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ABSTRACT
This article presents a focused electrospray beam source and discusses its potential for microfabrication. Its main elements are an electrospray emitter electrode (a point source of charged nanodroplets), an extractor electrode, a skimmer electrode, and an Einzel electrostatic lens. The focusing parameters of the source are calculated by integrating the equations of motion of the charged droplets in the axisymmetric electrostatic field generated by the electrodes. The results of the model are validated with a laboratory source replica by characterizing the sputtered region produced by the focused beam on a silicon target and comparing it with the image obtained with the model. In the experiments, the size of the focused beam at the image plane is at least 20 times smaller than that of the unfocused beam, despite the presence of aberrations that have a negative effect on the ability to concentrate the beam. In a well aligned source, the sputtered area is close to a disk, and spherical and chromatic aberrations are the most significant nonidealities making the size of the image larger than the ideal one. When the emitter is deliberately misaligned, spherical and chromatic aberrations continue increasing the size of the image, while astigmatism distorts its circular shape. All aberrations are reduced by increasing the strength of the focusing electrostatic field while maintaining the net acceleration potential of the beam. The focusing column increases the particle density of the beam and advances the development of electrosprayed nanodroplet beams as a tool for surface engineering.

I. INTRODUCTION

The use of atomic and cluster ion beams in the form of broad ion sources and the focused ion beam (FIB) has contributed to the creation and improvement of surface modification techniques such as physical sputtering, doping, and thin-film deposition.1–5 These processes rely on the transfer of the kinetic energy of the beam particles to the target, which is intense enough to alter its atomic arrangement, leading, for example, to surface amorphization6,7 and sputtering.8,9 The size of the projectile is a major factor determining the outcome of the impact. For example, at the kinetic energies required for sputtering, an atomic projectile penetrates deep into the target, while a cluster ion such as Ar2000 exchanges its kinetic energy and is stopped within a few atomic layers from the surface. As a result, cluster ions exhibit a distinct impact phenomenology not observed with atomic ions.10,11 Beams of electrosprayed nanodroplets have been introduced recently to exploit projectile size effects beyond what is possible with cluster ions, which have effective diameters limited to a few nanometers.13,14 The diameter D of electrosprayed droplets can be controlled from a few nanometers to tens of micrometers, while their charge-to-mass ratio q/m scales more favorably than that of cluster ions (q/m ∝ D−3/2 vs q/m ∝ D−3). This makes it easier to electrostatically accelerate them into the hypervelocity range typical of particle beams. Electrosprayed nanodroplets impacting on semiconductors and ceramics exhibit high physical sputtering rates and can amorphitize the surface.15,16 The sputtering rates are especially high for materials as inert as SiC and GaN.17,18 The main sputtering mechanism is knock-on atomic collisions, while thermal evaporation plays a minor role.19 These studies suggest no limitation on the material that can be sputtered. At lower impact velocities, electrosprayed droplets have been used for molecular-level etching of native silicon.
oxide on surface,

Increasing the particle density of nanodroplet beams enhances the sputtering rate proportionally; this can be done via electrostatic focusing. Furthermore, the point source nature of an electrospray enables strong focusing: charged droplets are produced in the breakup region of a long and stationary jet, with dimensions of the order of the diameter of the droplets, i.e., of tens of nanometers. Similar to FIB, strong electrostatic focusing can be used for high spatial resolution of the sputtered region and maskless micro-machining. The goals of this paper are to study the theoretical and experimental aspects of the electrostatic focusing of electrosprayed nanodroplet beams and demonstrate its feasibility. Because of the similarities with FIB, we use this technology as a guide.

The focused ion beam was introduced in 1974 by Seliger and Fleming, using a liquid metal ion source for ion implantation. Seliger’s focusing column consisted of a symmetric Einzel lens and a double-deflector system, capable of reducing the beam spot to 3.5 μm from an object aperture of 150 μm. Seliger and collaborators later developed a scanning ion probe system with a beam spot size of 100 nm and a current density of 1.5 A/cm², using a liquid Ga source. Almost a decade later, Orloff suggested a Köhler illumination design to achieve a 10 nm beam diameter. This column consisted of two condenser electrostatic lenses, two octupole deflectors to bring the beam to the center of an E × B separator, two objective electrostatic lenses, and two scanning octupoles. Since the introduction of the gas cluster ions in 1988, FIBs can use these projectiles for low energy bombardment, ideal for applications such as surface smoothing. Currently, advanced FIB columns are similar to Orloff’s design, and further research aims at micro-FIB columns for low cost or improved resolution. The beam spot size and brightness are affected by source nonidealities such as spherical and chromatic aberrations and astigmatism. A few studies show how aberrations can be minimized in FIB to achieve higher resolution. Several nonidealities are inevitable. For example, spherical aberration results from the deflection of high-angle ion trajectories by the stronger field. Although it cannot be eliminated, it can be minimized by using a higher accelerating voltage. Astigmatism is due to alignment errors and depends highly on manufacturing precision. Chromatic aberration, caused by the finite distribution of particle energies, is directly related to the physics of the formation of the charged particles and therefore is a property of the source. This article discusses the design of a focusing column for electrosprayed nanodroplet beams, the mathematical representation of the aberration figures, and demonstrates the design with a laboratory apparatus used to sputter a silicon target.

II. ELECTROSTATIC FOCUSING AND MODELING

A. Focusing column

We show in Fig. 1(a) the schematic of the electrodes shaping the beam and the configuration of the electric potentials. The axisymmetric focusing column consists of a cylindrical emitter and several planar electrodes including an extractor, a skimmer, a three-electrode Einzel lens, and a target. The target and the downstream electrode of the lens are at ground potential; the emitter electrode is at potential \( V_{EM} \) above ground; a voltage difference \( \Delta V_1 \) is applied between the emitter and the extractor to electrospray the fluid; the extractor, the skimmer, and the upstream electrode of the lens are at the same potential \( V_{EXT} = V_{EM} - \Delta V_1 \); and the potential of the center electrode of the lens, \( V_2 \), is adjusted to control the trajectories of the particles. All potentials are kept positive with respect to ground. The whole beam produced by the emitter passes through an orifice perforated in the extractor, while an orifice in the skimmer restricts the entrance of most of the beam into the lens and fixes the half angle of its envelope to 2°. The smallness of this angle allows the paraxial approximation when computing particle trajectories.

B. Beam tracing

We compute the trajectory of a charged particle by integrating its equation of motion subject to the electric field induced by the electrodes while neglecting the Coulombic repulsion between charged particles. To improve the accuracy of the integration, which in any practical geometry must be done numerically, the governing equations are transformed into the so-called Pitch equation.

To derive it, we start with the Laplace equation for the axisymmetric electric potential \( V \),

\[
\frac{\partial^2 V}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V}{\partial r} \right) = 0, \tag{1}
\]

where \( z \) and \( r \) are the axial and radial cylindrical coordinates. The expansion

\[
V(z, r) = \sum_{n=0}^{\infty} A_n(z) r^n \tag{2}
\]

with

\[
A_{n+1} = -\frac{A_n''(z)}{4(n+1)^2} \tag{3}
\]

fulfills Eq. (1) and converges rapidly to the solution near the axis. Note that the first element in the recursive relation (3) is equal to the potential along the axis, \( V(z, 0) = A_0(z) \). This solution combined with conservation of energy, \( \frac{1}{2} m v^2 + q V = q V_{RP} = \text{constant} \), reduces the equation of motion of the projectile to an ordinary differential
equation (ODE) for $r(z)$,

$$\frac{d^2r}{dz^2} + \frac{1}{2} \frac{V_\phi'}{V_\phi} \frac{dr}{dz} = -\frac{r}{V_\phi} \frac{V_\phi''}{4 V_\phi},$$  \hspace{1cm} (4)$$

where $V_\phi = V_{RP} - A_0$. The retarding potential $V_{RP}$ of an electro-sprayed droplet is, in general, different from the potential of the emitter due to losses in the electrospaying process and falls within a distribution. In our calculations, we will use a typical voltage loss of 200 V to estimate the average retarding potential of the droplets, $V_{RP} = V_{EM} - 200$. The trajectory of the particle is determined by integrating Eq. (4) with the initial position and angle of the trajectory as initial conditions. Note that the charge to mass ratio of the particle does not appear in this equation. This equation requires knowledge of the potential at the axis and, since the potential field is calculated numerically, numerical errors, especially on its second derivative, add up when integrating the trajectory. These numerical errors are reduced by introducing the reduced radius $R = r V_\phi^{1/4}$ which, when inserted in Eq. (4), yields the Pitch equation,

$$\frac{d^2R}{dz^2} = -\frac{3}{16} R \left( \frac{V_\phi'}{V_\phi} \right)^2.$$  \hspace{1cm} (5)$$

We use MATLAB’s ODE45 to integrate the equation of motion and the software COMSOL Multiphysics to compute the potential field for given potentials applied to the electrodes. An external MATLAB function executes the finite element model in COMSOL’s electrostatic module. Figure 2(a) shows the potential field for $V_{EXT} = 10$ kV and $V_2 = 0.5 V_{EXT}$, while Fig. 2(b) shows the potential along the axis for several values of the ratio $V_2/V_{EXT}$. The geometry of the electrodes and their potentials is defined in the MATLAB function calling COMSOL.

Figure 3 shows two typical particle trajectories along the lens, computed with the Pitch equation (5), with the nonreduced equation (4), and by direct time-integration of Newton’s equation of motion using the paraxial approximation for the electric field. The maximum difference is 0.2 $\mu$m and corresponds to the trajectories initiated off axis at 0.392 mm (the skimmer’s aperture radius) and calculated with the Pitch equation and the time integration. All integrations are done with MATLAB’s ODE45 using the same integration tolerance of $10^{-8}$. Both the time integration and the integration of the nonreduced equation require estimating a higher order derivative of the axial potential. Since the associated truncation is the main source of error in the estimation of the trajectory, the integration of the Pitch equation is the preferred method for computing particle trajectories under the various conditions of the lens.

The characteristics of the lens are readily computed once the particle trajectories become available. In particular, Fig. 4 shows the first and second focal lengths, the distance between the image plane and the center plane of the lens, and the lens magnification as a function of the ratio $V_2/V_{EXT}$ and different values of the emitter potential. The voltage difference between the emitter and extractor is kept at 2000 V in all calculations in this article, $\Delta V_1 = V_{EM} - V_{EXT} = 2000$ V. The emission point is located 14.5 mm upstream from the center plane of the lens.

C. Aberration figures

The characteristics of the focusing column in Fig. 4 were obtained using the Pitch equation, i.e., a paraxial approximation that
FIG. 4. Lens characteristics as a function of \( V_z/V_{\text{EXT}} \) and for different values of the emitter potential: red filled squares, \( V_{\text{EM}} = 12 \) kV; green filled squares, \( V_{\text{EM}} = 14 \) kV; blue filled squares, \( V_{\text{EM}} = 16 \) kV; and cyan filled squares, \( V_{\text{EM}} = 18 \) kV. (a) First focal length from the center of the Einzel lens; (b) second focal length; (c) distance of the image place from center of the lens; and (d) lens magnification.

retains terms up to second order in Eq. (2). The image estimated with this approximation generally exhibits differences with the actual one known as aberrations. Fabrication and assembly imperfections, the paraxial approximation, and the finite distribution of retarding potentials in the beam are sources of different types of aberration such as astigmatism, coma, distortion, curvature of field, and chromatic and spherical aberrations.\(^{33-35,37,39,44}\)

Aberrations cause a deviation \( \delta r \) of the radial coordinate of projectile at the image plane. This deviation is not the same for all particles in the beam but depends on conditions such as the emission angles and the retarding potential. For example, projectiles with higher emission angles are subject to a stronger radial electrostatic force translating into increased deflection. Thus, rays starting from the same point in the axis with identical retarding potentials but different emission angles do not converge into a single point in the image plane but are distributed within a disk. This nonideality is called spherical aberration. The spherical aberration figure \( \delta r \) is proportional to \( \tan^3 \gamma_0 \), where \( \gamma_0 \) is the acceptance angle of the outermost ray of the beam, \( \delta r = C_{so} M \tan^3 \gamma_0 \). The coefficient of spherical aberration, \( C_{so} \), is computed by integrating between the axial positions of the source and the image plane, \( z_s \) and \( z_I \).

\[
C_{so} = \frac{1}{16} \int_{z_o}^{z_I} \left( \frac{V(z) - V_0}{V(z_0) - V_0} \right)^{3/2} \frac{h^4}{[V(z) - V_0]^2} \left\{ \frac{5}{4} \frac{V''(z)}{V(z)} + \frac{5}{24} \frac{V''(z)}{[V(z) - V_0]^2} \right\} dz, \quad (6)
\]

and the principal rays \( h \) and \( g \) are two independent paraxial trajectories with the initial conditions \( g(z_o) = 1, h(z_o) = 0, g'(z_o) = 0, \) and \( h'(z_o) = 1 \). A linear superposition of the principal rays forms the general solution of the lens tracing equations,

\[
X(z) = X(z_o) g(z) + X'(z_o) h(z), \quad Y(z) = Y(z_o) g(z) + Y'(z_o) h(z). \quad (7)
\]

The spherical aberration can be minimized by reducing the acceptance angle of the beam. In our focusing column, the skimmer limits
the beam half angle to $2\alpha$. The resulting spherical aberration is shown in Fig. 5(a) as a function of the ratio $V_2/V_{EXT}$ and different values of the emitter potential. The spherical aberration initially decreases at increasing lens potential, reaching a minimum at $V_2/V_{EXT} = 1.1$, and increases with emitter potential. At an emitter potential of 12 kV, the spherical aberration yields a minimum disk diameter of 34 μm. The projectiles are not uniformly distributed within this disk; instead, the beam is highly focused near the axis, while the particles closer to the envelope of the beam blur the image, forming the 34 μm disk.

Astigmatism is due to the misalignment of the electrodes and/or nonaxisymmetric initial conditions for the trajectories, both of which result in the breakdown of axial symmetry. This causes the circular cross section of the beam to become elliptical. The elliptical beam turns into two straight lines on two curved image surfaces known as the tangential and sagittal image surfaces. Somewhere between these two image surfaces, the beam cross section becomes circular. The deviation from the Gaussian image depends on the initial coordinates of the particle $(X_0, Y_0)$ in the plane perpendicular to the axis and the emission angle $\gamma_0$. In an ideal axisymmetric lens, the trajectory of a particle with initial derivatives $X'_0$ and $Y'_0$ intersects the image plane (located at $z_I$) at coordinates $(X, Y)$, i.e., at $r = \sqrt{X^2 + Y^2}$. The astigmatism figure is the line defined by $\delta X(z_I)$ and $\delta Y(z_I)$,

$$\delta X(z_I) = 2A \left( X_0' X_0'' + X_0 Y_0' Y_0'' \right),$$
$$\delta Y(z_I) = \frac{Y_0'}{X_0'} \delta X(z_I).$$

Szilagyi provides formulae for the coefficient of astigmatism $A$,

$$A = \frac{M}{32} \int_{z_0}^{z_I} \left[ \frac{V(z) - V_0}{V(z_0) - V_0} \right]^{3/2} \left\{ \frac{3 V''(z)}{2 \left[ V(z) - V_0 \right]^2} g^2 h^2 + \frac{8 V''(z)}{\left[ V(z) - V_0 \right]^2} \left( g g' h h' + 16 g^2 h^2 - \frac{2 V'(z) V''(z)}{\left[ V(z) - V_0 \right]^2} \right) \times \left( g g' h^2 + g^2 h h' \right) - \frac{2 V''(z)}{\left[ V(z) - V_0 \right]} \left( g^2 h^2 + g g' h h' \right) + 8 g g' h h' + g^2 h^2 + g^2 h h'' \right\} \frac{dz}{4 \left[ V(z) - V_0 \right]} g^2 h^2 \right\}.$$  

FIG. 5. Aberration figures as a function of $V_2/V_{EXT}$ and for different values of the emitter potential: red filled squares, $V_{EM} = 12$ kV; green filled squares, $V_{EM} = 14$ kV; blue filled squares, $V_{EM} = 16$ kV; and cyan filled squares, $V_{EM} = 18$ kV. (a) Spherical aberration; (b) astigmatism; (c) axial chromatic aberration; and (d) magnification chromatic aberration.
We show in Fig. 5(b) the astigmatism figure as a function of $V_z/V_{EXT}$ and the emitter potential for an emission point placed 20 μm off-axis. This value is representative of the tolerance with which we can center the emitter in the laboratory source. The astigmatism of the source decreases at an increasing $V_z/V_{EXT}$ ratio.

The natural variation of the retarding potentials of the electrosprayed droplets causes chromatic aberration. The focusing field modifies more easily the trajectories of particles with lower retarding potentials, yielding different trajectories for particles that otherwise are emitted from the same point with an identical initial angle. Similar to spherical aberration, chromatic aberration causes blurriness of the image. When modeled, the resulting trajectory deviation includes axial and magnification terms with coefficients $C_1$ and $C_2$, respectively. The axial chromatic figure depends on the beam acceptance angle and the retarding potential spread $\Delta V_0$, while the magnification chromatic figure depends on the offset of the source and $\Delta V_0$, 

$$
\delta r_{ch1} = M C_1 \tan \gamma_0 \frac{\Delta V_0}{2[V(z_0) - V_0]},
$$

$$
\delta r_{ch2} = M C_2 \left( X_0^2 + Y_0^2 \right)^{1/2} \frac{\Delta V_0}{2[V(z_0) - V_0]},
$$

where $C_1$ and $C_2$ are given by

$$
C_1 = \int_{z_0}^{z_l} \left[ \frac{V(z) - V_0}{V(z_0) - V_0} \right]^{1/2} \left( \frac{3 V''(z)}{[V(z) - V_0]^{2/3}} \right) dz,
$$

$$
C_2 = \int_{z_0}^{z_l} \left[ \frac{V(z) - V_0}{V(z_0) - V_0} \right]^{1/2} \left( \frac{V''''(z)}{8 [V(z) - V_0]^{2/3}} \right) gh + \frac{g'h'}{2} dz.
$$

Similar to spherical aberration, chromatic aberration cannot be compensated with an axisymmetric electric field. Spherical aberration is dominant in columns with large beam acceptance angles, while chromatic aberration dominates in beams with small acceptance angles. Measurements of retarding potential distributions of electrosprayed droplets can be found in the literature. A distribution width (i.e., approximately twice the standard deviation of the distribution) of $\Delta V_0 = 200 V$ is typical and has been used for our estimates. Figures 5(c) and 5(d) show the axial chromatic aberration figure for an acceptance angle of 2°, and the magnification chromatic aberration figure for an emission point 20 μm off-axis. The calculations show that spherical aberration and axial chromatic aberration are the dominant mechanisms limiting the focusing of the electrospray source.

The total aberration figure can be estimated by combining the different components as

$$
\delta r = \sqrt{\delta r_{ch1}^2 + \delta r_{ch2}^2 + \delta r_{sph1}^2 + \delta r_{sph2}^2}.
$$

For example, for a point source located 20 μm off-axis, an emitter potential of 12 kV, and a ratio $V_z/V_{EXT}$ = 0.5, the resulting image is a disk with a radius of approximately 121 μm. Based on Fig. 5, the size of the image can be minimized by increasing the lens potential, i.e., the ratio $V_z/V_{EXT}$, and to a lesser degree by increasing the potential of the emitter.

III. EXPERIMENTS AND DISCUSSION

Figure 6 shows a section of the laboratory electrospray source, designed for mounting on the flange of a vacuum chamber. The electrodes are machined on brass, while insulating components are made of Delrin. Although this method results on higher fabrication errors than our previous microfabrication approach based on plasma activated bonding of lens electrodes and insulators (made of silicon and Borofloat glass wafers, respectively), 46,47 it is a better prototyping approach because it is less expensive and parts can be more easily made, modified, and replaced. The emitter, a metallized fused silica tube with a 45° chamfered tip, is mounted on a fixture whose position in the plane perpendicular to the axis can be controlled with 4 μm with a nominal accuracy of ±0.005 mm. This allows control of the alignment between the emitter and the lens. We use 1.00 mm glass wafers as the spacers between the electrodes of the lens to both accurately control the geometry and for the excellent electrical insulating properties of glass. The tip of the emitter is located 1.00 mm from the extractor, 11.25 mm from the skimmer, and 14.50 mm from the center plane of the lens.

The ionic liquid EMI-Im (1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide) is electrosprayed, and the resulting beam is directed to a silicon wafer. The operation of the electrospray source in the vacuum chamber has been described in detail elsewhere. 55,56 The fused silica line working as the emitter extends into an external reservoir storing the liquid. An applied pressure difference drives the desired flow of EMI-Im to the tip of the emitter, forming an electrospray upon applying the required potential. A turbomolecular pump backed by a mechanical pump sets the pressure inside the vacuum below 2 μTorr. The target is mounted on an XYZ linear translation stage inside the vacuum chamber, controlled with stepping motors and a LabVIEW application. The target is placed at a distance $z_l$ from the center plane of the lens, previously calculated with the model. A high voltage power supply provides the three separate lines of DC voltage required for the experiments; two lines supply up to 20 kV and the third line supplies up to 10 kV. We vary the potentials in 10 V increments, a sufficient resolution for our experiments. The highest potential applied to the electrodes is limited by
the breakdown voltage of the insulating materials under vacuum. We were able to apply up to 15 kV on the emitter and the center electrode of the lens with no sign of voltage breakdown. We used a voltage difference of 2000 V between the emitter and the extractor electrodes in all experiments. The electrospray and the target were monitored with a camera mounted on a monocular microscope.

Gamero-Castaño tabulates characteristics of EMI-Im electrosprays such as the average charge to mass ratio of the droplets, the beam current, and the average retarding potential at different mass flow rates. EMI-Im has a molecular mass of 391.12 amu and a density of 1520 kg/m³. We have operated the source at emitter potentials between 12 kV and 14 kV. For a typical average charge to mass ratio of 1571 C/kg, these acceleration voltages result on estimated impact velocities between 6.1 and 6.6 km/s and molecular kinetic energies between 76.4 eV and 89.2 eV. When EMI-Im nanodroplets impact on the silicon surface at these velocities, significant sputtering of the target occurs. Figure 7 shows the image left on the target by the beam after 180 s of bombardment. The potentials applied to the electrodes are \( V_{EM} = 12.00 \text{kV}, V_{EXT} = 10.00 \text{kV}, \) and \( V_2 = 5.00 \text{kV}, \) and the target is placed 21.34 mm from the center plane of the lens. The slightly distorted circular impression in Fig. 7 has a maximum width of 102 \( \mu \text{m}. \) In the absence of focusing, the beam sputters a circle 2.4 mm in diameter, i.e., the focusing column is reducing the diameter of the image by a factor of 20 under the conditions in Fig. 7.

The location of the image plane calculated with the model is used as a guideline to place the target in the experiments. Once the target is placed, we adjust the lens potential \( V_2 \) around its nominal value to obtain the maximum focusing of the beam. The difference between the nominal lens potential and the experimental optimum is always small and is due to tolerances in the fabrication of the column and uncertainties in the positioning of the target relative to the source.

Figure 8 shows the image left by the beam on a target located 15.15 mm from the center plane of the lens. The emitter potential is 14.00 kV. The model for focusing at a point is \( V_2 = 5.64 \text{kV}, \) while in the actual experiment the optimum lens potential is 5.70 kV. Although the target has been sputtered within a relatively circular region with a diameter of 170 \( \mu \text{m}, \) there is a much smaller central region with a diameter of 7 \( \mu \text{m} \) that is deeply carved, which appears as a bright spot. This central region must correspond to an area of the beam where most of the particles are focused on. A dark gray region with a maximum width of 80 \( \mu \text{m} \) surrounds the central bright spot; this area also exhibits significant sputtering although not as intense as in the central spot. The image of the beam then extends outwards through a region where the target is slightly changed, to a diameter of approximately 170 \( \mu \text{m}. \) Aberrations are the likely cause for the varying intensity of the particle flux along the radius of the image, a hypothesis that can be tested by estimating the aberration figures. For example, we estimate an image diameter of 28 \( \mu \text{m} \) associated with the astigmatism of a source 20 \( \mu \text{m} \) off-axis. This circle, shown by a yellow dashed line, surrounds the central bright and deeply carved region. The spherical aberration disk can be accurately estimated since it is fully determined by the well-known beam acceptance angle and the potential along the axis. The resulting disk, shown by a red dashed line, has a diameter of approximately 140 \( \mu \text{m}. \) The chromatic aberration can then be estimated as \( \delta r_{ab} = \sqrt{\delta r^2 - \delta r^2_{sh} - \delta r^2_{ch}}, \) with \( \delta r = 170 \mu \text{m}. \) This yields a chromatic aberration figure of 46 \( \mu \text{m}, \) which requires a droplet retarding potential distribution with a width of 119.4 V, a value that falls within the range observed in experiments.45 Note that this estimate for the chromatic aberration matches well the 80 \( \mu \text{m} \) diameter circumference bounding the first blurred region surrounding the deeply carved spot. This analysis suggests that it is possible to focus most of the nanodroplet beam in a submicrometric region as long as astigmatism is reduced by improving the alignment of the electrodes. The highly focused region will be surrounded by a blur caused by the unavoidable spherical and chromatic aberrations. As suggested by Fig. 5, increasing both the potential of the lens and the potential of the emitter will help reducing this blur. Although the contribution of astigmatism to the size of the focused image is small compared to the spherical and chromatic aberrations, astigmatism noticeably distorts the image.

![Photograph of the target after been struck by a focused electrospray beam for 180 s. \( V_{EM} = 12 \text{kV, } V_{EXT} = 10.00 \text{kV, } V_2 = 5 \text{kV.} \)](image-url)
IV. CONCLUSION

Beams of electrospayed droplets are amenable to strong electrostatic focusing. The point source nature of an electrospay helps concentrate the beam, while the natural distribution of retarding potentials of electrospayed droplets causes significant chromatic aberration. The analysis of a simple focusing column composed by an emitter, an extractor, a skimmer, and an Einzel lens suggests that spherical and chromatic aberrations are the main factors limiting the minimum beam spot size in an actual implementation. The characterization of a laboratory source confirms this hypothesis and furthermore shows that although spherical and chromatic aberrations cause a blur of the image with the expected size, most of the beam is focused on a much smaller spot limited by astigmatism in our implementation. The spherical and chromatic aberrations can be reduced by increasing the strength of the focusing field and the potential of the emitter. We expect that the much higher particle flux and the smallness of the beam spot made possible by electrostatic focusing will enable carving substrates of ceramics and other hard materials at rates orders of magnitude higher than what is possible with FIB technology, although with lower spatial resolution due to the natural chromatic aberration of a beam of electrospayed nanodroplets.

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