High Power Submillimeter-Wave Varactor Frequency Multipliers Based on Quasi-Vertical Schottky Diodes

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***Abstract*—This report summarizes the main outcomes of the research project awarded by the 2017 MTT-S Graduate Fellowship under the General Category. The work addresses the lack of high power solid-state sources in the submillimeter-wave band, by investigating a new device geometry, fabrication processes, and electrical characterization techniques. A new approach for fabricating quasi-vertical submillimeter-wave GaAs Schottky diodes heterogeneously integrated to high resistivity silicon substrates has been developed. The new method is robust and eliminates previous processing steps that were prone to result in wafer fracture and delamination. Diodes fabricated with the new process and measured in the 325–500 GHz range using on-wafer RF probes exhibit low parasitic capacitance and series resistance, achieving device characteristics comparable to the prior state-of-the-art submillimeter-wave diodes. Finally, an integrated 160 GHz frequency quadrupler based on the new fabrication process was developed and tested. It produced 100 mW of output power, achieving a peak efficiency of 25.5%.**

Index Terms— Frequency multiplier, Heterogeneous integration, Schottky diode, Submillimeter-wave, Wafer bonding.

I. Introduction

SUBMILLIMETER-WAVE technology has received substantial attention in the past decades, for its use in a variety of important applications, including radio astronomy, spectroscopy, plasma diagnostics, radar, imaging, and potentially communications [1]. One of the factors that limit the widespread of this technology is the lack of high power solid state sources, often coined the “terahertz gap”. Frequency multipliers are the best candidates to provide a source of stable, reliable, and compact power at terahertz. However, their efficiencies significantly degrade after each multiplication stage, leading to very low powers at 1 THz. One way of addressing this issue is to increase the input power to the first multiplication stage. Thus, power handling has become a major concern [2]. This project proposes a transformative approach to improve the thermal management and output power of frequency multipliers, by investigating new device geometries, fabrication processes, design innovations, and electrical and thermal characterization techniques.

II. Project Outcomes

A. Fabrication Process Development

Although previous efforts in heterogeneously integrating GaAs quasi-vertical Schottky diodes on Si have exhibited low parasitics at submillimeter-wave frequencies [3], the integration process used to fabricate these devices suffered from low-to-modest yields arising from various thermal processes employed. Figure 1 illustrates these issues and the various failure mechanisms associated with the epitaxial transfer process that frequently limited the usable material and yield of these devices.

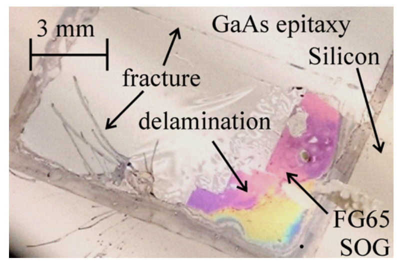

Fig. 1. Image illustrating fracturing and delamination of GaAs epitaxy bonded to silicon using Filmtronics FG65 SOG.

A revised process was developed to address these issues [4]. InGaAs cap layers are included in the epitaxy to allow the formation of a low resistance ohmic contact using a Ti/Pd/Au/Ti metal stack-up that does not require annealing. Elimination of the annealing step results in a smooth metal surface. Unlike previous processes involving lithographically formed ohmic contact pads, the metal stack-up is evaporated over the entire InGaAs cap layer and left unpatterned. Consequently, the surface of the GaAs wafer bonded to silicon is planar, eliminating an important contributor for wafer fracture. The wafer bonding step replaces SOG with SU-8, a negative epoxy-based photoresist commonly used in MEMS packaging applications to produce high-aspect ratio features. The relatively low curing temperature of SU-8 (100–140^{o}C) compared to SOG ($\sim$ 200^{o}C), coupled with its relatively lower percent volume shrinkage after crosslinking results in a more robust epitaxy transfer. Figure 2(a) shows a scanning electron microscope (SEM) image of a cross section of the bonded layers and illustrates the uniformity and lack of voids in the SU-8. An SEM image of a completed quasi-vertical diode is shown in Figure 2(b).

B. Electrical Characterization

RF characterization of the diodes is performed in the WR-2.2 (325– 500 GHz) band using an Agilent PNAX vector network analyzer and Cascade Microtech PA200 probe station

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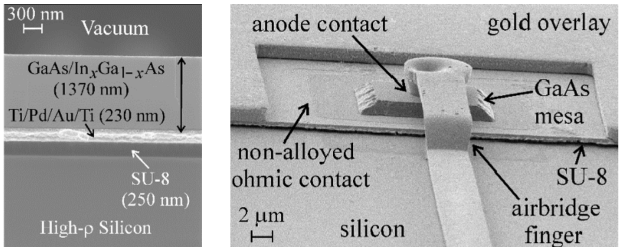

Fig. 2. (a) SEM of a cross-section of the bonded GaAs epitaxy, ohmic metal, SU-8 resist, and silicon substrate. (b) SEM of the quasi-vertical diode profile (diameter = 3 µm) showing the device mesa, underlying ohmic contact, and anode contact airbridge.

equipped with WM-570 frequency extenders from Virginia Diodes, Inc. and WR-2.2 on-wafer probes manufactured by Dominion MicroProbes, Inc. The diode junction capacitance and series resistance are obtained from the S-parameter data. The extracted junction capacitance for the annealed and unannealed diodes are, as anticipated the same. The normalized zero bias junction capacitance to anode area is 1.78 fF/µm^2. The series resistance extracted from these measurements indicate approximately 1 Ω lower value than that obtained with annealed ohmic contact diodes fabricated using the process described in [3].

C. 160 GHz Quadrupler

An integrated frequency quadrupler operating at 160 GHz, producing 100 mW of output power, and achieving peak efficiency of 25.5% was developed. The quadrupler design is based on prior art [5] and consists of GaAs Schottky diodes with epitaxy transferred to a micromachined silicon carrier forming a heterogeneously-integrated chip. The newly developed process was employed to realize the circuit [6]. Figure 3 shows a photograph of the chip mounted to its housing.

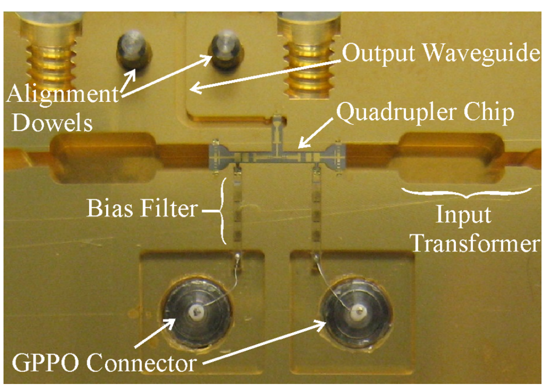

Fig. 3. The quadrupler chip mounted to its waveguide housing. The quadrature hybrid is not shown.

Output power of the quadrupler as a function of input power near the design frequency (160 GHz) is shown in Figure 4. The saturation characteristic of the multiplier is evident and a maximum output power of 100 mW (20 dBm) was measured at 159 GHz. This output power corresponds to an input power of 650 mW and overall quadrupler efficiency of 15%.

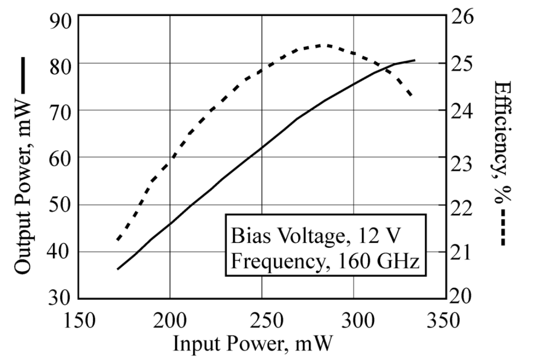

Fig. 4. Quadrupler output power and efficiency vs. input power.

III. IMS Experience and Future Plans

First of all, I would like to sincerely thank the IEEE Microwave Theory and Techniques Society for granting me the 2017 IEEE Graduate Fellowship Award. The work supported by the fellowship has led to two publications [5] [6] summarized in this report.

The fellowship's financial support helped me attend the International Microwave Symposium (IMS) 2017 in Honolulu, where I interacted with many professionals and industrial exhibitors. Upon my return from IMS, I decided to found an MTT-S student branch chapter at the University of Virginia. As of March 1st 2018, we have already hosted numerous speakers from academia and industry.

In terms of my career goals, I am open to both academia and industry positions. I would like to expand my knowledge of microwaves and millimeter-wave to more devices (HBT, HEMT, etc) and circuit topologies. I am also interested in pursuing interdisciplinary research involving the field of photonics, heat transport, and materials science. Stay tuned for more updates!

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