Diamond Heat-Spreaders for Submillimeter-Wave GaAs Schottky Diode Frequency Multipliers

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***Abstract*—We have attached CVD diamond film as a heat-spreader to our existing 250 GHz GaAs Schottky diode frequency tripler chip in o rder to improve its power handling capability. Using this first generation device, we were able to produce 40 mW at 240 GHz from a single frequency tripler with 350 mW input power at room temperature. We have also run finite-element thermal simulations and seen that the 30 µm thick diamond film dropped the temperature of the anodes by about 200° C. This break-through in thermal management increases the output power of frequency multipliers by nearly 100%.**

***Index Terms*—Diamond, Frequency multipliers, Heat-Spreader, THz source.**

I. Introduction

THE planar GaAs Schottky diode frequency multiplier chain is a very good candidate for compact reliable tunable terahertz sources due to low mass, wide electronic tunability, narrow line-width, low noise, and room temperature operation [1]. However, the output power of frequency multiplier chains is relatively low compared to recent quantum cascade laser (QCL) results in the 2-3 THz band [2]. Frequency multipliers are cascaded in chains to create terahertz sources. Thus, in order to generate high power at the output in the 2-3 THz range, we need to have high driving power in the first stage of the chain, typically in the 200 to 400 GHz range. In order to increase the power handling capability and output power, the doping concentration of the Schottky contact can be adjusted to increase the breakdown voltage, or the number of anodes per multiplier chip can be increased [3]. However, due to thermal issues the most promising technique to increase output power has been to power-combine two or more parallel stages. For example, the power available at 300 GHz can be doubled by using a 300 GHz dual-chip power combiner [4].

Currently, up to 800 mW of continuous-wave (CW) tunable W-band power is available by four-way power combining MMIC amplifier chips at W-band [5]. However, current-generation submillimeter-wave frequency multipliers cannot handle the input power of 800 mW due to thermal management problems. Therefore, we propose to use a diamond film as a heat-spreader in order to remove the heat more efficiently, resulting in increased power handling and output power.

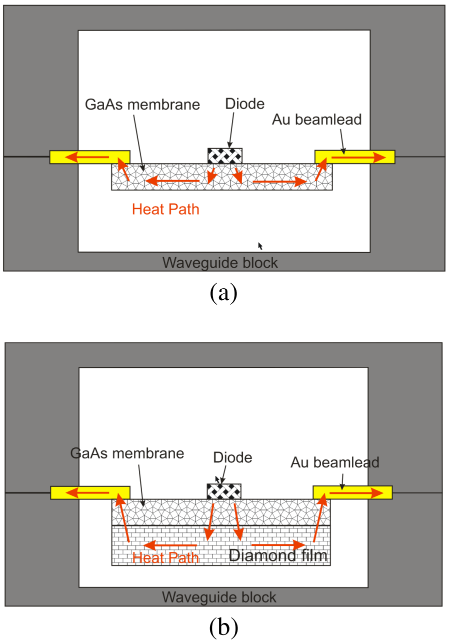

Figure 1. Simplified schematic view (not to scale). (a) Heat laterally transfers through GaAs membrane (thermal conductivity=46 W/m·K) to heat sink. (b) Heat laterally transfers through the CVD diamond film (thermal conductivity = 1000-1200 W/m·K) to heat sink.

II. Thermal Analysis

Figure 1 (a) shows the nominal schematic view of the 250 GHz tripler as placed in the split waveguide block. The heat generated at the anode transfers through a few-micrometer thick GaAs membrane and gold beamlead to the waveguide

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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 250 GHz tripler with a diamond film bonded to the backside of the GaAs substrate 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 which is a heat sink. The thermal conductivity of CVD diamond is 1000-1200 W/m·K and is 20 times greater than GaAs (46 W/m·K) and three times higher than silver (430 W/m·K). Since the thermal resistance of the chip is about three times lower with diamond than without, it reduces the maximum temperature rise by a similar factor.

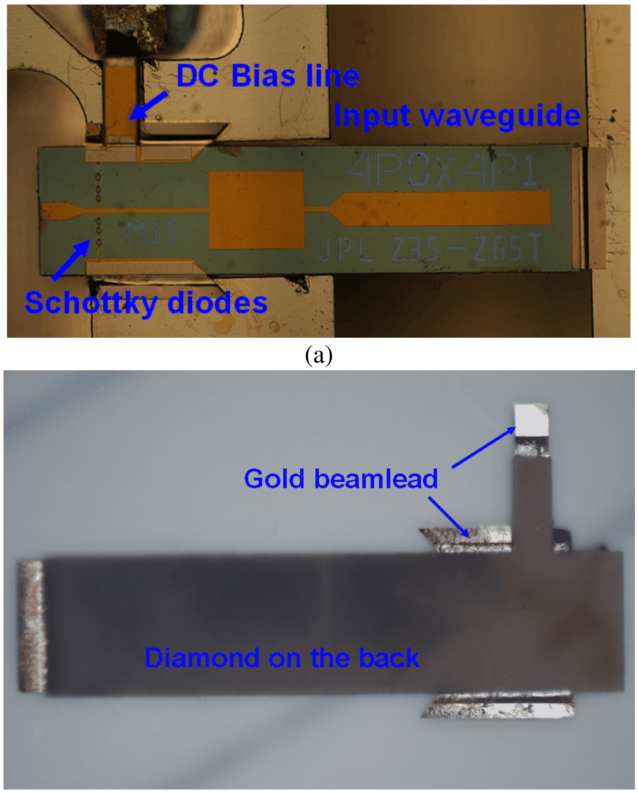
III. Microfabrication

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). 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. In order to etch the thick diamond film, the RF power, the gas flow, chamber pressure, and the bias voltage have been investigated in inductively coupled plasma (ICP) RIE. An etch rate of 550 nm/min has been used.

B. Microfabrication

JPL's Monolithic Membrane-Diode (MOMeD) process that results in extremely low parasitic Schottky diode chips has been discussed previously [6]. 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 a diamond film to the membrane. The diamond is patterned using an Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) system. The patterning of the diamond allows us to shape the diamond substrate, keeping the beamleads free for mounting and DC contacts. Figure 2 shows the front-side view of the 250 GHz tripler. The front-side view is the same as the tripler without the diamond. However, the back-side has the bonded diamond film for removing the heat efficiently.



(a)

(b)

Figure 2. (a) Front view of the 250 GHz tripler when mounted in one half of the split waveguide block. (b) View of the 250 GHz tripler chip showing the diamond film.

IV. Measured Results

Figure 3 shows the measured 250 GHz tripler's output power and conversion efficiency as a function of the input power at 238.8 GHz. At 200 mW input power, the efficiency was approximately 14 % for one with the diamond, and 11% for one without diamond. However, above 200 mW of the input power, the efficiency drops more slowly for the tripler with the diamond compared to the tripler without the diamond. The output power of the tripler without diamond peaks at 22 mW for the input power of 200 mW and thereafter starts to drop rapidly and fails at the input power of 240 mW. However, for the tripler with the diamond heat-spreader, the output power continues to climb as the input power increases. An output power of 40 mW at 350 mW input has been achieved from a single chip without any sign of degradation. In addition, reduction of operation temperature of Schottky diodes can increase the reliability.

Figure 4 shows the output power versus output frequency plot of the 250 GHz tripler for a chip with diamond and a chip without diamond. A frequency sweep was performed using flat input power levels at 100 mW, 200 mW, and 300 mW. The tripler without the diamond suffered a catastrophic failure at about 250 mW input power, and therefore no data was obtained for this chip at 300 mW. As the plot shows, adding the diamond layer improves the output power without degrading the bandwidth.

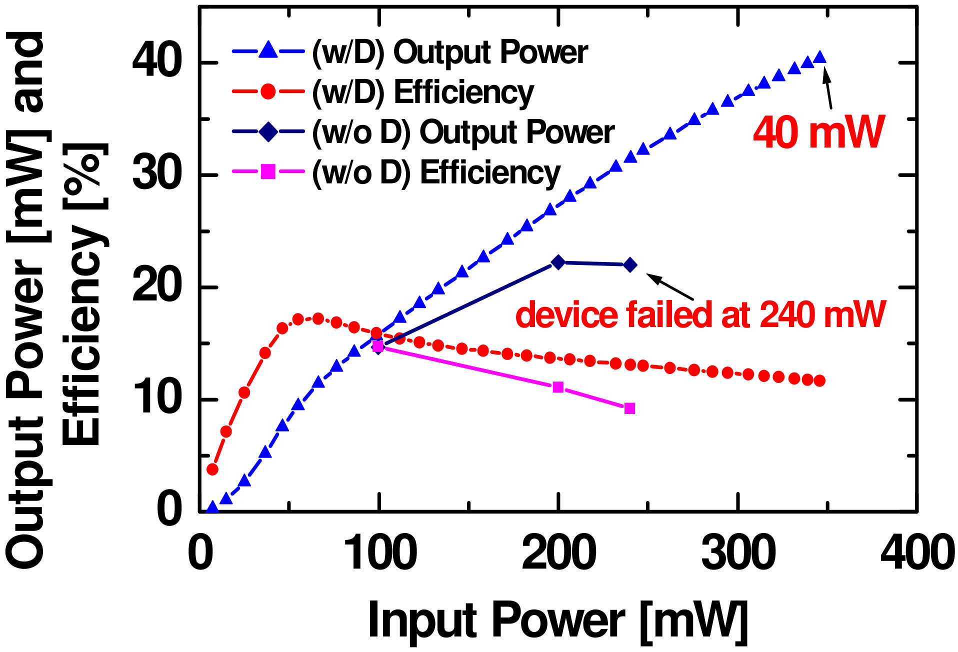


Figure 3. Output power and efficiency versus input power measured at 240 GHz for triplers operated at room temperature both with and without diamond heat-spreaders.

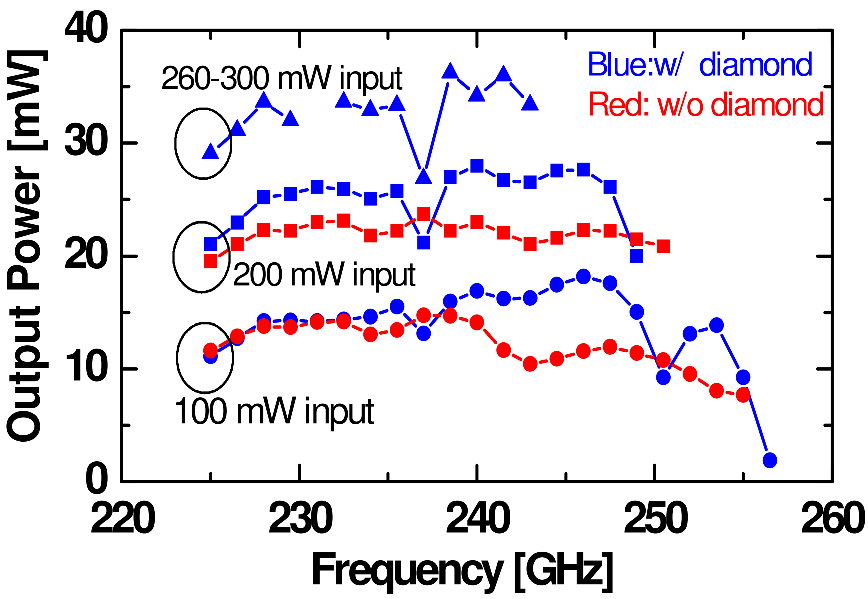


Figure 7. Output power versus output frequency for the 250 GHz tripler at room temperature. Chip without the diamond heat spreader suffered a catastrophic failure at 240 mW input.

V. Conclusion

This superior thermal management achieved with diamond provides a 100% increase in power handling capability. For example, we have achieved 40 mW output power at 240 GHz from a frequency tripler with 350 mW input power, while identical triplers without diamond suffered catastrophic failure at 250 mW input power. Optimizing the Schottky diode chips and waveguide circuits for the presence of the diamond substrate is expected to further increase the achievable output power. This increase in output power in the 250-350 GHz band is expected to increase the usable range of Schottky diode frequency multiplier chains to beyond 3 THz.

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