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Work Function of Cs-Free Materials for Enhanced H⁻ Surface Production

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Abstract. Materials with inherent low work function (WF) are the most promising alternatives to Cs evaporation in future negative ion sources. In a dedicated experiment lanthanated (WL10, WL2, MoLa, LaB₆) and bariated materials (TDC) as well as molybdenum implanted with Cs are studied regarding their achievable WF at ion source relevant conditions, in particular for temperatures below 500 °C. In contrast to their usual application as electron emitters at temperatures above 1000 °C, the work functions of the investigated materials under these conditions do not decrease below 3.6 eV (measured global minimum, achieved with LaB₆). For the lanthanated materials, the obtained WF values are stable under plasma exposure times of several hours. However, for all the materials the work function is subject to degradation in absence of heating or plasma exposure. Compared to Cs evaporation, with WF values measured down to 2.1 eV, none of the materials tested so far can be regarded as an actual alternative.

INTRODUCTION

Efficient production of negative ions requires surfaces with low work function [1]. Typically, evaporation and adsorption of Cs is used for this purpose [2, 3] as it has the lowest WF among all the elements (2.1 eV [4]). However, in addition, Cs is the most reactive alkali metal and its high vapor pressure leads to a high volatility of the surface layer. Hence, under conditions of negative ion sources with non-negligible amounts of impurities from the background gases (vacuum of 10⁻⁶ mbar) and interaction with the low pressure hydrogen plasma in front of the surface, high dynamics including deterioration [5] and redistribution [6] occur. The expected Cs consumption as well as a desired stable and homogenous work function thus drives the question for alternative materials to caesium [7].

It was already shown [8, 7] that under ion source plasma conditions only materials with low work function result in an enhanced negative ion density above the surface. Among those, Cs is by far the most efficient material. Under hydrogen plasma exposure, WF values around those of a virtually pure caesium layer, i.e. 2.0–2.2 eV, are reached [5]. In order to rate the determined results of alternative materials on the negative ion densities, dedicated measurements of the work function are performed at a separate setup with comparable conditions.

EXPERIMENTAL SETUP AND MATERIALS

Determination of the work function of different materials is performed at the laboratory setup ACCesS (planar ICP, $\varnothing = 15$ cm, $h = 10$ cm, 600 W max.) [9, 10, 5]. Influence of plasma exposure on the WF is investigated by measuring the WF in short intermediate gas phases (around 3 min) alternating with long plasma exposure times (minutes up to hours). Samples of minimum sizes of 2 × 2 cm are mounted on the sample holder, which is capable of heating the materials temperature controlled up to 450 °C. Detailed information on the setup and its diagnostics in vacuum and plasma can be found in the preceding publications. In particular, determining absolute work function values is based on the photoelectric effect using the enhanced Fowler method [11] by which an accuracy of about ± 0.1 eV is achieved.

Materials with expected low surface work function (below 2.8 eV) are widely used as electron emitter cathodes. Most of them need to be activated at high temperatures (up to 1500 °C) and their WF is usually determined at these high temperatures using the thermionic electron emission current. Operation of ion source grids at those high temperatures is, however, not easily viable: on the one hand, temperature stabilization and alignment of a multistage extraction and acceleration system is difficult at high temperatures. On the other hand, high thermionic electron emission will occur

which might interfere with the necessity of reducing the co-extracted electron current [3]. Thus, the achievable work function for 'low temperatures' (here $< 500\text{ }^{\circ}\text{C}$) is of interest. The investigated materials including their nominal WF values and the respective references are given in table 1.

RESULTS AND DISCUSSION

The low work function materials are tested regarding the influence of heating and plasma exposure on their work function. Stability and degradation behavior during the measurement campaigns is of interest as well. Figure 1 shows a typical evolution of a measurement campaign, exemplarily for LaB_6 .

After installing the sample in the experiment and before any treatment, the WF is higher than 4.2 eV, most probable due to adsorption of impurities at the surface from atmospheric air. Heating the sample in vacuum (10^{-6} mbar) to temperatures of slightly below $400\text{ }^{\circ}\text{C}$ decreases the WF to around 3.7 eV in minimum. After switching off the heating, the WF shows a slight degradation to values of around 4.0 eV at temperatures of around $60\text{ }^{\circ}\text{C}$. Igniting a hydrogen plasma in front of the sample surface with plasma parameters close to those of ion sources [9] leads to the influx of energetic particles and photons from the plasma [5]. A short pulse of 5 min is sufficient to directly enhance the WF to about 3.6 eV. The temperature of the sample surface during this first pulse is $125\text{ }^{\circ}\text{C}$ in maximum. The low WF is stable in plasma for at least about 2 h. A deterioration of about $+0.4\text{ eV/h}$ is observed after switching off the plasma.

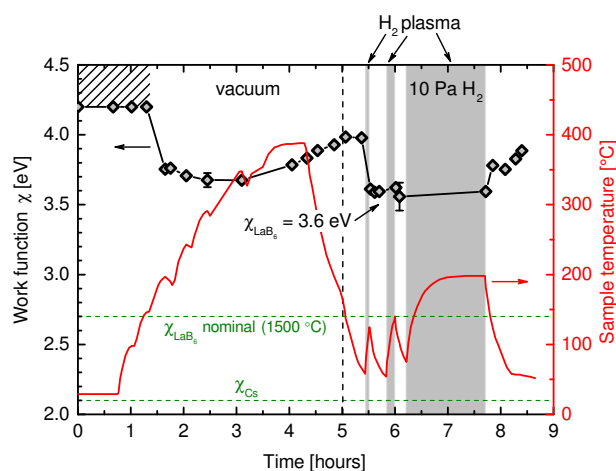


FIGURE 1. Work function of a LaB_6 bulk sample under influence of heating and H_2 plasma exposure (10 Pa, 250 W RF power).

This demonstrates, that the work function of LaB_6 can be decreased by removal of impurities from the surface. This can either be achieved by heating to temperatures of at least $250\text{ }^{\circ}\text{C}$ or by exposing the sample to an ion source relevant hydrogen plasma. In order to test even higher surface temperatures, the sample was also exposed to an Ar plasma (4 Pa, 400 W) reaching temperatures of up to $950\text{ }^{\circ}\text{C}$. However, the minimally achievable WF in all the cases was 3.6 eV. As activation is expected only at about $1500\text{ }^{\circ}\text{C}$ [18], the nominal WF of 2.7 eV could not be achieved. This highlights the necessity for operation at high surface temperatures.

Comparable campaigns were performed also for the other materials. The absolute values are given in table 1 and the main findings are listed below. Furthermore, all of the materials showed slight degradation with rates of around 0.2–0.4 eV/h after heating or after plasma exposure.

Cs-doped Mo: The nominal value for 6% surface coverage of Cs is around 3.9 eV, which was confirmed in experiment after a short plasma pulse of 4 min. However, with increasing plasma exposure time, the WF increased and after only 15 min of integrated plasma-on time, the work function of the bare molybdenum substrate was measured ($\approx 4.4\text{ eV}$). This behavior agrees well with the observations in Cristofaro et al. [10] and can be attributed to the removal of the thin Cs layer from the surface.

Lanthanated materials: A beneficial effect of heating and/or plasma exposure was observed for WL10, WL2 and MoLa. But for none of the materials WF values of below 3.9 eV could be obtained. The reason is again believed to be the low surface temperature, which was $950\text{ }^{\circ}\text{C}$ in maximum (reached during Ar plasma exposure). Hence, the materials cannot be activated under these conditions. Nevertheless, the work function was stable under long time temperature and plasma treatment.

Tungsten dispenser cathode (TDC): For the bariated TDC a specialized sample holder was used, capable of heating to temperatures of 1000 °C. A temperature dependent decrease of the WF could be observed: at 600 °C a value of 3.65 eV was reached. However, increasing the temperature further led to a steep increase of the dark current (probably electron emission from the hot surface) such that determination of the work function using photocurrents was no longer possible. Moreover, RBS measurements performed at probes from the chamber revealed, that the TDC emitted non-negligible amounts of barium and tungsten.

TABLE 1. Overview of the investigated low work function materials including their nominal work function (WF) and the actually measured values under ion source conditions. WL = lanthanated tungsten, MoLa = lanthanated molybdenum, LaB₆ = lanthanum hexaboride, TDC = tungsten dispenser cathode.

Material	Composition	Nominal WF	References	Measured WF	
				upon heating in vacuum (< 500 °C)	in plasma
Cs-doped Mo	6 % Cs at surface	≈ 3.9 eV	[12, 13]	–	3.9 eV unstable
WL10 & WL2	La ₂ O ₃ in W (1.0 % & 2 % La)	2.8 eV @ 1500 °C	[14, 15, 16]	4.3 eV	4.05 eV
MoLa	La ₂ O ₃ in Mo (0.7 % La)	2.6 eV @ 1500 °C	[17, 15]	3.95 eV*	3.95 eV
LaB ₆	bulk LaB ₆	2.7 eV @ 1500 °C	[18]	3.7 eV	3.6 eV
TDC (311)	3 BaO : CaO : Al ₂ O ₃ in porous W	2.1 eV @ 1000 °C	[19]	3.65 eV	[not possible]

* Value might be influenced by a possible oxidation of the aged sample surface.

CONCLUSIONS

The work function of several alternative materials to Cs evaporation were measured under ion source conditions, in particular at temperatures of below 500 °C, showing in minimum 3.6 eV for LaB₆. Only the bariated TDC might have a lower work function, but high electron emission currents and evaporation of barium and tungsten disqualify the material. In comparison, caesiated surfaces reach work functions down to 2.1 eV [5] at the same conditions. An increase of the negative ion density by a factor of around 2.5 was measured for Cs, whereas only enhancements by a factor of less than 1.5 were detected for the alternative materials [8, 7]. Hence, the determined WF values agree well with the determined influence on n_{H^-} , which illustrates the much lower performance of alternative materials compared to the effect of in-situ caesiation. However, in order to draw a final decision on any alternative material to Cs, a concluding test has to be made at an actual extraction system for negative ions, where the extracted currents including the influence on the co-extracted electron current can be investigated.

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