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THIN FILM CIRCUIT FABRICATION ON DIAMOND SUBSTRATES FOR HIGH POWER APPLICATIONS

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Abstract

Sandia Laboratories has developed a thin film diamond substrate technology to meet the requirements for high power and high density circuits. Processes were developed to metallize, photopattern, laser process, and, package diamond thin film networks which were later assembled into high power multichip modules (MCMs) to test for effectiveness at removing heat. Diamond clearly demonstrated improvement in heat transfer during 20 Watt, strip heating experiments with junction-to-ambient temperature increases of less than 24°C compared to 126°C and 265°C for the aluminum nitride and ceramic versions, respectively.

1. Thin Film Processing on Diamond Substrates

Evaluations were conducted on free standing, polycrystalline, diamond substrates to determine material properties which would influence thin film processes. Physical characteristics such as roughness, camber, thickness, size, etc. will effect both the processes used to define thin film patterns and the circuit elements after completion.

TABLE I. Surface characteristics of diamond vs. alumina substrates.

Substrate Type	R_a Frontside	R_a Backside	Camber
As-Deposited Dia.	4301 Å	> 25 µm	0.320 µm/mm
Polished Diamond	137 Å	1055 Å	0.320 µm/mm
Alumina (As-Fired)	1120 Å	1690 Å	1.800 µm/mm

Bulk characteristics of diamond are well known as a substrate material, but the primary property of high thermal conductivity (~ 1200 W/m·K) is the reason for its

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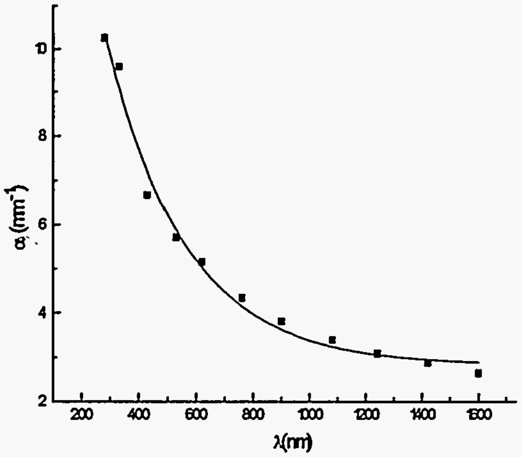

Fig. 1. Absorption Coefficient of Diamond to Nd:YAG Laser Beam.

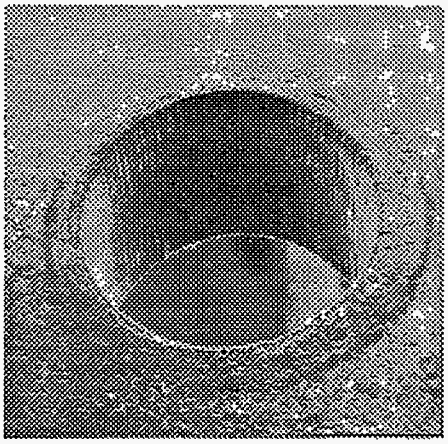

Fig. 2. Hole Drilled (1.5 mm) in Diamond Using Nd:YAG Laser.

increasing popularity for MCM applications. Past hybrid and MCM work at SNL was accomplished on as-fired alumina substrates with thermal conductivity of ~35.6 W/m•K. Profilometer measurements were made to compare surface smoothness and camber of diamond and alumina substrates. Measurements are shown in Table I.

Thin film processing consists of cleaning, vacuum metallizing, resist processing, etching, and stripping operations. Several tests were conducted to determine whether diamond would withstand these chemicals and operations. Results were positive as diamond remained stable when subjected to TFN etchants. Plasma cleaning and air firing of diamond substrates were the first processes where diamond showed any susceptibility to thin film operations. Oxygen plasma cleaning of diamond for one hour showed a small weight reduction (-0.018%). Air firing diamond at 600°C also produced a small weight reduction. However, air firing at 800°C for 60 minutes destroyed the diamond. Diamond weight was reduced by 69.2% and it was verified that diamond will burn up in the presence of oxygen (air) at temperatures over 600°C.

2. Laser Processing of Diamond

Laser machining and resistor trimming on diamond substrates is essential for many hybrid circuit applications. Work was done to determine if laser processing is feasible on diamond and whether it can be accomplished using a Nd:YAG laser. Research into laser beam absorption [1] showed that diamond has a greater absorption coefficient (α) at shorter wavelengths (Fig. 1). When thin film resistors on diamond substrates were laser trimmed, carbon residue created during trimming was shown to create a conductive path which shorted across the resistor trim region. This problem was resolved by defocusing the beam, reducing power, and precisely controlling the table feed of the laser using the fundamental laser wavelength of 1064 nM. Tantalum oxide was thus formed in the trim area and acted in the same manner as ablating the resistor material. Ta_2N resistors trimmed in this manner were found to be stable with time and temperature [1].

A shorter wavelength (532nm) was attempted for laser machining diamond since it absorbs energy more efficiently in this range. A frequency doubled Nd:YAG laser beam produced the shorter wavelength. Using this beam and a specially built optical trepan assembly, it was demonstrated that through-holes having excellent sidewall morphology were produced in diamond up to 0.25 inch thick (Fig. 2).

3. Thin Film Network Fabrication

Thin film networks (TFNs) were fabricated on diamond substrates by sputter deposition of the Ta_2N, Ti, and Pd metallizations followed by pattern plating of 4 μm gold conductors. Ta_2N resistors were then photoprocessed and temperature stabilized as the final operations. Gold wire and ribbon were used to test the bondability and metallization adhesion of the thin film network. One mil diameter gold wire and 1x3 mil gold ribbons were successfully loop bonded to the diamond circuit pads. Destructive pull testing of wire and ribbon loops showed metallization to be both bondable and adherent.

4. Circuit Assembly and Thermal Testing.

Thin film processes described above were used to fabricate TFNs for an edge-cooled, multichip module test circuit [2]. Test circuits were assembled using diamond, aluminum nitride, and alumina TFNs to make a comparison of the thermal efficiency between these substrate materials. Test circuit details are shown in Fig 3. The characteristics of the ATC03 die assembled on the test circuits and their use as heating elements in MCM thermal resistance studies have been discussed previously [3]. In the data presented here, a one dimensional (1D) model was used for thermal calculations on the three substrate types and these calculations were compared to experimental data. Thermal characteristics of the three substrate types were derived by heating the top row of ATC03 die at 5 Watts per die (20 Watts total) and measuring temperatures at the locations shown in Fig. 3. Thermal performance for the different substrates is shown in Fig. 4. The increase in junction

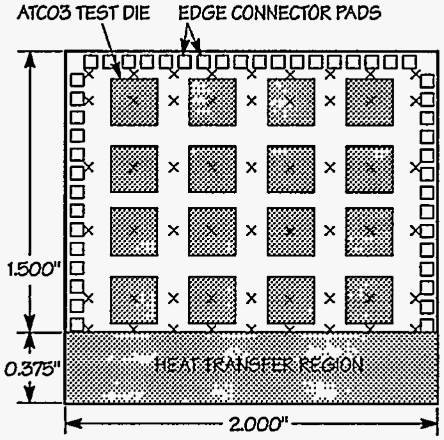

Fig. 3. Edge cooled thermal test circuit for substrate heating tests with fluoroptec temperature measurements taken at X marks.

temperature (ΔT) measured on the heated ATC03 die was 24.3°C for the diamond substrate as compared to 126°C for aluminum nitride and 265°C for alumina. Die junction temperature on the diamond test circuit was significantly lower due to the high thermal conductivity of the diamond substrate. Also, the surrounding substrate temperature remained cooler on the diamond substrate as shown in the thermal images of Fig. 4. A summary of thermal parameter calculations based on experimental measurements of the aluminum nitride and diamond test circuits is shown in Table II. These calculations show the thermal characteristics of diamond as being superior when selecting a TFN and MCM substrate material.

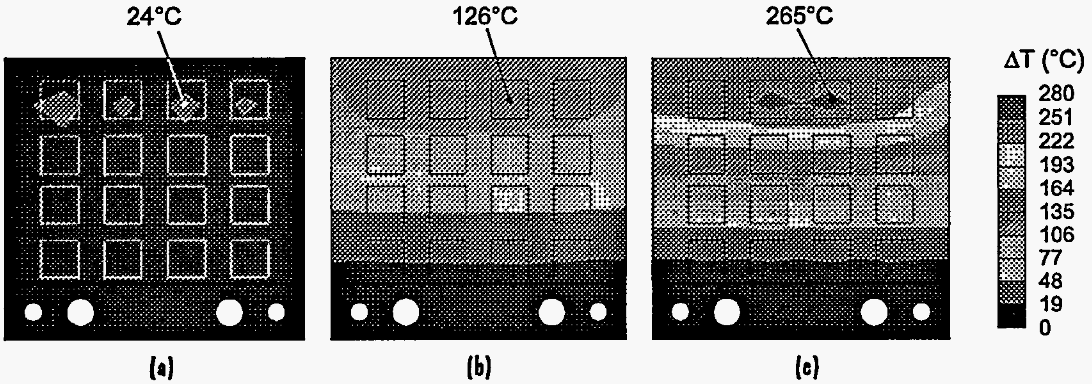

Fig.4. Comparison of thermal performance between (a) 0.0235 in. diamond, (b) 0.0201 in. AlN, and (c) 0.025 in. alumina substrates while heating top row of die with 20 W.

TABLE II. Calculated values of thermal resistance and conductivity of AlN and diamond substrates from measured data.

Substrate Type	Number of Heated Rows	Thermal Resistance (°C/W)	Thermal Conductivity (W/m·K)	Substrate Thickness (mils)
Al Nitride	1	5.79	248	20.1
Diamond	1	0.78	1620	23.5
Diamond	3	0.80	1593	23.5

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