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Doctoral dissertation outline

Title: Study on Resonant-Tunneling Diode Terahertz Oscillators with Cylindrical Cavity Resonator

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Terahertz (THz) and sub-Terahertz (sub-THz) frequency region, mainly from 0.1 to 10.0 THz, attracting more and more attention because of various promising applications, such as high-speed wireless data transfer or high-resolution radar systems, as well as THz imaging and spectroscopy [1-6]. Many organic materials exhibit unique absorption spectrum in the frequency range from 0.3 to 3.0 THz, and hence detection of such spectrum fingerprints is essential for security, medical and chemical applications [7-14]. One of the key active components for novel THz applications is a compact source of THz radiation in the range 0.3 – 3.0 THz, which could operate at a room temperature. One of the most promising solid-state electronic devices considered for THz sources is the resonant tunneling diode (RTD) [15-16] because it does not require complex auxiliary systems to operate at room temperature and could be used for fabrication of THz oscillator devices with sizes on the order of 0.5 mm or less. Recently, oscillation frequencies up to 1.98 THz [17] and relatively high output power ~0.4 mW at frequencies ~550 GHz [18] were achieved on single RTD oscillator structures with slot antenna. Higher output powers of up to 0.7 mW at frequencies around 1 THz could be obtained with RTD oscillator arrays [19]. Although, most of the experimental RTD oscillators are based on the slot antenna resonator, oscillation frequency range above 2 THz may be unreachable for RTD oscillators with slot antennas because of high intrinsic losses in the antenna and airbridge structure.

In this work new RTD oscillator structure with cylindrical cavity resonator was proposed for reaching frequencies above 2 THz. Oscillation frequency and output

power limitations were analyzed, and optimum device geometry was found based on the analysis results. Based on the dependences of the oscillation frequency on resonant cavity dimensions, a method of the oscillator structure optimization and matching with an RTD structure was proposed. It is revealed that there is only one combination of the resonant cavity dimensions which gives the maximum possible oscillation frequency for this type of structure. Analysis of the calculation results has shown that fundamental oscillation up to 2.77 THz could be expected for the RTD device considered in the present study [20].

Analysis of the output power dependencies on radius and height of the cylindrical resonant cavity shows that decrease in the resonant cavity size could lead to increase in the output power at a fixed frequency for this type of RTD oscillator. Moreover, in addition to the high-frequency oscillation limit, a rapid decrease in the output power in the lower frequency region was found for oscillator devices with larger RTD mesa areas. Rapid decrease in the output power may occur even at frequencies around 1 THz, which could considerably limit operational range for RTD oscillators with cavity-type resonators. To determine an approach for output power optimization and understand the nature of output power drop at lower frequencies, the output power behavior and connection with resonant cavity parameters were explained in detail. Results of the output power analysis and numerical calculation indicate that for the RTD structure and circular-resonator geometry considered in the present study, output powers up to 45 μW at 1.5 THz and up to 0.25 μW at 2.5 THz could be expected for single oscillator design [21].

During the first fabrication trials of the RTD oscillator with cylindrical resonant cavity resonator frequencies above 2 THz were not achieved because of imperfections in the fabrication process, which led to appearance of parasitic capacitance around RTD mesa. In this work fabrication process for the RTD oscillator device as well as challenges and techniques for fabrication of metallic sub-micrometer and micrometer size 3D structures were discussed, and new technique for fabrication of the quasi-3D metallic pillar structures was proposed. Main challenges in the fabrication process were related to the fabrication of 3D metallic structures, especially to the pillar which connects top part of the resonant cavity to the RTD mesa structure. Traditional fabrication techniques for micro- and nanotechnology applications are based mainly on planar technologies such as single-

layer or bi-layer resist processes or on quasi-planar technologies such as tri-layer resist process. However, to meet increasing technical requirements for novel micro- and nano-devices with 3D topology, new fabrication techniques such as dose-modulated (grey-tone) electron-beam (EB) lithography and greyscale photolithography in combination with other techniques are being developed. In this work a combination of grey-tone electron-beam lithography and tri-layer resist process were used to create 3D resist mask with total thickness of resists more than 6 μm , which allowed to fabricate 3D metal structures with feature size down to 0.5 μm and height of the whole structure up to 5 μm with clean lift-off after the electron-beam physical vapor deposition (EB-PVD) of the metal [22]. It was found that fabrication of metallic pillar structures with diameters less than 1 μm in thick (~ 2.4 μm) PMMA resist may require fine adjustment of the exposure dose and development time. However, result of the resist development and hence required development time may be hard to control by traditional nondestructive methods like optical microscopy or SEM. It was shown that to achieve predictable and controllable process results faster, two-step EB exposure of the fine patterns in PMMA resist layer could be used. As a result, pillar structures with radiuses down to 250 nm were fabricated in 2.4 μm thick PMMA resist. Fabrication of pillar structures with radiuses smaller than 250 nm could be achievable by simple decrease in pattern size and corresponding increase in the exposure dose, which could be done with commercial EBL software (GenISys BEAMER). Because electron scattering and backscattering effects were considered as a main cause of the pattern widening, EB exposure with electron energies above 50 keV may improve accuracy of the fabrication results and allow further decrease in pattern feature size. In addition, it was shown that gradual transitions across the vertical axis in a 3D resist mask created by the grey-tone EBL process could solve metal film separation problems which may occur between vertical pillar or wall structures and horizontal ceiling or bridge structures [22].

Fabrication techniques described in this work allow to create arbitrary quasi-3D and 3D metallic shapes with lithographic precision, and hence, application of the techniques is not limited only to RTD oscillators with cavity resonators but may be applicable to fabrication of various micro-electronic devices. Applicability of the described fabrication approach was proven by measurement of oscillation

characteristics for the fabricated RTD THz oscillators. Successful operation of the RTD oscillator devices confirms good electrical contact between RTD mesa structure and the RTD pillar structure as well as between resonant cavity and antenna parts.

Fabrication approach described in this work allowed to eliminate parasitic capacitance formed around RTD mesa. As a result of the structure optimization based on the theoretical analysis and elimination of the parasitic capacitance, increase in oscillation frequency of more than 250 GHz was achieved in comparison with the first fabrication trial for RTD THz oscillators operating at frequencies 1.5-1.7 THz [22].

Although oscillation frequencies above 2 THz were not achieved in this work because of high RTD capacitance values, good correlation between theoretical estimations and experimental measurements of the oscillation frequency allow to assume that the frequency range above 2 THz may be reached with another RTD structure. Therefore, one of the prospects for the future research is the optimization of the RTD layer structure, for example, by varying width of the quantum well and barriers, to achieve lower capacitance values and similar or higher peak current values in comparison with the RTD used in this work. Another goal for the future research could be measurement of the output power to confirm the theoretical calculations and applicability of the fabricated RTD oscillators for THz applications. In addition, decreasing radius of the tip for the RTD cone shaped pillar to enable fabrication of the oscillator devices with mesa areas down to 0.1 – 0.15 μm , as well as increasing cavity height up to 4-5 μm and making smooth transition between cavity top and cavity walls to decrease resistance of the cavity could be goals for further fabrication process optimization. Decrease in the RTD pillar radius could be achieved by application of smaller RTD pillar patterns and exposure with electron beam energies above 50 kV with the fabrication technique described in the dissertation.

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