THz resonant-tunneling diodes

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ABSTRACT

Recent progress in the development of resonant-tunneling diodes (RTDs) and THz RTD oscillators is described. Strategies and concepts to increase their operating frequencies are pointed out, different types of fundamental RTD oscillators and novel oscillator concepts are outlined.

Keywords: resonant-tunnelling diodes; THz oscillators; tunnel relaxation time; tunnel lifetime; travelling-wave oscillators

1. INTRODUCTION

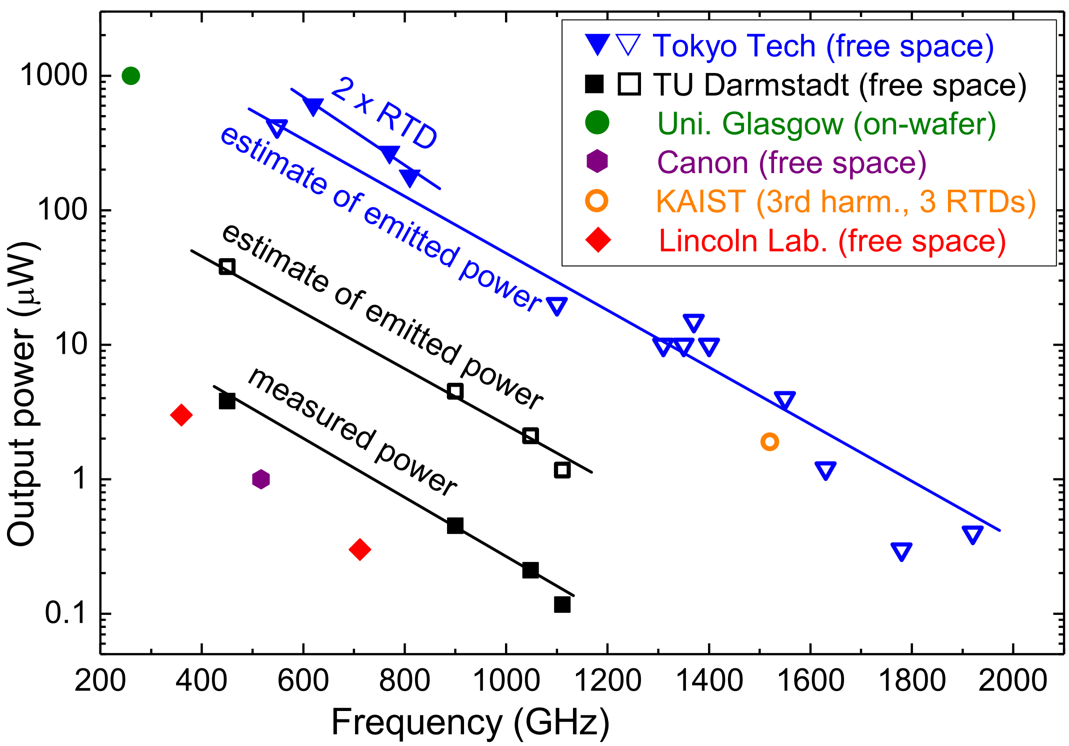

Figure 1. Reproduced from Ref. 1. The plot shows the present status for the output power of RTD oscillators in the sub-THz and THz range reported by different groups.

Resonant-tunneling diodes (RTDs) have re-emerged in the last decade as a promising and viable technology for sub-THz and THz radiation sources. RTD oscillators working above 1 THz have been demonstrated for the first time in 2010-2011.[2,3] Presently, their operating frequencies are getting close to 2 THz.[4,5] The contemporary

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RTD oscillators can deliver ∼0.5 mW at sub-THz frequencies and ∼10 μW at THz frequencies,[1–6] see Fig. 1. It was demonstrated that RTD oscillators could be as small as a fraction of mm^2, see Ref. 3, they consume low DC power and operate at room temperature. RTD oscillators have been used in high-speed wireless data-transmission experiments recently.[7,8] Despite these advantages, there are still limitations, which can be overcome as the understanding of the physics of the operation of RTDs and RTD oscillators is continuously improving and as new types and concepts of RTD oscillators are being suggested.

2. TYPES OF RTD OSCILLATORS

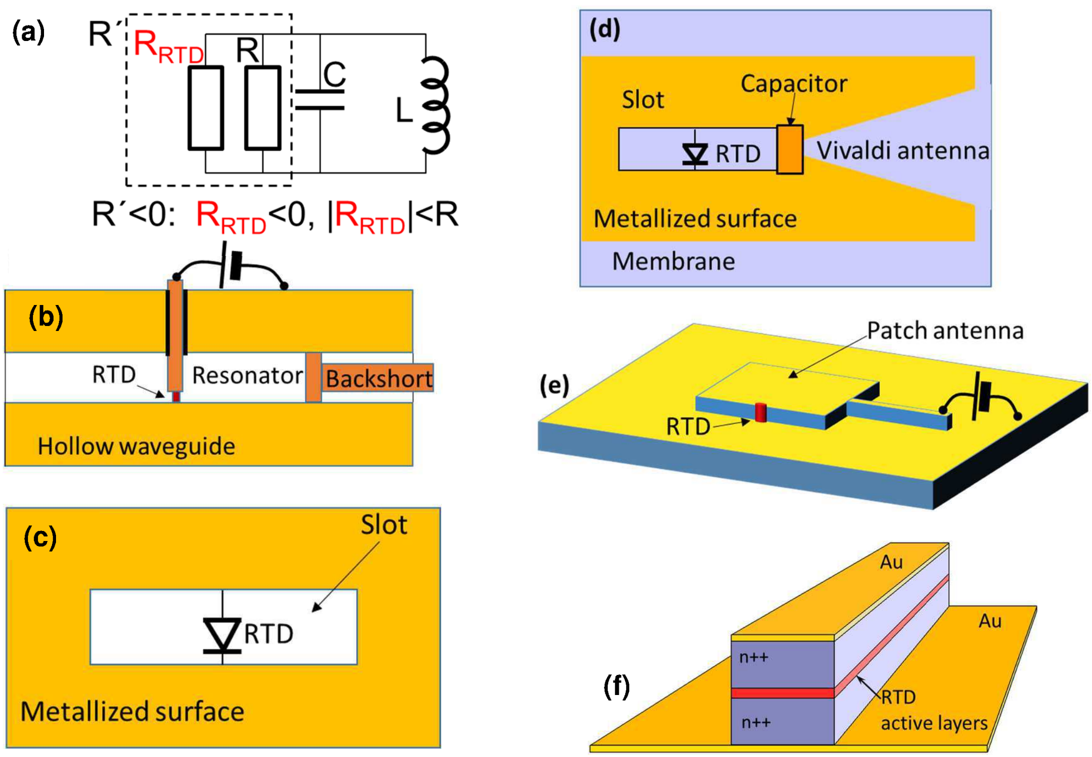

Figure 2. Reproduced from Ref. 1. Sketches of different types of RTD oscillators: (a) resonant LC circuit, (b) hollow-waveguide oscillator, (c) on-chip slot-antenna oscillator, (d) membrane slot-antenna oscillator with Vivaldi antenna, (e) patch-antenna oscillator, (f) travelling-wave microstrip RTD oscillator.

The basic principle of operation of RTD oscillators could be illustrated with a simple LC resonant circuit. RTD is connected in parallel with the circuit, see Fig. 2(a). If the negative differential conductance (NDC) of the RTD is large enough, so that it compensates for the losses (loss/radiation conductance) in the LC circuit and the sum of these two conductances is negative, then the LC circuit will become unstable and start oscillating. The LC circuit is replaced by an appropriate resonator or a resonant antenna in the case of sub-THz and THz RTD oscillators, see examples in Fig. 2.

Initially, RTD oscillators have been build on the basis of the hollow-waveguide resonators,[9] Fig. 2(b). Construction of such resonators, including mounting and contacting of RTDs is very challenging. Later on, integrated RTD oscillators on the basis of resonant slot antennas have been demonstrated,[10] see Fig. 2(c). The concept was further refined and optimised, different geometries and concepts of the slot antennas have been tried out to improve their operation at THz frequencies.[1,6] Due to high RTD capacitance, the dimensions of resonant slots are usually small compared to the emission wavelength. Such antennas are poor radiation emitters. To improve radiation efficiency, several concepts have been suggested. One is to use an asymmetric slots.[6,11] The small part of the slot then works as a resonator, the larger works as an efficient (almost non-resonant) emitter.

The other concept is to integrate the slot antenna resonator with an efficient emitting antenna, as it is sketched in Fig. 2(d). Vivaldi antenna has been used for this purpose, both THz oscillator and emitting antenna have been fabricated on a very thin dielectric free-standing membrane.[3] Another type of resonant antenna tested with RTDs are patch antennas, Fig. 2(e). However, such oscillators have been working only at sub-THz frequencies so far.[12]

Another promising concept is a microstrip travelling-wave RTD oscillator,[13] Fig. 2(f). Such oscillators could be seen as conceptually similar to THz quantum-cascade lasers (QCLs) with the metal-metal waveguide and with a single cascade period (an RTD) as their active core. However, contrary to THz QCLs, microstrip RTDs should be working at room temperature. Assuming realistic parameters of RTD layers (we took them from our past experimental studies) we show that microstrip RTD oscillators could be working up to ∼1.5 THz.[13] We expect that RTD layers specifically optimized for microstrip oscillators should extend the operating frequency even further.

3. TECHNOLOGICAL LIMITATIONS OF RTD OSCILLATORS

One of the main problems is related to reliable fabrication of sub-μm RTDs. The problem is most easily solved by the e-beam lithography,[1,6] however good control of RTD parameters relying on the optical lithography is also possible,[3] although it is much more challenging. The other critical issue is fabrication of good ohmic contacts. The ohmic resistance on the level of $1 - 10\,\mathrm{Ohm}\,\mu\mathrm{m}^2$ is usually required in THz RTDs.[1,6] It is achieved by increased In content and very high doping in the contact layers of RTDs ($\approx 2 - 5 \cdot 10^{19}\mathrm{cm}^{-3}$). Other than that, the fabrication process has to be carefully elaborated to reduce parasitics.

4. LIMITATIONS OF RTDS DUE TO TUNNEL TIME CONSTANTS

For operation of RTD oscillators, RTDs must provide gain, i.e., RTD conductance must be negative at the target oscillation frequency. However, the negative differential conductance of RTDs is rolling off with frequency and becomes positive at some point. That imposes a fundamental limitation on the operating frequencies of RTDs. The RTD-conductance roll-off is related to an internal relaxation time constant (τ_{rel}), which determines the tunnel relaxation rate of the charge perturbations inside an RTD. Two intuitive assumptions are usually made in this regard: (i) τ_{rel} is assumed to be equal to the tunnel lifetime (τ) of electrons in the quantum well of RTDs, (ii) it is assumed that τ imposes a fundamental limitation on the operating frequencies of RTDs, i.e., RTDs cannot exhibit negative differential conductance at frequencies $\omega\tau > 1$. We have demonstrated that both assumptions are not generally correct.

We have theoretically predicted that τ_{rel} is not limited by τ.[14,15] It turns out, that the relaxation processes could be much faster, as well as much slower than τ, depending on the operating regime of RTDs.[14,15] We have also predicted that RTDs with unusually highly-doped collector should exhibit negative differential conductance at frequencies far beyond limitations due to τ and τ_{rel}, i.e., when $\omega\tau \gg 1$ and $\omega\tau_{rel} \gg 1$.[15,16] We have proved the effects experimentally up to ∼600 GHz.[17–19] Following further along this line of development – relying on RTDs with heavily doped collector and rather low current density – we could demonstrate oscillators working at ∼1.1 THz in the regime $\omega\tau_{rel} \approx 1$.[3] The analysis of the oscillators suggests that multi-THz frequencies should be achievable with RTD oscillators and the RTD oscillators have much room for further optimization.[3,4,19] We have also shown that nonlinear characteristics of RTDs are strongly influenced by the Coulomb-interaction effects and by relaxation processes.[20] The calculated output power is in good agreement with the measurement results for RTD oscillators working in the high-frequency ($\omega\tau_{rel} \gg 1$) regime.[20]

Further on, we have brought the concept of an RTD with heavily doped collector to an extreme limit: we have increased the collector doping to the extend, that the lowest quantum-well subband of the RTD stays immersed under collector Fermi level. In such RTDs, the electrons are injected into the quantum well not only from the emitter side (which is usual for RTDs), but also from the collector. The oscillators with such RTDs were demonstrated to operate up to ∼1.5 THz.[4]

5. CONCLUSIONS

In conclusion, there is much room for further development in RTDs and RTD oscillators, that should enable operation of RTD oscillators at multi-THz frequencies and increase their output power. RTD oscillators have potential to evolve into enabling technology for real-world THz applications.

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