Optimization of focused ion beam performance

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The authors have analyzed how much current can be obtained in the probe of an optimized two-lens focused ion beam (FIB) system. This becomes relevant, as systems become available that have the potential to image and/or fabricate structures smaller than 10 nm. The probe current versus probe size curves were calculated for a commercial gallium-FIB, the nano-FIB system, and the helium microscope, using partly published, partly estimated system parameters. The current in sub-10 nm probes in the Ga systems turns out to be limited by the reduced brightness of the source and the chromatic aberration of the objective lens. In probes larger than 40 nm the current is limited by the angular current density and the spherical aberration of both lenses. The He system is limited at all probe sizes by the angular current density of the source and the chromatic aberration of both lenses in sub-5 nm probes and the spherical aberration of both lenses at probes larger than 10 nm. As the emission current of the He source is much smaller than that of the Ga source, the statistical Coulomb interactions in the gun lens region do not contribute to the total probe size, as is the case for the Ga systems. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3237132]

I. INTRODUCTION

In the rapidly expanding field of nanoscience and nanotechnology one needs tools capable of fabricating structures of sub-10 nm size. Focused ion beam (FIB) systems have that potential. However, it will be necessary to improve the design of the ion beam column such that the optimum performance is achieved, i.e., the largest possible current in a given probe size. We first consider a two-lens system based on a gallium liquid metal ion source (LMIS), which is the most frequently used ion source in FIBs. The smaller the spot into which a particle beam is focused, the smaller the probe current will be. For relatively large ion probes the current in the probe is determined by the chromatic aberration of both lenses and the angular current density at the current limiting aperture. This is a well known fact and it has been described by many workers.[1] However, going to smaller spot sizes the probe current is no longer determined by the angular current density but it is limited by the source brightness and the chromatic aberration of the probe forming lens. This fact apparently has been overlooked by many FIB designers, e.g., Ref. 2. The analysis below is similar to the analysis done by Kruit *et al.*,[3] who investigated the potential use of carbon nanotube electron emitters in electron microscopes.

II. CURRENT IN A PROBE

Typical FIBs are two-lens systems, consisting of an ion source, a gun lens, an objective lens, and a current limiting aperture, as sketched schematically in Fig. 1. The current limiting aperture, which limits the half-opening α at the probe, corresponding to a half-angle α_a at the source, is assumed to be at the position of the gun lens. When viewed from the aperture plane the ions seem to come from a circular area of diameter d_v, called the virtual source. The angular current density at the acceleration voltage V_a is determined from the current I, measured behind the aperture, and the solid angle subtended by the aperture, i.e.,

$$J_{\Omega a} = I/(\pi\alpha_a^2), \tag{1}$$

$J_{\Omega a}$ and the virtual source diameter define the reduced brightness of the ion source as[4]

$$B_r = \frac{4J_{\Omega a}}{\pi d_v^2 V_a}. \tag{2}$$

To form an ion probe the virtual source is imaged on a specimen with a total magnification M. As the reduced brightness is a conserved quantity throughout the ion optical system, the current in the probe is determined from

$$I = B_r\frac{\pi}{4}(Md_v)^2\pi\alpha^2 V, \tag{3}$$

where V is the accelerating voltage at the probe. In reality, however, this current is distributed over a blurred image of the source, as a result of diffraction and lens aberrations. To obtain the total probe size d_p, one usually adds the different contributions quadratically, but Barth and Kruit[5] have shown that the full width 50% (FW50), i.e., the width that contains 50% of the current, is best approximated by the following root power sum.

$$d_p = \{[d_I^{1.3} + (d_A^4 + d_S^4)^{1.3/4}]^{2/1.3} + d_C^2\}^{1/2}, \tag{4}$$

where d_I, d_A, d_S, and d_C are the FW50 diameters of the contribution from the source image, the diffraction disk, the spherical aberration, and the chromatic aberration, respectively. These contributions are given by

$$d_I = Md_v = M\left(\frac{4J_{\Omega a}}{\pi B_r V_a}\right)^{1/2}, \tag{5}$$

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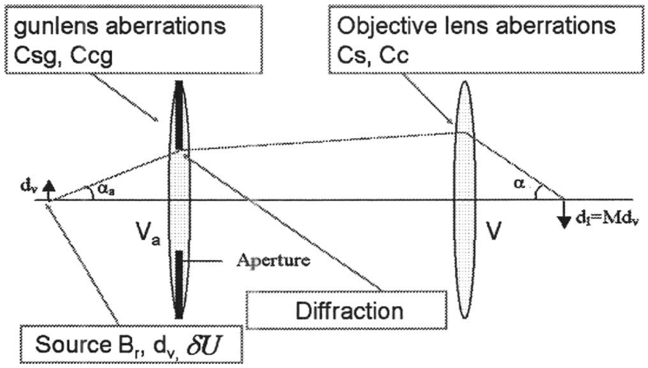

FIG. 1. Schematic drawing of a two-lens focused ion beam system. The properties determining the total probe size are indicated as d_v (virtual source diameter), B_r (reduced brightness), δU (FW50% energy spread), Ccg and Csg (chromatic and spherical gun lens aberration), Cc and Cs (chromatic and spherical objective lens aberration), diffraction due to the current limiting aperture, α_a (half-angle at the aperture plane), V_a (accelerating voltage at the aperture plane), α (half-angle at the probe), V (accelerating voltage at the probe), M (total magnification), and d_I (source image).

$$d_A = 0.54 \frac{M\Lambda}{V_a^{1/2}\alpha_a}, \tag{6}$$

with

$$\Lambda = \frac{h}{(2\times 10^{-3} e m_{\text{ion}}/N_A)^{1/2}} \quad (\text{in mV}^{1/2}), \tag{7}$$

where h is Planck's constant, e is the elementary charge, m_{ion} the atomic weight of the ions, and N_A is Avogadro's number,

$$d_S = K_S M \alpha_a^3 \left[Csg + \frac{1}{M^4}\left(\frac{V_a}{V}\right)^{3/2} Cs \right], \tag{8}$$

$$d_C = K_C M \alpha_a \frac{\delta U}{V_a}\left[Ccg + \frac{1}{M^2}\left(\frac{V_a}{V}\right)^{3/2} Cc \right]. \tag{9}$$

Here we took into account the aberrations of the gunlens, characterized by the chromatic aberration coefficient Ccg and spherical aberration coefficient Csg, and the objective lens with aberration coefficients Cc and Cs. δU is the FW50 of the source energy distribution, in which case the constant K_C is 0.6 [K_C=0.34 for δU being the full width at half maximum (FWHM) of the energy distribution]. The constant K_S is equal to $(1/2)^{5/2}$. We chose to express the aberration contributions in terms of the half-angle α_a at the aperture position, although we could have expressed them just as well in terms of the half-angle at the probe. Inserting Eqs. (5), (6), (8), and (9) in Eq. (4), the total probe size as a function of the total magnification M and the half-angle α_a takes the following form:

$$d_p = \left\{ \left[a_1\left(\frac{M}{\alpha_a}\right)^{1.3} + \left(\left(a_2\frac{M}{\alpha_a}\right)^4 + \left(\left[a_3 M + \frac{a_4}{M^3}\right]\alpha_a^3\right)^4\right)^{1.3/4}\right]^{2/1.3} + \left(\left[a_5 M + \frac{a_6}{M}\right]\alpha_a\right)^2 \right\}^{1/2}. \tag{10}$$

All other variables are lumped together in the constants a_1 to a_6. Equation (10) contains terms proportional to powers of M and terms inversely proportional to powers of M. That means that for a given half-angle α_a an optimum magnification exists, for which the total probe size d_p is minimum. The optimum magnification, in fact, determines an optimum half-angle at the probe α for which the contributions to the probe that increase with α (objective lens aberrations) balance the contributions that decrease with α (diffraction, source image, and gun lens aberrations). The current in the minimum probe is obtained from α_a and Eq. (1).

We will calculate the current versus optimum probe size curves for three different systems. First a typical FIB with a Ga LMIS. Second the nano-FIB system,[2] a FIB that was optimized for 5 nm fabrication resolution. Third the recently introduced helium-ion microscope Orion.[6] These systems are particularly interesting for the following reasons. The Ga-FIB is the workhorse of the FIBs used in the semiconductor industry and is often used for high-current milling applications. In the high-current regime the optimum probe is determined by the angular current density and the chromatic aberrations of the lenses. For low-current operation, and small probe sizes this is no longer true, and the present analysis will reveal what limits the probe size in this regime. The nano-FIB system is similar to the Ga-FIB, in the sense that it is also based on a Ga-LMIS, although with a different design than the commercial FIBs. Its optics is optimized for high-resolution milling, i.e., small probe size and low currents. It is claimed that by increasing the angular current density more current is obtained in the probe, suggesting that the current in the probe is limited by the angular current density.[2] It is therefore interesting to see whether this is true indeed in the small probe, low current regime. The He microscope is interesting to analyze because it has a gas field ionization source (GFIS), which is supposed to have a much smaller virtual source size [0.3 nm (Ref. 6)] than the Ga LMIS [38 nm Ref. 7]. To image such a small, almost pointlike, source into a few-nanometer probe the magnification is expected to be of the order of 1, in contrast to the large demagnification needed to image the LMIS into a few-nanometer spot. In the latter case the aberrations of the gunlens will be demagnified and will hardly contribute to the probe size. But in the GFIS case the gunlens aberrations may become equally important as the objective lens aberrations. Therefore, it is interesting to analyze what limits the probe size in this machine.

III. RESULTS

To calculate the current versus probe size curves for the three systems the parameter values were chosen as shown in Table I. For the LMIS in the Ga-FIB the measured reduced brightness at the quoted angular current density and gun lens voltage was taken from Ref. 7, corresponding to a virtual source diameter of 38 nm [Eq. (2)]. In Ref. 7 it was argued that the large virtual source size of the LMIS is, in fact, due to the statistical Coulomb interactions in the gun region, causing trajectory displacement of the ions. The energy spread is taken as 5 eV, a widely adopted value for the Ga

TABLE I. Values of the properties used to calculate the current in the probe of an optimized-focused ion beam system, for three different systems: a Ga FIB, using data from Ref. 7, the nano-FIB (Ref. 2), and the He FIB (Ref. 6). The properties listed are B_r (reduced brightness), d_v (virtual source diameter), $J_{\Omega a}$ (angular current density at the aperture plane), δU (FW50% energy spread), V_a (accelerating voltage at the aperture plane), Ccg and Csg (chromatic and spherical gun lens aberration), Cc and Cs (chromatic and spherical objective lens aberration), and V (accelerating voltage at the probe).

	Ga-FIB	nano-FIB	He microscope
B_r (A m^{-2} sr^{-1} V^{-1})	6×10^5	6×10^5	2×10^9
d_v (m)	3.8×10^{-8}	3.8×10^{-8}	0.3×10^{-9}
$J_{\Omega a}$ (A/sr)	2×10^{-5}	2×10^{-5}	2.5×10^{-6}
δU (V)	5	5	1
V_a (kV)	30	30	20
Csg (m)	0.25	0.25	0.25
Ccg (m)	2×10^{-2}	3×10^{-2}	2×10^{-2}
V (kV)	30	30	20
Cs (m)	0.5	0.1	0.5
Cc (m)	2×10^{-2}	2.2×10^{-2}	2×10^{-2}

LMIS. The aberration coefficients are usually proprietary information, so we made educated guesses, based on typical lens design parameters. For the nano-FIB system the aberration coefficients were published[2] for an early version of the system, so we can make better guesses here. Unfortunately the reduced brightness of the Ga source in this system was not measured, and therefore we assume the same source parameters as for the Ga-FIB. To be able to compare the two systems we assumed both systems to operate at 30 kV. The He microscope source parameters were taken from Ref. 6 at an acceleration voltage of 20 kV. The energy spread for this source is believed to be only 1 eV. Due to a lack of data, we chose to use the same aberration coefficients as for the Ga-FIB. Figure 2(a) shows the probe current versus probe size curve for the Ga-FIB system. Apart from the total probe size also the separate contributions to the total probe size are shown. It is clearly seen that at low current and small probe sizes the probe is dominated by the contributions from the source image and the chromatic aberration of the objective lens. The magnification is sufficiently small [see Fig. 2(b)] to make the contributions from the gun lens aberrations negligible, and, as expected, the diffraction term is completely absent. At high currents the optimized magnification is seen to become independent of the current [Fig. 2(b)] and the probe is seen to be completely dominated by the spherical aberration of both lenses. In Fig. 2(c) the optimized half-angle at the probe is shown as a function of the probe current. At high currents the angle increases rapidly which is why the aberrations start to dominate. Figure 3(a) shows the probe current versus probe size curve and the separate contributions for the nano-FIB system. The behavior is very similar to the Ga-FIB shown in Fig. 2. Figure 3(b) shows the comparison between the two systems, as well as a few data points of a published current-probe size curve for a FEI Company Ga-FIB.[8] The agreement between our calculations and the published data shows that our educated guess for the

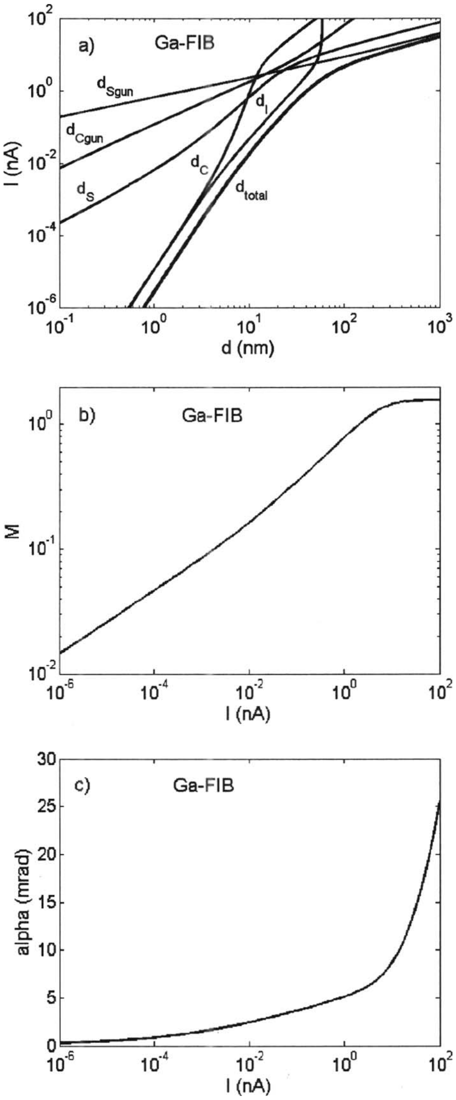

FIG. 2. (a) Probe current (I) vs probe size (d) curve for the Ga FIB. The total probe size is indicated as d_{total}. Also shown are the contributions to the total probe size from the source image (d_I), the spherical aberration of gun lens and objective lens ($d_{S\text{gun}}$, respectively, d_S), the chromatic aberration of gun lens and objective lens ($d_{C\text{gun}}$, respectively, d_C). All probe diameters are FW50 values. (b) The total magnification M as a function of the current I in the probe. (c) The half-angle at the probe (α) as a function of the current (I) in the probe.

aberration coefficients is pretty good. From Fig. 3(a) it is seen that for probe sizes between 1 and 10 nm the current is limited by the source image contribution (i.e., by the reduced brightness) and the chromatic aberration of the objective lens. In Ref. 2 it is argued that by increasing the angular current density, as a result of a higher extraction voltage, one gets more current in the probe. That is true but the probe is then no longer optimized. By increasing the angular current density the virtual source size increases, as well as the source image. So one ends up with more current, but in a larger probe. Optimizing the probe will result in exactly the same amount of current as for the lower angular current density, as dictated by the reduced brightness of the source. At larger probes there might be an advantage in going to higher angu-

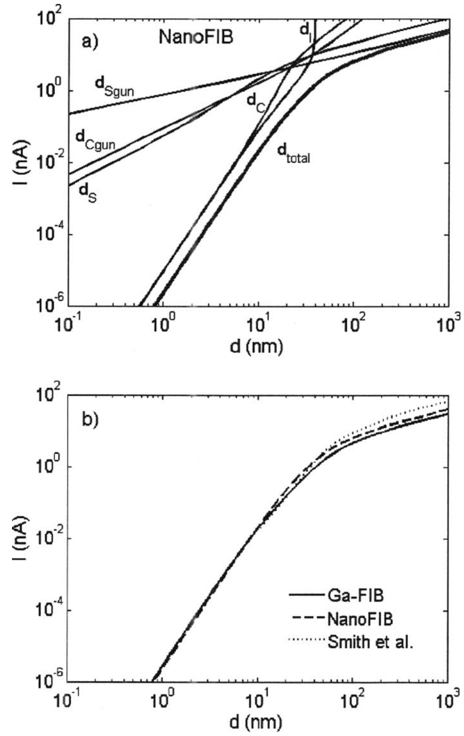

FIG. 3. (a) Probe current (I) vs probe size (d) curve for the nano-FIB (Ref. 2). The total probe size is indicated as d_{total}. Also shown are the contributions to the total probe size from the source image (d_I), the spherical aberration of gun lens and objective lens ($d_{S\text{gun}}$, respectively, d_S), the chromatic aberration of gun lens and objective lens ($d_{C\text{gun}}$, respectively, d_C). All the probe diameters are FW50 values. (b) The nano-FIB compared to the Ga-FIB from Fig. 2. Also shown are data from Smith *et al.* (Ref. 8), for a 30 keV Ga LMIS system, to compare our calculations with.

lar current densities, but more detailed calculations, including the exact geometry of the gun and the extractor electrode, would be needed to evaluate that. The required larger extraction voltage would certainly reduce the effect that the statistical Coulomb interactions in the source region have on the virtual source size.

Figure 4 shows the results for the He microscope. In Fig. 4(a) it is seen that for the light helium ions, diffraction is not negligible anymore in the low current regime. Below 100 fA the probe is dominated by the diffraction and the chromatic aberration of the objective lens. The smallest achievable probe size of 0.25 nm is in agreement with what has been claimed to be the resolution of the Orion instrument.[6] Interestingly one observes that nowhere the current is brightness limited. For probe sizes of around 1 nm the current is determined by the chromatic aberrations of the lenses, whereas at larger probe sizes the current is limited by the spherical aberrations. In the latter regime the magnification again becomes independent of the current, as is seen in Fig. 4(b). For completeness the half-angle at the probe is shown in Fig. 4(c).

IV. DISCUSSION

The calculation results have shown that the probe current in both the Ga-FIB and the nano-FIB is brightness limited

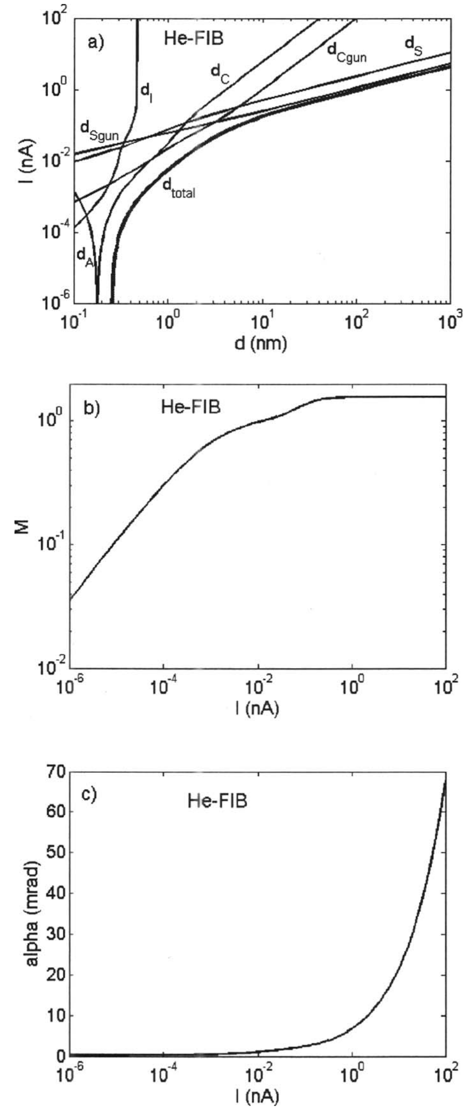

FIG. 4. (a) Probe current (I) vs probe size (d) curve for the He FIB. The total probe size is indicated as d_{total}. Also shown are the contributions to the total probe size from the source image (d_I), the diffraction (d_A), the spherical aberration of gun lens and objective lens ($d_{S\text{gun}}$, respectively, d_S), the chromatic aberration of gun lens and objective lens ($d_{C\text{gun}}$, respectively, d_C). All probe diameters are FW50 values. (b) The total magnification M as a function of the current I in the probe. (c) The half-angle at the probe (α) as a function of the current (I) in the probe.

for probe sizes smaller than 10 nm. In contrast, the probe current in the He microscope is not brightness limited over the full range of achievable probe sizes. In the high current regime the probe current in all three systems is determined by the spherical aberrations of both lenses. By observing that in certain regimes some probe contributions dominate over others we can derive approximate analytical expressions for the probe current as a function of probe size. Such expressions make more explicitly visible which parameters determine the probe current in specific regimes.

If, at low currents, the chromatic aberration of the objective lens is the dominant factor to blur the source image, we only have to keep the terms with a_1 and a_6 in Eq. (10). The current in the probe of FW50 size d_p is then given by

$$I_p = 1.71\frac{d_p^4 V^3 B_r}{\delta U^2 Cc^2}, \tag{11}$$

where δU is the FW50 of the energy spread (for a FWHM energy spread the prefactor is 5.4). If the spherical aberration dominates the blur we only keep the terms with a_1 and a_4 in Eq. (10) and the current in the probe of FW50 size is

$$I_p = 2.47\frac{d_p^{8/3} V B_r}{Cs^{2/3}}. \tag{12}$$

If the source image can be neglected and the chromatic aberrations of both lenses determine the probe size we only keep the terms with a_5 and a_6 in Eq. (10). The optimized magnification then results from balancing the chromatic aberration of the gun lens with the chromatic aberration of the objective lens and turns out to be independent of the current. The probe current in the FW50 probe size is then given by

$$I_p = 2.18\frac{d_p^2 J_{\Omega a} V_a^{1/2} V^{3/2}}{\delta U^2 Ccg Ccp}. \tag{13}$$

At high currents we can similarly balance the spherical aberration of the gun lens with the spherical aberration of the objective lens, i.e., keep the terms with a_3 and a_4 in Eq. (10). Again the optimized magnification of the system is independent of the current and the probe current is given by

$$I_p = 6.86\frac{d_p^{2/3} J_{\Omega a} V^{1/4}}{Csg^{1/2} Cs^{1/6} V_a^{1/4}}. \tag{14}$$

Most of the regimes where these approximate expressions are valid can be recognized in Fig. 5(a) for the Ga-FIB and in Fig. 5(b) for the He microscope. The power laws of Eqs. (11)–(14) are drawn in these figures together with the probe current versus probe size curves. For the Ga-FIB at low currents it is evident that Eq. (11) is a good approximation, and from this equation it is immediately seen that the current is limited by the reduced brightness and the chromatic aberration of the objective lens. At high currents it is clear that Eq. (14) approximates the results well, and the current is accordingly limited by the angular current density and the spherical aberration of both lenses. For the He microscope it is seen in Fig. 5(b) that the approximations of Eqs. (11) and (12) are not valid in any regime, but for currents ranging from 1 to 50 pA, the current is limited by the angular current density and the chromatic aberration of both lenses, according to Eq. (13). Thus, for pointlike sources like the He GFIS the high reduced brightness is not very useful because the lens aberrations dictate the performance. For currents above 50 pA the probe current is limited by the angular current density and the spherical aberration of both lenses, as described by Eq. (14).

A final comment should be made on the effect the statistical Coulomb interactions may have on the probe size. For the Ga-FIB and the nano-FIB the trajectory displacement of the ions due to the statistical Coulomb interactions in the gun region was effectively taken into account, as the large virtual source size of the Ga LMIS is caused by these interactions. However, for the He microscope we assumed a virtual source size of 0.3 nm, which is rather an estimated value based on the fact that the ions are emitted from a single atom tip. The trajectory displacements may very well enlarge this tiny source size. Its effect can be easily estimated by using the analytical equations from Janssen and Kruit.[9] At 20 keV extraction voltage the emission current is about 50 pA.[6] The average distance L_z between the ions, as given by

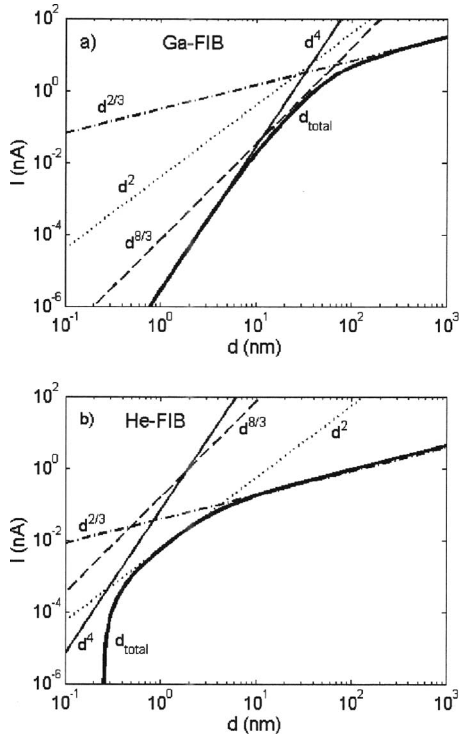

FIG. 5. Analytical approximations for the probe current I vs probe size d relation compared to the optimized calculation results (indicated as d_{total}) for the Ga-FIB (a) and the He-FIB (b). Indicated are the probe size power laws d^4, $d^{8/3}$, d^2, and $d^{2/3}$ corresponding to the probe current vs probe size relations given in Eqs. (11)–(14), respectively.

$$L_z = \frac{1}{I}\sqrt{\frac{2e^3 V_a}{m_{\text{ion}}}}, \tag{15}$$

is approximately 3 mm, i.e., much larger than the beam radius in the gun region. Therefore, we can safely assume that the relevant particle regime is the so-called pencil beam regime for which the contribution to the virtual source size due to trajectory displacement is

$$d_{\text{traj,pencil}} \simeq 0.145\frac{m_{\text{ion}}^{3/2}}{e^{7/2}\varepsilon_0}\frac{I^2 L^3 \alpha_a}{V_a^{5/2}}, \tag{16}$$

where L is the length of the gun segment up to the current limiting aperture. It is noted that the field is assumed to be uniform here, although in reality the accelerating field in the gun region is not. For L being equal to the value of Ccg, i.e., 2 cm, the trajectory displacement is 0.24 pm, i.e., extremely small. In case the current limiting aperture is further down the column, let us say at 10 cm from the source, the trajectory displacement would be 30 pm, still negligibly small. Therefore, at such small emission currents the effect of the statistical Coulomb interactions on the final probe size can safely be neglected. When using larger currents, however, and a current limiting aperture which is not in the gun lens, the Coulomb interactions will start affecting the probe size.[10–12]

V. CONCLUSIONS

We have analyzed three focused ion beam systems which have the potential to be used as tools to fabricate and/or image sub-10 nm structures: a commercial Ga-FIB, the nanoFIB system, and the He-ion microscope (Orion). We have calculated the largest possible current that can be achieved in a specific probe size for each system, using parameters that partly could be found in literature and partly were guessed in an educated way. It was found that the Ga-FIB and the nanoFIB behave very similarly, with the current in probes smaller than 10 nm being limited by the reduced brightness of the ion source and the chromatic aberration of the objective lens. At larger probes the current is limited by the angular current density at the aperture plane and the spherical aberration of both lenses. In contrast, due to its much smaller virtual source size, the probe current in the helium microscope is not limited by the reduced brightness at small probe sizes, but rather by the angular current density and the chromatic aberrations of both lenses (in the current range of 1–50 pA) and by the angular current density and the spherical aberration of both lenses at larger probe sizes and currents above 50 pA. To further optimize the Ga-LMIS systems one would have to optimize the gun lens design to minimize its chromatic aberration. This also holds for the He system which, in addition, would benefit also from an improved objective lens design with smaller aberrations, if still possible. The statistical Coulomb interactions in the gun lens region are known to deteriorate the reduced brightness of the Ga LMIS. This has been taken into account for the Ga systems by using realistic values for the virtual source size. For the He system, however, the emission current is so small, only 50 pA compared to 1 μA for the Ga LMIS, that the trajectory displacement due to the statistical Coulomb interactions hardly leads to an increased virtual source size.

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