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Technical Notes

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Demonstration of Microcoil Heaters for Microthrusters

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Nomenclature

A_d	=	cross-sectional area of spring wire
D	=	mean coil diameter
d	=	spring wire diameter
L_w	=	length of spring wire
N	=	no. of coil turns
p	=	coil pitch
R	=	electrical resistance
α	=	coil rise angle
ρ	=	resistivity

I. Introduction

A COLD/HOT gas microthruster etched in silicon is presented that uses three microcoil heaters in series to heat the propellant before it passes through the nozzle [1,2]. At ideal operating conditions the system is designed to give a specific impulse (I_{sp}) of 120 s using nitrogen gas. For the microthrusters to achieve this value the temperature of the gas must be raised from 300 K at the entry plane of the first coil to 1200 K (average gas temperature) at the nozzle inlet. Taking into account heat losses to the surroundings during thrusting, the surface temperature of the coils needs to be 1700 K [2].

An initial study investigating the use of carbon coils made by laser-induced chemical vapor deposition (LCVD) for cold/hot gas microthrusters reported that the coils could be heated in 60 mbar vacuum to temperatures near 1200 K before failing due to erosion caused by oxygen [2]. Later, it was reported that carbon coil surface temperatures were recorded as high as 2100 K in $\sim 10^{-6}$ mbar vacuum and 2200 K in 2 bar N_2 for tungsten-coated carbon coils.

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In this Note, coils of the same type as mentioned above are tested in thermal and environmental conditions that are thought relevant to their expected normal operating conditions. Though the high vacuum found in space is not reproduced for these experiments, the vacuum pressures used were sufficient enough to give useful results. The goal of this Note is to demonstrate for the first time whether or not LCVD-deposited carbon and tungsten-coated carbon microcoils can withstand low to medium-high temperatures for extended periods of time during thermal cycling without showing signs of degradation in relevant atmospheres. These results will then form the baseline for future demonstrations of the 120 s I_{sp} cold/hot gas microthruster operation.

II. Experimental

A. Equipment

A LabView script was written to control the voltage output from a Delta Elektronika SM7020-D power supply. The script also logged a time stamp, the voltage drop across the coil, and the current in the system every 5 s using a Keithley 2000 multimeter. Resistance was calculated using these values. Temperature measurements were manually recorded using a disappearing tungsten-filament pyrometer with accuracy better than ± 10 K.

B. Method

Four carbon coils deposited by LCVD were tested for this experiment: two naked carbon coils and two tungsten-coated carbon coils. The tungsten coating was applied to two of the coils using the LCVD process. For a detailed explanation of the coil fabrication process and the LCVD experimental setup, see [3]. To apply the coating the laser was focused on the outside surface of the coil while it was rotated and drawn downward [2].

One carbon coil and one tungsten-coated coil were resistively heated in $3.3–3.5 \times 10^{-6}$ mbar vacuum. The remaining two coils were heated in 2 bar N_2. Each experiment was 10 h long and consisted of three tests. The first test began with a minimum of five temperature calibrations to determine at which applied voltages the coil surface temperature reached 973 and 1173 K. These voltage values were then used by the LabView script to cycle the coil for 30 s at 973 K and 30 s at 1173 K for 2 h. At the end of the 2 h the coil was burned at the high voltage for an additional 2 h. The second test began, like the first, with a temperature versus applied voltage calibration up to 1173 K. The coil was then cycled for 30 s at 300 K (0–0.1 V) and 30 s at 1173 K for 2 h, and then burned at the high voltage for two more hours. The final test began with the temperature calibration as the first two tests and then the coil was burned at 1173 K for 2 h. Because the surface temperature of the coils could not be measured at temperatures below 973 K with the pyrometer, we cannot say with confidence that the coils did cool to 300 K within the 30 s allotted. Thus, 300 K in this context refers to the target temperature of the coil by passing a minimum voltage across it.

III. Results

Figure 1 shows a mounted tungsten-coated microcoil heater after testing. Tables 1 and 2 list the dimensions of the four coils and the voltages used for the experiments, respectively. Figure 2 shows the resistance versus time plots for the carbon coil heated in 3.5×10^{-6} mbar vacuum for the a) 973–1173 K and b) 300–1173 K cycles.

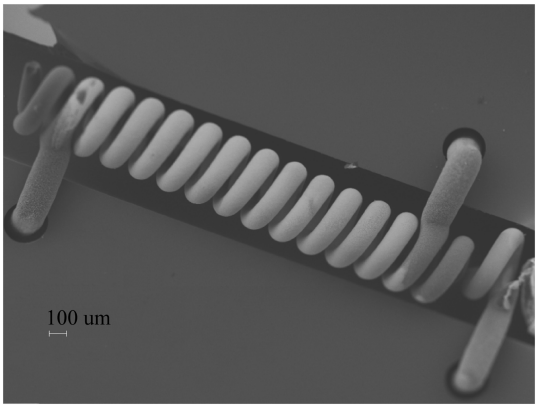

Fig. 1 Tungsten-coated microcoil after operational test in vacuum.

Figures 2c and 2d show the results for the carbon coil in 2 bar N_2 for the same thermal cycles as Figs. 2a and 2b, respectively. Note that the resistance for the higher temperature is the lower of the two series. The irregularities in Fig. 2a are due to short breaks during the experiment to correct communication problems between the computer and the multimeter and were solved within three cycles. Effects caused by these interruptions were considered minor. Data not shown for the carbon coils include the three tests where the coils were burned at 1173 K for 2 h. These data show that the resistance of the coil tested in vacuum decreases steadily to a final value of 164 Ω at the end of the 10 h experiment, while the other coil showed slight fluctuations around 158 Ω.

The plots shown in Fig. 3 are for the tungsten-coated coils and are arranged as those in Fig. 2. Here, the vacuum pressure was 3.3×10^{-6} mbar. During the 300–1173 K test for the vacuum-tested coil the resistance peaked at 49 Ω and then decreased to a final value of 47 Ω. However, for the nitrogen-tested coil, the resistance increased continuously from around 12 to 15 Ω during the experiment.

IV. Discussion

LCVD-deposited coils from the same batch have slight variations in dimensions and these variations increase between batches as listed in Table 1. The two most reproducible dimensions are N and p. The reproducibility of d is ± 5 μm and can exceed ± 17 μm for D. Differences in d and D have significant impacts on the resistance of the coils and are exemplified here. The equation for resistance is given as $R = \rho L_w / A_d$. L_w is calculated by $\pi DN / \cos\alpha$ and α is found from $\arctan(\rho/(\pi D))$. Thus, for coil (a) in Table 1, a 1 μm decrease in d will result in a 3.2% increase in resistance whereas a 1 μm decrease in D will decrease the resistance by 0.7%. This could account for the varying contact resistances between coils often attributed to silver glue and solder used for securing the electrical contacts. Variations in D are only encountered at the manufacturing level and play no dynamic role during operation. On the other hand, it is d that is of special interest for this application because it is known that the presence of oxygen (or other reactants) can erode the surface, thus, increasing the resistance by reducing d [2].

Inspection of the resistance evolution over the operating time shows some general trends. For carbon coils, the resistance generally decreases with increasing temperature and with time (at each operating temperature). These observations are attributed to the negative resistivity coefficient of graphite [4] and the graphitic core of the carbon microcoil is obviously the dominate current conductor of the coil [5].

The slight decrease in the resistance of the carbon coils observed over the duration of these operational tests can be due to an increase in the graphitic core diameter of the coils. It is possible that this region may grow at the expense of the amorphous carbon layer at elevated temperatures. A simple estimation of the magnitude of the diameter change that would be necessary is summarized by the following. Here, resistance versus temperature data for LCVD-deposited carbon coils [5] and the nominal coil dimensions from coil (a) are used. The model coil is assumed to be purely graphitic and shows that a 1 μm decrease in d would increase the resistance by 4 Ω. Thus, it can be said that the resistance change observed in the experiments on carbon coils is consistent with an explanation based on variations in d. It has not been possible to confirm such a small change by inspection, due to the impossible task of inspecting the same cross section before and after the operational test. Instead, one would have to make a statistical selection of cross sections on separate coils from the same batch—one set of sections taken before the tests, and the other after. This can be performed in a future study, but falls outside of the present work.

The tungsten-coated coils show a different behavior. The nitrogen-tested coil (d) has a low initial resistance (~12.5 Ω at 1173 K) compared to the vacuum-tested coil (c) (~47 Ω at 1173 K). This can be attributed to the different coil dimensions, but inspection

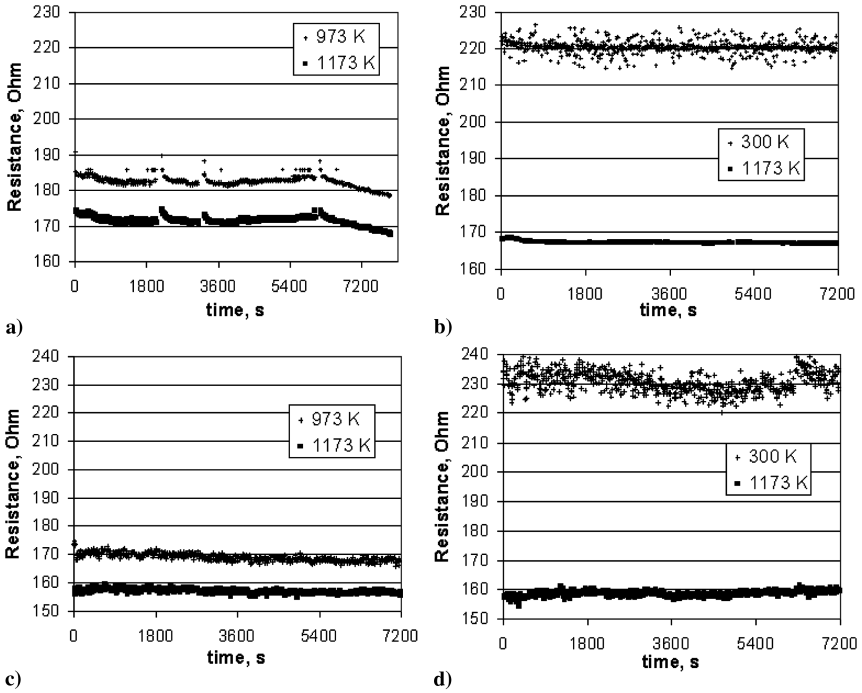

Fig. 2 Thermal cycling data for carbon coils heated in vacuum a), b) and 2 bar N_2 c), d).

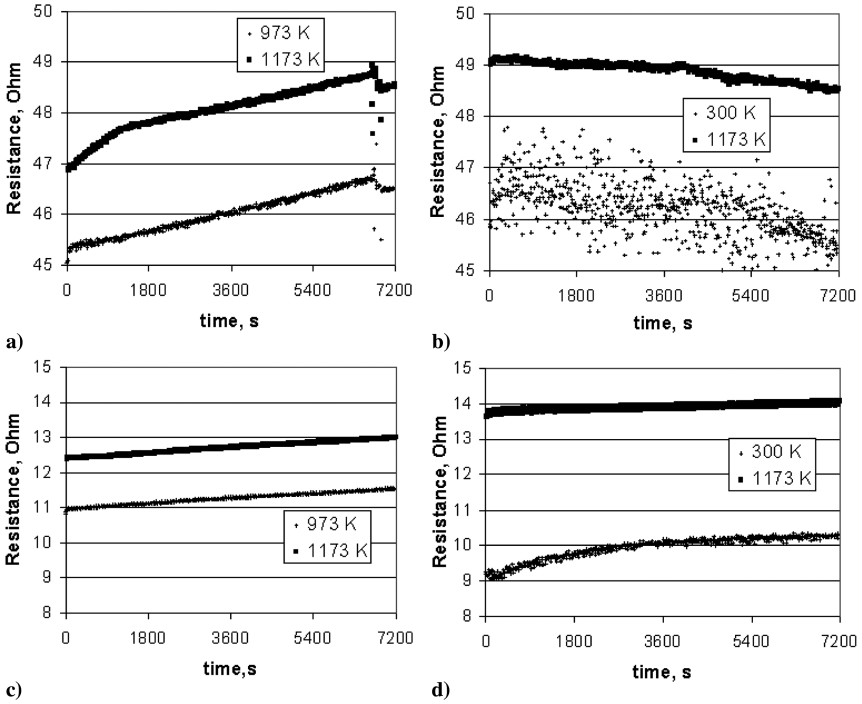

Fig. 3 Thermal cycling data for tungsten-coated carbon coils heated in vacuum a), b) and N_2 c), d).

of these values (Table 1) yields a fourfold difference of the tungsten coating thickness with respect to coil (c) having the thinner coating of the two (assuming that conduction is through the coating). This implies poor control of the tungsten coating thickness. Both tungsten-coated coils show resistance increasing with increasing temperature which supports the assumption that the coating is indeed the major current conductor (positive resistivity coefficient). Both coils also show a steady increase of the resistance in the first two tests but then the nitrogen continues in the same manner whereas in the vacuum test the resistance undergoes a decrease over the remaining portion of the test, passing the maximum in the cycling between room temperature and 1173 K, Fig. 3b.

The initial resistance increase of the tungsten-coated coils can be attributed to a decrease of the effective thickness of the coating. Inspection of the data shows that the total increase is approximately 4% for the vacuum test (before decreasing again) and approximately 20% for the nitrogen test (before the end of that test). The vacuum decrease from the maximum until the end of the test is also approximately 4%—a return to the initial value. These estimates were done for 1173 K.

A 20% increase of coil (d) resistance can—as the current flows primarily through the tungsten coating—be attributed to a loss of 20% of the coating as conductor material (i.e., one-fifth of the thickness). The analogous 4% change of resistance of coil (c) corresponds to 20 times less material lost to the coating (considering that the coating of coil (c) was 4 times thinner than that of coil (d).

Inspection of the coils in question after the test series revealed clearly that significant deposits had formed from and on the nitrogen-tested tungsten-coated coil, although the coating had not entirely disappeared. Moreover, similar deposits had also formed on the silicon walls of the channel. Although nothing like these deposits could be found on the vacuum-tested coil, this coil too had a clearly modified surface where it had been dissipating heat. From the compositional analysis of the materials in vacuum and nitrogen, it is reasonable to conclude that the tungsten coating forms a compound upon extended subjection to nitrogen gas at 1173 K, and that this compound is responsible for the stable resistance increase in coil (d). Although we cannot say from these tests if this deterioration will continue or abate, it can be reasonably assumed that the tungsten coating of coil (d) would be consumed completely in a test 5 times as long as this one. In vacuum, on the other hand, the changes of resistance (up and down) are not dramatic, and nothing suggests that the tungsten coating will not retain its desired function of this environment for extended operation.

Thus, the tungsten coating is judged to be incompatible with nitrogen propellant at 1173 K coil temperature for extended operations, although it may still be applicable for protective coatings should a noble gas be used as the propellant. Furthermore, the operation tests on the carbon microcoil heaters show no significant problems with their use in the environments, that is, nitrogen propellant and 1173 K maximum coil temperature. However, from previous experiments [2,5], we know that trace oxygen in any propellant (that is not extremely clean) can destroy carbon coils operating at higher temperatures. In such a situation, a protective coating would still be needed.

Table 1 Coil geometry summary after heating

Coil	D, μm	d, μm	p, μm	α, rad	N	L_w, μm
(a)	151	63	2.5	0.1692	12.5	6012
(b)	152	60	2.5	0.1701	12.5	6053
(c)	144	62	805	0.1858	12.5	5751
(d)	182	71	23.5	0.1408	12.5	7214

V. Conclusions

The resilience and performance of carbon microcoil heaters made by laser-induced chemical vapor deposition to be used as an efficient means for increasing the specific impulse of cold/hot gas

Table 2 Voltages applied to the coils during tests. Values are in volts

Coil		Cycle 973–1173 K	Constant 1173 K	Cycle 300–1173 K	Constant 1173 K	Constant 1173 K
(a)	V_{lo}	3.7	——	0.1	——	——
	V_{hi}	4.7	4.3	4.3	4.3	4.2
(b)	V_{lo}	8.9	——	0.1	——	——
	V_{hi}	10.1	10.1	10.1	10.1	10.1
(c)	V_{lo}	1.8	——	0.1	——	——
	V_{hi}	2.4	2.4	2.2	2.2	2.2
(d)	V_{lo}	2.7	——	0.2	——	——
	V_{hi}	3.5	3.5	3.5	3.5	3.6

microthrusters are investigated. Carbon coils with and without a protective tungsten coating are compared by testing them under conditions chosen to be representative of their operational environment. These conditions include thermal cycling between 300–1173 K and 973–1173 K for 2 h durations in $\sim 3 \times 10^{-6}$ mbar and 2 bar N_2. The results suggest that at these temperatures, carbon microcoils and nitrogen propellant are compatible, while tungsten-coated carbon microcoils show signs of degradation. However, for higher temperature applications, the tungsten-coated heater can possibly be used if the propellant (nitrogen) is replaced by a noble gas. Otherwise, a more resilient refractory coating must be found.

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