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Terahertz Oscillating InGaAs/AlAs Resonant Tunneling Diodes

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1. Introduction

The terahertz (THz) frequency range located between the lightwave and millimeter wave has been receiving considerable attention because of its many possible applications, such as imaging, spectroscopy, and high-capacity wireless communications [1]. Compact and coherent solid-state sources are important key components for various applications of the THz waves. The development of electron devices toward the THz range is also being progressed from the millimeter-wave side. Resonant tunneling diodes (RTDs) have been considered as one of the candidates for THz oscillators at room temperature [2]-[5]. In this paper, we report on our recent results of RTD oscillators in the THz range.

2. Device Structure

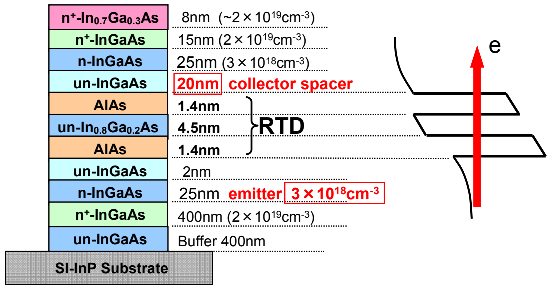
Figure 1 shows the cross section of the used RTD and the structure of fabricated oscillators. The RTD has a GaInAs/AlAs double-barrier structure on a semi-insulating InP substrate. The electrodes of the RTD are connected to the slot antenna that works as a resonator and a radiator, as shown in Fig. 1(b).

For a high available current density (i.e., high current-density difference between the peak and valley) and small capacitance, both of which are required for high frequency and high output power, we introduced high emitter doping concentration and thick collector spacer in the structure shown in Fig. 1(a). The peak current density and available current density were 18 and 9 mA/μm^2, respectively.

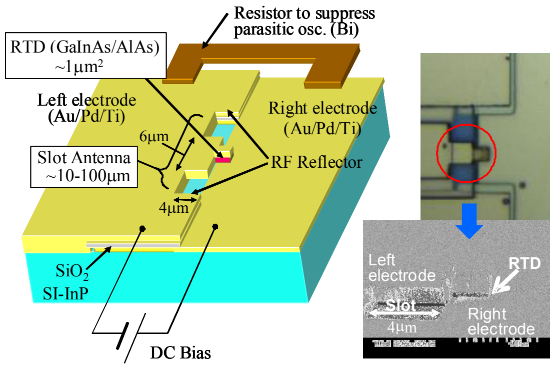
3. Oscillation Characteristics

For the oscillator shown in Fig. 1, a fundamental oscillation at 831 GHz was obtained with an output power of more than 1 μW at room temperature [4]. The dependence of oscillation frequency on mesa-area of RTD was theoretically calculated and compared with the measurement. The electron velocity in the collector transit region (spacer and depletion layers) estimated from this comparison was about 1×10^7cm/s which was smaller than the peak velocity reported for InGaAs (3×10^7cm/s). This discrepancy can be attributed to the Γ-L transition with high electric field.

The graded emitter and thin barrier structures were proposed and fabricated for suppressing the Γ-L transition and reduction of tunneling time to achieve oscillation at higher frequency [6]. Obtained output power as a function of oscillation frequency was shown in Fig. 2. Fundamental oscillation up to 1.04 THz is obtained with output power of 7 μW. This is the first fundamental oscillation of more than



(a)



(b)

Fig. 1 (a) Layer structure of RTD and (b) Oscillator with RTD integrated with slot antenna.

1 THz in room temperature single electronic devices.

The output power of RTD oscillators is usually small (1-10 μW). We proposed RTDs with offset-fed slot antennas for high output power. Fig. 3 shows the offset structure and theoretical output power and frequency as a function of offset $\delta = s/(\ell/2)$ which is displacement of the RTD from the center divided by the half length of the antenna[7]. The output power has a peak according to the change in radiation conductance of the antenna. From this calculation, 800 μW at 400 GHz and 300 μW at 600 GHz are theoretically possible.

In a preliminary experiment, 200 μW at 443 GHz with δ = 90% was obtained for RTDs with the available current density of 11 mA/μm^2 [7]. The DC-to-RF conversion efficiency was 1.1% without the external bismuth resistor. 130 μW at 488 GHz with δ = 91% and was also obtained [8]. The array configuration is also effective for high output power [9]. Output power of more than 1mW is expected by 3-5 elements with 200-300μW/element.

We found that the frequency of the RTD oscillators changes with bias voltage. The frequency change was typically around a few percent of the oscillation frequency. A

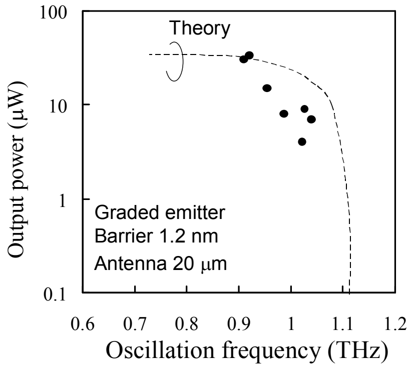
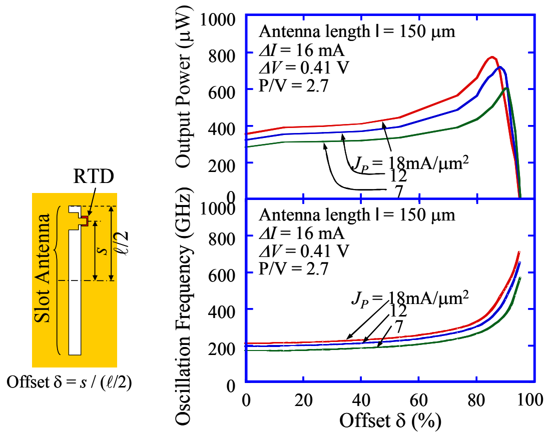


Fig. 2 Total output power as a function of oscillation frequency.



(a) (b)

Fig. 3 (a) Offset-fed slot antenna and (b) theoretical output power and frequency as a function of offset.

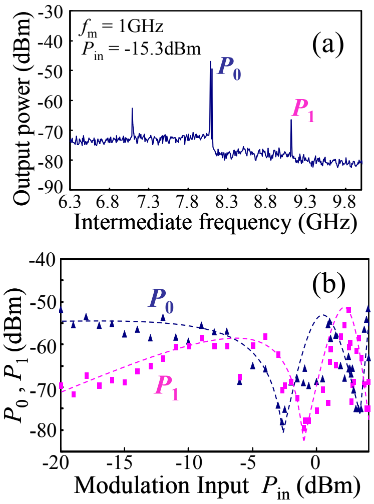


Fig. 4 (a) Heterodyne-detected spectra under bias modulation (b) spectral intensity as a function of input modulation.

possible mechanism of the frequency change is the change in electron tunneling time with bias voltage.

The spectral linewidths were measured to be about 10 MHz for the oscillation at 550 GHz with 1-10μW [10]. The measured result was in reasonable agreement with a theoretical calculation including the shot noise. The linewidth is inversely proportional to output power and square of the Q factor of the resonator.

The frequency change described above can be utilized for the direct frequency modulation which may be useful for a simple short-distance wireless communication in the sub-THz and THz range. Fig. 4 (a) shows a preliminary result of the spectra under the direct bias modulation at 1 GHz measured by the heterodyne detection. The spectral intensity as a function of input modulation power is shown in Fig. 4 (b) for the carrier and the first sideband components. The variation of the sideband intensity with modulation power indicates the property of frequency modulation. The modulation frequency is limited at present up to a few GHz by the capacitance of the large-area metal-insulator-metal reflectors at the edges of the slot antenna in Fig. 1(b). However, the area of these reflectors can be reduced without any influence on the oscillation characteristics, and the increase of the modulation frequency is expected.

4. Conclusions

Our recent results of room-temperature THz oscillators using RTDs were described. By a structure with high current density and small capacitance, a fundamental oscillation at 831 GHz was obtained in GaInAs/AlAs double-barrier RTDs integrated with slot antennas. A comparison with theoretical analysis shows a possibility of Γ-L transition in the collector transit region which brings about a long transit time. With a structure suppressing this transition, an oscillation up to 1.04 THz was obtained. An offset-fed slot antenna and power combining with array configuration was demonstrated for high output power. Frequency change with bias voltage and frequency modulation utilizing this property were also shown. Based on these results, we believe that a RTD oscillator is a possible candidate for compact THz sources.

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