Low-Voltage Arc in Alkaline-Earth Metal Vapors

A A Bogdanov and A M Martsinovsky
Ioffe Institute, 26 Politekhnicheskaya, St Petersburg 194021, Russian Federation

E-mail: amartsinovsky@gmail.com

Abstract. The work continues the earlier study of the Knudsen short (3 mm interelectrode distance) low-voltage arc in barium and strontium vapor. Probe measurements of plasma parameters for strontium were carried out in a wide range of discharge parameters (pressure $10^{-2}$ – $10^{-1}$ Torr, currents 0.5 to 30 A/cm$^2$, anode voltage up to 10 V) in a stationary mode. The main regularities of changes in plasma concentration and electron temperature by the current-voltage characteristic are established. The kinetics of non-stationary processes — ignition of the discharge and plasma decay after the end of a pulse, was also investigated. A number of differences in plasma behavior compared to cesium arc were found, however, in general, the behavior of strontium discharge plasma turned out to be quite close to that of cesium unlike low-voltage arcs in inert gases. This is explained by the similar nature of the energy level scheme in atoms of alkali and alkaline-earth metals.

1. Introduction
Low-voltage arcs burning at voltages lower than ionization potential were originally detected in inert gases [1]. Such a low burning voltage is explained by the presence of a potential well for electrons in the interelectrode gap and the stepwise generation of ions [1-3]. Such arcs also exist at low pressures, when the free path of the fast electrons of the cathode beam (electrons accelerated at the cathode potential drop) is longer than the interelectrode distance $d$. The plasma concentration $n_e$ at low pressures is small; therefore, the length of the electron beam relaxation in energy at pair Coulomb collisions is also greater than $d$. The mechanism of energy transfer from the cathode beam to the plasma under such conditions remained unclear.

The problem was solved in the study of the cesium arc. It was shown that when a low-pressure cesium discharge is ignited the stepwise generation of ions [4] and the intense heating of plasma electrons by a beam [5] begin at an early stage of discharge development, at concentrations $n_e \sim 10^{10}$ cm$^{-3}$. It was assumed that the heating occurs due to the energy of plasma oscillations [5] excited by the cathode beam [6]. It was shown [7] that such energy transfer is possible due to the damping of the Langmuir waves during the scattering of plasma electrons by atoms and ions. The experiment confirmed that the share of transmitted energy is really close to $\frac{1}{2}$ [8]. Thus, plasma heating due to collective processes turned out to be possible at volt beam energies (and not just kilovolt [9, 10]).

A more complete study of arcs in inert gases, for example, xenon [11, 12], showed that their macroscopic characteristics are very different from those of cesium discharges. Such characteristics include the localization of the glow, the existence of different modes, and the type of current-voltage characteristics (I–U characteristics). This difference is due to the large difference in the cross sections of elementary processes for the Cs atom and for inert gas atoms, the difference in the ionization potentials and the scheme of the energy levels of these atoms. In this regard, it was interesting to see...
the properties of the discharge in a different environment. For this, alkaline-earth metals barium and strontium were chosen, the atoms of which have a cesium-like energy level scheme, a slightly different ionization potential and relatively close sections of elementary processes. In addition, their adsorption on refractory metals provides even more than for cesium, emission from the cathode, which eliminates the need to use impregnated cathodes.

The results of the study of current-voltage characteristics of barium and strontium Knudsen arcs were presented in [13]. It turned out that the I–U characteristics and the laws of their changes with external parameters are very close to those of the cesium arc. Unfortunately, probe measurements in barium with BeO and Al2O3 as insulators of the non-working surface of the probe were not possible due to large leaks. Strontium was less aggressive. Therefore this paper presents the results of probe measurements of the plasma parameters in strontium arc.

2. Description of the experiment

Probe studies of the strontium arc plasma were carried out on a device with an encapsulated discharge gap [13], the design of which is schematically shown in Figure 1. The ends of molybdenum cylinders placed in a ceramic BeO tube with an interelectrode distance of \( d = 3 \text{ mm} \) served as electrodes. The cathode was indirectly heated up to temperature \( T_c = 1800 \text{K} \), strontium was placed into the cavity of the anode in a nipped off iron tube (this minimized strontium oxidation). The anode heater was tantalum foil wrapped around ceramics. The temperature of the anode determined the temperature of strontium in its cavity. Thus, the pressure of saturated strontium vapor \( p \) was determined from the anodic thermocouple readings.

![Figure 1. Experimental device with encapsulated interelectrode gap.](image)

The area of the holes in the anode, through which strontium vapor entered the discharge gap, was about 5 mm\(^2\). It is at least an order of magnitude greater than the area of cracks in the ceramic tube.
(mainly due to the viewing window), so that the strontium vapor pressure could be considered almost equilibrium and saturated.

A probe was made of gilded molybdenum wire with a diameter of 0.1 mm and a working length of 2 mm. It was inserted into a thin (0.6 mm diameter) beryllium ceramic tube, and soldered into a massive copper holder for heat sink. It was inserted into the discharge gap through the hole in the beryllium tube and was located approximately in the center of the gap.

Measurements were performed in a quasistationary mode to minimize heating of the probe and anode by currents from the discharge plasma. Rectangular voltage pulses with duration of ~ 50 μs were applied at the anode with a small repletion frequency (~ 100 Hz). During ignition and quenching of the discharge, the dependence of the current on time was recorded with a resolution of 50 ns. When registering the I–U characteristics, the anode current was measured at the end of the pulse. The probe I–U characteristics could be recorded at any time in the process under study with a time resolution of 50 ns using a special device using the gated integration principle with gate duration of 30 ns.

3. Experimental results and discussion

The parameters of the discharge plasma were investigated at strontium pressures of \( p = 10^{-2} - 10^{-1} \) Torr and currents of \((1 - 30) \text{ A/cm}^2\). Despite the relatively large interelectrode distance, this pressure region corresponded for strontium to a collisionless mode for electrons with respect to scattering by atoms. Accordingly, the probe was collisionless too. Therefore, a simple model of a Langmuir probe could be used to obtain plasma parameters from the probe characteristic. The plasma concentration is determined from the probe ionic saturation current, and the electron temperature is determined from the slope of the semilogarithmic probe characteristic.

![Figure 2](image)

Figure 2. Plasma parameters (a) of the strontium discharge along its I-U characteristic (b). Discharge modes: 1 – \( p = 1.2 \cdot 10^{-2} \) Torr, \( T_e = 1740 \) K; 2 – \( p = 2.5 \cdot 10^{-3} \) Torr, \( T_e = 1730 \) K; 3 – \( p = 1.4 \cdot 10^{-1} \) Torr, \( T_e = 1680 \) K.

Figure 2 shows a typical change in the concentration and electron temperature along the I–U characteristics \((U_a – \text{anode voltage})\). The nature of the change is close to what is observed for cesium: as the anode voltage rises, the electron temperature and concentration increase until the latter reaches saturation with a limiting degree of ionization. Under these conditions, the temperature of the electrons
$T_e$ depends primarily on the anode voltage and pressure. The effect of the current is substantially less as can be seen from the figure. The maximum concentration is the greater, the higher the pressure. The output to it is the faster, the greater the current. However, in a cesium discharge, before the transition to the state of complete ionization, $n_e$ is larger than in strontium, and the transition to full ionization in cesium occurs at lower $j$ and $U_a$. This is due to the fact that the cross section for stepwise ionization in strontium is noticeably less than in cesium, since the ionization and excitation potentials of the strontium atom exceed the corresponding values for cesium, and the excitation cross-sections of strontium atoms are smaller than those for cesium. For small $p$ (about $10^{-2}$ Torr) and $j \sim 1$ A/cm$^2$, a beam is seen on the electron branch of the probe current-voltage characteristics (the same as in the cesium discharge). With an increase in the discharge current, the beam part of the probe characteristic gradually decreases. In general, the dependences of $n_e$ on $j$, $p$, and $U_a$ in the strontium discharge are similar to those in cesium.

It is interesting to note that at $p = 10^{-2}$ Torr and $j > 10$ A/cm$^2$, the plasma concentration $n_e$ in the strontium discharge reaches $10^{14}$ cm$^{-3}$, in cesium at the same pressures, $n_e$ is substantially less. In part, this may be due to the fact that the kinetic of atoms and ions after discharge ignition in the strontium device was different from the cesium once. In cesium devices, the radial boundary of the discharge gap is open, the pressure of cesium vapor is the same throughout the flask, and the growth of the electron pressure in the discharge gap when the discharge is ignited is quickly compensated by the removal of heavy particles — atoms and ions. In the encapsulated device, the exit of heavy particles into the flask through leakages between ceramic and metal parts is negligible. In addition, when strong ionization of strontium atoms is achieved in a discharge, a significant number of double strontium ions Sr$^{2+}$ may appear, since the ionization potential of a single strontium ion Sr$^+$ is 10.38 eV, and the Sr$^+$ level scheme is similar to the schemes for alkali metals and is very favorable for quite effective stepwise ionization. The appearance of a significant number of Sr$^{2+}$ ions should lead to an increase in the ion current per probe at a constant concentration of ions in the gap. In a plasma consisting entirely of twofold ions, such an increase will be maximum and will be $(2)^{3/2} = 2.8$.

Figure 3. a – ignition of the discharge in strontium. $p = 2.2 \cdot 10^{-2}$ Torr, $d = 3$ mm, $T_k = 1495$ K, $U_a = 10.1$ V. Time dependence $j$ (1), $n_e$ (2) and $T_e$ (3). b – decay of strontium discharge plasma. $p = 1.4 \cdot 10^{-1}$ Torr, $d = 3$ mm

1 - $T_k = 1850$ K, $j_s = 33$ A/cm$^2$, 2 - $T_k = 1675$ K, $j_s = 5$ A/cm$^2$. 
Ignition of the discharge in strontium proceeds similarly to ignition in cesium (Figure 3a). There are three stages of development – delay, breakdown and relaxation. The growth of \( n_e \) is more delayed relative to the stage of a sharp increase in current (breakdown). At large \( j \) and \( U_a \), the plasma also goes into a state of complete ionization with similar \( T_e \), however, the development of ionization in Sr is slower than in Cs (difference in cross sections).

The decay of highly ionized plasma at relatively high pressures (Figure 3b) at the initial stage is determined by bulk three-particle recombination. The characteristic time of \( n_e \) decay is 6–7 \( \mu \text{s} \) (with \( n_e = 10^{15} \ \text{cm}^{-3}, \ T_e = 5\cdot10^3 \text{K} \)), which is in good agreement with the estimated time of three-particle recombination. As \( n_e \) decreases, the decay rate gradually decreases, and a transition to the ambipolar diffusion mode occurs. The rapid decay of \( T_e \) at the very beginning of the decay is due to inelastic collisions of electrons with atoms and ions. A further slower decrease of \( T_e \) is determined by the strong cooling effect of the emission electrons and by the volume heat release during the three-particle recombination process. Distribution of temperature \( T_e \) on the gap is determined by the electron thermal conductivity. \( T_e \) is compared with the temperature of the cathode with the transition to the ambipolar decay mode, when the volume heating is almost turned off.

### 4. Conclusion

Thus, the analysis of the characteristics and dynamics of the strontium Knudsen discharge plasma convincingly confirms that low-voltage arcs in alkaline-earth metal vapors in terms of the nature of the processes and their properties are quite close to low-voltage arcs in alkali metals.

### References

[1] Eckart C, and Compton K T 1924 *Phys. Rev.* **25** 139–46.
[2] Druyvesteyn M J 1930 *Z. Physik* **64** 781
[3] Druyvesteyn M J, and Penning F M 1940 *Rev. Mod. Phys.* **12** 87–176
[4] Kaplan V B, Martsinovsky A M, Tsirkel’ B I, and Yuriev V G 1972 *Sov. Phys. –Tech. Phys.* **16** 1130–35
[5] Bogdanov A A, Kaplan V B, Martsinovsky A M, and Yuriev V G 1979. *J de Physique Colloque* **40**, C7 337–38.
[6] Dyuzhev G A, Moyzhes B Y, Nemchinskiy V A, Startsev E A, Shkol’nik S M, and Yuriev V G 1972 *Sov. Phys. –Tech. Phys.* **16** 1910–13
[7] Bakshi T G, Kostin A A, Martsinovsky A M, and Yuriev V G 1979 *Tech. Phys. Let.* **5** 905–10 (in Russian)
[8] Bakshi T G, Bogdanov A A, Kaplan V B, Kostin A A, Martsinovsky A M, and Yuriev V G 1984 *Fisika plasmy* **10** 991–83 (in Russian)
[9] Lebedev P M, Onischenko I N, Tkach Yu V, Fainberg Ja B, and Shevchenko V I 1976 *Fisika plasmy* **2** 407–13 (in Russian)
[10] Ivanov A A, Soboleva T K, and Yushmanov P N 1977 *Fisika plasmy* **3** 52–62 (in Russian)
[11] Ban’kovskii N G, Martsinovskii A M, and Shigalev V K 1983 *Sov. Phys. Tech. Phys.* **28** 35–8
[12] Ban’kovskii N G, Bogdanov A A, Martsinovskii A M, Shigalev V K, and Yuriev V G 1983 *Sov. Phys. Tech. Phys.* **28** 779–83
[13] Bogdanov A A, Kaplan V B, and Martsinovskii A M 2018 *Technical Physics* **63** 789–92