Fabrication of an Inductively Coupled Plasma Antenna in Low Temperature Co-Fired Ceramic

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A miniature electrostatic thruster is being developed in Low Temperature Co-fired Ceramic (LTCC) at Boise State University. The thruster is composed of an antenna to create the plasma, a cylinder to contain the plasma, and grids to extract the plasma beam at high velocity. In this work, the development of the inductively coupled plasma (ICP) antenna in LTCC will be presented. This antenna is fabricated using DuPont 951 LTCC tape. A Direct Write dispenser is used to apply silver paste for the spiral ICP antenna. Using LTCC allows for the antenna to be embedded in the device under a thin sheet of LTCC dielectric, which protects the antenna from ion back bombardment during operation. This thin sheet is the seventh layer of the total device, with the ICP antenna one layer below the top. The design of the antenna is based on the research done by J. Hopwood. This article discusses the fabrication and performance of the ICP antennas in LTCC. These ICP antennas are operated at pressures from 10 mTorr to 1 Torr with radio frequencies (RF) of 500 MHz to 1 GHz to inductively couple with low-pressure argon to produce plasma. The performance of the antennas will be verified with data showing the start and stop power of the plasma at various pressures and an electric field map of the RF field above the antenna.

**Introduction**

Micropropulsion systems are currently being developed to meet a need to position small satellites in orbit as detailed by Yashko and Hastings. A variety of devices are being pursued including electric propulsion-based technologies such as resistojets, microcolloid thruster, and microdischarge plasma thrusters, as well as the more traditional chemical propulsion. In these projects with the exception of Zhang, the device was developed using traditional macro scale fabrication techniques or traditional silicon fabrication techniques including photolithography and deposition. The research that is currently being conducted at Boise State University involves the development of a miniaturized electric propulsion device for controlling microsatellites in space. Previously, BSU has developed a miniaturized hydrogen peroxide-powered chemical monopropellant thruster in ceramic materials. In addition to this research at BSU, a miniature electric thruster is being developed. This device uses an inductively coupled plasma (ICP) source that is fabricated using DuPont Low Temperature Co-fired Ceramic (LTCC) materials. This antenna will be combined with a containment cylinder and plasma extraction grids to form a complete thruster device; however, the scope of this study is limited to the ICP antenna device fabricated in LTCC and not the thruster as a whole or other components such as grids.

Low Temperature Co-fired Ceramic materials technology has been in use for several decades in the production of many different applications including electronic packaging, sensors, and energy systems. Some of these applications include microelectromechanical systems (MEMS) devices because of the advantages of the LTCC mechanical, electrical, and fabrication properties. LTCC materials are robust at high operational temperatures and harsh chemical environments. LTCC is a versatile platform for radio frequency devices due to its stable dielectric constant and loss tangent. Another advantage of LTCC is its low co-firing temperature, which enables the use of thick film metals embedded in the ceramic substrate. LTCC is also capable of reproducing three dimensional (3D) features within the device. With these known advantages, research has been performed in the development of plasma devices using LTCC. A cold plasma generator has been developed in LTCC in previous work at Boise State University. A mesoscale remote plasma generator in LTCC has been developed by the University of São Paulo. A microplasma generator was developed at The Pennsylvania State University by Baker, which uses a capacitively coupled microdischarge.

An ICP antenna generates a plasma by coupling Radio Frequency (RF) waves generated by a flat, spiral circuit through a thin dielectric layer. The RF fields accelerate electrons, which then undergo electron impact ionization with a neutral gas. If sufficient RF power and high enough gas density are maintained, a plasma can be generated. Such antennas are used commonly in semiconductor processing. These processing-based ICP antennas function at relatively low frequency ranges from 1 to 150 MHz. Hopwood has described the miniaturization of planar ICP antenna devices. The Hopwood research demonstrates that functional spiral antenna devices are possible with diameters less than 20 mm.

Electric thrusters are most efficient when a high fraction of the neutral gas is ionized to be used for thrust; therefore, the design and fabrication of the antenna must be optimized to increase this percentage.
and in turn produce more efficient propellant utilization. An effective device should be capable of operating at high temperatures and ionization environments while providing effective RF properties for embedded antennas. Significant research has been conducted in miniaturizing ICP sources by Hopwood, but these sources were fabricated using substrate materials other than LTCC. The Hopwood device was made of copper clad epoxy boards using an etching process for the spiral. Hopwood stated that excessive coil temperature for a helical coil limited plasma operation to a few minutes, while the planar PCB device did not suffer from excessive heat. The LTCC planar device also does not suffer from excessive heating after continuous operation. LTCC is a more effective substrate for RF applications due to a stable dielectric constant ($\varepsilon_r = 7.8$ @ 3 GHz) and low loss tangent ($\tan \delta = 0.006$ @ 3 GHz). Lastly, PCB devices are limited to primarily planar designs, as compared with LTCC devices, which are capable of 3D structures within the substrate, thus providing more design options for fabrication of the antenna, propellant delivery, and other thruster components. Based on a literature review, LTCC appears to be an effective platform for microplasma device development and offers several advantages over traditional microfabrication techniques. In addition, it appears that a miniature ICP device has not been attempted in LTCC. In this work, the design, fabrication, and performance of an ICP antenna in LTCC will be described.

**Design**

The miniature ICP in LTCC device is being developed as the plasma source for an electric microthruster device with a target diameter of 2 cm. To achieve this size, the ICP in LTCC antenna spiral design was based on the successful ICP devices developed by the Hopwood group. The initial LTCC materials-based antenna geometries and dimensions used in this research were based on Hopwood’s designs. At this desired antenna size, a targeted operating frequency near 900 MHz was required. The antenna reactance varies from capacitive to inductive then back to capacitive again over the wide frequency range used in these experiments (500 to 1 GHz). This transition is different from typical ICP antennas, which are designed to be inductive at a single frequency or narrow frequency range. In this proposed design, the antenna circuitry is embedded in a high dielectric constant material, LTCC, which increases the resulting capacitance. The metal is buried in the dielectric, so the capacitance between metal lines of the spiral is enhanced by the large dielectric constant of LTCC. At the high operating frequency near 900 MHz being targeted in this work, the antenna behaves more like an inductor. Based on the initial Hopwood design, various ICP geometries were produced and tested in which the antenna diameter and number of spiral turns were varied. The antenna geometries were then reproduced in the LTCC materials system using the CMEMS design/fabrication process described in a later section.

A total of 24 antenna spiral design configurations were initially developed for fabrication in LTCC materials to determine the feasibility of the concept. The number of spiral turns was varied from three to seven. The spiral pitch was varied from 0.5 to 1 mm. The overall antenna diameter was varied from 5.25 to 18 mm. Finally, devices were fabricated with antenna spirals either exposed directly to the ambient atmosphere or covered with various protective materials including thinner LTCC layers, glass encapsulate (DuPont QQ550), and ceramic paste (Ceramabond 552). The results of this feasibility study are presented in a later section.

A final design configuration was selected based on the results of the device feasibility testing. The spiral antenna described here is five turns with a 1 mm prefired pitch. The device consists of six layers of DuPont 951PX LTCC tape and a spiral antenna embedded beneath a thinner (50.8-μm thick prefired) seventh layer of DuPont 951P2 LTCC tape. Seven LTCC layers were used to obtain an overall device fired thickness of 1.2 mm to match the edge mount SMA connector. The antenna structure is contained in the top three layers of the device. Figure 1 shows an exploded view of the seven layer antenna concept in LTCC. The thinner dielectric top LTCC layer is positioned over the spiral antenna conductor trace to protect the antenna from ion back bombardment and to enhance inductive coupling to the plasma during operation. Protecting the ICP antenna from the generated plasma during operation by embedding the antenna electrode metal illustrates one of the advantages of using LTCC over traditional semiconductor fabrication techniques. The second layer from the top contains the spiral antenna, SMA connection pads, and two electrical vias connecting to circuit elements on layer three. The third layer
contains the circuit return path that connects the spiral antenna to the connection pad, which completes the circuit. In each of the seven layers, a 1 mm diameter (fired) propellant inlet port is positioned at the center of the ICP spiral antenna. This port results in a single 1 mm diameter fluidic via that provides Argon flow through the device and into the region above the ICP antenna. A top-down view of a completed antenna is shown in Fig. 2. The ICP spiral antenna beneath the thin ceramic layer and propellant inlet port at the center of the spiral are clearly visible in this image.

Fabrication

The antennas were fabricated using the standard CMEMS fabrication process as described by DuPont and Plumlee. The designs were prepared for fabrication using a 3D CAD package. Four separate devices were placed on a single 90 mm × 90 mm substrate as shown in Fig. 3. The conductor printing and laser routing patterns for each layer were then extracted from the part file. Six blank layers of DuPont 951PX were prepared for each device. Each individual layer was then routed using a 30 W Universal laser to produce the gas port opening, electrical vias, propellant via, and overall part outline. Each layer was then cleared of any routing residue prior to printing.

Following the laser routing, the spiral antenna was printed using DuPont 6145 silver paste with a fired resistivity of $5.4 \times 10^{-8} \, \Omega \cdot m$. This deposition was performed using an nScrypt 150-3Dn-HP microdispensing pump for 3D printing that is highly accurate in printing and dispensing. This direct write tool was used rather than stencils or hand printing to accurately reproduce the device antenna geometry. Consistency in the spiral trace pitch, width, and thickness are critical for repeatable performance. On each LTCC layer, two reference points were included in the laser routing pattern for aligning the direct write tool. As seen in Fig. 3, one was located in the bottom left corner at 5 mm × 5 mm, and one was in the top right at 85 mm × 85 mm. These reference points were used to align the design pattern with the LTCC sheet to ensure...
that the printed antenna pattern was coordinated with the locations of the electrical vias and propellant inlet port. The direct write was used with a 125 \( \mu \)m tip. Based on post fire measurements, this tip size produced antenna spiral trace widths of 360 \( \pm \) 30 \( \mu \)m width after lamination and firing. The trace thickness was observed to be 57 \( \pm \) 3 \( \mu \)m. Figure 4 shows these dimensions in a cross-sectional image of two traces in the antenna spiral. The thickness of the top LTCC layer was measured to be 35 \( \pm \) 3 \( \mu \)m. The gap measured between the traces of each turn was 540 \( \pm \) 40 \( \mu \)m as shown in Fig. 5. The direct write dispensing width has a precision of \( \pm \) 30 \( \mu \)m for the tip size used.

After the four antennas are printed, the electrical vias, SMA connection pads, and internal circuit connections were installed. These lower precision features were fabricated using stencils and by hand application of the DuPont 6141 paste. The stencils were designed on a 2D CAD program and then laser cut from standard transparency sheets using the Universal laser router. The paste was applied over the open areas of the stencil with a spatula to an even coating. This process is very similar to screen printing, but is instead performed by hand. Both the spiral layer and connection layer were placed in a VWR 1310 convection oven at 70°C to dry the silver paste.

The LTCC layers were then stacked and laminated in a two-step process. To ensure a flat antenna spiral surface, all seven layers were not laminated in one step as per the recommended fabrication process. The convex top of the silver trace would produce an uneven dielectric thickness between the antenna spiral and the surface of the device. To maintain a consistent dielectric thickness, the bottom six layers were stacked and laminated during a first lamination step at 70°C and 1.37 MPa for 5 min, which flattened the upper surfaces of the antenna traces and produced a semi-circular trace cross-section. The thin top layer was then attached in a second lamination step, which was performed at 70°C and 19.2 MPa for 10 min. The thickness and uniformity of the top layer of LTCC can be seen in Fig. 4. After the seven layers were laminated, the un-fired substrate was cut into four separate devices using the laser router. The four devices were then fired using the published LTCC firing profile. The firing profile ramps up to 350°C for binder burn-out then ramps to 850°C for liquid phase sintering; then the device is slowly cooled back to room temperature.

**Performance**

Each antenna device was characterized using a variety of tests. The conductivity of the antenna was first tested to verify if the antenna was functional using an HP multimeter. Via misalignment during fabrication could cause a short circuit in the device. The SMA connector was then attached to the device using a Weller hand-held soldering iron and Kester 44 rosin core solder. The test apparatus and testing procedures were fully described in Browning et al."
pressure of 1 mTorr using a roots type vacuum pump. The antenna device being tested is positioned on a test stand inside the chamber on a Teflon mounting fixture with an internal port to deliver argon to the fluidic port on the LTCC antenna. The laboratory RF system consists of a signal generator, a broadband (400–1000 MHz) 50 W amplifier, isolators, directional couplers with RF power detectors, a matching network, and an RF vacuum feed-through. The argon gas flow is delivered through a mass flow controller capable of providing a flow rate of 0–200 SCCM. The entire setup is controlled using a LabView interface. The ICP antenna and Teflon fixture are shown in Fig. 6. A block diagram of the ICP antenna device, vacuum chamber and test apparatus is shown in Fig. 7. The screen and accelerator grids along with the associated test hardware portrayed on the block diagram are beyond the scope of this study.

For each of the initial feasibility design configurations, the operating frequency was determined by driving the antenna device with an RF source and measuring the forward and reflected powers at 1.0 W and 0.1 W. The devices with the highest forward power to reflected power ratio were considered optimal. The best performing devices were found to be the five turn ×1 mm (prefired) pitch with no protective covering and the five turn ×1 mm (prefired) pitch with an LTCC top layer. Between the two, the device with the protective ceramic layer performed slightly better than without a protective layer. This correlates with the Hopwood results, which found the five turn spiral to be the highest performing device. Based on these results, the five turn, protected antenna with 1 mm pitch was used for the remainder of the tests in this research.

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**Fig. 6.** Plume of plasma discharge above the antenna mounted to a Teflon fixture.

**Fig. 7.** Block diagram of electrical, vacuum, and device set up.
The five turn, protected spiral antenna device was then tested for plasma ignition at a range of operating pressures. The vacuum chamber was evacuated to $10^{-4}$ Torr, and argon was bled in through the propellant port until the desired gas pressure was achieved. Each ICP antenna device was operated at a frequency providing the best impedance match. The RF input power was then swept from 0.0 to 50.0 W until the antenna produced plasma. Figure 6 shows the antenna with a plasma discharge over the surface of the device. If the antenna were able to light a plasma, further tests were then performed at lower pressures.

After confirming that the antenna could initiate plasma, ignition power and extinction power were measured at different frequencies and pressures. This test was performed by setting the pressure and frequency and sweeping through the RF power from 0.0 to 50.0 W. Once the plasma initiated, the ignition power was recorded. The power was then decreased slowly until the plasma was extinguished. This point was called the extinction power. The data were recorded for pressures varying from 150 to 1750 mTorr and frequencies varying from 450 to 1020 MHz. The antenna was impedance matched at each frequency. The best ignition power was seen at a range of pressures from 750 to 1750 mTorr and at 918 MHz, with a value of 4.0 W. This result can be seen in Fig. 8 where the ignition power versus frequency is shown for various pressures. The lowest extinction power was recorded at 900 to 1000 mTorr and a frequency of 918 MHz with a value of 0.2 W.

Antenna performance was also characterized using the measured RF electric field pattern produced spatially above the antenna surface. This test was described in more detail by Browning. The measurement was performed using a coaxial probe positioned 1 mm above the antenna, which then measured the RF electric field amplitude using a spectrum analyzer. The field amplitude was then measured in two dimensions to generate a contour plot as shown in Fig. 9. The fields are normalized to the maximum measured value for this case at 923 MHz. The concentric nature of the field patterns with various peaks around the outer perimeter generated by the antenna is clear in the plot. There is a minimum in the center at the location of the propellant inlet via. The fields were measured at other frequencies and found to decrease in relative amplitude corresponding to the general variation seen in the plasma ignition power data.

The devices were also inspected for cracks and defects. A Sonoscan D24 C-Mode Scanning Acoustic Microscope (C-SAM) was used to image the embedded spiral to detect defects in the substrate and electrodes. This device focuses an ultrasound beam at the test device and then receives reflected pulses. The return time of these reflected pulses is a function of distance and can be used to visualize internal features. Internal defects in the substrate produced during fabrication could potentially cause problems for long-term use due to thermal cycling during operation. Figure 10 shows a close-up of a section of the antenna spiral using the C-SAM. The antenna spiral shows some cosmetic disfiguring on some edges. The bottom right of the image is the gas inlet. Figure 11 shows a top view of the spiral and the return path from a lower magnification to widen the field of view. No apparent defects can be
observed with a reported C-SAM resolution of 7 μm. No degradation of the surface was visibly observed on the surface of the device after hours of continuous operation. Further testing is required, but long-term durability of the LTCC materials system in a plasma environment appears to be promising.

Future Work

Lifetime and LTCC degradation tests are planned for future experiments. The surface erosion stability is an important characteristic of the material needed for ICP antennas because plasma easily sputters away other materials. Degradation of the surface of the antenna would eventually cause failure. The silver spiral would quickly wear away if there was not a protective layer of LTCC on top of it.

Conclusions

The use of LTCC to develop a functional ICP device has been demonstrated. LTCC has been used in other microplasma applications and is being studied as a potential materials system for microelectric thruster fabrication. LTCC allows for the use of 3D features in the form of vias and embedded circuitry. Also even after hours of plasma operation, the surface of the LTCC shows no visible degradation. It was found that the five turn ×1 mm pitch antenna operating at 918 MHz was the most effective design for producing a plasma discharge. At these conditions, the minimum ignition power was found to be 4.0 W and the minimum extinction power was found to be 0.2 W. The 2-step lamination process was able to successfully reproduce the required antenna geometry in an LTCC fabrication process. Through this fabrication process, defects and cracking were found to be minimal and did
not immediately affect performance. Further thermal testing would be required to characterize effectively long-term durability of the design.

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