Use of the Rise Distance Method to Measure Beam Size of a FIB

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Introduction

The performance metric of greatest interest to the user of a focused ion beam (FIB) system is generally its resolution. Because of the difficulty in defining and measuring the resolution of a FIB system directly, its performance is often assessed using a method related to the beam quality instead [1, 2]. This consists of the measurement of the *rise distance* of the beam current as the beam passes across an edge, which, for low currents where spherical aberration can be neglected, is closely related to the full width at half maximum (FWHM) of the current density of the ion beam [3]. The edge, also known as the "knife edge," corresponds to a sharp discontinuity in a specimen, as can be practically found on the surface of a graphite specimen. Because the rise distance can be used to obtain an idea of the dimension of the waist of a beam, it is, perhaps, an indication of the quality of an instrument. Because the rise distance depends on the quality of an edge, it is sometimes called *edge sharpness*. This concept bears similarities with the *image sharpness* method developed to assess the performance of SEMs, usually on gold nanoparticles on carbon specimen [4]. Rise distance is actually a convolution of the current density distribution with the properties of the knife edge and depends strongly on the spatial distribution of the secondary electron yield of the edge. By using the rise distance, different systems can be compared in a quantitative way [5]. To compare instruments, the identical specimen must be used and the measurements must be done in an identical way. This article discusses the method and some pitfalls in its application.

Rise Distance Method

The rise distance of a focused beam system is often called resolution. It does not relate straightforwardly to resolution because the definition often proposed for resolution, following Rayleigh, refers to the ability to distinguish two objects in an image. The edge sharpness is a convolution of the beam current density distribution with the spatial distribution of the edge. The concept of the rise distance measurement is shown in Figure 1 for a beam described by a current distribution J(r) ($A \cdot cm^{-2}$). As a beam crosses a knife edge (either a physical discontinuity or an actual edge), the current striking the knife edge increases, and a plot of the intercepted beam current against position looks like what is depicted in Figure 2. In this case, the current density distribution J(r) of a FIB was calculated and then integrated to give the current I(x) as a function of position. Experimentally, the intercepted beam current is measured via secondary electrons (Figure 3).

Some Experimental Problems

Although the rise distance method appears to be an appropriate way to estimate the beam size of a FIB, some source of errors or misinterpretation must be kept in mind. First, what is detected is not the beam current itself but rather the secondary electrons produced by the beam; if the secondary electron yield is not constant, artifacts can be produced. Second, instrumental problems such specimen drift and damage may play a role, but provided the right selection of experimental parameters and specimen—so far graphite has proven favorable in this respect—they turn out to be fairly minor. Third, the noise issue is important because in a single beam sweep any individual pixel may contain only a few ions. The variability of the secondary electron yield may be important.

Figure 3 shows an actual rise distance measurement made by sweeping a 1 pA Ga^+ ion beam rapidly over a discontinuity in a graphite specimen. The effect of noise is significant as each pixel in the image sees only a few ions. Although the actual FWHM of the beam is ~4 nm, in the single sweep shown in Figure 3 the beam has a 20-percent to 80-percent rise distance of 1.8 nm. Clearly a single measurement can lead to significant error.

In Figure 4 we show the distribution of 10,000 20-percent to 80-percent rise distances resulting from a theoretical calculation of the "noisy" current for a FIB, from Figure 2b. For simplicity, the data are presented as a series of bins of width 0.5 nm located at x_i = 2.75 nm, 3.25 nm, 3.75 nm, 4.25 nm, 4.75 nm, and 5.25 nm, containing 2, 110, 2192, 6717, 964,

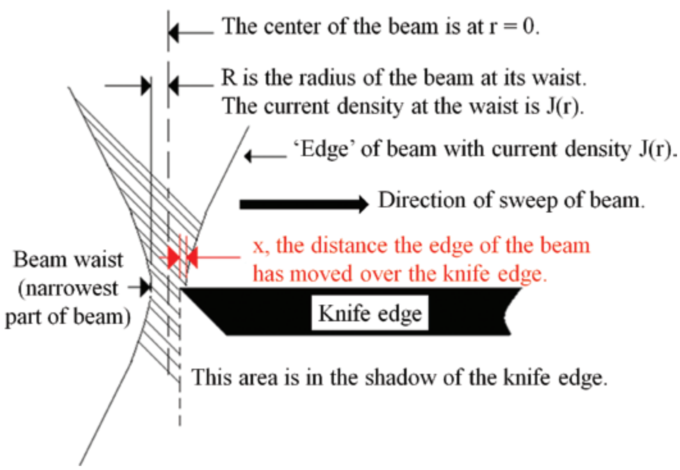

Figure 1: The concept of a rise distance measurement. As the beam sweeps from left to right, the current intercepted by the knife edge rises from 0 to 100 percent of its full value. The distance over which this takes place is a measure of the beam size (see Figure 4).

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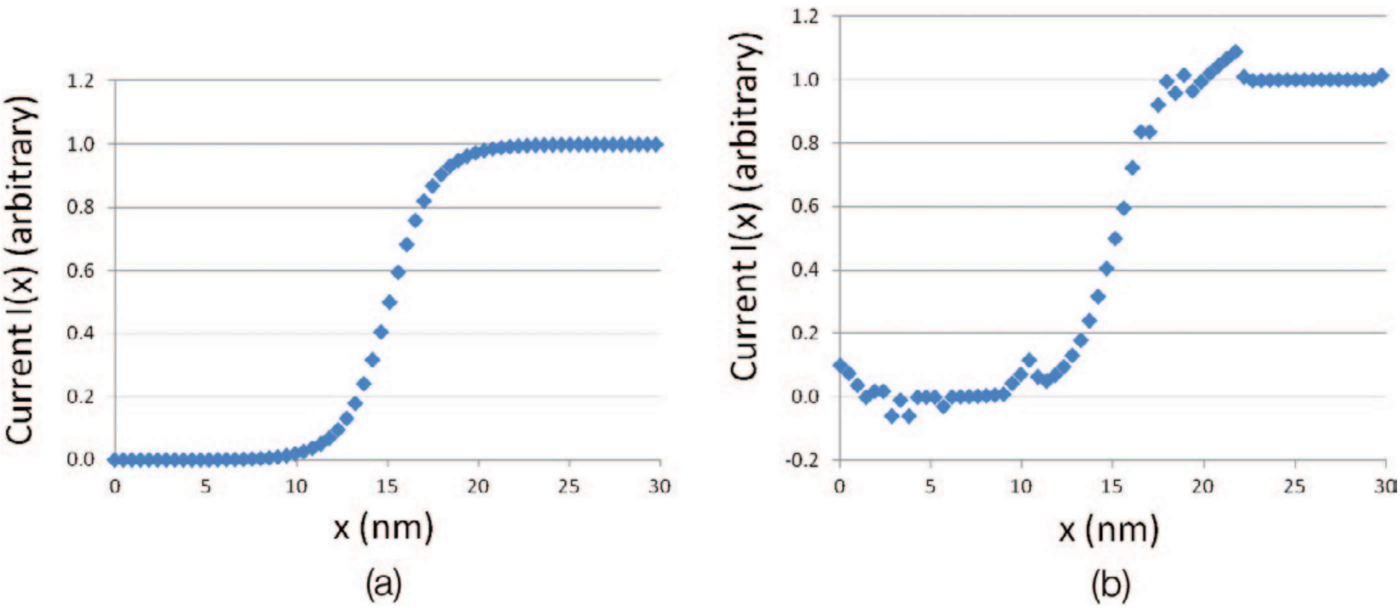

Figure 2: (a) The calculated rise distance measurement for a given Ga ion beam and (b) the rise distance for the same Ga ion beam as Figure 2a, with random noise added.

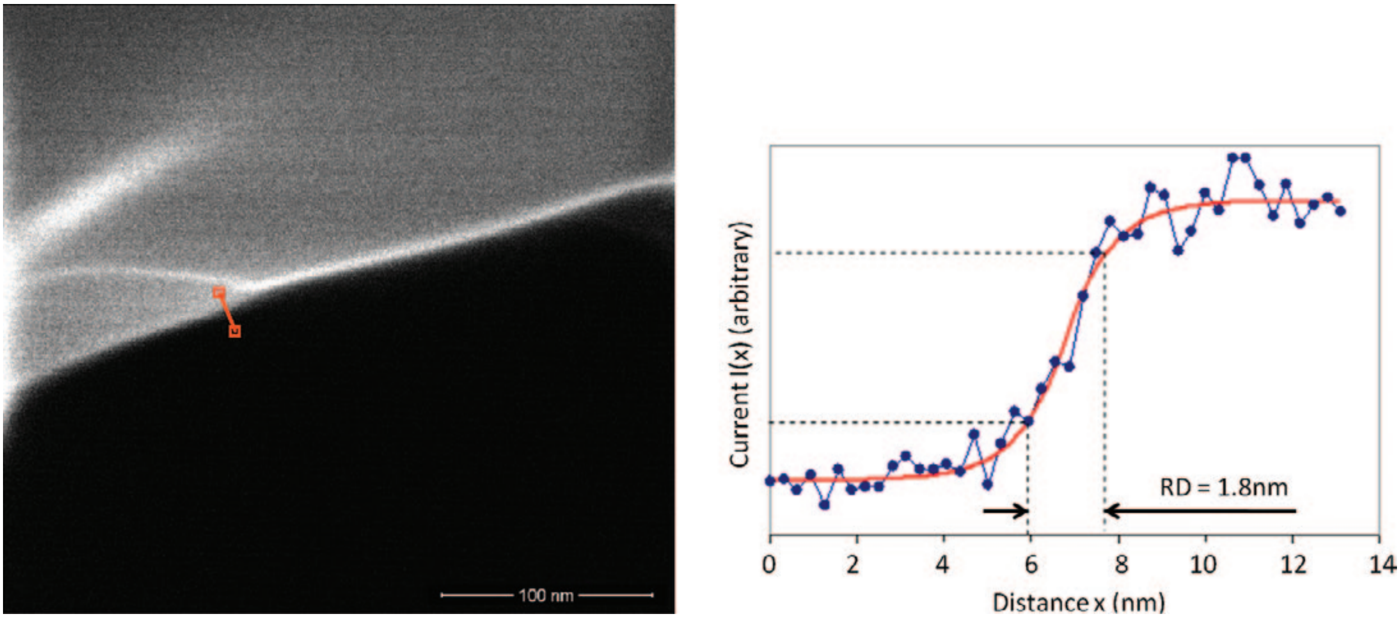

Figure 3: An experimental rise distance measurement showing the fluctuations due to beam statistical noise. A sharp edge within a graphite specimen is being used here as a knife edge. At the location shown by the red arrow in the micrograph, the beam increases from 20 percent to 80 percent of its full value in a distance of 1.8 nm. Note the bright line at the edge at the right side of the micrograph (see discussion in the text).

and 15 measurements, respectively. For these data the average rise distance was 3.7 nm, and the variance was 0.3 nm. The smallest rise distance, 2.75 nm, lies 3 standard deviations from the mean. The probability of this would be about 1 part in 8,000, so the odds of finding a 2.8-nm rise distance are small.

The Case of Non-uniform Knife Edge

Yet another problem with the rise distance measurement comes from a non-uniformity of the knife edge and a consequent varying secondary electron yield. Consider an ion beam with current density distribution J(r) that strikes a knife edge with a curved end of radius rc, as shown in Figure 5. The secondary electron yield depends strongly on the angle between the beam direction and the normal to the specimen surface. A simulation of the yield of secondary electrons from Si bombarded by 30 keV Ga^+ ions was made by Ohya and Ishitani [6]. We used their results to calculate the effect on the rise distance measurement of the non-uniform secondary electron yield from the knife edge. We found that the results depend strongly on the relative magnitudes of the radius rc and the FWHM radius of the current density, as shown in Figures 6a and 6b.

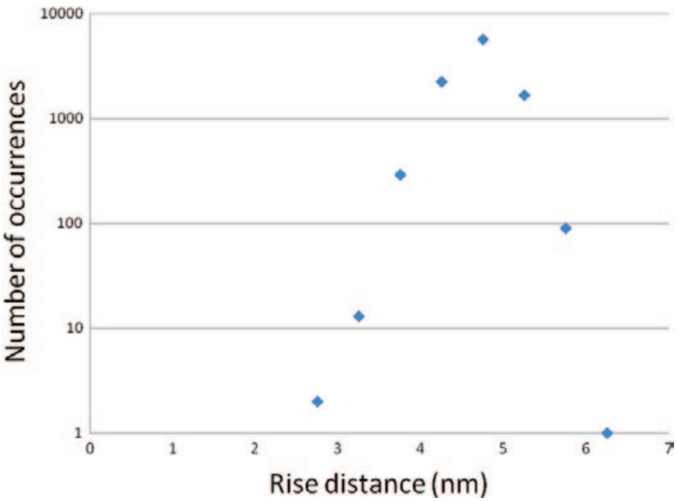

Figure 4: Simulated distribution of 10,000 20-percent to 80-percent rise distances calculated for a FIB system with 1 pA current suffering from shot noise in the beam current proportional to the square root of the current. The average rise distance was 3.7 nm for the conditions chosen, and the standard deviation for the shot noise limited beam was 0.3 nm. Note the vertical scale is logarithmic.

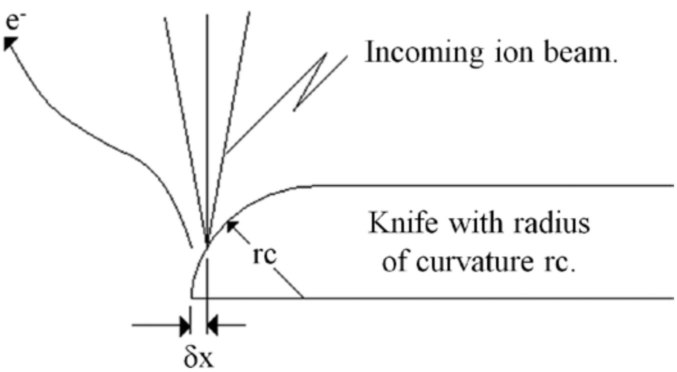

Figure 5: A knife edge with a curved edge of radius rc is scanned by an ion beam. The center of the beam has moved a distance δx from the end of the knife edge. e^- represents a secondary electron.

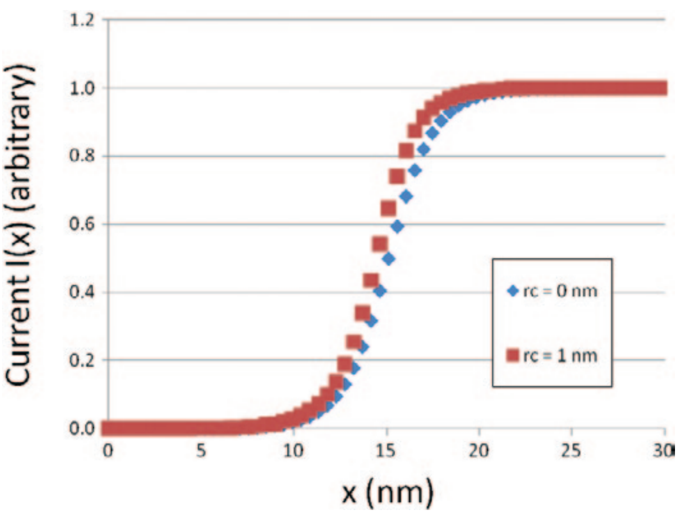

Figure 6a: The rise distance of a beam with FWHM ≈ 4 nm striking a rounded knife edge with radius rc = 1 nm and rc = 0 nm. The 20-percent to 80-percent rise distances are 3.1 and 3.5 nm, respectively, where the maximum value of the current is used in each case. Note there is no statistical noise in these figures.

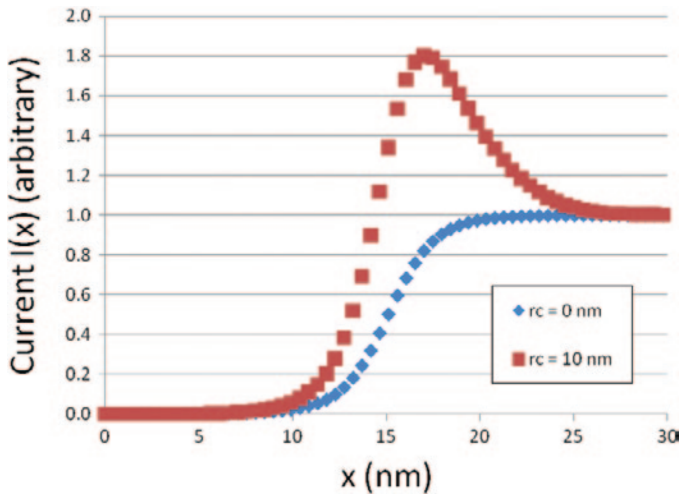

Figure 6b: The rise current I(x) calculated for beam with r_{FWHM} ≈ 4 nm for a knife edge with a radius of curvature rc = 10 nm and for rc = 0 nm. In both cases the results are normalized to the current for the largest value of x. The rise distances are 2.2 and 3.5 nm, respectively. rc = 10 nm = 2.5* r_{FWHM}.

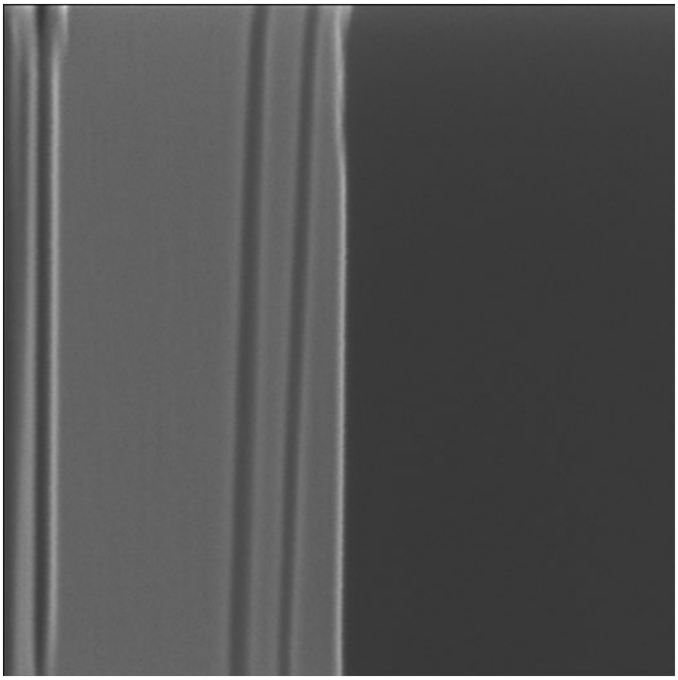

Figure 7: A micrograph of a knife edge taken with a Ga^+ ion beam. Note the bright line at the right edge of the specimen, corresponding to the effect shown in Figure 6b. The effect is stronger than in the micrograph shown in Figure 3.

Clearly, in the case where there is a curvature larger than the beam FWHM, the results are distorted, possibly severely. An actual example is shown in Figure 7. Although the dimensions and exact morphology of the non-uniformity of the knife edge are not known, it is clear that there is an edge effect causing a significant increase in secondary electron emission.

Conclusions

We believe it is reasonable to conclude that rise-distance measurements offer realistic estimates of the size of the waist of a FIB. However, it is critically important that the measurement be done in a reproducible way so that one can have confidence in its reliability. That means making enough measurements to ensure statistical validity and avoiding "cherry-picking" of the data to make it appear the result is better than it actually is. As is always the case in attempting to measure quantities such as resolution, there are numerous factors that can lead to significant inaccuracies. The issue of beam noise can easily be accounted for by averaging the results. The issue of distortion of the results due to specimen morphology can be taken into account by looking carefully to see whether the rise distance is strictly monotonic. If these issues are not considered, the results are likely to be optimistic. All measurements of this type must be evaluated with great care.

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