Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp626-627

Room-Temperature Resonant-Tunneling-Diode Terahertz Oscillator

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Abstract

The recent results of our resonant-tunneling-diode (RTD) terahertz oscillators are reported. A fundamental oscillation up to 1.55 THz was obtained at room temperature by reducing the delay time and optimization of antenna length. A high output power of 610 μW at 620 GHz was achieved by a two-element offset-antenna array. A novel RTD oscillator integrated with a patch antenna for the extraction of output power without Si lens was investigated. Wireless data transmission at 540 GHz was demonstrated up to 3 Gbps. For a higher data rate, a novel oscillator structure for high-frequency modulation was proposed, and a very high cut-off frequency of ~30 GHz was obtained. A preliminary experiment on a varactor-tuned RTD oscillator was conducted, and a wide tuning range of ~11% was achieved for the center frequency of 655 GHz.

1. Introduction

Novel applications using terahertz waves have become possible owing to the recent development of terahertz sources. These terahertz applications will become popular if compact solid-state semiconductor light sources are realized. For semiconductor single oscillators, quantum cascade lasers have been intensively studied from the optical side [2]-[4]. The operation frequency of electron devices is also making significant progress from the millimeter-wave side. Among the electron devices [5]-[7], resonant tunneling diodes (RTDs) have been considered as a candidate for terahertz oscillators at room temperature [8]-[14].

In this paper, we report on our recent results for RTD oscillators: fundamental oscillations up to 1.55 THz at room temperature by reducing the delay time and high output power (~610 μW) oscillation at 620 GHz with a two-element offset-antenna array. A novel RTD oscillator integrated with patch antenna is shown for the radiation of output power without using a Si lens. A preliminary experiment on wireless data transmission with direct intensity modulation of the RTD is reported, and a novel oscillator with a high cutoff frequency for modulation at a high data rate is shown. A wide frequency-tunable RTD oscillator integrated with varactor diode is also reported.

2. Device Structure and Oscillation Characteristics

An RTD oscillator consists of an AlAs/InGaAs RTD mesa and a slot antenna on a semi-insulating InP substrate [11]. An oscillation is obtained when the negative differential conductance of the RTD overcomes the loss of the antenna, where the frequency is determined by the resonance circuit constructed by the slot antenna and RTD. The slot antenna functions as a resonator and radiator.

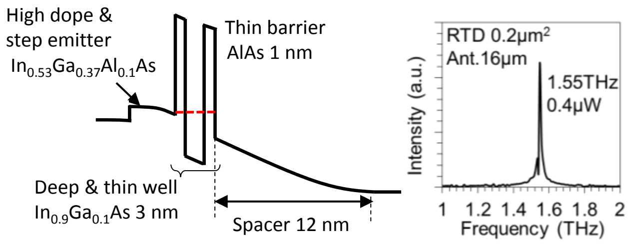

Fig. 1 Schematic band structure and oscillation spectrum with an optimum spacer thickness of 12 nm. A high-doped step emitter structure is employed for high current density with reduced bias voltage.

The negative differential conductance degrades as the frequency increases because of the intrinsic delay time, which consists of the dwell time in the resonance region and the transit time across the collector depletion region. To maintain the negative differential conductance in the high-frequency region, the delay time should be reduced. We employed a thin barrier and well structure to reduce the dwell time and optimized the depletion-layer thickness to reduce the transit time. Fig. 1 shows the schematic band diagram and oscillation spectrum. Because the optimization of antenna length is also effective for high frequency oscillation, we employed 16-μm-long antenna. A fundamental oscillation up to 1.55 THz is obtained [13], which is the highest fundamental oscillation for room-temperature single electronic devices.

The maximum available output power can be extracted from an RTD when the impedance matching condition is satisfied, which is when the radiation conductance of the antenna becomes half of the absolute value of the negative differential conductance [11]. However, the radiation conductance of a conventional center-fed slot antenna was too small, and the matching condition was not satisfied. With the combination of an offset-fed slot antenna and optimization of the antenna width, the radiation conductance was increased, and a high output power can be achieved [14]. The power combined with the array configuration is also effective for a high output power. We fabricated a two-element array of the offset slot antennas, and obtained a combined output power of 610 μW at 620 GHz [14].

For the extraction of output power, we employ a Si hemispherical lens. However, a Si lens is bulky and not easy to handle. Thus, we proposed and fabricated RTD oscillators integrated with slot-coupled patch antennas for the extraction of output power without the use of Si lenses [15]. Output power radiation through the patch antenna and an antenna directivity of ~7 dBi were obtained. It will be possible to obtain a high directivity by array configuration.

3. Data Transmission and Modulation Characteristics

As a preliminary experiment, wireless data transmission using an RTD was demonstrated [16]. The obtained bit error rate was 3×10^{-5} at 3 Gbps. The bit rate was limited by the parasitic elements surrounding the oscillator core. Fig. 2 shows the structure proposed for high-frequency direct modulation [17]. The parasitic element of the metal-insulator-metal capacitor, which is used for the separation of the DC bias and the formation of the slot antenna, is reduced for high-frequency modulation. We measured the high-frequency response of the novel oscillator using a vector network analyzer (VNA). A very high cut-off frequency of ~30 GHz was obtained (Fig. 2), and high bit rate is expected with this structure.

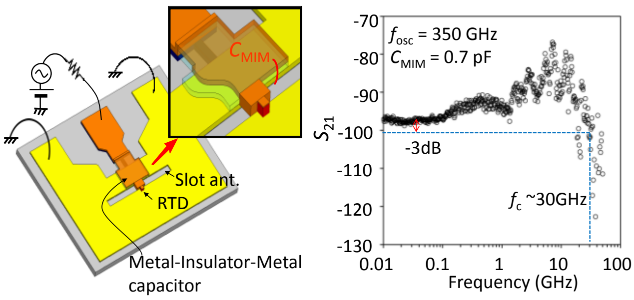

Fig. 2 Schematic structure and modulation characteristics of the RTD oscillator for high-frequency modulation.

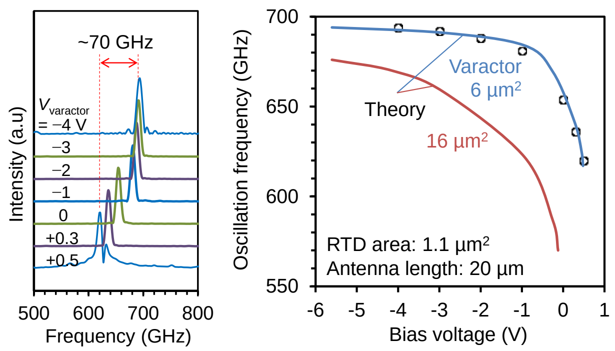

Fig. 3 Tuning spectra and the dependence of the oscillation frequency on the bias voltage of the varactor diode.

4. Frequency Tuning with Varactor Diode

Terahertz spectroscopy using the specific absorption spectra of various molecules is one of the key applications in the terahertz range [1]. In order to realize wide frequency tuning for spectroscopic application, we proposed and fabricated a novel RTD oscillator integrated with a varactor diode [18]. As a preliminary experiment, we fabricated an oscillator with a 20-μm-long antenna, 1.1-μm² RTD mesa, and 6-μm² varactor-diode mesa and measured the tuning range. Frequency tuning from 620 to 690 GHz (~11% of the center frequency at 655 GHz) is obtained by the change in the depletion-layer capacitance of the varactor diode for a DC sweep from −4 to +0.5 V (Fig. 3). The experimental results agree well with the theory, and a larger tuning range (~100 GHz) is expected by utilizing a large-area varactor diode.

Acknowledgments

The authors thank Emeritus Professors Y. Suematsu and K. Furuya of the Tokyo Institute of Technology for their continuous encouragement. We also thank Professors S. Arai and Y. Miyamoto and Associate Professors M. Watanabe and N. Nishiyama of the Tokyo Institute of Technology for fruitful discussions and encouragement. This work was supported by Scientific Grants-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology, Japan; the Industry–Academia Collaborative R&D Program from the Japan Science and Technology Agency, Japan; and the Strategic Information and Communications R&D Promotion Programme (SCOPE) from the Ministry of Internal Affairs and Communications.

References

[1] M. Tonouchi, *Nat. Photonics*, **1**, 97 (2007).
[2] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, *Nature*, **417**, 156 (2002).
[3] B. S. Williams, *Nat. Photonics*, **1**, 517 (2007).
[4] S. Fathololoumi, E. Dupont, C. W. I. Chan, Z. R. Wasilewski, S. R. Laframboise, D. Ban, A. Mátyás, C. Jirauschek, Q. Hu, and H. C. Liu, *Opt. Express*, **20**, 3866 (2012).
[5] L. A. Samoska, *IEEE Trans. Terahertz Sci. Technol.*, **1**, 9 (2011).
[6] Y. M. Tousi, O. Momeni, and E. Afshari, *IEEE J. Solid-State Circuits*, **47**, 3032 (2012).
[7] U. R. Pfeiffer, Y. Zhao, J. Grzyb, R. Al Hadi, N. Sarmah, W. Förster, H. Rücker, B. Heinemann, *ISSCC Dig. Tech. Papers*, 256 (2014).
[8] S. Suzuki, M. Asada, A. Teranishi, H. Sugiyama, and H. Yokoyama, *Appl. Phys. Lett.*, **97**, 242102 (2010).
[9] M. Feiginov, C. Sydlo, O. Cojocari, and P. Meissner, *Appl. Phys. Lett.*, **99**, 233506 (2011).
[10] Y. Koyama, R. Sekiguchi, and T. Ouchi, *Appl. Phys. Express*, **6**, 064102 (2013).
[11] M. Asada, S. Suzuki, and N. Kishimoto, *Jpn. J. Appl. Phys.*, **47**, 4375 (2008).
[12] H. Kanaya, R. Sogabe, T. Maekawa, S. Suzuki, and M. Asada, *J. Infrared, Millimeter and Terahertz Waves*, **35**, 425 (2014).
[13] T. Maekawa, H. Kanaya, R. Sogabe, S. Suzuki, and M. Asada, *EOS Annual Meeting, Terahertz Sci. Tech.*, 20, Camogli, Italy, (2014).
[14] S. Suzuki, M. Shiraishi, H. Shibayama, and M. Asada, *IEEE J. Selected Topics Quantum Electron.*, **19**, 8500108 (2013).
[15] K. Okada, S. Suzuki, and M. Asada, *Int. Conf. Indium Phosphide and Related Materials (IPRM2014)*, Montpellier, France, May 2014.
[16] K. Ishigaki, M. Shiraishi, S. Suzuki, M. Asada, N. Nishiyama, and S. Arai, *Electron. Lett.*, **48**, 582 (2012).
[17] K. Minoguchi, K. Okada, S. Suzuki, and M. Asada, *Int. Conf. IRMMW-THz*, Th P3-59, Mainz, Germany, (2013).
[18] S. Kitagawa, S. Suzuki, and M. Asada, *J. Infrared, Millimeter and Terahertz Waves*, **35**, 445 (2014).