Hollow cathode gun for electron beam annealing

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Abstract. An electron gun with a hollow cathode was tuned to be used in electron beam annealing. Electron beams with an energy of 1 keV and a current of 100 mA were obtained. It is shown that the diameter of the electron beam varies in the range from 7 to 5 mm, while the specific power is from $2 \cdot 10^5$ to $2 \cdot 10^4$ W/m². Such electron beams have a soft, non-destructive effect on the surface and are suitable for electron beam annealing of various films.

1. Introduction
Crystallization methods that use direct action on the original film are divided into the following: laser annealing [1], flash lamp annealing [2], thermal plasma jet [3], and electron beam crystallization [4, 5].

The electron beam has a high specific power, due to which heating occurs very quickly and in a strictly defined place. Exposure to high-energy electron beams leads to local high-speed heating of the sample. In [6], an electron beam with a current density from 1 to 100 mA/cm² was used for the crystallization of a-GeAu film. In this case, at a current density of about 50 mA/cm², the original films crystallized. The authors of [7] showed that an electron source based on a discharge with a hollow cathode can generate a pulsed beam with a current density of up to 8 A/cm², which provides modification of the surface of alumina ceramic.

This work is devoted to the optimization of an electron source [8] based on a discharge with a hollow cathode for its use in electron-beam annealing of thin films.

2. Experiment
The experiments were performed on a low-density gasdynamic setup at the Institute of Thermophysics. A scheme of the experimental setup is shown in Figure 1. The electron beam $I$ was generated in an electron source $2$ based on a hollow-cathode discharge, which was developed at the Institute by the group headed by Dr. Sharafutdinov [8].

The discharge system consists of a hollow cathode, stainless steel anode and accelerating copper electrode. The anode was located at a certain distance from the accelerating electrode. Ceramic insulators have been used in electron guns to insulate electrically the cathode, anode and accelerating electrode. For producing an elevated electron density on the axis, the hollow cathode was “immersed” in the magnetic field generated by permanent magnets. Circulating vacuum oil was used for cooling the discharge chamber. The discharge gas (helium) was fed directly into the hollow cathode. The electron beam was formed by applying potential $U = -1$ kV to the anode relative to the grounded accelerating electrode.
A long-focus magnetic lens 3 was used to change the shape of the electron beam. Part of the beam was cut out with 5 mm aperture 4. The cross section of electron beam after aperture was measured by probe 5, installed on two component coordinate mechanism 6. The probe was 1 mm long and 15 mm in diameter. The electron beam energy and current were 1 keV and 100 mA.

**Figure 1.** Scheme of experimental setup.

Figure 2 shows a photograph of the electron beam for 30 mA focusing current. It is clear that the focus of the electron beam is between the exit from the electron gun and the aperture and it is divergent. Figure 3 shows an example of a measured cross section of electron beam.

**Figure 2.** Photo of electron beam.  
**Figure 3.** Cross section of electron beam.
During processing the experimental data, the size of the electron beam was taken as the width at half maximum, calculated from electron beam cross section. Specific power was equal to: \( q = I \cdot U / S \), where \( U \) is the accelerating potential, \( S \) is the area of the probe, \( I \) is the average current in the range of \( 0.95 \cdot \text{Imax} \pm 5\% \).

3. Results

Figure 4 geometrically shows for a fixed 30 mA focusing current (and, therefore, a constant position of the beam focus) that the size of the electron beam decreases with increasing distance to the aperture. It was experimentally found that with the increasing focusing current the focus of the beam moves to the electron gun exit. It is easy to show that in this case the beam size will also decrease at a constant distance to the diaphragm. This behavior will persist until the beam qualitatively changes its shape from diverging to another by changing the focusing current.

Figure 5 shows the experimental dependences of the electron beam size on the distance to the aperture at different focusing currents. The distance from the aperture to the probe was constant and equal to 40 mm.

![Figure 4](image1.png)  
**Figure 4.** Geometric diagram of electron beam distribution at 30 mA focusing current.

![Figure 5](image2.png)  
**Figure 5.** Dependences of the electron beam size on the distance to the aperture at different focusing currents.

It can be seen from Figure 5 that the size of the electron beam decreases with increasing distance from the electron gun and focusing current, which confirms the above geometric calculations.

With an increase in the focusing current, the focus of the electron beam moves to the electron gun exit, and the electron beam in the “gun – aperture” section becomes more and more defocused. This fact leads to the fact that less and less fraction of the beam falls into the hole in the aperture, which leads to a decrease in the specific power. With an increase in the distance from the electron gun to the aperture and, accordingly, to the probe, the scattering of the electron beam increases by air molecules of the residual atmosphere in the vacuum chamber. This also leads to a decrease in specific power. These effects are illustrated in Figure 6.
Figure 6. Dependence of the specific power on the distance to the aperture for various focusing currents.

4. Summary
An electron gun with a hollow cathode was tuned to be used in electron beam annealing. Electron beam of 1 keV and 100 mA were obtained. It is shown that the diameter of the electron beam varies in the range from 7 to 5 mm, while the specific power is from $2 \cdot 10^5$ to $2 \cdot 10^4$ W/m$^2$ (this is equivalent to a current density of 0.02 – 0.002 A/cm$^2$) depending on the distance to the processing surface and on the focusing current. Such electron beams have a soft, non-destructive effect on the surface and are suitable for electron beam annealing of various films.

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