Pitfalls in the Measurement of FIB Beam Size

On the Way to an Accurate Estimation of the Focused Ion Beam Size

Focused ion beam (FIB) systems using heavy ions such as Ga are widely used for machining at the 10 - 100 nm level. In order to be able to perform this function precisely it is necessary to have an accurate estimate of the beam size. The commonly used method to measure FIB size is the rise distance method, well known in scanning electron microscopy (SEM), but this is subject to a number of errors that can result in an estimate that is optimistic relative to the true beam size. Unfortunately, the lessons learned from SEM about possible inaccuracies in the method seem to have been lost in scanning ion microscopy. We discuss one source of error and show how it may be avoided.

Introduction

One of the most important parameters of a focused ion beam (FIB) system is the beam size. It is the beam size that determines, to a large extent, the usefulness of the system. FIB systems using liquid metal ion sources (LMISs) are widely used for micro (nano) -machining. If one needs to mill 20 nm openings in a semiconductor device, the beam clearly needs to be < 10 nm in size. Therefore it is important to have a reliable and accurate way to estimate the beam size.

Since the primary application of a FIB is milling rather than imaging, classical methods for determining the size of a beam in an electron microscope are not terribly useful. Point-to-point resolution is dependent mainly on the narrowest part of the beam - the top ~10% of the current density distribution. The current in the tails of the distribution affect the image contrast but not so much the resolution. Another problem, of course, is that with a heavy ion (Ga, e.g.) FIB the beam will rapidly erode small features used for point-to-point measurements, making it difficult to obtain accurate results. The method most often used to estimate the beam size of a FIB is by measuring the distance over which the current striking a well defined edge rises from one value to another. This is called the rise-distance method [1, 2, 3] (and references therein) What is usually measured is the secondary...
electron current generated when the ion beam strikes the edge (often called a knife edge), because most FIB systems are set up to detect mainly the secondary electrons (fig.

1) rather than the ion beam itself, although that can certainly be done. Because of the simplicity of this method more precise methods such as one proposed by Harriot [4], are much less frequently used.

The rise-distance method is conceptually straightforward, but there are a number of experimental pitfalls that should be kept in mind when using it. The problem is that their effect often leads to an underestimate of the true rise-distance, thus giving a false idea of the capabilities of a system. Two important pitfalls include: 1) varying secondary electron yield due to knife edge morphology and size and/or varying secondary electron yield for a given beam-specimen angle; 2) statistical effects resulting from shot noise. The effect of statistical fluctuations has been discussed in some detail previously [5]; we are interested here only in pitfall #1, although we wish to emphasize that statistical fluctuations in beam current can lead to very significant spreads in the results of rise distance measurements of a given beam and a very significant under-estimation of a true beam size.

**Experimental Results on the Effect of Knife Edge Shape and Size**

A LaB6 crystal was used as a knife edge. It was mounted in a specimen holder and its potential relative to ground could be adjusted. The specimen holder also contained a small Al plate underneath the LaB6 and electrically isolated from it. Secondary electrons generated when the ion beam struck the Al plate were detected and served to allow an amplified measurement of the transmitted ion current. The Al plate had no structure and so the secondary electron current generated on it by the ion beam was essentially exactly proportional to the ion
current. In this arrangement, by changing the relative potentials of the LaB₆ crystal and the Al plate it was possible to switch rapidly between detecting secondary electrons and detecting the transmitted ion current.

Figures 2a and 2b represent typical images recorded using the secondary electron detector mounted above the FIB sample. In figure 2, the LaB₆ knife edge is located in the left hand side of the image. The Ga⁺ ion beam impinges the sample from above and secondary electrons are captured by the detector. The radius of curvature at the edge of the cleaved LaB₆ sample causes a changing angle of incidence for the ions, causing an increased secondary electron yield and a concomitant brightening of the image at the edge of the sample (fig. 3). When the LaB₆ crystal is held at ground potential and the Al plate is charged positively, secondary electrons created by the Ga⁺ ion beam impinging on the Al plate are prevented from escaping, so the image of the area where the Al plate is located appears dark.

An average of several line scans over the LaB₆ crystal is shown in figure 3. The secondary electron current shows a clear signature of the changing secondary electron yield of the crystal while the ion current shows no structure - it is identical to what would be obtained from an infinitely sharp knife edge.

The immediately obvious effect of the bright edge in the "standard" image scan (Red Data Set) is the inability to differentiate this curve and extract a meaningful FWHM from the data. One usually assumes a Gaussian (or Gaussian-like) beam spatial intensity profile when operating at low ion currents, the integral of which results in a scan profile much like the data from the transmitted Ga⁺ beam in which there is no bright edge. Differentiation of this data set would result in a Gaussian (or Gaussian-like) curve from which one could infer a FWHM. An example of this is shown in figure 4 where the raw and fitted (non-linear least squares fit to a Gaussian) data resulting from the differentiation of the transmitted current.

There are some interesting features of this result. The transmitted ion curve corresponds to what one would get for the secondary electrons if the secondary yield η(x,y) was constant. The maximum value of the secondary electron curve is a function of the relative sizes of the ion beam and the radius of the knife edge. The fact that the secondary electron current rises to a value near the knife edge that is several times its final value results in a rise distance quite different from the transmitted current, as shown in table 1. Indeed the error can be as much as 25%, which means that since FIBs and SEMs are capable of 5 nm beam sizes or better, for practical purposes rise distances measured using secondary electron current...
will tend to be optimistic because it is difficult to produce a knife edge with a radius of curvature significantly less than 5 nm.

**Discussion**

It is important to be able to measure the beam size of a FIB in order to be able to apply it to fine micromachining tasks. Since the beam size is generally estimated by measuring the rise distance across a knife edge it is important to know that such measurements are reliable. There are two main sources of error when measuring rise distance - statistical fluctuations and the effect of the shape and size of the knife edge. As has been shown [5], the effect of statistics can be quite large - about one time in ~10^4 an instrument that averages a 5 nm rise distance can be expected to produce a result of around 2 nm. However, this is a simple problem to avoid and any result that shows significant noise in the rise distance data should be ignored.

By measuring the secondary electron current rise distance and comparing with the transmitted current rise distance we see that the former measurement can give a distorted result for the beam size. The considerable increase in secondary electron yields, due to the large angle (close to 90°) between the beam and the specimen normal at the point where the beam first encounters the knife edge, results in a spike in the secondary electron current. The secondary yield is several times larger than when the beam has moved to the right and the angle between the beam and the specimen normal is closer to 0°. As a result of this steep increase in secondary electron current the apparent rise distance is reduced, and this can result in an apparent reduction of the beam size by as much as 25%. To avoid error it would be necessary to measure the radius of curvature of the knife edge and then do a calculation to estimate the amount of correction that would be needed. Alternatively, one could detect the transmitted ion current and plot the result directly. The latter is a much simpler and probably more accurate approach.

**References**


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