A Wafer-Level Diamond Bonding Process to Improve Power Handling Capability of Submillimeter-Wave Schottky Diode Frequency Multipliers

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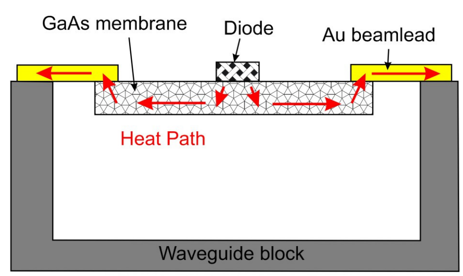
***Abstract* — We have developed a robust wafer-level substrate bonding process that has allowed us to bond CVD diamond to GaAs membrane-based submillimeter-wave Schottky diode frequency multipliers. The high thermal conductivity of CVD diamond allows the chip to dissipate heat more efficiently thus increasing the power handling capability of the chips. This process has resulted in single-chip multiplier devices working in the submillimeter-wave range that can handle hundreds of milliwatts of input power. Output powers of 40 mW at 250 GHz and 27 mW at 300 GHz from a single chip have been demonstrated with this method. It is expected that by power combining these chips it is now possible to achieve a wideband 300 GHz signal with more than 100 mW of power. This represents a dramatic improvement in the current state of the art and allows one to begin realizing submillimeter-wave radar applications.**

***Index Terms* — Submillimeter wave, GaAs Schottky diode, diamond, heat-spreader, THz source, frequency multiplier.**

I. Introduction

The planar GaAs Schottky diode frequency multiplier is a critical component for the local oscillator (LO) for submillimeter wave heterodyne receivers. They provide low mass, electronic tunability, broad bandwidth, long life time, and room temperature operation. The use of a W-band (75 GHz – 110 GHz) power amplifier followed by one or more frequency multiplier is the most common implementation of submillimeter-wave sources from 200 GHz to 2000 GHz. Recently, W-band GaN-based MMIC power amplifiers and power-combined GaAs power amplifiers have provided the possibility of generating watt level powers at W-band [2-3]. As more power at W-band is available to the multipliers, the power handling capability of multipliers becomes more important. High operating temperature due to the high input power leads to degradation of conversion efficiency or catastrophic failure [4]. A number of techniques to increase power handling such as increasing the number of anodes per chip and power combining chips have already been implemented in our current designs [5]. However, temperature rise for a given input power is directly proportional to the Schottky diode-to-block thermal resistance. Thus, we need to reduce the thermal resistance in order to reduce the operating temperature.

The goal of the technique presented here is to reduce the thermal resistance by attaching the diamond film as a heat-spreader on the backside of multipliers in order to improve the power handling of the submillimeter wave frequency multipliers. The thermal analysis, diamond etching process, microfabrication, and submillimeter-wave measurement results will be presented.



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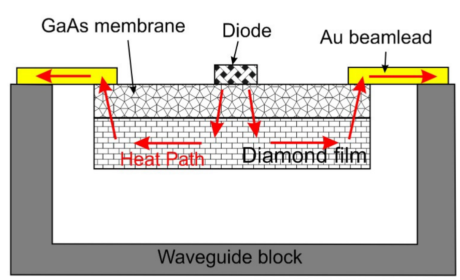

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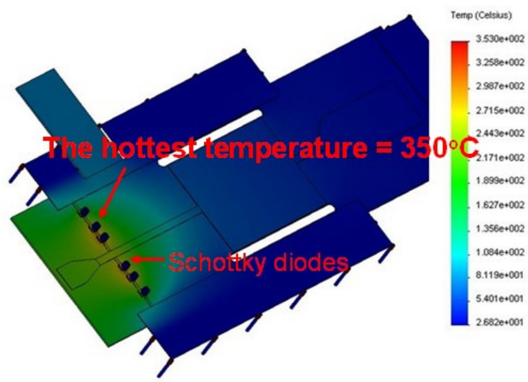
Figure 1. Simplified schematic view (not to scale). (a) Heat laterally transfers through GaAs membrane (thermal conductivity=46 W/m·K) to heat sink. (b) Heat laterally transfers through the diamond film (thermal conductivity = 1000-1200 W/m·K) to heat sink.

II. Thermal analysis

Figure 1 (a) shows the nominal schematic view of the 300 GHz tripler as placed on the bottom half of the split waveguide block. The heat generated at the anode transfers along the few micronmeters thick GaAs membrane and gold beamlead to the waveguide block, which is a heat sink. The thermal conductivity of GaAs is approximately 46 W/m·K and this thermal conductivity value decreases as the temperature increases. Figure 1 (b) shows the proposed schematic view of the 300 GHz tripler bonded with a diamond film on the backside of the tripler to remove the heat more efficiently. The polycrystalline diamond film works as a heat spreader which removes the heat by thermal conduction to a heat sink. In this structure, the heat goes to the diamond film and then transfers through the diamond film laterally and goes back to the gold beamlead and waveguide block. The thermal conductivity of a diamond is 1000-1200 W/m·K and is 20 times greater than GaAs (46 W/m·K). Since the thermal resistance of the chip with diamond film is about 3 times smaller, it reduces the maximum temperature by a similar factor. We have confirmed the chip temperature profile with thermal simulations as depicted in Figure 2. The diode area is the hottest spot and the diamond film can reduce this approximately by 200 °C according to the thermal simulation.



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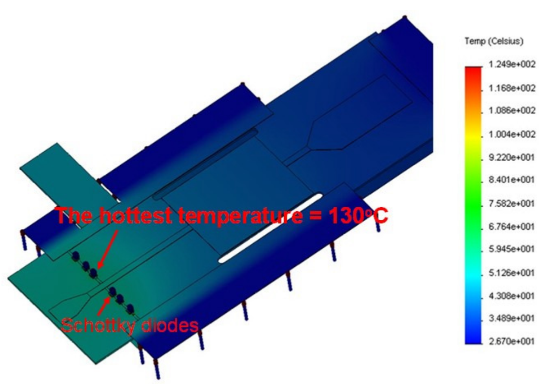

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Figure 2. FEM thermal simulation results for 300 GHz tripler with 250 mW input power. Since the device is enclosed in a block, there is no airflow resulting in negligible convection. (a) Without the diamond heat-spreader, the hottest temperature is about 350°C around Schottky diodes. (b) With the diamond heat-spreader, the hottest temperature drops from 350 °C to 125 °C.

III. Microfabrication Technology

A. Diamond Etching Process

Polycrystalline diamond deposited by hot-filament chemical vapor deposition (CVD) has been selected as the material for providing thermal management due to the high thermal conductivity (1000-1200 W/m·K), which is approximately 2.5 times greater than copper (401 W/m·K) and 20 times greater than GaAs (46 W/m·K). It is an electrical insulator (resistivity = 10^{15} Ω/cm) and has a moderate relative dielectric constant of 5.7. Because it is the hardest material known and it is chemically inert, it is extremely difficult to pattern the diamond, especially thick films. The etch rate of diamond in oxygen plasma is typically about 300 nm/min [6]. In order to improve the etch rate, the RF power, the gas flow, chamber pressure, and the bias voltage have been investigated in inductively coupled plasma (ICP) RIE. Figure 3 shows the etch rate as a function of microwave power. The etch rate increases linearly with increasing microwave power in the range of 600-1000 W. This is due to an increase in the amount of the oxygen radicals that can reach the diamond film surface. The highest etch rate is 850 nm/min. However, to avoid overheating of the sample, an etch rate of 550 nm/min has been used. The selectivity between diamond and nickel used as an etch mask is about 60:1.

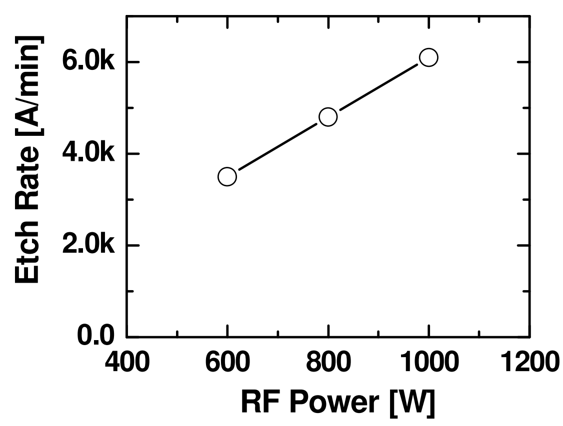
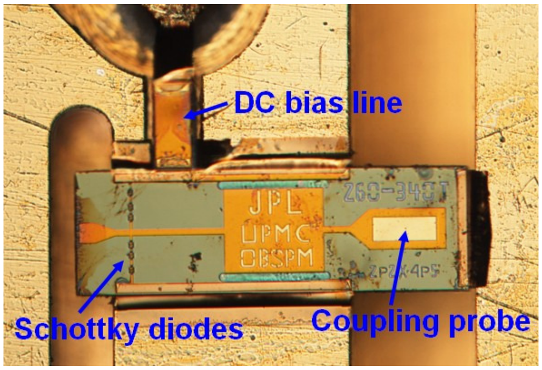


Figure 3. Diamond film etch rate versus RF power. Bias voltage was 150 V and chamber pressure was 2.5 mTorr.

B. Microfabrication

JPL's Monolithic Membrane-Diode (MOMeD) process that results in extremely low parasitic Schottky diode chips has been discussed previously [7]. The frontside processing forms the Schottky diode, RF components and on-chip capacitors.

The backside processing is used to remove the substrate and enable chips that are made on a very thin layer of GaAs to improve RF tuning. We have modified the backside processing sequence to allow us to mount the membrane to a CVD diamond substrate. The diamond is patterned using nickel and etched via an ICP RIE system. The patterning allows us to shape the diamond substrate, keeping the beamleads free for mounting.



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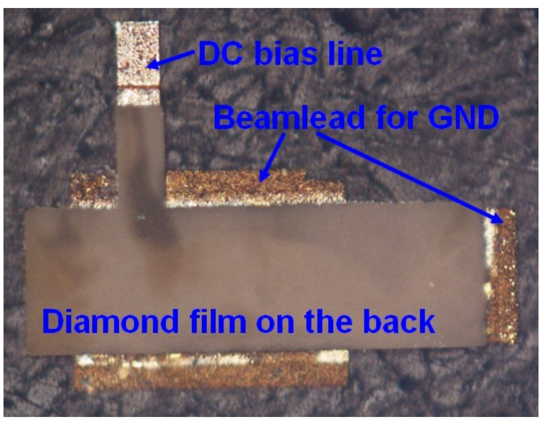

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Figure 4. (a) Front view of the 300 GHz tripler when mounted in one half of the split waveguide block (b) View of the 300 GHz tripler chip showing the diamond film.

IV. RF MEASUREMENTS

The source used to test the triplers was composed of an Agilent synthesizer with a 75-110 GHz millimeter-wave source module followed by a WR10 isolator, one of two power-combined amplifiers to cover either the 92-110 GHz band (for the 300 GHz tripler) or the 75-85 GHz band (for the 250 GHz tripler), a precision rotary dial attenuator, and another WR10 isolator. Each power-combined amplifier is capable of producing up to 350 mW of power in its respective frequency range. The calibration of the input power was made using an Erickson Instruments PM2 waveguide power meter. The output power of the triplers was measured using the same Erickson PM2 power meter with a WR10 to WR4 transition (for 250 GHz measurements) or WR10 to WR3 transition (for 300 GHz measurements) on the power meter's input. The results presented here were not corrected for the transition loss.

For all of the measurements, the power amplifier was kept saturated. The reverse bias voltage of each multiplier was kept above -18 V for input powers below 200 mW and above -15 V for input powers above 200 mW.

A. Power Sweep Comparison

Figure 5 shows the 300 GHz tripler's output power and conversion efficiency measured as a function of input power at 296 GHz. At 200 mW input power, the efficiency was ~9 % for two different triplers, one with diamond and one without. However, above 200 mW the efficiency drops more slowly for the tripler with diamond compared to the tripler without diamond. The output power of the chip without diamond peaks at 22 mW for 300 mW input and thereafter starts to drop fast, whereas with the diamond heat-spreader the output power continues to climb to 27 mW at 408 mW input before saturating. This output power from a single chip is slightly

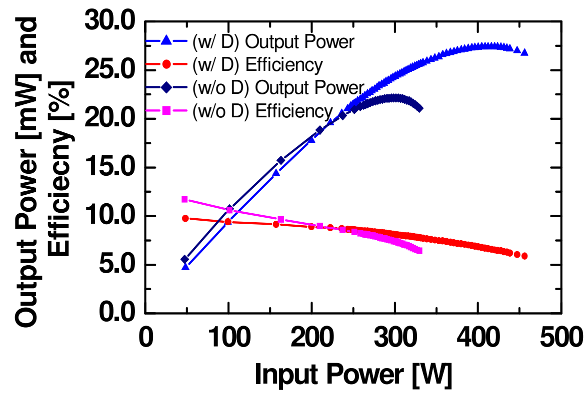


Figure 5. Output power and efficiency measured at 296 GHz versus input power for 300 GHz triplers with and without diamond heat-spreader at room temperature.

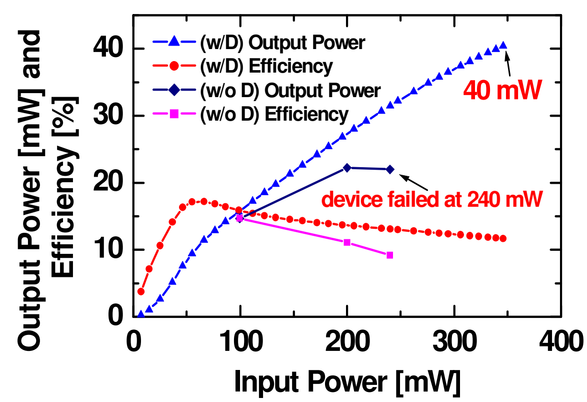


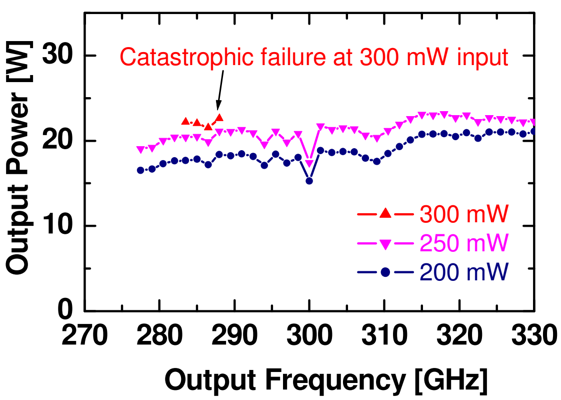
Figure 6. Output power and efficiency measured at 240 GHz versus input power for 250 GHz triplers both with and without diamond heat-spreader at room temperature.

higher than the 26 mW output power from the dual-chip power combiner of [7]. With a dual-chip power combining technique, we are able to produce 54 mW at 300 GHz.

A similar measurement was made for the tripler designed to cover the 235-265 GHz range. For the tripler with diamond heat-spreader, the conversion efficiency remained above 10% even up to 350 mW input for 40 mW of output power from a single multiplier chip. When the same measurement was attempted for the tripler without diamond, we see that the conversion efficiency starts to drop below 10% above 200 mW input. Without a diamond heat spreader, the chip failed at about 240 mW input power.

B. Frequency sweep comparison

Figure 7 shows the output power versus output frequency for the 300 GHz tripler using chips (a) without diamond and (b) with diamond. A frequency sweep was performed using flat input power levels starting at 200 mW and incrementing every 50 mW up to 400 mW. The chip without diamond suffered a



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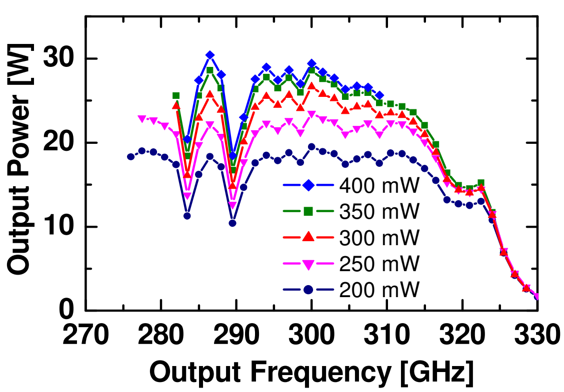

(b)

Figure 7. Output power versus output frequency for the 300 GHz tripler at room temperature. (a) Chip without the diamond heat spreader suffered a catastrophic failure at 300 mW. (b) Output power of the chip with diamond degrades rapidly above 315 GHz.

catastrophic failure at around 300 mW input power. Figure 7 (b) indicates that the diamond seems to have an effect on the frequency response. The output power degrades rapidly above 315 GHz, and there are power suck-outs at some of the lower frequencies.

IV. Conclusions

Diamond heat-spreaders reduce the anode temperatures of submillimeter-wave frequency multipliers by at least 200 ^{o}C at 250 mW input power compared to and identical tripler without diamond, according to thermal simulations. This superior thermal management provides a 100% increase in power handling capability. For example, we have achieved 40 mW output power from the 250 GHz tripler at 350 mW input power and 27 mW output power from the 300 GHz tripler at 408 mW input power, while the triplers without diamond suffered catastrophic failures. Increasing the available power from submillimeter-wave sources is the first step of a larger project to enable future frequency multiplier chains to the 1-3 THz band with greatly increased output power and bandwidth.

Acknowledgement

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