the RTD outside the antenna electrodes to suppress low-frequency (2–3 GHz) parasitic oscillations of the external bias circuits. The structure of the RTD with high-indium-composition layers is shown in Fig. 1 (a). The details of the device structure and fabrication process were described in ref. 4.

From the top; cap n^+-Ga$_{0.3}$In$_{0.7}$As ($\sim 2 \times 10^{19}$ cm^{-3}, 8 nm)/n^+-GaInAs (2×10^{19} cm^{-3}, 15 nm)/GaInAs (undoped, 5 nm)/high-indium-composition transit layers (see below for details)/barrier AlAs (1.2 nm)/well Ga$_{0.2}$In$_{0.8}$As

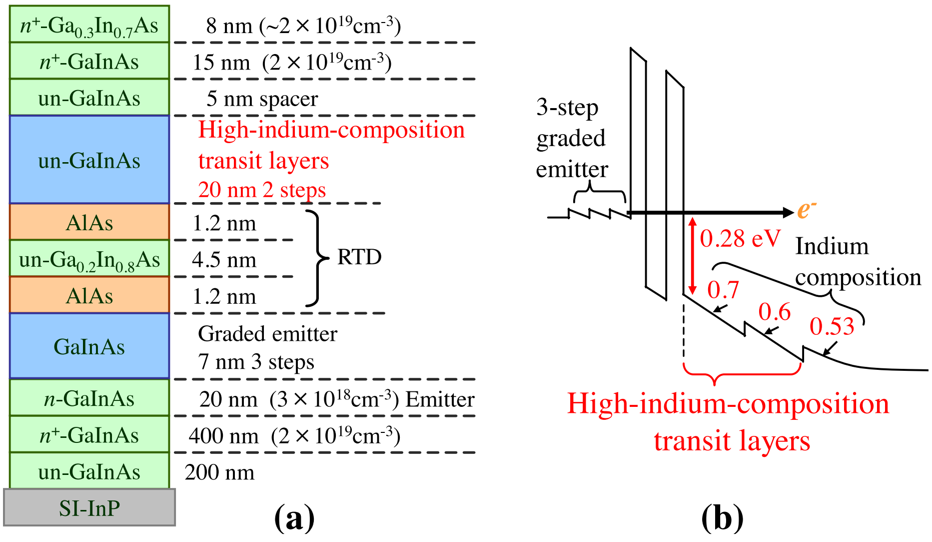

Fig. 1. (a) Structure of RTD with high-indium-composition layers. GaInAs layers shown without composition are lattice-matched to InP except for the graded emitter and the high-indium-composition transit layers (see text for details). (b) Potential profile of RTD with high-indium-composition transit layers under an applied voltage.

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DOI: 10.1587/elex.9.385
Received January 19, 2012
Accepted February 06, 2012
Published March 10, 2012

(undoped, 4.5 nm)/barrier AlAs (1.2 nm)/graded emitter layers (see below for details)/n-GaInAs ($3 \times 10^{18}\,\mathrm{cm}^{-3}$, 20 nm)/$n^{+}$-GaInAs ($2 \times 10^{19}\,\mathrm{cm}^{-3}$, 400 nm)/GaInAs (undoped, 200 nm). GaInAs without suffix of composition stand for $\mathrm{Ga_{0.47}In_{0.53}As}$ (latticed-matched to InP). The high-indium-composition transit layers in the above structure are composed of $\mathrm{Ga_{0.4}In_{0.6}As}$ (undoped, 10 nm)/$\mathrm{Ga_{0.3}In_{0.7}As}$ (undoped, 10 nm) from the top. The graded emitter layers are; spacer $\mathrm{Ga_{0.53}In_{0.47}As}$ (undoped, 2 nm)/n-$\mathrm{Ga_{0.51}In_{0.49}As}$ ($3 \times 10^{18}\,\mathrm{cm}^{-3}$, 2.5 nm)/$n$-$\mathrm{Ga_{0.49}In_{0.51}As}$ ($3 \times 10^{18}\,\mathrm{cm}^{-3}$, 2.5 nm) from the top.

The contact resistance of the electrode on the cap layer was reduced by the strained composition with a high doping concentration. Thin barriers are used to reduce the tunneling time. The first resonant level and peak voltage were reduced by the strained well structure. These layers were grown on a semi-insulating InP substrate using metal organic vapor phase epitaxy [9]. Fig. 1 (b) shows the potential profile of the RTD described above under an applied bias voltage. Because the bias voltage for the negative differential conductance (NDC) is reduced with the graded emitter, the Γ–L transition can be suppressed due to the reduced electric field at the collector region. This may result in a reduced collector transit time.

In addition, we adopted high-indium-composition layers at the collector region. These layers have large Γ–L separations (0.71 eV and 0.61 eV for $\mathrm{Ga_{0.3}In_{0.7}As}$ and $\mathrm{Ga_{0.4}In_{0.6}As}$, respectively) in contrast to GaInAs lattice-matched to InP (0.55 eV). Furthermore, the launching velocity at the exit of the tunneling barrier is higher than that of the lattice-matched case due to low effective mass and high potential step. The launching energy is 0.28 eV for $\mathrm{Ga_{0.3}In_{0.7}As}$, while 0.16 eV for the lattice-matched case.

From these conditions, the collector transit time can be reduced, although the effect may be insufficient at present because the structure is not optimized. Measured current-voltage characteristics are shown in Fig. 2 (a). A very high peak current density J_P of $28\,\mathrm{mA}/\mu\mathrm{m}^2$ with a peak-to-valley current ratio of 2 was obtained by thin barriers of 1.2 nm and high emitter doping

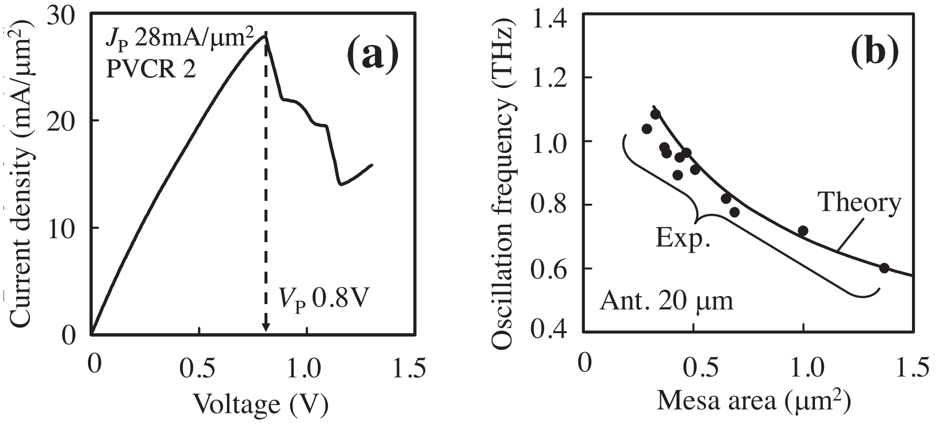

Fig. 2. (a) I–V characteristics of RTDs with high-indium-composition transit layers. (b) Dependence of oscillation frequency on RTD mesa area.

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Received January 19, 2012
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Published March 10, 2012

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EXpress

concentration of $3 \times 10^{18}\,\mathrm{cm}^{-3}$.

3 Oscillation characteristics

The output power was measured with a He-cooled Si composite bolometer. Oscillation spectra were measured with a Fourier transform infrared spectrometer. Fig. 2 (b) shows the dependence of the fundamental oscillation frequency on mesa area. The oscillation frequency increased with decreasing mesa area due to decreasing capacitance. The highest oscillation frequency was 1.08 THz at the mesa area of $0.33\,\mu\mathrm{m}^2$, as shown in Fig. 3 (a). The output power was $5.5\,\mu\mathrm{W}$. This result is the second highest fundamental oscillation frequency reported in an electronic single oscillator at room temperature, which is close to the highest one [8]. The output power in our device is more than ten times higher than that in [8], probably because the capacitance of our RTD is smaller due to the thick collector transit layer, which results in a larger antenna and higher radiation conductance at the oscillation frequency.

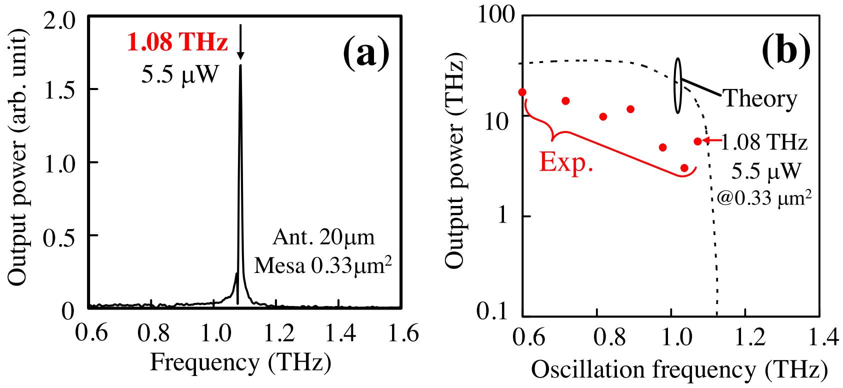

Fig. 3. (a) Measured spectrum of room-temperature fundamental oscillation at 1.08 THz. (b) Total output power as a function of oscillation frequency.

There was a limit of the mesa area below which the oscillation was not obtained because of the condition that the NDC is too small to compensate the loss of the antenna. The maximum frequency of the oscillator is determined by this limit, and it was slightly higher than that of the oscillator without the high-indium-composition transit layers. From the comparison between the measured and theoretical results, the collector transit velocity was estimated. The details of the estimation method were described in ref. 10.

Around 10% higher transit velocity than the structure without high-indium-composition layers was estimated. The oscillation frequency was increased with increasing transit velocity, the structure with the high-indium-composition layers is considered to be slightly effective for high frequency. In future, a detailed discussion will be required in order to identify the most effective factor for high frequency oscillations from increase of Γ–L transition, increase of launching energy, and reduction of effective mass. A structure optimization is necessary for higher frequency based on the discussion, but

DOI: 10.1587/elex.9.385
Received January 19, 2012
Accepted February 06, 2012
Published March 10, 2012

other structures may be more effective.

The total output power as a function of oscillation frequency was shown in Fig. 3 (b). The output powers of around 10 μW were obtained in 0.6–1 THz range. The experimental variation of the output power with frequency reasonably agrees with theory. Higher output power is also possible by the reduction in tunneling and transit times.

4 Conclusion

Fundamental oscillations up to 1.08 THz with the output power of 5.5 μW was achieved at room temperature in GaInAs/AlAs RTDs with thin barriers, graded emitter, and high-indium-composition transit layers. A possible increase in collector transit time due to the Γ–L transition has been discussed in the RTDs oscillating at 1.04 THz reported recently, in which the graded emitter was introduced to suppress this transition with a reduced electric field. In this study, high-indium-composition transit layers were adopted in addition to the graded emitter for further reduction in collector transit time with large Γ–L separation as well as with the increment of the launching velocity. Further increase in frequency and output power was considered to be possible by optimizing the RTD structure.

Acknowledgments

We thank Emeritus Professors Y. Suematsu and K. Furuya of the Tokyo Institute of Technology for their continuous encouragement. We also thank Professor S. Arai; Associate Professors Y. Miyamoto, M. Watanabe, and N. Nishiyama of the Tokyo Institute of Technology; and Doctors T. Enoki and M. Ida of NTT Photonics Laboratories for their fruitful discussions and encouragement. Some of the authors were supported by a Scientific Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology, Japan (S.S. and M.A.), by Industry-Academia Collaborative R&D from Japan Science and Technology Agency, JST (M.A.), and by Strategic Information and Communications R&D Promotion Programme from the Ministry of Public Management, Home Affairs, Posts and Telecommunications (S.S.).

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