

Research highlights

RESONANT TUNNELLING DIODES (RTDS)

THz RTD oscillators

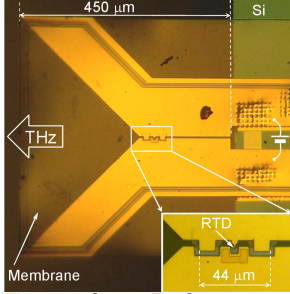


Figure from Ref. 1

We have set records for the operating frequencies of RTD oscillators at 1.1 THz in 2011 (Ref. 1) and 1.46 THz in 2014, see Ref. 2. That were the record frequencies for all existing active semiconductor devices. Our RTD oscillators are among the smallest (and perhaps the smallest) THz sources, their size is only a fraction of mm² (see the picture). RTD oscillators are probably the most promising THz sources for practical applications: RTDs consume current in the mA range and operate at the bias below 1 V, the oscillators work at room temperature and provide rather high output power. Our analysis shows that there is much room for further improvement of the characteristics and parameters of RTD oscillators.

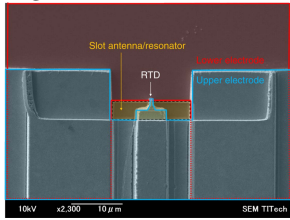


Figure from Ref. 2

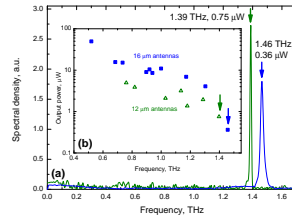


Figure from Ref. 2

Traveling-wave microstrip RTD oscillators

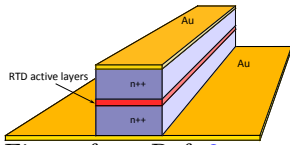


Figure from Ref. 3

We have shown that realization of a hybrid THz source, which combines advantages of both THz quantum-cascade lasers and RTD oscillators, is possible. That could be done in microstrip RTD oscillators.³ Such oscillators are similar to THz QCLs with a metal-metal waveguide and with the active part of only a single QCL period (an RTD) as their active core. Assuming realistic parameters of RTD layers, we have shown that such oscillators should be working at sub-THz and THz frequencies.³ The oscillators are room-temperature devices and potentially they could provide high output power due to large active volume of the RTD layers.

RTD response time

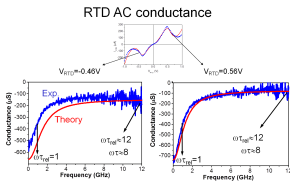


Figure from Ref. 4

The quasi-bound-state lifetime (τ) is usually supposed to be imposing a fundamental inherent limitation on the operating frequency and the charge relaxation time (τ_{rel}) of RTDs. However, we have shown theoretically that the simple picture is not generally correct.⁶⁻⁸ First, we have shown that the Coulomb interaction effects can lead to large reduction/increase of τ_{rel} .^{6,8} Second, we have shown that the operating frequencies of special RTDs with heavily-doped collector should be limited neither by τ , nor by τ_{rel} ; specifically, the differential conductance of such RTDs should stay negative at the frequencies far beyond the limits imposed by both time constants, i.e., when $\omega\tau \gg 1$ and $\omega\tau_{rel} \gg 1$.^{7,8} We have proved both effects experimentally.⁴

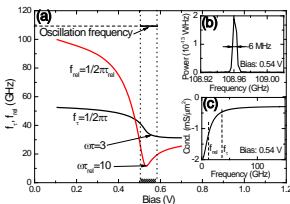


Figure from Ref. 5

Further on, we have demonstrated that RTD oscillators can also operate far beyond τ and τ_{rel} limits. The parameters $\omega\tau$ and $\omega\tau_{rel}$ in our oscillators were $\omega\tau \approx 3$ and $\omega\tau_{rel} \approx 10$ at 109 GHz.⁵ Then we have demonstrated similar behavior of RTD oscillators at much higher sub-THz frequencies: $\omega\tau \approx 1.2$ and $\omega\tau_{rel} \approx 3$ at 564 GHz.⁹ That shows that RTD oscillators with proper design of RTDs are limited neither by τ , nor by τ_{rel} .

RTD theory

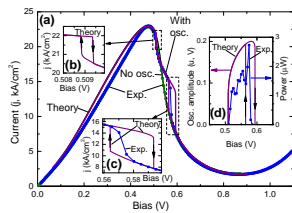


Figure from Ref. 10

Accurate static and dynamic theoretical models for description of RTDs and RTD oscillators are developed,^{1,2,4-8} including a non-linear analysis of large-signal oscillations in RTDs.¹⁰ Realization of the record RTD oscillators and analysis of the Coulomb-interaction and relaxation-time effects in RTDs mentioned above are based on the developed theory. The theory has also allowed us to identify a new operation regime of RTDs: RTDs with strong back injection from collector, when the quantum-well subband stays emerged under the collector Fermi level.² Such RTDs have been working at the record frequency of 1.46 THz.²

THz PHOTOMIXING SYSTEMS AND SOURCES

CW photomixing systems

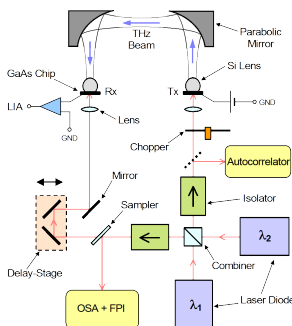


Figure from Ref. 11

We have demonstrated performance of cw photomixing systems at the state of the art level in the past.¹¹ Further, we have suggested a concept, how to control THz phase in the cw THz photomixing systems with the help of an electro-optical phase modulator.¹² The concept allows one to get rid of all movable mechanical components in cw THz systems and enables all-fiber realization of the systems. That makes tremendous improvement in reliability and simplicity of the THz systems possible. The whole system could be even integrated in one chip. We have demonstrated the concept experimentally.^{12,13} Additionally, the concept enables implementation of a special saw-tooth modulation of the THz phase and that makes possible the measurement of both THz amplitude and phase with a single sampling point per frequency.¹³ As a result, the measurement speed of the system is increased by an order of magnitude without performance degradation. The concept is presently used around the world in the commercial cw photomixing systems.

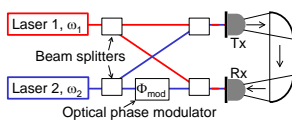
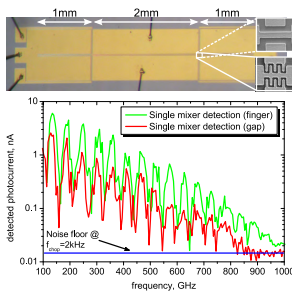


Figure from Ref. 12

On-chip THz sub-systems and sensors



Figs. from Ref. 14

We were investigating optically driven on-chip cw THz spectrometers on the basis of coplanar waveguides and photomixers.¹⁴ We have applied the measurement concept outlined above to such integrated on-chip THz subsystems: we modulate nothing but the THz phase in our measurements. The approach drastically reduces the noise and therefore solves the major difficulty in cw on-chip measurements. In addition, we improve the signal level and signal-to-noise ratio of our on-chip THz transceiver even further by employing finger photomixers. We have improved the dynamic range of the transceiver by several orders of magnitude as compared to standard chopping techniques. This allowed us to extend the frequency range of cw on-chip THz transceiver beyond 1 THz, which is roughly a factor of 5 improvement as compared to previous reports.

P-i-n photodiodes

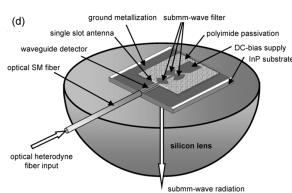
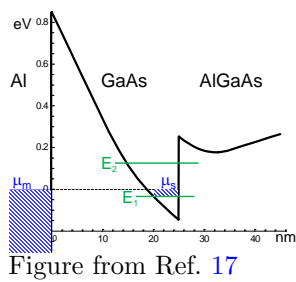


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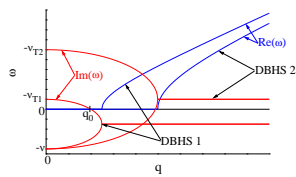
We have achieved the record frequency of 460 GHz with p-i-n photodiodes in 2001.¹⁵ Further on, an analytical model of the uni-travelling-carrier p-i-n photodiodes has been developed by us in 2007.¹⁶ The different mechanisms of THz-power limitation of the photodiodes were analyzed and we could show that the increase of the output THz power of the photodiodes by an order of magnitude as compared to the present state-of-the-art should be possible.

TUNNEL SCHOTTKY STRUCTURES WITH 2D ELECTRON CHANNELS



A novel mechanism of negative differential conductance (NDC) in HEMT-like structures with tunneling between the gate and the channel has been predicted theoretically by us.¹⁷ The mechanism is an inherent property of tunnel Schottky structures with 2D channels. Our experimental results¹⁸ indicate that the mechanism does indeed lead to decrease in the tunnel conductance in such structures and that, with certain modifications of the structures, it should lead to NDC. The developed theory is in very good quantitative agreement with a wide range of various experimental tunnel-spectroscopy data on the tunnel Schottky contacts with 2D channels (see, e.g., Ref. 19). Such structures can become a basis for novel active devices for THz frequencies.

PLASMONICS



We have theoretically described a mechanism of instability and self-excitation of 2D plasmons in the quantum well of an RTD (regions with $\text{Im}(\omega) > 0$ in the Fig.).²⁰ Under certain conditions, the mechanism should lead to filamentation of current through the RTDs and appearance of characteristic features in the RTD I-V curves. We have also predicted excitation of junction plasmons at the Schottky interface and in the semiconductor-dielectric-semiconductor structures at THz frequencies.²¹ Further, we were investigating plasmonic mechanism of resonant THz transmission through sub-wavelength metal gratings and plasmonic enhancement of the radiation efficiency of fs photoconductive emitters in time-domain THz systems.

LITERATUR

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