Integrated GaAs Diode Technology for Millimeter and Submillimeter-wave Components and Systems

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ABSTRACT

GaAs Schottky barrier diodes remain a workhorse technology for submillimeter-wave applications including radio astronomy, chemical spectroscopy, atmospheric studies, plasma diagnostics and compact range radar. This is because of the inherent speed of these devices and their ability to operate at room temperature. Although planar (flip-chip and beam-lead) diodes are replacing whisker contacted diodes throughout this frequency range, the handling and placement of such small GaAs chips limits performance and greatly increases component costs. Through the use of a novel wafer bonding process we have fabricated and tested submillimeter-wave components where the GaAs diode is integrated on a quartz substrate along with other circuit elements such as filters, probes and bias lines. This not only eliminates the cost of handling microscopically small chips, but also improves circuit performance. This is because the parasitic capacitance is reduced by the elimination of the GaAs substrate and the electrical embedding impedance seen by the diodes is more precisely controlled. Our wafer bonding process has been demonstrated through the fabrication and testing of a fundamental mixer at 585 GHz ($T_{\text{mix}} < 1200$K) and a 380 GHz subharmonically pumped mixer ($T_{\text{mix}} < 1000$K). This paper reviews the wafer bonding process and discusses how it can be used to greatly improve the performance and manufacturability of submillimeter-wave components.

INTRODUCTION

Over the past several decades, there has been a surge of interest in high-resolution spectroscopy in the submillimeter-wave portion of the electromagnetic spectrum (300 GHz to 3 THz) for applications such as radio astronomy [1], studies of the Earth’s upper atmosphere [2], chemical spectroscopy [3], plasma diagnostics [4] and compact range radars. Also, many new applications can now be envisioned, such as high-resolution collision avoidance radar, remote detection of chemical and biological toxins, medical diagnostics and ultra wide-band communication systems. These applications require versatile and robust receiver components that can be manufactured reliably and cost efficiently, and most importantly, operate at room...
temperature. In these cases, GaAs Schottky barrier diodes are the technology of choice for the non-linear mixer element and as a frequency multiplier to generate the required local oscillator power.

Several research groups have successfully used discrete planar diodes in millimeter and submillimeter wave applications in both waveguide and quasi-optical receivers [5,6,7]. Such a mixer is depicted in Fig. 1. It uses a discrete planar diode soldered to a quartz microstrip circuit and has no mechanical tuning elements. At 585 GHz the measured double sideband mixer noise temperature is 1,800K with a conversion loss of 7.6 dB at an LO power level of about 1 mW [8]. Although this performance is competitive with the best reported in this frequency range, the mixer is challenging to assemble. In fact, simulations have indicated that a misalignment of only 10 microns can affect conversion loss by as much as 1.5 dB [9].

The integration of the GaAs diode directly on the quartz circuit both alleviates the assembly problems and improves performance. Since the quartz itself becomes the diode’s substrate, only a very thin GaAs epitaxial layer is necessary. This minimizes the problem of higher order modes in the channel and greatly reduces the shunt capacitance, thereby allowing better coupling to the diode over a broader bandwidth. Furthermore, since both the diode structure and the surrounding circuitry are fabricated lithographically, alignment with micron precision is obtained. This not only improves repeatability, but also increases the accuracy of circuit simulation tools since the circuit will be fabricated exactly as designed.

Fig. 1: The 585 GHz discrete planar diode mixer design [8] that was used as the basis for our demonstration of the MASTER process.
Our integration process is named the Method of Adhesion by Spin-on-dielectric Temperature Enhanced Reflow or MASTER [10,11]. The basic concept is to bond a semiconductor (GaAs) to an alternative substrate (quartz) using a thin bonding agent. For this work, a spin-on-dielectric (SOD) available from Filmtronics, Inc. (Type 400FA-4000) was used due to its material properties, availability, and reasonable price. The mixer fabrication process began with a GaAs wafer (roughly 10 mm x 12 mm and 625 µm thick). The GaAs substrate was heavily doped n-type and roughly 0.6mm thick. The epitaxial layers, in order of growth, were, i) 2 µm of undoped Al_{0.45}Ga_{0.55}As, ii) 5.2 µm of 6x10^{18} cm^{-3} n-GaAs, and iii) 0.1 µm of 4x10^{17} cm^{-3} n-GaAs. A 600 nm SiO\textsubscript{2} passivation layer was deposited on the GaAs surface using atmospheric pressure chemical vapor deposition. Circular anode wells roughly 600 nm in diameter were etched into the oxide to within 60-70 nm of the GaAs surface by standard lithography and reactive ion etching. The SnNi/Au ohmic contacts were plated and alloyed, and then electroplated with additional Au to form a low resistance contact. The wafer was then mounted face-down in wax (Apiezon-W, melting point of 100°C) on a silicon carrier and the bulk GaAs substrate and AlGaAs etch stop layer were removed by a wet chemical etch.

MASTER wafer bonding began with the cleaning of the GaAs and the quartz surfaces. The SOD was then spin applied to the quartz substrate (30 mm diameter, 150 µm thick) and baked on a hotplate to yield a solid film about 0.5 µm thick. The GaAs and SOD/quartz surfaces were then brought together and bonded under vacuum at elevated temperature. We have experimented with a variety of bonding recipes [12,13] and found that the required temperature is less than 200°C and the applied pressure is much less than one atmosphere. After cooling, the Si carrier was removed from the front surface of the GaAs wafer by remelting the wax on a hotplate. At this point we have essentially replaced the thick GaAs substrate with a quartz wafer held in place by the quartz-SOD-GaAs bond.

Next, the remainder of the circuit fabrication was completed. First, the GaAs outside of the device areas was removed to reveal the SOD layer. The H\textsubscript{2}SO\textsubscript{4}-based wet etch created a 55° slope between the GaAs edge and the SOD and did not attack the GaAs/SOD interface. The SOD was then plasma etched to reveal the surface of the quartz substrate. The thin SiO\textsubscript{2} layer protecting the GaAs anode surface was then etched in buffered oxide etchant (BOE) and a thin layer of Ti/Au was electron beam evaporated over the entire wafer. This thin metal formed the Schottky anode contact as well as a “seed-layer” to allow the electroplating of the metal circuitry. Photoresist was then applied to the wafer and the diode fingers and microstrip circuitry were defined and plated through the photoresist [14]. After plating and photoresist removal, an RIE process followed by a brief wet etch removed the thin evaporated metals from areas outside of the fingers, contact pads and circuit lines. The surface channel was then etched to form a low parasitic air bridge under the fingers and a plasma etch removed the SOD from the surface channel area. In the final devices, shown in Fig. 2, the only remaining SOD is sandwiched beneath the small device pads.

To complete the process, the wafer was mounted face down in wax on a silicon carrier and the quartz substrate was chemically thinned to the design thickness of 38 µm and diced into individual circuits. An SEM view of a typical circuit after dicing is shown in Fig. 2. The I-V quality and uniformity are excellent and consistent with our typical devices fabricated on GaAs substrates with electroplated platinum anodes.
Fig. 2: GaAs on quartz mixer circuits. Left: The quartz wafer showing an array of circuit designs. The only GaAs is a 3 \( \mu \)m layer below the metal pads on the center strip. Right: A diced circuit showing the finger airbridge. These mixers have yielded record performance and repeatability at 585 GHz.

MASTER MIXER PERFORMANCE

The design for the 585 GHz integrated circuits was based upon the discrete diode waveguide mixer discussed earlier [8]. The circuit design parameters were selected using Sonnet, an electromagnetic field simulator, and Hewlett Packard’s Microwave Design System (MDS). Initial RF testing of the mixers was performed in UVA’s Far Infrared Receiver Laboratory. The LO source was a CO\(_2\) pumped FIR laser. The waveguide block, mixer assembly, and RF test setup are explained in the literature [8,9]. However, in the case of the integrated devices, the diode mounting only requires placing the mixer circuit in the block, butting the waveguide probe against the input waveguide, and attaching two bond wires. Table I summarizes the results and includes state-of-the-art measurements from the literature for comparison [15,16,17]. This data clearly indicates that the new integrated mixers are among the best ever tested in this frequency range. This is achieved without whisker contacts, with no handling or soldering of discrete chips and with no mechanical tuners. Also, we have assembled three mixers that all yielded identical results (+/- 10%), showing a high level of repeatability.

FUTURE DIRECTIONS

This GaAs-on-dielectric integration process can be adapted to a wide range of new submillimeter-wave components. Our next goal is to use this technology to develop highly integrated frequency multipliers. For low power applications we plan to integrate both Schottky and heterostructure-barrier varactor diodes with additional circuitry, including bias capacitors, integrated tuning inductors, microstrip filters and waveguide probes. For higher powers, we are pursuing the integration of frequency multipliers on high thermal conductivity substrates. This is important to minimize thermal effects that reduce electron mobility and can limit device lifetime.
### TABLE I: SCHOTTKY MIXER PERFORMANCE IN THE 500 - 700 GHz RANGE

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>Device Technology</th>
<th>(T_{\text{sys}}) (K)</th>
<th>(T_{\text{mix}}) (K)</th>
<th>(L_{\text{mix}}) (dB)</th>
<th>(P_{\text{LO}}) (mW)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>557</td>
<td>Whisker-contacted, mech. tuners</td>
<td>1600</td>
<td>1200</td>
<td>8.0</td>
<td>-</td>
<td>[15]</td>
</tr>
<tr>
<td>585</td>
<td>MASTER, fixed-tuned</td>
<td>1631</td>
<td>1135</td>
<td>6.6</td>
<td>1.74</td>
<td>this work</td>
</tr>
<tr>
<td>585</td>
<td>MASTER, fixed-tuned</td>
<td>1799</td>
<td>1341</td>
<td>6.7</td>
<td>0.35</td>
<td>this work</td>
</tr>
<tr>
<td>585</td>
<td>MASTER, fixed-tuned @ 77K</td>
<td>970</td>
<td>880</td>
<td>7.2</td>
<td>-</td>
<td>this work</td>
</tr>
<tr>
<td>585</td>
<td>Discrete planar, fixed-tuned</td>
<td>2380</td>
<td>1800</td>
<td>7.6</td>
<td>1.16</td>
<td>[8]</td>
</tr>
<tr>
<td>640</td>
<td>QUID integrated, mech. tuners</td>
<td>2720</td>
<td>1636</td>
<td>7.9</td>
<td>0.35</td>
<td>[16]</td>
</tr>
<tr>
<td>640</td>
<td>QUID integrated, mech. tuners, subharmonic</td>
<td>-</td>
<td>2500</td>
<td>9.0</td>
<td>3.5-3.8</td>
<td>[17]</td>
</tr>
<tr>
<td>640</td>
<td>MASTER, mech. tuners, subharmonic</td>
<td>-</td>
<td>2396</td>
<td>11</td>
<td>4.7</td>
<td>[10]</td>
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<tr>
<td>650</td>
<td>Whisker-contacted, mech. tuners @ 77K</td>
<td>1750</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[15]</td>
</tr>
<tr>
<td>690</td>
<td>Discrete planar, fixed-tuned</td>
<td>2970</td>
<td>2240</td>
<td>8.8</td>
<td>1.0</td>
<td>[8]</td>
</tr>
</tbody>
</table>

**Notes:** All results are fundamental mixers at room temperature except as noted.

### CONCLUSION

The GaAs-on-dielectric integration technology described in this paper yields low-noise submillimeter-wave mixers which are easy to assemble and repeatable. Also, the simplified and precise circuit geometry allows CAD tools to accurately predict circuit performance. This will lead to circuit designs with improved efficiency and greater bandwidths. This technology is readily extended to other circuits such as balanced and subharmonically pumped mixers and multipliers for frequencies extending through several terahertz. It is also amenable to the incorporation of additional passive structures such as resistors, capacitors and inductors, as well as beam-leads to replace bond wires. Thus, this new integration technology will make possible the development of high-performance, low-cost and reliable submillimeter-wave integrated circuits for the wide range of scientific, military and commercial applications that is now envisioned.

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