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High Performance Microstrip Resonant Tunneling Diode Oscillators as Terahertz Sources

(Invited Paper)

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***Abstract* — This paper presents monolithic microwave integrated circuits (MMIC) employing large size resonant tunneling diode (RTD) with high power at high frequencies. This is achieved by proper design of the resonating inductances which are realized by shorted microstrip transmission lines with low characteristic impedances (Z_0 = 10.4 Ω). Two oscillators were fabricated using photolithography. Oscillation frequencies of 312 GHz delivering 0.15 mW and 262 GHz delivering 0.19 mW were measured for oscillators employing a single 4 µm × 4 µm and 5 µm × 5 µm RTD devices, respectively.**

***Index Terms* — monolithic microwave integrated circuit (MMIC), resonant tunneling diode (RTD), oscillator, J-band, THz sources.**

I. INTRODUCTION

TERAHERTZ (THz) radiation, whose frequency range lies between millimeter-waves and infrared light in the electromagnetic spectrum, has many potential applications in different scientific fields such as medical diagnostics, security imaging, and wireless communication [1]. THz technology, however, suffers from the lack of efficient and practical radiation sources and so this part of the electromagnetic spectrum has been known as the THz gap. Quantum cascade lasers (QCLs) and far infrared (FIR) gas lasers can operate in the THz gap and can emit tens of milli-Watts power [2]. However, both are bulky with QCLs requiring cryogenic cooling although QCL sources operating at room temperature and limited to >1 THz frequencies have been demonstrated recently [3]. In addition, they require high power to operate. Many THz (gap) electronic sources, on the other hand, today are based on low frequency sources with multiplier chains to achieve the THz signal [4]. The efficiency of this architecture is low and the sources are not compact. Therefore, a number of electronic devices including Gunn diodes, IMPATT diodes, resonant tunneling diodes (RTDs), etc have been considered for use as THz sources, especially in the 0.1 - 3 THz range. Of these, the InP-based resonant tunneling diode (RTD) is the fastest electronic device and has the potential to construct compact oscillators that can operate up to 2.5 THz and at room temperature [5]. Indeed, a number of demonstrations of this large RTD bandwidth have been reported recently [6]. Demonstrations of wireless transmission using RTD oscillators at 300 GHz [7], 500 GHz [8], and 350 GHz with intensity modulation up to 30 GHz [9] have also been reported. Individual RTD oscillators, however, exhibit low output power in the micro-Watt range, partly due to using small RTD device sizes chosen to reduce the RTD self-capacitance [10], while high power in the milli-Watt range is desirable. To provide a perspective for this, practically relevant output powers of at least 10mW at 90 GHz, 5mW at 160 GHz and 1mW at 300 GHz are required [11], for example, for the future wireless indoor communications in femtocell scenarios [12], and these are yet to be demonstrated as single compact electronic sources in integrated circuit form.

To increase the output power of RTD oscillators, we have developed designs that employ the largest possible devices and also developed an oscillator circuit topology that employs two RTD devices. Using this approach, 28 GHz and 76 GHz InP-based RTD oscillators with around 1 mW were realized [13], [14]. Thereafter, D-band oscillators operating at 125 GHz, 156 GHz and 166 GHz, with output power of 0.34 mW, 0.24 mW, 0.17 mW, respectively, were also demonstrated [15]. These oscillators used a shorted coplanar waveguide (CPW) lines of characteristic impedance (Z_o) of 50 Ω to realize the inductances required to resonate with the device self-capacitance for a given target oscillation frequency. However, at very high frequencies, the length of the shorted CPW line becomes extremely short (3 µm) and so limits that maximum oscillation frequency. In this paper, we extend the previous work by using shorted microstrip lines to realize lower inductance values which can be used with large RTD devices to produce higher frequencies and high power. For example, for a given RTD device size in the oscillator circuit, the required length of the shorted microstrip line (with Z_o =10.4 Ω) will be longer (88 µm) compared to the required length when CPW with $Z_o = 50\ \Omega$ is employed (3 μm), to achieve the same oscillation frequency. Calculations show that the performance could be further improved and extended deeper into the THz regime using this approach.

II. FABRICATION AND CHARACTERIZATION

The layer structure of the RTD wafer which was used in the oscillators reported here was grown by molecular beam epitaxy (MBE) by IQE Ltd on a semi-insulating InP substrate. It employs a 4.5 nm $In_{0.53}Ga_{0.47}As$ quantum well, 1.4 nm AlAs barriers and 25 nm spacers. This double barrier quantum well (DBQW) design offers a current density J_P of ~3 mA/μm^2 and a PVCR of 3.5. The collector and emitter layers are made of highly doped $In_{0.53}Ga_{0.47}As$ material (3×10^{19} cm^{-3}) doped with Si.

The RTD devices were fabricated using optical lithography techniques. Two RTD mesa sizes, 4 μm × 4 μm and 5 μm × 5 μm, were fabricated. Chemical wet etching (H_3PO_4:H_2O_2:H_2O=1:1:38) was used to define the RTD mesa. This recipe has an etching rate of around 100nm/min. Polyimide PI-2545 was used for device passivation. An SEM of a fabricated RTD device is shown in Figure 1. The RTD devices exhibit a peak-valley bias voltage difference (ΔV) of around 0.6 V and peak-valley current difference (ΔI) of around 25 mA for the 4 μm × 4 μm devices. For 5 μm × 5 μm devices on the same sample, $\Delta V = 0.6$ V and $\Delta I = 45$ mA.

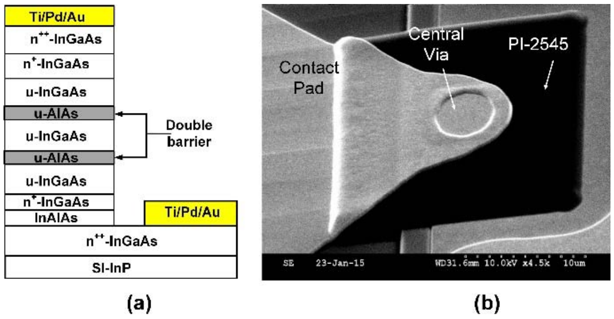


Fig. 1. The schematic epitaxial layer structure of an RTD device. (b) SEM of a fabricated 5×5 μm RTD device.

III. OSCILLATOR DESIGN

The device cut-off frequency (f_{max}) can be first estimated from

$$f_{\max} \approx \frac{1}{2\pi C_n \sqrt{R_n R_s}} \qquad (1)$$

where

$$R_n = \frac{1}{G_n} = \frac{2\Delta V}{3\Delta I} \qquad C_n = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

and R_s the device contact resistance given by $R_s = \rho/A$ with ρ the specific contact resistance obtained from transmission line method (TLM) and A the device/mesa area; •V and •I are found from the device IV characteristics; C_n is the self-capacitance of the device, with d is the thickness of the DBQW structure including the spacer layer on the collector side. It arises principally from electron accumulation on the emitter side of the barrier, the depleted spacer on the collector side and the n-type collector. ε_r is the relative permittivity of InGaAs while ε_0 is the permittivity of free space. ρ was 52 Ω-μm^2 giving f_{max} of 340 GHz and 400 GHz for 9 μm^2 and 25 μm^2 devices, respectively.

The RTD oscillator design approach presented here employs one RTD device as shown in Fig. 2 (a). The shunt resistor R_e is used to suppress the low frequency bias oscillations and the bypass capacitor C_e is used to short-circuit the RF signal to ground avoiding RF power dissipating over R_e [16]. Inductance L is designed to resonate with the RTD self-capacitance to obtain the desired frequency. R_L is the load resistance. The small signal equivalent circuit of the circuit of Fig. 2 (a) is shown in Fig. 2 (b). The RTD is modelled by its lumped equivalent circuit model, a negative differential conductance $-G_n$ in parallel with the self-capacitance C_n, and so the oscillator is a parallel resonant circuit.

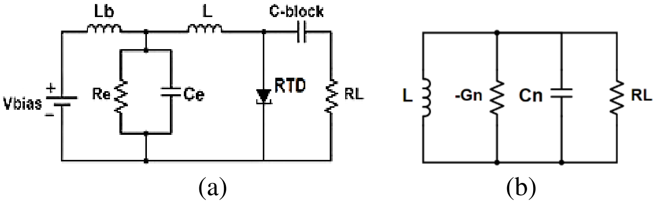


Fig. 2. (a) The RTD oscillator schematic circuit. (b) RTD oscillator RF equivalent circuit excluding parasitic elements.

The circuit topology was realized in MMIC form as shown in Fig. 3. A thin film NiCr resistor R_e was used to suppress bias oscillations by choosing it such that $R_e < 1/G_n$ [16]. The bypass capacitor C_e was realized as metal-insulator- metal (MIM) capacitor. Thin dielectric layer Si_3N_4 (75 nm) was deposited by inductively coupled plasma (ICP) chemical vapor deposition (CVD). The inductance L was realized by a shorted microstrip transmission line. The microstrip line structure consisted of a 20 μm wide signal line on top of a 1.2 μm thick polyimide. With this configuration, the characteristic impedance of the microstrip line is 10.4 •. It is noted that the microstrip line structure as shown in Fig. 3 is shorted by the end of bypassing capacitor C_e at the desired frequency, and it therefore acts as an inductor (when its electrical length is less than 90º). R_L was introduced by the input impedance of the spectrum analyzer or power meter which is usually 50 .

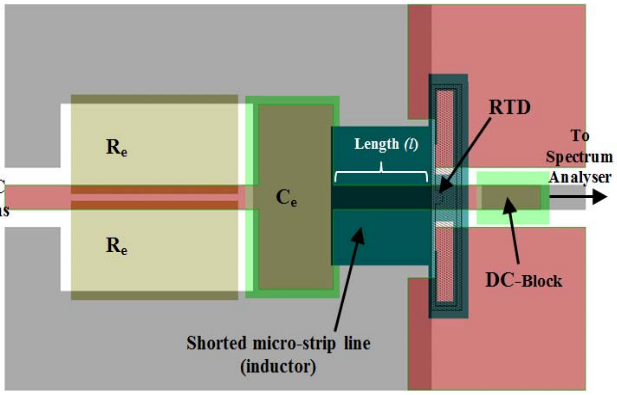
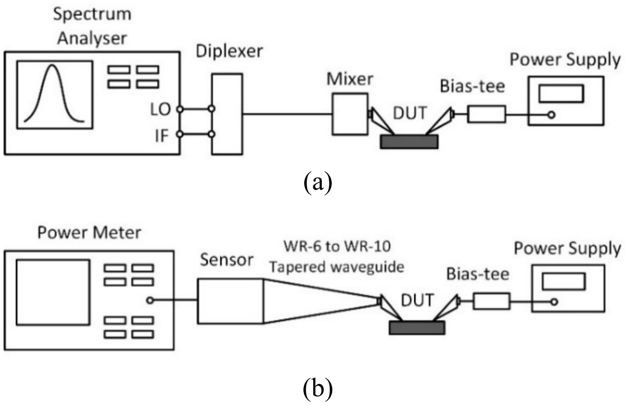


Fig. 3. The RTD oscillator layout.

IV. OSCILLATOR MEASUREMENT

A. Measurement Setup

The oscillators were measured on-wafer by using Agilent E4448A spectrum analyzer. A WR-03 GSG Picoprobe was used to probe the output of these oscillators. The schematic diagram of the measurement setup is shown in Fig 4 (a).



(a)

(b)

Fig. 4. Schematic diagram (a) on-wafer spectrum measurement. (b) Power measurement setup for J-band frequencies.

The signal was mixed down by using J-band harmonic mixer from Farran Technology. The spectrum analyzer and mixer were connected through a diplexer which is used to separate the local oscillator (LO) and intermediate frequencies (IF). With build in signal identification function of spectrum analyzer, the oscillation frequency was accurately identified. On the other end, the oscillator was DC biased through GSG Cascade probe with external bias-tee. As the conversion loss of the mixer is not accurately specified by the manufacturer, the actual output power was measured by power meter (Erikson PM4). Since the input of power sensor head is WR-10 (W-band) waveguide, A WR-03 to WR-10 tapered waveguide was used as shown in Fig. 4 (b).

B. Measurement Results

Different oscillators, each employing either a single 4 µm × 4 µm or 5 µm × 5 µm RTD devices, with different shorted microstrip lengths and Z_0 = 10.4 • were fabricated and measured. For the oscillator that employs a single 4 µm × 4 µm RTD device and 88 µm long shorted microstrip line, 312 GHz oscillation frequency was measured as shown in Fig. 5. The output power was 0.15 mW. Oscillation frequency of 262 GHz and 0.19 mW output power were measured from the oscillator that employs 5 µm × 5 µm RTD device and 65 µm long shorted microstrip line as shown in Fig. 6.

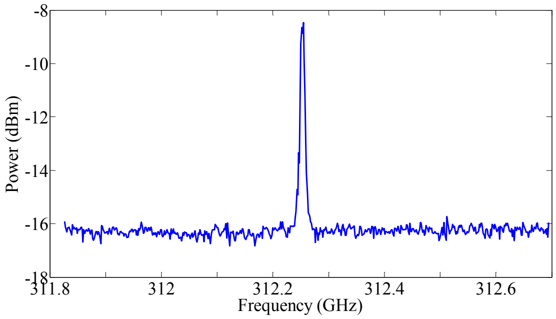


Fig. 5. Measured spectrum of the 312 GHz RTD oscillator.

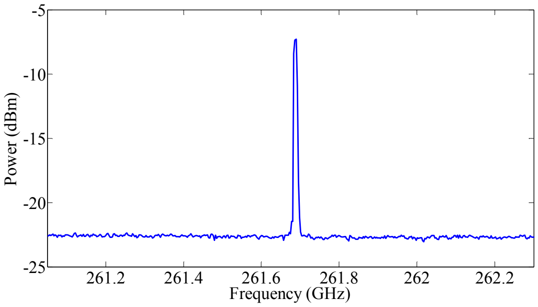


Fig. 6. Measured spectrum of the 262 GHz RTD oscillator.

C. Discussion

The experimental results presented above prove the feasibility of generating high THz frequency even when large size RTD devices are used. Although the device capacitance of the RTD device is larger than that of smaller RTD devices, high oscillation frequencies can still be easily achieved with low inductance values realized by low Z_0 shorted microstrip lines. Fig. 7 shows the calculated oscillation frequency versus shorted microstrip lengths of different Z_o and different RTD device sizes employed in the oscillator circuits. They show that 10 µm long microstrip lines can be used to realise oscillators up to about 1.1 THz when employing two 4 µm × 4 µm RTD devices connected in parallel to increase the power. For 2-µm shorted microstrip lines, an oscillation frequency of 2 THz can be achieved. To achieve these high frequencies, the device cut-off frequency needs to be extended and this can be achieved through lower resistance Ohmic contacts, for instance, by using a high indium content contact layer as already demonstrated by others [17]. Indeed, equation (1) shows that the cut-off frequency (f_{max}) can be reduced by reducing R_s and R_n, both of which can be realized by using larger mesa area RTD devices. Careful epitaxial layer design can offset the increased device capacitance from the larger devices.

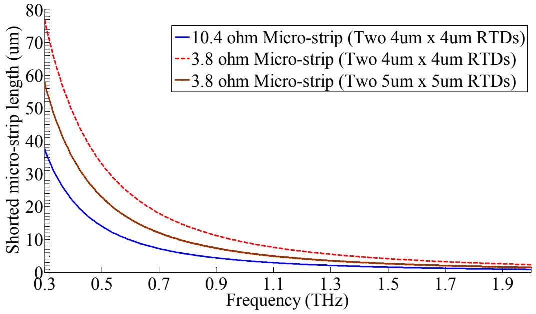


Fig. 7. Calculated oscillation frequency versus microstrip length.

V. CONCLUSION

An RTD oscillator design methodology to provide high power and high oscillation frequency was described in this paper. The circuits were fabricated using photolithography employing large area devices of 4 µm x 4 µm and 5 µm x 5 um delivering output powers of 0.15 mW and 0.19 at 312 GHz and 262 GHz, respectively. Theorical estimation shows that oscillation frequencies ~ 2 THz could be achieved. With improved epitaxial layer structures and oscillator designs, it is expected that the output power will reach several milliwatts. This work shows the promising potential of RTD oscillators as terahertz (THz) sources for high speed wireless communications, etc.

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