Conventional vs. Island THz Slot-Antenna Resonant-Tunneling-Diode Oscillators

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***Abstract*— By eliminating the n++ layer (island design), we have reduced the surface ohmic losses in the slot antenna of THz resonant-tunnelling-diode (RTD) oscillators by approximately a factor of 2. That has allowed us to demonstrate slot-antenna RTD oscillators with the output power of 2.2 µW at the fundamental frequency of 1.74 THz. We present also comparative data on conventional and island slot antenna RTD oscillators.**

I. INTRODUCTION

The use of the THz range outside of the specialized research laboratories remains hampered by the lack of sufficiently simple solid-state THz sources. Resonant-tunnelling-diode (RTD) oscillators are one of the most promising devices to solve this problem [1,2]. However, making them work at THz frequencies (and especially around 2 THz) is an extremely challenging task [3]: one needs to make such oscillators nearly perfect and minimize all possible losses and parasitics in the oscillators. In this work, we demonstrate that a dominant loss mechanism of slot antenna RTD oscillators at around 2 THz can be dramatically reduced (by a factor of ≈ 2) by a modification of the oscillators' design and fabrication process. That leads us to the demonstration of very high fundamental operating frequencies of such oscillators with a record output power in the frequency range 1.6-1.74 THz.

II. ISLAND DESIGN

The simplest RTD oscillator is constructed by integrating an RTD into a slot-antenna resonator/antenna. Only such RTD oscillators have been demonstrated to be working at frequencies around 1.5 THz and higher [1,3-5]. To make them work at so high frequencies and to improve their output power, one needs to minimize the losses and parasitics in the RTD oscillators. Here we are focused on the ohmic losses in the slot antennas of the oscillators. The currents in the antenna conducting layers are responsible for such losses. In the conventional design of a slot-antenna RTD oscillator [1-5], the antenna metallization (gold) is deposited on top of an n++ RTD contact layer, see Fig. 1(a). In the assessment of the losses in the n++ layer, two considerations are important. First, the typical thickness of the n++ layer in RTD oscillators is around 500 nm and this thickness becomes comparable to the skin depth in the n++ layer at THz frequencies. At 2 THz, the skin depth in InGaAs layer with the n-doping of 5 x 10^{19} cm^{-3} is also approximately 500 nm, i.e., the current at the bottom of a conventional slot antenna is dominantly localized in the n++ layer. Second, the magnitude of the currents is approximately the same at the top and bottom surfaces of a slot antenna. That means, that one half of the total antenna current is localized in the highly resistive (compared to gold) n++ layer which leads to large ohmic losses in the slot antennas at around 2 THz.

To reduce these losses, the n++ should be removed everywhere, where possible. In our "island" design of slot-antenna RTD oscillators, see Fig. 1(b), n++ layer is left only as an island directly under the RTD as its bottom contact layer and removed elsewhere. In this case, the current at the bottom side of the slot antenna is flowing in the gold layer, in which the metal conductivity is approximately 40 times higher than in the n++ layer (with the above parameters). This leads to a significant reduction in the antenna ohmic losses.

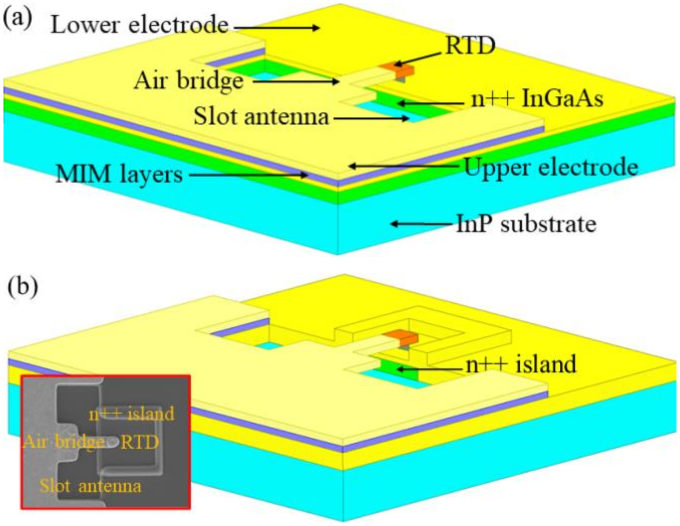

Fig. 1. Schematic of (a) a conventional and (b) an island slot-antenna RTD-oscillator designs. The inset shows an SEM picture of a fabricated island RTD oscillator.

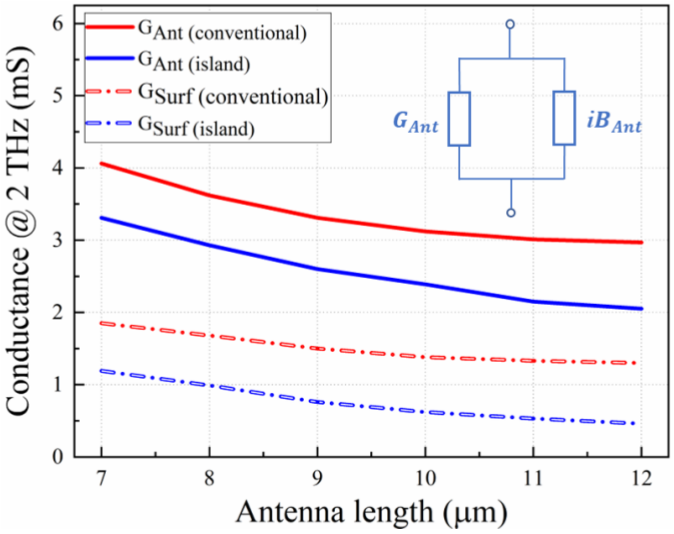

Fig. 2. The total conduction loss at 2 THz as a function of slot-antenna length. Red and blue curves are the calculation results for a conventional and an island slot-antenna RTD oscillators, respectively. The inset shows an equivalent circuit of the slot antenna with conductance G_{Ant} and susceptance B_{Ant}.

In Fig. 2, we show the simulation results at 2 THz for the total loss conductance of the slot antenna and its part corresponding to the surface losses. The plots show that the

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island design allows one to reduce the ohmic losses by approximately a factor of 2 which leads to a significant reduction of the total slot-antenna losses. The calculations are done for the structures sketched in Fig. 1 with the following parameters: slot width is 4 µm, slot length is in the range 7-12 µm, 150 nm SiN is used as dielectric in the metal-insulator-metal (MIM) capacitor, the upper gold electrode of MIM is 300 nm thick, the lower MIM electrode consists either of 100 nm gold on top of n++ 500 nm InGaAs with the doping of 5x10^{19} cm^{-3} (conventional design) or 600 nm gold (island design); the structures are fabricated on top of semi-insulating InP substrate.

III. EXPERIMENTAL RESULTS

In this work, we have used an RTD-wafer design with a high current density of 23.6 mA/µm^2 and a particularly high peak-to-valley current ratio of 3.7. In the past, we have used this RTD wafer in double-RTD patch-antenna oscillators operating up to ≈ 1.1 THz [6].

In the fabrication of conventional slot-antenna RTD oscillators, we have used only optical lithography. Therefore, only RTDs with mesa areas larger than 0.3 µm^2 could have been reliably fabricated. In the fabrication of island slot-antenna RTD oscillators, in addition to the optical lithography, we have used electron-beam lithography at two fabrication steps, that has allowed us to fabricate smaller RTD mesas with the areas in the range 0.11-0.37 µm^2. The island dimension was 4×4 µm^2 with approximately 1 µm offset between the RTD mesa and the edge of the slot antenna, see Fig. 1. Other parameters of the layers of the RTD oscillators are specified above.

The measured oscillation frequencies of conventional and island slot antenna RTD oscillators with the slot length of 10 µm are shown in Fig. 3. The data are well in agreement with the expected simulated oscillation frequencies of the oscillators. Since the conventional slot antenna RTD oscillators were fabricated fully with the optical-lithography process, they have slightly higher (by ≈ 0.5 fF) parasitic capacitance between the airbridge and the bottom RTD contact layer. This resulted in the slight reduction of their operating frequencies compared to the simulations and the more accurately fabricated island design, see Fig. 3. The oscillation spectra have been measured with Fourier-transform interferometer. The spectra are clean, they exhibit no additional lower-frequency lines, which confirms that the oscillators were working at the fundamental frequency. Island oscillators with the RTD-mesa area less than 0.15 µm^2 were not oscillating and this behavior suggests (according to the simulation results in Fig. 3) that our RTDs had the contact resistance of ≈ 1.5 Ω µm^2. This is also a typical contact resistance we measured on test samples with transfer-length method. Due to the limitations of the optical-lithography process and its limited yield, we could not experimentally test the lower working bound for the RTD-mesa areas in the conventional design. However, the simulation data in Fig. 3 suggest, that for given RTD parameters and given contact resistance, the upper frequency bound for the island design is at 1.8 THz, while for the conventional design it is at 1.55 THz. The difference in the maximum oscillation frequency is the direct consequence to the reduction of the ohmic losses in the island design.

Further, the output power of the oscillators has been measured by a calibrated pyroelectric sensor. For island oscillators, we report the radiated power of 5-2.2 µW in the frequency range 1.2-1.74 THz. At frequencies 1.6-1.74 THz, these are the highest reported radiated power levels.

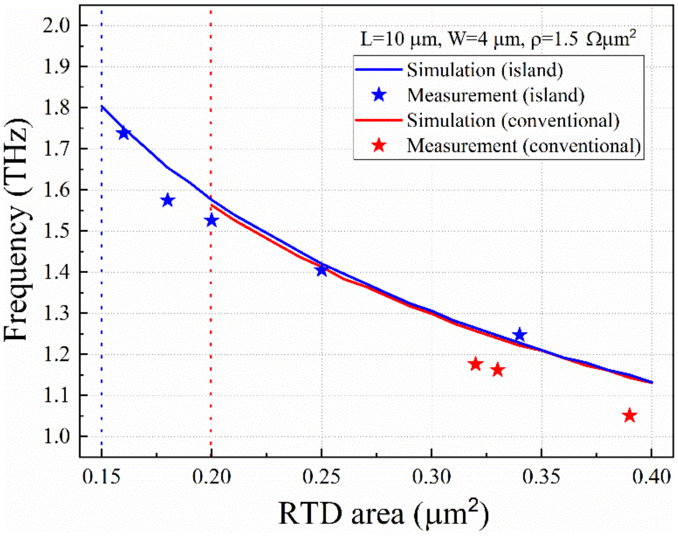

Fig. 3: Measurement (stars) and simulation (lines) data on fundamental oscillation frequencies vs. RTD area for the slot length of 10 µm and the width of 4 µm for a conventional and an island designs of the RTD oscillators. The theoretical curves are calculated assuming the RTD contact resistance of 1.5 Ω µm^2. The dotted lines indicate the upper frequency bound in each case.

IV. SUMMARY

Island design of on-chip slot-antenna RTD oscillators allows one to strongly reduce the ohmic antenna losses. In this work, we report on operation of such island oscillators in the frequency range 1.2-1.74 THz with the radiated output power of 2.2 µW at the fundamental frequency of 1.74 THz. We also show, that the conventional, but otherwise identical, RTD oscillators would have been limited to the operation at frequencies below 1.55 THz.

ACKNOWLEDGEMENT

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