Investigation of the interaction of dense noble gas plasmas with cold cathodes: III—Arc spot ignition on pure and doped W cathodes

Sonja Frohnert | Jürgen Mentel

Abstract
The study of the commutation of atmospheric pressure noble gas arcs on cold cathodes made of Al, Cu, Ti, graphite, Au, Pd, and Pt is extended to W cathodes. Rods with a diameter of 2 mm are inserted in a UHV tight stainless steel vessel filled with Ar 5.6 or Kr 4.8. The negatively biased electrodes are brought into interaction with arc plasma by a magnetic blast field. Their end faces are mostly polished with diamond grinding powder; some are electrolytic polished, others additionally covered with a thick oxide layer or pasted with W powder. Moreover, electrodes are investigated being doped with Al, K, and Si or doped with ThO2. The arc commutation is observed by short time photography, streak camera records, and temporally highly resolved optical spectroscopy for a lower and higher voltage applied between the arc plasma and the commutation electrode (CE). Varying the electrode properties revealed that basically ionized vapour of electrode material and less distinctly lowering of the work function by doping accelerate the arc commutation. It is initiated by plasma ions, which initially generate secondary electrons across the whole end face of the electrode. Since the electron emission varies locally, the multiplication of ions within the plasma layer by emitted electrons varies too. The positive feedback between both provokes a constriction of the commutation current and the power input into an arc spot. The electrode vapour promotes at first the development of an arc spot but finally quenches it by cooling the plasma layer in front of it.

KEYWORDS
arc spot, boiling temperature, cold cathode, ion bombardment, secondary electron emission

1 | INTRODUCTION
The formation of arc spots on cold cathodes is already observed for a long time in high voltage engineering as a corollary of flashovers. It is also observed in many applications of plasma technology. They are listed by the ref. [1–6] being given in ref. [1]. In spite of its technical importance, the physics of arc spot ignition on cold cathodes is up to now not really generally understood. To remove this deficit a vertically burning arc was initially drawn between an upper anode and
a lower cathode in atmospheric pressure air and subsequently blown by a magnetic blast field on a negatively biased horizontally arranged so-called commutation cathode. The delay time of arc commutation, called commutation time $t_c$, was measured for 24 pure and 3 technical materials. In addition, examples of arc commutation were recorded by high-speed photography. Moreover, traces of arc commutation generated on the end face of the cathode were investigated by scanning electron microscopy (SEM)\cite{2-5} But the findings of the extensive investigations did not result in a satisfying general understanding of arc spot ignition.

One reason may be that air is a too complicated gas atmosphere. Therefore, the investigations of arc commutation and with it arc spot ignition were continued substituting air with noble gases. For this purpose, a new experimental setup was developed.\cite{6} It consists of a discharge vessel made of stainless steel, which can be pumped down to UHV before it was filled with Ar 5.6 or Kr 4.8 at a pressure of 0.1 MPa. The arc commutation was characterized by electric measurements and high-speed photography. Moreover, it was supplemented by in situ photomicrographs with a micro-objective (Questar QM 100) of the end face of the electrode within the discharge vessel when the arc was already extinguished. With the micro-objective, surface structures with a dimension of 1 $\mu$m could be resolved. The findings show some influence of surface structures on arc spot ignition but a better physical understanding of arc spot ignition, for example, a dependence on the properties of the electrode material could not be achieved by the investigation in pure argon.

A third approach to obtain a better understanding of arc spot ignition was made by Frohnert in ref. \cite{7} by refining the experimental setup and the diagnostics of arc spot ignition applied in ref. \cite{6} especially by improving the observation of optical spectra emitted by the plasma in front of the CE. A detailed description of the experimental setup, of the optical diagnostics, and their application to electrodes made of pure Al, Cu, Ti, and graphite is published in ref. \cite{1}. The end faces of the electrodes were polished with diamond suspensions of grain sizes down to a diameter of 0.25 $\mu$m before they were inserted into the discharge vessel. The arc commutation on cathodes made of Au, Pd, and Pt was investigated within the same experimental setup by the same diagnostic tools. Only the treatment of the end faces of some Pd electrodes was supplemented by pasting them with Pd powder with grain sizes of 1.2–2.5 $\mu$m. The results are given in ref. \cite{8} and compared with those given in ref. \cite{1}.

One of the most important materials in plasma technology is pure and doped tungsten. Tungsten electrodes are applied, for example, in arc welding\cite{9,10} or in high-intensity discharge (HID) lamps.\cite{11} The formation of arc spots on cold tungsten electrodes of HID lamps plays especially a role when the lamps are ignited\cite{12-15} It starts the heating up of the electrodes ending in a diffuse, spot- or emitter spot mode of cathodic arc attachment.\cite{16-22} Tungsten sticks out by reason of its high melting temperature of 3695 K and boiling temperature of 6203 K. The boiling temperature is much higher than the boiling temperature of the tungsten oxides WO$_2$ and WO$_3$ amounting to 2003 and 2110 K.\cite{23,24} The order of the boiling temperatures of tungsten and tungsten oxides is reversed compared to the other metal electrodes. On the other hand, the average work function of pure tungsten amounts to $\Phi = 4.55$ eV, the work function of WO$_3$ approximately to $\Phi = 9.2$ eV. By doping tungsten with ThO$_2$ the work function can be dropped to $\Phi = 3$ eV.\cite{25}

At first, the experimental setup and the applied diagnostics are given in ref. \cite{1,7,8} are shortly repeated. Moreover, an additional treatment of the end face of the electrode by oxidation and electrolytic polishing is described. Measurements were performed on pure tungsten electrodes, the end face of which was only polished, additionally oxidized, pasted with tungsten powder or additionally electrolytic polished. Moreover tungsten electrodes, doped with 10 ppm Al, 70 ppm K and $\leq 7$ ppm Si, called BSD or AKS electrodes, and tungsten electrodes, doped with 3 wt% ThO$_2$, called G30 electrodes, were investigated. The BSD-electrodes were only grinded but not polished. The doped and grinded tungsten electrodes are used in HID lamps. Finally, an interpretation of the measuring results is given.

2 EXPERIMENTAL SETUP

The experimental setup applied subsequently is already presented quite completely in ref. \cite{1}. It can be subdivided in accordance with the detailed description in ref. \cite{1} in six parts as it is shown in ref. \cite{8}.

Part 1: It presents the discharge vessel, which encapsulates two upright horn electrodes, between which an arc was operated in atmospheric pressure Ar 5.6 or Kr 4.8. It is supplemented by the generation of a magnetic blast field by two Helmholtz-coils, which blows the arc plasma towards the so called CE above the horn electrodes, and by the generation of a trigger pulse for the high-speed cameras and streak camera by the absorption and deflection of a laser beam indicating the formation of plasma in front of the CE. Details are given in section 2.1, 2.2, 2.3 in ref. \cite{1}. 
Part 2: It gives the electric circuit, by which the ignition of the arc, its supply with current, and its interruption is executed and the formation of an arc spot is recorded electrically on the cold commutation cathode. It condenses section 2.4 in ref. [1].

Part 3: It illustrates the controlling of the experiment by electric measurements. It summarizes section 2.5 in ref. [1].

Part 4: It is devoted to the optical setup composed of a streak camera, a high-speed camera, and a grating spectrograph equipped with another high-speed camera positioned in the image plane of the spectrograph, by which two time-shifted spectra can be recorded. It recapitulates section 2.6.1, 2.6.2, 2.6.3, and 2.6.4 in ref. [1].

Part 5: It sketches the investigation of the end face of the commutation cathode by exposures taken with a field emission SEM before and after arc spot ignition. Some more information is given in section 2.7 in ref. [1].

Part 6: It describes the treatment of the end face of the CEs by several procedures. The end faces were made plane, smooth, and subsequently polished within a special polishing machine being constructed for this purpose. The finishing was made with diamond grinding powder. The smallest grain size being applied amounted to 0.25 μm (D0.25). More details are available in section 2.8 of ref. [1].

A still smoother surface was formed in ref. [8] by encapsulating electrodes subsequently within a capillary, which was pumped down to UHV while they were annealed within a high-frequency furnace. To form a well-defined oxide layer on the tungsten surface the capillary was flooded with air at the end of the annealing procedure in vacuum. The heating was continued until the electrode adopts a green–turquoise colour.

In ref. [8] additionally a procedure is given, by which the end face of electrodes was pasted with powder with a grain size from 1.2 to 2.5 μm. Powdery electrode material was affixed with a solution of methyl cellulose onto the end face of the electrode. Subsequently, the pasted electrode was dried, enclosed in a capillary, which was pumped down to UHV, and glowed so long within an high-frequency furnace, until 10⁻⁶ Pa was approached by the sintering process within the capillary.

To remove oxide layers from tungsten electrodes additionally an electrolytic polishing procedure was applied in ref. [7]. For this purpose the W electrode, which should be prepared for an examination of arc commutation, was dipped together with another tungsten electrode into a NaOH solution and operated as anode together with the other tungsten cathode by a DC current. Between both DC voltages of 13 V were applied until a bright metallic surface was established at the anode.

3 RESULTS AND DISCUSSION

As in ref. [1,8] two temporally shifted spectra, recorded in front of the CE with the DICAM PRO camera, a short time photo of the arc also taken in front of the CE with the Proxitronic NanoCam approximately 270 ns after arc spot ignition and a streak camera record of the arc spot ignition taken with the Hamamatsu streak camera are brought together in one figure. It facilitates the analysis of arc spot ignition on cold tungsten cathodes. Along the streak camera record the opening moments of the DICAM PRO camera and of the Proxitronic NanoCam are designated. The combination of photos is supplemented by SEM pictures of the end face of the cathode taken with different enlargements after arc spot ignition, some figures also with SEM pictures taken before arc spot ignition.

3.1 Arc spot ignition on cold pure tungsten cathodes

Figure 1 gives four pictures taken during arc spot ignition on a cathode consisting of a rod with a diameter of 2 mm made of pure W (99.95%), the end face of which is polished with diamond suspensions of decreasing grain sizes down to D0.25. The experiment was performed with an Ar 5.6 filling of the discharge vessel. The arc was ignited as in previous experiments by the gap between the horn electrodes, but an acceleration of arc commutation by an additional voltage $U_2$ was omitted. The commutation time amounted to $t_c = 121 \mu s$, in another ignition experiment 208 μs was measured.

Both spectra were recorded between 370 and 475 nm at 285 ns and at 1.59 μs after the start of $t_c$ with an exposure time of $t_{exp} = 300$ ns. When the second spectrum was taken $i_c$ was already switched off. Both spectra are dominated as in front of other electrode materials investigated in ref. [1,8] by Ar I and Ar II lines. Moreover, the line at $\lambda = 402.1$ nm may be identified with the tungsten W I line at $\lambda = 400.875$ nm, the tungsten atomic line at $\lambda = 407.436$ nm is presumably obscured by an Ar line. The attribution of the line at $\lambda = 437.6$ nm to the three WI lines at 436.479, 437.253, and 437.849 nm and of the line at $\lambda = 458.8$ nm to the WI line at 458.685 nm is uncertain. The appearance of the discharge recorded by the
FIGURE 1  Ignition of an arc spot in Ar 5.6 on the end face of a cold W cathode, polished down to D0.25, being characterized by two temporally shifted spectra, a short time photo, and a record by a streak camera. It is triggered by \( i_c \). Acceleration of arc spot ignition by \( U_2 \) is omitted. The commutation time amounted to \( t_c = 121 \mu s \).
NanoCam with an exposure time of $t_{\text{exp}} = 100$ ns immediately after the onset of $i_c$ shown in Figure 1 is dominated by a plasma ball attached to the front edge of the cathode, as is indicated by the light emission above the edge. A similar plasma ball in front of a cold W cathode operated also in argon under the same conditions is already shown in ref. [26]. The plasma balls are characteristic for an arc commutation without an additional support by a voltage $U_2$ (see figures 14, 21, 24, and 27 in ref. [1] and figures 1, 5, 11 in ref. [8]). The triggering of the streak camera was initiated by $i_c$. The streak camera record, which starts together with the exposure of the NanoCam visualizes the switching off of $i_c$ after 0.65 μs by a reduction of light emission.

Figure 2 shows four pictures taken during arc spot ignition in Kr 4.8 on a cathode with the same properties as in Figure 1. The arc was ignited between the horn electrodes. As in Figure 1 an acceleration of arc commutation by an additional voltage $U_2$ was dispensed. Both spectra were recorded between 315 and 420 nm at 345 ns and 1.65 μs after the start of $i_c$ with an exposure time of $t_{\text{exp}} = 300$ ns and $t_{\text{exp}} = 600$ ns. When the second spectrum was taken $i_c$ was already switched off. The line at 401 nm can be attributed to the W I line at $\lambda = 400.875$ nm. The lines at $\lambda = 393.5$ nm and at $\lambda = 396.9$ nm may be related to krypton ion lines. But, it is rather difficult to relate the lines to single transitions. The quasi continuous emission extending from 390 nm to shorter wavelengths may be attributed to tungsten oxide molecular bands caused by oxygen traces in Kr 4.8. A similar but spectroscopically higher resolved spectrum emitted under similar conditions in front of a cold W cathode was already shown in ref. [27], figure 3. The appearance of the discharge recorded by the NanoCam with an exposure time of 100 ns immediately after the onset of $i_c$ shows different to Figure 1 a luminous layer covering nearly the whole end face of the cathode. The streak camera record triggered by the start of $i_c$ confirms the observation by the NanoCam. Moreover, it shows the switching off of $i_c$. The commutation time could not be registered.

The same shape of arc attachment on the end face of a cold W cathode but in argon was already shown in Figure 2 of ref. [26]. The commutation time amounted to $t_c = 367$ μs according to ref. [28], figure 4.3.13, which is much longer than $t_e$ being required to start the formation of the plasma ball in Figure 1. A similar attachment of a Kr arc was observed on a cold Ti cathode in ref. [7], figure 8.13, under the same conditions as in Figure 2. The commutation took place after an extremely long commutation time $t_c = 5723$ μs while the formation of a plasma ball on a Ti cathode in ref. [1], figure 24 occurred under the same conditions at $t_e = 2247$ μs. The spectrum in ref. [1], figure 24 emitted by the plasma layer within visible spectral range is composed of Kr I and Kr II lines with some Ti I lines in between. The formation of a less distinct plasma layer in the case of $U_2 = 0$ V covering the whole end face of the cathode at the beginning of the commutation of an argon arc on a Cu electrode is shown in ref. [1], figure 21, on a Pd cathode in ref. [8], figure 5 and of a krypton arc on an Al cathode in ref. [1], figure 16. Further examples can be found in ref. [7], some of them are given subsequently.

The measurements shown in Figure 3 were performed in Ar adjusting the same operation conditions as in Figure 1. In addition, the arc commutation was accelerated with $U_2 = 600$ V by the circuit version b given in figure 4 of ref. [1]. The commutation current $i_c$ was switched off after 3.4 μs. Both spectra at the top of the figure were recorded within a wavelength interval from 355 to 460 nm with an exposure time of $t_{\text{exp}} = 200$ ns. The upper spectrum was recorded within a time interval between 285 and 485 ns after arc spot ignition, the lower spectrum after 2.49 μs. The spectra consist of Ar I and Ar II lines and maybe of an Ar III line at $\lambda = 385.832$ nm. Some lines may be interpreted as W I lines. But, the interpretation is doubtful since the most prominent W I line at $\lambda = 400.875$ nm is missing.

The shape of the discharge was recorded immediately after arc commutation by the NanoCam with an exposure time of 10 ns. It shows as in preceding experiments a plasma channel extending from the CE towards the hole within the blind in front of the gap between the horn electrodes. The streak camera is triggered by a photo-diode signal showing the starting of arc commutation after 4.4 μs and subsequently an irregular motion of the cathode spot on the end face of the CE. It indicates small transient electron-emitting sites. A similar irregular motion of the cathode spot on the end face of a pasted Pd cathode after arc spot ignition by $U_2 = 900$ V was already shown in figure 12 of ref. [8].

Figure 4 shows as a reference two SEM pictures of the end face of the CE. The end face was polished down with diamond suspensions of decreasing grain sizes to D0.25 before the electrode was placed within the discharge vessel. The pictures were taken with scales of length of 20 and 2 μm. The darker areas are presumably covered by an oxide layer.

Figure 5 presents four SEM pictures of traces generated by cathode spots during arc commutation onto the end face of a polished W electrode taken with scales of length of 20, 2, 1 μm, and 200 nm. The discharge vessel was filled with Ar 5.6. Only some but extremely small craters with diameters less than 1 μm can be found on the two lower pictures of the end face of the electrode, which was only polished down to D3.
Ignition of an arc spot in Kr 4.8 in the case of $U_2 = 0$ V on the end face of a cold W cathode, polished down to D0.25, being characterized by two temporally shifted spectra, a short time photo, and a record by a streak camera. It is triggered by $i_c$. The commutation time $t_c$ could not be registered.
FIGURE 3  Ignition of an arc spot in Ar 5.6 on the end face of a cold W cathode, polished down to D0.25, being characterized by two temporally shifted spectra, a short time photo, and a record by a streak camera being triggered by a photo diode signal. The ignition is accelerated by an additional voltage $U_2 = 600$ V. The commutation time amounted to $t_c = 4.4 \, \mu s$
FIGURE 4  Two scanning electron microscopy pictures of the end face of a W electrode polished down to D0.25 taken with scales of length of 20 and 2 μm before it was exposed to the commutation of an arc.

FIGURE 5  Four scanning electron microscopy (SEM) pictures of the end face of a W cathode. The end face shown on the upper left picture was polished down to D0.25 and taken with a scale of length of 20 μm. The traces were generated by 25 arc commutations in atmospheric pressure Ar and \( i_c \) lasting 5 μs. The end faces of the cathode shown by the three other SEM pictures were polished down to D3, the traces were generated by 10 arc commutations in Ar and \( i_c \) lasting 3.2 μs. The scale of length of the upper right picture amounts to 2 μm, of the lower left picture 1 μm and of the lower right picture 200 nm.

3.2  Arc spot ignition on a cold pure tungsten cathode covered with a thick oxide layer

The measurements in Figure 6 were performed adjusting quite the same operation conditions as in Figure 1 (\( U_2 = 0 \) V). The end face of the tungsten cathode was also polished down to D0.25 with diamond suspensions of decreasing grain sizes. Different from the cathode investigated in Figure 1 the tungsten rod was additionally glowed within a high-frequency furnace at first under UHV conditions and subsequently in air until it adopts a green–turquoise colour.
FIGURE 6 Ignition of an arc spot in Ar 5.6 on the end face of a cold W cathode polished down to D0.25 and subsequently covered with a thick oxide layer by glowing in air. $U_2 = 0 \text{ V}$, $i_c = 2.8 \text{ mA}$. It is characterized by two temporally shifted spectra, a short time photo and a record by a streak camera, being triggered by $i_c$. The commutation time amounted to $t_c = 20 \mu s$.

Filling gas: Argon 5.6
Pressure: 1,061 mbar
$U_1 = 1.9 \text{ kV}$
$U_2 = 0 \text{ V}$
Nanocam $t_{exp}=100 \text{ ns}$
$g = 6.0$
Streak $t_{exp}=1 \mu \text{s}$
$g = 3.5$
Dicam $t_{exp}=300 \text{ ns}$
$t_{exp}=1 \mu \text{s}$
$g = 99 \%$
Shut-off after $0.65 \mu \text{s}$

**Trigger times:**

1. Exposure
   - Nanocam

2. Exposure
   - Dicam: outside of sweep-time of the streak-record

$T_{exp} = 1 \mu \text{s}$
Both spectra at the top of the figure were recorded as in Figure 1 within a wavelength interval from 370 to 475 nm. The upper spectrum was taken at 285 ns after arc spot ignition, the lower spectrum was at 1.59 μs when $i_c$ was already switched off. The exposure time of both spectra amounted to $t_{exp} = 300$ ns. Both spectra consist of Ar I and Ar II lines and of numerous W I lines. A list of stronger W I lines between 400 and 475 nm are given in Table 1. They are identified within the spectrum or at least indicated. It is noticeable that all lines are emitted by low lying levels compared to the ionization energy $E_i = 7.98$ eV of tungsten. The lines are an indication of tungsten vapour in front of the cathode being generated by the vaporization of tungsten oxide and its dissociation within the plasma boundary layer in front of the electrode. Within the chosen wavelength interval tungsten ion lines are missing. But, a partial ionization of the filling gas indicated by the emission of Ar II lines has to be assumed, therefore, also of the tungsten vapour.

The shape of the discharge in Figure 6 taken by the NanoCam with an exposure time of $t_{exp} = 100$ ns after its triggering by the onset of $i_c$ shows a plasma ball near the edge of the end face of the cathode. It corresponds to the majority of the appearances of the discharge immediately after arc spot ignition in the case of $U_2 = 0$ V. The triggering of the streak camera was initiated by $i_c$. The streak camera record shows at the beginning of arc spot ignition besides a bright arc spot the formation of a plasma layer as in ref. [1], figures 16 and 21 and in ref. [8], figure 5. It disappears approximately after 300 ns. Moreover, it shows the switching off of the arc after 0.65 μs. The low commutation time $t_c = 20$ μs is very special in the case of $U_2 = 0$ V. Repeating the experiment $t_c = 55$ μs was measured.

Figure 7 presents as a reference two SEM pictures of the end face of the CE before it was inserted into the discharge vessel. The end face was polished down with diamond suspensions of decreasing grain sizes to D0.25 and then glowed

| $\lambda$ (nm) | $E_u$ (eV) | $E_l$ (eV) | $gf$ |
|---------------|------------|------------|------|
| 400.875       | 3.457      | 0.366      | 0.374|
| 404.660       | 3.4296     | 0.366      | 0.045|
| 406.995       | 3.644      | 0.599      | 0.0415|
| 407.436       | 3.4        | 0.366      | 0.196|
| 417.119       | 3.570      | 0.599      | 0.0303|
| 426.934       | 3.27       | 0.366      | 0.0524|
| 429.461       | 3.25       | 0.366      | 0.184|
| 430.021       | 3.247      | 0.366      | 0.0677|
| 465.985       | 2.66       | 0.0        | 0.0127|
| 468.052       | 3.247      | 0.599      | 0.0312|

*Note: In addition, the product of the statistical weight $g$ of the upper line level and the oscillator strength $f$ of the line is given.*

**FIGURE 7** Two scanning electron microscopy pictures of the end face of a W electrode polished down to D0.25 and subsequently covered with a tungsten oxide layer taken with scales of length of 200 and 2 μm before it was exposed to the commutation of an arc
**Figure 8** Four scanning electron microscopy pictures of the end face of a W cathode. The end face was polished down to D0.25 and subsequently covered with a tungsten oxide layer. The cathode was charged with 13 ignitions in Ar 5.6 lasting 0.65 μs. The scale of length of the upper left picture amounts to 200 μm, of the upper right picture 20 μm, of the lower left picture 2 μm and of the lower right picture 1 μm within a high-frequency furnace under UHV conditions and subsequently in air to cover the surface with an oxide layer. The pictures were taken with scales of length of 200 and 2 μm.

Figure 8 shows four SEM pictures generated by arc spot ignition on the polished and subsequently with an oxide layer covered end face of the CE. The upper left picture was taken with a scale of length of 200 μm, the upper right with 20 μm, the lower left picture with a scale of length of 2 μm, and the lower right with 1 μm. The discharge vessel was filled with Ar 5.6 at a pressure of 1061 mbar. The traces were generated by 13 arc commutations and by $i_c$ lasting 0.65 μs. The SEM pictures show an extremely large circular crater with a diameter of 14 μm and in it tiny craters with diameters of less than 100 nm. Within the crater the electrode surface indicates traces of melting. Similar arc traces were already observed on the end face of a copper electrode generated by the commutation of an arc operated in air.\cite{3}

### 3.3 Arc spot ignition on a cold tungsten cathode pasted with tungsten powder

The measuring results presented in Figure 9 were obtained by adjusting quite the same operation conditions as in Figures 1 and 6 in case of $U_2 = 0$ V. The end face of the electrode rod was pasted with tungsten powder by the procedure described in section 2, part 6, of ref. \cite{8}. Both spectra at the top of Figure 9 were recorded within a wavelength interval from 370 to 475 nm. The upper spectrum was recorded at 385 ns after arc spot ignition, the lower spectrum at 1.59 μs. The exposure time $t_{exp}$ of both spectra amounted to 500 ns. Both spectra consist of Ar I and Ar II lines. Moreover, the W I line at 400.875 nm is indicated, the line at 407.1 nm may be attributed to the W I line at 407.463 nm, the line at 415.4 nm to the W I line at 417.119 nm, the line at 427 nm to the W I line at 426.934 nm. The strong W I line at 429.461 nm is indicated, other less pronounced W I lines are obscured by the argon spectrum.

The shape of the discharge in Figure 9 is documented by a photo with the NanoCam with an exposure time of 100 ns after its triggering by the onset of $i_c$ consists of a plasma ball attached on the end face of the CE. It does not differ from the shape of the discharge in front of a smooth cold cathode at the beginning of an arc spot ignition, which is not accelerated by an additional voltage $U_2$. The streak camera record being triggered by the rise of $i_c$ and started together with the
Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode, the end face of which is pasted with tungsten powder. $U_2 = 0$ V, $i_r = 5.86$ mA, $t_r = 1.8$ μs. It is characterized by two temporally shifted spectra, a short time photo and a record by a streak camera, being triggered by $i_c$. The commutation time amounted to $t_c = 69$ μs.
NanoCam shows two arc spots, the first one is accompanied by the initiation of arc commutation and corresponds to the photo taken by the NanoCam, the second one is ignited approximately 1.8 $\mu$s later and initiates the quenching of the first spot. The commutation time amounted to $t_c = 59$ $\mu$s. But also much higher commutation times are observed for pasted tungsten electrodes, for example, $t_c = 198$ $\mu$s, ref. [7] indicating a large scatter of $t_c$.

The measurements summarized in Figure 10 were performed adjusting quite the same operation conditions as in the Figures 1, 3, 6, and 9. The arc commutation was accelerated with $U_2 = 950$ V by the circuit version a given in figure 3 of ref. [1]. The commutation current $i_c$ was switched off after 0.72 $\mu$s. Both spectra at the top of the figure were recorded within a wavelength interval between 380 and 485 nm. The upper spectrum was recorded at 405 ns after arc spot ignition with an exposure time of 800 ns; the much weaker lower spectrum was recorded after 1.41 $\mu$s with an exposure time of 2 $\mu$s when $i_c$ is already switched off. The spectrum consists of Ar I lines and some Ar II lines with some stronger W I lines in between. Especially the 429.461 nm line is different from Figure 9 not obscured by argon lines.

The shape of the discharge was taken immediately after arc spot ignition by the NanoCam with an exposure time of 10 ns. It shows that the arc spot ignition takes place near the edge of the end face of the electrode rod. The spot is the starting point of the plasma channel directed towards the hole in the centre of the blind in front of the horn electrodes. The streak camera is triggered by the photo diode signal. It confirms the ignition of the arc spot after the commutation time $t_c = 2.34$ $\mu$s and the switching off of $i_c$ 0.72 $\mu$s later. The diameter of the starting point of arc commutation amounts approximately to 70 $\mu$m, which is of the same order of magnitude as the diameter at the starting point of arc commutation on the pasted Pd cathode being accelerated by $U_2 = 900$ V according to figure 12 in ref. [8].

Figure 11 gives as a reference two SEM pictures of the pasted end face of the CE before it was exposed to arc commutation. The pictures were taken with scales of length of 200 and 2 $\mu$m. The left picture indicates that the end face of the electrode surface is not completely pasted.

Figure 12 shows four SEM pictures taken with scales of length of 200, 10, 2, and 1 $\mu$m. They reproduce traces of 15 Ar arc commutations by a commutation current $i_c$ lasting 0.65 $\mu$s. On the picture taken with a scale of length of 1 $\mu$m tungsten particles being pasted on the electrode surface can be identified, which were converted into microcrystals within the arc spot.

### 3.4 Arc spot ignition on an electrolytic polished cold pure tungsten cathode

The measuring results given in Figure 13 were obtained by adjusting quite the same operation conditions as in Figures 1, 6, and 9. But different from the cathode in Figures 1, 6, and 9 the end face of the cathode rod was additionally electrolytic polished by the procedure given at the end of Section 2. By the procedure, tungsten oxide layers were removed.

Both spectra at the top of Figure 13 were recorded within the wavelength interval from 370 to 475 nm. The upper spectrum was taken 345 ns, the lower spectrum 1.65 $\mu$s after arc spot ignition. The exposure time of both spectra amounted to $t_{\text{exp}} = 300$ ns. Both spectra consist of Ar I and Ar II lines. The assignment of the line at $\lambda = 407.4$ nm to the W I line $\lambda = 407.436$ nm is doubtful since the stronger W I line at 400.875 nm is missing. The line may be assigned to a contamination line $\lambda < 407$ nm being indicated in figure 12 of ref. [24] left of the W I line $\lambda = 407.436$ nm line. Other typical W I lines was not observed.

The shape of the discharge was recorded by the NanoCam after its triggering immediately after arc spot ignition with an exposure time of 100 ns. It shows not only the bright arc spot on the cathode surface but also a tail-like arc column directed towards the gap between the horn electrodes. The streak camera record being triggered by the rise of $i_c$ starts with a luminous layer, which covers the whole end face of the cathode. In it, a cathode spot is formed, by which the commutation current $i_c$ is completely taken over after several hundred nanoseconds. The commutation time amounted to $t_c = 144$ $\mu$s.

The measurements presented in Figure 14 were performed adjusting the same operation conditions as in Figure 13. Only the arc commutation was additionally accelerated with $U_2 = 600$ V by the circuit version b given in figure 4 of ref. [1]. The commutation current $i_c$ was already switched off after 0.65 $\mu$s. Both spectra at the top of the figure were recorded as in Figure 13 within a wavelength interval from 370 to 475 nm with an exposure time $t_{\text{exp}} = 300$ ns. The upper spectrum was recorded as in Figure 13 at 345 ns after arc spot ignition, the lower spectrum at 1.65 $\mu$s. At this moment the commutation current was already switched off. Both spectra consist as in Figure 13 of Ar I and Ar II lines. They are less intense than in Figure 13. Tungsten lines are missing.

The shape of the discharge was recorded by the NanoCam being triggered immediately after arc spot ignition with an exposure time of 100 ns. It differs only by a brighter arc channel from the picture given in Figure 13. The streak camera
Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode, the end face of which is pasted with tungsten powder. It is characterized by two temporally shifted spectra, a short time photo, and record by a streak camera being triggered by a photo diode signal. The ignition is accelerated by an additional voltage $U_2 = 950$ V. The commutation time amounted to $t_c = 2.34 \mu$s.
FIGURE 11 Two scanning electron microscopy pictures of a pasted end face of a W cathode taken with a scale of length of 200 and 2 μm before it was inserted into the discharge vessel and exposed to arc commutation.

FIGURE 12 Four scanning electron microscopy pictures of the pasted end face of a W cathode taken with scales of length of 200 and 10 μm (upper left and upper right picture), 2 and 1 μm (lower left and lower right picture) after 15 Ar arc commutations, t_c was switched off after 0.65 μs.

record shows a very bright arc spot immediately after arc spot ignition. Its intensity decreases abruptly approximately after 50 ns. Presumably the arc spot has moved at this moment across the front edge of the end face of the cathode as is already indicated by the short time photo taken with the NanoCam. It may also explain the low intensity of the optical spectra. The commutation time amounted to t_c = 9.2 μs.

Two SEM pictures of the end face of the CE with scales of length of 200 and 20 μm after electrolytic polishing are presented in Figure 15 as a reference. The dark structures at the end face are tungsten-dendrites generated during the polishing procedure described at the end of Section 2. Subsequently, they are inserted into the discharge vessel, in which they were exposed to arc commutation in Ar 5.6 at a pressure of 1,066 mbar.
**FIGURE 13** Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode in the case of $U_z = 0$ V. Its end face is additionally electrolytically polished. It is characterized by two temporally shifted spectra, a short time photo and a recording by a streak camera, being triggered by $i_c$. The commutation time amounted to $t_c = 144 \mu$s.
FIGURE 14 Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode the end face of which is electrolytic polished. The ignition is accelerated by $U_0 = 600$ V. It is characterized by two temporally shifted spectra, a short time photo and a recording by a streak camera being triggered by $i_c$. The commutation time amounted to $t_c = 9.2$ $\mu$s.
FIGURE 15  Two scanning electron microscopy pictures of the electrolytic polished end face of a W electrode taken with a scale of length of 200 and 2 μm before it was inserted into the discharge vessel and exposed to arc commutation.

FIGURE 16  Four scanning electron microscopy pictures of the electrolytic polished end face of a W cathode taken with scales of length of 200 and 20 μm (upper left and right picture), 2 and 1 μm (lower left and lower right picture) after 12 Ar arc commutations. $i_c$ was switched off after 0.65 μs.

Figure 16 presents four SEM pictures of traces generated by 12 cathode spot ignitions on the end face of a electrolytic polished tungsten electrode taken with scales of length of 200 and 20 μm (upper left and upper right picture), 2 and 1 μm (lower left and lower right picture). The pictures present tungsten-dendrites already shown in Figure 15, and crystal like particles with a diameter of 1–2 μm. But craters being generated by arc commutations onto numerous other investigated electrodes are missing. It is correlated to the absence of W-lines within the spectra emitted by the arc spot.

3.5  Arc spot ignition on a cold tungsten cathode doped with Al, K, and Si (BSD- or AKS-material)

Figure 17 presents four pictures captured during arc spot ignition on the end face of a BSD-cathode. The electrode was treated by grinding as BSD-electrodes, which are inserted into HID lamps. The measurements were performed at quite
FIGURE 17  Ignition of an arc spot in Ar 5.6 on the end face of a cold BSD-electrode (tungsten doped with ppm amounts of Al, K, and Si) in the case of $U_2 = 0$ V. The end face was only grinded. It is characterized by two temporally shifted spectra, a short time photo and a record by a streak camera, being triggered by $i_c$. The commutation time amounted to $t_c = 78 \mu$s.
equal conditions as the measurements presented in Figures 1, 6, 9, and 13 without acceleration by \( U_2 \). The pressure of the Ar 5.6 filling of the discharge vessel amounted to 1,061 mbar. The arc commutation took place at \( t_c = 78 \mu s \).

Both spectra given at the top of the figure were recorded within a wavelength interval between 345 and 450 nm at 285 ns and 1.79 \( \mu s \) when \( t_c \) was already switched off since 1.14 \( \mu s \). The exposure time of both spectra amounted to \( t_{\text{exp}} = 500 \) ns. The spectra are composed of Ar I and Ar II lines, Al II lines at \( \lambda = 345.826 \) nm, \( \lambda = 394.400 \) nm, \( \lambda = 396.152 \) nm and seven Al II lines between \( \lambda = 358.655 \) nm and \( \lambda = 358.744 \) nm.[30] The aluminium spectrum is quite similar to that, which is emitted by a cathode spot formed by Kr plasma in front of a cold Al cathode. The spectrum is presented in ref. [1], figure 16. Tungsten lines are missing, even the strong line at \( \lambda = 400.875 \) nm. Potassium lines being emitted within the considered wavelength interval are so weak that they could not be identified. The wavelengths of the strong K atom resonance line duplet amount to 766.490/769.896 nm. They are above the recorded wavelength interval.

The record of arc spot ignition by the NanoCam triggered by the onset of \( i_c \) captured a time interval of 100 ns. It shows a plasma ball attached on the end face of the cathode similar to those, which were observed in front of a polished tungsten cathode in Figure 1, and additionally an oxidized tungsten cathode in Figure 6, a tungsten cathode with a pasted end face in Figure 9 and a tungsten cathode with a polished end face in ref. [26]. The streak camera was triggered by the start of \( i_c \). It shows a luminous layer at the beginning of arc commutation, which contracts to a spot within 100 ns.

The measurements given in Figure 18 were performed under the same operation conditions as the measurements presented in Figure 17. Only the arc commutation was accelerated by \( U_{\text{ac}} = 600 \) V. The commutation time amounted to \( t_c = 6 \) \( \mu s \), the commutation current was switched off after 0.65 \( \mu s \). Both spectra at the top of Figure 18 were recorded under the same conditions as the spectra in Figure 17. They differ scarcely. The discharge in front of the CE recorded by the NanoCam with an exposure time of 100 ns immediately after arc spot ignition is formed by a rolling channel similar to that in Figure 14. At the beginning of the streak camera record, triggered by \( i_c \), a thin bright layer in front of the cathode surface is shown. It contracts within 20 ns to a highlighted arc spot, which disappears after \( i_c \) is switched off.

The traces of 17 arc spot ignitions in Ar 5.6 on the end face of the BSD-cathode are presented on four SEM pictures in Figure 19 with scales of length of 200, 20, 2, and 1 \( \mu m \). Only bright larger areas can be identified on the cathode surface presumably generated by locally enhanced heat transfer, by which a thin layer covering the end face of the electrode is removed. Fully developed craters are missing. The SEM pictures are similar to those in Figure 16 generated by arc spot ignition on an electrolytic polished end face of a tungsten cathode and to those generated by cathode spot ignition on the end face of a Pt cathode given in Figure 19 of ref. [8].

### 3.6 Arc spot ignition on cold tungsten cathodes doped with ThO\(_2\)

Figure 20 presents four pictures taken during arc spot ignition on a cathode made of tungsten doped with 3 w% ThO\(_2\) (G30), which is as the W electrode investigated in Figure 1 polished with diamond suspensions of decreasing grain sizes down to D0.25. The arc was ignited within a Ar 5.6 filling of the discharge vessel between the horn electrodes within it. An acceleration of arc commutation by an additional voltage \( U_2 \) was not applied. The commutation time amounted to \( t_c = 69 \mu s \).

Both spectra at the top of the figure were recorded between 340 and 445 nm at 385 ns and 1.89 \( \mu s \) after the start of \( i_c \) with an exposure time of \( t_{\text{exp}} = 500 \) ns. When the second spectrum was taken, \( i_c \) was already switched off. Both spectra consist predominately of Ar I and Ar II lines. The spectrum taken at 385 ns shows also some lines, which can be attributed to thorium according to ref. [30] instead to Ar II or W I lines:

The Th I line at \( \lambda = 371.944 \) nm \( (E_u = 3.33 \text{ eV}) \) and the Th II lines at \( \lambda = 401.913 \) nm \( (E_u = 3.08 \text{ eV}) \), \( \lambda = 408.504 \) nm \( (E_u = 4.3 \text{ eV}) \), \( \lambda = 408.652 \) nm \( (E_u = 3.03 \text{ eV}) \), \( \lambda = 409.475 \) nm \( (E_u = 3.03 \text{ eV}) \), \( \lambda = 428.204 \) nm \( (E_u = 3.66 \text{ eV}) \), \( \lambda = 438.186 \) nm \( (E_u = 3.66 \text{ eV}) \), \( \lambda = 439.111 \) nm \( (E_u = 3.66 \text{ eV}) \).

The spectrum taken at 1.89 \( \mu s \) shows additional to lines attributed within the upper spectrum to thorium, some more Th I and Th II lines namely the Th I lines at \( \lambda = 344.258 \) nm \( (E_u = 4.21 \text{ eV}) \), at \( \lambda = 347.121 \) nm \( (E_u = 4.05 \text{ eV}) \) and the Th II line at \( \lambda = 374.119 \) nm \( (E_u = 3.5 \text{ eV}) \), the Th I/Th II line at \( \lambda = 420.889 \) nm \( (E_u = 2.94 \text{ eV/3.76 eV}) \) and in addition the most pronounced W I line at \( \lambda = 400.875 \) nm.

The appearance of the discharge taken by the NanoCam immediately after the onset of \( i_c \) with an exposure time \( t_{\text{exp}} = 100 \) ns is dominated as in Figure 1 by a plasma ball attached to the end face of the cathode. The triggering of the streak camera was initiated by the start of \( i_c \). The streak camera record starts together with the photo by the NanoCam and reflects switching off of \( i_c \), 0.65 \( \mu s \) after arc commutation by a reduction of light emission.
FIGURE 18 Ignition of an arc spot in Ar 5.6 accelerated by \( U_{2b} = 600 \) V on the end face of a cold BSD-electrode, which was only ground. It is characterized by two temporally shifted spectra, a short time photo and a record by a streak camera being triggered by \( i_c \). The commutation time amounted to \( t_c = 6.0 \) μs.
The measurements presented in Figure 21 were performed adjusting the same operation conditions as in Figure 20. Only the arc commutation was additionally accelerated by $U_2 = 400$ V. The commutation time amounted to $t_c = 4.8 \mu s$, the commutation current $i_c$ was switched off after 0.65 $\mu s$. Both spectra at the top of the figure were recorded within a wavelength interval from 315 and 420 nm with an exposure time of 300 ns. The upper spectrum was taken within a time interval from 385 to 685 ns, the record of the lower spectrum was started at 1.69 $\mu s$. The spectra show some Ar II and presumably also some Ar I lines between 390 and 400 nm. Some other lines considered as Ar II lines may be also attributed according to the spectra in Figure 20 to Th lines, namely to the Th I line at $\lambda = 371.944$ nm, the Th II lines at $\lambda = 401.913$ nm, $\lambda = 408.504$ nm, $\lambda = 408.652$ nm and $\lambda = 409.475$ nm. In addition some other thorium lines are indicated, namely the Th I lines at $\lambda = 344.258$ nm and $\lambda = 347.121$ nm and the Th II line at $\lambda = 374.119$ nm.

The shape of the discharge was recorded by the NanoCam triggered immediately after arc commutation with an exposure time of 100 ns. It shows a plasma ball being attached to the end face of the cathode and an arc column, which starts from the left side of the plasma ball towards the hole within the blind in front of the horn electrodes. The streak camera record being triggered by the rise of $i_c$ looks totally different from that in Figure 3 taken in front of a cathode made of pure tungsten. It starts with a luminous layer, which covers nearly the whole end face of the cathode. It contracts to a cathode spot, by which the commutation current $i_c$ is taken over, within several 10 ns. Moreover, it shows the switching off of $i_c$ after 0.65 $\mu s$. The luminous layer in front of the cathode may be generated by a large number of electron-emitting sites being distributed uniformly on the end face of the cathode.

Figure 22 reproduces four SEM pictures of the end face of a tungsten cathode doped with 3 wt% of ThO$_2$ (G30), on which traces of 10 arc commutations in Ar 5.6 are left by the commutation current $i_c$ during a time interval of 0.65 $\mu s$. The upper left and upper right picture were taken with a scale of length of 2 $\mu m$, the lower left and right picture with a scale of length of 1 $\mu m$. The pictures show surface areas with fusing traces. Only very tiny craters can be identified within the lower right SEM-picture similar to those in Figure 8.
FIGURE 20 Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode doped with 3 wt% ThO₂ (G30) polished down to D0.25, being characterized by two temporally shifted spectra, a short time photo, and a record by a streak camera, which is triggered by $i_c$. Acceleration of arc spot ignition by $U_2$ is omitted, $i_c = 8$ mA, $t_c = 11.7$ μs. The commutation time amounts to $t_c = 69$ μs.
FIGURE 21  Ignition of an arc spot in Ar 5.6 on the end face of a cold tungsten cathode doped with 3 wt% ThO₂ (G30) polished down to D0.25, being characterized by two temporally shifted spectra, a short time photo, and a record by a streak camera, which is triggered by \( i_c \).

The arc spot ignition was accelerated by \( U_2 = 400 \) V. The commutation time amounts to \( t_c = 4.8 \) μs.
FIGURE 22 Four scanning electron microscopy pictures of the end face of a W cathode doped with 3 wt% ThO$_2$ (G30) polished down to D0.25. The upper left and right picture were taken with a scale of length of 2 μm, the lower left and right picture with a scale of length of 1 μm. The traces were generated by 10 arc commutations in Ar5.6, executed by $i_c$ lasting 0.65 μs.

4 | CONCLUSION

The properties of electrodes made of tungsten differ distinctly from those made of aluminium, copper, titanium, and graphite investigated in ref. [1] and of those made of gold, palladium, and platinum investigated in ref. [8]. The boiling temperature $T_b = 6203$ K is at least 2000 K higher than the boiling temperature of all other electrode materials and the melting temperature $T_m = 3695$ K is at least 1600 K higher than those of the other materials. But the boiling temperatures of $T_b = 2003$ K and $T_b = 2110$ K of the tungsten oxides WO$_2$ and WO$_3$ are distinctly lower than those of the metallic electrodes. Another property of tungsten is that its average work function $\Phi = 4.55$ eV can be reduced by doping the bulk material with ThO$_2$ ref. [25] La$_2$O$_3$, ref. [31,32] Ce$_2$O$_3$ ref. [22] or other rare earth oxides.

As in the examples presented in ref. [1,8] the arc commutation is accelerated if the voltage drop between the arc plasma and the CE is increased. Moreover, the arc commutation is always accompanied by the emission of ion lines and/or atomic lines emitted by high lying levels of the filling gas in front of the cathode. They are an indication of a bombardment of the cathode by ions of the filling gas being accelerated within a thin plasma layer in front of it. [33] The ion bombardment induces the emission of secondary electrons. The ratio between the number of secondary electrons and ions is determined by the secondary electron emission coefficient $\gamma_i < 1$. ref. [34] The secondary electrons start the arc commutation if they are accelerated by the field in front of the cathode onto a kinetic energy, which is required to ionize the filling gas. Their acceleration to sufficient high energy is demonstrated by the observed spectra.

An additional emission of tungsten lines and lines of metals, by which the tungsten electrodes are doped, depends sensitively on the preparation of the electrode surface. If the end face of the tungsten cathode is not only mechanically but also electrolytic polished to clean it from tungsten oxide the spectra presented in Figures 13 and 14 are free from tungsten lines. If the end face of the tungsten cathode is additionally covered with a thick tungsten oxide layer by an additional glowing in a high-frequency furnace after the mechanic polishing procedure at least 10 atomic tungsten lines could be identified within the spectra presented in Figure 6. They provide evidence of tungsten vapour in front of the cathode produced by the dissociation of vaporized tungsten oxide in front of it. The tungsten ions, which are present within the tungsten vapour, increase the bombardment of the cathode surface by ions and with it the secondary electron emission. It
explains the reduction of the commutation time from \( t_c = 144 \mu s \), which is measured, if the cathode surface is additionally electrolytic polished, to \( t_c = 20 \mu s \), if the cathode surface is covered with a thick tungsten oxide layer.

Principally the same effect is found if the arc commutation on a pure tungsten cathode given in Figure 1 and on a BSD-cathode given in Figure 17 is compared. The spectra in Figure 1 show in addition to the Ar I and Ar II lines only a hint to W I lines. In the spectra presented in Figure 17 in addition aluminium atom and ion lines are observed, caused by doping of BSD-electrodes with aluminium, but tungsten lines are missing. The bombardment of the end face of the cathode consisting of pure tungsten in addition by potassium and aluminium ions generated in front of the BSD-cathode reduces the commutation time from \( t_c = 121 \mu s \) to \( t_c = 78 \mu s \).

In ref. [1] the time, elapsing until arc commutation on a pure aluminium cathode took place, elongates to \( t_c = 244 \mu s \) under the same operation conditions as in Figure 17. The increase may be traced back to an \( \text{Al}_2\text{O}_3 \) layer by which the end face of the cathode was covered. \( \text{Al}_2\text{O}_3 \) is an excellent electrical insulator. Therefore, the arc commutation is started by a special dielectric barrier discharge, which needs some time to build up the breakdown voltage of the oxide layer.\(^{[35]}\) The same interpretation may be applied to the results obtained with electrodes made of titanium, requiring \( t_c \geq 2247 \mu s \), and copper, requiring \( t_c \geq 106 \mu s \) for arc commutation.\(^{[11]}\) Oxide layers do not occur on electrodes made of graphite, gold, palladium, and platinum. The commutation times, elapsing until arc spot ignition on cathodes consisting of these materials takes place, amount to \( t_c < 100 \mu s \). In front of these electrodes optical emission of the electrode material—atomic and ionic lines and in front of the graphite electrode C\(_2\) bands—was spectroscopically proven. It is indicating, that ionized electrode material enhances the ion bombardment of the cathode surface causing a reduction of the commutation time \( t_c \) of these materials.

Substituting the pure tungsten cathode being considered in Figure 1 by a G30 cathode (tungsten doped with 3 wt\% \( \text{ThO}_2 \)) the commutation time is reduced from \( t_c = 121 \mu s \) to \( t_c = 69 \mu s \). The reduction may be traced back not only to the bombardment of the cathode by thorium ions, but also to the formation of a thorium mono layer on the end face of the tungsten cathode. By the thorium mono layer the work function of tungsten is reduced from \( \Phi = 4.55\, \text{eV} \) to a minimum value of \( \Phi = 3\, \text{eV} \), if the coverage of the cathode surface by thorium atoms amounts approximately to 50\%.\(^{[25]}\) By the reduction of the work function the electron emission of the tungsten surface is increased and with it the commutation time \( t_c \) reduced. The commutation times \( t_c \) measured in ref. [1] have already given a hint for a reduction of \( t_c \) by a decrease of the work function \( \Phi \). But comparing the commutation time \( t_c = 78 \mu s \) of the BSD-cathode with \( t_c = 69 \mu s \) of the G30 cathode suggests that also the commutation time of the thoriated cathode may be determined predominantly by the secondary electron emission generated by thorium ions.

Pasting the end face of the W cathode with dusty electrode material causes a large scatter of the commutation time. For example, values of \( t_c = 59 \mu s \) and \( t_c = 198 \mu s \) were measured. The transmutation of tungsten particles into microcrystals by arc commutation shows that they convert by a power input from a plasma sheath, which envelopes the particles, into liquid droplets, which cool down subsequently. It differs from pasting the end face of a palladium cathode in ref. [8], which results in a quite low commutation time \( t_c = 74 \mu s \). Moreover, records of the end face of the Pd cathode by SEM after arc commutation show a rippled surface formed by molten dusty particles with tiny craters in between\(^{[8]}\) (Figure 15). The different effect of arc commutation on the surface structure of pasted tungsten and palladium cathodes may be attributed to the different melting temperatures of W and Pd amounting to \( T_m = 3695\, \text{K} \) and \( T_m = 1828.05\, \text{K} \). An implosion induced by the recoil of abruptly vaporizing electrode material may also have an influence on the deformation of the dusty particles.

The investigation of the interaction of a dense plasma with cold cathodes made of Al, Cu, Ti, graphite, Au, Pd, Pt, and W can be summed up as follows:

The arc commutation on a cold cathode is started by a bombardment of the whole end face of the electrode with ions generated within a pre-sheath, which separates the positive space charge sheath in front of the cathode from the bulk plasma.\(^{[33]}\) A review on this subject is given in ref. [19]. The ion bombardment initiates the emission of secondary electrons by the cathode surface.\(^{[34]}\) The emitted electrons, subsequently accelerated in the space charge sheath in front of the cathode, enhance the power input into the plasma boundary layer in front of the cathode increasing the number of ions by which the cathode surface is bombarded. A luminous layer covering the whole end face of the cathode at the beginning of numerous streak camera records visualizes the increased electron temperature causing an enhanced ionization rate in the pre-sheath. It is predominantly observed when the arc commutation takes place in krypton instead in argon. The higher ionization energy and lower mass of argon shorten presumably the light emission of the layer so that its record becomes more difficult. The interpretation confirms the role of secondary electron emission obtained by numerical modelling cold cathodes of high-pressure arc plasmas.\(^{[36]}\)

The electron emissivity varies in general as a function of the position on the end face of the cathode. It is increased first of all by a locally enhanced secondary electron emission coefficient \( \gamma_i \) and less distinctly by a locally lowered work function.
or by locally increased electric field strength in front of tips on the electrode surface. It produces a jump up within these areas of the power input and with it the electrode temperature and electron emission especially by secondary electron emission, but later on maybe also by field emission, thermo-field emission, and thermionic-emission.[37] The locally enhanced electron emission causes a concentration of the current transfer to an arc spot. It is accompanied by a further increase of the local surface temperature and of the vaporization of electrode material, until its boiling temperature $T_b$, and a vapour pressure is reached equal to that of the gas filling or even exceeded. The ionization energy of the atoms within the vapour consisting of electrode material is in general lower than that of the filling gas. As it is already discussed above the ion density in front of the cathode and the ion current into the cathode spot are further increased by the vapour and with it the power input into the arc spot. It is accomplished by a rising commutation current. Examples are: cathodes consisting of tungsten covered with a thick oxide layer being investigated in Section 3.2, cathodes consisting of aluminium with $T_b = 2743 \text{ K}$, of copper with $T_b = 2868 \text{ K}$, of titanium with $T_b = 3533 \text{ K}$, of graphite with $T_b = 4023 \text{ K}$, being investigated in ref. [1], and cathodes consisting of gold with $T_b = 3243 \text{ K}$ and of palladium with $T_b = 3233 \text{ K}$, being investigated in ref. [8].

The vapour consisting of electrode material generates not only a positive but also a negative feedback. It cools the plasma in front of the electrode since its initial temperature is the distinctly lower boiling temperature of the electrode material. Therefore, the difference between a positive and negative feedback of the vaporized electrode material on the development of the cathode spot decreases with increasing vaporization rate. When the difference becomes higher at a different point on the electrode surface it is taking over the commutation current. An example is shown in Figure 9. The former arc spot goes out leaving a crater on the surface. By a repetition of this process, several craters are formed on the cathode surface during arc commutation. Their distribution depends on the structure of the electrode surface and in addition on the thermal properties of the electrode material. When the operation of argon arcs with graphite electrodes was investigated many years ago it was already observed that an enhanced vaporization of graphite may disturb a stationary current transfer onto the cathode.[38–40]

A counterexample is given by mechanically and additionally electrolytic polished tungsten cathodes. Its investigation in Section 3.4 neither shows tungsten lines within the optical spectrum recorded in front of the CE nor craters on the SEM records of the electrode surface after arc commutation. A special case is doped tungsten cathodes. When the arc commutates on BSD cathodes and may be also on thoriated cathodes vaporized and subsequently ionized doping material supports at first the arc commutation. But the local depletion of doping material with locally increasing electrode temperature promotes the extension of the current transfer zone and hampers the formation of craters.

An example in between are cathodes consisting of platinum with $T_b = 4100 \text{ K}$. Its investigation in Section 3.3 of ref. [8] shows Pt lines within the optical spectrum recorded in front of the cathode, but craters on the SEM records taken after arc commutation are rare. It indicates that platinum vapour is presumably already produced by sputtering and evaporation at electrode temperatures below the boiling temperature.

Preceding investigations at hot tungsten cathodes have already demonstrated that the positive feedback effect of an ion current from the plasma side, governed by the dependence of the Saha-equation on the electron temperature, and an electron emission of the cathode, determined by the dependence of the Richardson-equation on the electrode temperature, is the basic process enabling cathode operation.[17–19]

5 | OPEN QUESTIONS AND FURTHER APPROACH

The investigation of arc commutation on differently prepared cold tungsten cathodes has clarified the basic mechanism of arc spot ignition to a large extent. Its principal understanding may be the starting point for more detailed experimental investigations and theoretically modelling. The commutation times $t_c$ being required for an interpretation of the experimental results should be made more reliable by additional measurements. A higher temporal resolution may further improve an understanding of arc commutation on cold cathodes. They may answer the question of whether the arc spot ignition is always initiated by an extended luminous layer between the bulk plasma and the cathode surface. An up to now missing relation between the arc traces recorded by SEM pictures and the voltages, by which the arc commutation is initiated, has to be made up. A first attempt was already made by the two SEM records of arc traces on the end faces of Al cathodes, given in ref. [1], Figures 13 and 15. An attempt should be made to check spectroscopically the presence of oxygen.

Measurements applying other gas fillings, for example, $H_2$ or Xe to reduce the difference between ionization energy of the filling gas and of the electrode material may confirm the interpretation. A variation of the filling gas pressure and of the voltage applied between the arc plasma and the CE may deliver additional information on arc spot ignition.
Pasting the end face of tungsten electrodes or doping solid tungsten with other materials may show interesting effects. An improved understanding of arc commutation onto cold cathodes may be achieved by an investigation of arc commutation onto cold anodes. By reason of the field inversion in front of cold anodes there may be some similarities between cathode and anode.[34,41,42] An improved understanding of arc commutation may help to implement measures by which arcing in plasma devices can be prevented.

ACKNOWLEDGEMENTS

The authors are indebted to Deutsche Forschungsgemeinschaft, which has financed to a large extent the research (Reference number of the project Me 615/20-1, Me 615/20-2). They are also indebted to Dr Ralf D. Neuser at the Central SEM Facility of Geo—Sciences at RUB, who has generated the SEM pictures presented within the paper, and to the Institute of Plasma Physics, TU Hannover, under the direction of the late Prof Dr W. Bötticher, which has provided on loan the Hamamatsu streak camera. The authors appreciate the interest in this research by the late Prof Dr J. Heberlein, University of Minnesota, Minneapolis, of the retired Prof Dr H.-J. Kunze, RUB, and Prof Dr P. Awakowicz, holding the chair AEPT at RUB. Open Access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

Research data are not shared.

REFERENCES

[1] S. Frohnert, J. Mentel, Investigation of the Interaction of a Dense Noble Gas Plasma With Cold Cathodes: I Experimental Setup and Application to Al, Cu, Ti and Graphite Cathodes Contrib. Plasma Phys. 2022, in press.
[2] K. P. Nachtigall, J. Mentel, IEEE Trans. Plasma Sci. 1991, 19-5, 942.
[3] K. P. Nachtigall, J. Mentel, IEEE Trans. Plasma Sci. 1991, 19-5, 947.
[4] R. Bayer, J. Schein, M. Schumann, J. Mentel, IEEE Trans. Plasma Sci. 1997, 25-5, 1096.
[5] R. Bayer, J. Schein, M. Schumann, J. Mentel, IEEE Trans. Plasma Sci. 1997, 25-5, 1110.
[6] J. Schein, M. Schumann, D. Nandelstaedt, J. Mentel, IEEE Trans. Plasma Sci. 1997, 25-5, 897.
[7] S. Frohnert, PhD Thesis, Ruhr-Universität, Bochum, Germany, Berlin Tenea 2004
[8] S. Frohnert, J. Mentel, Investigation of a Dense Noble Gas Plasma With Cold Cathodes: II Arc Spot Ignition on Au, Pt and Pd Cathodes Contrib. Plasma Phys. 2022, in press.
[9] I. Choquet, Weld. World 2018, 62-1, 177.
[10] M. Baeva, U. Hurland, Weld. World 2019, 63-2, 377.
[11] J. Waymouth, Electric Discharge Lamps (Monograph in Modern Electrical Technology), MIT Press, Cambridge, MA 1971.
[12] M. Czichy, T. Hartmann, J. Mentel, P. Awakowicz, J. Phys. D: Appl. Phys. 2008, 41, 144027.
[13] T. Hoebing, A. Bergner, B. Koch, F. Manders, C. Ruhrmann, J. Mentel, P. Awakowicz, J. Phys. D: Appl. Phys. 2014, 47, 205501.
[14] A. Bergner, S. Groeger, T. Hoebing, C. Ruhrmann, U. Hechtfischer, G. Tochadse, J. Mentel, P. Awakowicz, J. Phys. D: Appl. Phys. 2014, 47, 355205.
[15] A. Bergner, M. Engelhardt, S. Bienholz, C. Ruhrmann, T. Hoebing, S. Groeger, J. Mentel, P. Awakowicz, J. Phys. D: Appl. Phys. 2015, 48, 025201.
[16] S. Lichtenberg, D. Nandelstaedt, L. Dabringhausen, M. Redwitz, J. Luhmann, J. Mentel, J. Phys. D: Appl. Phys. 2002, 35, 1648.
[17] S. Lichtenberg, L. Dabringhausen, O. Langenscheidt, J. Mentel, J. Phys. D: Appl. Phys. 2005, 38, 3112.
[18] L. Dabringhausen, O. Langenscheidt, S. Lichtenberg, M. Redwitz, J. Mentel, J. Phys. D: Appl. Phys. 2005, 38, 3128.
[19] M. S. Benilov, J. Phys. D: Appl. Phys. 2008, 41, 144001.
[20] M. Westermeier, O. Langenscheidt, J. Reinelt, J. Mentel, P. Awakowicz, IEEE Trans Plasma Sci. 2008, 36, 1176.
[21] A. Bergner, F. H. Scharf, G. Kuehn, C. Ruhrmann, T. Hoebing, P. Awakowicz, J. Mentel, Plasma Sources Sci. Technol. 2014, 23, 054005.
[22] J. Mentel, J. Phys. D: Appl. Phys. 2018, 51, 033002.
[23] M. Redwitz, L. Dabringhausen, S. Lichtenberg, O. Langenscheidt, J. Heberlein, J. Mentel, J. Phys. D: Appl. Phys. 2006, 39, 2160.
[24] J. Mentel, J. Heberlein, J. Phys. D: Appl. Phys. 2010, 43, 02302.
[25] A. Bergner, M. Westermeier, C. Ruhrmann, P. Awakowicz, J. Mentel, J. Phys. D: Appl. Phys. 2011, 44, 505203.
[26] J. Schein, M. Schumann, J. Mentel, IEEE Trans Plasma Sci. 1996, 24-1, 59.
[27] M. Schumann PhD Thesis, Ruhr-Universität, Bochum, Aachen: Shaker Verlag Germany 1997
[28] J. Schein PhD Thesis, Ruhr-Universität, Bochum Germany 1996.
[29] H. U. Obbarius, M. Kock, J. Phys. B: At. Mol. Phys. 1982, 15, 527.
[30] NIST, atomic spectra database. Retrieved from https://www.nist.gov
[31] T. Hoebing, P. Hermanns, A. Bergner, C. Ruhrmann, H. Traxler, I. Wesemann, W. Knabl, J. Mentel, P. Awakowicz, J. Appl. Phys. 2005, 118, 023306.
[32] H. Traxler, I. Wesemann, W. Knabl, M. Nilius, M. Morkel, T. Hoebing, J. Mentel, P. Awakowicz, Int. J. Refract. Metals Hard Mater. 2018, 74, 93.
[33] H. Schmitz, K. U. Riemann, J. Phys. D: Appl. Phys. 2001, 34, 1193.
[34] B. Chapman, Glow Discharge Processes, Wiley, New York 1980.
[35] U. Kohlschütz, Plasma Chem. Plasma Process. 2003, 23, 1.
[36] D. F. N. Santos, M. Lisnyak, N. A. Almeida, L. G. Benilova, M. S. Benilov, J. Phys. D: Appl. Phys. 2021, 54, 195202.
[37] E. Murphy, R. Good, Phys. Rev. 1956, 102, 1464.
[38] J. Mentel, Appl. Phys. 1977, 14, 269.
[39] J. Mentel, Appl. Phys. 1977, 14, 361.
[40] J. Mentel, Appl. Phys. 1978, 15, 179.
[41] J. Heberlein, J. Mentel, E. Pfender, J. Phys. D: Appl. Phys. 2010, 43, 023001.
[42] T. Hoebing, A. Bergner, P. Hermanns, J. Mentel, P. Awakowicz, J. Phys. D: Appl. Phys. 2016, 49, 155504.

How to cite this article: S. Frohnert, J. Mentel, Contributions to Plasma Physics 2022, 62(7), e202100216. https://doi.org/10.1002/ctpp.202100216