Dual Cathode Ion Source for Axcelis' High Energy Implanters

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Abstract

Axcelis high energy implanters such as the Purion VXE and XEmax use LINAC technology to accelerate ions to very high energies, as much as 15 MeV for arsenic ions. To achieve efficient acceleration and small tool footprint, multiply charged ions, such as As^{+++} or As^{++++}, are extracted from the ion source. However, this requires high arc voltages and power leading to short source life due to sputtering. We mitigated this source life issue in two ways. Firstly, we developed a stepped cathode, which increased source life three- to fivefold compared to a standard cathode. Secondly, we implemented a dual cathode configuration, which further increased source life by about a factor of four. A simple model is presented which explains the underlaying mechanism for the surprising and unexpected source life improvements of this dual cathode configuration.

1. Introduction

Axcelis' high energy implanters are integral to the manufacture and future development of a broad range of semiconductor devices, including memory, logic, image sensors, discrete power, and analog devices. Such applications span the use of various species such as boron, phosphorus, and arsenic, as well as aluminum and nitrogen for power devices. For energies ranging from tens of keV up to 15 MeV Axcelis' patented linear accelerator (LINAC) technology requires the injection of high charge states to cover the upper region of this broad energy range. Especially for the highest energies high charge states up to 3+ or 4+ need to be accelerated to achieve the high-end range. However, such high charge states require the operator to run the ion source close to maximum arc voltage and power. Usually, this in turn leads to a dramatic reduction in source life, because the ions in the ion source plasma sputter the indirectly heated cathode (IHC) [1] at an accelerated rate causing premature cathode punch through. Sputter rates increase with beam intensity (arc current) and energy (arc voltage). High charge state arsenic ions typically result in the shortest source lifetimes; they not only require high arc current and voltage, but in addition the heavy arsenic ion have a higher sputter yield than boron or phosphorous ions. In this paper we present two hardware solutions to address the short source lifetimes observed for high charge state arsenic operation: firstly, we developed a so-called stepped cathode; secondly, we implemented dual cathodes. Either can be implemented independently, but the biggest gain and longest source lifetimes were observed when combining the two.

2. Source life issues with standard IHC ion sources

As mentioned in the previous section, when optimizing the source for multiply charged arsenic extraction high arc currents and high arc voltages are required. The sputter rate is linear dependent on the beam intensity or arc current but shows a third order polynomial energy dependence (see Fig.1a), i.e. arc voltage increases have a bigger effect than arc current increases. In addition, because the sputter rate also increases logarithmically with ion mass (see Fig. 1b). Hence, running multiply charged arsenic such as As^{+++} is one of the worst conditions for the ion source and usually leads to premature failure of the cathode after typically only 20-30 hours for the standard single cathode ion source (see Fig. 1c).

For this standard single IHC ion source, we observed that in most of the cases a still intact solid front part (originally cylindrical slug) of the cathode would simply fall off (see Fig. 1e) leading to premature source failure. This indicated that the source plasma not only sputtered the front of the cathode but more importantly also the thin sidewalls (see Fig. 1d) even though the so-called cathode shield surrounding the IHC was designed to prevented that. The authors were able to learn from this failure mechanism and develop a new cathode and cathode shield design as explained in the next section.

3. Stepped cathode improvements

Based on the observations of the failed cathodes a new cathode and cathode shield was designed (see Fig. 2a). To prevent the ion source plasma from reaching and sputtering the thin walls of the cathode a step-shaped cathode was designed [3] which is fitted into a surrounding longer cathode shield that conforms to the stepped cathode shape. This in effect creates a so called “tortuous path” preventing the source plasma from reaching and sputtering the thin walls.

This led to an increase of cathode life, and therefore source life, from 20-30 hours to about 100 hours, corresponding to a source life improvement of about 3 – 5x.

In addition, the smaller radius of the solid front part of the cathode which faces the interior of the arc chamber (Fig. 2b) creates a narrower plasma column compared to the standard cathode (Fig. 1d) which is advantageous for multiply charged species operation as the plasma density is increased, benefitting the production of higher charge states of the ions and therefore either higher extracted beam currents or lower power consumption, which in turn leads to lower sputter rates and longer source life.

4. Dual Stepped Cathode

In order to further increase source life a dual cathode scheme was implemented [4] as shown in Fig. 2c. By using a single relay (K1) power to the respective filaments, and hence activation and thermal emission of electrons of the respective cathodes, can be switched without changing the number of power supplies already installed for Axcelis' high energy standard IHC ion source, i.e. only 1 filament PS, 1 cathode PS, 1 arc PS is needed. When one cathode (for example cathode 1 at the top) is activated, the second cathode (cathode2 at bottom) is inactive and acts as a repeller or anti-cathode and is not thermionically emitting electrons. Instead, because it is tied to the same potential as the active cathode, it will repel electrons originating from the thermally emitting active cathode, pushing them back into the source plasma and enhancing the ionization processes.

As mentioned above, using a stepped cathode approach already improved source lifetime by about 3-5x for As^{+++}. When using manual switching between cathodes for prototype testing over several days (see Fig. 4a) it was initially expected that in combination with the dual cathode the lifetime would be doubled, with source life expected to be of about 200 hours. However, we observed an increase of source life by a factor of four instead of a factor of two, resulting in over 400 hours of run time before cathode punch through and filament opening occurred. Possible reasons for this dramatic and unexpected increase will be explored in section 5.

After initial manual prototype testing the cathode switching routine was automated in Axelis' ion implanter software for the Purion XEmax. Switching times and cathode run time durations were made variable and can be chosen depending on customer demand. Depending what recipe mix customers need to implant a careful chosen switching scheme can lead to optimized and prolonged source life performance.

5. Deposits and Simple Model

A dual cathode arc chamber equipped with two stepped cathodes before testing began is shown in Fig. 3a. In comparison the same dual cathode configuration but after about 400 hours of testing is shown in Fig. 3b. Both cathodes show punch-through and filament failure. In addition, tungsten deposits due to sputtering and apparent material removal of the two cathodes led to visible deposits and tungsten build up on the extraction slit (blue arrow in Fig. 3d) and on the rear of arc chamber (red arrows in Fig. 3e and 3f) in close proximity to the cathodes. No deposits were found on the front of the extraction slit (Fig. 3c) as it didn't have direct line of sight to the cathodes.

These deposits point to the underlaying reason why the source life was unexpectedly increased for the dual source configuration by a factor of four instead of two. When the authors investigated a simple model calculating cathode thicknesses vs run time (see Fig. 4b) a sputter rate for the active cathode was assumed which matched the 100 hours of run time for the single stepped cathode. However, the authors could only match the dual cathode source life of about 400 hours when assuming a negative sputter rate of about -54% for the inactive cathode. A negative sputter rate is equivalent to a deposition rate. In other words, the model matched the observed source lifetime only for the case that about half of the removed tungsten from the active cathode was accumulated on the inactive cathode.

This deposition rate of the inactive cathode might appear rather high. However, the tungsten atoms that are being sputtered off the active cathode typically follow a cosine distribution as function of angle [5]. In other words, the advancement of the sputtered off tungsten atoms after leaving the active cathode surface is mostly unidirectional and parallel to the long arc chamber axis. They will progress towards the anti-cathode which is in direct line of sight of the active cathode giving one likely reason for the rather high deposition rate of the anti-cathode.

In addition, the mean free path λ of the gaseous tungsten being released from the active cathode due to sputtering can be estimated using the following formula:

$$\boldsymbol{\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 p}} \qquad \textbf{(1)}$$

with k_B being the Boltzmann constant, T the temperature, d the kinetic diameter and p the pressure.

With formula (1) a value of about 110mm for the mean free path of the sputtered off tungsten atoms can be calculated assuming T = 500 °C, p = 10^{-3} Torr and d = 400 pm. This value is a good estimate and indicates that the mean free path equals about the distance between the two cathodes suggesting that collisions are negligible and that the tungsten atoms are moving unimpeded and preferentially to the anti-cathode front surface, where they are deposited giving a second likely reason for the relative high deposition rate.

Considering the cosine distribution of the sputtered tungsten atoms and their large mean free path it appears plausible that the simple cathode thickness model and the assumption that half of the sputtered material of the active cathode was redeposited on the inactive cathode mirrors reality quite accurately.

6. Conclusion

The authors were able to successfully improve the source life for Axelis' Purion high energy tools, specifically for the operation and implantation of multiply charged arsenic ions. In total the initial source life of Axelis' standard high energy IHC ion source was improved by more than 10x using a stepped cathode design in combination with a dual cathode configuration. The standard cathode's thin side walls are prone to early failure. The new stepped cathode design mitigates this issue by creating a tortuous path, so that the source plasma is prevented from reaching and sputtering the thin walls, improving source life three- to five-fold. In combination with a dual cathode configuration and switching scheme, which only requires a single relay, the source life was further improved by another factor of four, leading to a total of about 400 hours of source life. A simple model for the cathode thickness was developed which explains the advantages and achieved source life improvements of the dual cathode configuration by assuming a negative sputter rate for the inactive cathode.

Conflict of Interest Statement

No funds, grants, or other support was received.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

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[4] W. Platow et al., "Extended Lifetime Dual Indirectly-heated Cathode Ion Source", US patent 11,798,775 B2

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Figure captions

Fig. 1. (a) Sputter yield vs energy for arsenic into into a tungsten target with polynomial fit. (b) Sputter yield vs ion mass at 100eV with logarithmic fit. (c) Standard ion source arc chamber with standard cathode and repeller configuration. (d) Enlarged view of standard cathode with standard shield. (e) Three failed cathodes with fallen off slugs.

Fig. 2. (a) Ion source arc chamber with stepped cathode. (b) Enlarged view of stepped cathode with modified cathode shield. (c) Dual cathode configuration with power supplies and relay wiring schematic.

Fig. 3. (a) Photograph of dual cathode arc chamber configured with stepped cathodes before testing. (b) Dual cathode arc chamber after about 400 hrs. (c) Front and (d) back of arc slit showing deposits. Enlarged view of (e) cathode 1 and (f) cathode 2 at end of life.

Fig. 4. (a) Table of run times for each cathode until failure. (b) Simplied model of single cathode and dual cathode thicknesses vs run time.

Fig. 1

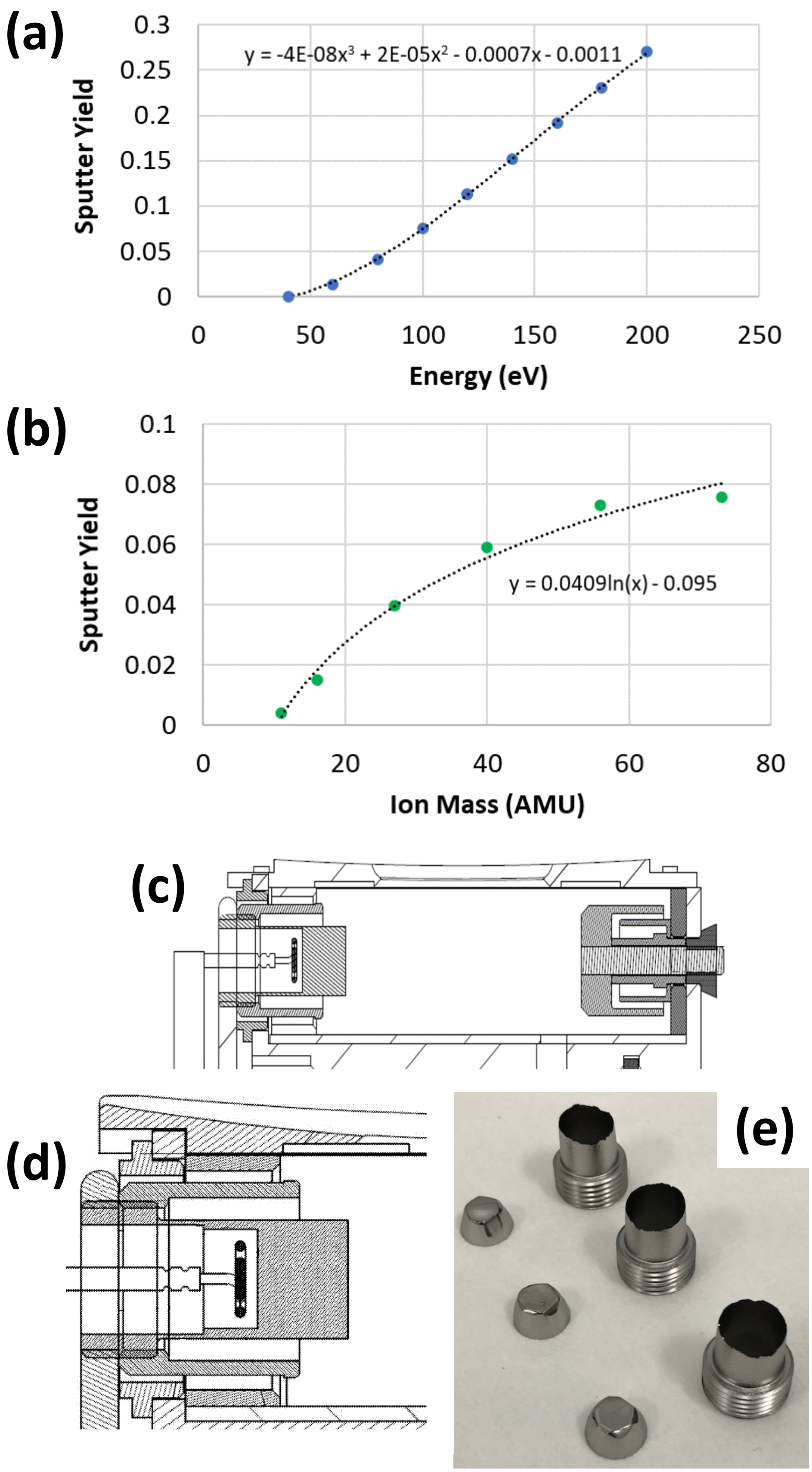

(a)
y = -4E-08x³ + 2E-05x² - 0.0007x - 0.0011
Sputter Yield
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
Energy (eV)
(b)
y = 0.0409ln(x) - 0.095
Sputter Yield
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
Ion Mass (AMU)
(c)
(d)
(e)

Fig. 2

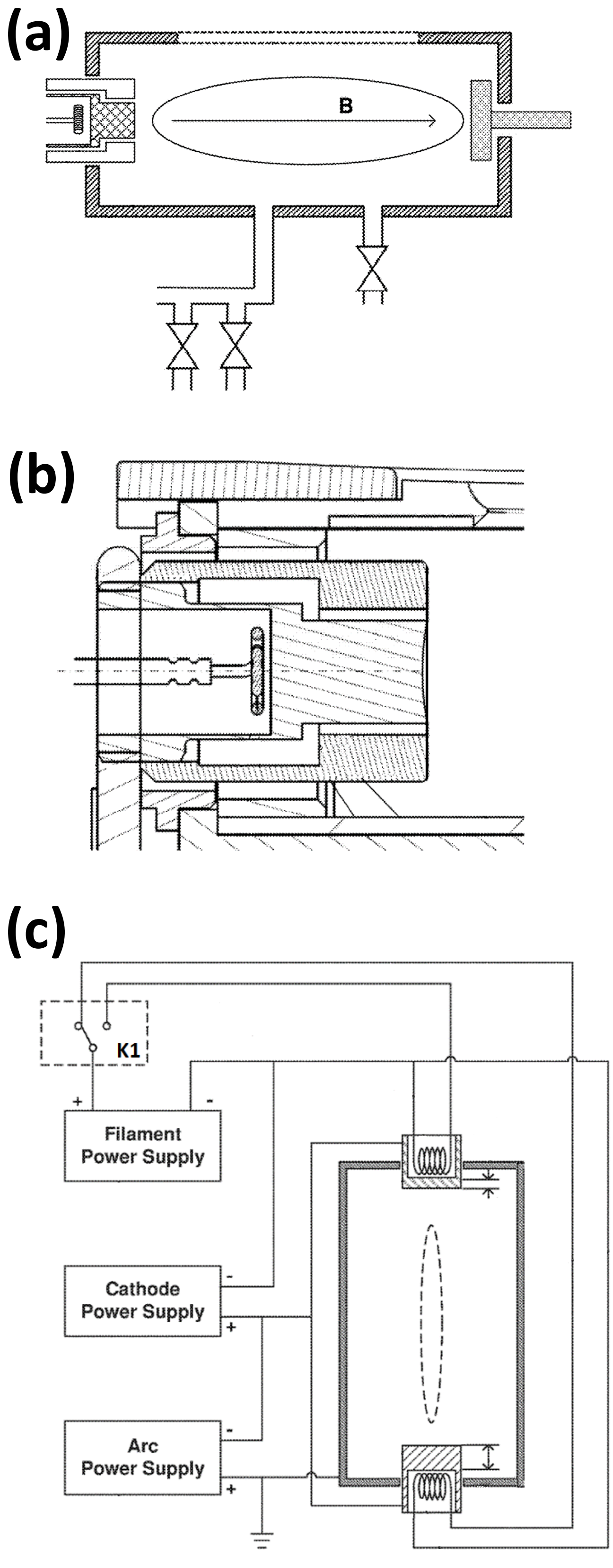
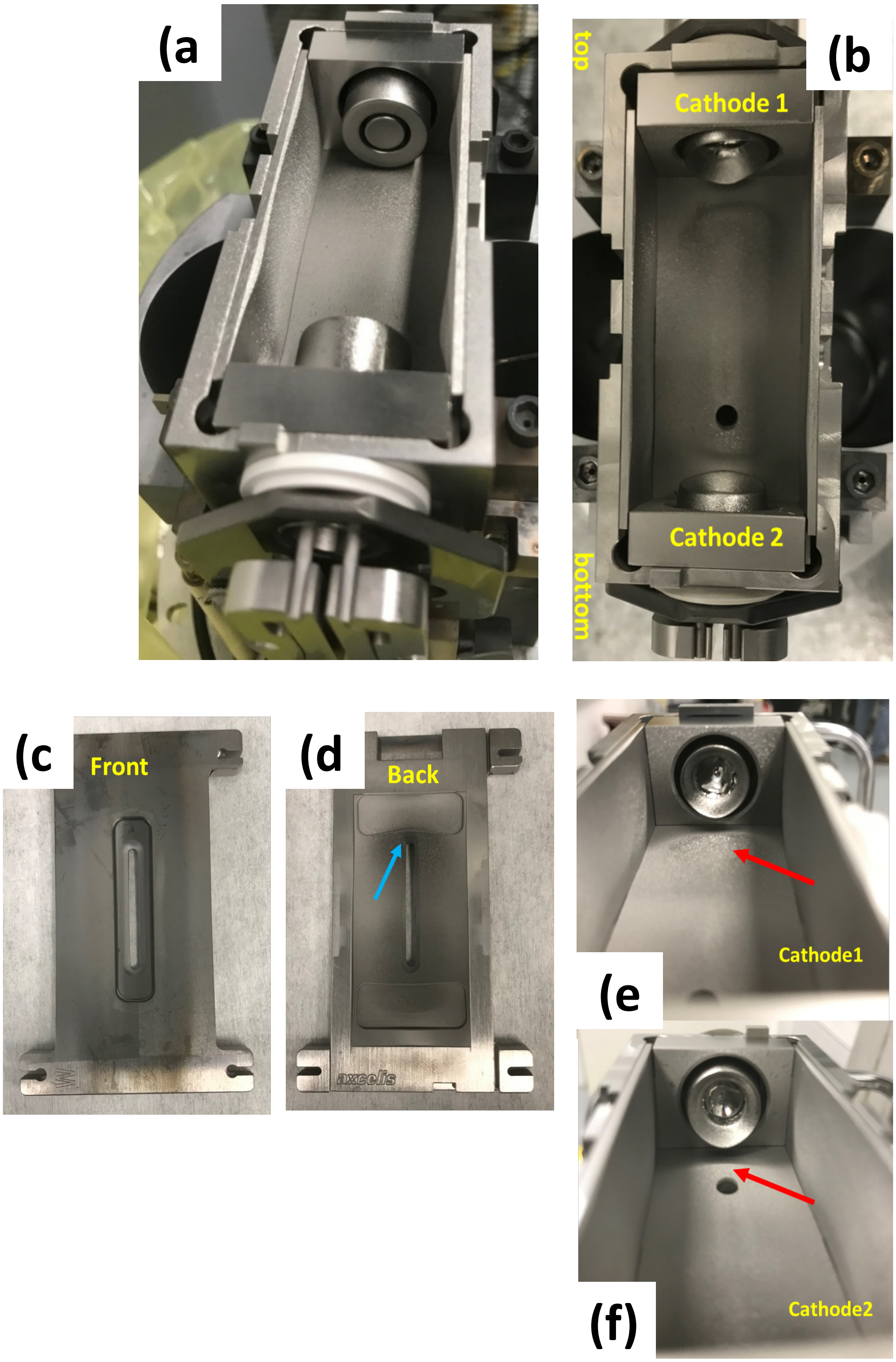

(a)
B
(b)
(c)
K1
+
-
Filament
Power Supply
Cathode
Power Supply
-
+
Arc
Power Supply
-
+

Fig. 3



(a
(b
top
Cathode 1
Cathode 2
bottom
(c
Front
(d
Back
axcelis
Cathode1
(e
Cathode2
(f)

Fig. 4

(a)

Day	Run time (hrs)	Cathode	Total (hrs)
1	55	1	55
2	97.3	2	42.3
7	147	1	49.7
9	194	2	47
11	211	1	17
13	235	2	24
15	274	1	39
19	343	2	69
22	414	1	71

(b)