Monolithic Schottky-Collector Resonant Tunnel Diode Oscillator Arrays to 650 GHz

M. Reddy, S. C. Martin, A. C. Molnar, R. E. Muller, R. P. Smith, P. H. Siegel,
M. J. Mondry, M. J. W. Rodwell, H. Kroemer, and S. J. Allen, Jr.

Abstract—**We report monolithic array oscillators incorporating Schottky-collector resonant tunnel diodes (SRTD's). In the SRTD, a 0.1-μm width Schottky collector contact provides a greatly reduced device series resistance, resulting in an estimated 2.2 THz maximum frequency of oscillation. A 64-element oscillator array oscillated at 650 GHz while a 16-element array produced 28 μW at 290 GHz.**

RESONANT tunnel diode (RTD) waveguide oscillators have been reported at frequencies as high as 712 GHz [1]. These frequencies are currently beyond the highest frequency transistor oscillators built to date [2]. Power levels achieved by discrete waveguide RTD oscillators are limited by constraints imposed on maximum device area for suppressing parasitic bias circuit oscillations [3]. Higher power levels can be obtained with monolithic RTD oscillators in which these constraints are eliminated by on-wafer bias stabilizers [4]. Power levels can then be further increased using quasi-optical array RTD oscillators [5]. Here, we report monolithic Schottky-collector RTD (SRTD) oscillator arrays with on-wafer Schottky-diode bias stabilizers. A 64-element array oscillated at 650 GHz. To our knowledge this is the highest oscillation frequency achieved by a monolithic oscillator. Additionally, a 16-element array produced 28 μW at 290 GHz.

The single element RTD oscillator circuit [Fig. 1(a)] consists of a 0.1-μm contact stripe InGaAs SRTD located in the center of a slot antenna, resonant at the desired frequency of oscillation, f_{osc}. The SRTD's have a peak current density of $5 \cdot 10^5$ A/cm^2 at a peak voltage of 0.95 V, a current peak to valley ratio of 1.7, a measured peak negative conductance of -19 mS/μm^2, a parasitic capacitance of 3.0 fF/μm^2, a parasitic resistance of 2.2 Ω-μm^2, and a quantum well lifetime of 0.12 ps. These parameters are normalized to the SRTD effective area which is twice the SRTD junction area to account for the spreading of electric field beneath the 0.1-μm Schottky-collector. From the dc and microwave parameters, the 0.1-μm contact stripe InGaAs SRTD has an estimated maximum frequency of oscillation $f_{\max}$, of 2.2 THz [6], although such high $f_{\max}$ values are difficult to verify experimentally. A low-impedance Schottky-diode is located within $\lambda_{\mathrm{osc}}/4$ from the SRTD for suppressing both dc bistability and parasitic oscillations in the bias circuit at frequencies below the antenna's resonance [4]. At the antenna's resonant frequency, the low-impedance Schottky-diode is decoupled from the SRTD and the SRTD is shunted only by the antenna's radiation impedance. To ensure oscillation, the SRTD junction area is increased until the SRTD negative conductance exceeds the antenna radiation conductance at f_{osc}. This condition is satisfied by SRTD's with junction area larger than 0.2 μm^2. Larger SRTD junction areas provide design margin but also detune the slot antenna from its resonant frequency due to an increased parasitic SRTD capacitance. The maximum SRTD junction area per single element oscillator was 0.8 μm^2 to prevent device burnout at the high operating current density. SRTD oscillator arrays were designed with varying slot antenna lengths and varying SRTD junction areas with the objective of building oscillators in the 100–1000 GHz frequency range. The arrays were obtained by repeating the single element slot antenna coupled oscillator [Fig. 1(a)] into rows and columns. The separation between the adjacent elements for various frequency array designs was chosen to be less than the corresponding wavelength in the substrate to ensure a single main lobe in the radiation pattern of the antenna arrays.

Array fabrication requires monolithic integration of 0.1-μm contact stripe InGaAs SRTD's, Schottky-diode bias stabilizers, MIM capacitors, N++ resistors, slot antennas, and airbridges. The molecular beam epitaxial layer structure (Fig. 2) consists of graded bandgap AlInGaAs Schottky-diode [7] layers grown beneath the InGaAs SRTD layers. The SRTD layers consist of five monolayer AlAs barriers in the double barrier heterostructure which yield current densities in the vicinity of $5 \cdot 10^5$ A/cm^2. Fabrication (Fig. 2) starts with exposing the Schottky-diode surface layers by etching away the SRTD layers in regions where the bias stabilizer is required. A nonselective etch (3:1:50, H_3PO_4:H_2O_2:H_2O) is used to etch away most of the layers and stop within the 1000 Å AlInAs layer. A selective etch (1:1:4:1, CH_3CHOOH:HBr:HCl:H_2O) then removes the remaining AlInAs layer and stops on the InGaAs cap layer of the Schottky-diode. Subsequently, ohmic contacts

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M. Reddy, A. C. Molnar, M. J. Mondry, M. J. W. Rodwell, and H. Kroemer are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA.

S. C. Martin, R. E. Muller, R. P. Smith, and P. H. Siegel are with the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, Pasadena, CA 91109 USA.

S. J. Allen, Jr. is with the Center for Free-Electron Laser Studies, University of California, Santa Barbara, CA 93106 USA.

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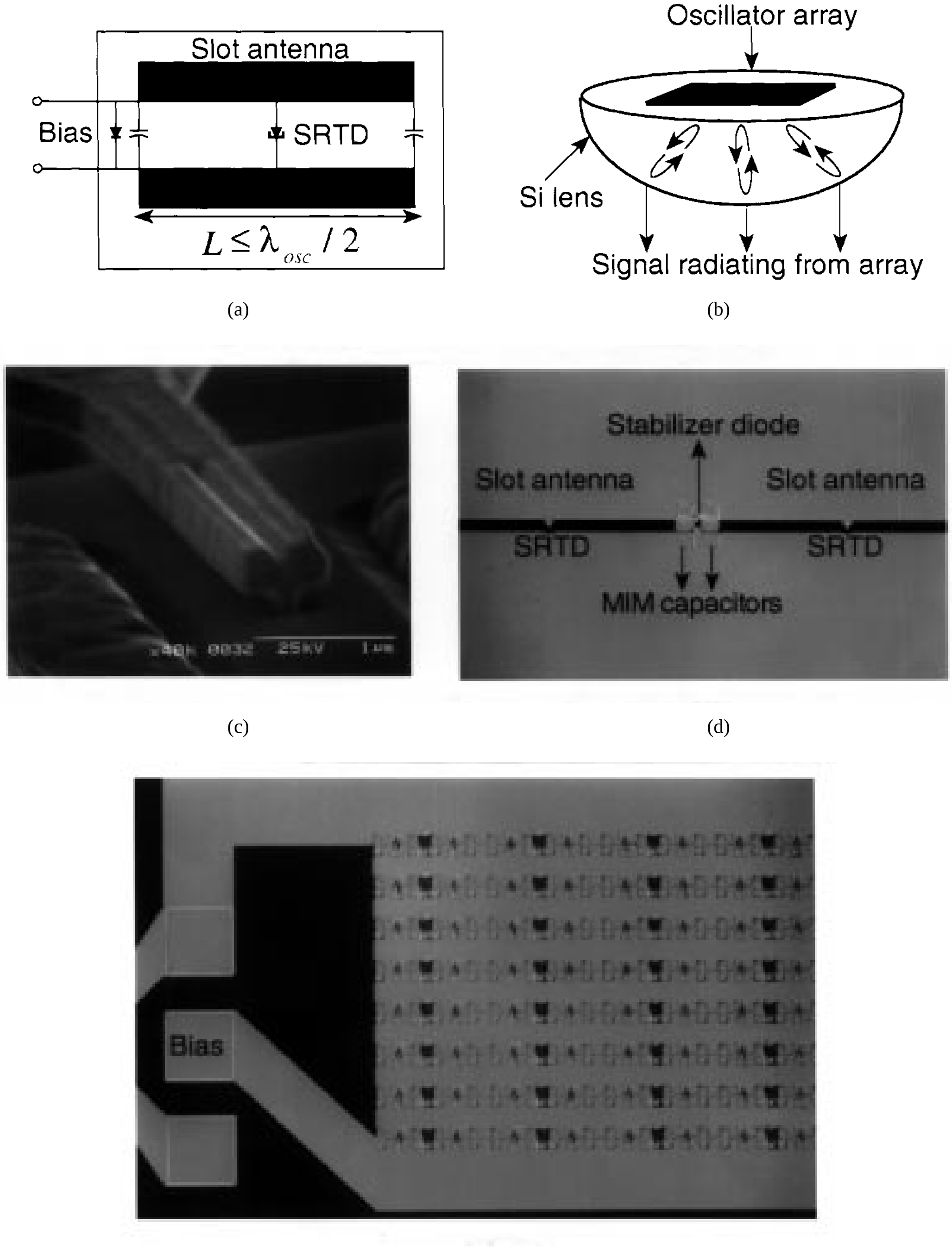


(a) (b)

(c) (d)

(e)

Fig. 1. (a) Circuit schematic of a monolithic slot-antenna coupled SRTD oscillator, (b) quasi-optical oscillator array on a Silicon lens which forms the oscillator's resonant cavity, (c) SEM photograph of a 0.1-μm contact stripe InGaAs SRTD, (d) photograph of a section of an oscillator array, and (e) photograph of a 64-element SRTD oscillator array.

to the N++ layers of both the SRTD and the Schottky-diode are formed by first recess etching and then depositing and annealing Au–Ge–Ni metal. The 0.1-μm Schottky-collector for the SRTD is then defined using an airbridge electron beam collector process [8]. Mesa isolation is achieved using a wet etch (3:1:50, H_3PO_4:H_2O_2:H_2O) and is followed by interconnect metal deposition (Ti/Pt/Au). A 1000-Å thick, PECVD SiN film is then patterned to access both the bottom plate of the MIM capacitors and the surface layers of the Schottky-diode. Posts and evaporated airbridges provide the second level of interconnections, the top plate of the MIM capacitors and the stabilizer diode's Schottky-contact metal. Array photographs are shown in Fig. 1(c)–(e).

The arrays were tested with a quasi-optical configuration [Fig. 1(b)]. The 23-mm diameter Si hyperhemispherical lens on which the oscillator array is placed forms the array's external resonant cavity, determining both the oscillation frequency and the oscillator Q. For arrays oscillating below 250 GHz, the oscillator array output was detected directly using a broad band bowtie-antenna-coupled Schottky diode harmonic mixer.

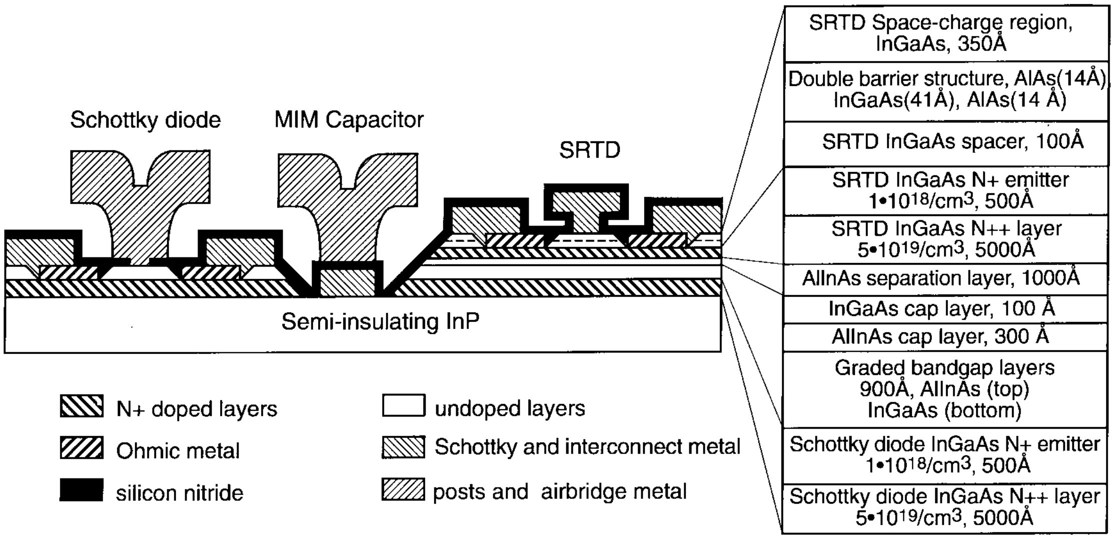
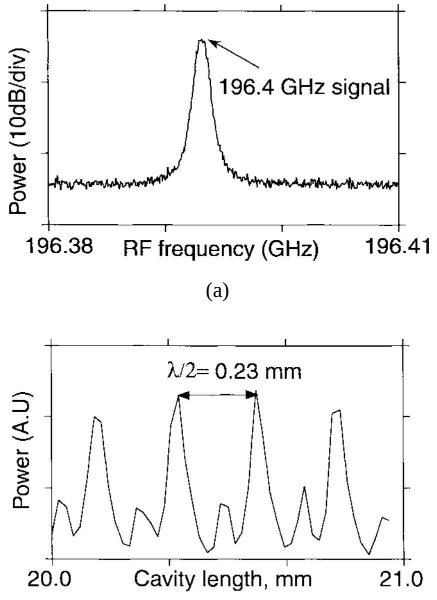


Fig. 2. Cross-sectional view of the SRTD oscillator showing monolithic integration of the SRTD, Schottky-diode, MIM capacitor, and airbridges as realized in an eight-mask IC process.



(a)

(b)

Fig. 3. Measurements of oscillator arrays: (a) spectrum of a two-element array at 196 GHz tested with a Schottky-diode harmonic mixer and (b) detected power of a 64-element array as a function of Fabry–Perot interferometer cavity length showing transmission peaks separated by 0.23 mm (a 650-GHz signal).

The harmonic mixer downconverts the signal frequency to the 2–12 GHz passband of a spectrum analyzer. A two-element array oscillated at 109 GHz. A second two-element array having shorter slot length oscillated at 196 GHz [Fig. 3(a)]. A 16-element array oscillated at 94 GHz [9]. This array radiated 5% of its output power into a secondary cavity mode at 108 GHz.

For arrays oscillating above 250 GHz, the signals were detected by a liquid helium cooled Ge bolometer or a less sensitive but calibrated thermo acoustic power detector. A Fabry-Perot interferometer measures the signal wavelength and hence the frequency. A 64-element array produced oscillations at 650 GHz [Fig. 3(b)]. Other arrays oscillated at 290, 300, 310, 470, and 560 GHz (Table I).

TABLE I
SUMMARY OF RESULTS OBTAINED WITH VARIOUS SRTD OSCILLATOR ARRAYS DESIGNED WITH PARAMETER VARIATION OF TOTAL SRTD JUNCTION AREA, SLOT ANTENNA LENGTH, AND NUMBER OF UNIT CELL ELEMENTS IN THE ARRAY

# of array elements	Total SRTD area (μm^2)	Slot length (μm)	Osc. freq (GHz)
16	3.2	544	94
2	1.6	430	109
2	1.6	217	196
16	6.4	157	290
16	12.8	121	300
2	1.6	121	310
16	6.4	84	470
16	6.4	53	560
64	19.2	51	650

The output power of a 16-element array oscillating at 290 GHz was measured to 28 ± 2 μW by the thermo-acoustic power detector. This corresponds to a 440 W/cm^2 power per unit SRTD junction area. This measured power does not correct for reflection and diffraction losses in the beam path, which may be substantial. Power measurements of the higher frequency oscillator arrays using the thermo-acoustic detector proved difficult as the power levels were close to the instrument's threshold and a Ge bolometer was then used instead. Direct electrical connection to the individual SRTD's is not possible at sub-mm-wave frequencies. Therefore, we cannot conclusively establish that every array element is oscillating. However, we note that except for the 100 GHz designs (where both the two-element and the 16-element arrays have similar SRTD junction areas) the detected signal levels of the 16-element oscillator arrays are approximately an order of magnitude larger than the two-element oscillator arrays.

For designs above 500 GHz, the slot length becomes comparable to the capacitor, stabilizer diode and the SRTD dimensions. The physical layout then fails to conform well to a slot antenna. We believe that the highest oscillation frequency (650 GHz) obtained is limited by these layout considerations.

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