

Fabrication and Performance of Planar Schottky Diodes with T-Gate-Like Anodes in 200-GHz Subharmonically Pumped Waveguide Mixers

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Abstract—A T-gate-like structure has been developed, fabricated, and tested as the anode for millimeter and submillimeter-wave Schottky diodes. The low parasitics of the *T-anode* diodes yield extremely high cutoff frequencies, making the diodes useable at frequencies well beyond 1 THz. The diodes were tested as an antiparallel-pair, integrated monolithically with microstrip circuitry on a quartz substrate, in a subharmonically pumped waveguide mixer. A double sideband noise temperature of 600 K with a conversion loss of 4.7 dB were measured at 200 GHz. This is believed to be the lowest noise temperature ever reported for a room-temperature subharmonically pumped Schottky diode mixer at this frequency.

I. INTRODUCTION

THE surface channel etched (SCE) diode structure, first proposed by Bishop *et al.* [1], has been extensively used for millimeter and submillimeter-wave mixers and multiplier circuits that require planar Schottky diodes. Recent results have indicated that SCE planar diodes can perform as well as whisker contacted diodes at least up to 350 GHz [2]–[4]. Technology has also been developed and demonstrated that utilizes an SCE GaAs Schottky diode process to make diodes monolithically integrated with microstrip circuitry that is mounted upside down on a quartz substrate and back etched to leave only the necessary GaAs [5]. These QUID (quartz-substrate upside down integrated device) structures eliminate the need for soldering or bonding the very small discrete diode packages in place on millimeter-wave circuits and, at the same time, allow the implementation of GaAs devices on substrates (quartz, silicon, sapphire, etc.) with dielectric properties more suitable for submillimeter-wave operation.

Most high-frequency diodes use a circular anode with an air-bridge type finger that connects the anode to the ohmic contact. As the anode diameter is reduced for higher frequency operation and the finger width becomes larger than the anode diameter, this structure induces a strong parasitic capacitance between the finger tip and the region surrounding the anode. This parasitic capacitance is difficult to tune out and results in deteriorating the circuit performance at high frequencies.

In this letter we report on the design and performance of a T-gate-like structure in which the anodes are shaped like a “T” and the finger or air-bridge between the anode and the ohmic

contact is made in the same step as the anodes. This structure is readily scaled to frequencies above 1 THz and also results in lower parasitics than conventional circular air-bridge type diodes. Antiparallel-pair T-anode devices monolithically integrated on quartz microstrip circuits using the QUID process [5] have been fabricated and tested in a room-temperature subharmonically pumped mixer operating at 200 GHz. The measured mixer noise temperature and conversion loss are 600 K DSB and 4.7 dB, respectively, which is believed to be the best performance ever obtained in this configuration at this frequency.

II. DEVICE DESIGN AND FABRICATION

The T-anodes are formed using a process reported by Muller *et al.* [6] that was developed for very-high-frequency Schottky contact resonant tunneling diode structures by Allen *et al.* [7]. The process uses multiple e-beam scans at different doses and a trilevel PMMA coating to enable one to separately define the footprint and the side beams of the T-anode structure. Moreover, the finger that becomes the air-bridge after the surface channel etch is also formed in the same step. A layer of 496 K molecular weight PMMA, with 4% solids content, is spun on the wafer at 4000 RPM. The resulting film is then cured at 170° to form a 300-nm-thick layer. A middle layer (actually two layers of a copolymer of PMMA and methacrylic acid) is deposited next and cured. Each layer after cure is about 400 nm. Finally, the top layer (2300 K molecular weight PMMA with 1% solids content) is spun on, resulting in a 100-nm-thick layer after cure. The e-beam exposure is performed with a JEOL JBX 5DII electron beam lithography system in the high-resolution mode.

After exposure the chip is immersion developed at room temperature using three different solutions. The top layer is developed in chlorobenzene, which aggressively dissolves the exposed PMMA but does not affect the copolymer layer. A one to one mixture of isopropanol and methanol opens the copolymer layer. Since PMMA is insoluble in this solution, the copolymer can be overdeveloped enough to undercut the PMMA and provide a good lift-off profile. Finally, The footprint is defined by developing the bottom layer in a one-to-one mixture of MIBK and isopropanol. This solution provides enough contrast to define tenth micron lines.

Fig. 1 shows a closeup of one of the T-anodes. Once the surface channel is etched to isolate the devices, the process

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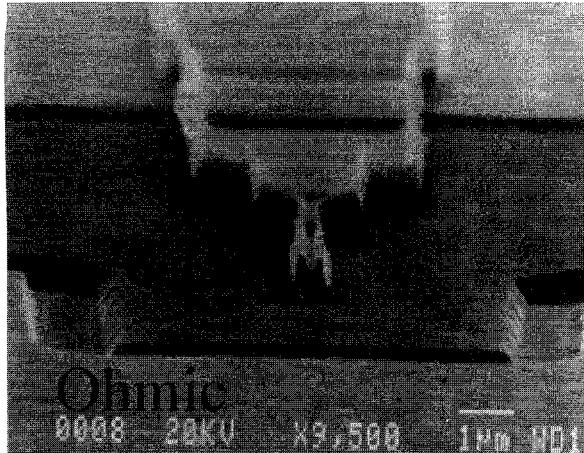


Fig. 1. A closeup SEM of the T-anode structure before the QUID process. The anode area is nominally $0.25 \mu\text{m}$ by $4 \mu\text{m}$.

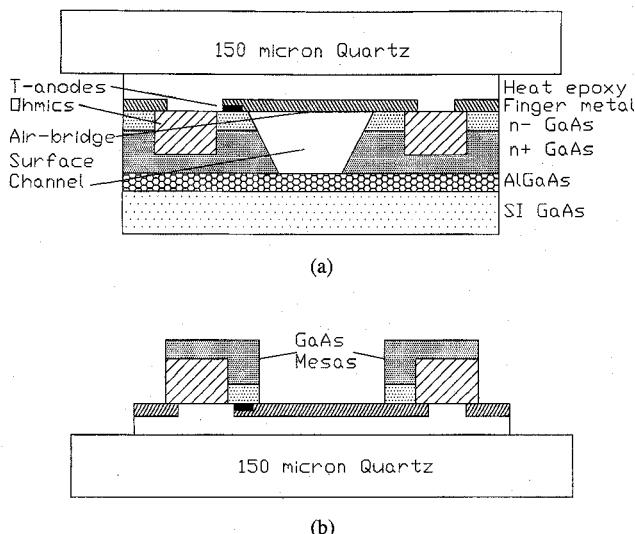


Fig. 2. A cut-view schematic representation (not to scale) of the starting point and the end point of the QUID process. (a) The fabricated chip is bonded upside down on the quartz substrate with the help of a heat cured adhesive. (b) After lapping, selective wet chemical etching and removal of the AlGaAs layer the chip is patterned to remove all of the GaAs except for enough material to cover the ohmic and Schottky contacts. This makes sure that there is no excessive GaAs in the waveguide channel.

schematically depicted in Fig. 2 (QUID process) is followed in order to obtain structures that can easily be tested in a waveguide block. For 200-GHz operation the top epilayer is doped $2.0 \times 10^{-17} \text{ cm}^{-3}$ and is 1000 \AA thick. The heavily doped layer is about $2.5 \mu\text{m}$ thick. Shrinking the anode area for use at higher frequencies involves no change to the fabrication process. Also, since no oxide etching is involved and the anode foot print is defined by the e-beam, anodes made with this technique are extremely uniform. If surface passivation is desired, a thin layer of oxide can be deposited after the anodes have been put down.

The major advantages of the T-anode diode structure are reduced parasitic capacitance and resistance and extremely small realizable anode areas. Both of these characteristics are critical for increasing the sensitivity of millimeter and

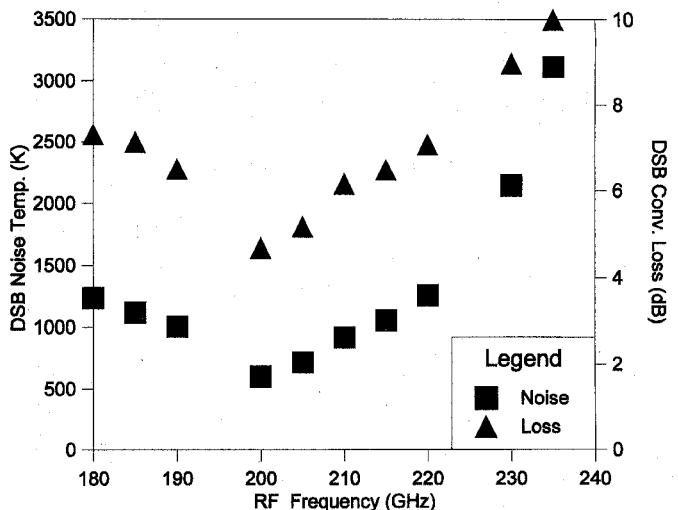


Fig. 3. Double sideband noise temperature and conversion loss of the tested subharmonic mixer as a function of the signal frequency.

submillimeter-wave mixers. DC characteristics for the T-anode QUID Schottky diode pair (diode A/diode B) used in the measurements reported in this letter are: ideality factor 1.16/1.20, reverse saturation current $6.8 \times 10^{-16}/1.8 \times 10^{-15} \text{ A}$, series resistance 9.7/8.7 Ohms. The process has not been fully optimized yet and it is expected that diode performance and uniformity will improve in the future. The total device capacitance, measured before the chip was flipped upside down and without the filter structures, is 9–10 fF. Each anode is calculated to have about 3 fF of capacitance and thus the parasitic capacitance of the diode pair is calculated to be 3–4 fF. The total capacitance of the structure after QUID processing and dicing was measured to be 17 fF. The extra capacitance is due to the microstrip filter structure, which contributes about 3–4 fF, and the higher dielectric constant of the bonding adhesive.

III. MIXER MEASUREMENTS

The completed structure, consisting of a pair of antiparallel diodes, two quartz microstrip filters and a waveguide coupling probe was tested in a subharmonically pumped mixer block at 200 GHz. A detailed description of the waveguide block and the measurement procedure has been described in [4]. Fig. 3 shows the measured double sideband noise temperature and conversion loss optimized over a band centered at 200 GHz, optimized at each RF frequency, with an IF of 1.5 GHz. The required LO power at the optimum noise temperature was excessively high, about 30 mW, due to a resonance in the filter design, but drops to 8 mW at 102.5 GHz where the noise temperature is about 15% worse. At 115 GHz the required LO power is only 1.5 mW. The IF output impedance at the optimum noise temperature is about 200 Ohms. It is noteworthy to point out that these results are 30% lower than the best reported whisker-contact diode mixers and somewhat lower than the best GaAs discrete chip-type diode mixers.

(measured with the same circuit under identical conditions) at this frequency [4].

IV. CONCLUSION

Schottky diodes with T-anodes have been fabricated and tested. These devices are easily scaled to THz frequencies and have lower parasitics than comparable air-bridge type circular-anode planar Schottky diodes. A waveguide mixer incorporating the new T-anode diodes has yielded what is believed to be the best performance for a subharmonic mixer at 200 GHz. Work has already begun on a scaled device for 640 GHz and is planned for implementation at 2.5 THz.

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REFERENCES

- [1] W. Bishop, K. McKinney, R. Mattauch, T. Crowe, and G. Green, "A novel whiskerless diode for millimeter and submillimeter wave applications," in *1987 IEEE-Int. Microwave Symp. Dig.*, June 1987, pp. 607-610.
- [2] T. Newman, W. L. Bishop, K. T. Ng, and S. Weinreb, "A novel planar diode mixer for submillimeter-wave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 12, pp. 1964-1971, Dec. 1991.
- [3] B. J. Rizzi, T. W. Crowe, and N. R. Erickson, "A high-power millimeter-wave frequency doubler using a planar diode array," *IEEE Microwave and Guided Wave Lett.*, vol. 3, no. 6, pp. 188-190, June 1993.
- [4] P. Siegel, R. Dengler, I. Mehdi, J. Oswald, W. Bishop, T. Crowe, and R. Mattauch, "Measurements on a 215 GHz subharmonically pumped waveguide mixer using planar back-to-back air bridge schottky diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 11, Nov. 1993.
- [5] I. Mehdi, M. Mazed, R. Dengler, A. Pease, M. Natzic, and P. H. Siegel, "Planar GaAs schottky diodes integrated with quartz substrate circuitry for waveguide subharmonic mixers at 215 GHz," in *IEEE Int. Microwave Symp. 1994 Dig.*, 1994, pp. 779-782.
- [6] R. E. Muller, S. C. Martin, R. P. Smith, S. A. Allen, M. Reddy, U. Bhattacharya, and M. J. W. Rodwell, "Electron beam lithography for the fabrication of air-bridged, submicron Schottky Collectors," *J. Vac. Sci. Technol. B*, vol. 12, no. 6, p. 3668, 1994.
- [7] T. Allen, M. Reddy, M. J. W. Rodwell, R. P. Smith, S. C. Martin, J. Liu, and R. E. Muller, "Submicron schottky-collector AlAs/GaAs resonant tunnel diodes," in *Proc. Int. Electron Device Meet.*, Washington, D.C., Dec. 1993.