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Influence of the ion extraction conditions on the ion beam parameters

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A method of theoretical analysis concerning a plasma gun of charged particles has been presented. For this purpose a division of the gun region into the following subregions: the proper gun, lens, and drift space has been made. The influence of particular gun regions on the beam emittance and the slope of the phase graph is described. The dependence of the beam emittance upon both the voltage and current of the beam is given.

1. Introduction

Recently an increasing interest in the ion sources is observed, which is caused by the widespread application of ion beams in the semiconductor technology.

The most frequently used source of ion is plasma.The spread of initial velocities of ions as well as all the shape deformations of the emitting plasma surface result in nonzero emittance during the emission.

This primary value of emittance may not be diminished along the further path of the beam. Thus, the basic problem is to design such an extraction system that the initial value of emittance be as small as possible.

In this paper the evolution of the graph for the beam in the extraction system is discussed; it has been pointed out that the region of beam formation has the largest effect on the beam parameters. The analysis was based on matrix calculations.

2. Beam motion in the phase space

When dealing with the ion beam in the phase space instead of discussing the six-dimensional hiper-volume it is possible in many cases to divide it into three two-dimensional subspaces and consider properties of certain plane figures.

In the Gaussian optics the plane phase figure is reduced to an ellipse, which may be approximated by a suitable parallelogram [1].

Figure 1 presents a graphic transformation of the phase graph from the initial point of the coordinate z_1 (continuous line) to the final point of the coordinate z_2 (broken line).

The transformation of the point $A_1(r_1, r_1')$ to the point $A_2(r_2, r_2')$ and the transformation of the coordinate r_1 of the point B_1 to the coordinate r_2 of the point B_2 is defined by the transformation matrix through the region analysed. It may be shown that [2]

$$\Theta_2 = \frac{r_1}{r_2}\Theta_1 \Delta, \; r_2' + \Theta_2 = r_1\left[a_{21} + \frac{\Theta_1}{r_1}\Delta\right] + a_{22}r',$$

where Δ — determinant of the transformation matrix for the region analysed,
r_1, r_2 — rays of the beam at the points of coordinates z_1 and z_2 on the axis,
Θ_1, Θ_2 — angles between the extreme trajectories of the particles emerging from the points of coordinates r_1 and r_2.

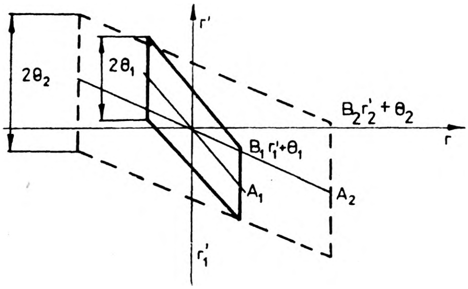

Fig. 1. Transformation of the phase graph from the point of coordinate z_1 to the point of coordinate z_2 on the axis

3. Analysis of the particle movement within the ion gun

The region of the ion gun may be divided into three subregions (Fig. 2). The transformation matrices attributed to the particular subregions of the ion gun have been determined by applying different methods of analysis according to the specific features of each subregion.

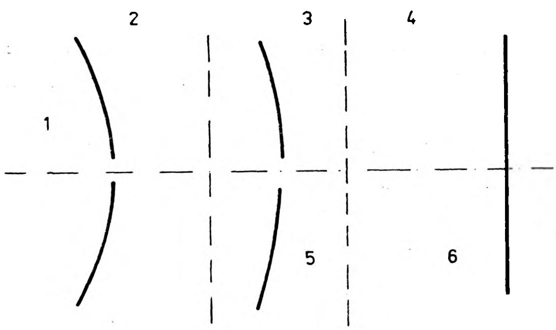

Fig. 2. Division of the gun region into three subregions: 1 — plasma, 2 — proper gun region, 3 — lens region, 4 — drift region, 5 — extracting electrode, 6 — collector

The starting point was the Busch equation which takes account of the space charge effect [3]

$$4U\frac{d_r^2}{dz^2}+2\frac{dU}{dz}\frac{dr}{dz}+\left(\frac{d^2U}{dz^2}+\frac{\varrho}{\varepsilon_0}\right)r=0.$$

3.1. Gun region

In this region the trajectories of the particles, perpendicular to the cathode (plasma) surface are straight lines (principle trajectories). The equation of these trajectories has the form

$$r = a\cdot z. \tag{1}$$

An arbitrary trajectory $r(z)$ in the region of the proper gun may be represented by the product of function representing the trajectory described by eq. (1) and a certain function $\varphi(z)$ of the form

$$\varphi(z) = \int\limits_{z_0}^{z} \frac{dz}{\sqrt{U(z)}\, z^2} + D.$$

Hence, the trajectory $r(z)$ is described by the formula

$$r(z) = az\left[\int\limits_{z_0}^{z} \frac{dz}{\sqrt{U(z)}\, z^2} + D\right].$$

3.2. Lens region

For this region it has been assumed that the defocussing influence of the space charge may be neglected and the particle trajectory is described by the Busch equation. The potential distribution along the lens axis may be obtained using one of the analog methods or by numerical calculations.

3.3. Drift region

The solution of the motion equation is given by the relation [3]

$$z = \frac{1}{R'_0} \int\limits_{1}^{R} \frac{dR}{\sqrt{A \ln R + 1}},$$

where $R = r/r_0$,
$R'_0 = r'_0/r_0$,
r — radius-vector,
r_0 — initial value of the radius-vector,
r'_0 — initial slope,

$$A = \frac{I}{2\pi\varepsilon_0 \sqrt{\frac{2e}{M}}\, U^{2/3} r_0},$$

where U — beam energy,
M — ion mass,
I — beam current.

For the low perveance of beam
$A \ln R \ll 1,$
hence,

$$z = \frac{R-1}{R'_0} - \frac{A}{2R'_0}[R(\ln R - 1) + 1] + \frac{3}{4}\frac{A^2}{R'_0}\left[\frac{R}{2}(\ln^2 R - 2\ln R + 2) - 1\right].$$

The particles moving along the trajectory create the space charge. The arbitrary trajectory $R(z)$ of the particle moving in the field of this charge may be calculated in the way similar to that used in the region of the proper gun.

It may be shown that [2]

$$R(z) = r(z)\left[C \int_{z_0}^{z} \frac{1}{r^2(z)} dz + D\right],$$

where C, D — constants.

4. Calculations and conclusions

The exemplified analysis of the ion gun properties has been carried out in the system shown in Fig. 3. The broken line was used to mark the planes separating the ion gun region from the lens region and the drift region. The calculations have been performed for the Ar^+ ion beam for ion currents $I = 1, 4, 8, 12$ 16 mA.

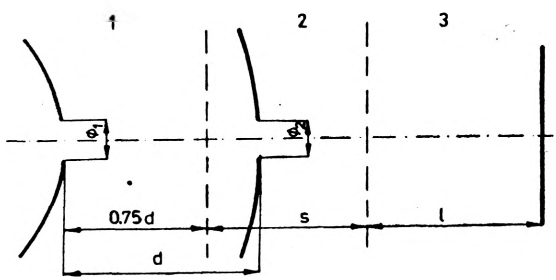

Fig. 3. Geometry of the analysed gun: 1 — proper gun region, 2 — lens region, 3 — drift region. $\Phi_1 = 3$ mm, $\Phi_2 = 4$ mm, $d = 8$ mm, $l = 30$ mm, $s = 3.3$ mm

In Figure 4 the results of calculations are given in the form of curves representing the dependence of complex elements of the transformation matrix $[M]$ upon the beam current and the extraction voltage.

The knowledge of all elements of the transformation matrix allows us to determine the beam emittance as well as to finalize its phase plot.

The analysis of the Fig. 5 indicates distinctly that the decrease of beam emittance with the increase of the beam energy is the greater the greater is the current value of the beam. In the case of not too great current value (1, 4, 8 mA) its influence on the beam emittance is weakening above the extraction voltage of about 18 kV. For the currents of higher value no region of the reduced influence on the emittance is observed. The evolution of the phase graph is presented in Fig. 6.

The positive slope of the phase graph axis indicates that the beam is divergent. The region of the proper gun has the largest influence on the properties of the emitted beam. The lens region has no decisive effect on the beam properties, although, under certain conditions ($I = 1$ mA, $U_z = 25$ kV) when the emitting surface is concave and the space charge density is high its influence on the value of the larger half-axis of the phase graph and on its slope becomes comparable with the influence of the drift region and the proper gun. The shorther the drift region the smaller is its effect.

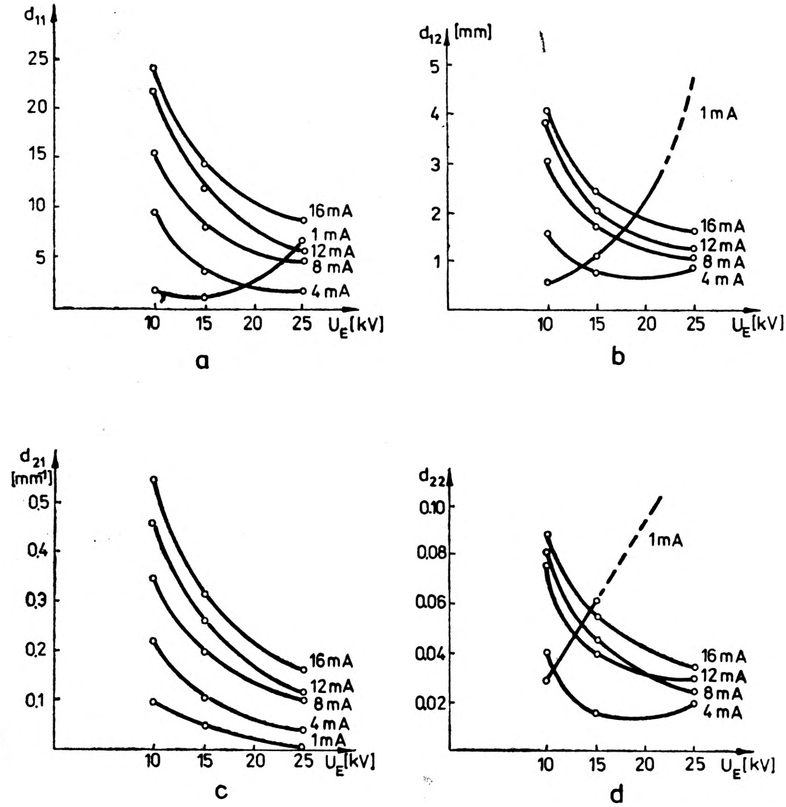

Fig. 4. Dependence of the elements of the complex transformation matrix upon the beam current and the extraction voltage: a — d_{11}, b — d_{12}, c — d_{21}, d — d_{22}

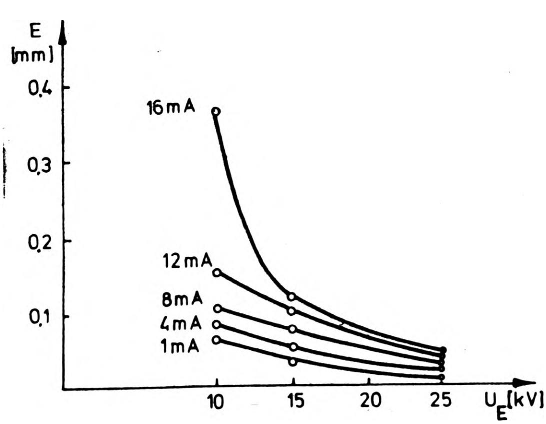

Fig. 5. Dependence of the emittance upon the beam current and the extraction voltage

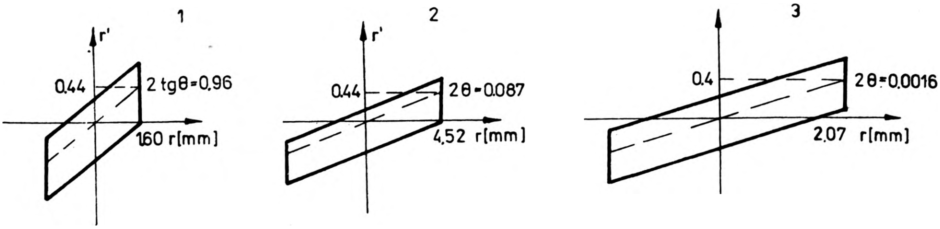

Fig. 6. Evolution of the phase graph of the beam during its run through the particular regions of the gun: $U_E = 15$ kV, $I = 12$ mA, 1 — plasma surface, 2 — lens region, 3 — drift region (end)

5. Experiment

The above conclusions have been verified experimentally. The scheme of the measuring system is shown in Fig. 7. This system is composed of three pairs of deflecting plane-parallel plates. Only this part of the beam that was introduced to the input of the system at the distance $x = k_1 v_1$ from the axis will pass through the aperture in the diaphragm

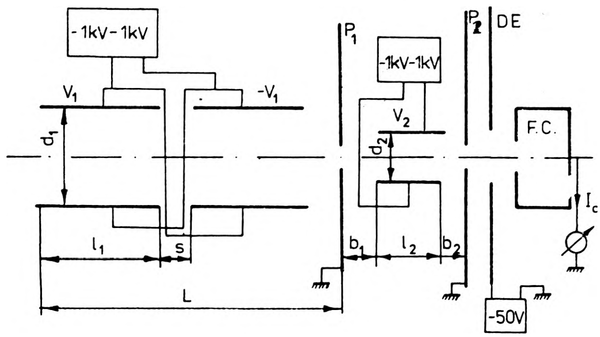

Fig. 7. Scheme of the system to measure the beam emittance. *DE* — decelerating electrode. $d_1 = 10$ mm, $l_1 = 56$ mm, $s = 72$ mm, $L = 185$ mm, $b_1 = 9$ mm, $d_2 = 5$ mm, $l_2 = 20$ mm, $b_2 = 16$ mm

P_1, while only the particles, whose trajectory inclination amounts to $x' = k_2 v_2$ will pass through the aperture in the diaphragm P_2. The purpose of the measurements is to find out to what degree the results of theoretical calculations are consistent with the experiment. It was expected that the absolute values of emittance and the phase graph slope would differ from the calculated values. The differences are, above all, due to the following assumptions and approximations:

— plasma surface is an ideal sphere,

— whole beam reaches the collector, while, in reality, the diaphragm in the extracting electrode creates the aperture,

— current density distribution in the beam is uniform,

— electrokinetic potential value is assumed to be independent of the extraction conditions.

The shift of the phase curves (Fig. 8) with respect to the origin of the coordinate system indicates most probably the inaccurate centering with respect to the measuring system.

The knowledge of the real value of emittance and the transformation matrix in the whole region of the gun allows to determine the electrokinetic potential U_T at the plasma surface. The results of calculations are presented in the table.

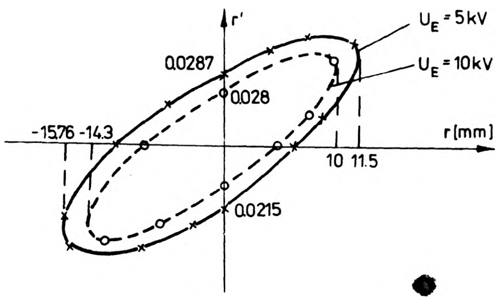

Fig. 8. Measured phase curves for: $U_E = 5$ kV, $I = 0.9$ mA, $U_E = 10$ kV, $I = 1.4$ mA

Table

U_E(kV)	I(mA)	E(mm)	U_T(V)	U_{anode}(V)
5	0.9	0.274	98.5	66
10	1.4	0.252	164.5	70

The obtained values of the electrokinetic potential are the measure of the average value of the initial energy of ions emitted by the plasma surface in a duoplasmotron. The high value of this energy follows from the existence of the "potential hill" in the intermediate electrode mode region, which causes the appearence of the directed ion streams of higher energy.

When investigating the energy distribution of ions D_3 extracted from duoplasmotron Bacon [4] has stated that the majority of ions have the energy exceeding the anode potential by about 20 V, but there exist ions, the energy of which exceeds the anode potential by about 100 V. In the case of other plasma ion sources, where directed ion streams do not exist, the initial energy of ions is connected only with their plasma temperature.

References

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Влияние условий экстрагирования ионов на параметры ионного пучка

Предложен теоретический метод анализа плазмового источника заряженных частиц. Для этой цели было произведено разделение источника на область собственно источника, линзы и пролёта. Анализ был произведён с помощью матричного исчисления. Описано влияние отдельных областей источника на эмитанс пучка, угол наклона фазого графика. Представлена зависимость светимости пучка от напряжения экстрагирования и тока пучка.