

Cathode Spot Movement in Vacuum Arc Using Silicon Cathode

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Abstract: This paper examines challenges related to the use of silicon (Si) as the cathode in a vacuum arc thruster, specifically the low mobility of silicon cathode spots. Results of experiments using two electric leads to the cathode vice one are discussed and show that the location of the cathode spot concentration can be moved by using a second lead. Mass consumption was also found to increase with a second lead. This could have significant implications for a new proposed concept for end-of-life maneuvers for cubesats, whereby the silicon solar arrays are used as the cathode.

Nomenclature

B	= magnetic field
J	= electric field

I. Introduction

Current standard debris mitigation practices dictate spacecraft be moved to a disposal orbit at the end of their operational life. For satellites in low Earth orbit (LEO) this generally requires lowering the spacecraft to an altitude that will allow for atmospheric reentry within twenty-five years. For cubesats this altitude is approximately 600 km. At present this means that satellites at higher LEO orbits must be designed and built with a propulsion system, and they must retain sufficient propellant to perform an end-of-life maneuver. This poses a problem for cubesats, which, due to restrictions on the use of pressurized tanks and challenges with component miniaturization, do not typically have propulsion systems. One possible solution would be for the satellite to use an electric propulsion system such as a vacuum arc thruster. Further mass savings could be realized if, instead of using a dedicated propellant for the end-of-life maneuver, the satellite used its own structure as propellant. Vacuum arc thrusters use a solid metallic cathode for their propellant. Therefore, the structural material of the satellite theoretically provides a ready source of propellant. The exteriors of cubesats are generally composed of body-fixed solar arrays, typically composed of silicon. However, silicon poses unique challenges for generating a vacuum arc. In particular, the cathode spots generally have very low mobility. This could cause problems with non-uniform erosion of the cathode. Two methods for controlling cathode spot motion are the introduction of a magnetic field and relocating the negative lead on the cathode. Experiments were conducted using the second technique. It was found that the location of the cathode spots on a silicon cathode could be moved using a second electric lead. Mass consumption was also increased by using a second lead.

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II. Self-Consuming Satellite

A. Debris Mitigation Guidelines

The motivation for this work is a new concept for performing end-of-life maneuvers for cubesats. When cubesats are launched they are manifested as secondary or auxiliary payloads. To protect the integrity of the primary payload the use of pressurized systems on cubesats is limited, pyrotechnics are largely restricted, and toxic or corrosive materials such as certain propellants are discouraged. For these reasons, and because of difficulties involved with the miniaturization of propulsion system components, cubesats are normally not built with a propulsion system.

Under international debris mitigation guidelines^{1,2} spacecraft in LEO should be left in an orbit in which natural forces lead to atmospheric reentry within a reasonable time (generally twenty-five years). Consequently, upon completion of their mission cubesats are left in orbits that slowly decay due to the effects of atmospheric drag. This restricts cubesats to circular orbits of approximately 600 km or lower, greatly limiting their utility. If a cubesat were capable of performing an orbit lowering maneuver at the end of its operational life, it could be launched into and perform its mission at a higher altitude, thereby increasing the types of missions it could perform.

B. End-of-Life Maneuver

To add a propulsion system to a cubesat for the purpose of performing an end-of-life maneuver, the challenges identified above (no corrosive propellants or pressurized tanks, etc.) must be addressed. In addition, cubesats are limited to a 10 cm x 10 cm x 10 cm volume and 1.33 kg mass per unit. Adding a propulsion system, including propellant, reduces the mass and volume available to the payload and other subsystems.

Mass and volume savings could be realized if the spacecraft structure were used as the propellant. After the completion of the satellite mission the structure could be consumed to provide the necessary thrust to lower the satellite orbit in order to meet debris mitigation guidelines. Vacuum arc thrusters use a metallic cathode as their propellant. In addition, the exterior surfaces of cubesats are typically composed of body-fixed solar arrays. The solar cells in these arrays are frequently composed of silicon. If a cubesat could be built with a vacuum arc propulsion system that uses the silicon solar cells as the propellant, the satellite could operate at higher than normal altitudes and still meet debris mitigation guidelines by performing an end-of-life maneuver.

Ideally the cells within the solar array could be packed in such a way that the substrate material could be used as the anode in the vacuum arc. Alternatively anode material could be distributed throughout the array. "Thruster" firings would need to be executed in pairs (Fig.1) to prevent the introduction of a rotation moment. A drawback of this approach is that the satellite is consuming the power source needed to generate the arc. Further study is necessary to determine whether sufficient impulse can be generated by this system before power falls below a minimum level.

C. Vacuum Arcs Using a Silicon Cathode

A vacuum arc is an electrical discharge that occurs in the plasma ejected from micron-sized luminous areas on the cathode surface called cathode spots³. At high voltage cathode heating and breakdown occur, generating a quasi-neutral plasma that is ejected at high velocity from the cathode spot. It is the ejection of this material that provides the thrust from a vacuum arc thruster.

In most metal materials the cathode spots displace themselves chaotically on the surface of the cathode⁴. However, because silicon is a metalloid and a semiconductor cathode spots cluster in a small region and do not move across the cathode. This can result in non-uniform erosion of the cathode. To avoid this a magnetic field can be introduced, which will induce spot mobility in a retrograde direction, $B \times J$ ⁵. However, this magnetic field might interfere with the attitude control system on the spacecraft if magnetometers and magnetic torquers are used. An alternative method would be to sequentially use multiple electric leads to the cathode to induce motion in the cathode spots. The latter method was investigated, and the results reported below.

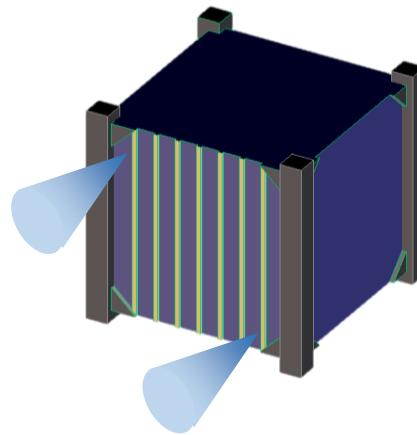


Figure 1. Concept for self-consuming satellite.

Silicon solar cells are used as the cathode in a vacuum arc propulsion system.

III. Experiment

A. Setup

Two experiments were performed using flat plate arc sources in a vacuum chamber. Both arc sources used a silicon cathode and steel anode separated by a boron nitride insulator of approximately 1 mm and coated with carbon paint. The cathode in the first experiment had a single electric lead, whereas the cathode in the second experiment had two leads, as shown in Fig. 2. In the second experiment the arc was initiated in one lead, then switched to the other lead for the duration of the experiment. Both experiments were run for approximately 130 minutes at 38 pulses per minute. This resulted in approximately 5,000 pulses in each experiment.

B. Results

Figure 3 shows photographs of the two silicon cathodes used after the experiments were run. A single region of cathode spot erosion is evident in the cathode used in the first experiment using a single cathode. Two cathode spot regions can be seen in the cathode used in the second experiment where two negative leads were used. The region in the upper left corner is where the arc originated when the first lead was used, and second, larger region in the middle of the upper edge of the cathode is where the arc appeared when the second lead was used instead. The color differences between the two cathodes is a result of lighting conditions.

Figure 4 shows before and after images of the cathode used in the first experiment taken using a scanning electron microscope. Features seen in both images are circled in red, and the region of erosion is circled in yellow. The arc appears to have initially been generated at the location of some impurities in the material.

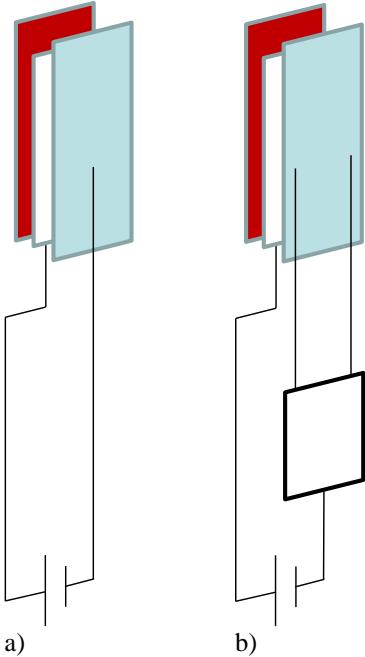


Figure 2. Arc source configuration.
A single lead a) was used to the cathode in the first experiment, and two leads b) were used in the second experiment.

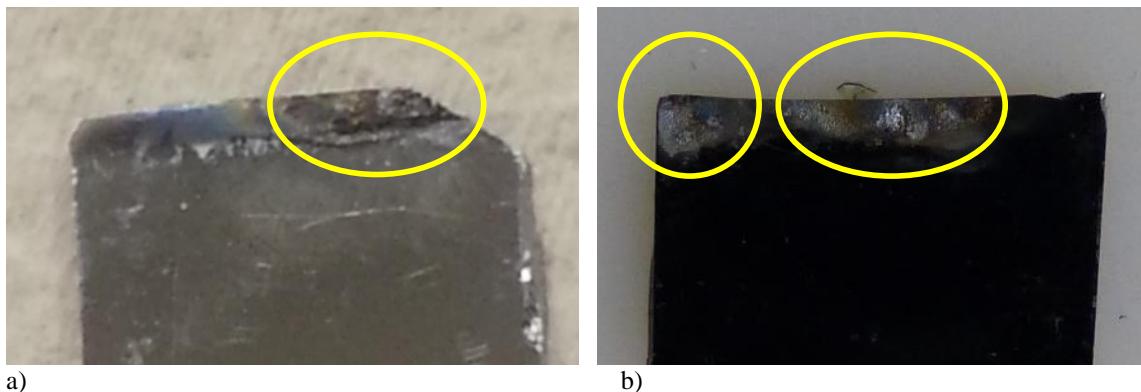


Figure 3. Photographs of silicon cathodes following experiment.

The cathode used in the first experiment a) shows a single isolated region of erosion, whereas the cathode used in the second experiment b) shows two separate spot regions.

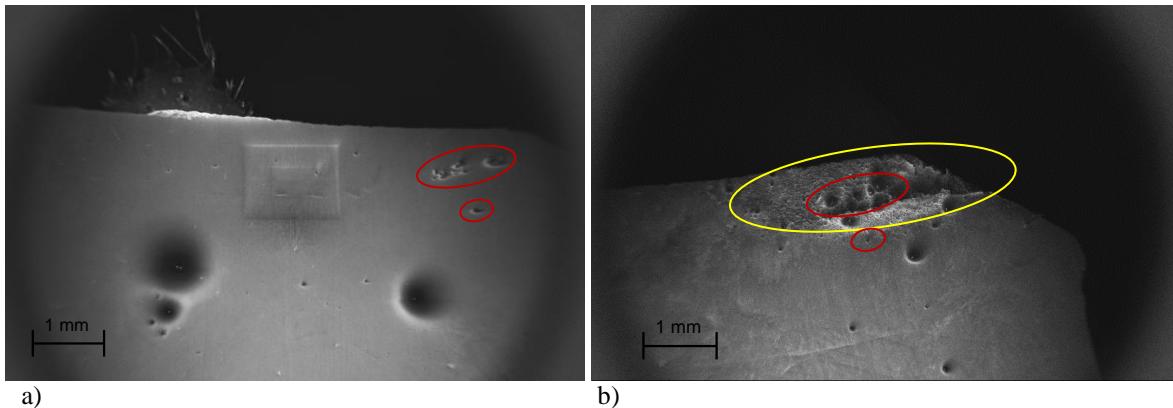


Figure 4. Silicon cathode from single lead experiment.

Images of the single lead silicon cathode from the first experiment taken a) before and b) after the experiment using a scanning electron microscope. Common features are circled in red, and the cathode spot region is circled in yellow.

Figure 5 shows before and after images of the cathode used in the second experiment taken using a scanning electron microscope. Features seen in both images are again circled in red, and the regions of erosion are circled in yellow. As stated previously, the region in the upper left corner is where the arc originated when the first lead was used, and the second, larger region in the middle of the upper edge of the cathode is where the arc appeared when the second lead was used instead. Significant melting is evident at the edges of this region.

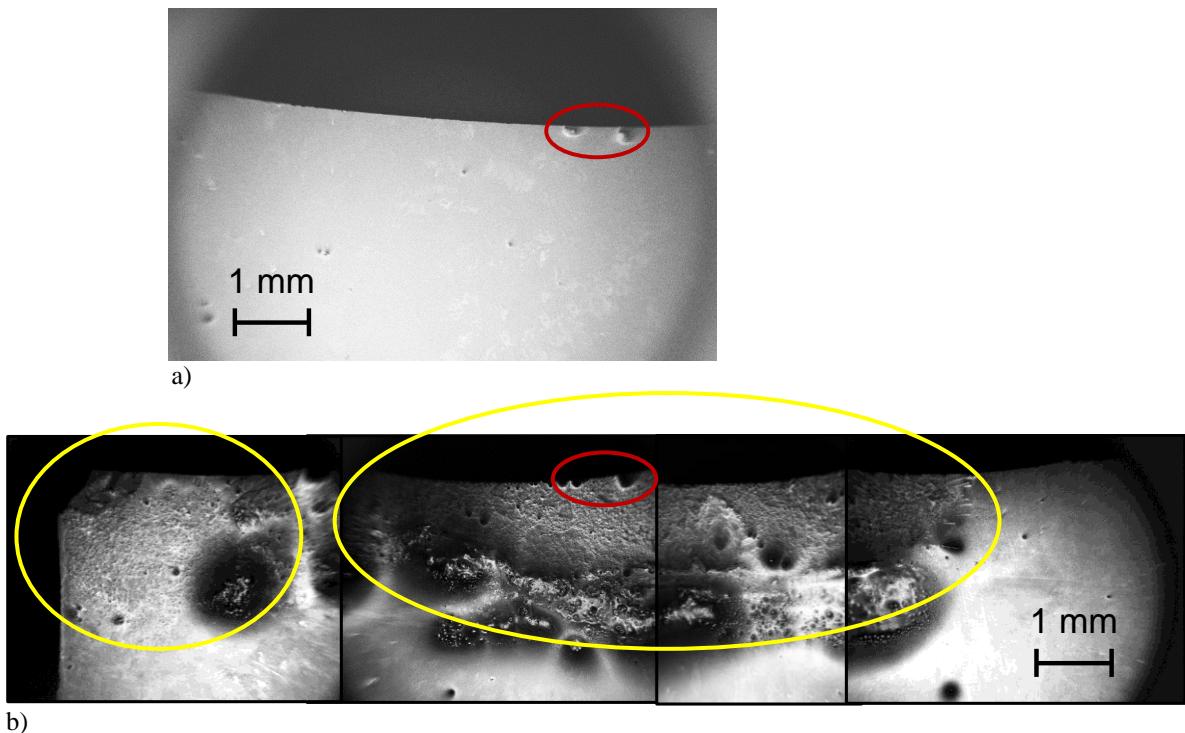


Figure 5. Silicon cathode from dual lead experiment.

Images of the dual lead silicon cathode from the second experiment taken a) before and b) after the experiment using a scanning electron microscope. Common features are circled in red, and the cathode spot regions are circled in yellow.

C. Erosion Rates

The mass of the cathodes was determined before and after each experiment, and mass loss calculated. The mass loss during the first experiment using a single lead was 100 μg , and the mass loss during the second experiment using two leads was 180 μg , an 80% increase. Arc current readings were taken during the experiment as shown in Fig. 6, and used to calculate a transported electric charge of 1500 μC per pulse. Since there were approximately 5,000 pulses each experiment this results in 7.5 C in each experiment, and an erosion rate of 13.3 $\mu\text{g}/\text{C}$ in the first experiment and 24 $\mu\text{g}/\text{C}$ in the second. Erosion rates depend on the cathode material used and are more typically in the 50-500 $\mu\text{g}/\text{C}$ range⁶. Nevertheless, a significant increase in the erosion rate was seen when the cathode spot region was moved using two leads on the cathode.

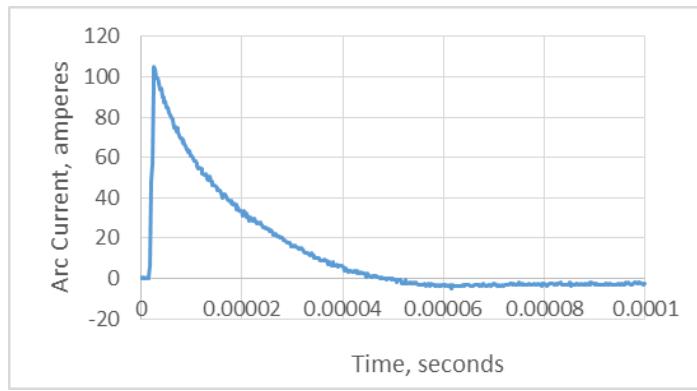


Figure 6. Arc current over one pulse.

Arc current was used to calculate transported electric current and erosion rate

IV. Conclusions

The cathode spots on a silicone cathode were found to be immobile, clustering around a single region on the cathode material. By using two negative leads to relocate the source of the electric current it was found that the location of the spot region could be moved. In addition, creating a new spot region in this manner resulted in an increased erosion rate. This could have important implications in a propulsion system such as the one described in this paper that uses a satellite's solar cells as the cathode material to generate a vacuum arc.

References

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